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SEG ltr, 11 Aug 1967

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ASD-TDR-63-203

FINAL REPORT ON IMPOSED HIGH FREQUENCY VIBRATIONS AND THEIR EFFECT ON CONVENTIONAL GRINDING OF HIGH THERMAL RESISTANT MATERIALS

TECHNICAL DOCUMENTARY REPORT NR. ASD-TDR-63-203
January 1963

Fabrication Branch
Manufacturing Technology Laboratory
Aeronautical Systems Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

ASD Project NR: 7-757

Prepared under Contract AF 33(600)-40122 by the Sheffield Corporation: Subsidiary of Bendix Corporation, Machine Tool Research Laboratory, Dayton, Ohio, Richard N. Roney, Dante Giardini

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ASD-TDR-63-203

FINAL REPORT ON IMPOSED HIGH FREQUENCY VIBRATIONS AND THEIR EFFECT ON CONVENTIONAL GRINDING OF HIGH THERMAL RESISTANT MATERIALS

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Prepared under Contract AF 33(600)-40122 by the Sheffield Corporation: Subsidiary of Bendix Corporation, Machine Tool Research Laboratory, Dayton, Ohio, Richard N. Roney, Dante Giardini

ASD TDR-63-203
Sheffield Corporation
Dayton, Ohio

Dated: January 1963

MANUFACTURING METHODS FOR IMPOSED HIGH FREQUENCY VIBRATION SYSTEMS

FINAL TECHNICAL DOCUMENTARY REPORT NR: ASD - TDR - 63-203
January 1963

ASD Project NR 7 - 757

Written by:

Project and Chief Technical Engineer — Richard N. Roney

Ultrasonic Engineer — Dante Giardini

Approved by:

Manager Machine Tool Division — Walter M. Burkart

The work reported in this document has beer made possible through the support and sponsorship extended by the AFSC Aeronautical Systems Division, Wright - Patterson Air Force Base under Contract No. AF33(600)-40122. It is published for information only and does not necessarily represent recommendations or conclusions of the sponsoring agency.

FOREWORD

This Final Technical Documentary Report covers all work performed under AF33(600)-40122 from 2 October, 1959 to 15 November, 1962. The manuscript was released by the authors on January 24, 1963 for publication as an ASD Technical Report.

This contract with the Sheffield Corporation, of the Bendix Corporation, Dayton, Ohio, was initiated under ASD Manufacturing Methods Project 7-757, "Imposed High Frequency Vibration System and its effect on Conventional Grinding of High Thermal Materials". It was administered under the technical direction of Floyd Whitney of the Fabrication Branch, Manufacturing Technology Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base Ohio.

Sheffield personnel are R. N. Roney, Project and Chief Technical Engineer, and D. Giardini, Ultrasonics Engineer. The entire project was under the guidance of Mr. Walter Burkart, Manager of the Machine Tool Division, Sheffield Corporation.

This project has been accomplished as a part of the Air Force Manufacturing Methods Program. The primary objective of the Air Force Manufacturing Methods Program is to develop, on a timely basis, manufacturing processes, techniques and equipment for use in economical production of USAF materials and components. The program encompasses the following technical areas.

Rolled Sheet, Forgings, Extrusions, Castings, Fiber and Powder Metallurgy
Component Fabrication, Joining, Forming, Materials Removal
Fuels, Lubricants, Ceramics, Graphites, Non-metallic Structural Materials, Solid State Devices, Passive Devices, Thermionic Devices.

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional Manufacturing Methods development required on this or other subjects will be appreciated.

ABSTRACT
TECHNICAL DOCUMENTARY REPORT

ASD - TDR 63-293
24 January. 1963

FINAL REPORT ON IMPOSED HIGH FREQUENCY VIBRATIONS AND THEIR EFFECT ON CONVENTIONAL GRINDING OF HIGH THERMAL RESISTANT MATERIALS

R.N.Roney and D. Giardini
THE SHEFFIELD CORPORATION
SUBSIDIARY OF BENDIX CORP.
MACHINE TOOL LABORATORY

Vibrations from 60 cycles to 40,000 cycles per second were investigated for possible application to grinding. Direct vibration of the part being ground and vibration of the grinding wheel itself were used. Most successful in performance was the wheel vibrating in the 20,000 cycles per second frequency range. Benefits to conventional grinding are lower grinding temperature, lower power to grind, greater grinding ratios, no impairment to surface finish, no impairment to mechanical properties as to cracks, fatigue or tensile strength, even though using harder wheels than those normally used.

An internal, external and surface grinder was modified to an ultrasonic grinder by attaching an ultrasonic spindle which vibrated the special ultrasonic wheel and hub assembly.

Numerous grinding tests were made from which test criteria were established for the simulated production runs made on each of the three grinder types.

Operational feasibility, adaptability to specific grinding operations, design variations and substantiation of previous findings were made. Simulated production grinding runs showed that on Ti6Al-4V, the volume removed improved over four fold and grinding ratios improved five fold. On H-11, the grinding ratios improved two to three fold and on 15-7 MO, the grinding ratios improved nearly two fold with 50% power reduction.

Procurement specifications, on industrial ultrasonic grinding machines, basically in the form of supplements to existing specifications, were made to include centerless as well as surface, external and internal grinders.

* *

PUBLICATION REVIEW

This Report has been reviewed and is approved.

FOR THE COMMANDER:

J R Marsh
Jack R. Marsh
Assistant Chief,
Manufacturing Technology Laboratory
Directorate of Materials and Processes

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LIST OF CHARTS, TABLES, GRAPHS, AND PHOTOGRAPHS

LIST OF ABBREVIATIONS AND SYMBOLS

A_L	Longitudinal Amplitude
AM	Amplitude Modulation
A_R	Radial Amplitude
B & K	Bruel & Kjaer
B F O	Beat Frequency Oscillator
CPS	Cycles per Second
div. or division	50 millionths of an inch
d	Bar diameter
db	Decibels
dm	Average Diameter
E.M.F.	Electromotive Force
F	Fahrenheit
F_r	Radial Resonant Frequency
FM	Frequency Modulation
FPM	Feet Per Minute
g	A unit of acceleration equal to 32.16 feet per second
ips	Inches per Second
kc	Kilocycle
N	Poisson's Ratio
P	Density of Rod
P-P	Peak to Peak
R_C	Rockwell Hardness (C scale)
R M S	Root Mean Square
R P M	Revolution per Minute
S A E	Society of Automotive Engineers

LIST OF ABBREVIATIONS AND SYMBOLS (continued)

SFM-SFPM	Surface Feet per Minute
S-N Curve	Stress vs. Number of Cycles
X	Magnification
λ	Wave Length
Yo	Young's Modulus of Rod
VAW Meter	A device used to measure voltage, current and power
ι	Direction of vibration particle motion

Grinding Wheel Marking
A sample or typical marking is given below:

Abrasive Type		Grain Size		Grade		Structure		Bond Type		Manufacturer's Record
A	-	36	-	L	-	5	-	V	-	23

SECTION 1

1.1 Introduction

The materials necessary to prevent complete or partial disintegration by frictional heat, fatigue and others, frequently fall in the category of High Thermal Resistant Materials. There are numerous instances now, and there will be many more in the future, of present machining practices being pushed to the limit in order to fabricate or generally alter the part geometry.

Though the present state of the machining art is in most cases capable of altering parts to desired configuration, there is a need in certain fields, such as the grinding field, for more rapid material removal rates, as well as certain improvements desired, as in alleviation of surface residual stresses, surface checking, lower grinding temperatures, etc.

If economical methods of producing and changing the configuration of a part made of these super alloys were possible, costs of space vehicles and high speed aircraft would be considerably less; materials presently available with excellent required characteristics could be used, and machining time could be brought within the realm of economic possibility. It is toward a solution of these problems that this project is directed.

Until the last few years there was little use for any High Thermal Resistant Materials as conventional aircraft, automotive equipment, electrical appliances and all other items produced in this country and abroad could very easily use conventional materials which could be easily altered to any part configuration desired. With the advent of the space age, new methods of machining and forming parts had to be developed. The development of adequate machining methods, while they have increased in leaps and bounds, have not nearly stayed abreast of the new materials developed.

Within the past decade, vibrations of high frequencies up to 40,000 cycles per second have permitted machining of the materials of hardness beyond the realm of possibility during World War II. Germanium, quartz, glass, ferrites are some of these materials which are beyond the realm of normal machining but which are being machined with ultrasonics in limited sizes. It is thought that these ultrasonic vibratory units, in combination with that of conventional machining methods, could result in a definite increase in material removal rate, alleviate residual stresses, hardness change, and surface cracking.

The application of vibrations to conventional grinding has been used by grinding operators on piece part rates. They have been known to deliberately induce vibrations to the wheel mount to increase grinding rates, and thus, number of pieces per hour. Some experimental work, from 60 to 120 cycles per second, has been conducted by Russian Scientists. Some published data are available concerning vibrations induced to the wheel by metal embedded within the grinding material and on applications of ultra - sonics to workpieces while grinding.

1.2 Purpose

The purpose of this project is to determine if the application of induced vibrations of varying frequencies, including ultrasonics, either into the workpiece or the grinding wheel, will alleviate production problems of grinding in the series of super alloys currently planned for use in aircraft, engines and missiles. These problems are of such magnitude at present, that certain of these steels present bottlenecks and serious production obstacles which are restraining weapons systems design advancements. It may be possible as a result of this project to completely eliminate such problems or considerably improve grinding operations of these super alloys. Positive results should considerably raise the level of confidence in accepting and extending practical use of various grinding processes.

This project is divided into three phases. Phases I and II were generally exploratory. Phase III is fundamentally the application of the process as developed in Phase I and II to simulated production grinding involving surface, internal, and external or cylindrical grinding.

Total program length, originally scheduled for two years, has been extended principally for a materials testing program run in Phase II.

PHASE I - PRELIMINARY EXPERIMENTAL WORK

1.3 TEST MECHANISM & WHEEL & SAMPLE RECOMMENDATIONS

1.3.1 Test Material Selection

In the initial portion of the project, to evaluate instrumentations, test specimen coupling, and over all adaptability of the various modes of vibration, specimens of SAE 1020 were used. As these were proved out under test, SAE 4340 and 440C Stainless and 15-7MO were added. Test specimen dimensions are 1/2" X 1/2" X 3".

The four materials selected for actual testing after coupling methods, vibration modes and frequencies had been determined through test and experimentation as representative samples of High Thermal Materials, approved by Manufacturing Methods Division, Wright-Patterson Air Force Base are:

1. H-11 die steel hardened to RC 56-58
2. Titanium Alloy T16A1-4V, hardened to RC35-40
3. Precipitation Hardening Stainless Steel 15-7 MO
4. High Temperature Alloy Rene 41 hardened to RC40-42

1.3.2 Conventional Grinding

An actual written specific definition of conventional grinding is not available. Therefore, we have contacted a major grinding wheel concern to establish for us the most universally accepted wheels, speed, feed, etc., variables in the conventional grinding process:

1. Wheel size (diameter and width)
2. Grit sizes
3. Hardness
4. Wheel R. P. M.
5. Table Speed (feet per minute)
6. Depth of Cut
7. Wheel wear

The Carborundum Company, Niagara Falls, New York, was selected as a leading manufacturer of grinding wheels, and recommended the following* on the selected materials:

Wheel size	-	7" X ½" X 1¼"
Wheel Speed	-	3450 R P M (excepting 1500 to 2500 S F M on T16A1-4V) (2)(3)

1. Surface Grinding

Table Speed	-	50 feet per minute
Depth of Cut	-	.002" per pass
Cross Feed	-	1/32" per pass

Material		Wheel
(a)	H-11 Die Steel	AA46-G8-V40
(b)	Titanium Alloy T16A1-4V	AA46-I8-V40
(c)	Precipitation Hardening Stainless 15-7 MO	AA46-H8-V40
(d)	Udimet 40 or Rene 41	AA46-I8-V40

2. Cylindrical Grinding

Work Speed	-	70 S F M
Table Speed	-	12" per minute
Infeed	-	.002" per traverse
All Materials	-	Use wheel specifications listed above

*By private communication.

3. <u>Centerless Grinding</u>

Work Speed	-	100 S F M
Angle Feed Wheel	-	2^{o}
Angle Work Blade	-	15^{o}
Blade Above Center	-	1/16" for ½" to 3/4" diameter stock
All Materials	-	Use wheel specifications listed above
Feed Wheel	-	A80-R2-R

1.3.3 <u>Test Mechanism</u>

A test mechanism, or mock-up grinder, for evaluating the selected vibration and permitting as many modes and methods as possible, was selected. The simplest application of high frequency vibration was to the piece part, employing standard electronic transducers with capabilities of up to 40,000 cycles per second. The size of these standard transducers, when mounted vertically on the work table, was in excess of 18 inches, which meant the wheel must clear the table by 18 inches. It was also necessary to mount the transducer in a horizontal plane, requiring the grinder to be capable of adjusting to within approximately six inches under the wheel.

Investigations of all grinders resolved, finally, in the selection of a No. 13 Brown and Sharpe Universal grinder. With a simple extension mounted on the spindle housing, heights of twenty or more inches between the wheel and work table were possible. With its single column construction, adaptability of any size spindle diameters was made possible. With the addition of accessories, cylindrical or external grinding tests can be accomplished. Other accessories permit that of internal grinding, and centerless applications.

Modifications of table speed, wheel R P M, spindle extensions, can easily be accomplished. This permits testing of the selected vibrations modes and their applications in the initial stages of the investigation, permitting accurate accumulation of data for final selection of the grinder for Phase II.

1.3.4 <u>Test and Evaluation Program</u>

Tests were conducted on the vibration of the piece part in various modes and on wheel vibration in one mode, in a surface grinder type application. Results of these tests have guided us in evaluation of the method of applying vibrations and the selection of a Phase II test grinder, which, will be of the reciprocating table surface type.

SECTION 2

2. Instrumentation

The following is a report on the instrumentation which concerns the recording of data such as temperature, frequency and amplitude of transducer vibration, the amplitude of the vibration present at the spindle, marker, spindle power and the forces acting due to the travel of the grinding wheel over the workpiece.

2.1 Temperature

The temperature of the workpiece was measured by a thermocouple iron and constantan wires welded to the workpiece to measure the change in temperature at the exact center of the workpiece. The signal from the thermocouple was fed into two Tektronix Type D Preamplifiers connected in cascade. The signal was boosted to a useful level, and fed into the FM channel of an Ampex series FR-1100 Tape Recorder and placed on the tape for later reference. Placed on the tape, along with the temperature trace, was a marker trace. This enabled one to detect the exact position of the thermocouple trace in relation to where the grinding wheel was on the workpiece. The marker trace is explained in section 2.9.

When the signal was taken off of the tape, it was recorded on a B&K Type 2304 Level Recorder, incorporating a B&K Type 4610 Inverter. The data from the level recorder was processed and placed in table form.

2.2 Vibration

The amount of vibration applied to the workpiece was measured with a B&K Type 4329 Accelerometer. This accelerometer was not placed in direct contact with the workpiece as no commercially available accelerometer could measure the accelerations which are present at the workpiece when ultrasonics are applied. The magnitude of acceleration at this point is 40,000 g's or more. The position of the accelerometer was adjusted so that the vibration of the air between the accelerometer and the tool holder would give a reading which was in agreement with the actual P-P amplitude of vibration of the workpiece.

The distance between the transducer and the accelerometer was approximately .020". Once the accelerometer was set and calibrated, it was not moved until all the tests were completed. In order to establish a calibration curve for the accelerometer, a

National Scientific Instrument Type 4015 600 Power Optical Microscope was mounted, permitting the excursion of the workpiece to be measured and related to the voltage produced by the accelerometer. This information was used to determine the P - P amplitude of the vibration for the test runs.

The signal from the accelerometer was fed into a B&K Type 2110 Audio Frequency Spectrometer, where, it was amplified enabling it to be recorded on magnetic tape. For this signal a direct record amplifier in an Ampex series FR - 1100 Tape Recorder was used.

To get the information from the magnetic tape, the accelerometer signal was palyed through the audio frequency spectrometer and two traces were made on the level recorder. One was made without filtering and another with everything but 20KC filtered out. This was done so that we could determine the amount of distortion present in the 20 KC signal at the workpiece. From this information tables could be made and conclusions drawn.

The amplitude of vibration present in the spindle was measured by the use of two B&K Type 4329 Accelerometers, one in the vertical axis and the other in the horizontal axis. These two signals were fed into a two channel selector and then into the level recorder. This information could be put into chart form for further reference.

2.3 Marker

A marker signal was superimposed on the thermocouple trace for the purpose of telling the exact position of the trace in relation to the grinding wheel. It was also fed into the tape recorder on a separate channel for the purpose of comparing the marker signal to the marker on the thermocouple trace.

The marker was produced by a batter in series with a potentiometer and a microswitch. The microswitch was mounted on the grinder and two hardened steel blocks, with an eccentric ground on each, were mounted so that they would move with the table. The blocks were adjusted so the microswitch would be actuated the instant the grinding wheel touched, and again when it left the workpiece. These two pulses were fed into the tape recorder.

The power consumption of the spindle was measured with a John Fluke Manufacturing Company, Model 101 VAW Meter. The Motor was connected in one phase of the three phase power line feeding the spindle motor. The total power would then be three times the meter reading. This information was recorded on the Ampex Tape Recorder by voice, along with the run number, the pass number, the depth of cut, and other information which was pertinent for that particular pass.

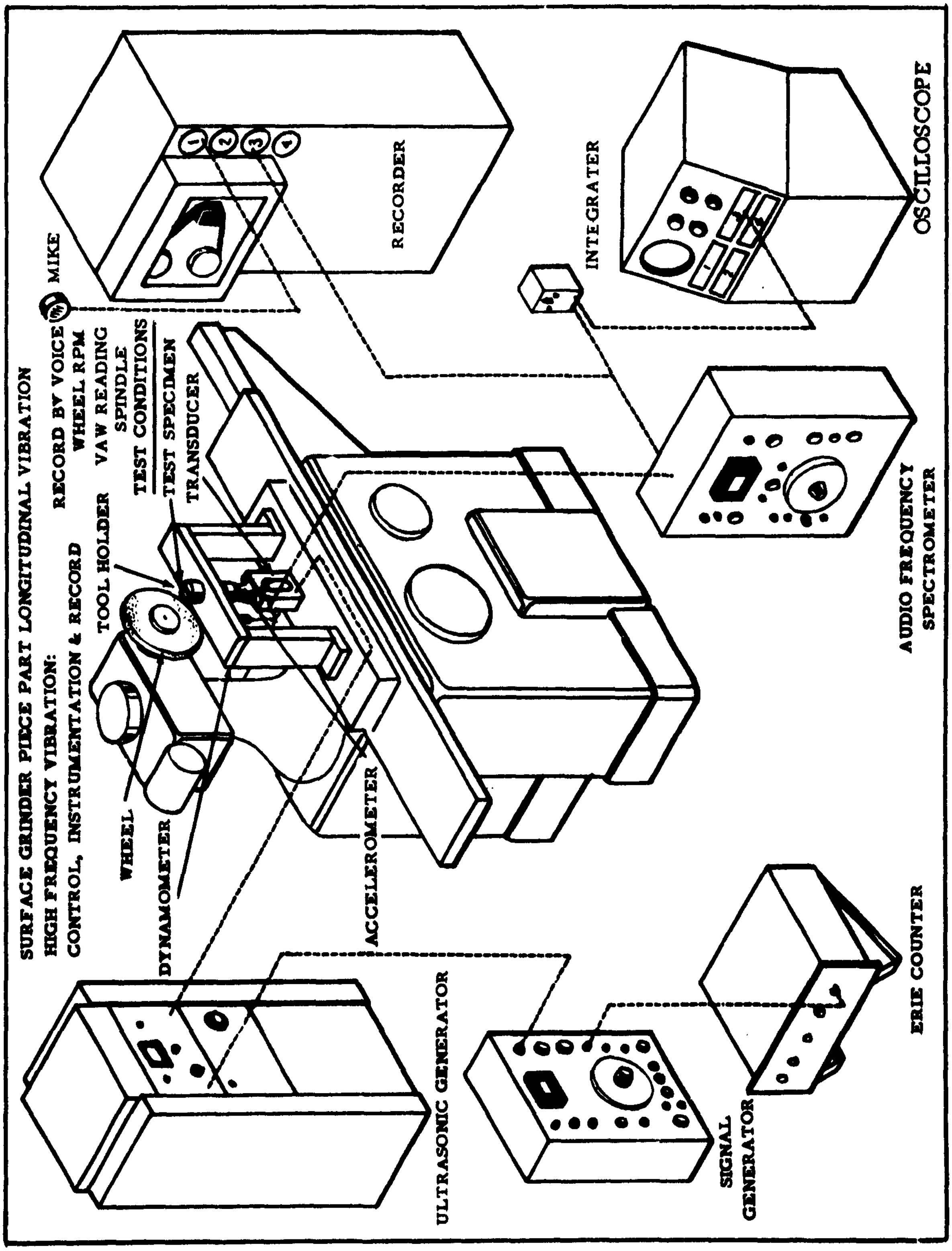

SURFACE GRINDER PIECE PART LONGITUDINAL VIBRATION
HIGH FREQUENCY VIBRATION:
CONTROL, INSTRUMENTATION & RECORD
RECORD BV VOICE
WHEEL RPM
VAW READING
SPINDLE
TEST CONDITIONS
MIKE
RECORDER
1
2
3
4
INTEGRATER
OSCILLOSCOPE
TOOL HOLDER
TEST SPECIMEN
TRANSDUCER
WHEEL
DYNAMOMETER
ACCELEROMETER
AUDIO FREQUENCY SPECTROMETER
ULTRASONIC GENERATOR
SIGNAL GENERATOR
ERIE COUNTER

Figure 1

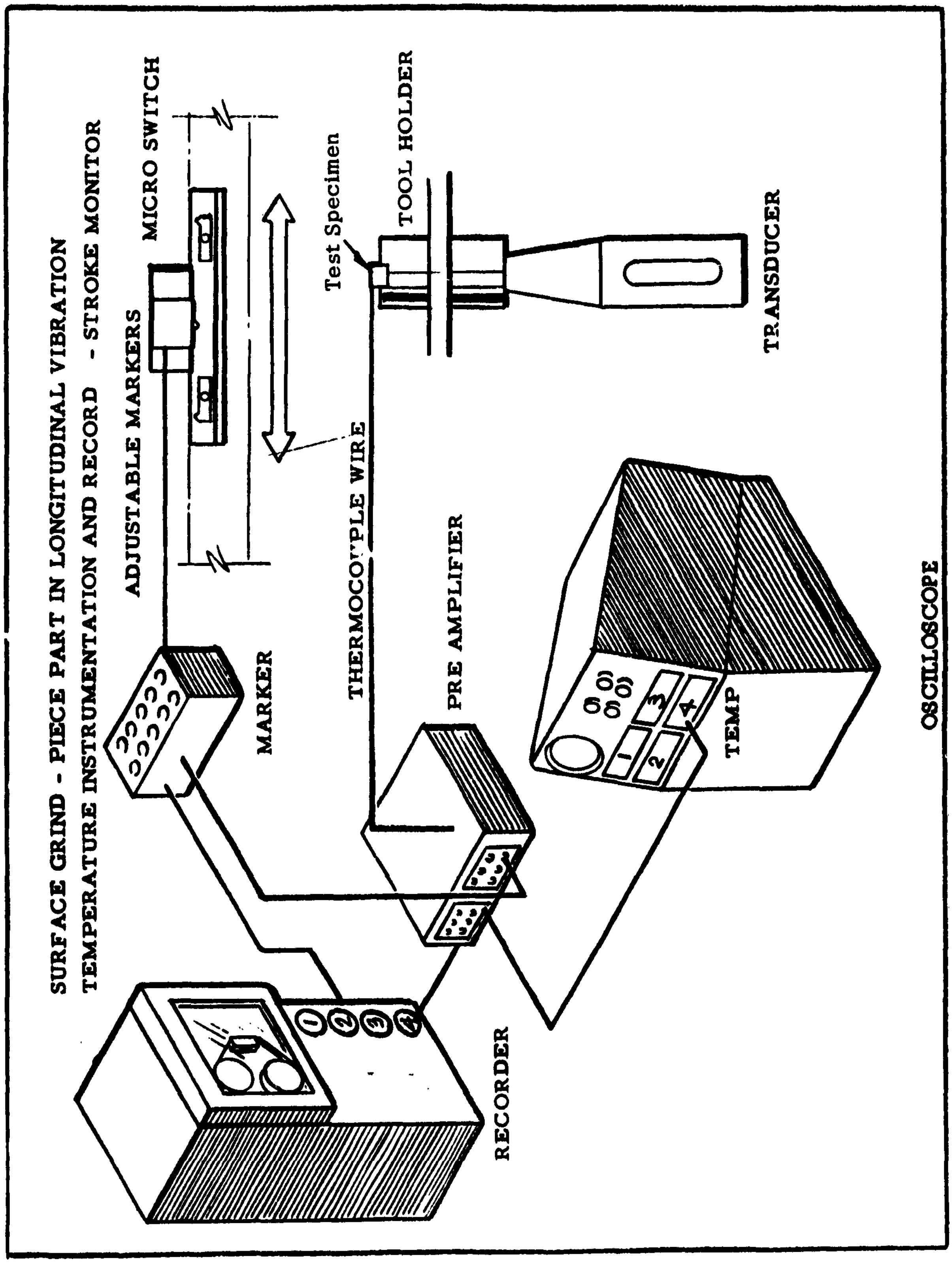

SURFACE GRIND - PIECE PART IN LONGITUDINAL VIBRATION
TEMPERATURE INSTRUMENTATION AND RECORD - STROKE MONITOR
MICRO SWITCH
ADJUSTABLE MARKERS
Test Specimen
TOOL HOLDER
TRANSDUCER
THERMOCOUPLE WIRE
MARKER
PRE AMPLIFIER
TEMP
OSCILLOSCOPE
RECORDER

Figure 2

During the course of the project, experiments showed that the spindle power and the temperature time traces were a function of the same variables which is believed to be the frictional phenomena and the energy of deformation.

With this relationship in evidence, the temperature time traces were eliminated from the instrumentation and the Spindle Power was recorded using a John Fluke 101 VAW Meter, a Bruel and Kjaer Type 2304 Level Recorder and a 4610 Inverter. The D C Voltage generated across the VAW meter terminals was fed into the Inverter and then to the Level Recorder.

In order to carefully control the frequency of vibration being applied to the workpiece by the ultrasonic generator, a B&K Type 1013 Beat Frequency Oscillator was used. A Model 400 Erie Counter was used to monitor the frequency of the B.F.O.

2.4 Thermocouple Interpretation, Welding and Calibration

To adequately resolve the changes in temperature of the workpiece, during grinding, it is necessary to use a temperature sensing device. The use of thermocouples was decided upon as the best method to accomplish this. It was then necessary to find the most satisfactory method of mounting the thermocouple on the workpiece.

The thermocouple must be so mounted that it will withstand surface particle accelerations of 40,000 g's or greater. Any air spaces or other insulating effect, that would be detrimental to the response of the thermocouple, must be held to the minimum.

2.5 Thermoelectric Thermometers

At the junction of two dissimilar metals, there exists an e.m.f. known as the Seebeck Effect, which is a function of temperature. If the circuit is closed by another remote junction of the two conductors, another opposing e.m.f. exists at the other junction. If these junctions are at the same temperature, the e.m.f.'s are equal and opposite, and no current flow will result. However, if one junction is at a higher temperature, the e.m.f. at the hot junction will exceed that at the cold junction, and a current will flow which is dependent on the resistance, involves a dissipation of energy in heating the conductor, but, the current may be used to perform work.

The electrical energy is derived from an absorption of heat at the hot junction and a rejection of heat at the cold junction, so that the device is a thermo-dynamic engine for the conversion of heat to electrical power. This relationship is actually parabolic, but inasmuch as the second order term is small enough to be disregarded, the relationship is essentially linear.

Usuable thermocouple materials:

1. Platinum and an alloy of 10% Rhodium with platinum

2. Copper and Constantan

3. Chromel-P and Alumel

4. Chromel-P and Constantan

5. Iron and Constantan was used on this project because of suitable temperature range and large thermal e.m.f.

A technique was then devised to flash-weld a small diameter wire to the workpiece to form a thermocouple, consisting of the workpiece and the wire; the idea being to improve response. With the use of suitable guiding fixtures, the junction may be placed on the workpiece with satisfactory response, a wire of small diameter was used. (.003" and smaller).

Due to the surface treatment and differences of reaction between various metals when subjected to an electrical arc, it is necessary to change the voltage current relationships to suit the particular metal concerned.

Because of the attrition of the material in the small diameter wire when heated, it is necessary to confine the area of molten flow to the end of the wire as much as possible. This necessitates the use of a comparatively large current with a duration of a few milli-seconds.

This presented a problem as to the rate of feed of the wire into the welding operation. This was satisfactorily resolved by insuring the irregularity of the contacting surfaces and placing the wire under compression, which operates satisfactorily with the short period allowed for the flash. Welds using this method have been satisfactory for the tests performed to date.

2.6 Operation of the Welder

The position of the thermocouple on the workpiece or specimen is determined by the use of appropriate measuring instruments with the accuracy required as to placement tolerance. For this operation, micrometers and gage blocks are used to place a scribed line a known distance from the top of the workpiece to be tested. A steel scale, accurate to 1/100", is used to determine the midpoint of the thermocouple location along the line.

The flash welder, shown in figure 6, must be connected to a suitable source of power. The correct voltage for the metals being used is selected from the potentiometers on the welder. The ground return of the welder is clipped to the workpiece to assure a good connection. The wire to be welded to the workpiece is securely fastened, for good contact, to the probe of the positive lead. A good connection may be made by winding a few turns tightly about the tip of the probe, leaving about two inches of straight wire beyond its tip. The tip of the wire to be welded is then placed at the junction of the scribed lines. The pressure on the wire is now increased until a bow in the wire, about 3/8 of an inch from normal, is formed. The discharge button is then depressed and an arc will occur at the end of the wire, welding it to the workpiece. The wire is then unwound from the probe tip leaving the wire welded to the workpiece. It may be supported by a soldered joint. A return or ground wire is welded to the workpiece by the same method.

2.7 Calibration

The thermoelectric power can vary in each test material due to differences in material, impurities, resistivity, etc. It was necessary to determine the thermoelectric power of each test specimen. The calibration apparatus is shown in figure 5.

2.8 Vibration Mode of Workpieces

Two modes, longitudinal and flexural, have been selected in which to vibrate the work specimens. The longitudinal is characterized by particle motions parallel to the axis of propagation. The flexural mode is characterized by particle motions usually at right angles to the axis of propagation, the waveform being analagous to the violin string.

Approach of Grinding Wheel to Axis of Propagation

Referring to - Longitudinal Mode - Method A:(see Fig. 7)

Note particularly that the axis of the transducer, which is the axis of longitudinal vibration, is normal to the grinding wheel spindle axis.

Referring to - Longitudinal Mode - Method B:(see Fig. 8)

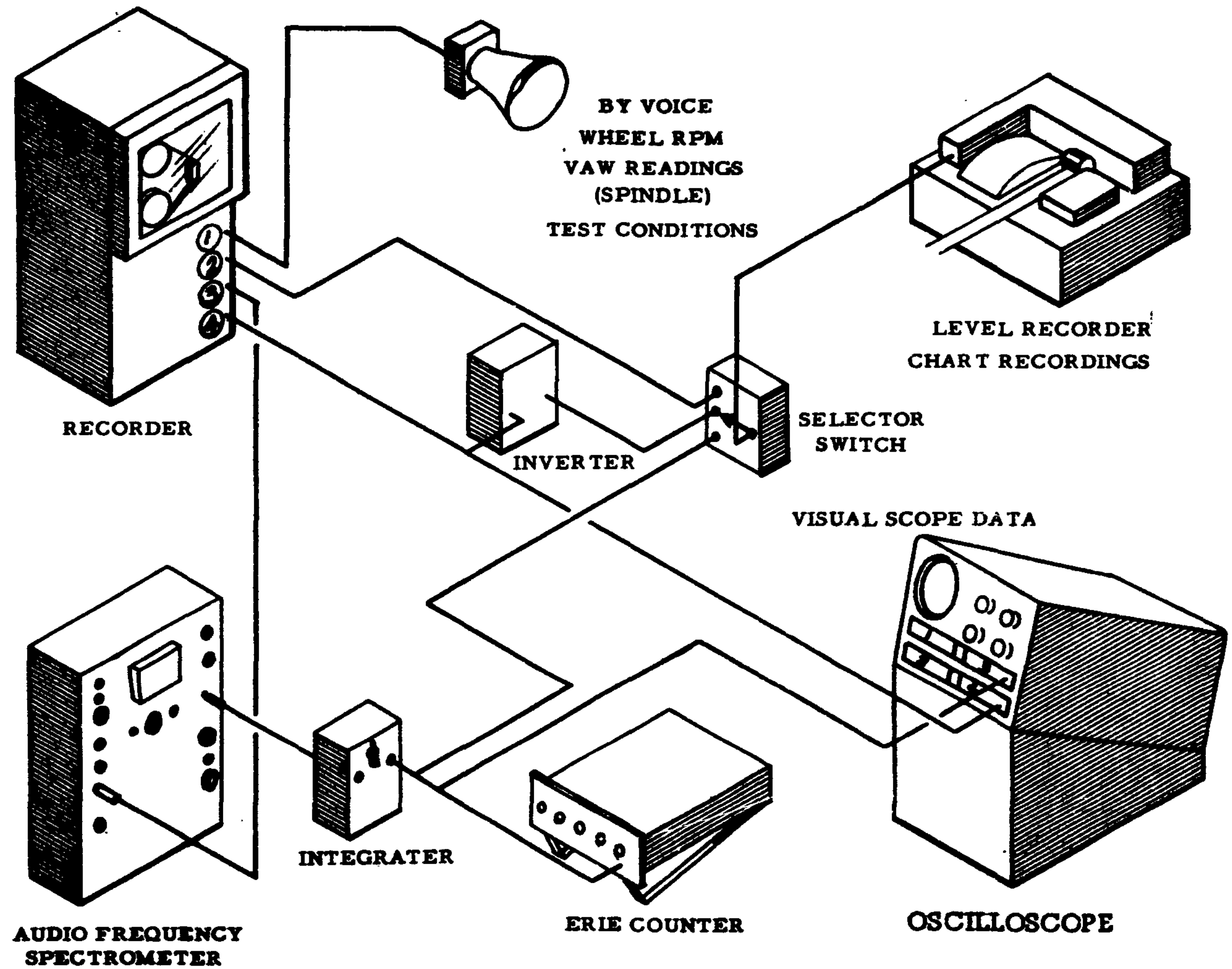
Note that the transducer axis and the direction of longitudinal vibration propagation is parallel to the grinding wheel spindle axis.

Referring to - Flexural Mode - Method B: (see Fig. 9)

Note that the propagation direction of the flexural mode is normal to the spindle axis - Particle motion is parallel to the spindle.

Referring to - Flexural Mode - Method A: (see Fig. 10)

Note that the propagation direction of the flexural mode is in the direction of table travel (normal to the spindle axis) and the particle motion is normal to the spindle axis and normal to the table travel.



RECORDER PLAY BACK CIRCUIT FOR DATA EVALUATION

Figure 3

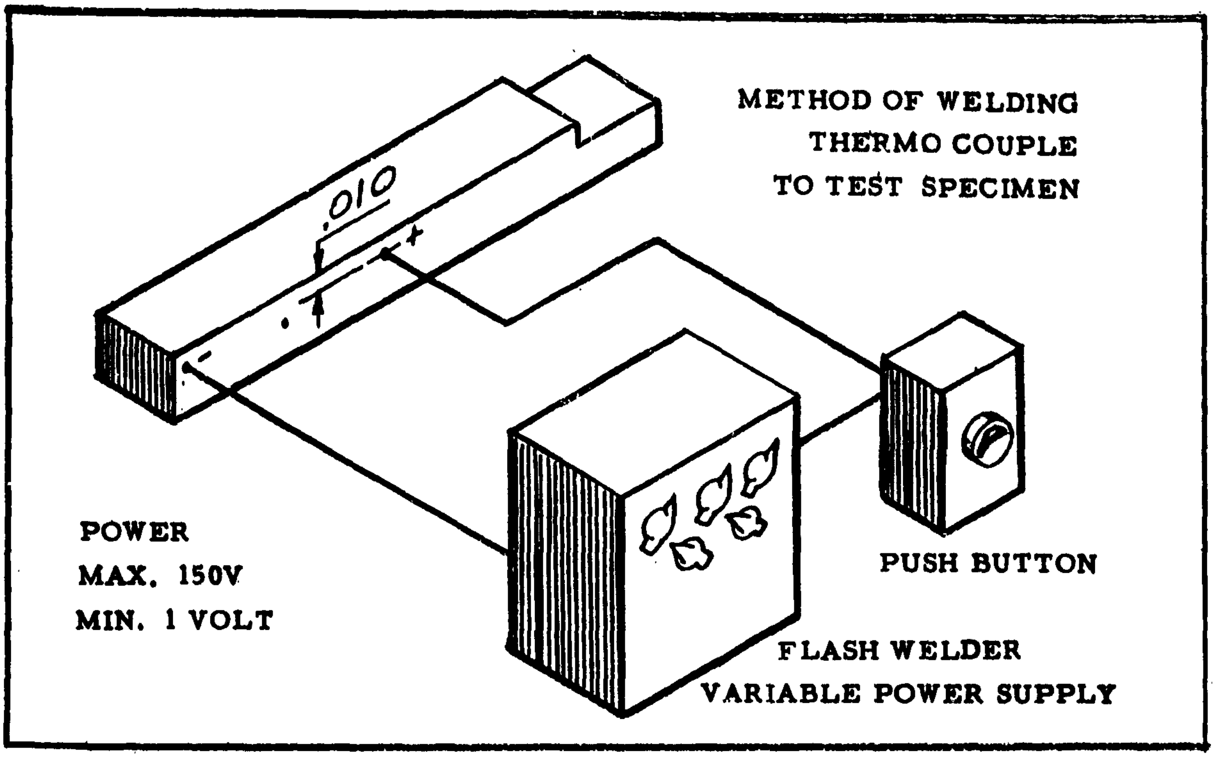

METHOD OF WELDING
THERMO COUPLE
TO TEST SPECIMEN
.010
POWER
MAX. 150V
MIN. 1 VOLT
PUSH BUTTON
FLASH WELDER
VARIABLE POWER SUPPLY

Figure 4

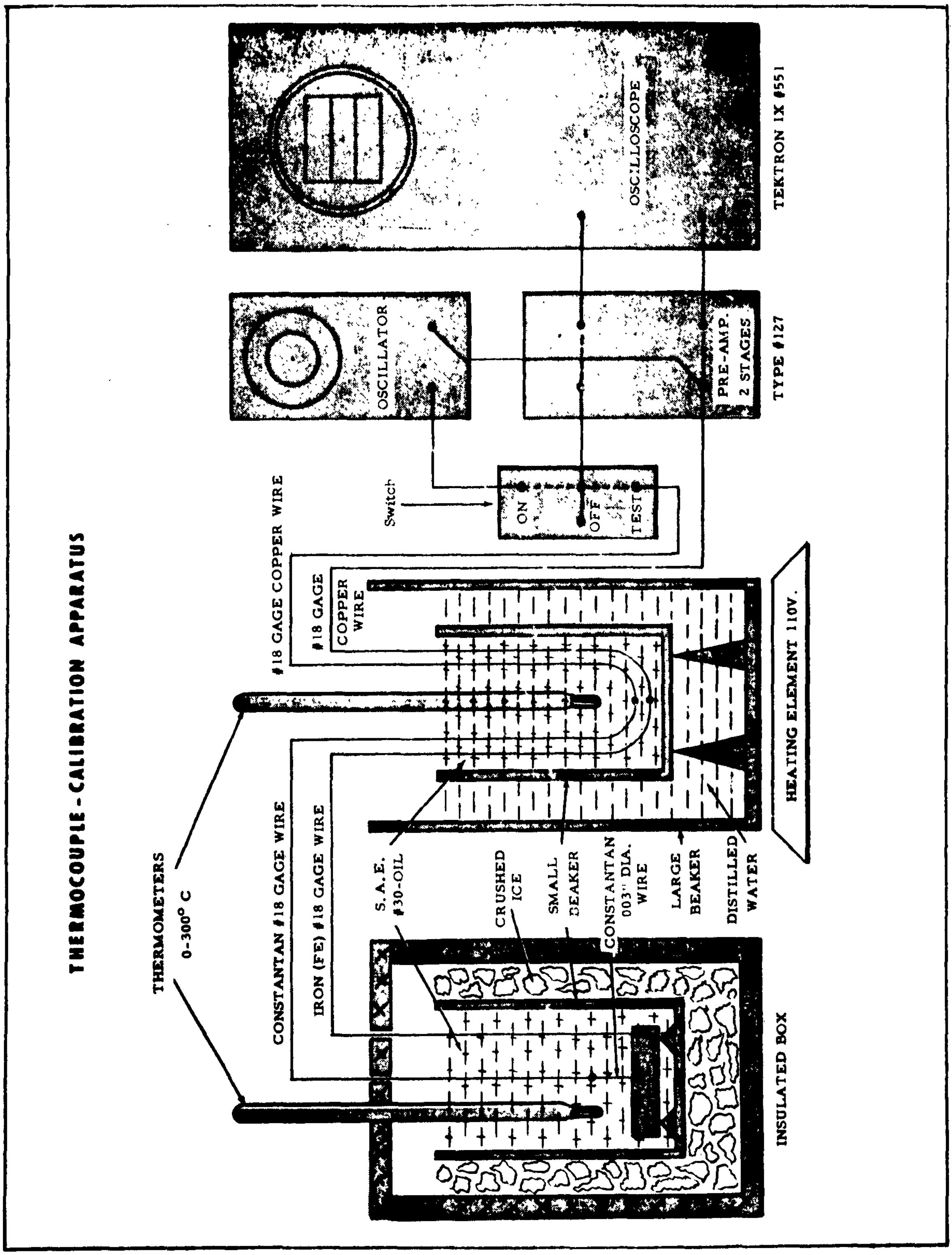

THERMOCOUPLE - CALIBRATION APPARATUS
THERMOMETERS
0-300° C
CONSTANTAN #18 GAGE WIRE
IRON (FE) #18 GAGE WIRE
S.A.E. #30-OIL
CRUSHED ICE
SMALL BEAKER
CONSTANTAN .003" DIA. WIRE
LARGE BEAKER
DISTILLED WATER
INSULATED BOX
HEATING ELEMENT 110V.
#18 GAGE COPPER WIRE
#18 GAGE COPPER WIRE
Switch
ON
OFF
TEST
OSCILLATOR
PRE-AMP. 2 STAGES
TYPE #127
OSCILLOSCOPE
TEKTRON IX #551

Figure 5

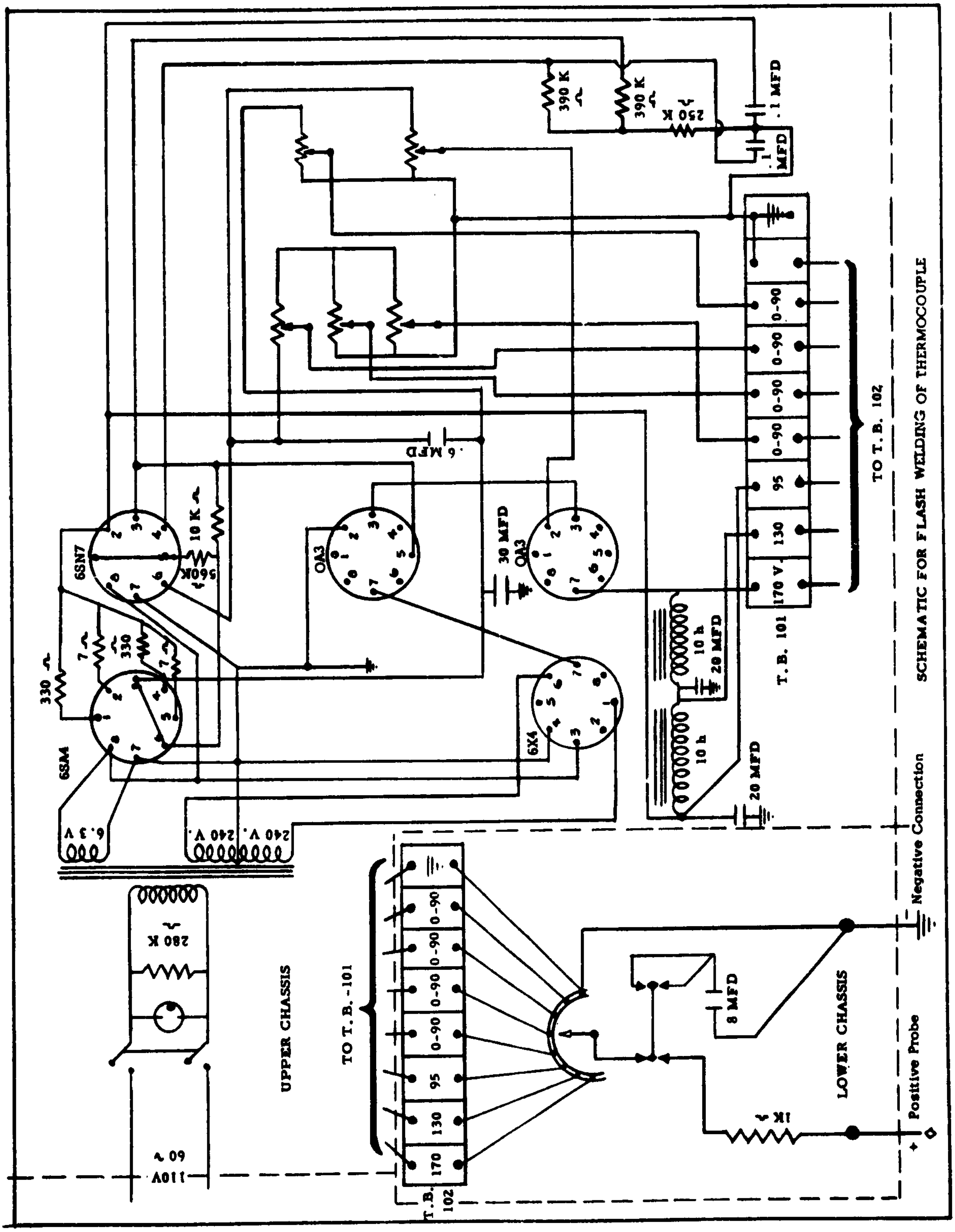

SCHEMATIC FOR FLASH WELDING OF THERMOCOUPLE
UPPER CHASSIS
LOWER CHASSIS
TO T.B. 102
TO T.B.-101
T.B. 101
T.B. 102
170 V
130
95
0-90
6SN7
6SA4
OA3
6X4
390 K
250 K
.1 MFD
.6 MFD
30 MFD
20 MFD
10 h
10 K
560K
330
7
280 K
6.3 V
240 V.
110V
60 ~
8 MFD
1K
Negative Connection
Positive Probe

Figure 6

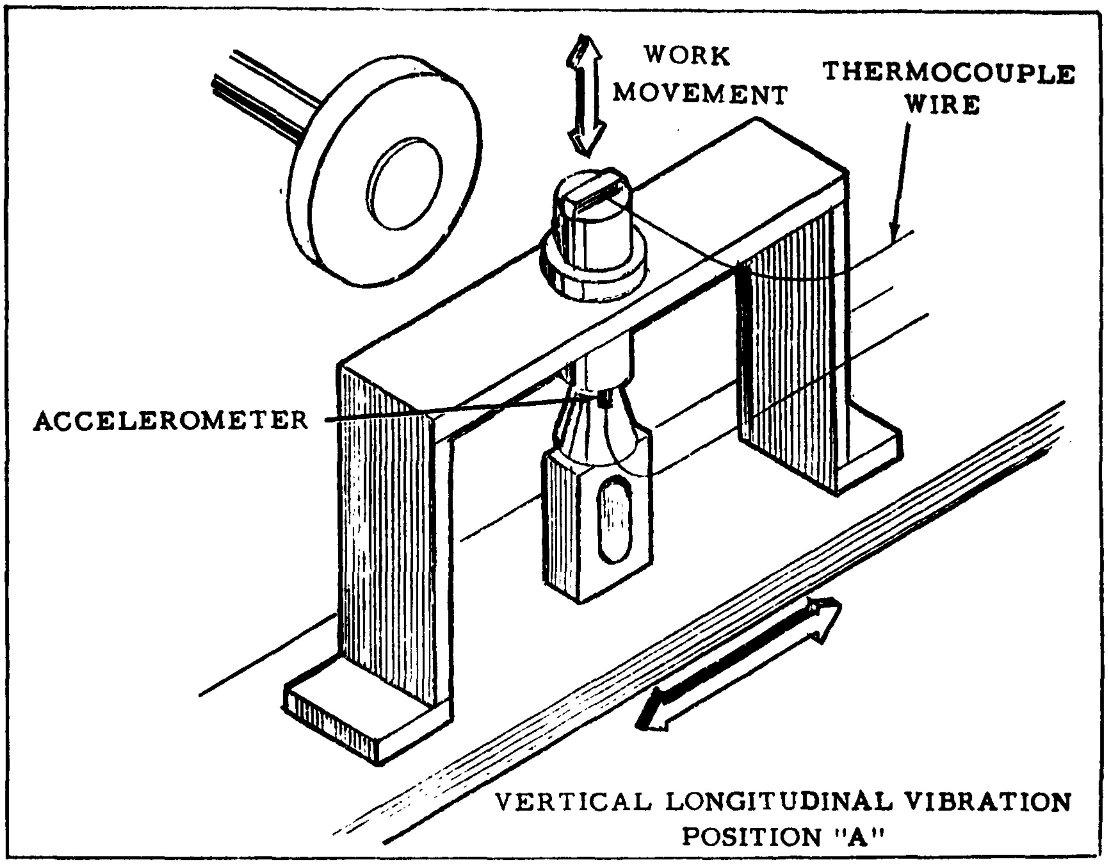


Figure 7

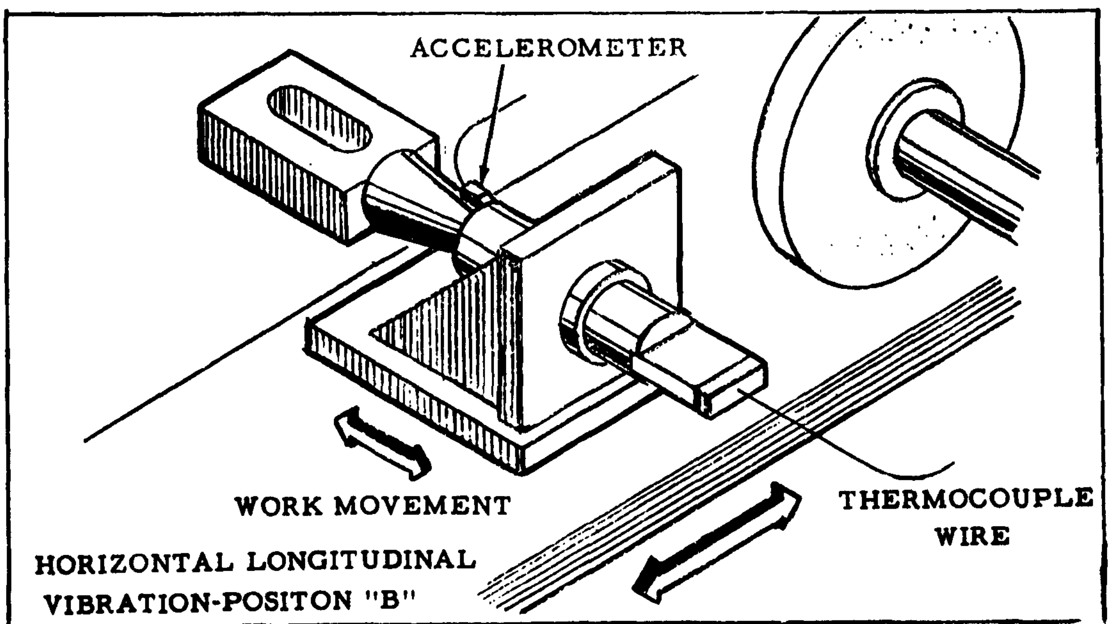


Figure 8

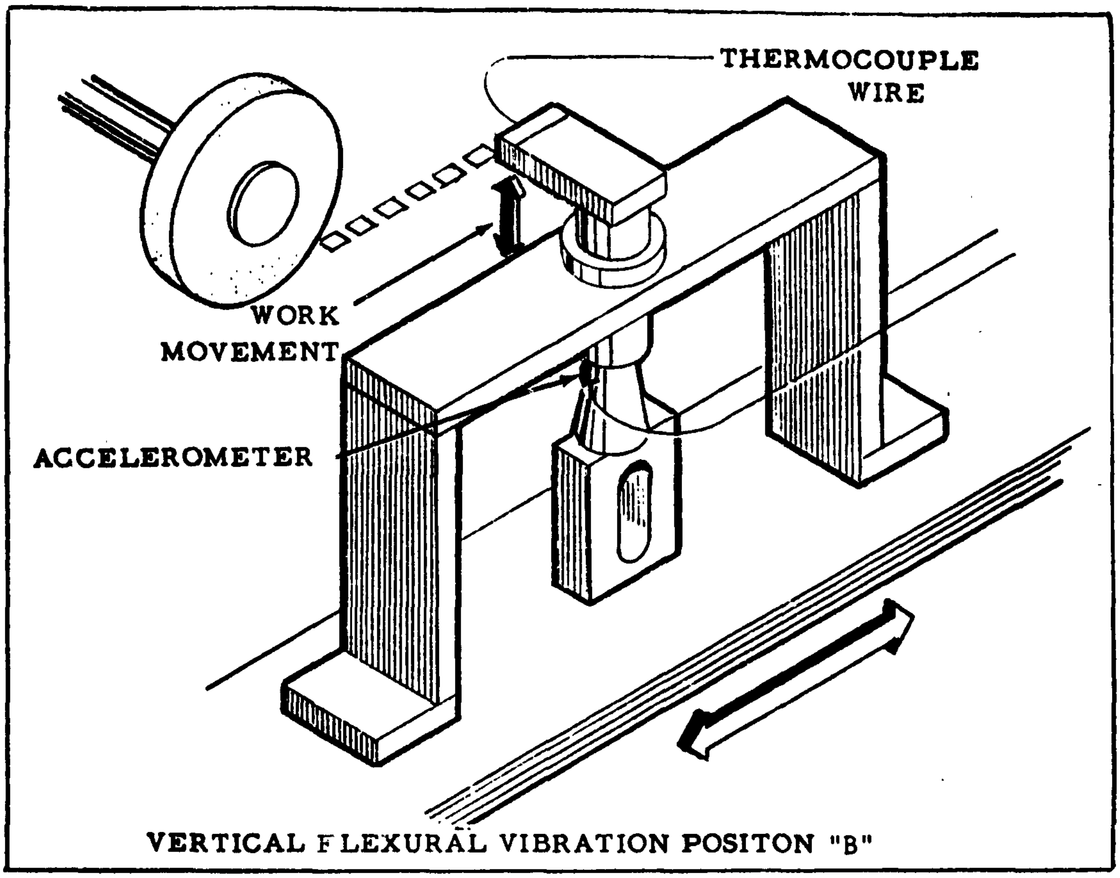


Figure 9

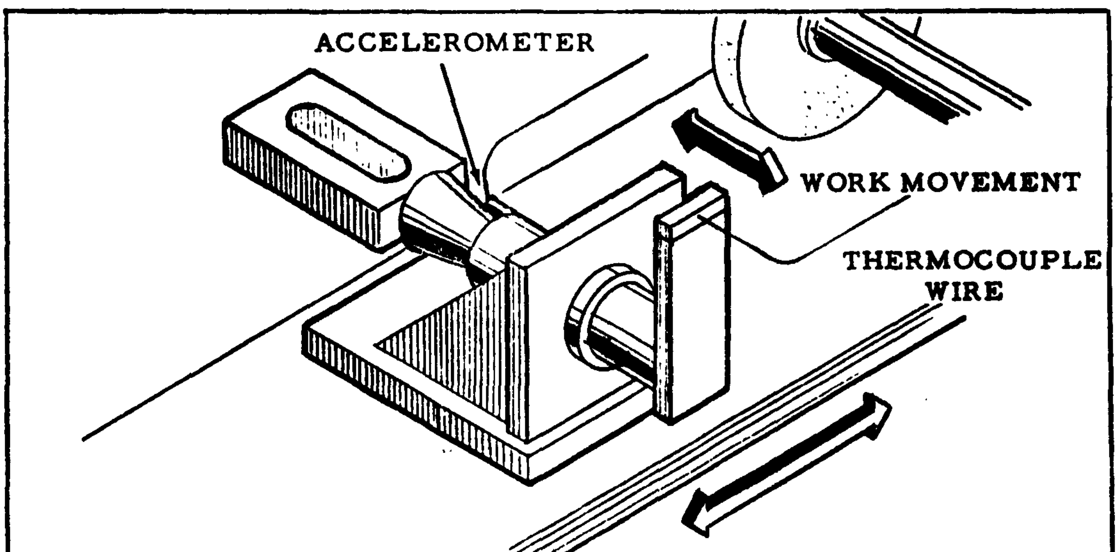
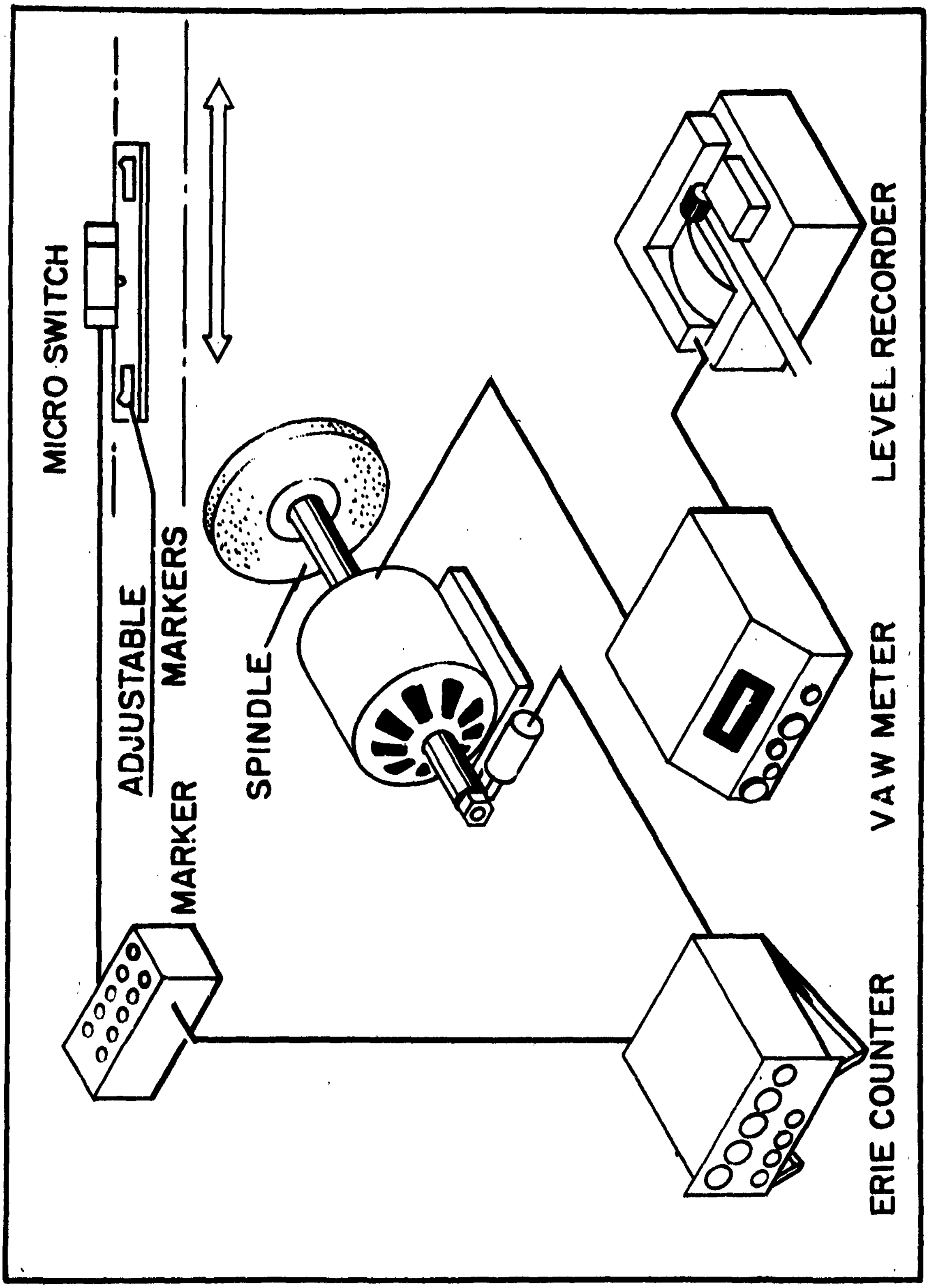


Figure 10

2.9 Spindle Revolutions While Grinding

Revolution of spindle count while grinding was accomplished by mounting an Electra Model 3015-A Transducer at the end of the spindle shaft. A hex nut was attached to the end of the shaft. When the spindle revolved, the hex nut broke the magnetic field of the transducer creating six pulses for every revolution of the spindle. These pulses were fed to a Model 400 Erie Counter. In order to count the number of pulses during the time the wheel was on the workpiece it was necessary to feed a gate pulse to the counter when the grinding wheel touched, and again when it left the workpiece. These pulses were supplied by a marker system consisting of a battery in series with a potentiometer and a microswitch. The microswitch was mounted on the grinder, and two hardened steel blocks, with an eccentric ground on each, were mounted so that they would move with the table. The blocks were adjusted so that the microswitch would be actuated at the right instant. When the counter received the first gate pulse, it would begin to record the pulses; similarly the second gate pulse would stop the count. The count of the counter divided by six equals the number of revolutions the grinding wheel made during its pass across the workpiece.

Test passes were made before each grinding run and under the conditions existing during grinding to determine repeatability of the number of revolutions per pass.



SPINDLE COUNT AND MARKING SYSTEM

Figure 11

SECTION 3

3. Data Collection

3.1 Grinding Tests

Initially, all grinding tests were fully instrumented to record the temperature rise of the test specimen under conditions of ultrasonic assisted grinding. Identical runs were made, except for the lack of vibration, in order to afford a comparison. To monitor the uniformity of vibration level, a recording was made of the acceleration and frequency imparted to the workpiece while grinding.

All runs were made dry and the wheels were diamond dressed. The amplitude of vibration for tests was from 5 to 19 divisions (1 division equal to 50 micro-inches peak to peak). Runs were made as a function of the amplitude and the depth of cut. The samples for testing were of SAE 1020, 4340, 440C and 15-7MO stainless. Grinding wheels used:

38A46-H8VBE
38A100-I6VBE
AA60-S8-V40
AA60-R8-V40
32A-60-L7-VG

Two grinding techniques were employed in making test runs:

(a) Grinding the specimen with a 7/16" wide plunge cut. The depth of cut varied in increments of .0003". A set of five passes consisted of one run.

(b) Grinding the specimen employing a crossfeed, using 10 steps of .050" width on each pass. A set of three passes consisted of one run.

The majority of runs were of the plunge cut type. These runs were recorded on chart headings, such as spindle current reading, ultrasonic frequency, conventional grinding, depth of cut, etc. Swarf was taken on 1st, 3rd, and 5th pass. A check-out list, including instrumentation, ultrasonic generator performance, etc., was used prior to each run. During the run a commentary of visual and running performance was logged.

3.2 Workpiece Coupling

The very wide dynamic range of amplitude chosen for the eventual investigation, (0-2000 micro-inches P-P), requires extra consideration to the means and methods of attaching the workpiece to the source of vibration. If a silver soldering technique was employed, giving one the strongest bond normally afforded, the distortion of the piece parts would not permit a careful analysis of the test specimen. The use of a mechanical or threaded connection has several disadvantages, namely, low endurance for the high amplitudes and the requirement for excellent matching of resonant frequency. Mechanical bonds are lacking in the prevention of heat rise in the joined surfaces as well as strength, and would, in many cases, cause the early failure of specimens. A soft-solder of 60 PB-40SN was selected with soldering temperature maintained at $400^{o}F$ or less. This provides sufficient bond strength, commensurate with piece deformation due to heat distortion.

The selection of soft solder (60PB-40SN) for Flexural and Longitudinal modes, therefore, becomes a compromise between bond strength on one hand and workpiece distortion on the other.

Exceptions to the solder mounting were made when vibrating at 60 to 1000 cycles per second. This is because the stress at the lower frequencies is low enough to permit other bonds.

Further, test specimens are to be secured with 910 Eastman cement for the additional ultrasonic spindle tests.

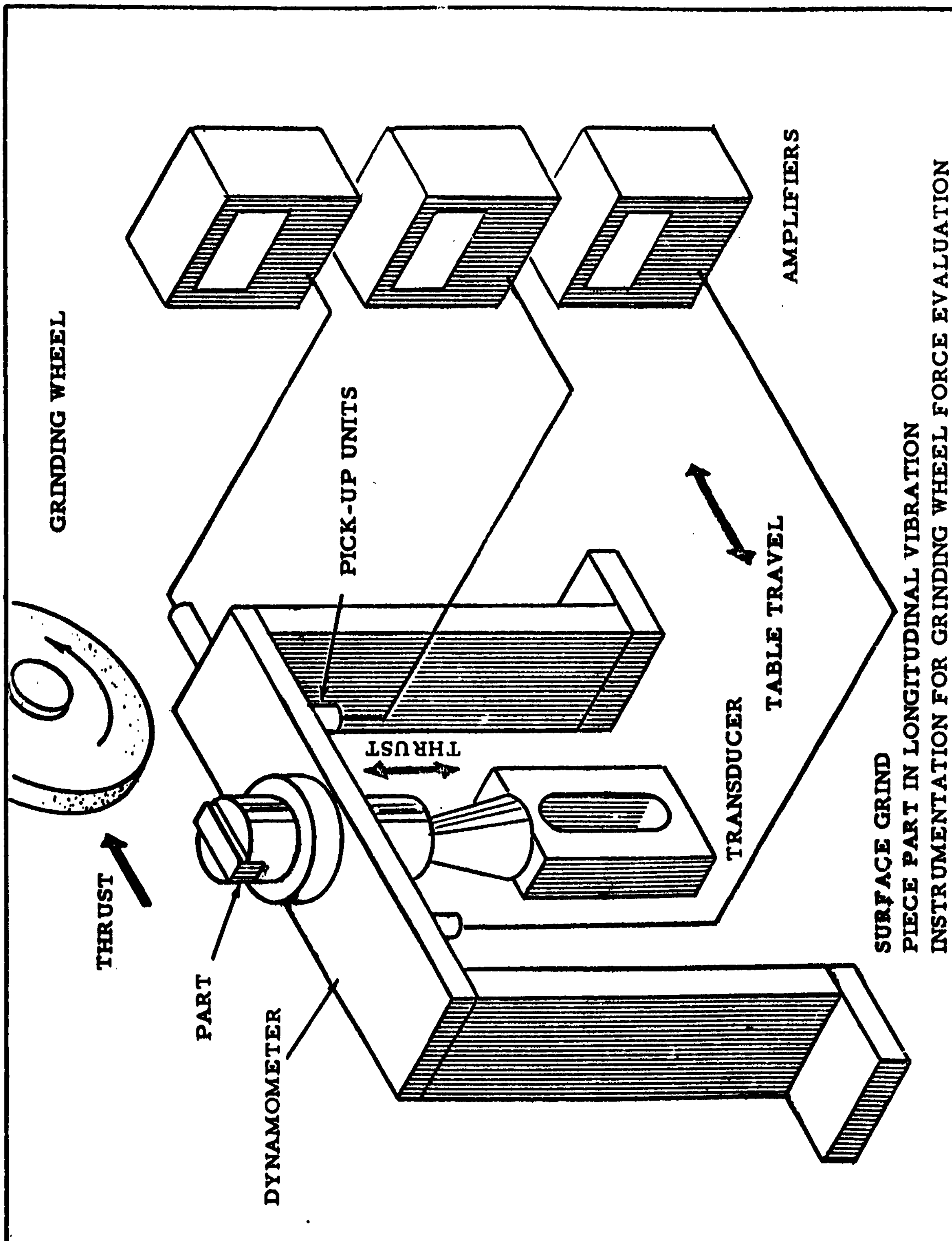
3.3 Method of Dressing Grinding Wheel

Grinding wheels on all test runs were diamond dressed with a 033-Wheel Truing Tool Company diamond. The wheel, revolving at grinding speed (6180-6320 SFM), was adjusted down to contact with the vertically mounted diamond. The wheel was moved to one side and adjusted down (.003-.006"). The table to which the diamond was fixed was moved slowly under the rotating wheel past the opposite edge. The direction of table motion was reversed, passing the diamond again under the wheel. If the wheel surface was not clean, the process was repeated.

3.4 Grinding Forces

The forces which are exerted during grinding were measured by accurate dimensional measuring equipment. The transducer support was designed to allow movement which would be indicated to an amplifier. The force in a horizontal line, parallel to the table and opposite to that of the table movement, was indicated at amplifier # 1. The vertical forces caused by grinding, were indicated at two amplifiers: # 2 and # 3. These meters were calibrated by dead weight methods. The amount of deflection caused by grinding would then indicate the force in pounds. (figure 12)

Calibration of amplifiers was accomplished without any problems. However, during actual grinding tests, the amount of variables introduced by table travel, wheel vibration, grinder vibration and induced ultrasonic vibration, proved very erratic and seemed to be unreproducible. Therefore, further instrumentations of this nature, to evaluate grinding wheel contact forces were abandoned.



SURFACE GRIND
PIECE PART IN LONGITUDINAL VIBRATION
INSTRUMENTATION FOR GRINDING WHEEL FORCE EVALUATION

Figure 12

3.5 Swarf Collection and Analysis

Swarf is collected in an envelope held in the spark stream of a designated pass. If the pass is not typical (too shallow or too deep), of a designated series of passes, the envelope is discarded. The swarf saved is evaluated for a ratio of spheroids to chips, size of spheroids, general description of chips (color and evenness of size), and, the adherence of spheres to chips.

To evaluate the swarf, the envelope is emptied on a glass plate and quartered until an aliquot remains. This small quantity is evenly distributed and viewed through an American Optical Stereoscopic Microscope at 54X. The chips and balls of 10 locations are counted and averaged. All envelopes of swarf of this same run are evaluated in the same manner, and the total of all is averaged. To measure the diameter of spheres, a Sheffield Micro-hardness tester with optical magnification of 400X was used. The filar-micrometer eyepiece is calibrated in microns and adjusted by a micrometer screw moving a sliding hair line to or from a stationary, adjustable line. The first 20 spheroid diameters, of a representative sample of each pass, are measured and averaged. Each pass of a run is measured and averaged in the preceding manner, as is the sum of all passes.

The results are charted, permitting evaluation of conventional grinding to grinding with ultrasonic aid. If sufficient heat is generated, the material removed during grinding will be oxidized and spheroids will be formed. A lesser heat generated will increase the number of chips which is indicative of a lower temperature during grinding.

3.6 Swarf Adhesion to Glass

A second method of swarf evaluation was accomplished by using clear glass. A $1\frac{1}{2}$" square piece of window glass was inserted in the spark-stream during grinding. If sufficient heat is generated, particles of the swarf will fuse to the glass. The higher the temperature the greater the amount of particles will be visible. Figures 87 to 92 picture representative runs of conventional and various amounts of divisions of vibrations. As will be noticed, the deeper the amount of cut, the more heat generated and the darker the glass due to adhesion of metal particles. It is also obvious that the higher the divisions, or stroke of vibration, the lesser the amount of chips or spheroids adhering to the glass.

3.7 Ultrasonic Vibrating Grinding Wheel (see figure 15)

A prototype of an ultrasonically vibrated grinding wheel has been designed and built to further explore vibration aided grinding. It consists of:

(a) Grinding wheel assembly (hub bonded to wheel)

(b) Transducer assembly (1000 Watt Transducer)

(c) Slip ring and pulley assembly (slip rings, drive pulley and shaft adaptor)

(d) Bearing support assembly (mounting plate and bearing supports)

This spindle assembly replaces the existing spindle on the test grinder. The "V" belt drive is arranged to facilitate change of spindle speeds from 2150 to 3875 RPM.

The radial mode of ultrasonic vibration was selected for use on the prototype ultrasonic spindle.

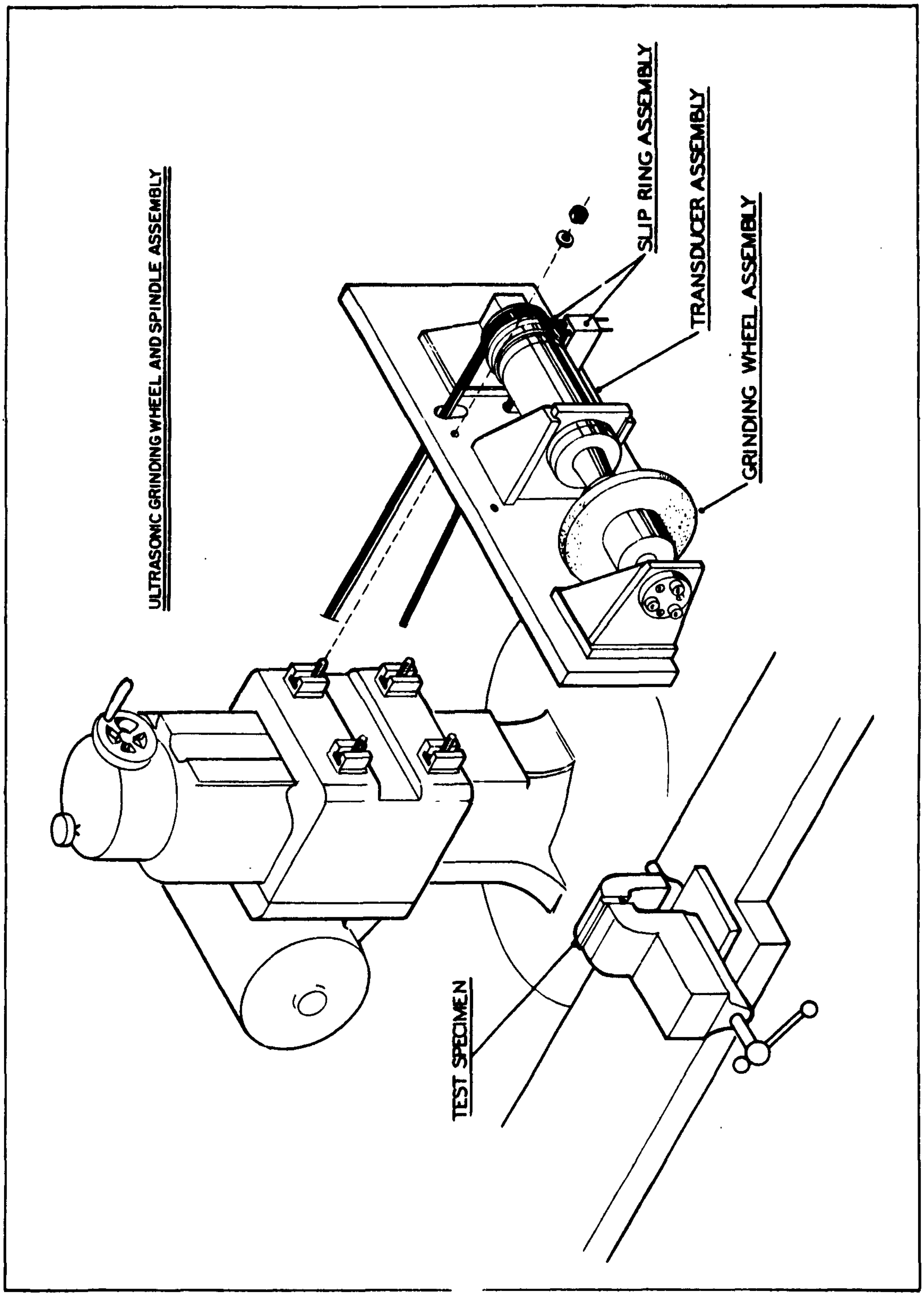

ULTRASONIC GRINDING WHEEL AND SPINDLE ASSEMBLY
SLIP RING ASSEMBLY
TRANSDUCER ASSEMBLY
GRINDING WHEEL ASSEMBLY
TEST SPECIMEN

Figure 13

3.8 Grinding Wheel Hubs

Two different grinding wheel hubs have been designed and are being tested. The first hub is a 3" diameter bar whose half-wave length is cut for 20 kc., having a 4½" diameter flange at its nodal point. A grinding wheel was bonded with Armstrong Epoxy Bond at this nodal point. One end has a ½ - 28 tapped hole 3/4" deep for attachment to the transducer, the other, a 60° tapered center to receive a nylon support. This center support is at the nodal point to reduce the particle motion and to isolate vibration from the frame of the machine. It will also alleviate bending stresses at the "hub-to-transducer" junction. Radial cracking of the wheel occurred during the curing of the adhesive bond. This was remedied by slowly increasing and decreasing the temperature during bonding and curing. The wheel assembly was excited at its radial resonance, and vibrated for 15 minutes at 3 division stroke (150 micro-inches). Occasionally, the wheel would crack and be destroyed by a violent flexural mode that would appear while tuning the wheel for this radial mode. This was corrected by maintenance of low power setting while tuning for the radial mode.

The second hub, a 5 inch in diameter disc, has a ½-28 tapped hole for attachment to the transducer. An advantage of this design is the reduction of the shear stress at the "hub-to-transducer" junction eliminating the outboard support. The grinding wheel is bonded to the disc using Armstrong Epoxy cement. Testing as before revealed that both radial and flexural modes could be excited.

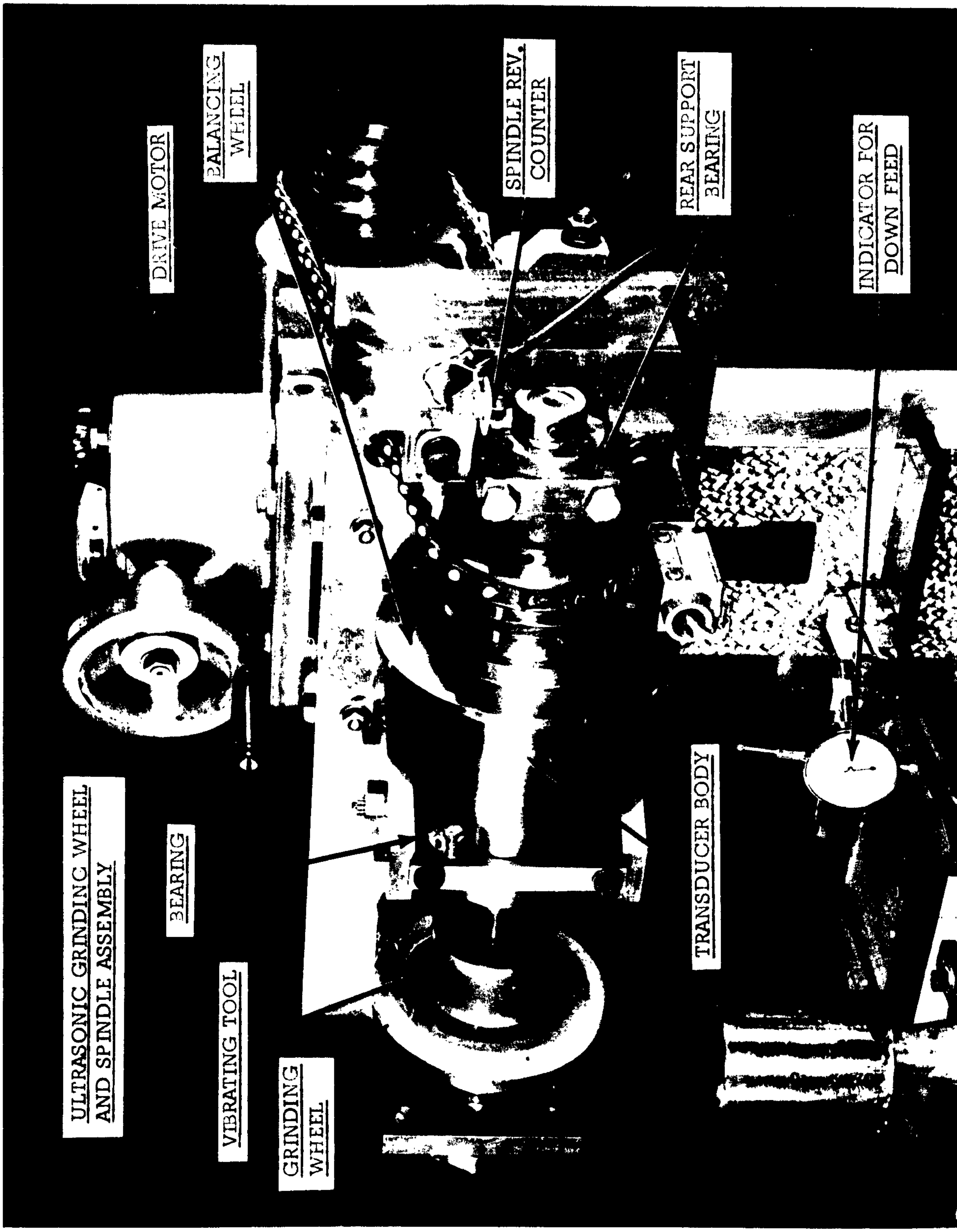
3.9 Ultrasonic Spindle Testing and Grinding

The ultrasonic spindle has been mounted to the test mechanism after assembly and balance. There, it has been electrically and mechanically connected. Having a 3 speed drive selection, (2150, 2700, 3875), the lower speed (2150 RPM) was used for the breaking-in period. While turning at the latter RPM the grinding wheel was tuned at a low power setting. The maximum speed and amplitude of vibration of the grinding wheel was reached in 3 steps, as performance warranted.

Grinding tests were started as in the past. However in this case, the grinding wheel was vibrated rather than the test specimen. The test specimen was rigidly attached as was customary in conventional grinding techniques.


TEST GRINDER SET UP FOR BOTH WHEEL AND PIECE PART VIBRATIONS
DOWN FEED
ADJUSTABLE CENTER SUPPORT
ULTRASONIC SPINDLE
TEST SPECIMEN
ULTRASONIC LONGITUDINAL VIBRATION TRANSDUCER
MARKER SYSTEM

Figure 14



DRIVE MOTOR
BALANCING WHEEL
SPINDLE REV. COUNTER
REAR SUPPORT BEARING
INDICATOR FOR DOWN FEED
ULTRASONIC GRINDING WHEEL AND SPINDLE ASSEMBLY
BEARING
VIBRATING TOOL
GRINDING WHEEL
TRANSDUCER BODY

Figure 15

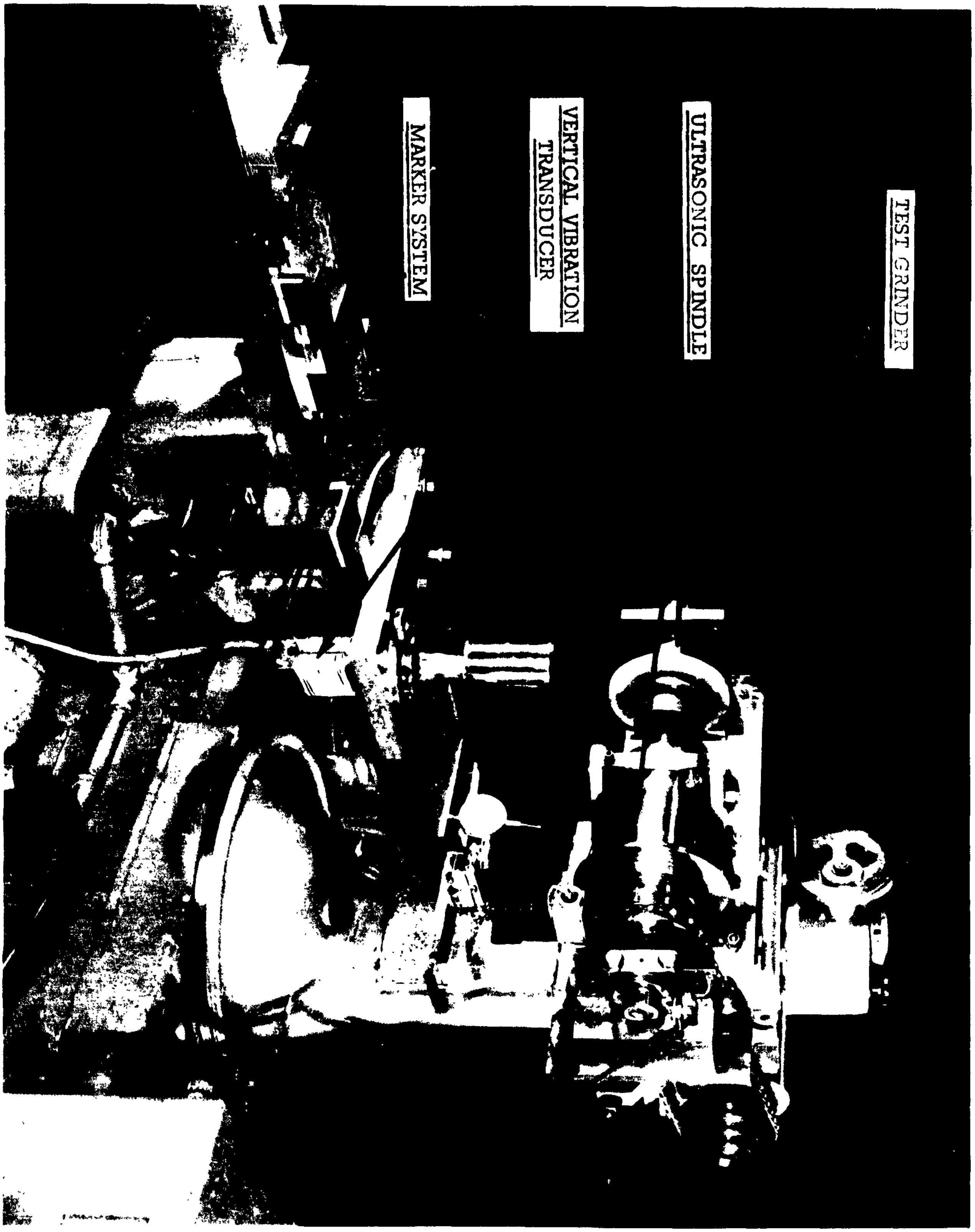

TEST GRINDER
ULTRASONIC SPINDLE
VERTICAL VIBRATION
TRANSDUCER
MARKER SYSTEM

Figure 16

3.10 Low Frequency Vibration Grinding

Since magnetostrictive transducers are inefficient in power output at frequencies below 10 kc, it became necessary to design, build and test an electrodynamic type that would have sufficient power. At first, a device similar in design to a loud speaker transformer was used in grinding tests of 500 cps to 1000 cps.

This unit consisted of two assemblies:

A. Lower "E" lamination steelstack having coil around center of "E". Polarizing current is introduced to this coil from a modified ultrasonic generator.

B. Upper "E" lamination steel stack having coil around center of "E", alternating current of controlled frequency is introduced to this coil from a modified transducer generator.

Next a 60 cycle, 200 watt, 110 volt vibrator made by the Pressed Steel Company, Muskegon, Michigan, was obtained. This offered a simple, inexpensive low frequency vibration source. This unit had a resonant armature excited by the 60 cycle line frequency. All of the 60 cycle grinding tests were performed with this vibrator. Finally, a 220 volt, 300 watt, 60 cycle vibrator was designed, fabricated and tested for future use. The amplitude and power of vibration could be varied by an adjustment screw.

3.11 Grinding at the Nodal Region (Antinode of Stress)

In previous grinding tests using ultrasonic vibrations, the test specimen was mounted to a tool holder where maximum particle motion and minimum stress occurs. This distance is a quarter wave length from the nodal region of the tool holder. The test specimen was brazed to this region.(figure 20) In this position the specimen is under maximum stress and minimum particle motion. Due to this stress, difficulty was encountered in maintaining a bond between specimen and the tool holder. However, the few specimens that did hold, showed no change in spindle power between comparative grinding tests of ultrasonic and conventional grinding.

3.12 Wheel Bonding

Four methods of wheel bonding have been explored for use in the ultrasonic spindle assembly:

A. Carborundum Wheel #A60-N150-M1/4. The manufacturing of this wheel consisted of a build up of layers of grit and metal by an electroplating process to a total of 1/4" thickness. This rim enclosed the peripheral surface of a 7½" diameter hole to which was soldered a stainless steel hub. The only way resonance could be obtained was to reduce the outside diameter of the wheel, which meant cutting off the grinding material thus rendering the wheel useless. Further tests along this line were discontinued.

B. Armstrong Epoxy A-4. Using the epoxy bond extreme cleanliness of the bonding surfaces is important. The metal hub bonding surface was knurled to increase bond area. The epoxy was applied to both mating surfaces, being careful not to create bubbles. The setting up and curing of the epoxy had taken place at the same time, in an oven, at curing temperature. If the bond was allowed to set up before curing, cracking of the wheel would occur. This is due to the differences of expansion coefficients, between the metal hub and aluminum-oxide grit wheel. This bond is the only one that has been used so far on the ultrasonic spindle.

C. Cupric Oxide and Phosphoric Acid Bond. In the prescribed proportions, a mixture of cupric oxide and phosphoric acid were mixed. This was then applied to both the inside diameter of the grit wheel and knurled outside diameter of the wheel hub. Wheel and hub were then joined and left 24 hours to air dry. When ultrasonically excited the bond life was found to be very short.

D. Silver Bonded Grit. The grinding wheel was ultrasonically cleaned in distilled water. Then it was placed in a silvering solution, (Rochelle Salt Method). Sufficient time was allowed for silvering the wheel surface to a suitable thickness. The wheel was then copper plated to (2 mils) in thickness. The inside diameter was then tinned with soft solder and sweated on a wheel hub. The latter bond seems promising by offering longer endurance and improved heat dissipation possibilities.

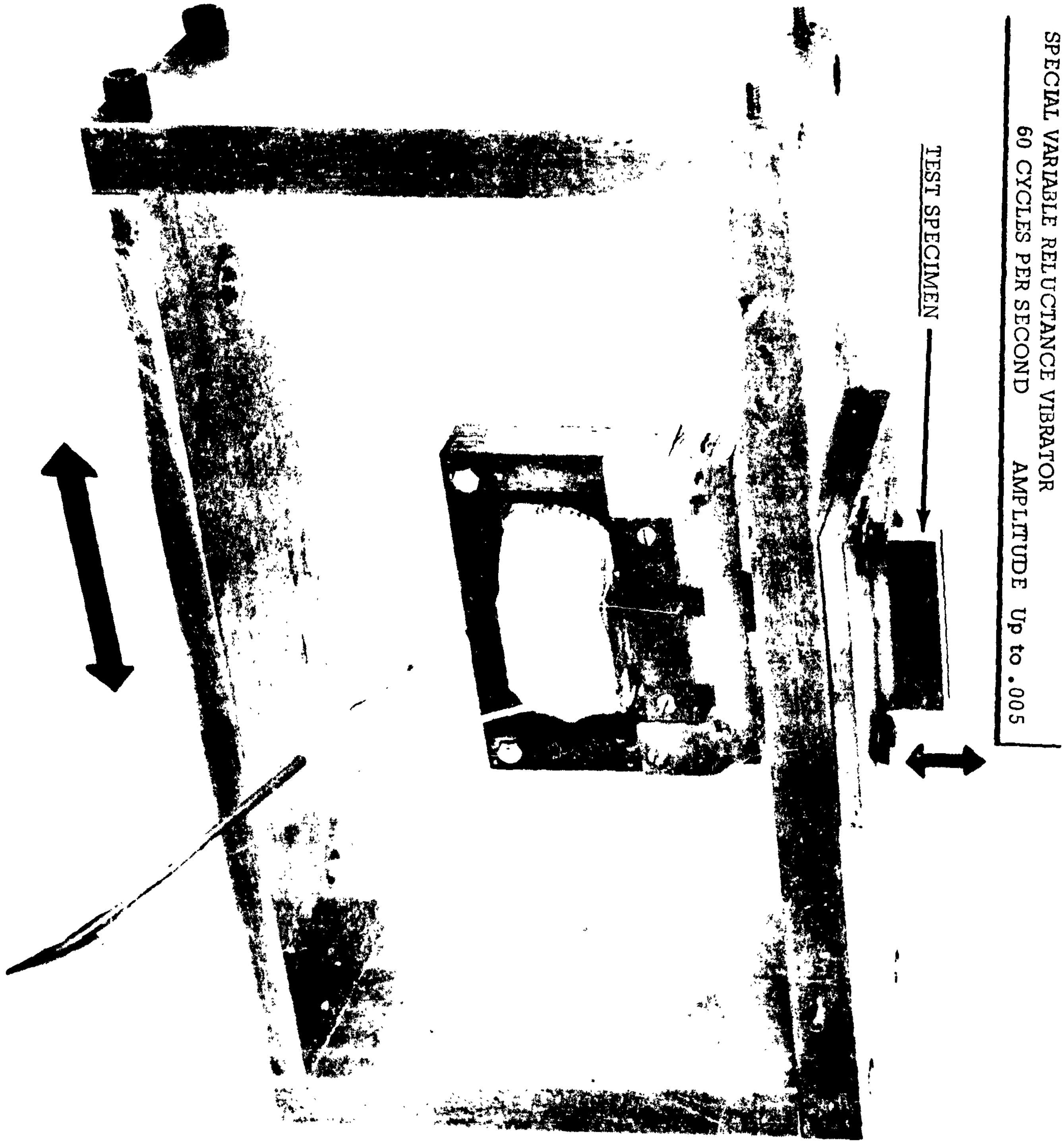
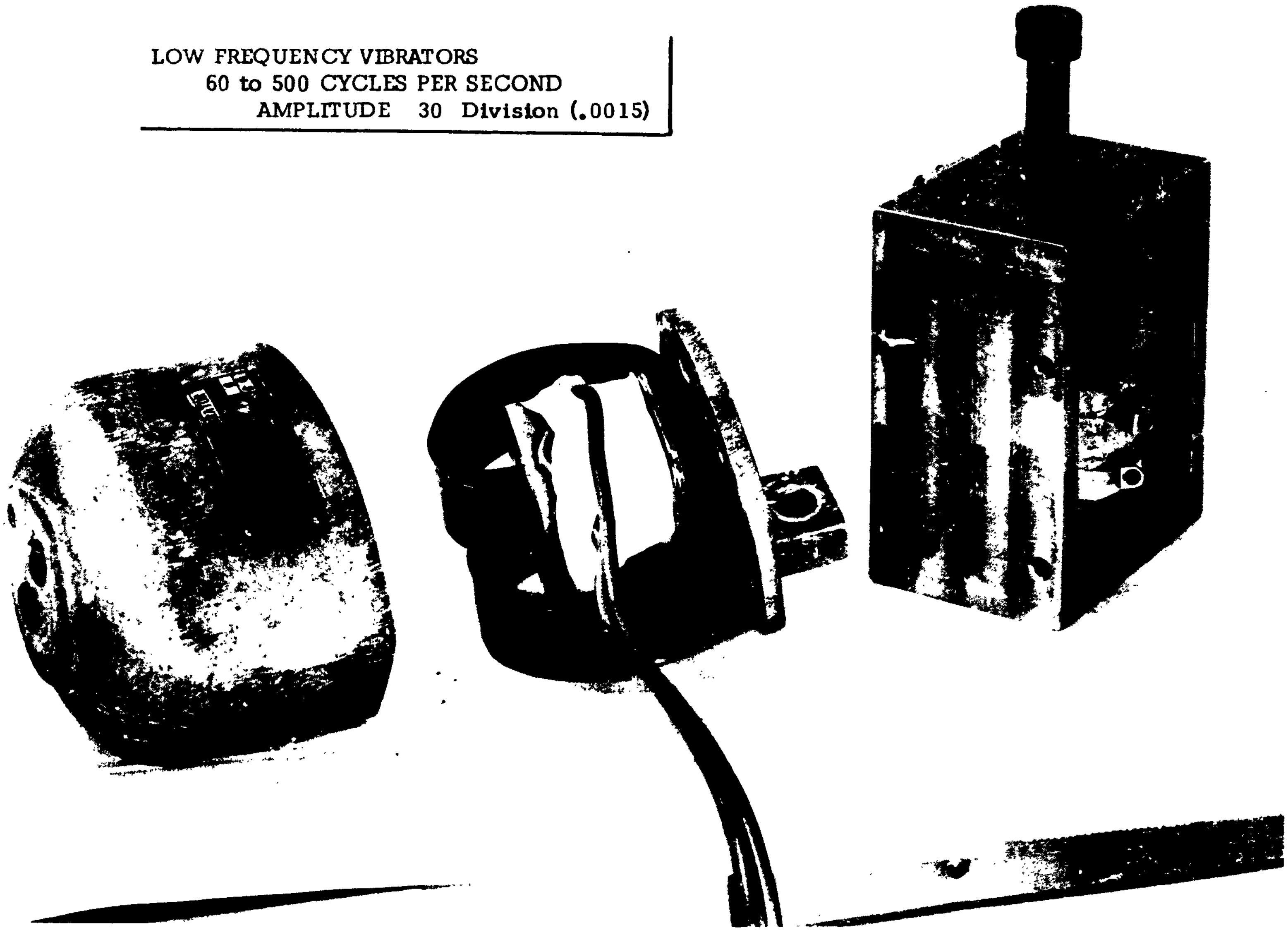

SPECIAL VARIABLE RELUCTANCE VIBRATOR
60 CYCLES PER SECOND
AMPLITUDE Up to .005
TEST SPECIMEN

Figure 17



LOW FREQUENCY VIBRATORS
60 to 500 CYCLES PER SECOND
AMPLITUDE 30 Division (.0015)

Figure 18

3.13 Frequency and Amplitude Modulation Grinding

An electronic circuit was designed and tested for obtaining variables in frequency and amplitude modulations. With this, grinding tests were performed on specimen 15-7 MO material using a .0009" depth of cut. The following combinations of frequency modulations were used:

(a) 8 cps modulation 1200 cycle swing

(b) 32 cps modulation 1800 cycle swing

(c) 64 cps modulation 2000 cycle swing

Grinding tests using amplitude modulation of varying combinations will be investigated in the future.

3.14 Ultrasonic Wet Grinding

Grinding tests using a thin water film on the test specimen surface were made with and without ultrasonic vibration. Sufficient information was collected to substantiate another advantageous grinding technique. Grinding temperatures were lower using ultrasonic wet grinding as compared to conventional wet grinding. To accurately measure the differences in grinding temperatures, a stable and uniform wetting system would have to be set up.

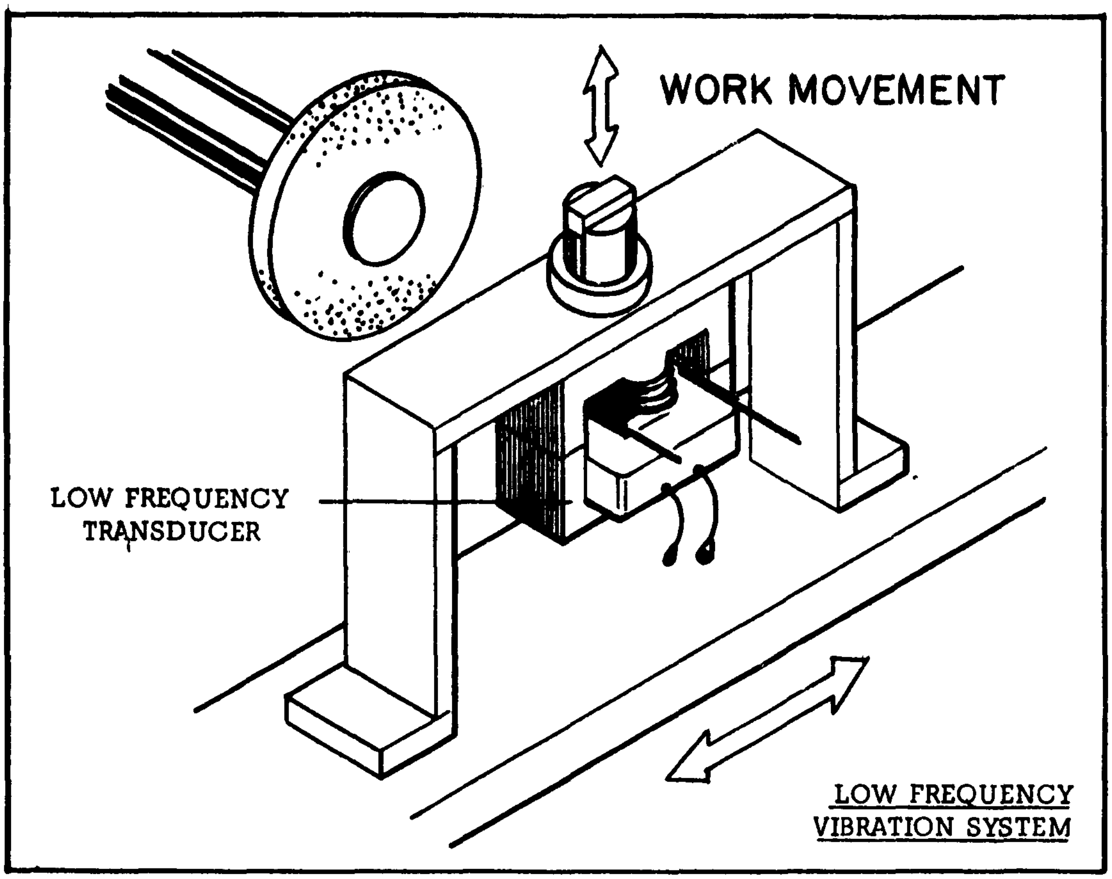


Figure 19

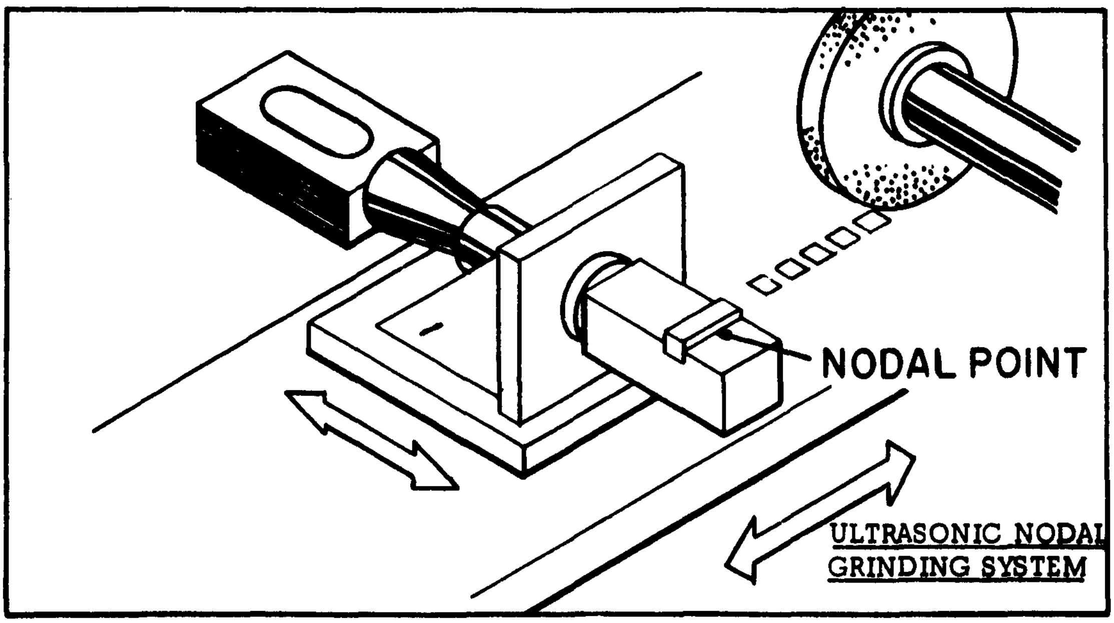
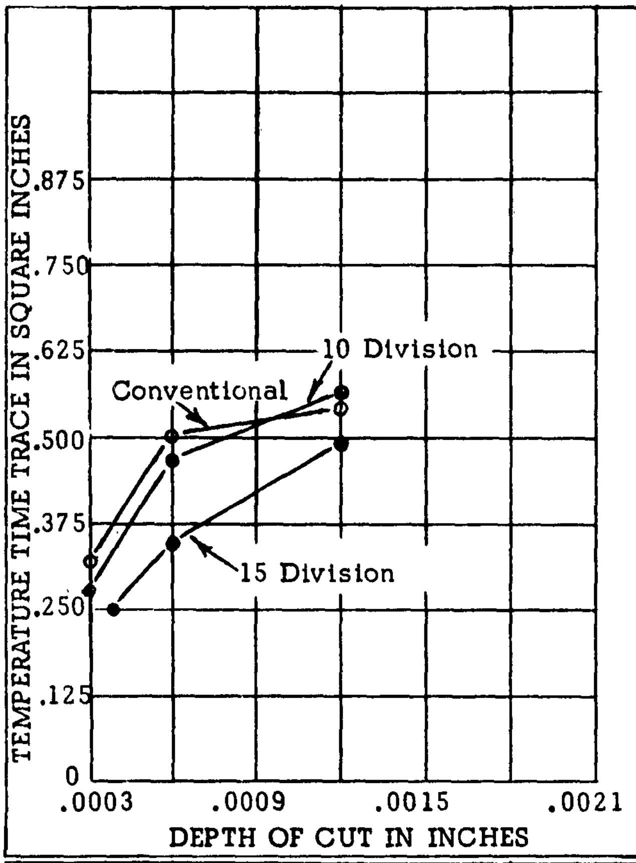


Figure 20

PHASE I

SECTION 4

GRINDING TESTS - DATA



SURFACE GRINDING

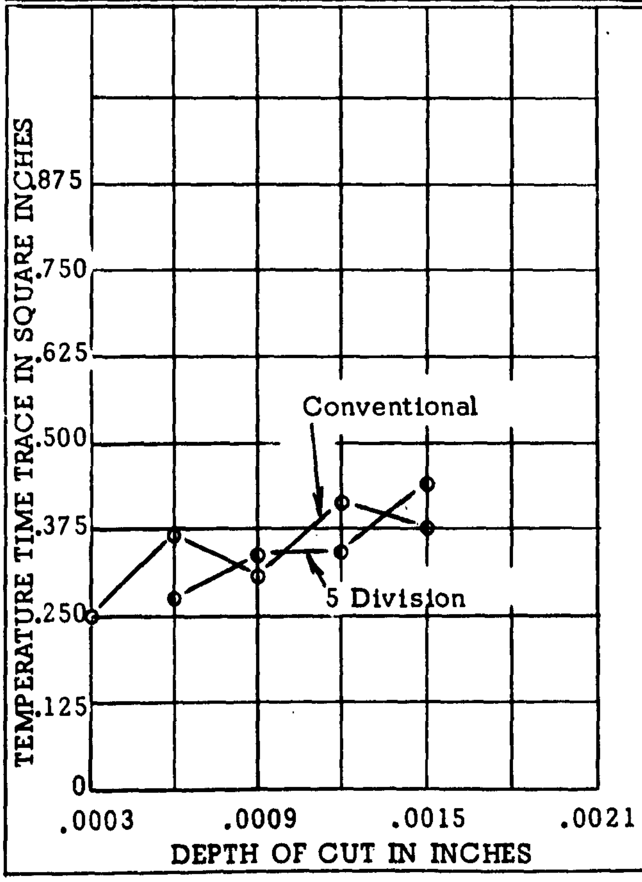
TEMPERATURE TIME TRACE AREA AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	1020
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM
Longitudinal Mode	
Method A	(see pp 19 & 20)
20 KC Range	

O Conventional
◐ 10 Division
● 15 Division

Run Numbers: I - 11-18

Figure 21



SURFACE GRINDING

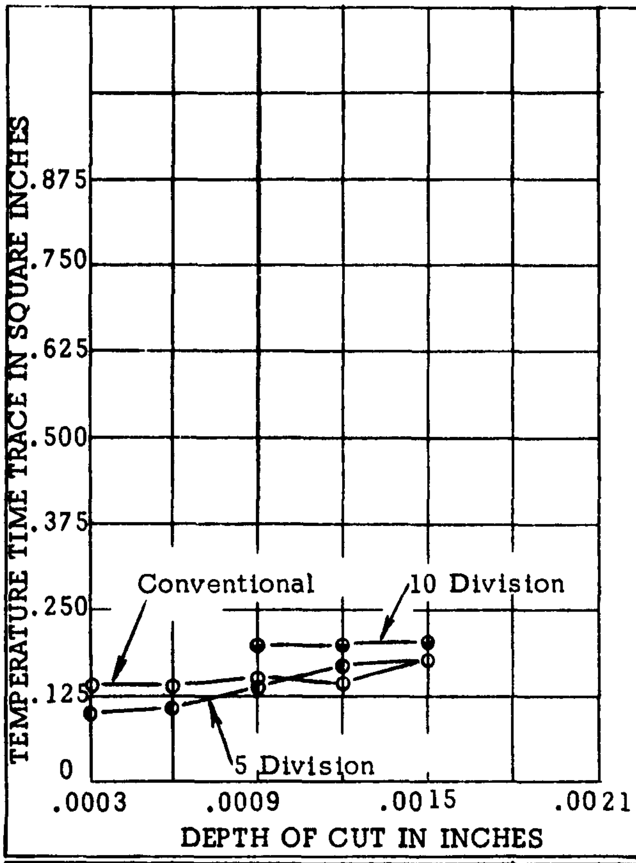
TEMPERATURE TIME TRACE AREA AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	440 C
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM
Longitudinal Mode	
Method A	(See pp 19 & 20)
20 KC Range	

O Conventional
◐ 5 Division

Run Numbers: I - 29-39

Figure 22



SURFACE GRINDING

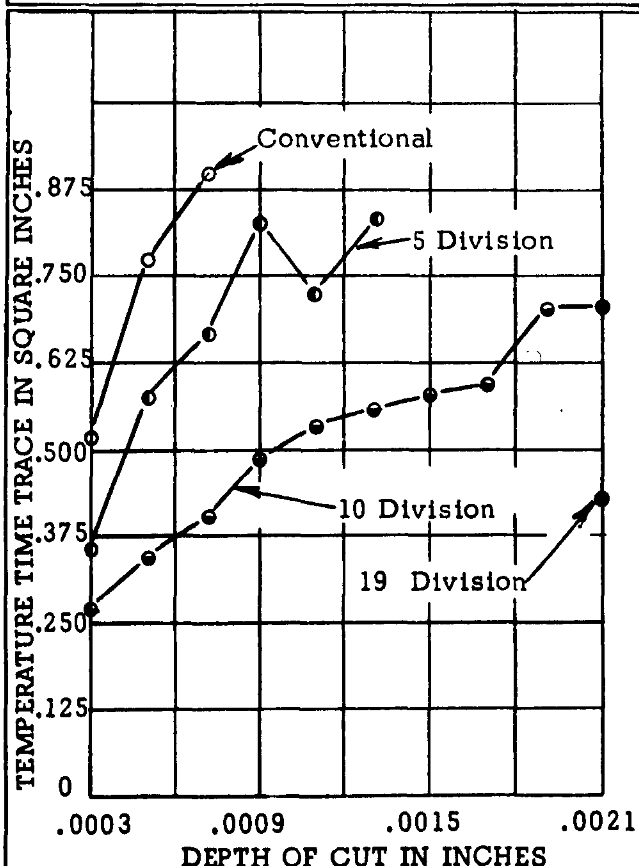
TEMPERATURE TIME TRACE AREA AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	4340
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM
Longitudinal Mode	
Method A (see pp 19 & 20)	
20 KC Range	

O Conventional
◐ 5 Division
● 10 Division

Run Numbers: I - 7-10, 26-28, 40-52

Figure 23



SURFACE GRINDING

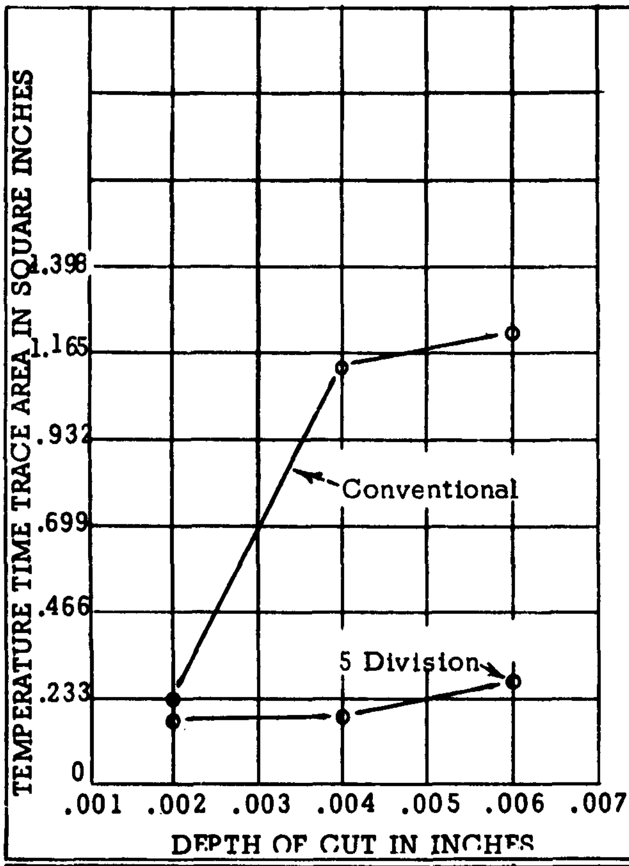
TEMPERATURE TIME TRACE AREA AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	4340
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM
Longitudinal Mode	
Method A (see pp 19 & 20)	
20 KC Range	

O Conventional
◐ 5 Division
● 10 Division
● 19 Division

Run Numbers: I - 66-88

Figure 24



SURFACE GRINDING

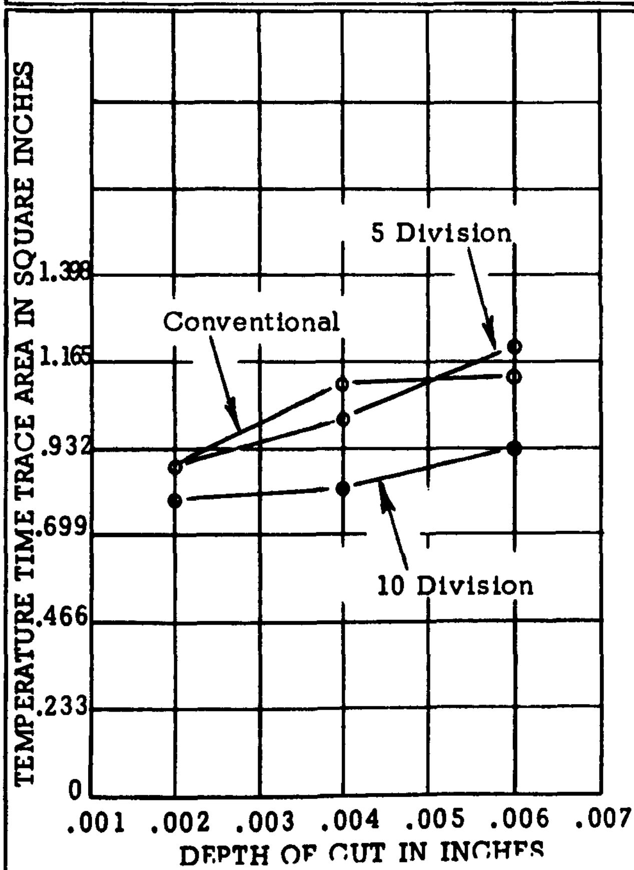
TEMPERATURE TIME TRACE AREA AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	440 C
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM
Longitudinal Mode	
Method A (see pp 19 & 20)	
20 KC Range	
.050" Cross Feed	10th Step

O Conventional
● 5 Division

Run Numbers: I - 53-58

Figure 25



SURFACE GRINDING

TEMPERATURE TIME TRACE AREA AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	4340
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM
Longitudinal Mode	
Method A (see pp 19 & 20)	
20 KC Range	
.050" Cross Feed	10th Step

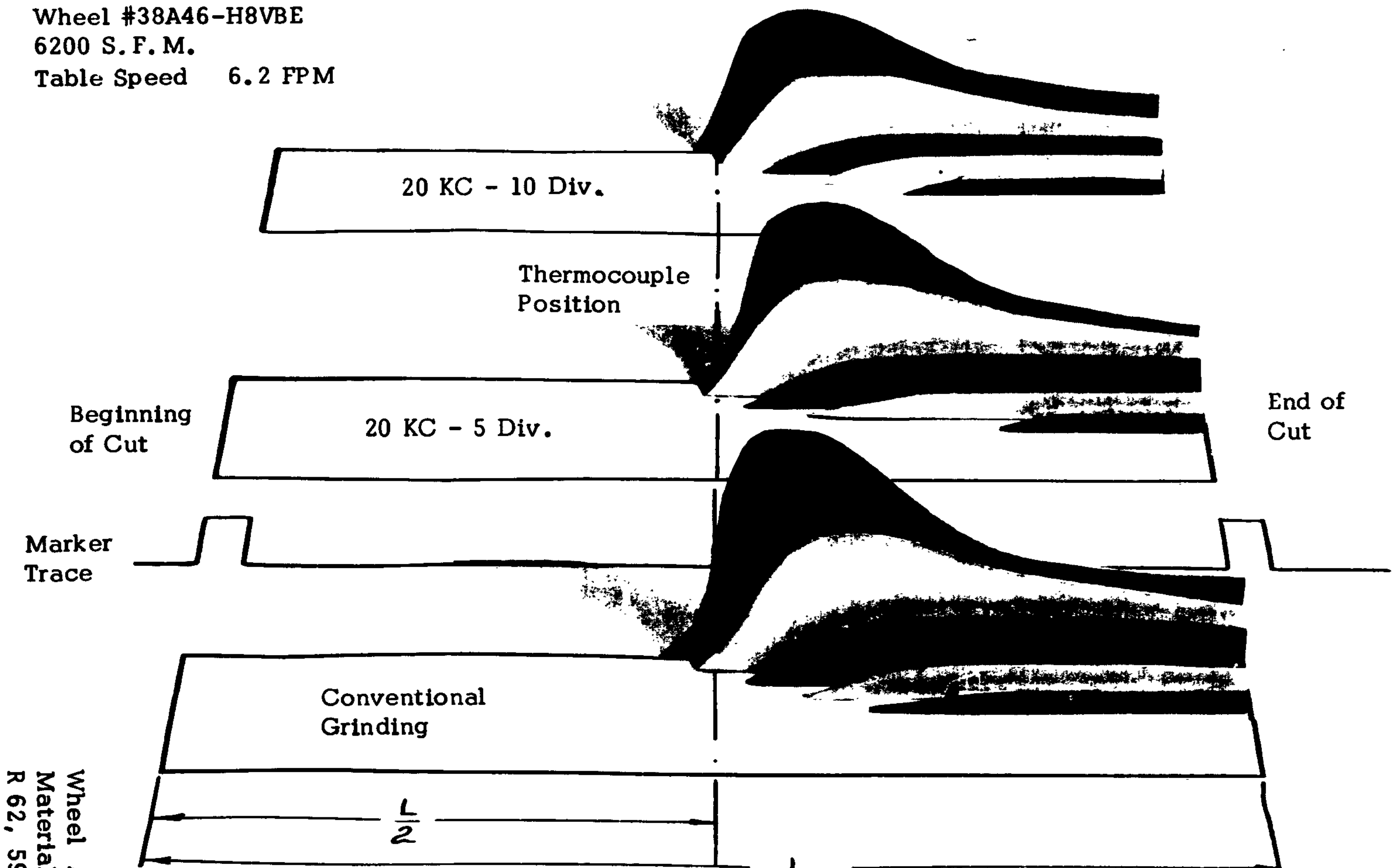
O Conventional
◐ 5 Division
● 10 Division

Run Numbers: I - 59-65

Figure 26

PICTORIAL PRESENTATION OF RISE IN TEMPERATURE
AS A RESULT OF GRINDING IN TEN .050" STEPS
ACROSS WIDTH OF TEST SPECIMEN

Longitudinal Mode
20 KC Range
.002" cut
Material - 4340
Wheel #38A46-H8VBE
6200 S.F.M.
Table Speed 6.2 FPM



Note: No Temperature Time Traces for first five steps.

Wheel A
Material F
R 62, 59, 65[1]

Figure 27

TEMPERATURE TIME TRACE

Longitudinal Mode - Method "A" - 20 KC - .002 cut - .050 cross feed

Wheel #38A46-H8VBE - 6200 SFM - Material SAE 4340

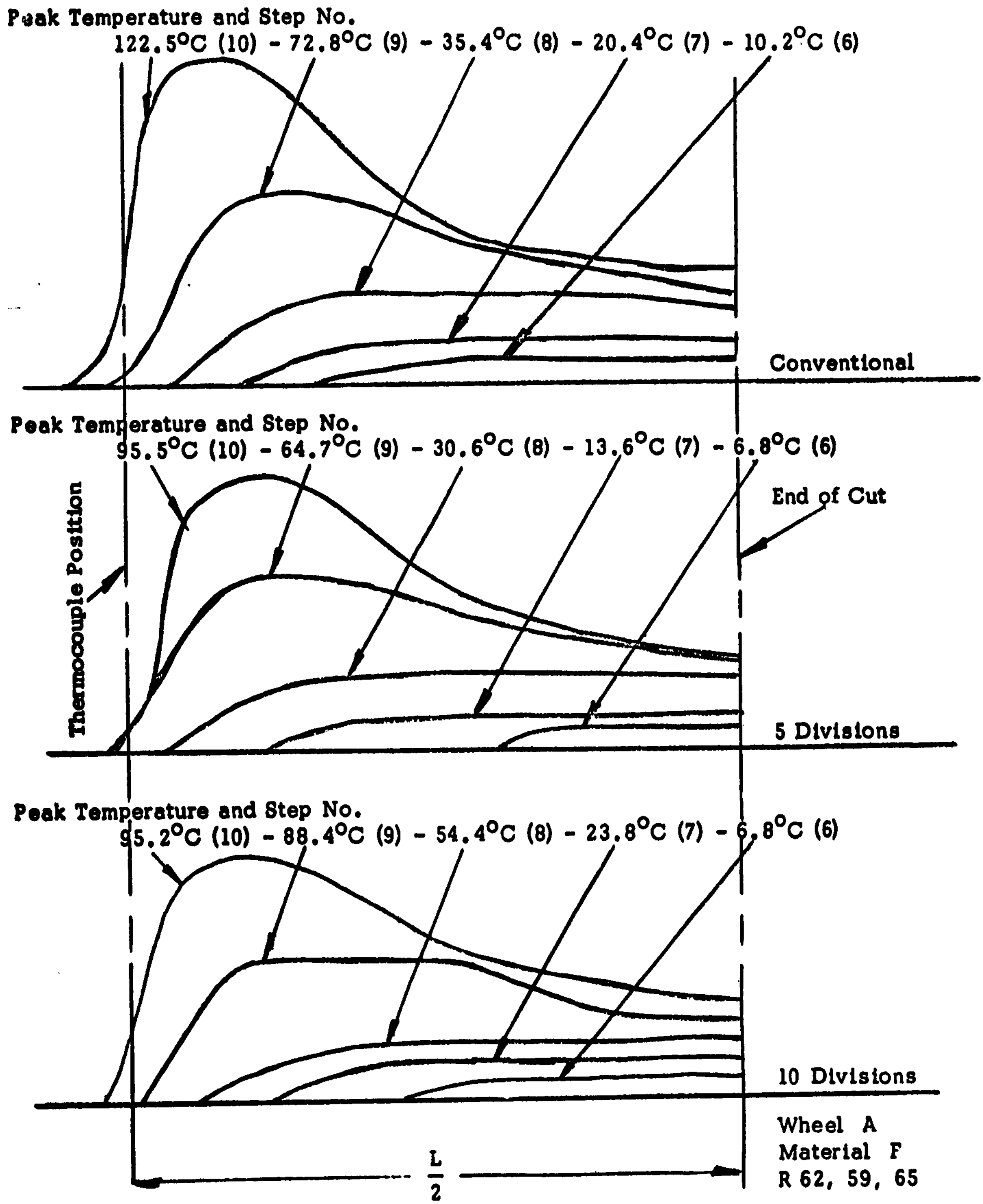
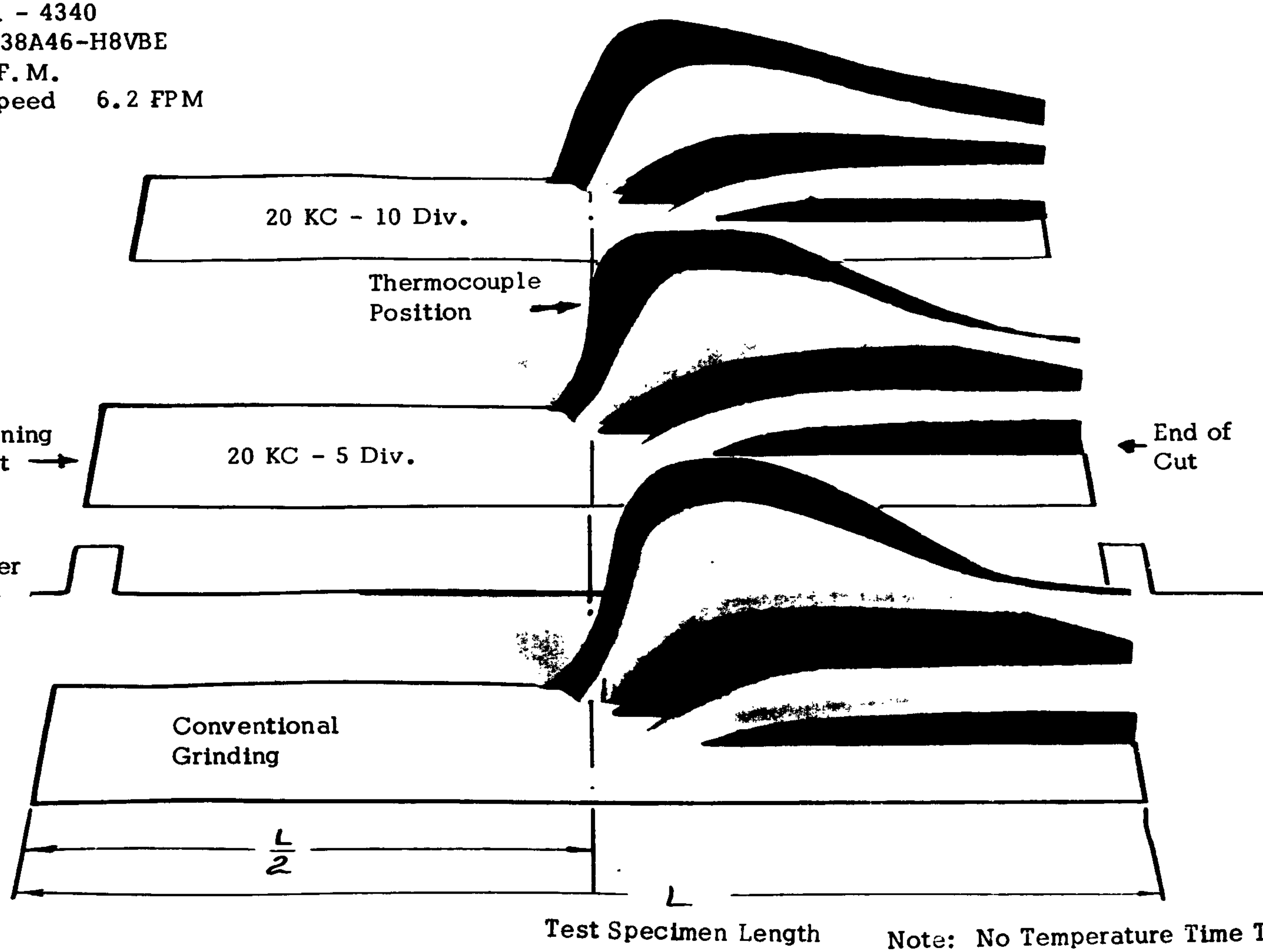


Figure 28

Longitudingal Mode
20 KC Range
.004" cut
Material - 4340
Wheel #38A46-H8VBE
6200 S.F.M.
Table Speed 6.2 FPM

PICTORIAL PRESENTATION OF RISE IN TEMPERATURE
AS A RESULT OF GRINDING IN TEN .050" STEPS
ACROSS WIDTH OF TEST SPECIMEN



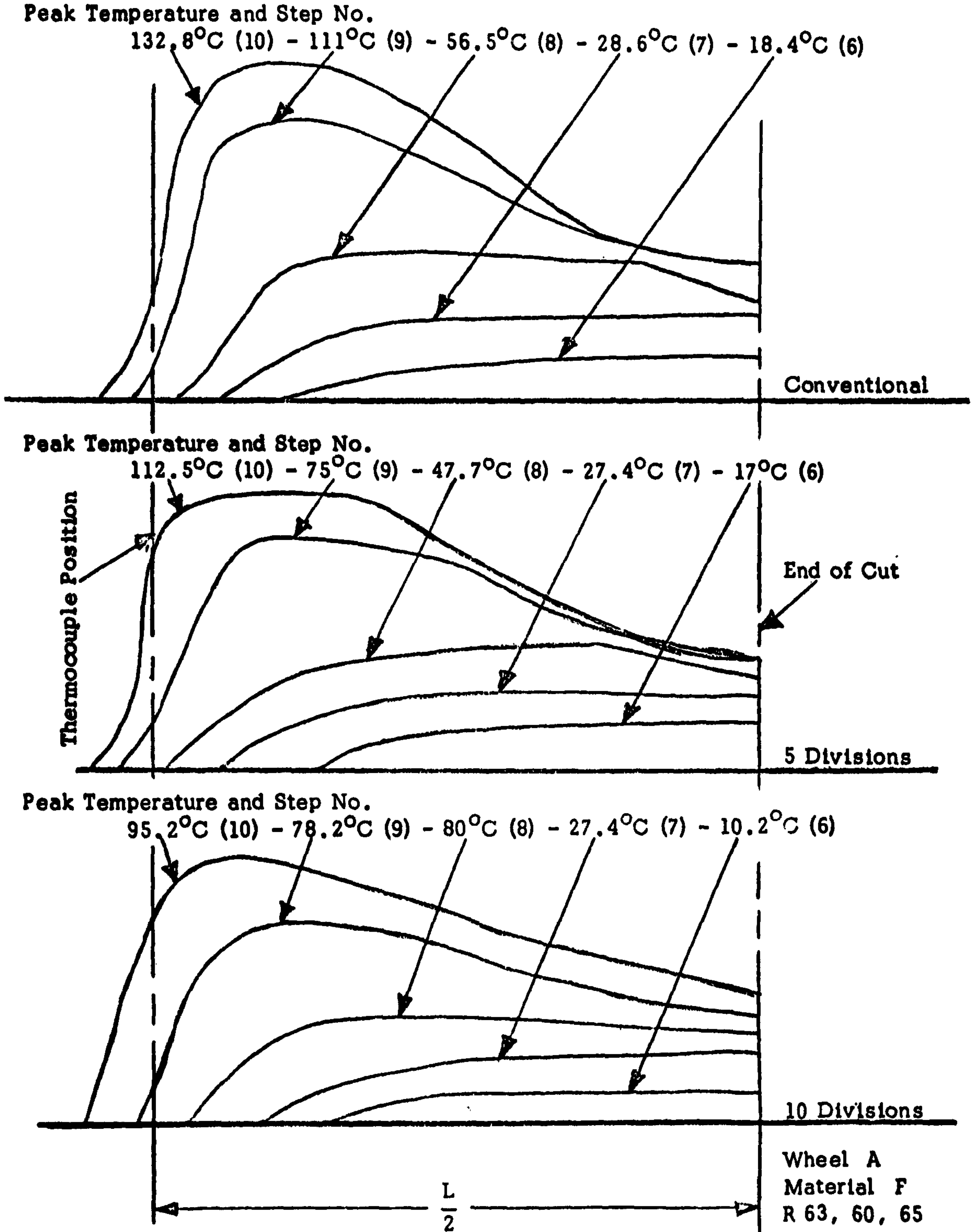
Note: No Temperature Time Traces
for first five steps.

Wheel A
Material F
R 63, 60, 652

Figure 29

TEMPERATURE TIME TRACE

Longitudinal Mode - Method "A" - 20 KC - .004 cut - .050 cross feed
Wheel #38A46-H8VBE - 6200 SFM - Material SAE 4340

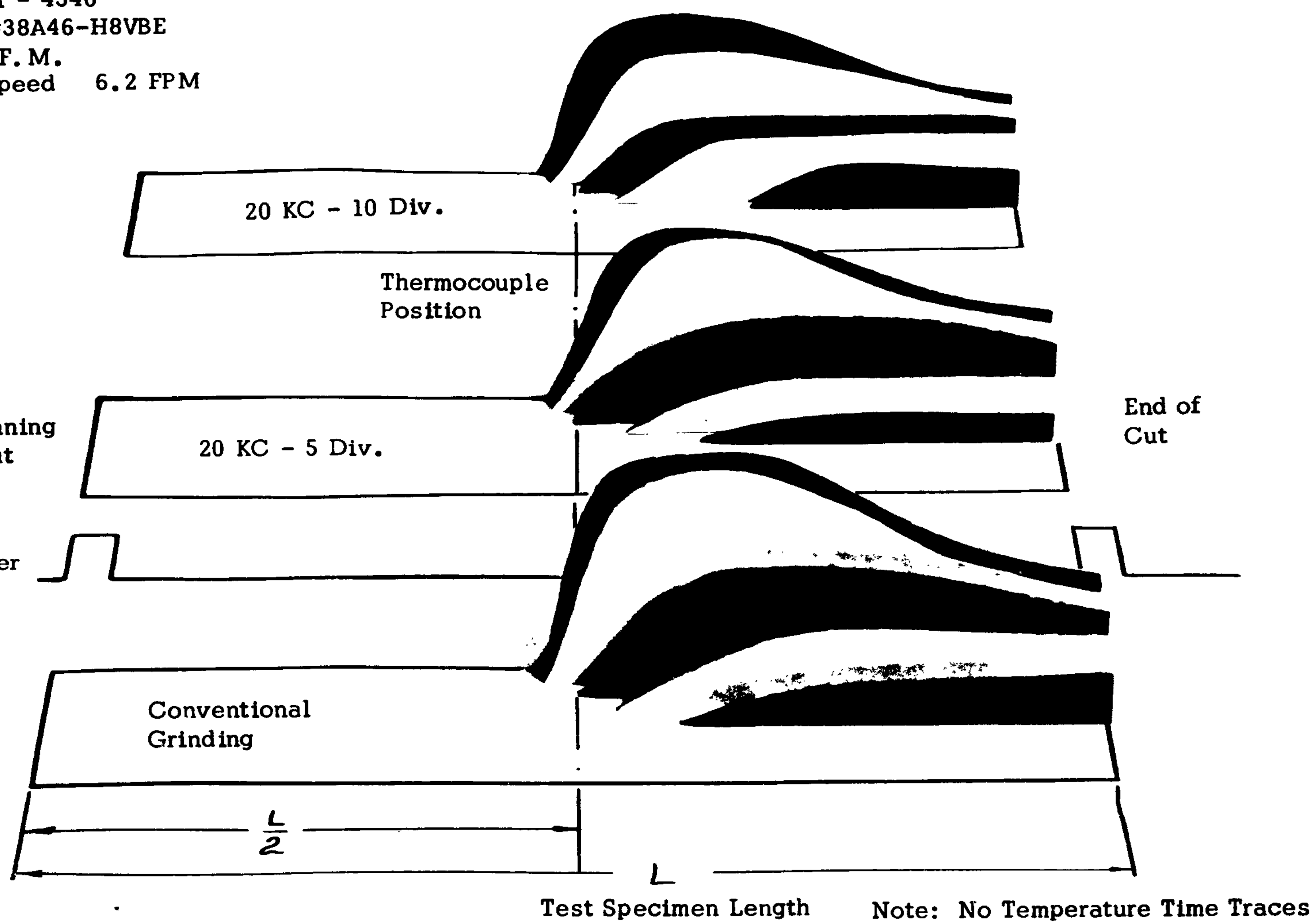


Wheel A
Material F
R 63, 60, 65

Figure 30

Longitudinal Mode
20 KC Range
.006" cut
Material - 4340
Wheel #38A46-H8VBE
6200 S.F.M.
Table Speed 6.2 FPM

PICTORIAL PRESENTATION OF RISE IN TEMPERATURE AS A RESULT OF GRINDING IN TEN .050" STEPS ACROSS WIDTH OF TEST SPECIMEN



Note: No Temperature Time Traces for first five steps.

Wheel A
Material F
R 64, 61, 65_3

Figure 31

TEMPERATURE TIME TRACE

Longitudinal Mode - Method "A" - 20 KC - .006 cut - .050 cross feed

Wheel #38A46-H8VBE - 6200 SFM - Material SAE 4340

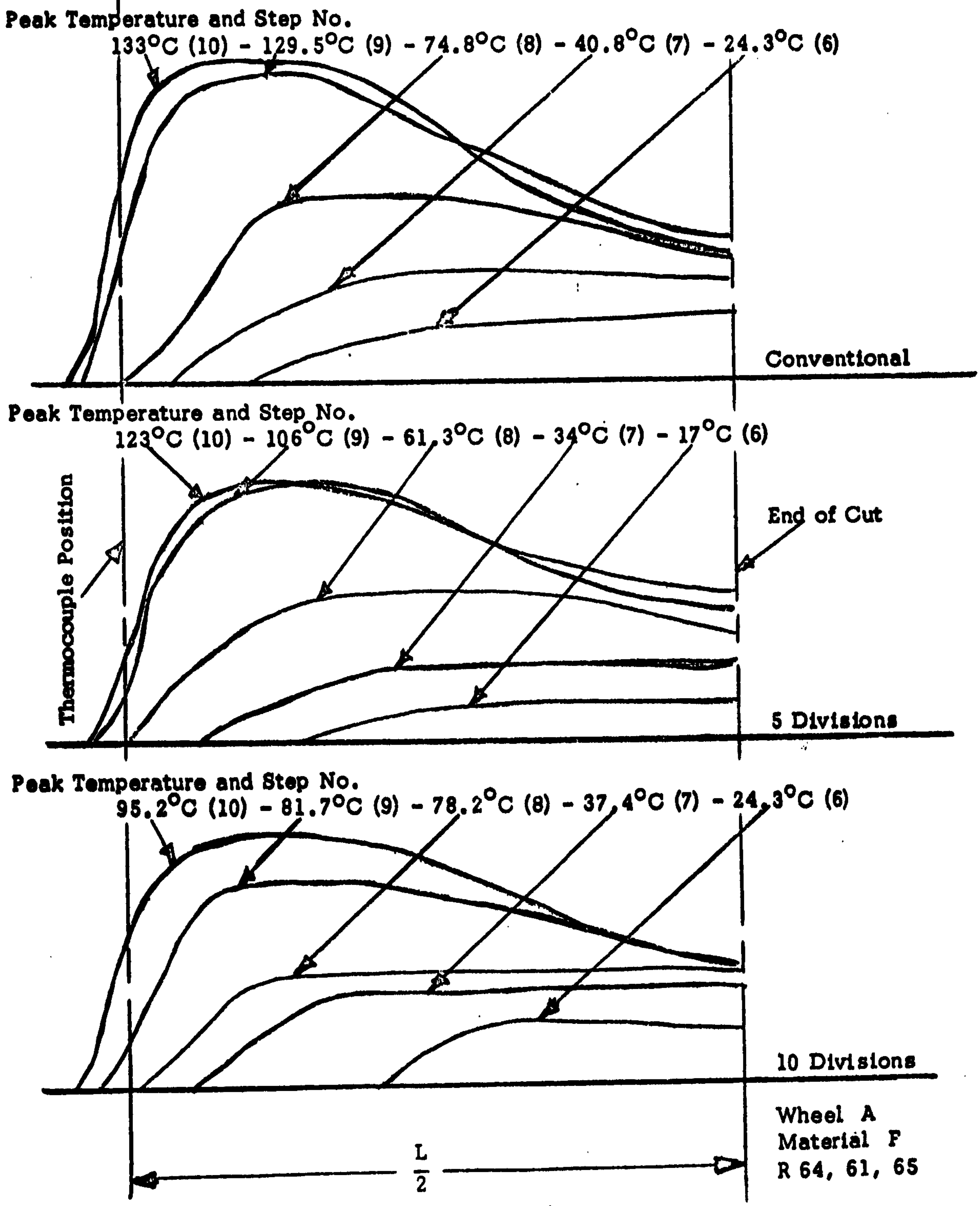


Figure 32

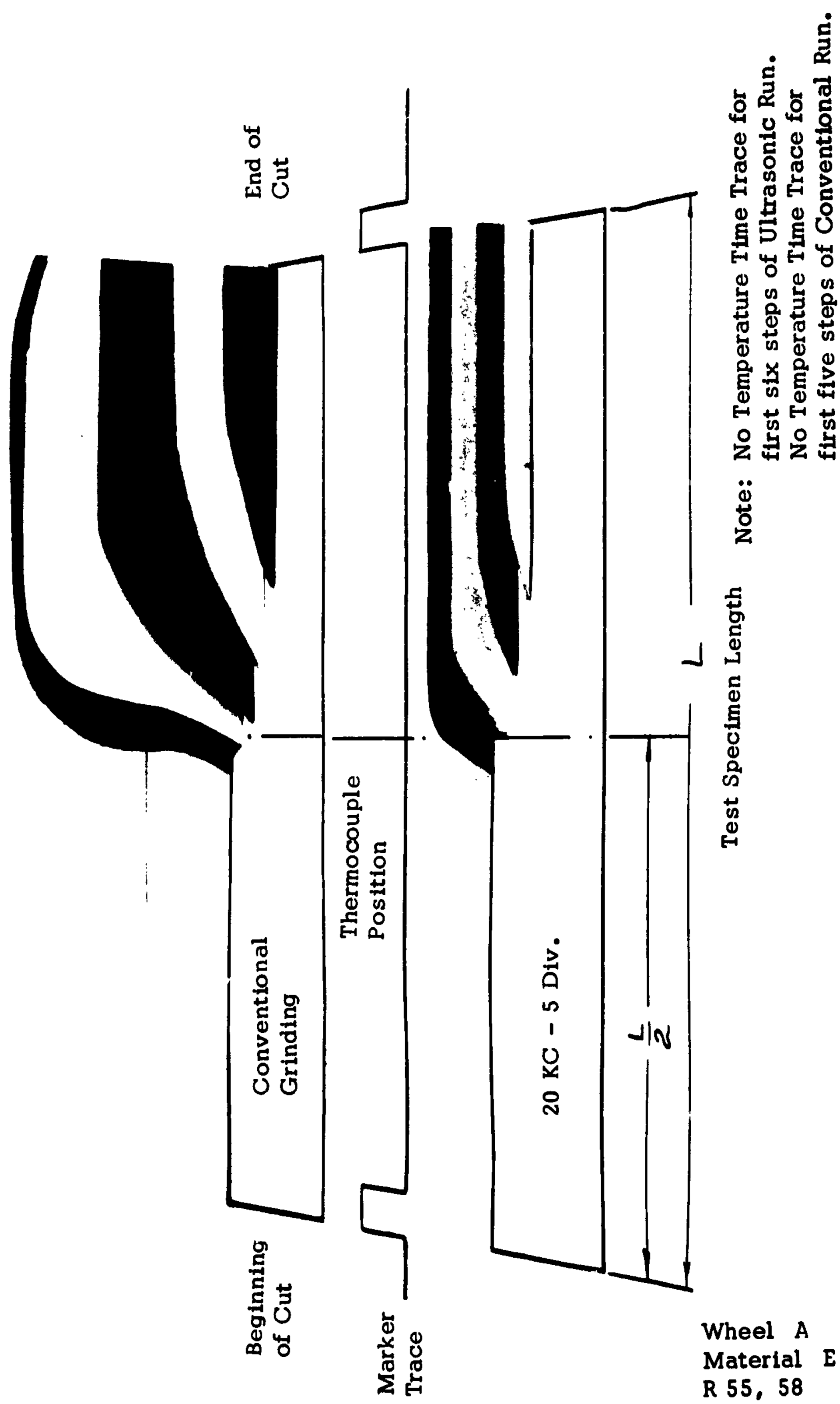

End of Cut
Conventional Grinding
Thermocouple Position
20 KC - 5 Div.
$\frac{L}{2}$
L
Test Specimen Length
Beginning of Cut
Marker Trace
Note: No Temperature Time Trace for first six steps of Ultrasonic Run.
No Temperature Time Trace for first five steps of Conventional Run.
Wheel A
Material E
R 55, 58

Figure 33

TEMPERATURE TIME TRACE

Longitudinal Mode - Method "A" - 20 KC - .006 cut - .050 cross feed

Wheel #38A46-H8VBE - 6200 SFM - Material 440C

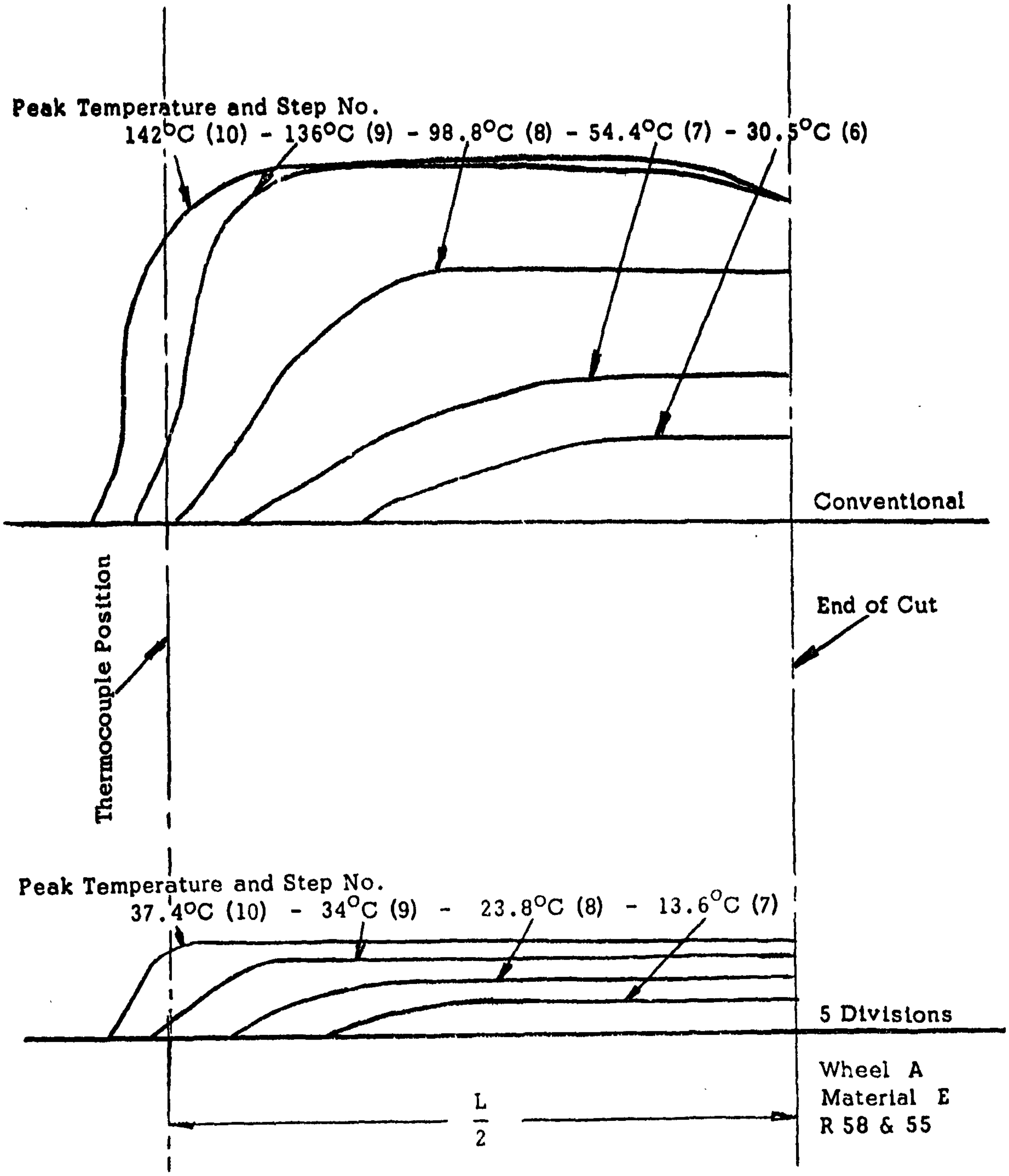
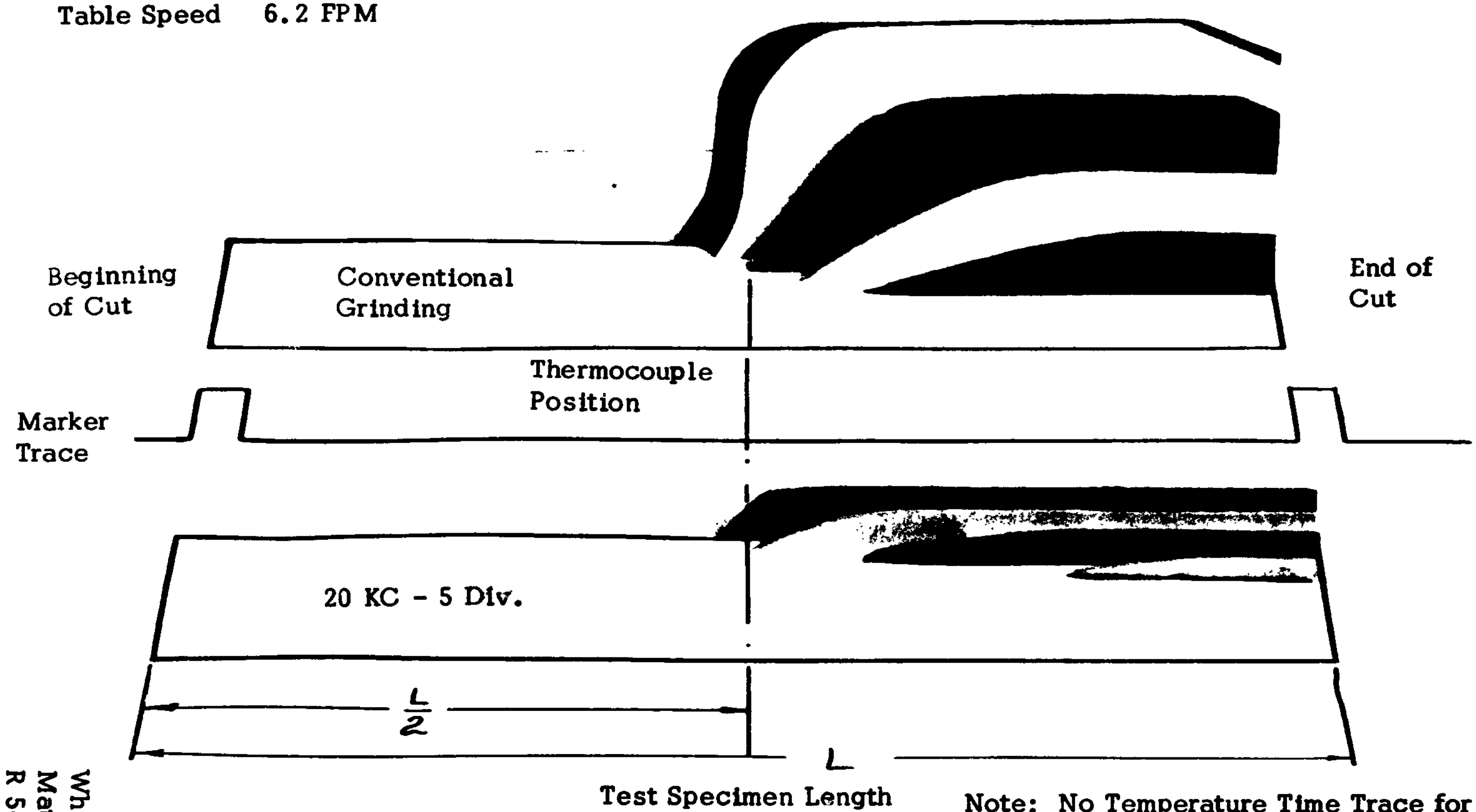


Figure 34

Longitudinal Mode
20 KC Range
.004" cut
Material - 440C
Wheel #38A46-H8VBE
6200 S.F.M.
Table Speed 6.2 FPM

PICTORIAL PRESENTATION OF RISE IN TEMPERATURE AS A RESULT OF GRINDING IN TEN .050" STEPS ACROSS WIDTH OF TEST SPECIMEN



Note: No Temperature Time Trace for first six steps of Ultrasonic Run.
No Temperature Time Trace for first five steps of Conventional Run.

Wheel A
Material E
R 54, 57

Figure 35

TEMPERATURE TIME TRACE

Longitudinal Mode - Method "A" - 20 KC - .004 cut - .050 cross feed

Wheel #38A46-H8VBE - 6200 SFM - Material 440C

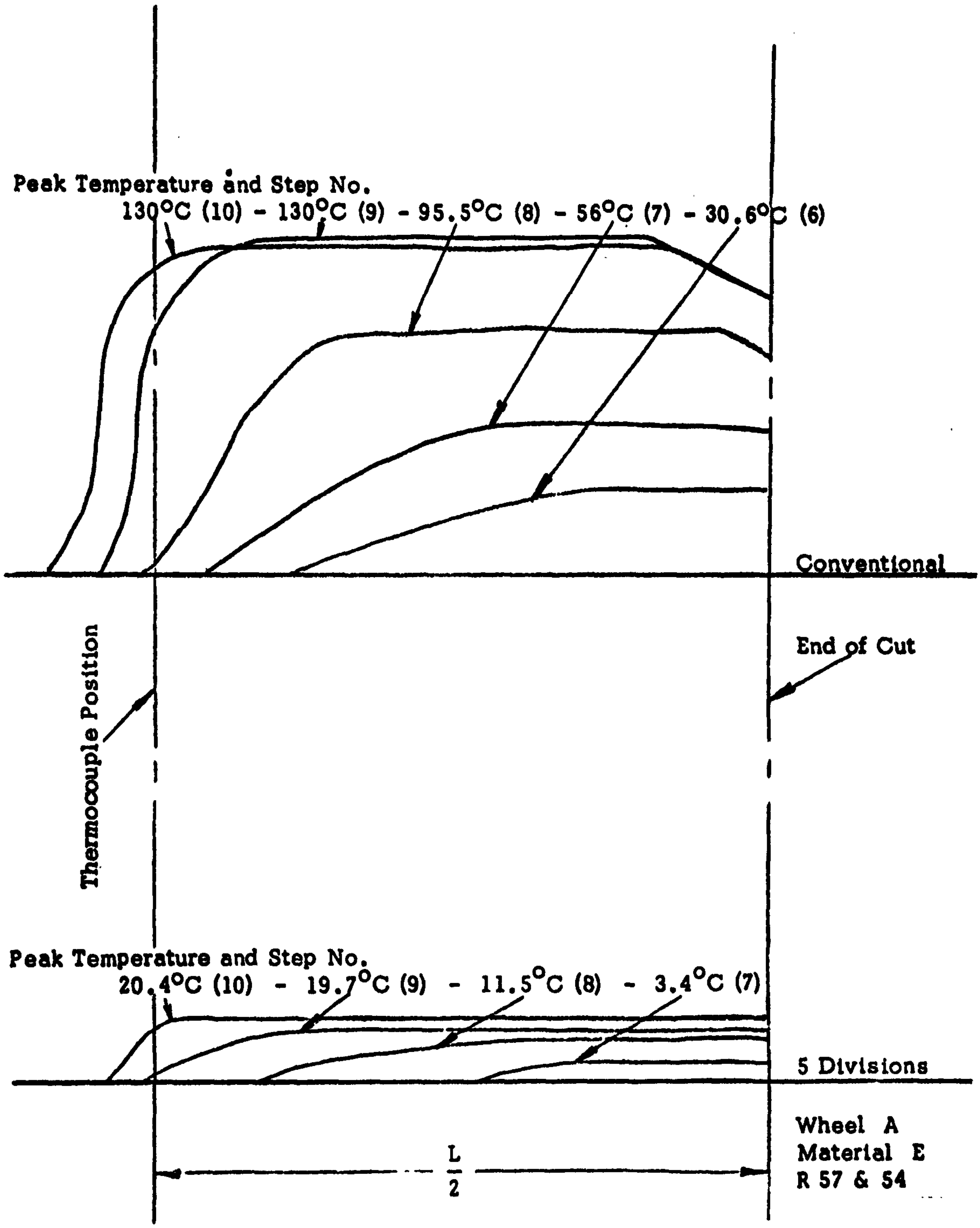
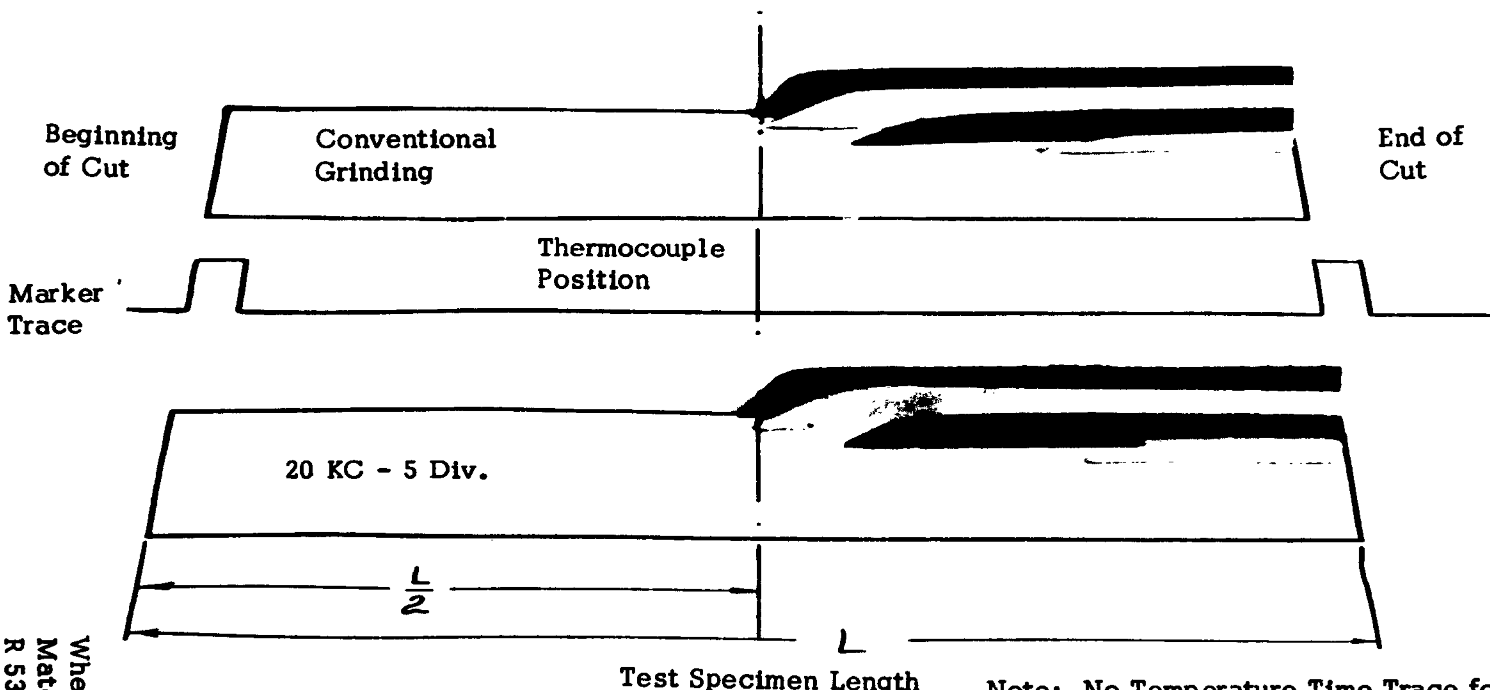


Figure 36

Longitudinal Mode
20 KC Range
.002" cut
Material - 440C
Wheel #38A46-H8VBE
6200 S.F.M.
Table Speed 6.2 FPM

PICTORIAL PRESENTATION OF RISE IN TEMPERATURE
AS A RESULT OF GRINDING IN TEN .050" STEPS
ACROSS WIDTH O: TEST SPECIMEN



Note: No Temperature Time Trace for first six steps of Ultrasonic Run.
No Temperature Time Trace for first five steps of Conventional Run.

Wheel A
Material E
R 53, 56

Figure 37

TEMPERATURE TIME TRACE

Longitudinal Mode - Method "A" - 20 KC - .002 cut - .050 cross feed

Wheel #38A46-H8VBE - 6200 SFM - Material 440C

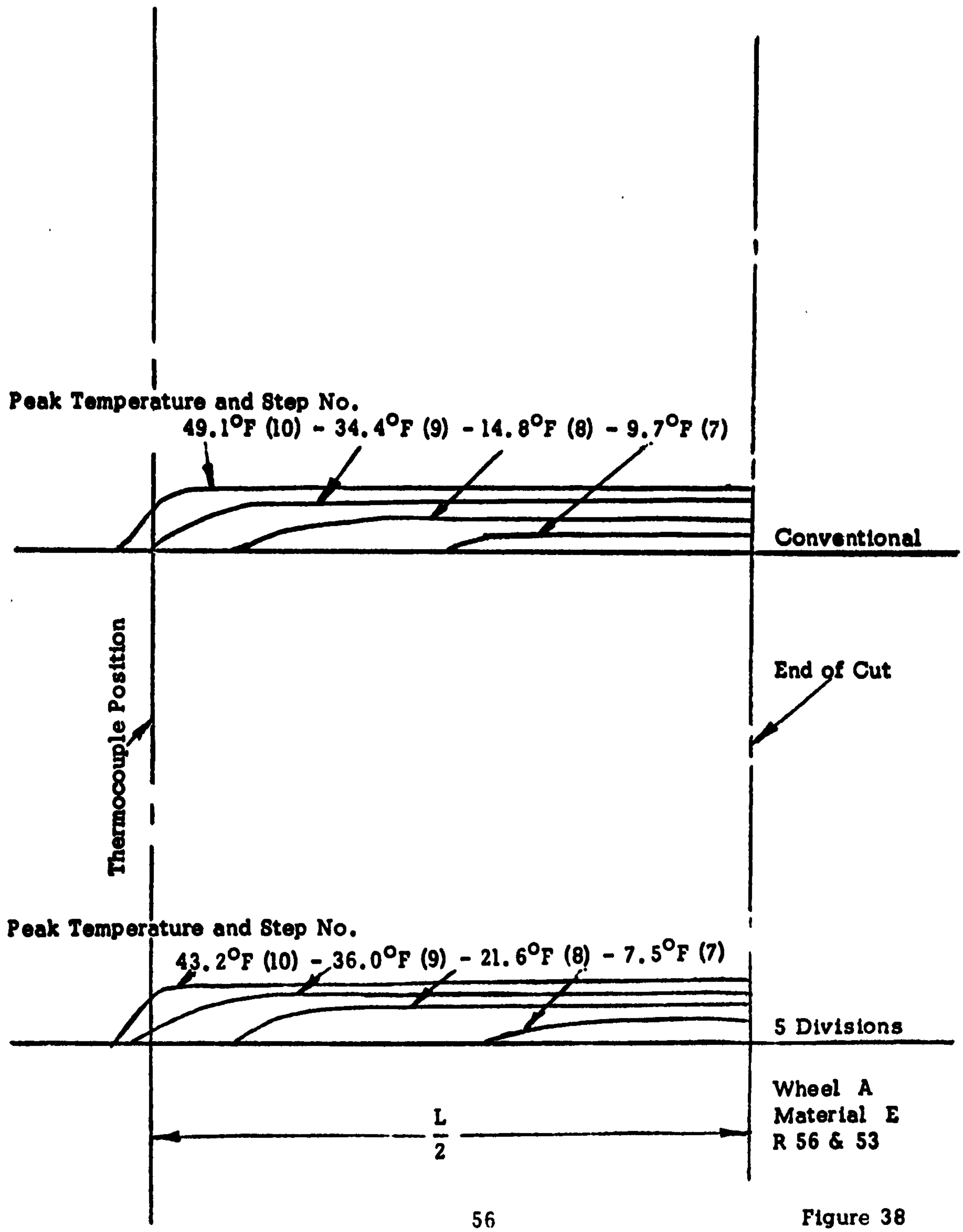
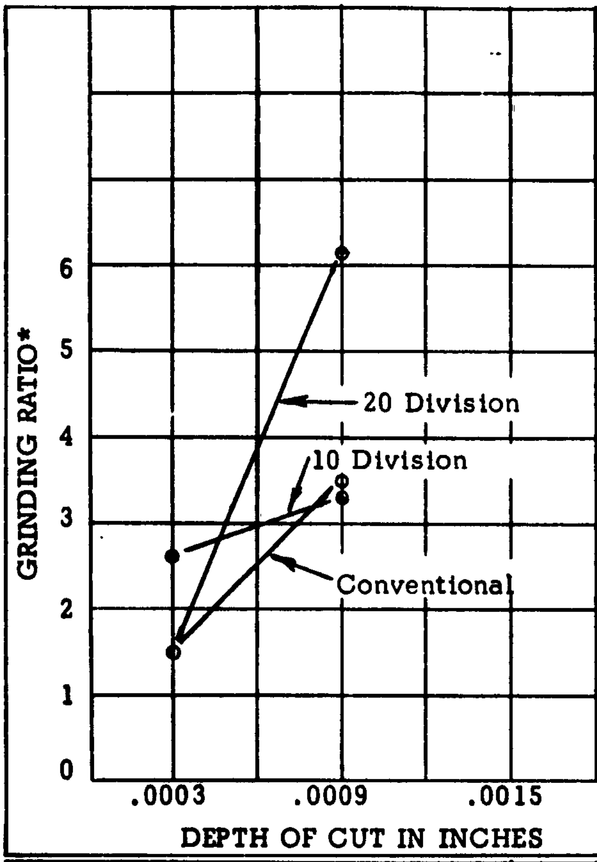


Figure 38



SURFACE GRINDING

GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

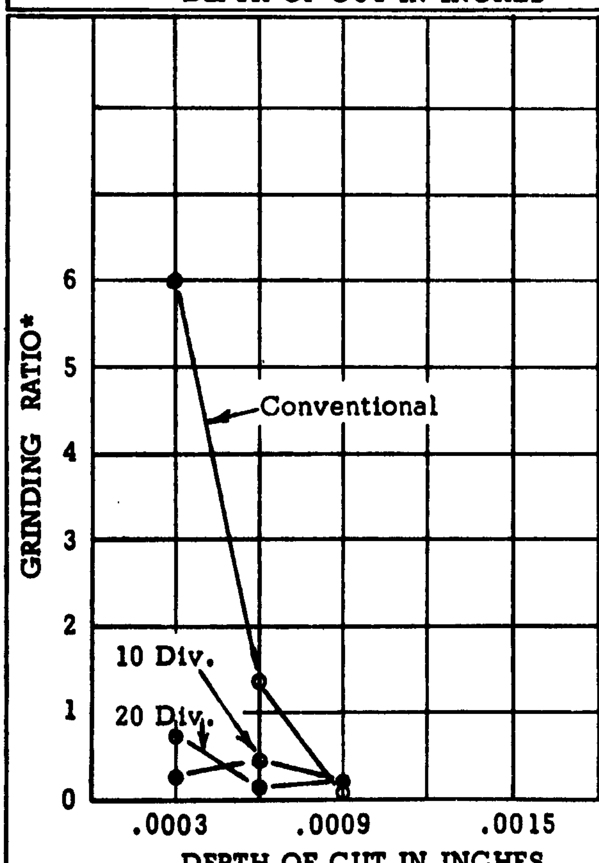
Material	15 - 7 MO
Wheel	32A60-L7V6
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Flexural Mode	(see pp 19 & 20)
Method A	10 KC Range

O Conventional
● 10 Division
● 20 Division

$$*\text{GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

I

Figure 39



SURFACE GRINDING

GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

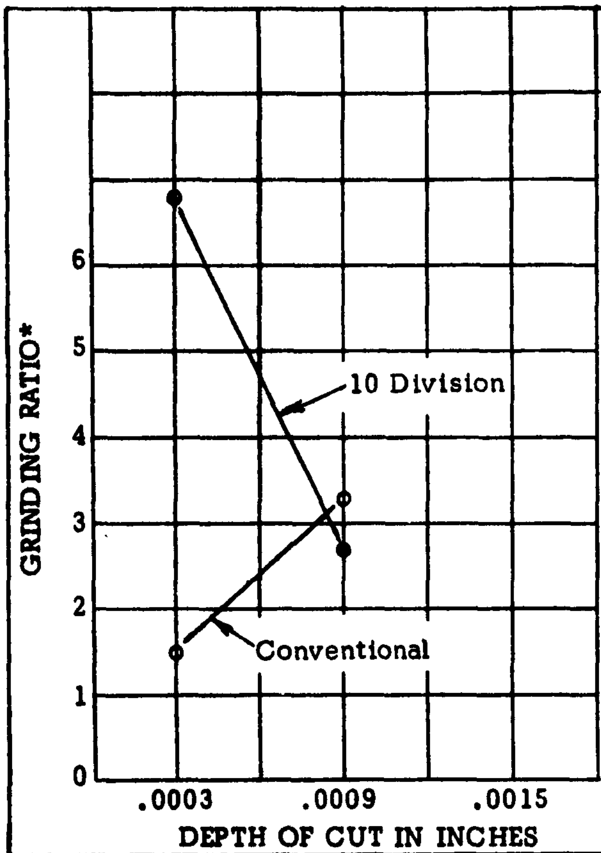
Material	15-7 MO
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode	(see pp 19&20)
Method A	20 KC Range

O Conventional
● 10 Division
● 20 Division

$$*\text{GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

I

Figure 40



SURFACE GRINDING

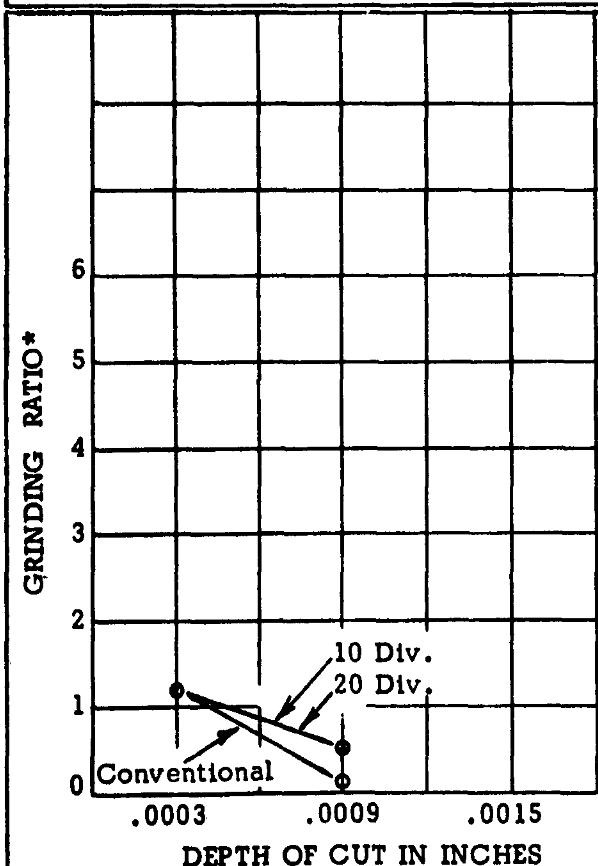
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	32A60-L7VG
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM
Longitudinal Mode (pp. 19 & 20)	
Method A	20 KC Range

O Conventional
● 10 Division

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Figure 41



SURFACE GRINDING

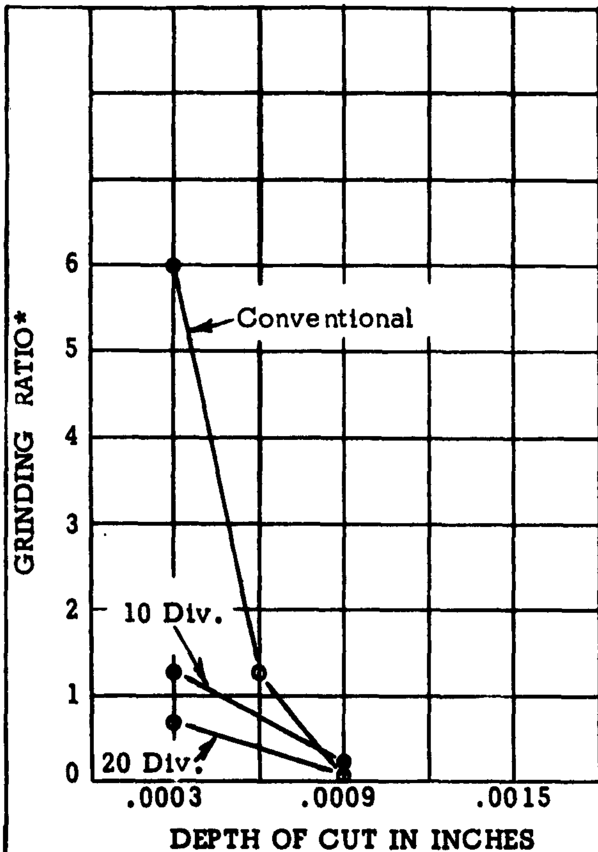
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode (pp. 19 & 20)	
Method A	20 KC

O Conventional
● 10 & 20 Division

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Figure 42



SURFACE GRINDING

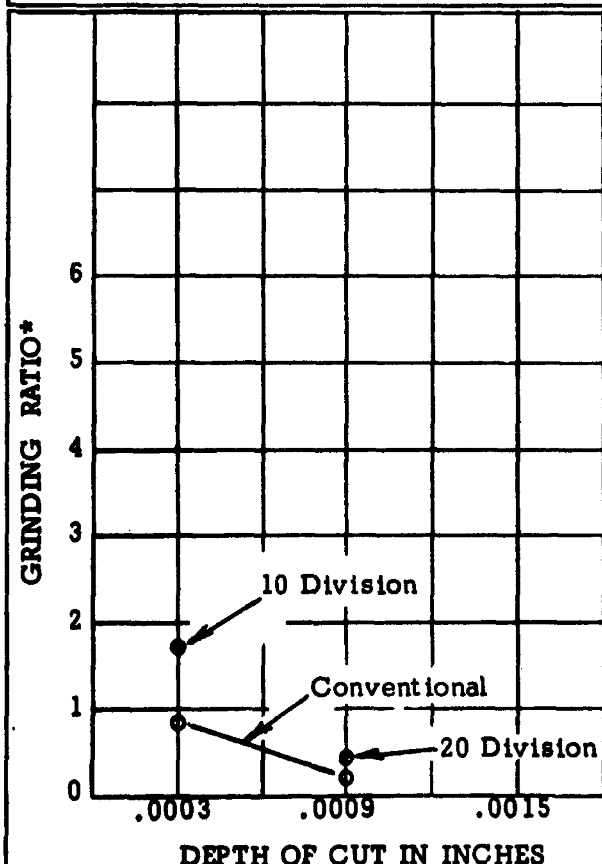
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 15-7 MO
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 35 FPM
Longitudinal Mode (pp. 19 & 20)
Method A 25 KC Range
O Conventional
● 10 Division
● 20 Division

*GRINDING RATIO= $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

I

Figure 43



SURFACE GRINDING

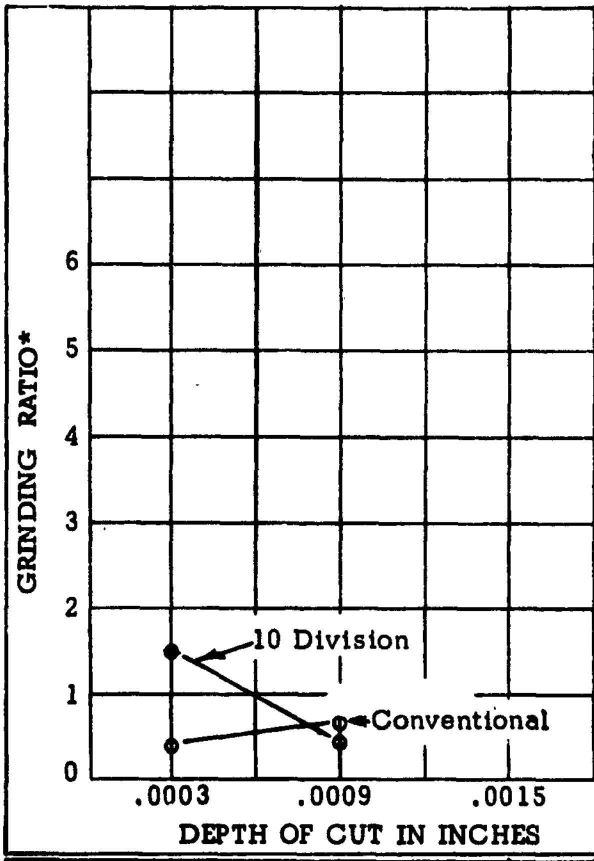
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 15-7 MO
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 35 FPM
Flexural Mode (pp. 19 & 20)
Method A 20 KC Range
O Conventional
● 10 Division
● 20 Division

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

I

Figure 44



SURFACE GRINDING

GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

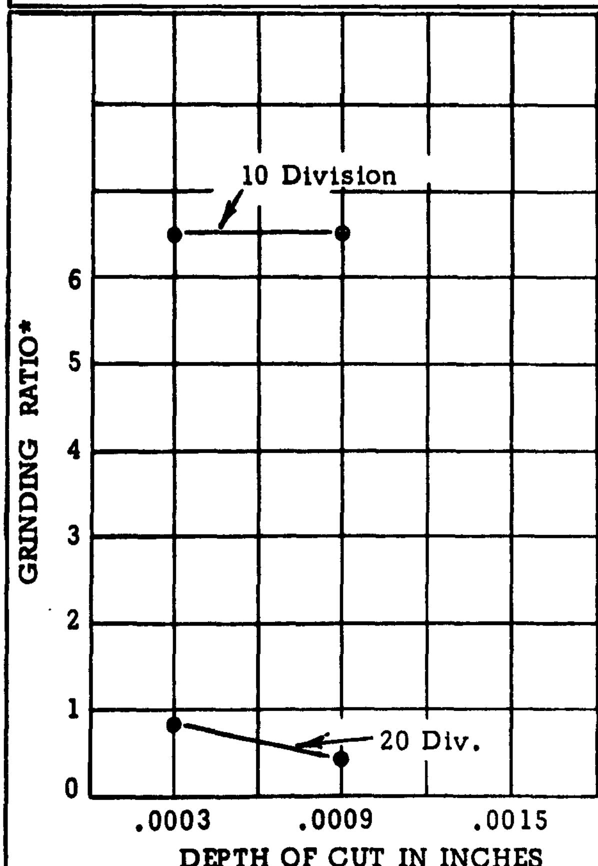
Material	4340
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode	(pp. 19 & 20)
Method A	20 KC

O Conventional
● 10 Division

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

I

Figure 45



SURFACE GRINDING

GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

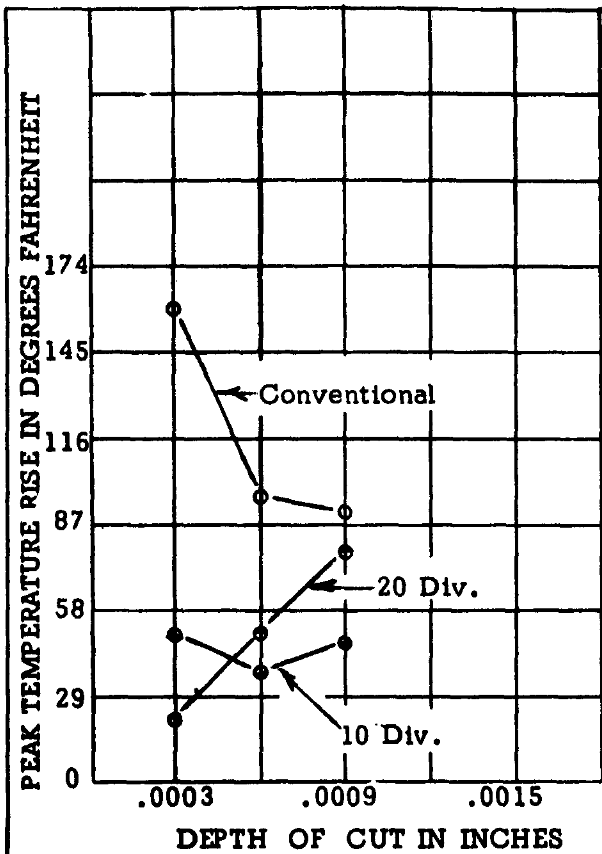
Material	4340
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode	(pp. 19 & 20)
Method A	25 KC Range

● 10 Division
● 20 Division

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

I

Figure 46



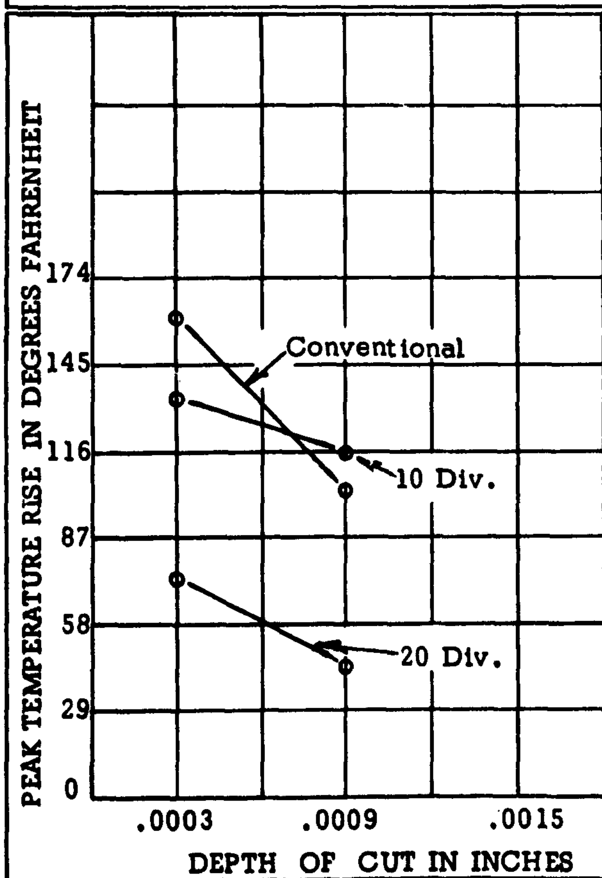
SURFACE GRINDING

PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 35 FPM
Longitudinal Mode (pp. 19 & 20)
Method A 20 KC Range
O Conventional
● 10 Division
● 20 Division

Run Numbers: I - 98A-106

Figure 47



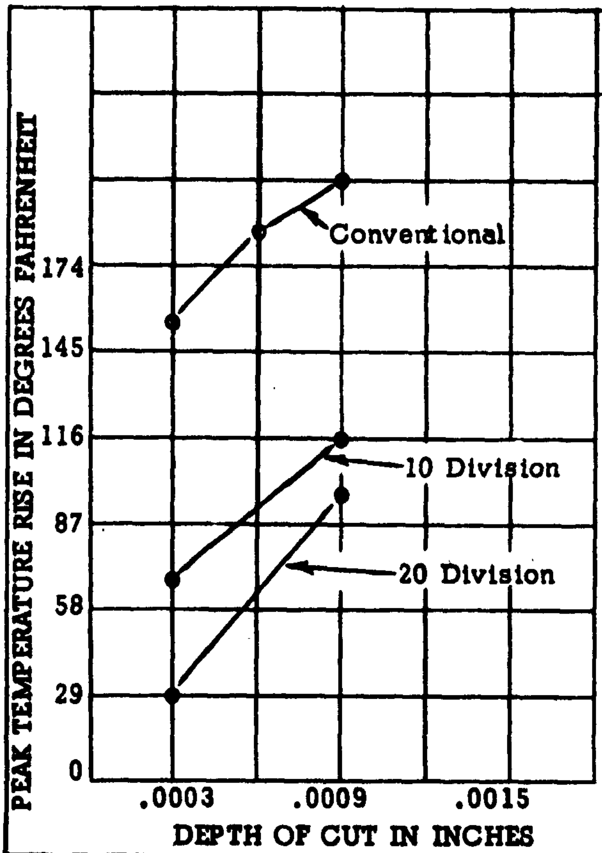
SURFACE GRINDING

PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 15-7 MO
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 35 FPM
Longitudinal Mode (pp.19 &20)
Method A 25 KC Range
O Conventional
● 10 Division
● 20 Division

I

Figure 48



SURFACE GRINDING

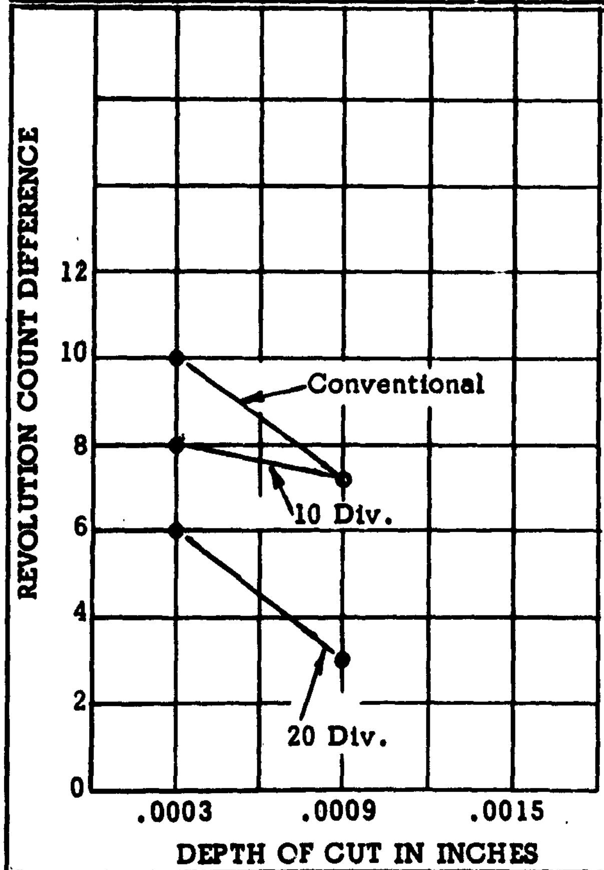
PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	4340
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode	(pp. 19 & 20)
Method A	25 KC Range

O Conventional
● 10 Division
● 20 Division

I

Figure 49



SURFACE GRINDING

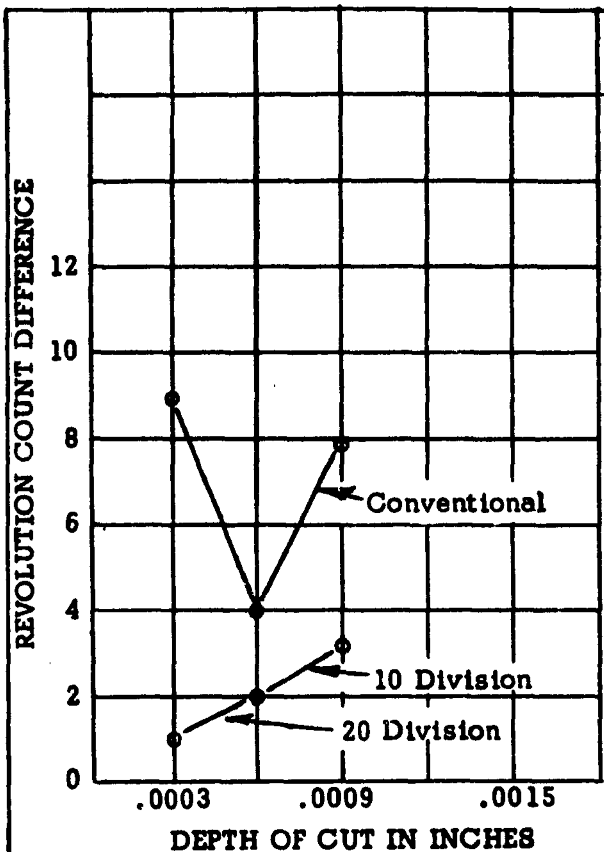
REVOLUTION COUNT DIFFERENCE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode	(pp.19 & 20)
Method B	20 KC

O Conventional
● 10 Division
● 20 Division

I

Figure 50



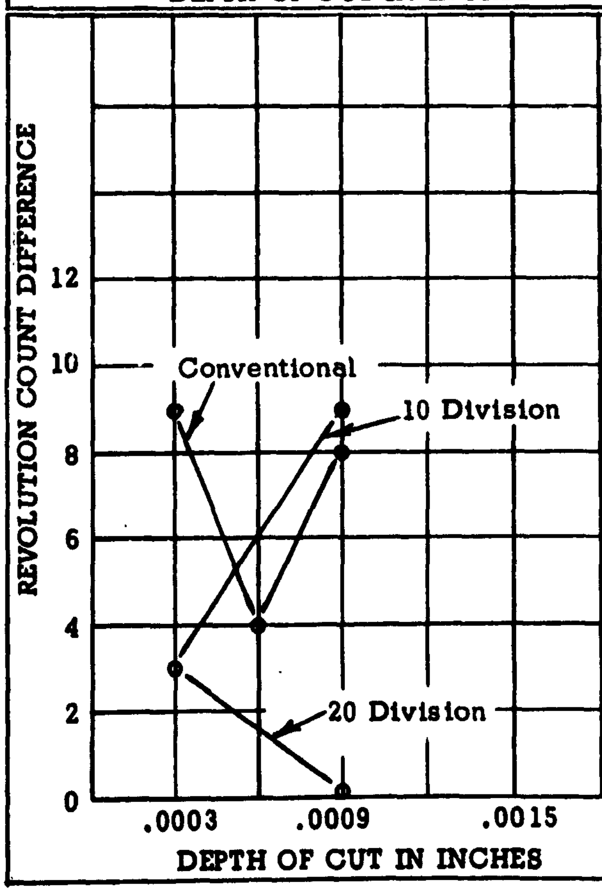
SURFACE GRINDING

REVOLUTION COUNT DIFFERENCE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 15-7MO
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 35 FPM
Longitudinal Mode (pp.19 & 20)
Method A
O Conventional
● 10 Division
● 20 Division

I

Figure 51



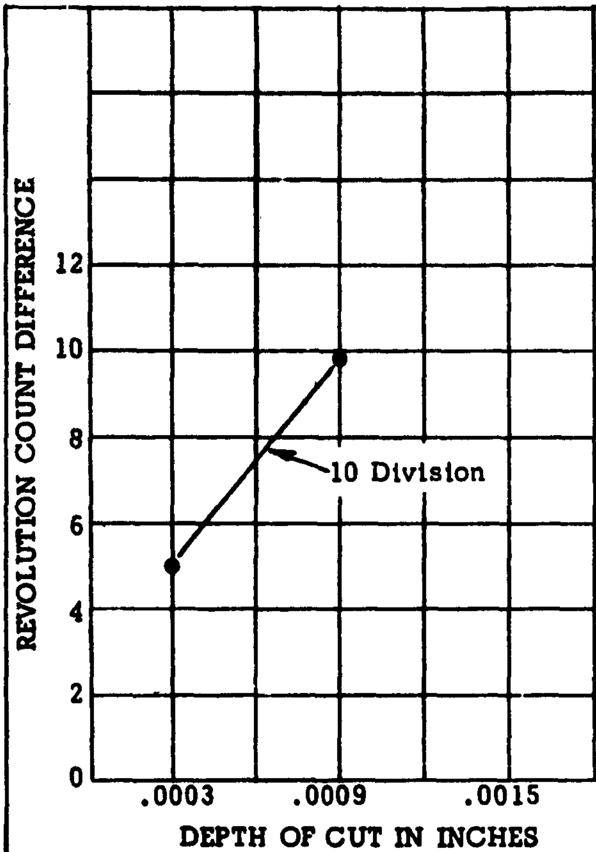
SURFACE GRINDING

REVOLUTION COUNT DIFFERENCE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 15-7 MO
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 35 FPM
Longitudinal Mode (pp.19 & 20)
Method A 25 KC Range
O Conventional
● 10 Division
● 20 Division

I

Figure 52



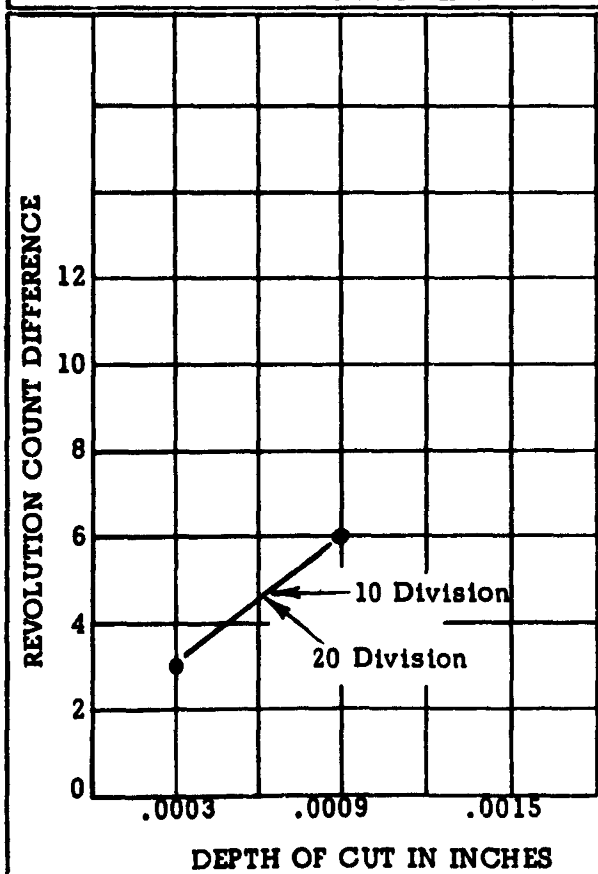
SURFACE GRINDING

REVOLUTION COUNT DIFFERENCE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 35 FPM
Longitudinal Mode (pp.19 & 20)
Method B 20 KC Range
● 10 Division

I

Figure 53



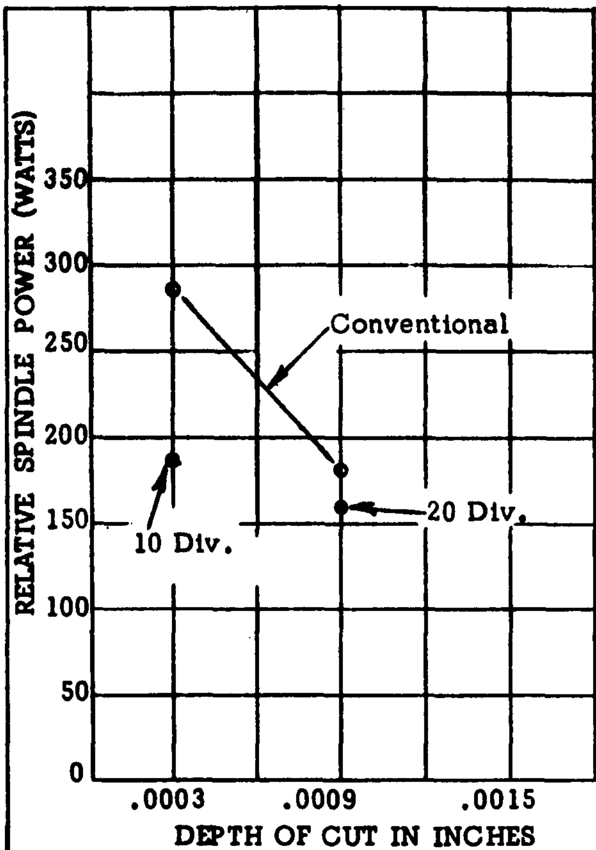
SURFACE GRINDING

REVOLUTION COUNT DIFFERENCE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 35 FPM
Longitudinal Mode (pp.19 & 20)
Method A 25 KC Range
● 10 & 20 Division

I

Figure 54



SURFACE GRINDING

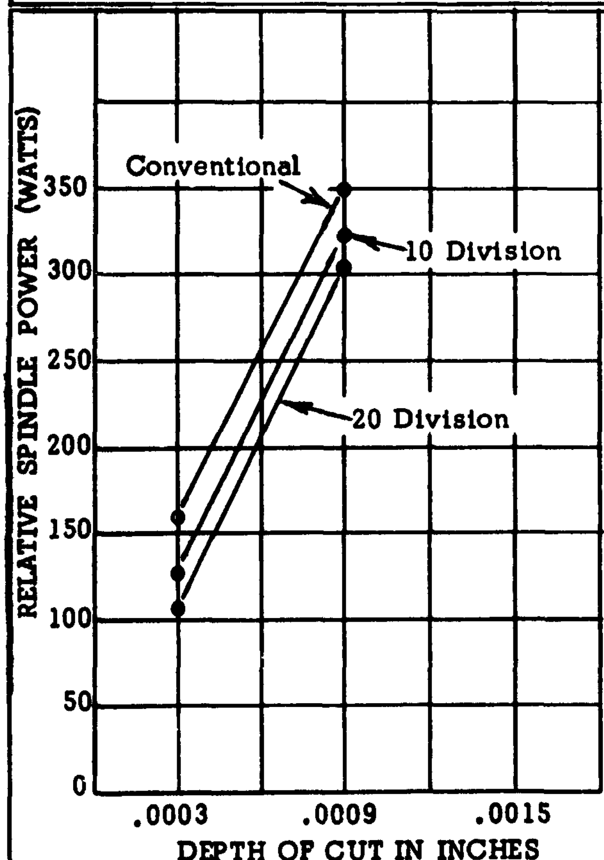
SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7MO
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Flexural Mode	(pp. 19 & 20)
Method A	
20 KC Range	

O Conventional
● 10 Division
● 20 Division

I

Figure 55



SURFACE GRINDING

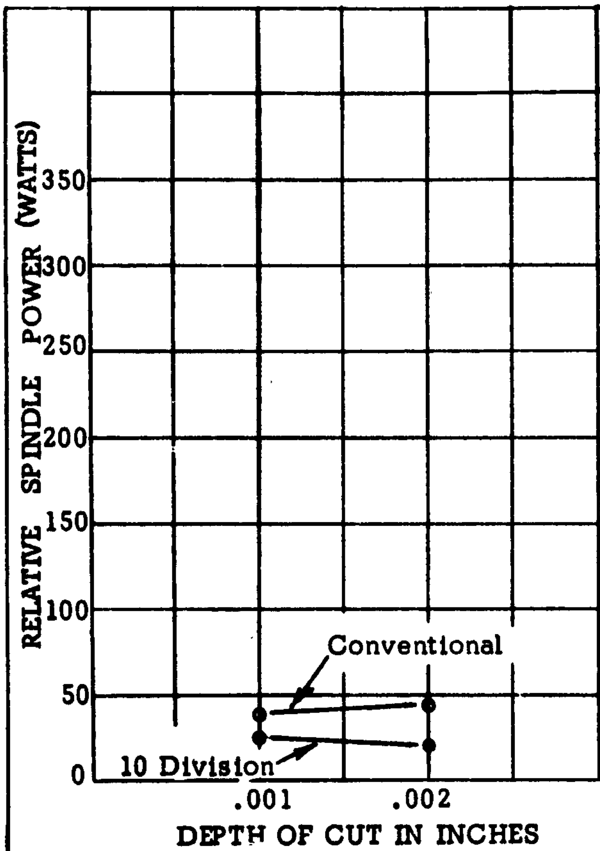
SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	32A60-L7VG
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Flexural Mode	(pp. 19 & 20)
Method A	
20 KC Range	

O Conventional
● 10 Division
● 20 Division

I

Figure 56



SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7MO
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM

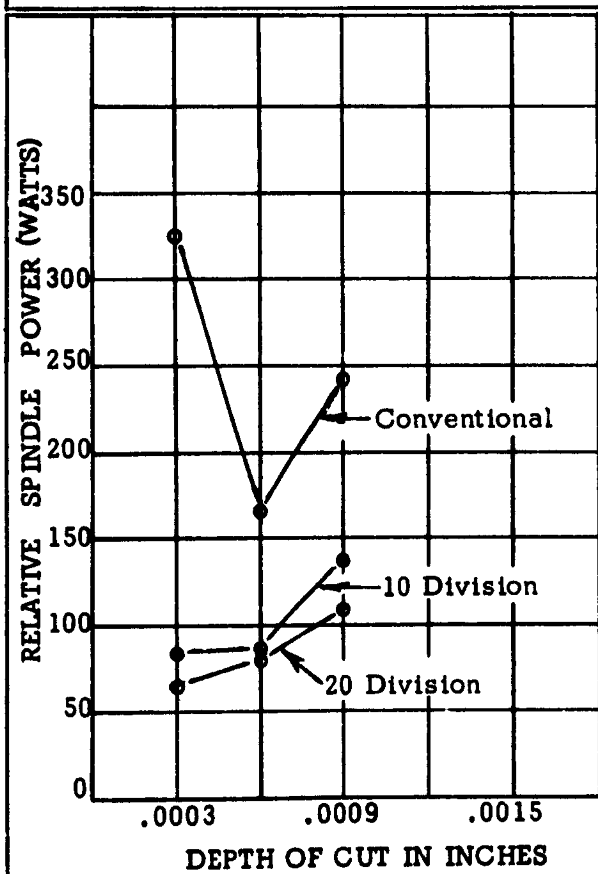
Longitudinal Mode(pp.19 & 20)
Method A
20 KC Range

Infeed	.050"

O Conventional
● 10 Division

I

Figure 57



SURFACE GRINDING

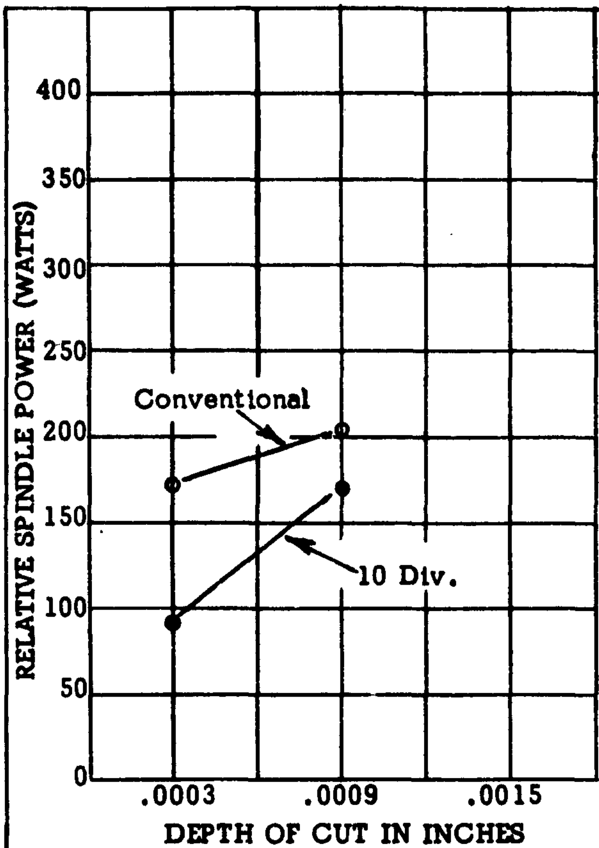
SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7MO
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Longitudinal Mode(pp.19 & 20)
Method A
20 KC Range
O Conventional
● 10 Division
● 20 Division

I

Figure 58



SURFACE GRINDING

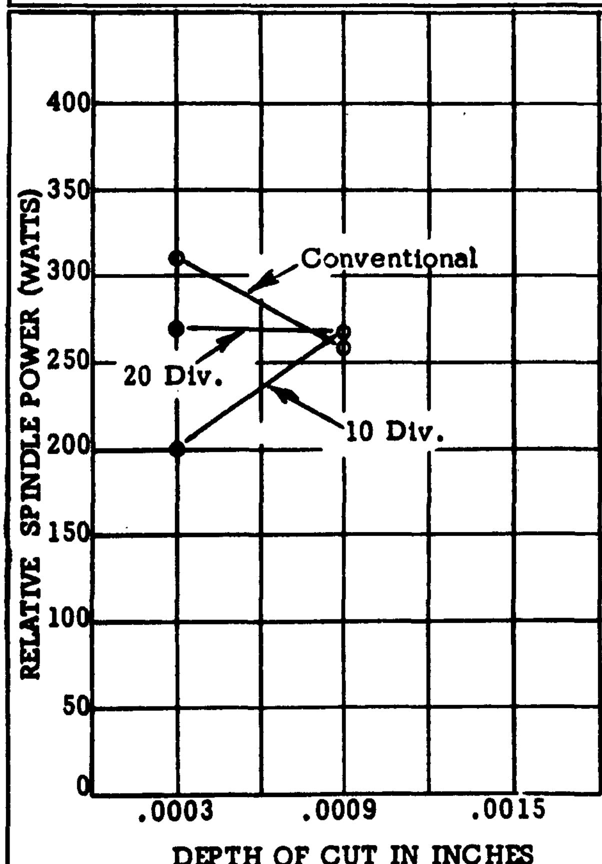
SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7MO
Wheel	38A80-H8VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode	(pp.19&20)
Method A	20 KC Range

O Conventional
● 10 Division

I

Figure 59



SURFACE GRINDING

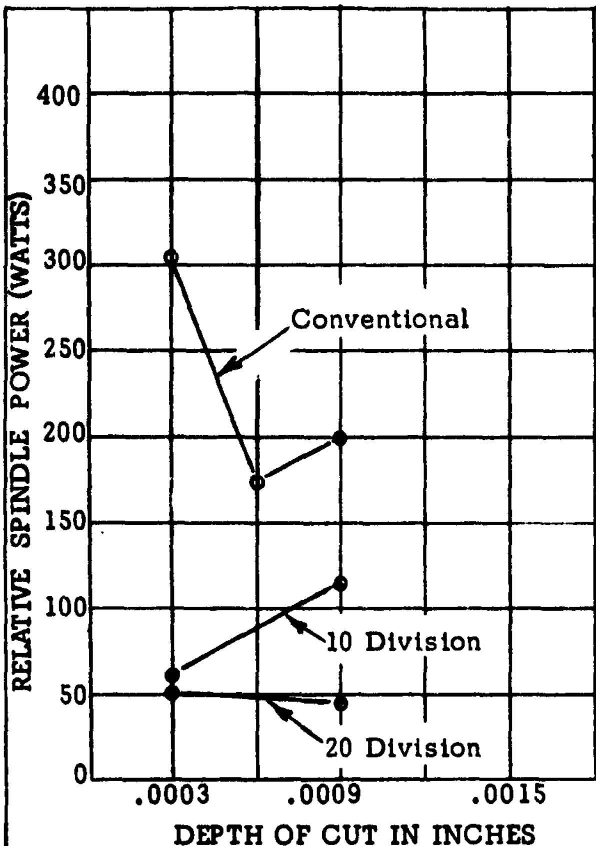
SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode	(pp.19 &20)
Method B	20 KC Range

O Conventional
● 10 Division
● 20 Division

I

Figure 60



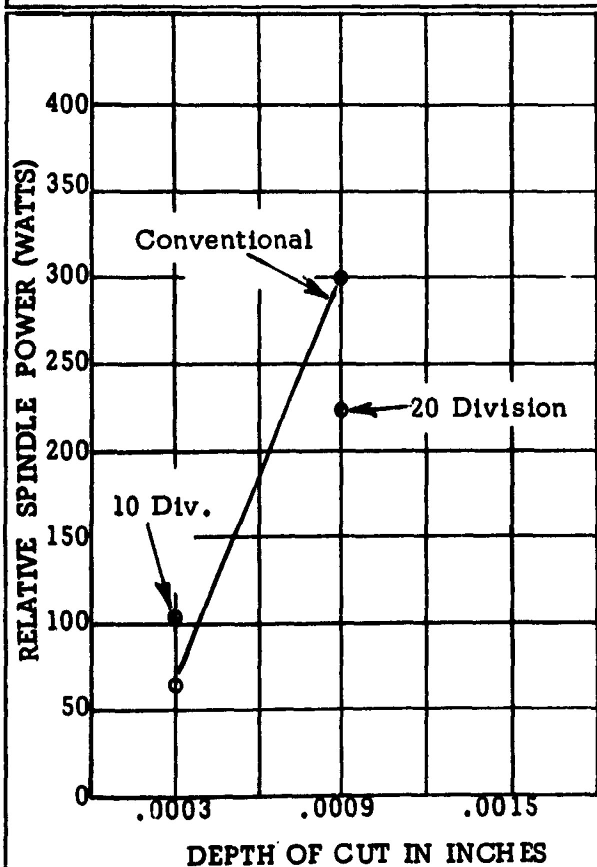
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 15-7 MO
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 35 FPM
Longitudinal Mode (pp. 19 & 20)
Method A 25 KC Range
0 Conventional
● 10 Division
● 20 Division

I

Figure 61



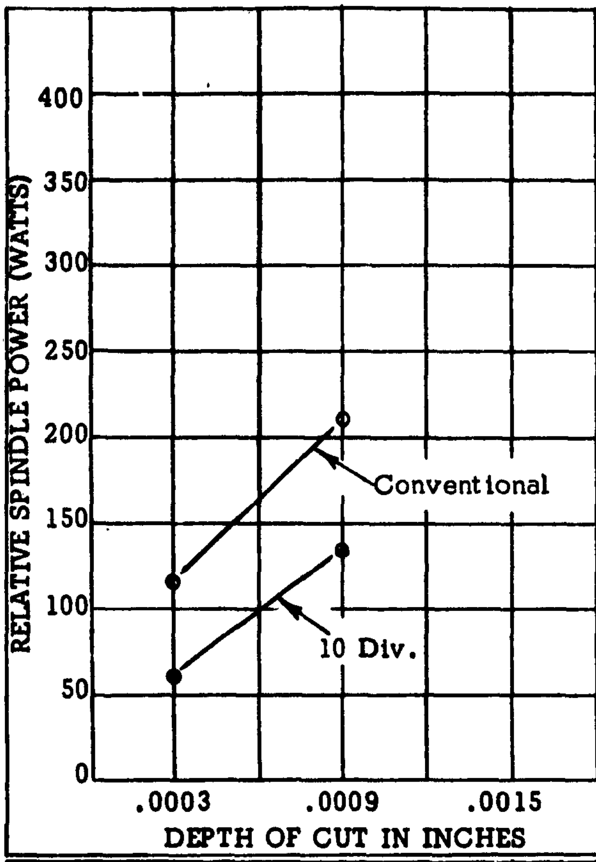
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 35 FPM
Flexural Mode (pp. 19 & 20)
Method A 20 KC Range
0 Conventional
● 10 Division
● 20 Division

I

Figure 62



SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

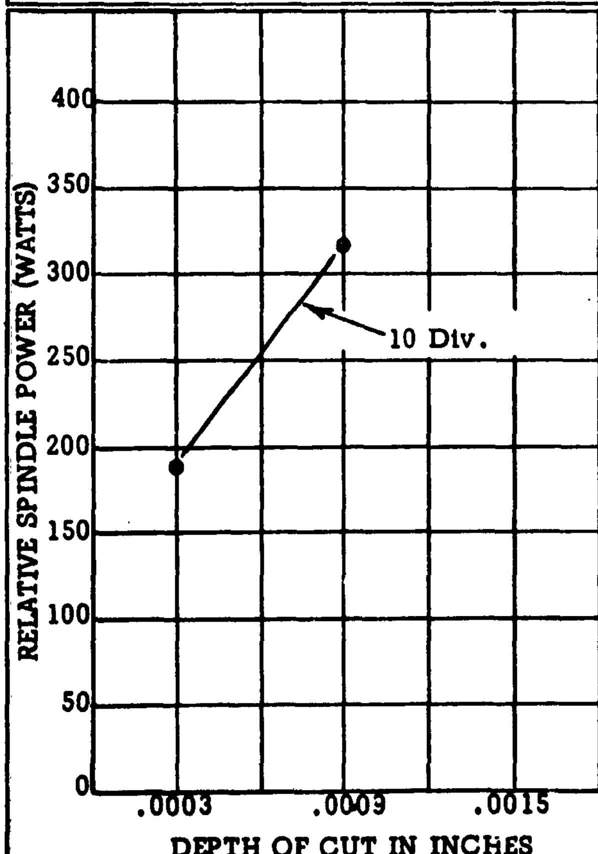
Material	4340
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode (pp. 19 & 20)	
Method A	20 KC Range

0 Conventional

● 10 Division

I

Figure 63



SURFACE GRINDING

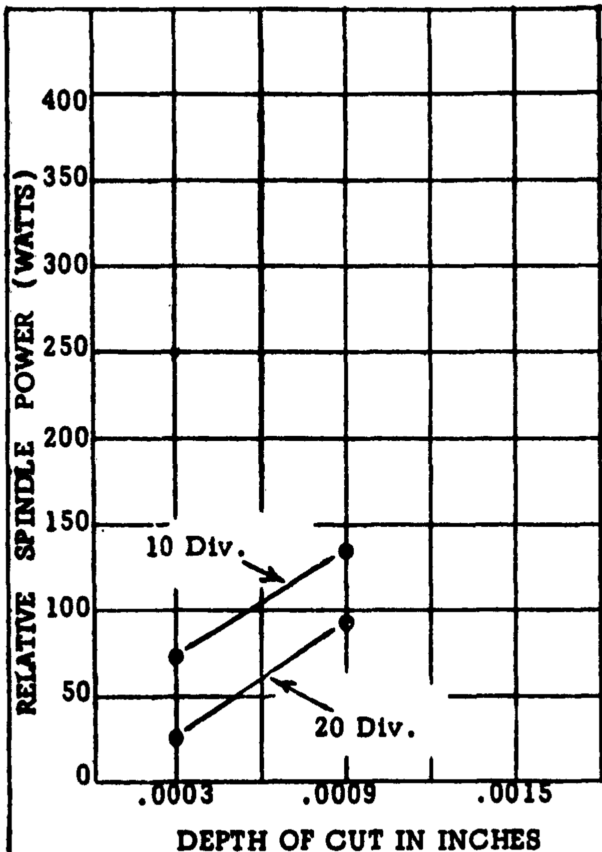
SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	4340
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode (pp.19 & 20)	
Method B	20 KC

● 10 Division

I

Figure 64



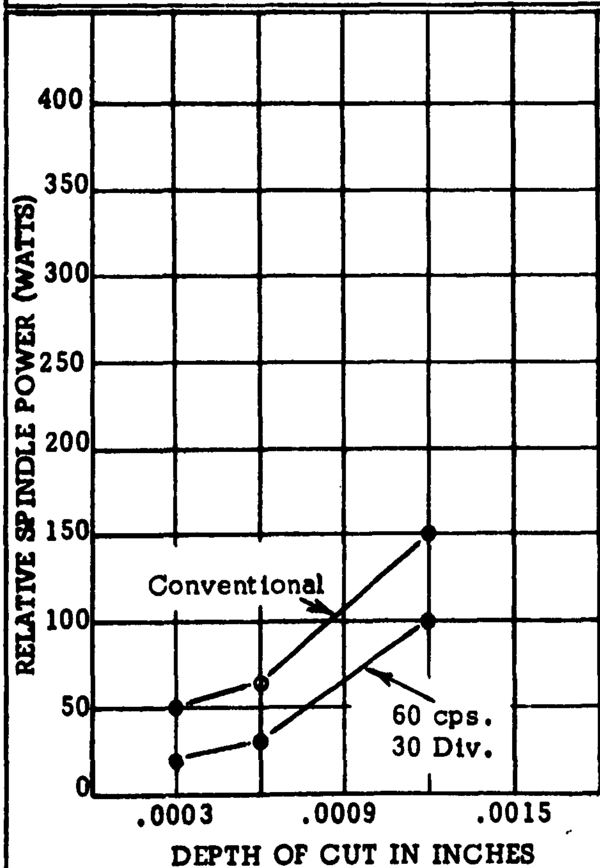
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 35 FPM
Longitudinal Mode (pp. 19 & 20)
Method A 25 KC Range
● 10 Division
● 20 Division

I

Figure 65



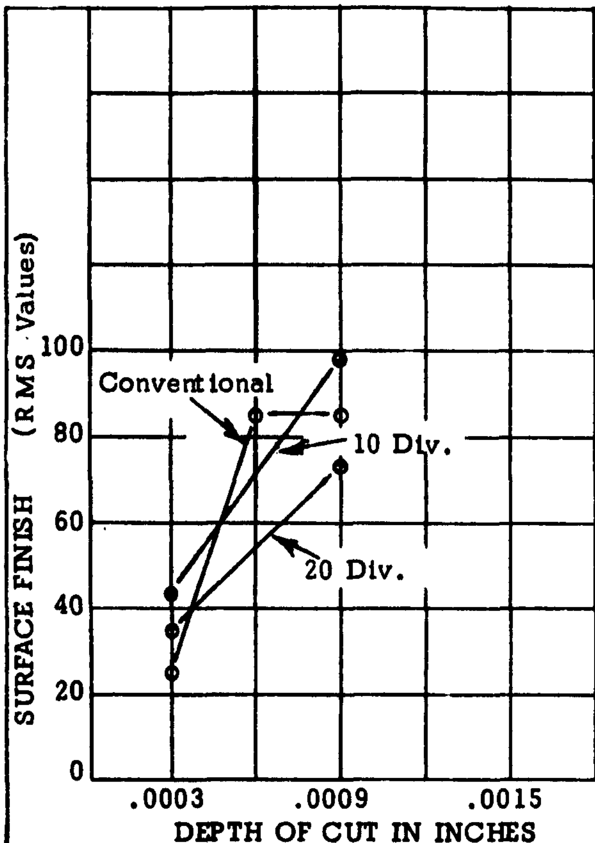
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A46-H8VBE
Wheel Speed 6200 SFPM
Table Speed 8 FPM
Longitudinal Mode (pp. 19 & 20)
Method A
O Conventional
● 60 cps 30 Div.

I

Figure 66



SURFACE GRINDING

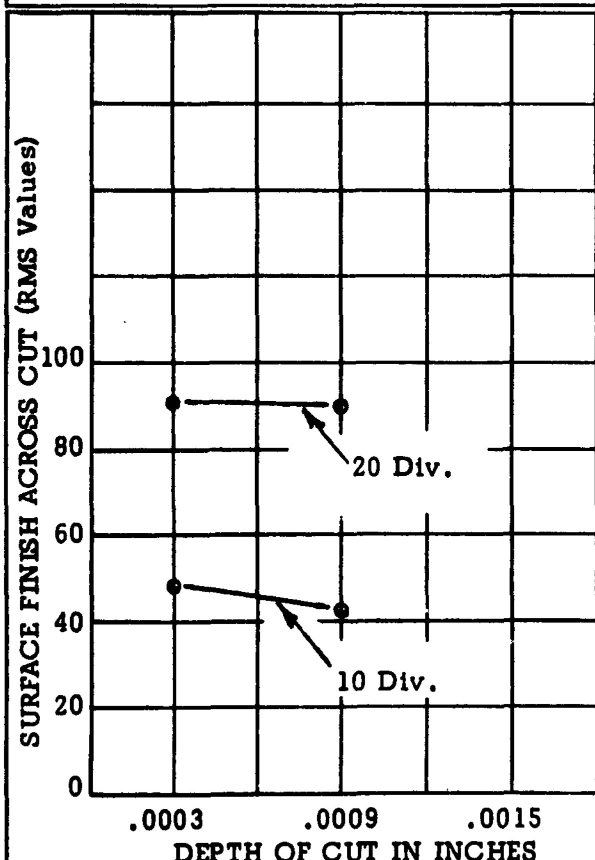
SURFACE FINISH (RMS) AS A FUNCTION OF DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7MO
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode	(pp. 19 & 20)
Method A	25 KC Range

0 Conventional
● 10 Division
● 20 Division

I

Figure67



SURFACE GRINDING

SURFACE (RMS ACROSS CUT) AS A FUNCTION OF DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	4340
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode	(pp. 19 & 20)
Method A	25 KC Range

● 10 Division
● 20 Division

I

Figure 68

MICRO-HARDNESS CHECKS* ON TEST SPECIMENS

Material - 15-7 MO - Longitudinal Mode - Method A - 20 kc
Wheel - 38A100I6VBE 6200 SFPM
Table Speed - 35 FPM

Depth of Cut	Conventional		10 Div.		20 Div.	
	Before	After	Before	After	Before	After
.0003"	526	542	526	579	548	570
.0006"	536	498	548	580	541	583
.0009"	541	560	541	576	526	571

Figure 69

MICRO-HARDNESS CHECKS* ON TEST SPECIMENS

Material - 15-7 MO - Longitudinal Mode - Method A - 25 kc
Wheel - 38A100I6VBE 6200 SFPM
Table Speed - 35 FPM

Depth of Cut	Conventional		10 Div.		20 Div.	
	Before	After	Before	After	Before	After
.0003"	526	542	531	514	548	542
.0009"	536	498	531	548	526	560

* Using Sheffield Micro-Hardness Tester - All Values Vickers - Average 3 Tests

Figure 70

MICRO-HARDNESS CHECKS* ON TEST SPECIMENS

Material 15-7 MO - Longitudinal Mode - Method A - 25 kc
Wheel 38A100I6VBE 6200 SFPM
Table Speed 35 FPM

Depth of Cut	Conventional		10 Div.		20 Div.	
	Before	After	Before	After	Before	After
.0003"	261	Tests not run	261	245	230	264
.0009"	263	Tests not run	263	261	284	287

Figure 71

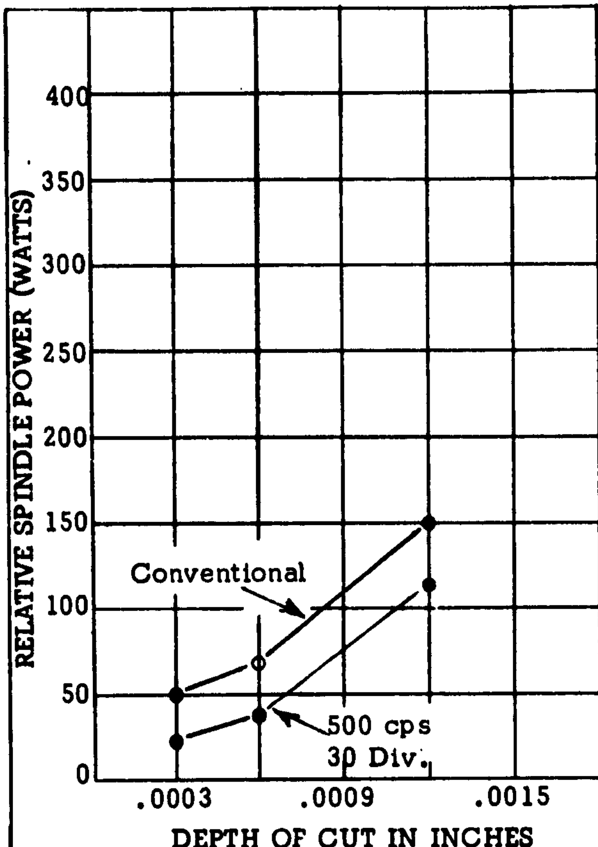
MICRO-HARDNESS CHECKS* ON TEST SPECIMENS

Material 15-7 MO - Longitudinal Mode - Method B - 20 kc
Wheel 38A100I6VBE 6200 SFPM
Table Speed 35 FPM

Depth of Cut	Conventional		10 Div.		20 Div.	
	Before	After	Before	After	Before	After
.0003"	531	---	536	548	546	---
.0009"	484	560	526	---	516	530

Figure 72

* Using Sheffield Micro-Hardness Tester - All Values Vickers - Average 3 Tests

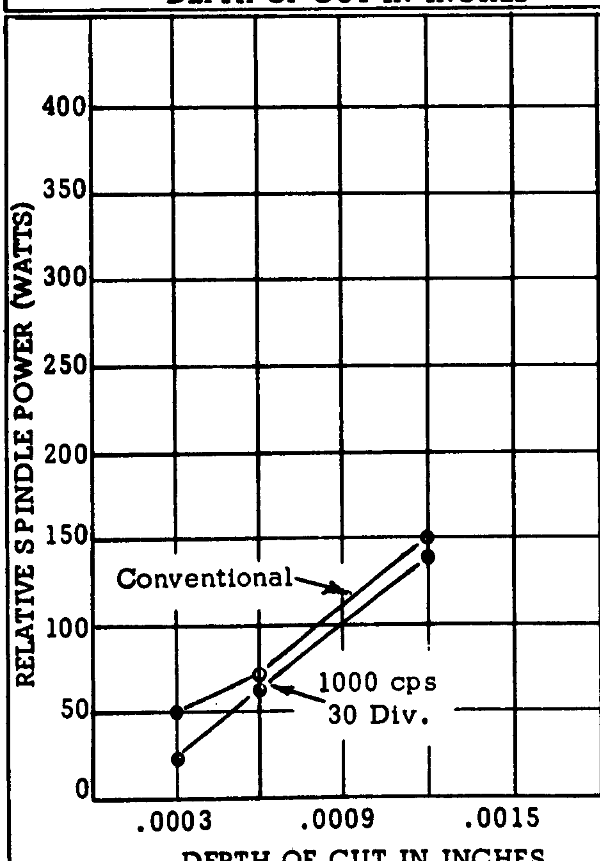


SURFACE GRINDING

<u>SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER</u>

Material 4340
Wheel 38A46-I8VBE
Wheel Speed 6200 SFPM
Table Speed 8 FPM
Longitudinal Mode
Method A (pp. 19 & 20)
O Conventional
● 500 cps 30 Div.

Figure 73

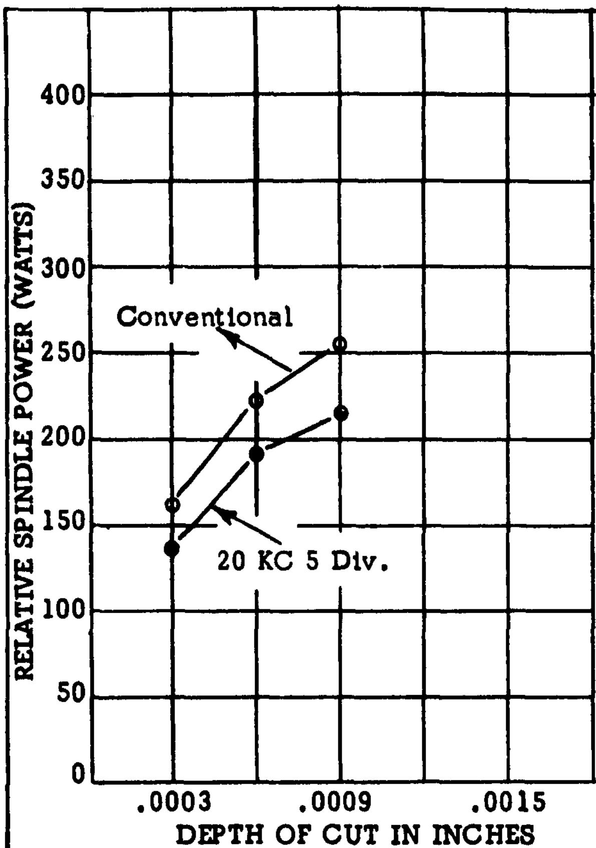


SURFACE GRINDING

<u>SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER</u>

Material 4340
Wheel 38A46-H8VBE
Wheel Speed 6200 SFPM
Table Speed 8 FPM
Longitudinal Mode
Method A (pp. 19 & 20)
O Conventional
● 1000 cps 30 Div.

Figure 74



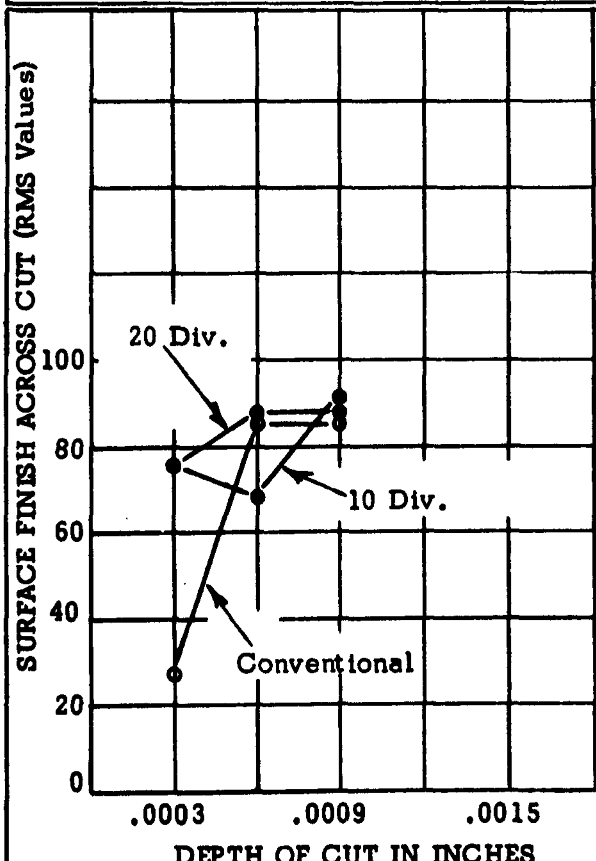
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	32A60-L7V6
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Radial Mode	(pp. 19 & 20)
Ultrasonic Spindle	20 KC Range
O	Conventional
●	5 Division

I

Figure 75



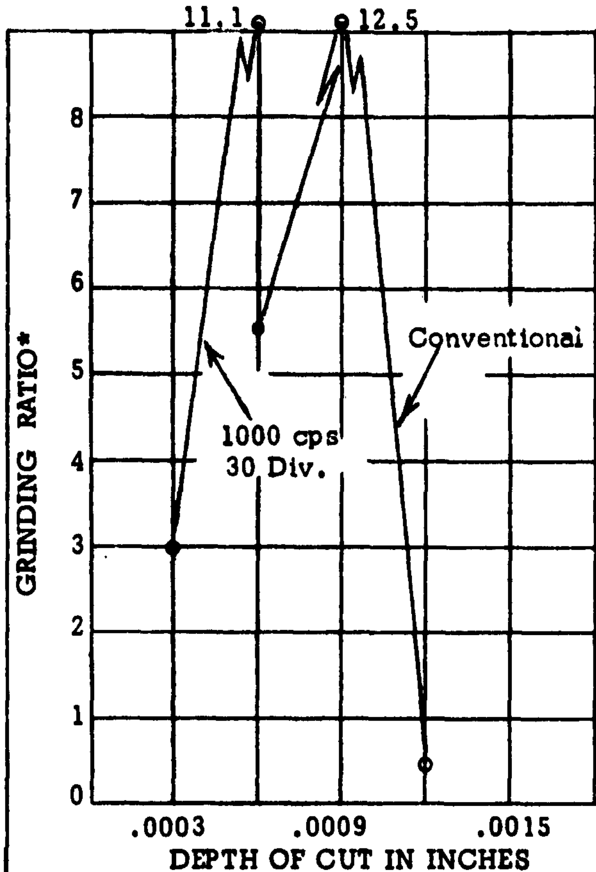
SURFACE GRINDING

SURFACE (RMS ACROSS CUT) AS A FUNCTION OF DEPTH WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	38A100-I6VBE
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Longitudinal Mode	(pp. 19 & 20)
Method A	20 KC Range
O	Conventional
●	10 Division
●	20 Division

I

Figure 76



SURFACE GRINDING

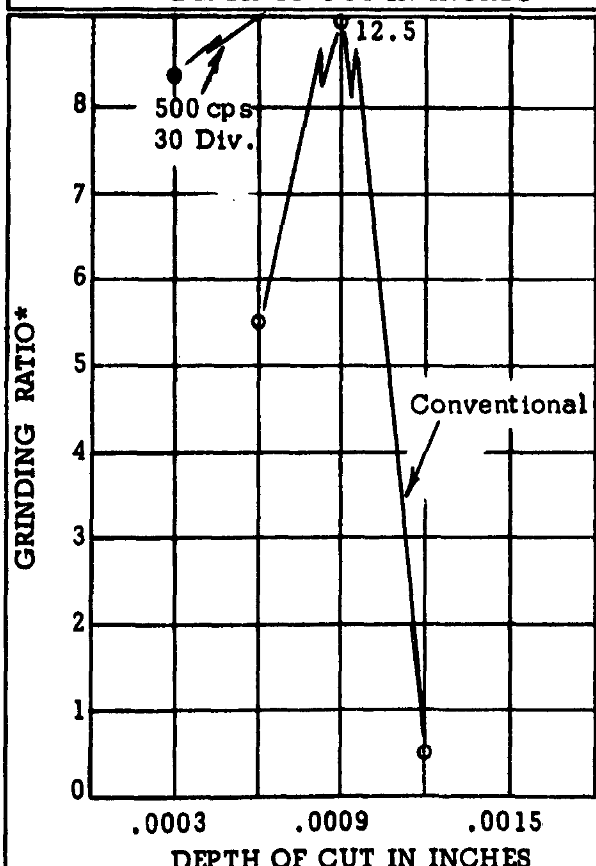
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A46-H8VBE
Wheel Speed 6200 SFPM
Table Speed 8 FPM
Longitudinal Mode
Method A (pp. 19 & 20)
O Conventional
● 1000 cps. 30 Div.

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

I

Figure 77



SURFACE GRINDING

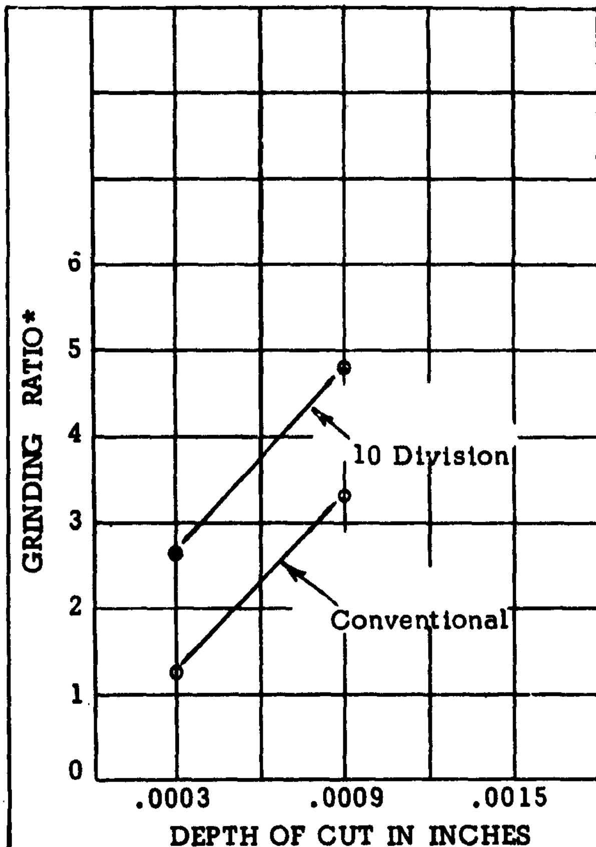
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A46-H8VBE
Wheel Speed 6200 SFPM
Table Speed 8 FPM
Longitudinal Mode
Method A (pp. 19 & 20)
O Conventional
● 500 cps 30 Div.

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

I

Figure 78



SURFACE GRINDING

GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

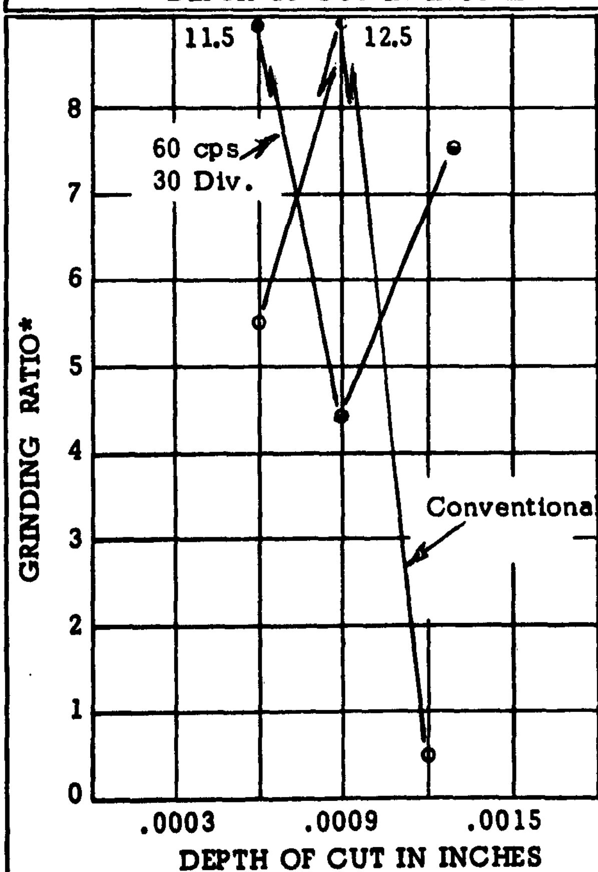
Material	4340
Wheel	38A100-I6V3E
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Flexural Mode	(pp. 19 & 20)
Method A	20 KC Range

O Conventional
● 10 Division

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

I

Figure 79



SURFACE GRINDING

GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

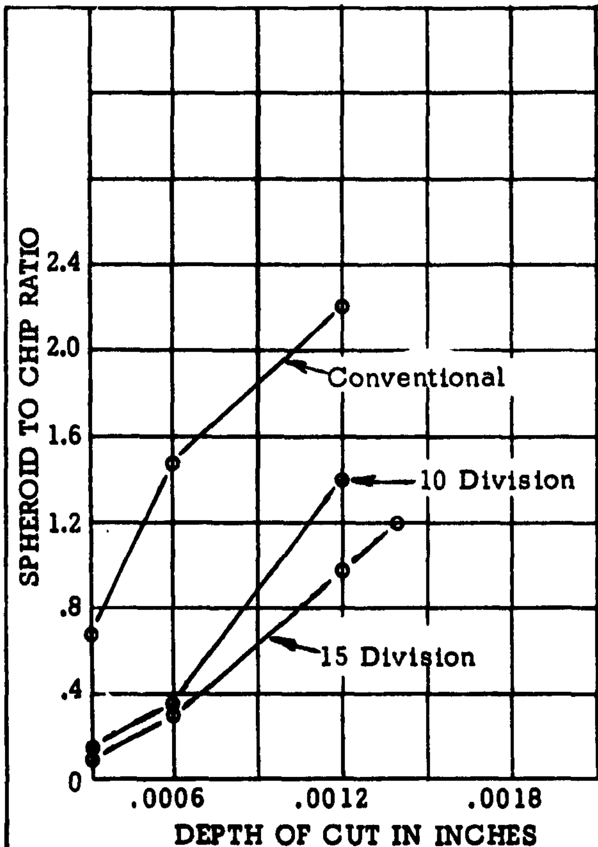
Material	4340
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	8 FPM
Longitudinal Mode	
Method A	(pp. 19 & 20)

O Conventional
● 60 cps 30 Div.

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Lost}}$$

I

Figure 80



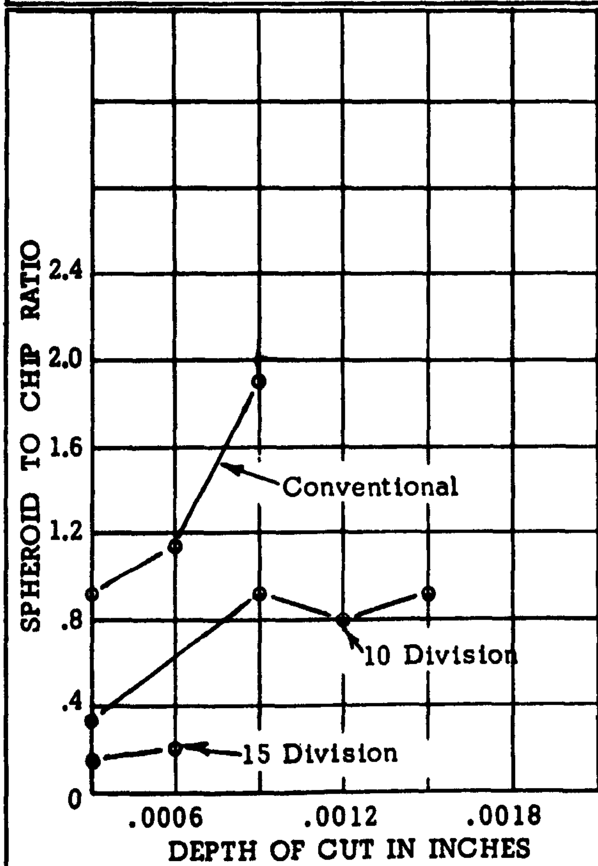
SURFACE GRINDING

SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material SAE 1020
Wheel 38A46-H8VBE
Wheel Speed SFPM 6200
Table Speed 6.2 FPM
Longitudinal Mode
Method A (pp. 19 & 20)
20 KC Range
O Conventional
● 10 Division
● 15 Division

Run Numbers: I - 3-4, 11-18

Figure 81



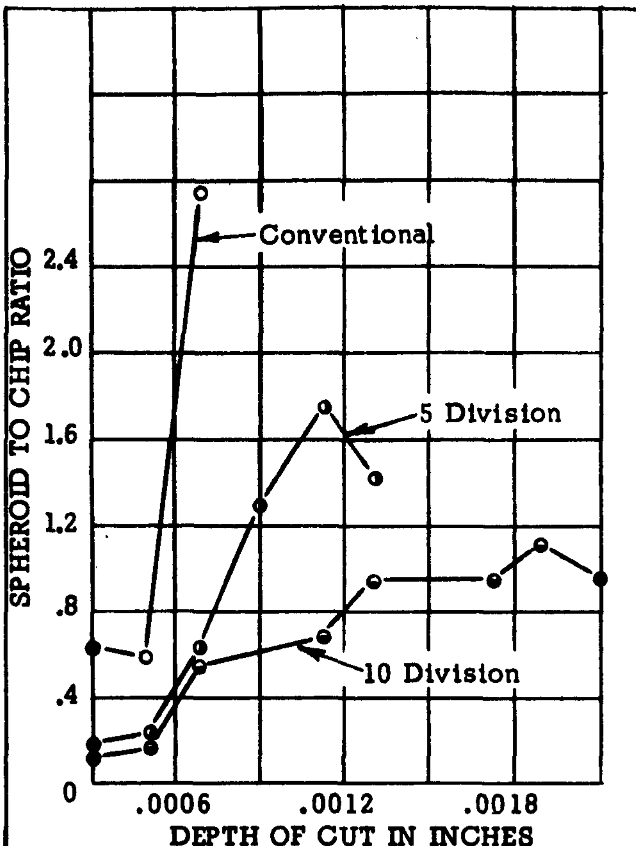
SURFACE GRINDING

SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A46-H8VBE
Wheel Speed 6200 SFPM
Table Speed 6.2 FPM
Longitudinal Mode
Method A (pp. 19 & 20)
20 KC Range
O Conventional
● 10 Division
● 15 Division

Run Numbers: I-7-10, 25-28, 40-52

Figure 82



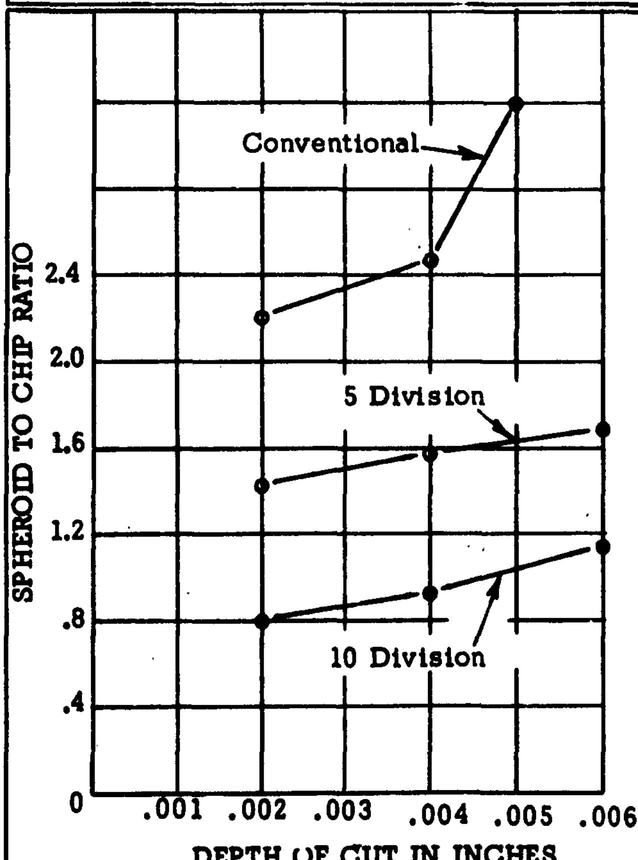
SURFACE GRINDING

SPHEROID TO CHIP RATIO AS A FUNCTION OF DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 6.2 FPM
Longitudinal Mode
Method A (pp. 19 & 20)
20 KC Range
O Conventional
◐ 5 Division
◒ 10 Division

Run Numbers: I-66-88

Figure 83



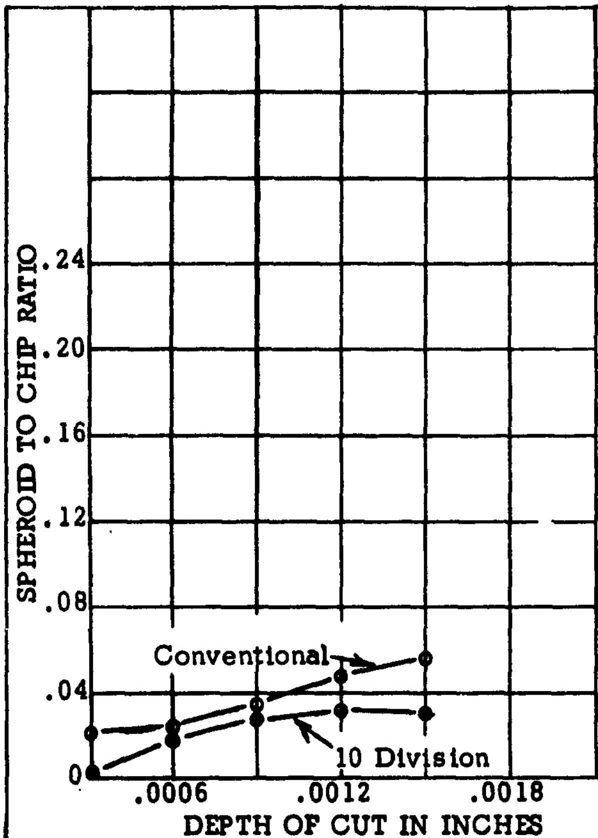
SURFACE GRINDING

SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A46-H8VBE
Wheel Speed 6200 SFPM
Table Speed 6.2 SFM
Longitudinal Mode
Method A (pp. 19 & 20)
20 KC Range
Cross Feed .050"
O Conventional
◐ 5 Division
◒ 10 Division

Run Numbers: I-59-65

Figure 84



SURFACE GRINDING

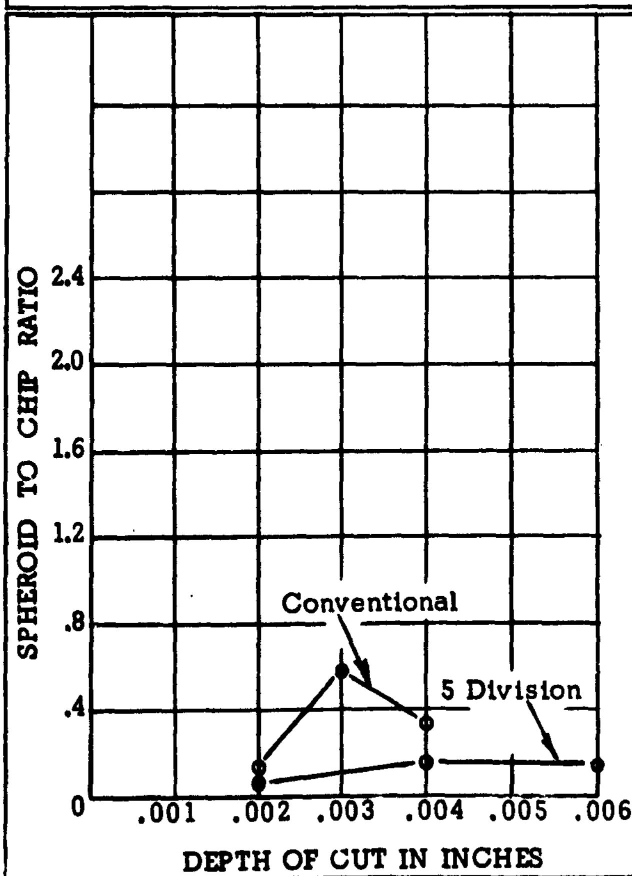
<u>SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER</u>

Material	440C
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM

Longitudinal Mode
Method A (pp. 19 & 20)
20KC Range
0 Conventional
● 10 Division

Run Numbers: I - 29 - 39

Figure 85



SURFACE GRINDING

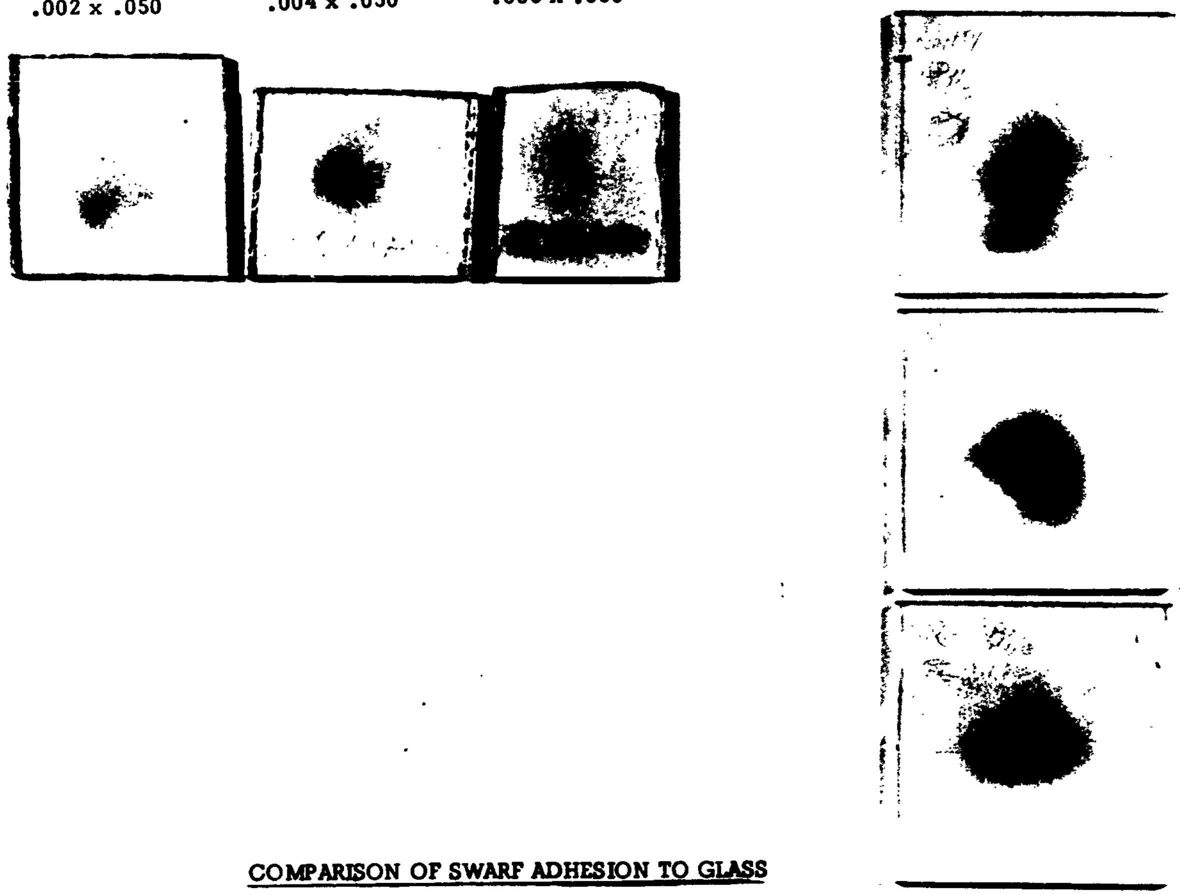
<u>SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER</u>

Material	440 C
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM
Cross Feed	.050"

Longitudinal Mode
Method A (pp. 19 & 20)
20 KC Range
0 Conventional
● 5 Division

Run Numbers: I - 53-58

Figure 86



COMPARISON OF SWARF ADHESION TO GLASS

Figure 87

WHEEL " A " - MATERIAL 4340

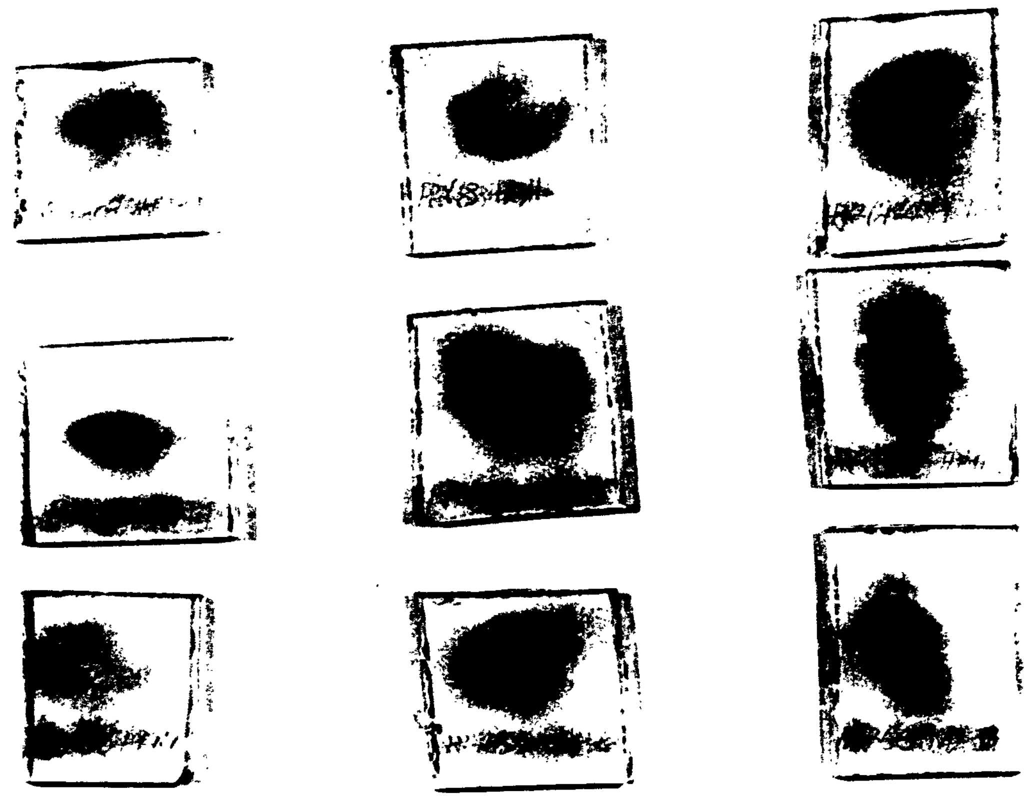
DEPTH AND WIDTH IN INCHES

.002 x .050 | .004 x .050 | .006 x .050

CONVENTIONAL GRINDING

5 DIVISIONS OF STROKE

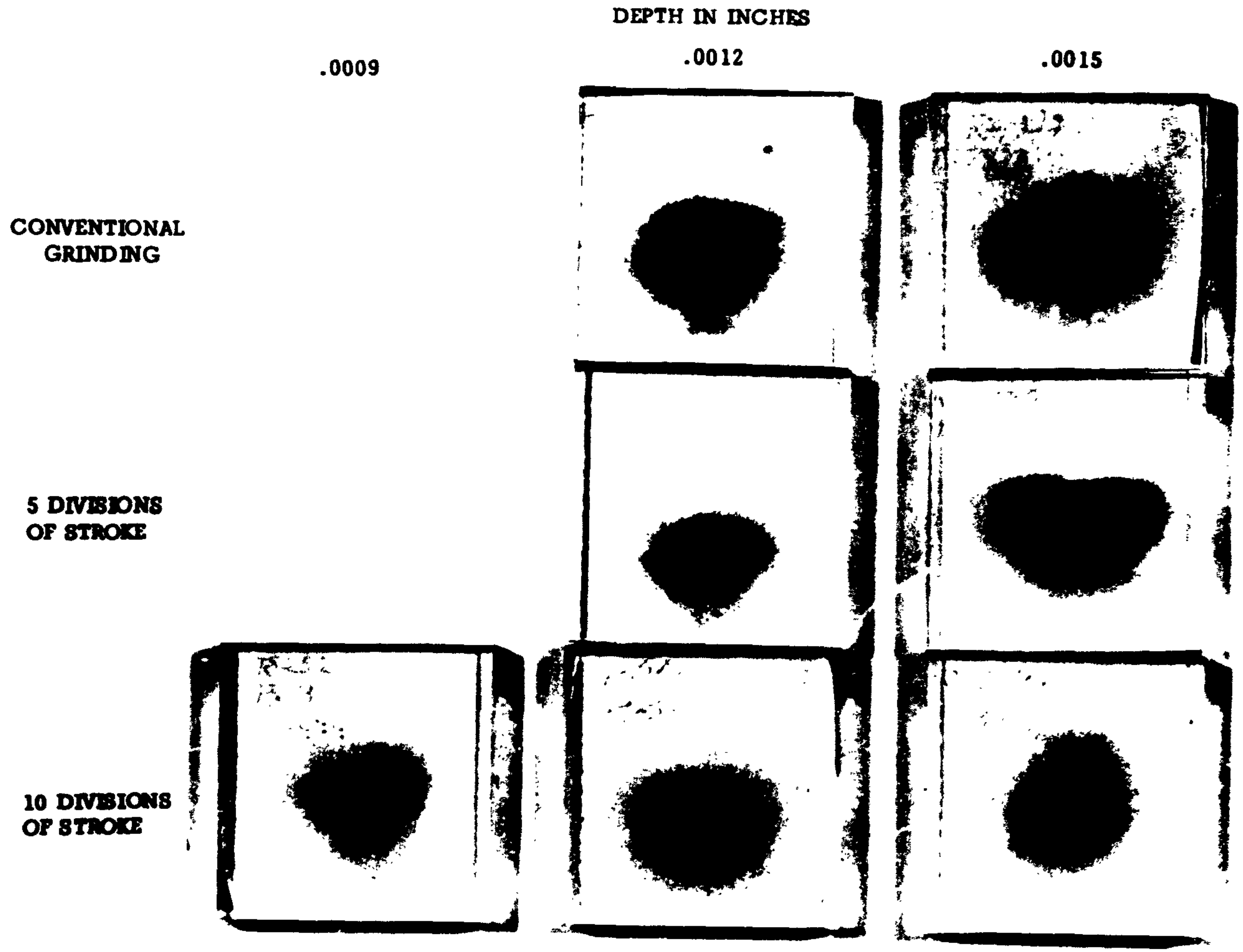
10 DIVISIONS OF STROKE



COMPARISON OF SWARF ADHESION TO GLASS

Figure 88

WHEEL " A " - MATERIAL 4340



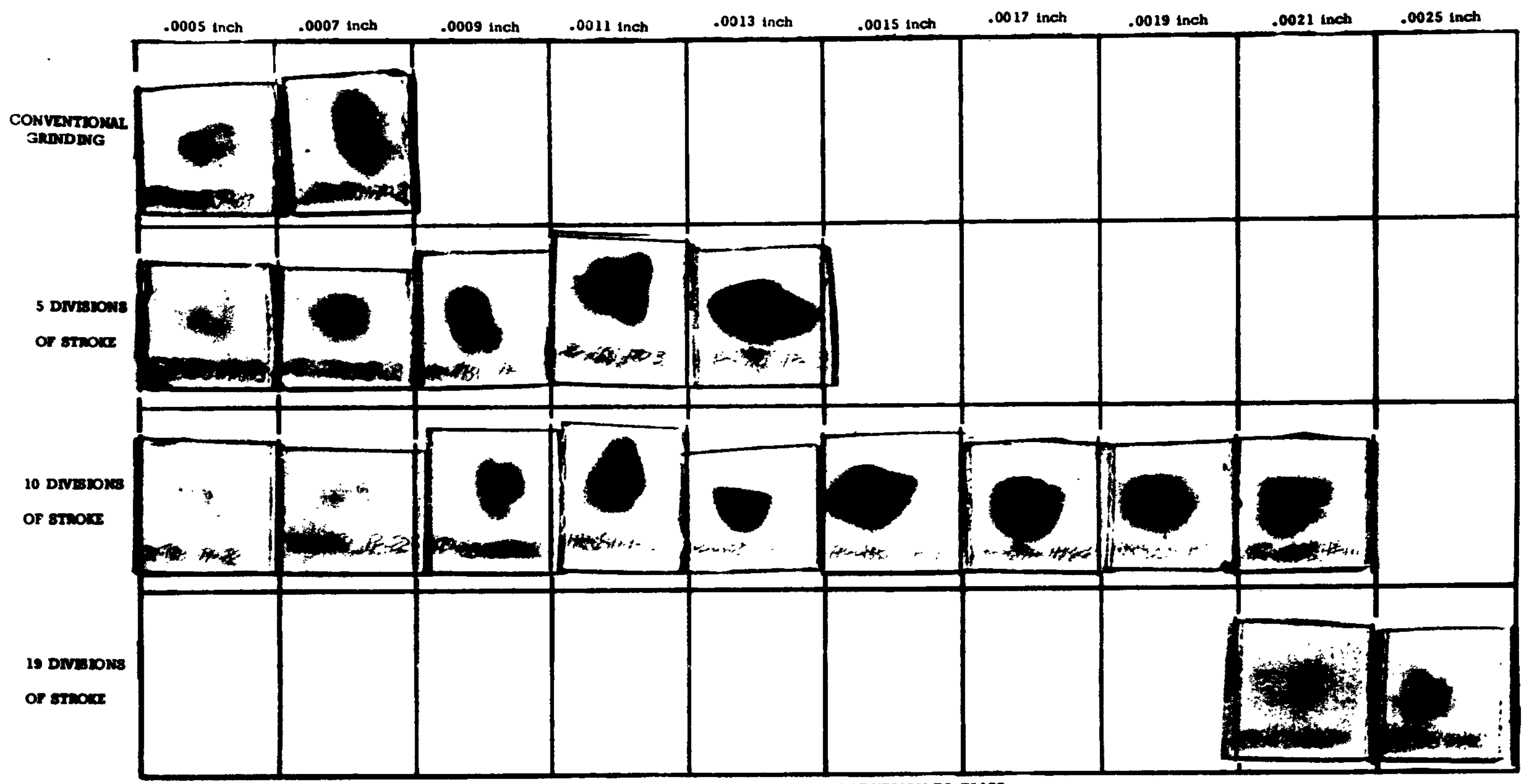
COMPARISON OF SWARF ADHESION TO GLASS

Figure 89

WHEEL " B "

MATERIAL " 4340 "

DEPTH OF CUT



COMPARISON OF SWARF ADHESION TO GLASS

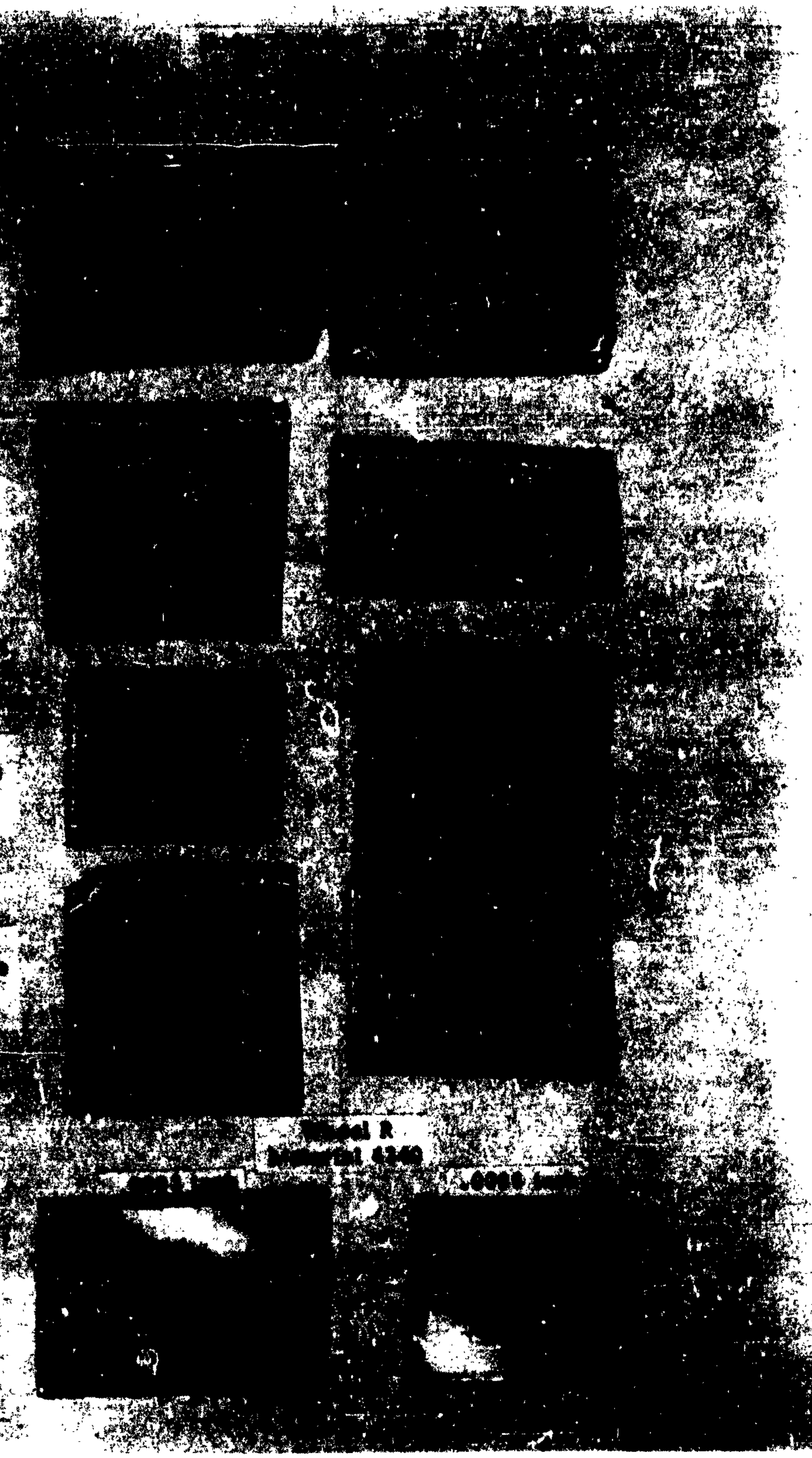
Figure 90

Material [illegible]
10 Divi[illegible]
Table Speed
35 ft. per min.

Material 4340
10 Divisions of stroke
Table Speed
8.7 ft per min.

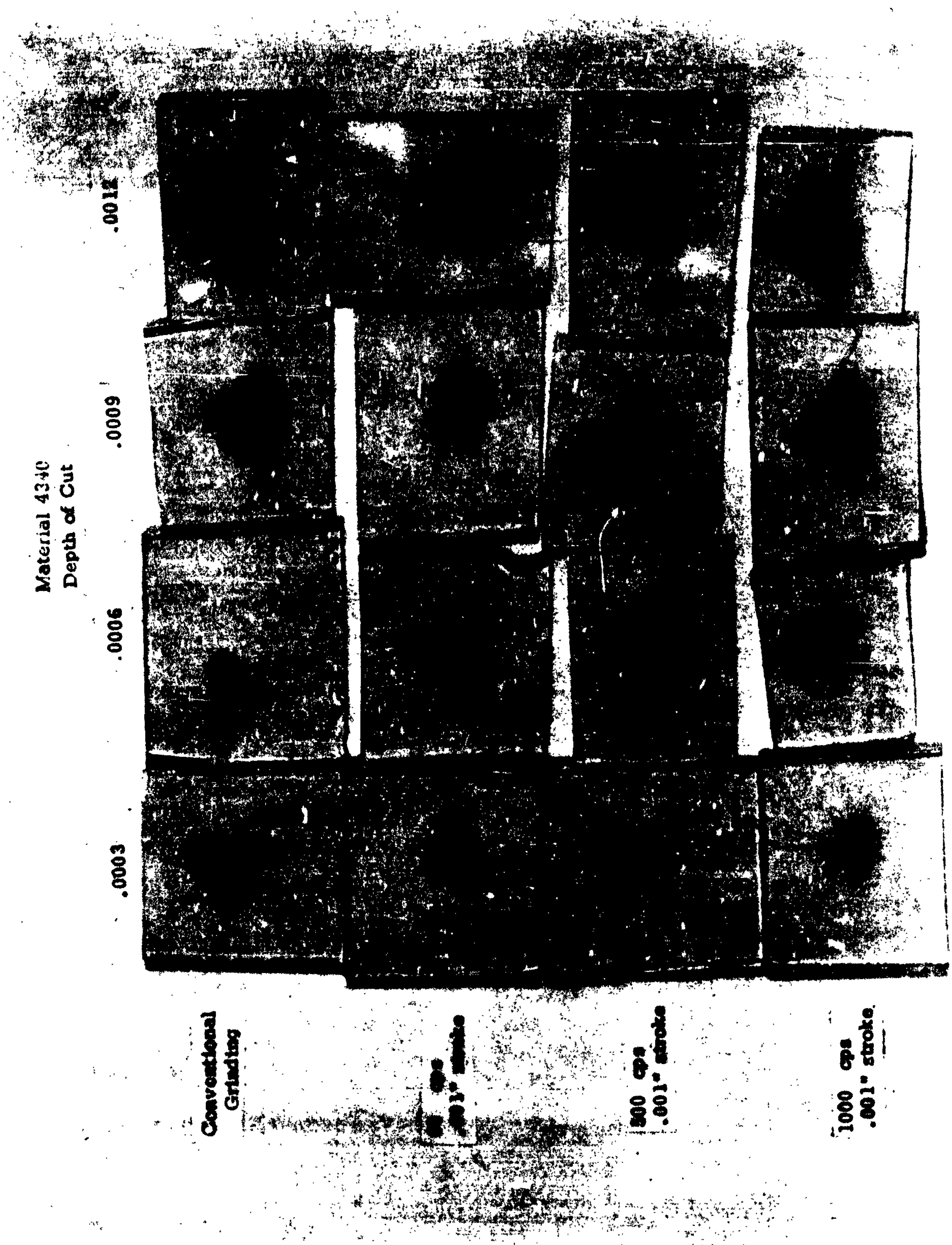
Material 15-7 MO
10 Divisions of Stroke
Table Speed
35 ft. per min.

Material 15-7 MO
10 Divisions of [illegible]
Table Speed
8.7 ft. per [illegible]



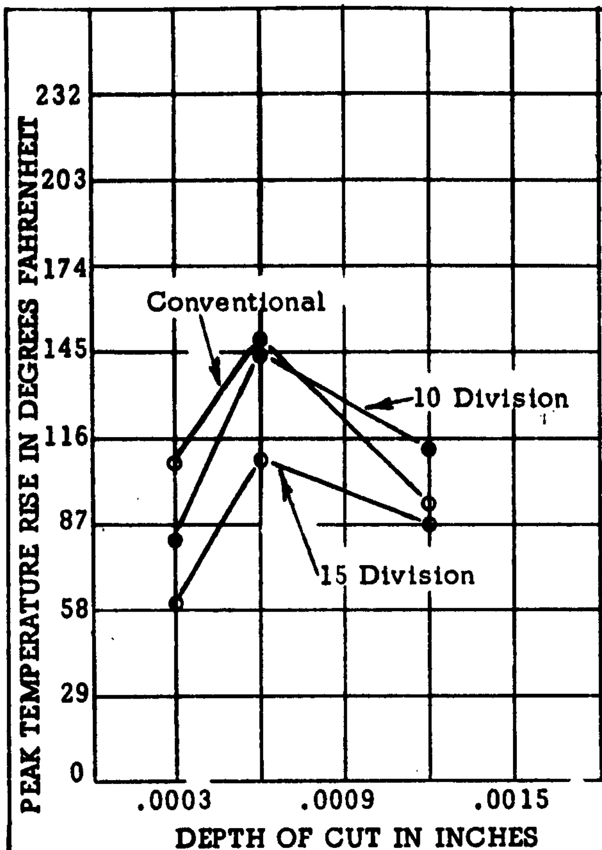
60 cps
.001" stroke

Figure 91



Material 4340
Depth of Cut
.0003
.0006
.0009
.0012
Conventional Grinding
500 cps
.001" stroke
1000 cps
.001" stroke

Figure 92



SURFACE GRINDING

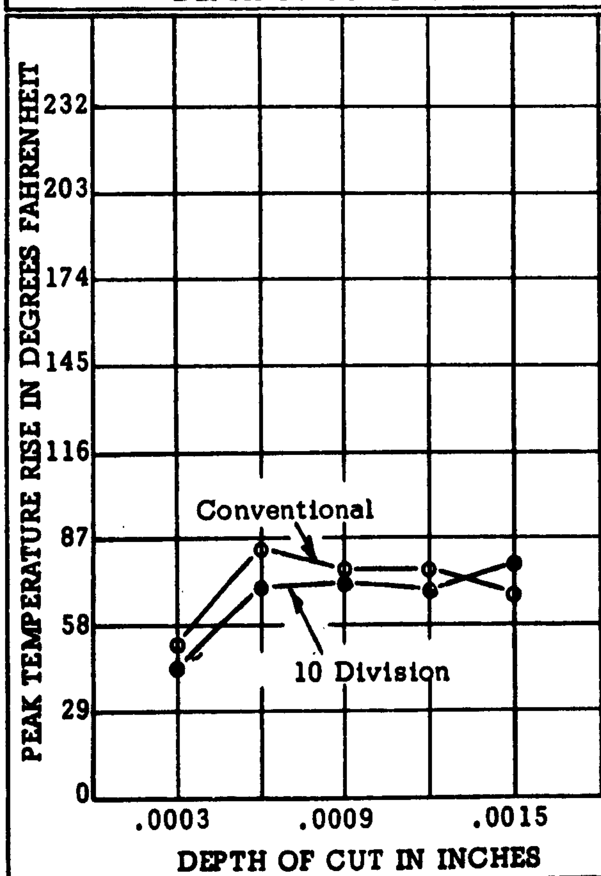
PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	1020
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM
Longitudinal Mode	(pp. 19 & 20)
Method A	20 KC Range

0 Conventional
● 10 Division
● 15 Division

Run Numbers: I - 3-4, 11-18

Figure 93



SURFACE GRINDING

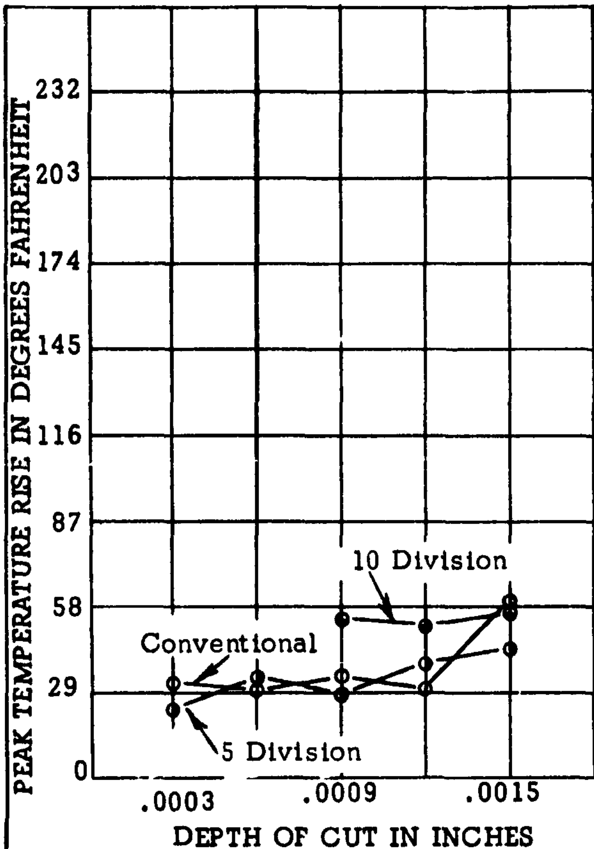
PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	440 C
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM
Longitudinal Mode	(pp. 19 & 20)
Method A	20 KCRange

0 Conventional
● 10 Division

Run Numbers: I - 29-39

Figure 94



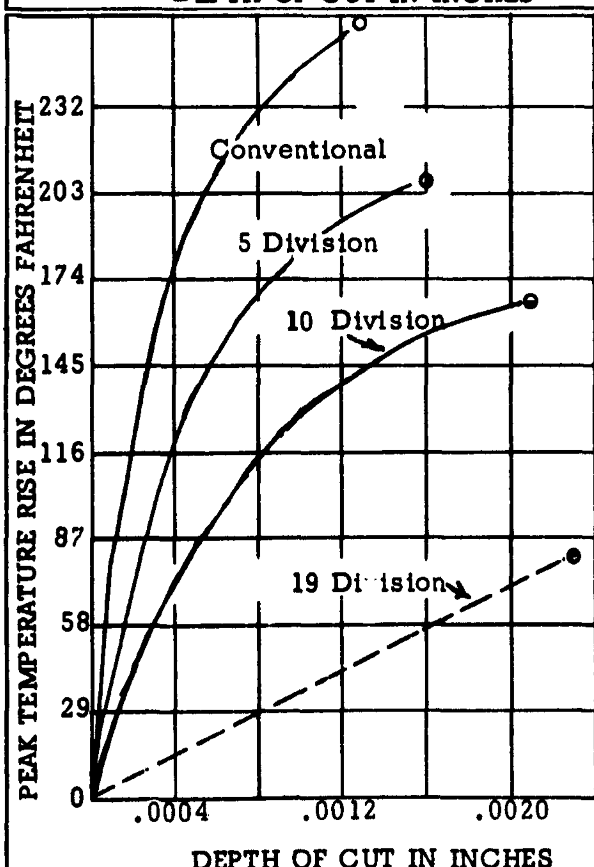
SURFACE GRINDING

PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A46-H8VBE
Wheel Speed 6200 SFPM
Table Speed 6.2 FPM
Longitudinal Mode (pp. 19 & 20)
Method A 20 KC Range
0 Conventional
5 Division
10 Division

Run Numbers: I - 7-10, 25-28, 40-52

Figure 95



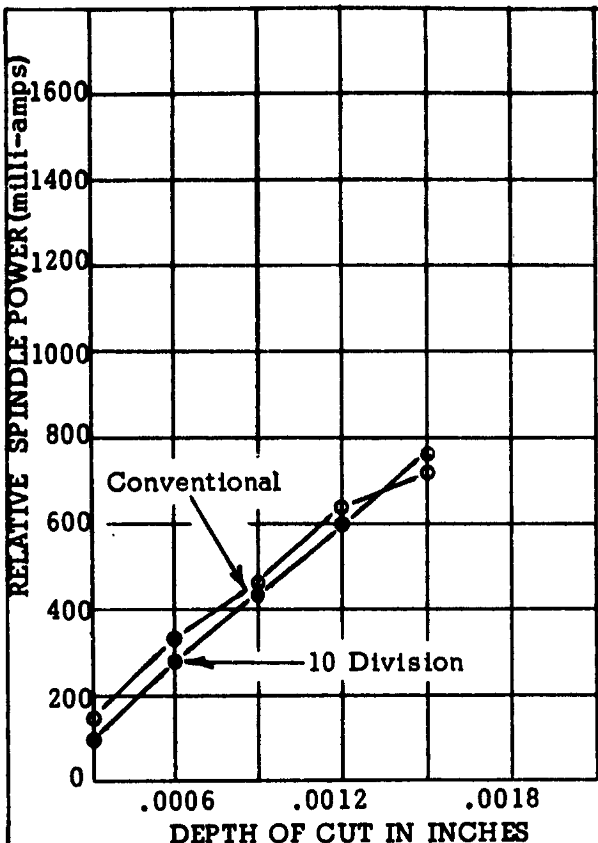
SURFACE GRINDING

PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 6.2 FPM
Longitudinal Mode (pp. 19 & 20)
Method A 20 KC Range
0 Conventional
5 Division
10 Division
19 Division

Run Numbers: I - 66-88

Figure 96



SURFACE GRINDING

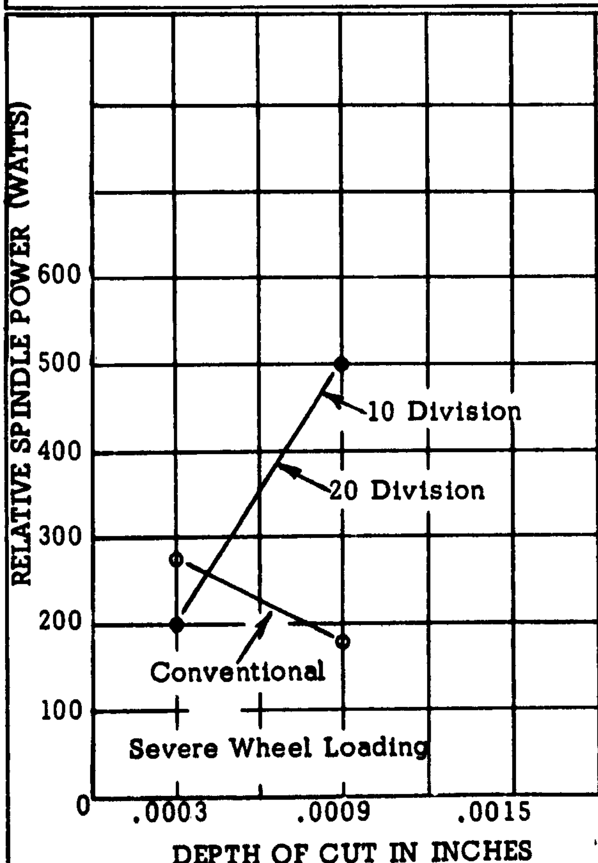
SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	440C
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM

Longitudinal Mode
Method A (pp. 19 & 20)
20 KC Range
O Conventional
● 10 Division

Run Numbers: I - 29-39

Figure 97



SURFACE GRINDING

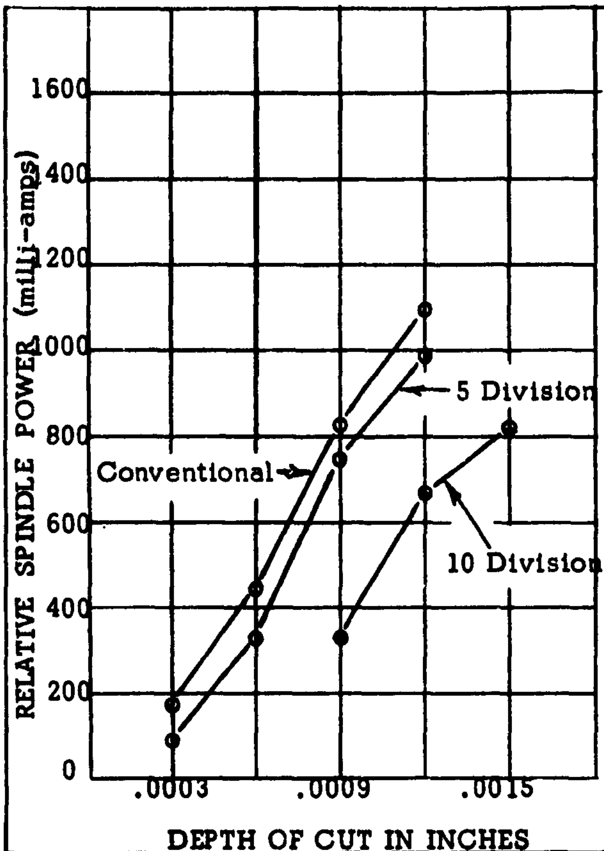
SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	32A60-L7VG
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Flexural Mode (pp. 19 & 20)
Method A
10 KC Range
O Conventional
● 10 & 20 Division

I

Figure 98



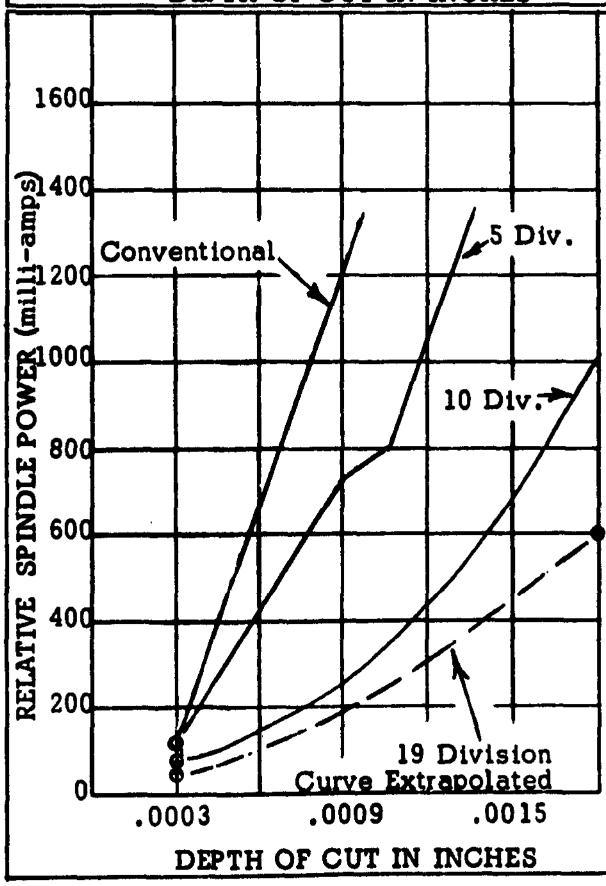
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A46-H8VBE
Wheel Speed 6200 SFPM
Table Speed 6.2 FPM
Longitudinal Mode (pp. 19 & 20)
Method A 20 KC Range
O Conventional
◐ 5 Division
● 10 Division

I

Figure 99



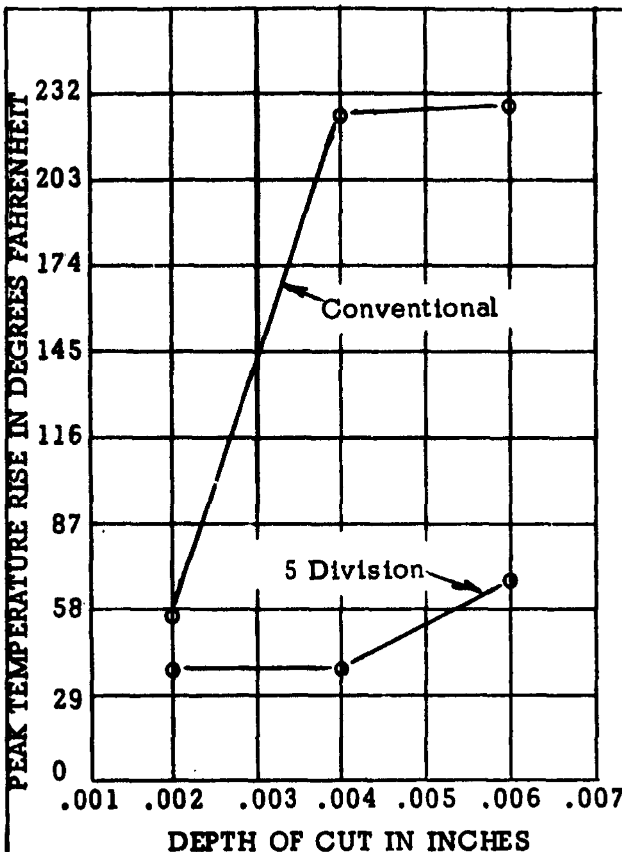
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material 4340
Wheel 38A100-I6VBE
Wheel Speed 6200 SFPM
Table Speed 6.2 FPM
Longitudinal Mode (pp. 19 & 20)
Method A 20 KC Range
O Conventional
◐ 5 Division
● 10 Division
● 19 Division

I

Figure 100



SURFACE GRINDING

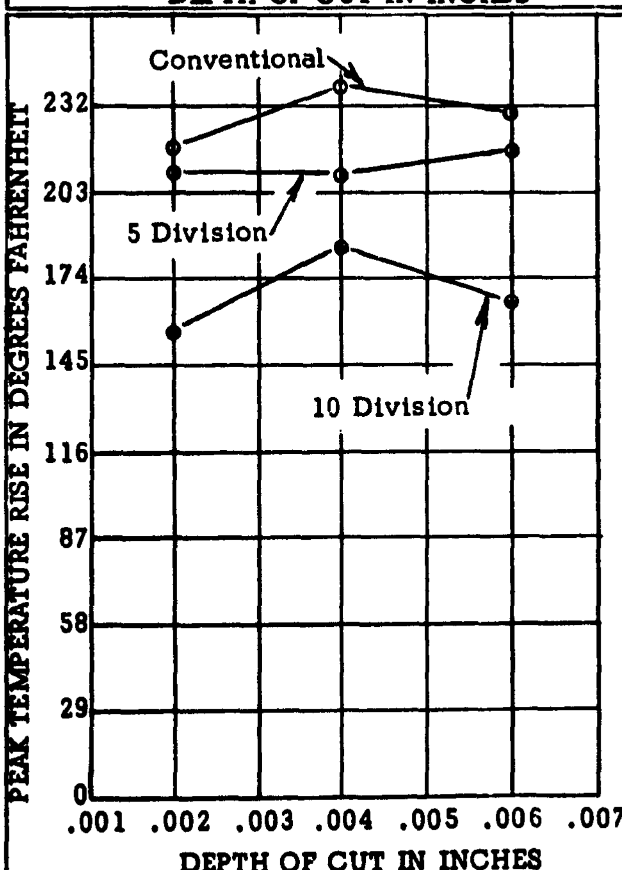
PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	440 C
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM
Cross Feed	.050"
Longitudinal Mode (pp. 19 & 20)	
Method A	20 KC Range

0 Conventional
◑ 5 Division

Run Numbers: I - 53-58

Figure 101



SURFACE GRINDING

PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	4340
Wheel	38A46-H8VBE
Wheel Speed	6200 SFPM
Table Speed	6.2 FPM
Longitudinal Mode (pp. 19 & 20)	
Method A	20 KC Range
Cross Feed	.050" 10th step

0 Conventional
◑ 5 Division
● 10 Division

Run Numbers: I - 59-65

Figure 102

SECTION 5

5. Conclusions

5.1 Possible Stress Differences to be expected

The particle motion for Longitudinal mode, method A, is normal to the grinding wheel grinding surface. Since dynamic stress due to vibration is zero on the surface of specimen being ground, conditions should be different for the same particle motion. But in Flexural vibration, method B, where surface dynamic stress is present it is hypothesized that the alternating stresses due to the flexural modes, would relieve the initial surface residual stresses slightly, and greatly reduce any tendency for formation of grinding induced thermal or residual stresses. This effect should be greatest for shear stresses in vibration as the source of activation energy for stress relief, similar to situations prevailing during normalizing. This condition is believed to occur prior to twinning of the Frank Reed loops.

It has been earlier reported, that longitudinal vibration, method A, would cause increased wheel breakdown, (probably due to impact fracturing of abrasive bonds). Comparisons between longitudinal method B and Flexural Method A, should be valuable due to their inherent differences between relative motions of wheel and work.

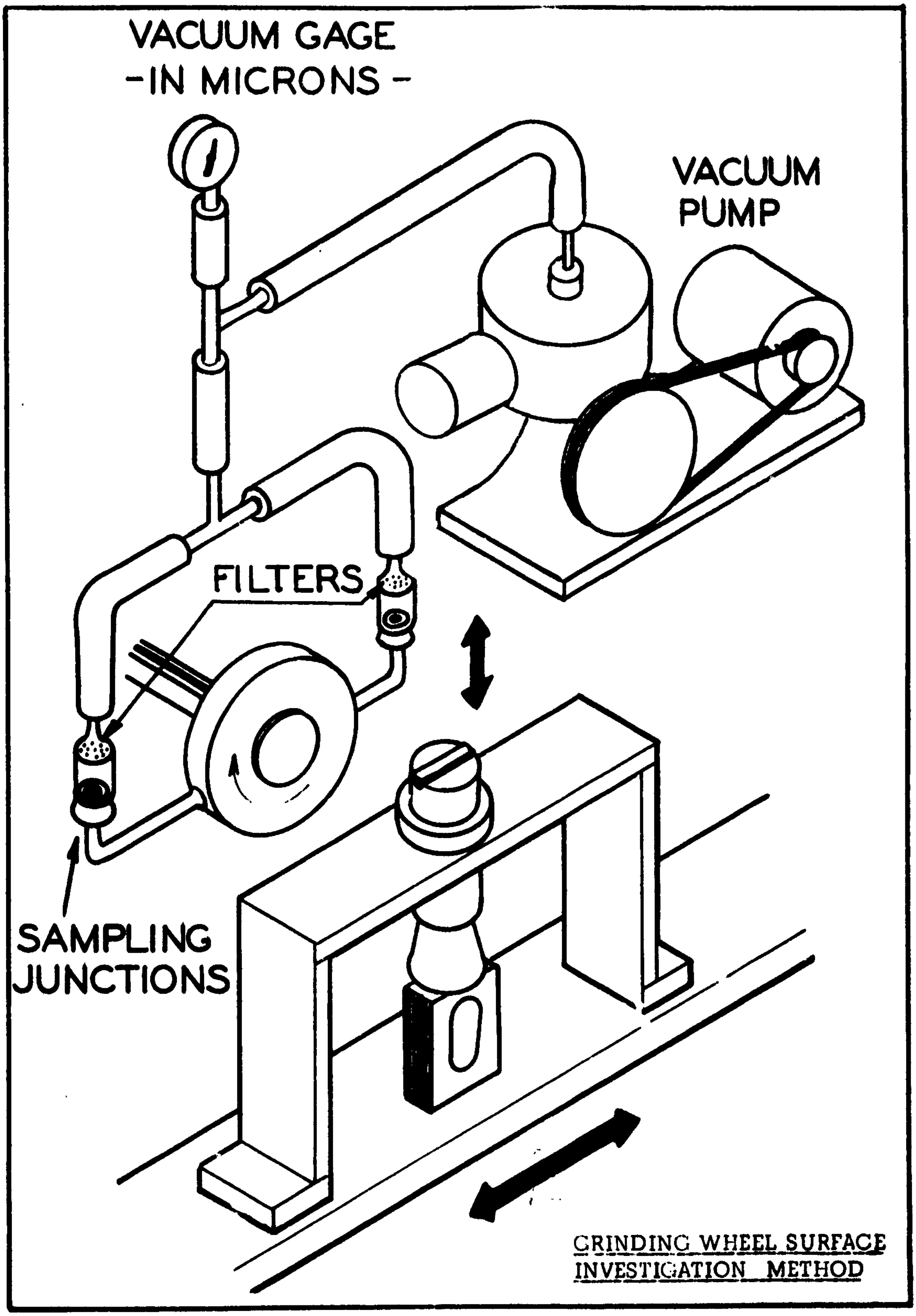

VACUUM GAGE
-IN MICRONS -
VACUUM
PUMP
FILTERS
SAMPLING
JUNCTIONS
GRINDING WHEEL SURFACE
INVESTIGATION METHOD

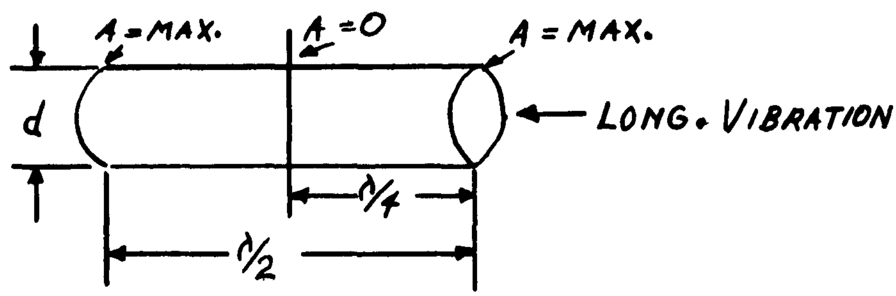
Figure 103

5.2 Grinding Wheel Surface Investigation

Lower temperatures occur in vibration assisted grinding and compared to conventional grinding this opens many fields of investigations. (pp.45-56) One theory being, that during contact of the wheel over the vibration excited test specimen, normally embedded steel swarf is thrown loose from the peripheral surface of the grinding wheel caused by propagated vibration transmitted through wheel from the test specimen. When apparatus for this test is set up, samples of fine filter paper will be taken at two points 180° from one another, around grinding wheel. Quantitative swarf evaluation of vibration assisted grinding as compared to conventional grinding can then be measured.

5.3 Radial Vibration of Wheel

If a cylinder of uniform cross-section is subjected to longitudinal vibration at high frequencies, where the direction of travel of the wave is parallel to the long axis of the cylinder, the particle motion will be in the direction of propagation and the cylinder will undergo elastic extension and contraction. The amplitude of vibration of a longitudinal wave is greatest at the extremities of a bar, provided it is considered one-half wave in length and essentially free at both ends. The amplitude of vibration is zero at the midpoint of this uniform bar.



Where: d = Bar Diameter

$\lambda/2$ = 1/2 wave length

A = Amplitude of vibration

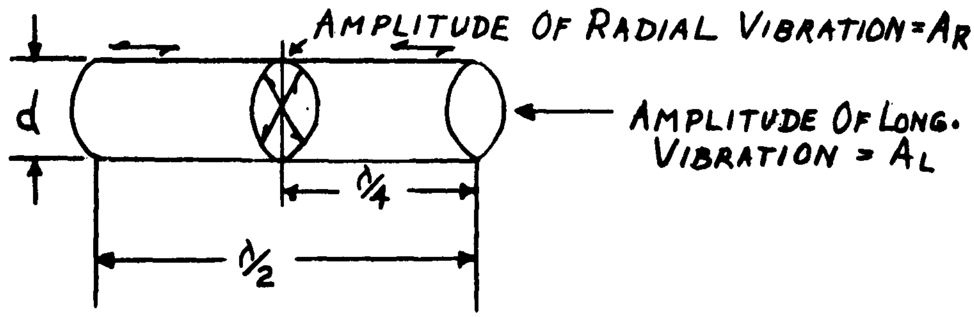
However, at the instant the amplitude is maximum at the extremities or loops we find that at the midpoint or node a contraction in the diameter of the member occurs. The magnitude of this contraction is governed approximately by the amplitude, diameter of bar, and Poisson's ratio which is the ratio of the change in diameter to its change in length. The radial displacement then can be computed according to the following relation: $A_R = NdA_L$

Where: A_R = Radial displacement

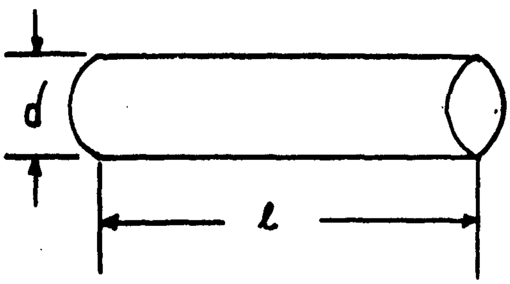
N = Poisson's ratio

d = Bar diameter

A_L = Longitudinal Amplitude



As a bar increases in diameter, maintaining all else constant, there will be an increase in the radial amplitude observed. A maximum will occur however at the diameter dependent on the frequency of the vibration wherein the longitudinal driving frequency matches the radial resonant frequency of the bar. Under these conditions the radial resonant frequency for rods or tubes can be computed as follows where:



$$f_r \simeq \frac{1}{\pi d_m}\sqrt{\frac{Y_o}{(1-\mu^2)\rho}}$$

Where: f = radial resonant frequency

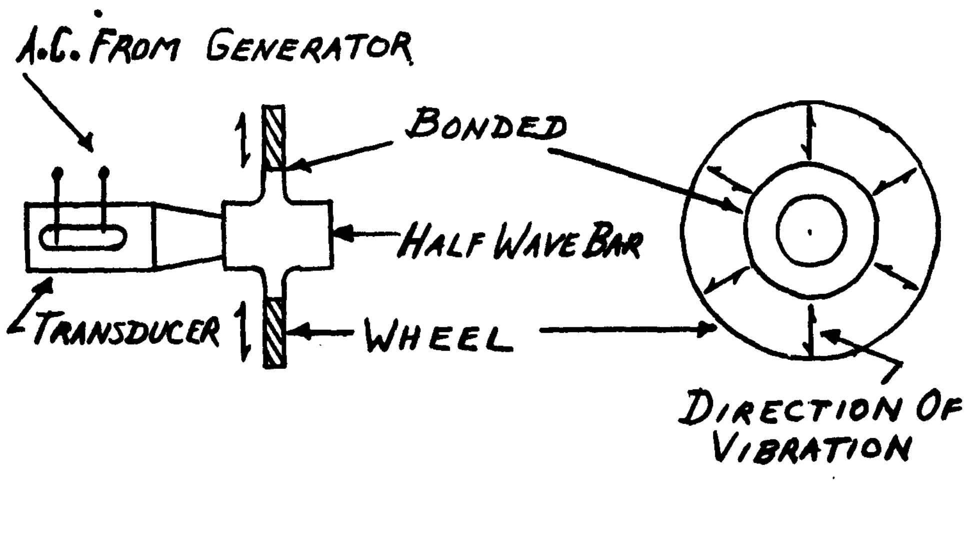
d_m = average diameter (whether rod or tube)

Y_o = Young's modulus of rod

N = Poisson's ratio

P = Density of rod

Since it is possible to achieve reasonable amplitudes at high frequencies in the radial mode, it seems possible to attach a grinding wheel to this radially dilating bar in such a manner as to permit the radial dilation of the grinding wheel. Such a motion to the wheel would impart a longitudinal vibration to the workpiece being ground at the point of grinding and in the case of large workpieces, minimize the amount of vibration power required to perform. In addition, differences in grinding behavior might be apparent from the opposite approach of vibrating workpiece. A wheel might be attached as below:



5.4 Discussion of Test Results

The graphs of the test data indicate that there is considerable difference betwen vibration assisted and conventional grinding under the conditions of the test set-up. Note the lower peak temperature (figures 47 to 49) and the greatly reduced spindle power (figures 55 to 66), in addition to the lower spheroid to chip ratio (figures 81 to 86) and the lower temperature time trace areas (figure 21 to 26). The differences are less for the (38A46-H8-VBE) wheel A, but this is attributed to the wheel breakdown and the lower cutting points per square inch, as opposed to the (38A100-I6-VBE) wheel B. Grinding tests using (32A60-L7-VG) wheel C substantiated less wheel wear due to wheel hardness.

5.4.1 Grinding Swarfs Interpretation

Under close scrutiny, the chips in the swarfs collected from test specimens showed a large difference between vibration assisted grinding and conventional grinding. Those of the conventional grinding showed burning, oxidation, discoloration, etc., while those of the vibration assisted grinding did not show any signs of oxidation, burning, etc. The latter contained smaller chip lengths than those of conventional grinding under all comparison tests, varying in depth of cuts on all test specimens.

Grinding swarf analyzed from 15-7MO material showed a considerable difference in burned and oxidized residue caused by temperature differences of conventional and vibration assisted grinding. This difference is the complete absence of spheroids brought about by the lower grinding temperatures in the vibration assisted grinding swarf.

In the swarf evaluation, figures 87-92, show representative runs of conventional and ultrasonic runs of various amplitudes. As will be noticed, the deeper the amount of cut, the more heat generated and the darker the glass due to adhesion of metal particles. It is also obvious that the higher the divisions, or stroke of vibration, the lesser the amount of chips or spheroids adhering to the glass.

5.4.2 Temperature Time Trace Presentation

The runs performed with a 10 step crossfeed of .050" increments gave us a better temperature time trace display (figures 28-38) Notice, in figures 93-96, the temperature differences between the vibration grinding and conventional grinding. Figures 28-38 are photographs of temperature time traces, three times scale, taken from level recorder tapes. These traces emanate from the surface outline area of the test specimen.

5.4.3 Grinding Ratio

As shown in figures 39-46; 77-80, little differences can be noted in the grinding ratios between vibration assisted and conventional grinding. However, harder sample grinding wheels of the "R" and "S" type are to be tested to insure favorable and efficient grinding ratios.

5.4.4 Swarf Adhesion to Glass

Quantitative swarf adhesion to glass, figures 87-92, is definitely greater in those samples of conventional grinding brought on by the higher comparative grinding surface temperatures.

5.4.5 Association of Temperature, Spindle Power, and Spindle Revolutions Count

There is a definite association between surface temperature and spindle power (figures 55-66;73-75;97-100). Both are a function of the same variables. Frictional phenomena and the energy of deformation are believed to be these variables.

Another direct effect of spindle power during grinding is the revolution count of the grinding wheel while on the test specimen surface. (figures 51-54)

5.4.6 Surface Finish, Stress, and Hardness

Visually, the ultrasonic ground finish appeared finer than that of the conventional surface. Checking the surface with a profilometer showed neither inferior nor superior finish comparison (figures 65-66). Because the overall length of the test specimen was only 3" using a plunge cut, and not having more than one run for comparison, these tests cannot be conclusive.

The "Before" and "After" grinding hardness checks made with a micro-hardness tester (figures 69-72) reveal little change in hardness. However, this state of affairs cannot as yet, be considered conclusive.

5.4.7 Test Grinder Selected

A Brown and Sharpe #13 Universal Surface Grinder has been selected for modification in Phase II. The spindle attachment being outboard of the column permits the use of the ultrasonic spindle developed and run for a short period in Phase I. Basically the modification of the grinder in alterations is restricted to the spindle. The modification of operation of the machine will be altered in so far as the grinding techniques are concerned, such as table speed, depth of cuts, spindle R.P.M., etc.

5.4.8 Ultrasonic Spindle

Based upon the results obtained in Phase I, it appears very promising to use the ultrasonic spindle to obtain identical or improved results in comparison to the vibration of the workpiece.

Continued effort is needed however, to fully substantiate these benefits and correlation between surface temperatures measurements and surface stress on parts is required. More work is necessary in the direction of improved wheel life. Past experience indicates failure caused by bond fatigue at the wheel hub junction. The work on soft soldering of standard wheels by the employment of the silver plating process will be conducted. This seems quite promising.

PHASE II

SECTION 6

INSTRUMENTATION

6 Instrumentation

The following section is concerned with the instrumentation for the proper data handling of all grinding tests. It will cover the test equipment used, its function and its application to these tests.

This section will also discuss the phenomena measured which includes the amplitude of spindle vibration, the amplitude of the ultrasonic spindle grinding wheel vibration, the amplitude of transducer vibration, spindle power and workpiece temperature.

6.1 Test Equipment

6.1.1 Tektronix Oscilloscope Type 551. The type 551 oscilloscope is a dual-beam, laboratory type instrument used for observing wave forms involving fast rise-time pulses and transients. Separate and identical amplifiers are provided for each beam. Dual-sweep plug-in preamplifiers are used in the vertical deflection system, which permits viewing of four simultaneous signals.

The type 551 oscilloscope is used in all grinding tests as a constant visual monitor of all phenomena being measured. It is used as the test data is being put on the Ampex tape recorder and as it is taken off.

6.1.2 Tektronix D. C. Preamplifier Type D. The type D preamplifier is a high-gain, differential, calibrated, D. C. preamplifier which is used in conjunction with the Tektronix type 551 oscilloscope.

Two type D preamplifiers are used in cascade to amplify the thermocouple information taken from the workpiece. The over all gain of the two preamplifiers in cascade is 57 db. The two amplifiers take a signal in the range of a few millivolts and amplify it to a usable range of 1 to 2 volts.

6.1.3 Bruel & Kjaer (B&K) Beat Frequency Oscillator Type 1013. The type 1013 oscillator is a variable beat frequency oscillator used for measurements in the frequency range of 200 to 200,000 cycles per second.

The beat frequency oscillator was used in order to carefully control the frequency of vibration being applied to the ultrasonic spindle and workpiece by the ultrasonic generator.

6.1.4 B & K Audio Frequency Spectrometer Type 2110. The type 2110 audio frequency spectrometer was designed for electrical, electro-acoustical and vibration measurements and analysis in the audio frequency range.

The audio frequency spectrometer was used to amplify and analyze vibration signals from the accelerometers. The accelerometers measured the vibration of the spindle and the workpiece.

It was found that interpretation of the spindle and workpiece vibration did not add any conclusive information to the analysis of ultrasonic grinding The vibration measurements therefore were discontinued.

6.1.5 B & K Level Recorder Type 2304. The type 2304 level recorder is a high speed instrument for recording signal level variations within the frequency range of 20 to 200,000 cycles per second.

The level recorder is used to permanently record the level of the signals taken from the Ampex tape recorder.

6.1.6 B & K Inverter Type 4610. The type 4610 inverter is used as an accessary to the high speed level recorder. It is used for the recording of D. C. and slow A. C. signals. A 400 cycle output signal proportional to the input D. C. signal is fed to the level recorder.

The inverter is used for converting the D. C. thermocouple signal to a 400 cycle A. C. signal for presentation to the level recorder.

6.1.7 B & K Accelerometer Type 4329. An accelerometer is a mechanical electrical transducer, the voltage output of which is proportional to the magnitude of the acceleration to which the transducer is subjected.

6.1.8 Electra Transducer Model 3015A. The Electra Transducer used in conjunction with the Erie counter and the marker box was used to count spindle revolutions.

It was found that interpretation of the spindle revolution s did not add any conclusive information to the analysis of ultrasonic grinding. The spindle revolution measurements were therefore discontinued.

6.1.9 Erie Counter Model 400. The model 400 counter is a digital device used for the counting of periodic and aperiodic electrical events and the precise measurements of frequency, period and time intervals.

In order to carefully control the vibrations of the workpiece and the ultrasonic spindle, the Erie counter was used to monitor the frequency of the beat frequency oscillator.

6.1.10 Ampex Tape Recorder Series F. R. - 1100. The model FR - 1100 Ampex tape recorder/reproducer is a 4 track, 4 speed, F. M. and direct record magnetic tape recorder. The frequency response on direct record at a tape speed of 60 ips is 150-150,000 cps $\pm$ 3 db. The frequency response on frequency modulated F. M. input is 0 - 10,000 cps $\pm$ ½db with a signal to noise ratio at 1% harmonic distortion of 40 db.

The excellent frequency response of this recorder on F.M. input made it a very accurate method for recording thermocouple information. The 3 direct record channels were used for accelerometers, power and voice recording.

Much phenomena measured was recorded on the Ampex tape recorder during the actual grinding runs. It could then be taken off when ready for analysis.

6.1.11 John Fluke VAW Meter Model 101. The model 101 VAW meter is a high impedance instrument used for the measurement of A. C. volts, amperes and watts from 20 to 200,000 cycles per second.

The power consumption of the spindle was measured with the VAW meter for each grinding pass. The VAW meter was connected to one phase of the three phase power line feeding the spindle motor. The total power was then assumed to be three times the VAW meter reading.

6.1.12 National Scientific Instrument Microscope Type 4015. The type 4015 microscope is a 600 power microscope with a calibrated, graduated reticle. Each division on the reticle is equal to 50 millionths of an inch.

The microscope was used to measure the amplitude of vibration of the ultrasonically excited grinding wheel and workpiece. Throughout this report the divisions of amplitude referred to are in reference to this microscope.

6.1.13 Miscellaneous. A standard cell and various meters were used as necessary for calibration and setup.

6.2 Phenomena Measured

6.2.1 Test Specimen Temperature. To adequately resolve the change in temperature of the workpiece, during grinding, it was necessary to use a temperature sensing device. The temperature sensing device had to be accurate, with good resolution in the range of a few degrees and have a very fast response.

For these reasons, an iron and constantan thermocouple with a .003" diameter wire was used. Iron and constantan were used because of suitable temperature range and large thermal e.m.f. The .003" diameter wire was used because of the fast thermal response of small diameter wire.

6.2.2 Vibration. The amplitude of vibration of the spindle and of the workpiece was measured with B & K accelerometers. It was found that the vibration was so small that interpretation of the vibration of the spindle and workpiece did not add any conclusive evidence to the analysis of ultrasonic grinding. The vibration measurements were therefore discontinued.

6.2.3 Spindle Revolution. This measurement was discontinued because the time involved in setting it up could be used for more grinding runs and the benefit toward ultrasonic grinding analysis was small.

6.2.4 Ultrasonic Vibration Amplitude. Since both the grinding wheel and the workpiece were ultrasonically vibrated it was necessary to measure and maintain the amplitude of vibration. A 500 X National Scientific Instrument Company microscope with a calibrated reticle was used for this purpose.

6.2.5 Spindle Power. The power consumed by the grinder spindle was measured by connecting one phase of the three phase motor to the VAW meter. The spindle power is a function of two variables which are believed to be the frictional phenomena and the energy of deformation.

6.3 Calibration

6.3.1 Thermocouple Calibration. The thermoelectric power generated by each test specimen varies due to differences in material. It was therefore necessary to determine the thermoelectric power of each material. The calibration apparatus is shown in figure 104, page 108.

Two 400ml beakers were filled with S.A.E. 30 weight oil. One beaker was immersed in melting ice and the other was immersed in boiling distilled water. A thermocouple was welded to each type of test specimen. The test specimen was then carefully immersed in the cold bath (32° F. cold junction). The thermocouple was then terminated in the hot bath (212° F. hot junction). The signal was taken from there, amplified and measured on the Tektronix scope. In this way the thermoelectric voltage for a known temperature difference for each material was found.

6.3.2 D. C. Preamplifier Calibration. The electrical signal taken from the thermocouple attached to the workpiece was too small in amplitude to be properly recorded. It was therefore necessary to amplify it to a uceful range. For this purpose two Tektronix type D preamplifiers connected in cascade were used.

It was necessary to accurately calibrate these preamplifiers in order to have a representative amplification of the thermocouple trace. The most difficult part of the calibration is the D. C. balancing of the preamps. This is accomplished by putting zero signal into the first preamp, changing the range switch from minimum to maximum position and adjusting for zero D. C. shift in the output. This signal is viewed on the Tektronix scope. The same procedure is followed for the second preamp.

A 1 millivolt P. P. 20 kc sine wave is put into the first preamp. The two preamps are then adjusted for a 1.5 volt peak to peak output. This gives the two units in cascade an over all gain of 57 db. The input signal must be a sine wave of known accuracy. The B & K beat frequency oscillator is used for this purpose.

6.3.3 Level Recorder Calibration. The level recorder is calibrated with the use of a standard cell. The inverter is connected to the level recorder and the standard cell voltage is connected to the input. The input potentiometer is then adjusted for 1 volt as shown on the level recorder chart.

To set the zero level, zero signal is put into the level recorder from the tape recorder. The thermocouple and preamps are connected to the tape recorder. The tape recorder and level recorder are started and the vertical position control on the first preamp is adjusted for the desired zero level as shown on the level recorder chart.

6.4 Measuring Method

6.4.1 Data Acquisition. The instrumentation for data acquisition was set up as shown in figure 108, page 112. All data was recorded on the series FR-1100 Ampex tape recorder for each grinding pass. The data could then be taken off the magnetic tape for analysis as many times as necessary.

The thermocouple had to be mounted so that it would withstand surface particle acceleration of 40,000 g's and greater. Any air spaces or other insulating effect, that would be detrimental to the response of the thermocouple, had to be held to a minimum. A technique previously devised was used to flash weld the .003" diameter wire to the workpiece to form the thermocouple, consisting of the workpiece and the wire. The position of the thermocouple on the workpece was determined by the use of appropriate measuring instruments. The thermocouple placement is shown in figure 105, page 109.

The thermocouple signal was amplified through the Tektronix type D preamps and recorded on the Ampex tape recorder on the F. M. input channel. The Tektronix scope was used to monitor the thermocouple signal before and after amplification.

The accelerometer signal was amplified in the spectrometer preamp and then recorded on a direct record channel on the Ampex tape recorder.

The spindle power was measured with the VAW meter and then recorded on a chart for each grinding run.

The B & K signal generator with the Erie Counter, as a frequency monitor, was used to carefully control the frequency of the ultrasonic vibration.

6.4.2 Data Playback. The accelerometer signal was taken from the recorder and played through the audio frequency spectrometer (see figure 106, page 110). Two separate traces were made on the level recorder. One was made without filtering and another with everything except the 20 kc filtered out.

The thermocouple signal was played through the inverter and recorded on the level recorder (see figure 107, page 111).

The data from the level recorder was processed and placed in table form and has been included in this report.

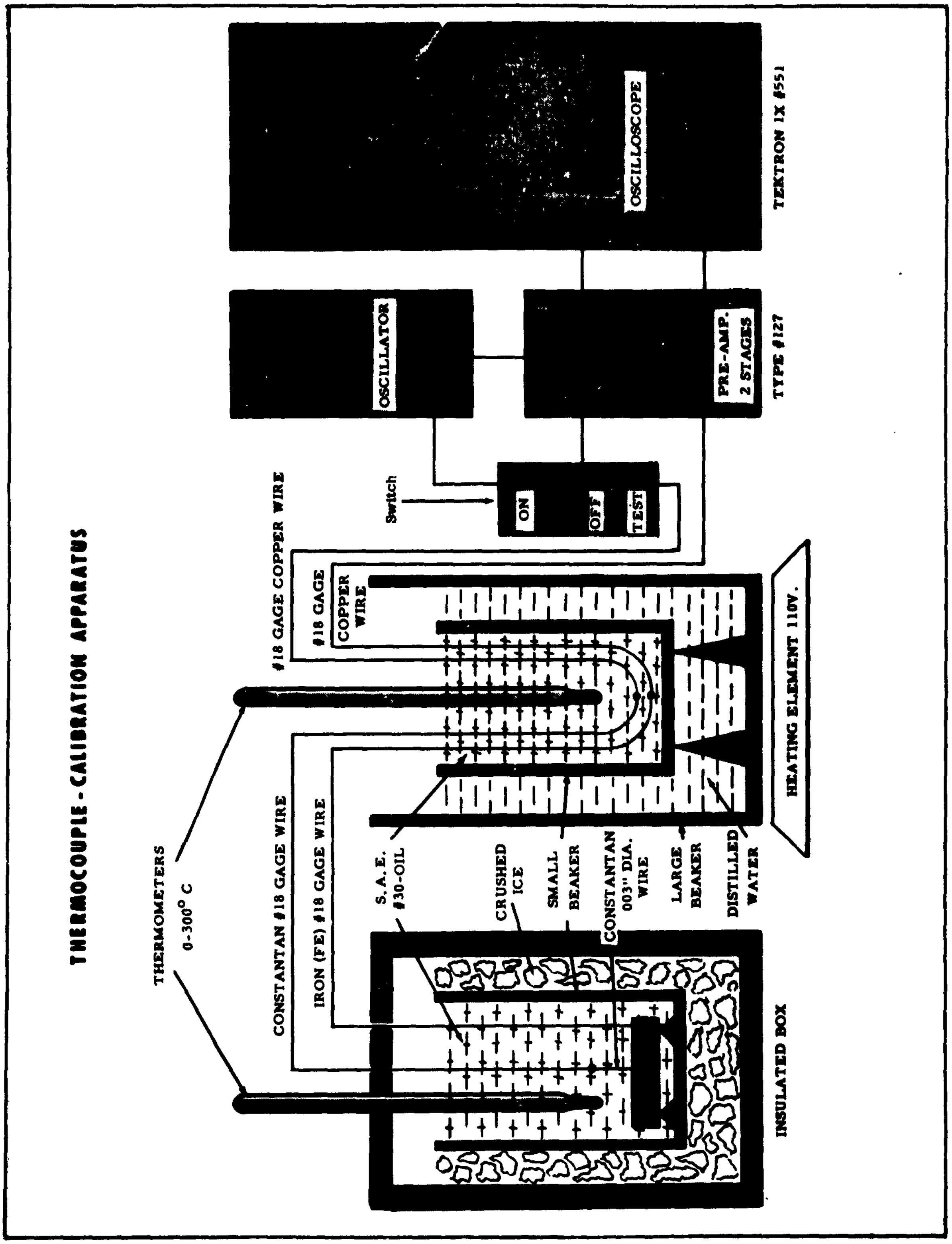

THERMOCOUPLE - CALIBRATION APPARATUS
THERMOMETERS
0-300° C
CONSTANTAN #18 GAGE WIRE
IRON (FE) #18 GAGE WIRE
#18 GAGE COPPER WIRE
#18 GAGE
COPPER
WIRE
S.A.E.
#30-OIL
CRUSHED
ICE
SMALL
BEAKER
CONSTANTAN
003" DIA.
WIRE
LARGE
BEAKER
DISTILLED
WATER
INSULATED BOX
HEATING ELEMENT 110V.
Switch
ON
OFF
TEST
OSCILLATOR
PRE-AMP.
2 STAGES
TYPE #127
OSCILLOSCOPE
TEKTRON IX #551

Figure 104

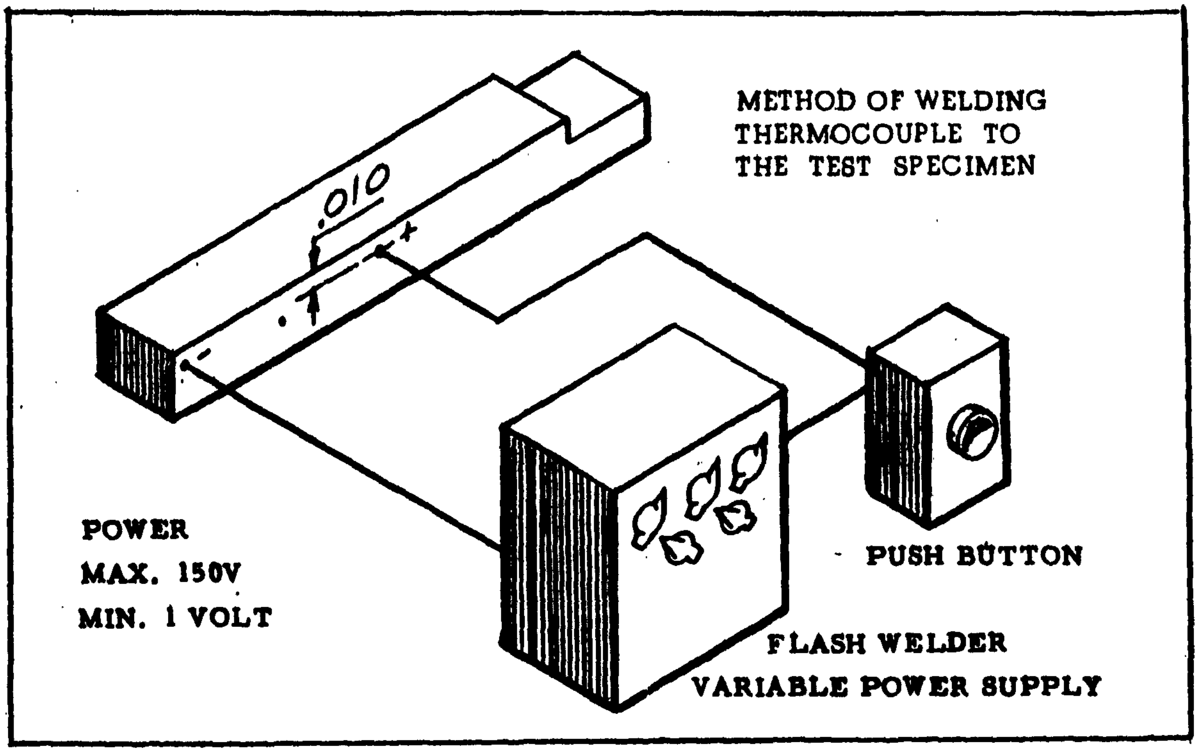
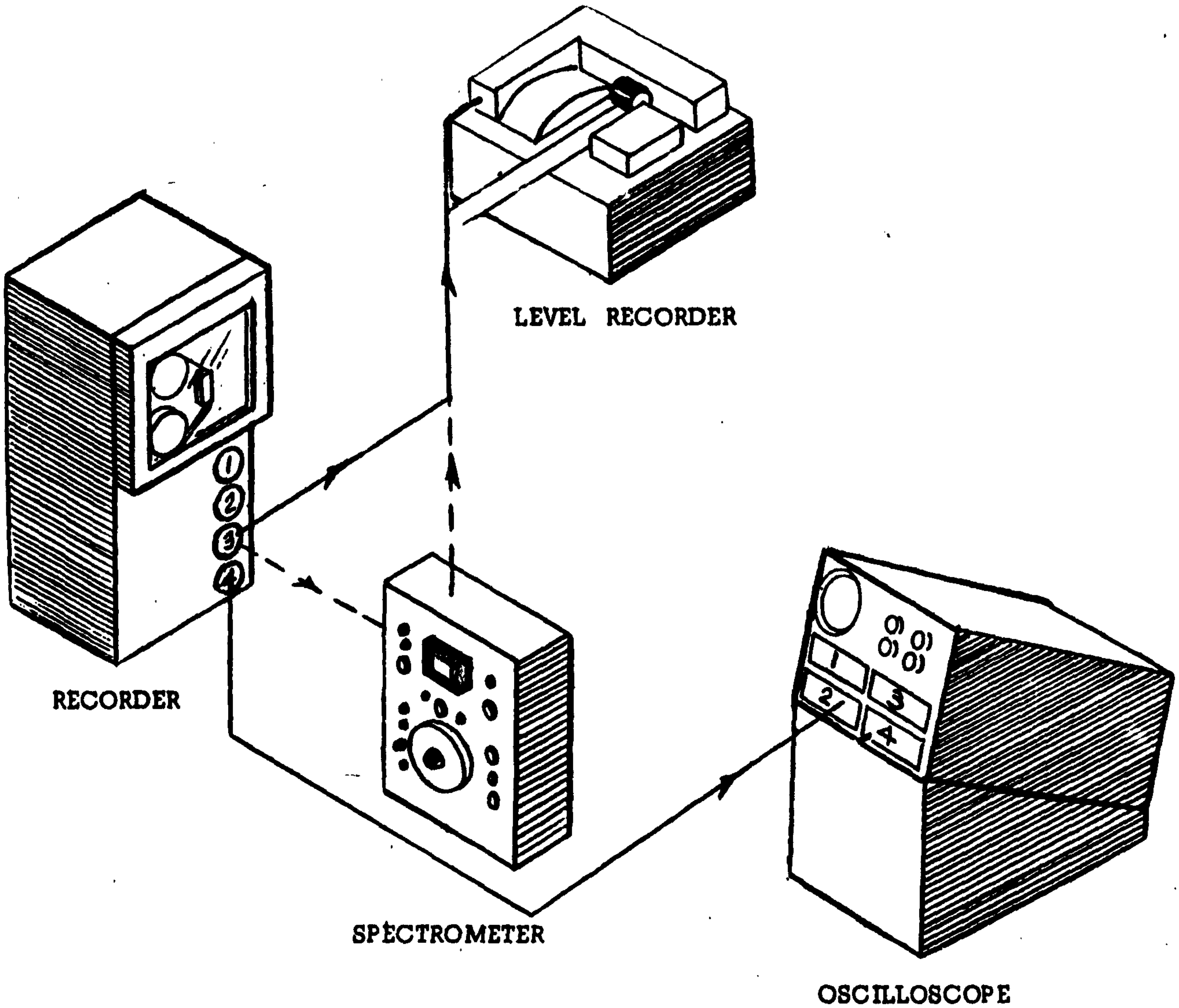
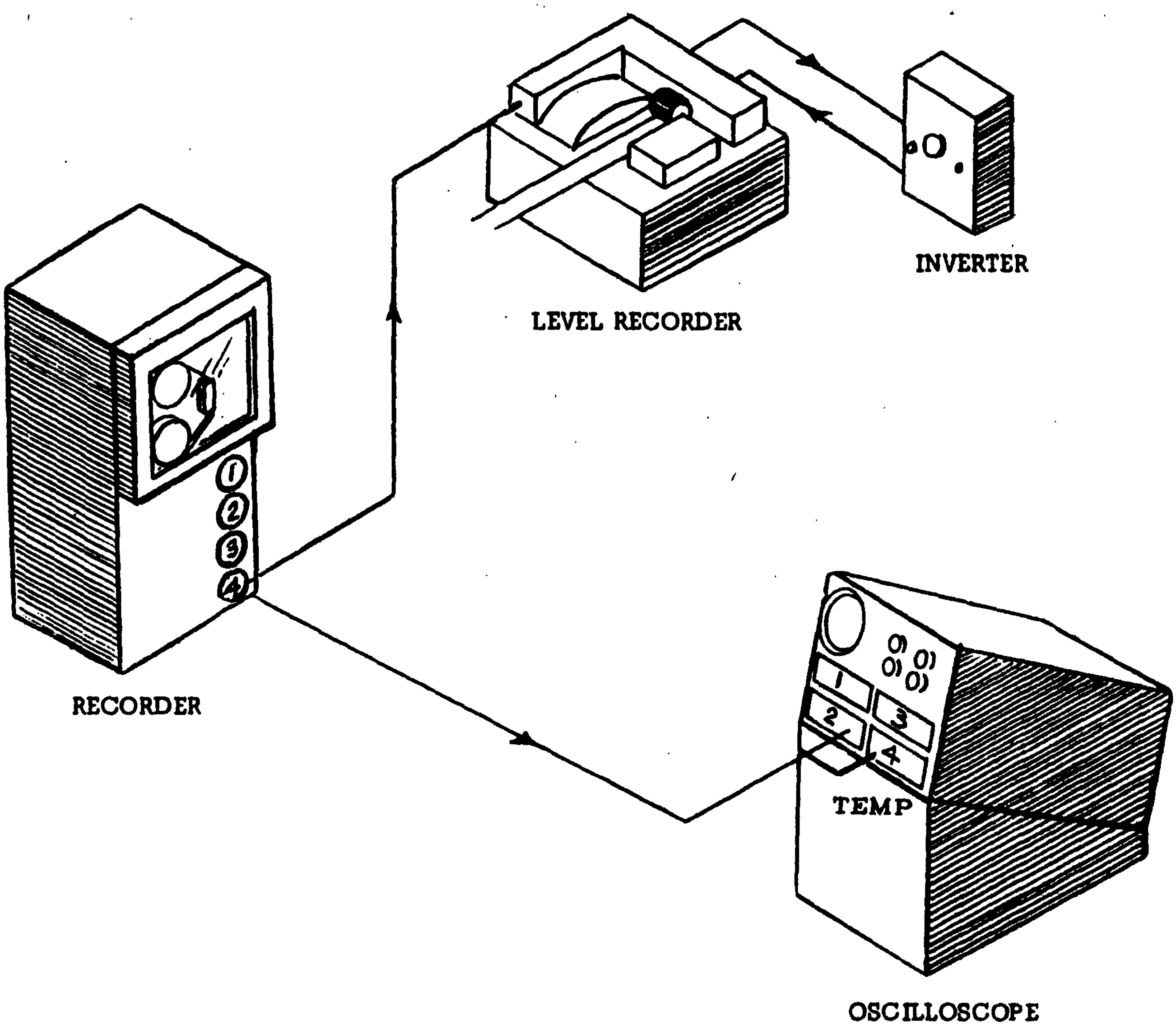

METHOD OF WELDING THERMOCOUPLE TO THE TEST SPECIMEN
.010
+
-
POWER
MAX. 150V
MIN. 1 VOLT
PUSH BUTTON
FLASH WELDER
VARIABLE POWER SUPPLY

Figure 105



PLAYBACK FOR ACCELEROMETER - INFORMATION

Figure 106



PLAYBACK FOR THERMOCOUPLE - INFORMATION

Figure 107

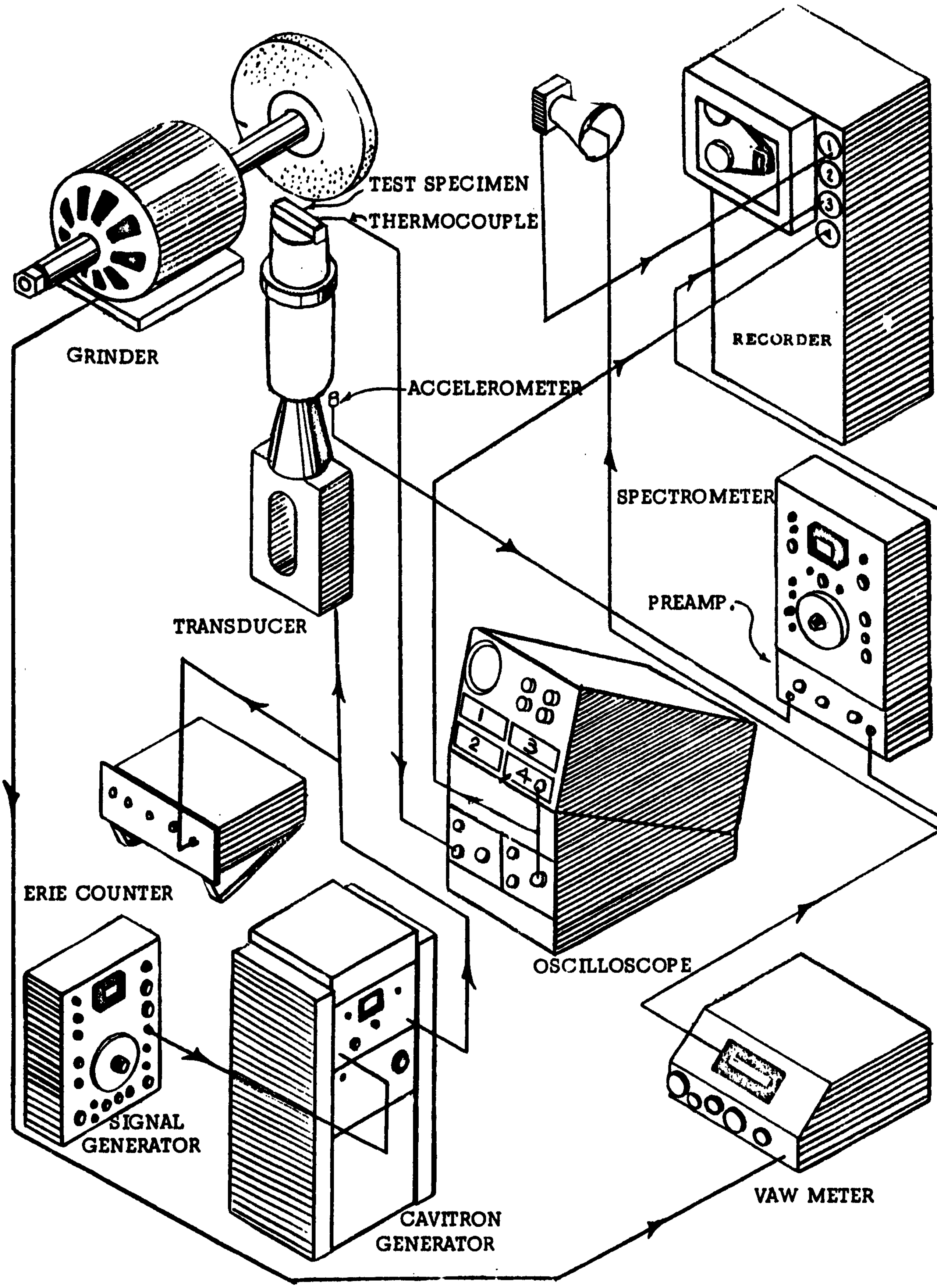


Figure 108 INSTRUMENTATION RECORDING HOOK-UP

PHASE II

SECTION 7

DATA COLLECTION

7. DATA COLLECTION

7.1 Grinding Tests

Initially, all grinding tests were fully instrumented to record the temperature rise of the test specimen under conditions of conventional and ultrasonic assisted grinding. A comparison could then be evaluated. Two grinding wheels were selected from the five grinding wheels used in Phase I. They were: AA60-L8-V40 and AA60-R8-V40. Both wheel types were used for the grinding test runs.

Manner of Making Tests

Runs 200 - 320

(A) Grinding the specimen with a 7/16" wide plunge cut, three depths of cut were used: .0003", .0006", and .0009", and each depth of cut having five passes.
(B) A swarf was collected on the second pass and a swarf to glass was taken on the fifth pass.
(C) Each run was logged on a separate run sheet having headings of: (1) date, (2) type of run (conventional, ultrasonic spindle, longitudinal mode A, 60 cycles vibration, longitudinal mode A and ultrasonic spindle, (3) depth of cut, (4) wheel diameter before grind, (5) wheel diameter after grind, (6) spindle power in watts) for each pass, (7) remarks for visual inspection of wheel loading.
(D) Surface finish tests were made on each run.

Runs 400 - 496

(A) Grinding the specimen using .050" infeeds for .001", .0015" and .002" depth of cut. 50% of runs were dry ground using CIMCO coolant. Wheel speed 6200 SFPM - Table Speed 35 FPM.
(B) Filter paper was used to collect the swarf for examination in the middle of each run.
(C) Each run was logged on a separate run sheet having headings of: (1) date, (2) type of run (ultrasonic spindle or conventional), (3) depth of cut, (4) wheel diameter before and after grind, (5) spindle power in watts (titanium only), (6) photograph of wheel loading, (7) photograph of workpiece, (8) wet or dry grinding, (9) workpiece inspection for burns or checks and cracks.
(D) Surface finish tests were made on each run.
(E) 200 X photomicrographs were made on each run specimen.

7.2 Workpiece Coupling - Work Vibrated

The only amplitude of vibration chosen for the test specimen mounted to the toolholder (longitudinal mode A)(Figure 7, page 19)was 15 divisions (1 division equal to 50 micro-inches peak to peak). Due to the high acceleration forces imparted to the test specimen under ultrasonic vibration, mechanical bond of the test specimen to the tool holder was eliminated. A soft solder of 60PB -40SN was selected with soldering temperature maintained at or about 400°F. Silver solder was considered but was eliminated because of the possibility of altering the test specimen through excessive heat and thereby distortion.

Of the four types of test specimens used, only two (H-11 die steel and 15-7MO Steel) could be soldered directly to the toolholder. The remaining two (Titanium 6Al-4V and Rene 41) had to have their respective surfaces copper plated prior to soldering. Many methods of plating were attempted without success prior to finding a successful method. The following is the procedure used in copper plating both titanium and Rene 41 test specimens.

(1)	Dip specimen in alkaline cleaner	- 2 minutes
(2)	Dip specimen in hydrochloric acid	- 2 minutes
(3)	Place in mixture of 3 parts water to 1 part acid, using a 3 volt reverse current	- 2 minutes
(4)	Nickel Flash	- 2 minutes
(5)	Copper Plate	-½hour at low voltage

When vibrating the test specimen at 60 cycles, Eastman "910" cement was used as the bonding agent. The acceleration forces (being low) were well within the bonding strength of the cement. The advantages of this type of bond over the soft solder were its rapid specimen removal and installation to the toolholder.

Workpiece Coupling - Wheel Vibrated

All runs made using the ultrasonic vibrated wheel from run 400 on were mounted to a vise in the normal manner (see figure 13, page 29).

7.3 Method of Dressing Grinding Wheel

Grinding wheels on all test runs were diamond dressed with a .003 Wheel Truing Tool Company diamond. The wheel, revolving at grinding speed (6180-6320), was adjusted down to contact with the vertically mounted diamond. The wheel was moved to one side and adjusted down (.003"-.006"). The table to which thediamond was fixed was moved slowly under the rotating wheel past the opposite edge. The direction of table motion was reversed, passing the diamond again under the wheel. If the wheel was not clean, the process was repeated.

7.4 Swarf Collection and Analysis

Swarf is collected in an envelope held in the spark system of a designated pass. The swarf is evaluated for a ratio of spheroids to chips, size of spheroids, general description of chips (color and evenness of size), and the adherence of spheres to chips.

To evaluate the swarf, the envelope is emptied on a glass plate and quartered until an aliquot remains. This small quantity is evenly distributed and viewed through an American Optical Company Stereoscope Miscroscope at 54X. The chips and balls of 10 locations are counted and averaged. All envelopes of swarf of this same run are evaluated in the same manner, and the total of all is averaged. To measure the diameter of spheres, a Sheffield Micro-hardness tester with optical magnification of 400X is used. The filar micrometer eye piece is calibrated in microns and adjusted by a micrometer screw moving a sliding hair line to or from a stationary, adjustable line. The first 20 spheroid diameters of a representative sample of each pass are measured and averaged. Each pass of a run is measured and averaged in the preceding manner, as is the sum of all passes.

The results are charted, permitting evaluation of conventional grinding to grinding with ultrasonic aid. If sufficient heat is generated, the material removed during grinding will be oxidized and the spheroids will be formed. A lesser heat generated will increase the number of chips which is indicative of a lower temperature during grinding.

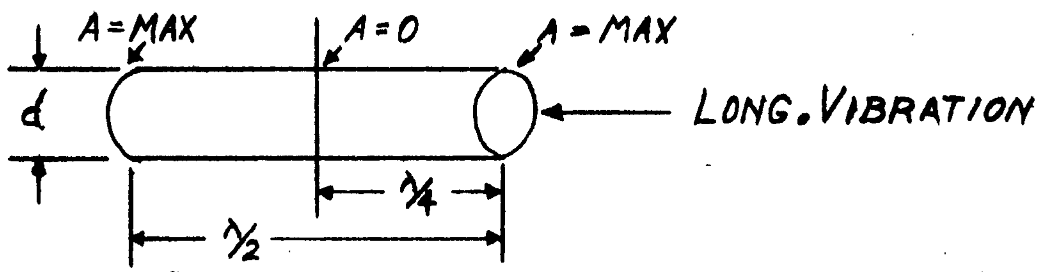
7.5 Swarf Adhesion to Glass

A second method of swarf evaluation was accomplished by using clear glass. A square piece of plate glass was inserted in the spark stream during the fifth grinding pass of every run. If sufficient heat is generated, particles of swarf will fuse to the glass. The higher the temperature, the greater the amount of particles will be visible. Pages 238 to 240 picture representative runs of conventional, ultrasonic spindle (using 3 division amplitude of vibration), longitudinal mode A, 60 cycles vibration, longitudinal mode A with ultrasonic spindle using the three depth of plunge cuts (.0003", .0006", and .0009").

As will be noticed, the deeper the amount of cut the more heat generated and the darker the glass due to adhesion of metal particles. It is also obvious that the high stroke of longitudinal mode A and the combination of the ultrasonic spindle (3 divisionstroke) plus the high stroke longitudinal mode A runs alone we had the least amount of chips or spheroids adhering to the glass. This was the direct result of a very low grinding ratio where the grinding energy which normally dissipated into heating the chips and spheroids went into wheel breakdown. Comparatively lower spindle power and temperature traces were also noticed. (See pages 226 to page 227.)

7.6 Radial Vibration of Wheel

If a cylinder of uniform cross-section is subjected to longitudinal vibration at high frequencies, where the direction of travel of the wave is parallel to the longitudinal axis of the cylinder, the particle motion will be in the direction of propagation and the cylinder will undergo elastic extension and contraction. The amplitude of vibration of a longitudinal wave is greatest at the extremities of a bar, provided it is considered one-half wave in length and essentially free at both ends. The amplitude of vibration is zero at the midpoint of this uniform bar.



Where: d = bar diameter

$\lambda/2$ = 1/2 wave length

A = Amplitude of vibration

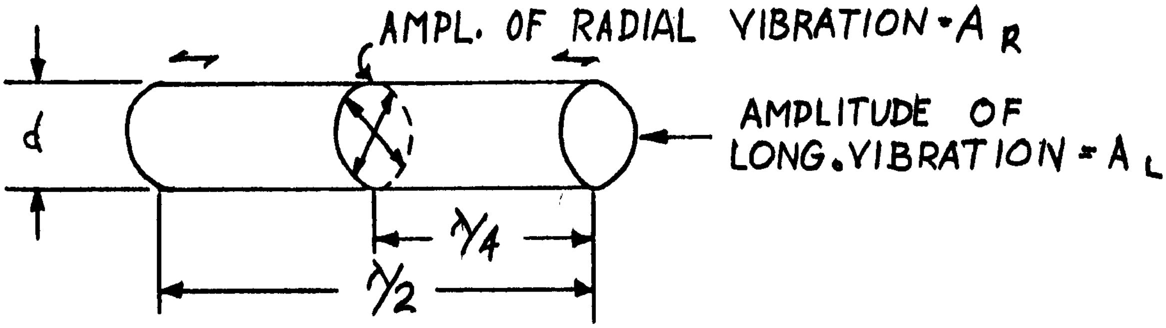
However, at the instant the amplitude is maximum at the extremities or loops we find that at the midpoint or node a contraction in the diameter of the member occurs. The magnitude of this contraction is governed approximately by the amplitude, diameter of bar, and Poisson's ratio which is the ratio of the change in diameter to its change in length. The radial displacement then can be computed according to the following relation: $A_R = \nu d A_l$

Where: A_R = Radial displacement

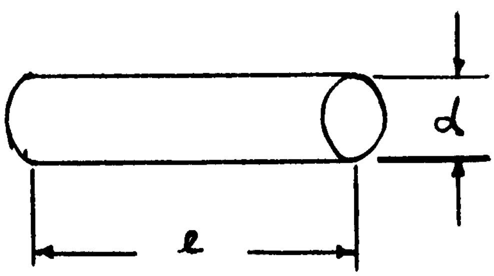
ν = Poisson's ratio

d = Bar diameter

A_L = Longitudinal Amplitude



As a bar increases in diameter, maintaining all else constant, there will be an increase in the radial amplitude observed. A maximum will occur however at a diameter dependent on the frequency of vibration wherein the longitudinal driving frequency matches the radial resonant frequency of the bar. Under these conditions the radial resonant frequency for rods or tubes can be computed as follows:



$$f_r \simeq \frac{1}{\pi d_m}\sqrt{\frac{Y_0}{(1-\mu^2)\rho}}$$

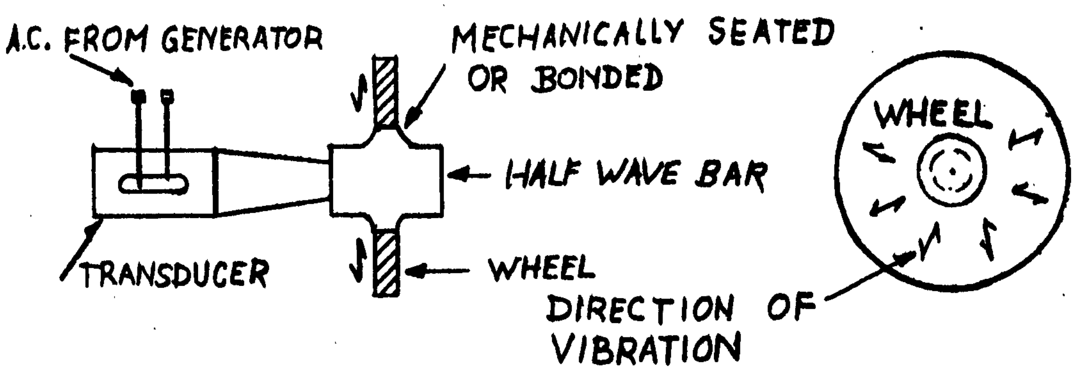
Where: f = radial resonant frequency

d_m = average diameter (whether rod or tube)

Y_0 = Young's modulus of rod

μ = Poisson's ratio

ρ = Density of rod



7.7 Ultrasonic Vibrating Grinding Wheel (See Figure 13, page 29)

The Ultrasonic spindle assembly used consisted of:

(A) Grinding wheel assembly (hub-bonded to wheel)
(B) Transducer Assembly (1000 Watt transducer with water cooled housing)
(C) Slip ring and pulley assembly (slip ring, carbon brushes, drive pulley, and shaft adaptor)
(D) Bearing support assembly (Mounting plate and bearing support)

This spindle assembly replaces the existing spindle on the test grinder. The "V" belt drive is arranged to facilitate change of spindle speeds from 2150 to 3875 R.P.M. The radial mode of (3 division stroke) vibration was selected for use on the ultrasonic spindle.

7.8 Grinding Wheel Hub

The grinding wheel hub used was a 3" diameter bar whose half wave length is for 20 kc, having a $4\frac{1}{2}$" diameter flange at its nodal point. A grinding wheel was bonded with Armstrong epoxy bond at this nodal point (see page 119). One end has a $\frac{1}{2}$ - 28 tapped hole 3/4" deep for attachment to the transducer, the other, a 60° tapered center to receive a nylon support. This center support is at the nodal point to reduce the particle motion and to isolate vibration from the frame of the machine. It will also alleviate bending stresses at the "Hub to Transducer" junction. Radial cracking of the wheel occurred during the curing of the adhesive bond. This was remedied by slowly increasing and decreasing the temperature during bonding and curing. The wheel assembly was excited at its radial resonance, and was vibrated for 15 minutes at 3 Div. stroke (150 micro-inches). Occasionally the wheel would crack and be destroyed by a violent flexural mode that would appear while tuning the wheel for this radial mode. This was corrected by maintenance of low power setting while tuning for the radial mode.

7.9 Ultrasonic Spindle Operation

All grinding runs were performed using this spindle. One amplitude (3 divisions) was used when executing runs requiring ultrasonic spindle vibration.

Considerable trouble was encountered at first with the main bearing, but later rectified with the use of proper lubricants and felt seals enclosing the bearings. The grinding wheel was run at two speeds, (a) 4000 SFM and (b) 6200 FM.

7.10 Low Frequency Vibration

The 60 cycle grinding runs were performed with a 220 V, 300 Watt, 60 cycle vibration mounted on a solid frame (see figure 12, page 26) that, as an assembly, was easily attached to the top of the grinder feed table. The amplitude and power of vibration could be varied by an adjustment screw.

7.11 Wheel Bonding

The four methods of wheel bonding are explained as follows:

A. Carborundum Wheel A60N150-M1/4. The manufacturing of this wheel consisted of a build up of layers of grit and metal by an electroplating process to a total of $\frac{1}{4}$" thickness. This buildup produced a wheel of $7\frac{1}{2}$" outside diameter and an inside diameter of 4.323". The inside diameter of this rim was soldered to a stainless steel hub. The only way resonance could be obtained was to reduce the outside diameter of the wheel, which meant cutting off the grinding material thus rendering the wheel useless. Further tests along this line were discontinued.

B. Cupric Oxide and Phosphoric Acid Bond. In the prescribed proportions, a mixture of cupric oxide and phosphoric acid were mixed. This was then applied to both the inside diameter of the grit wheel and knurled outside diameter of the wheel hub. Wheel and hub were then joined and left 24 hours to air dry. When ultrasonically excited the bond life was found to be very short.

C. Silver Bonded Grit. The grinding wheel was ultrasonically cleaned in distilled water. Then it was placed in a silvering solution, (Rochelle Salt method). Sufficient time was allowed for silvering the wheel surface to a suitable thickness. Two mils of copper was electroplated to the inside diameter of the wheel. The inside diameter was then tinned with soft solder and sweated on a wheel hub. The latter bond seems promising by offering longer endurance and improved heat dissipation possibilities.

D. Armstrong Epoxy A-4. Using the epoxy bond, extreme cleanliness of the bonding surfaces is important. The metal hub bonding surface was knurled to increase bond area. The epoxy was applied to both mating surfaces, being careful not to create bubbles. The setting up and curing of the epoxy had taken place at the same time, in an oven, at curing temperature. If the bond was allowed to set up before curing, cracking of the wheel would occur. This is due to the different expansion coefficients between the metal hub and aluminum-oxide grit wheel. This bond is the only one that has been used so far on the ultrasonic spindle.

7.12 Test Specimens Used

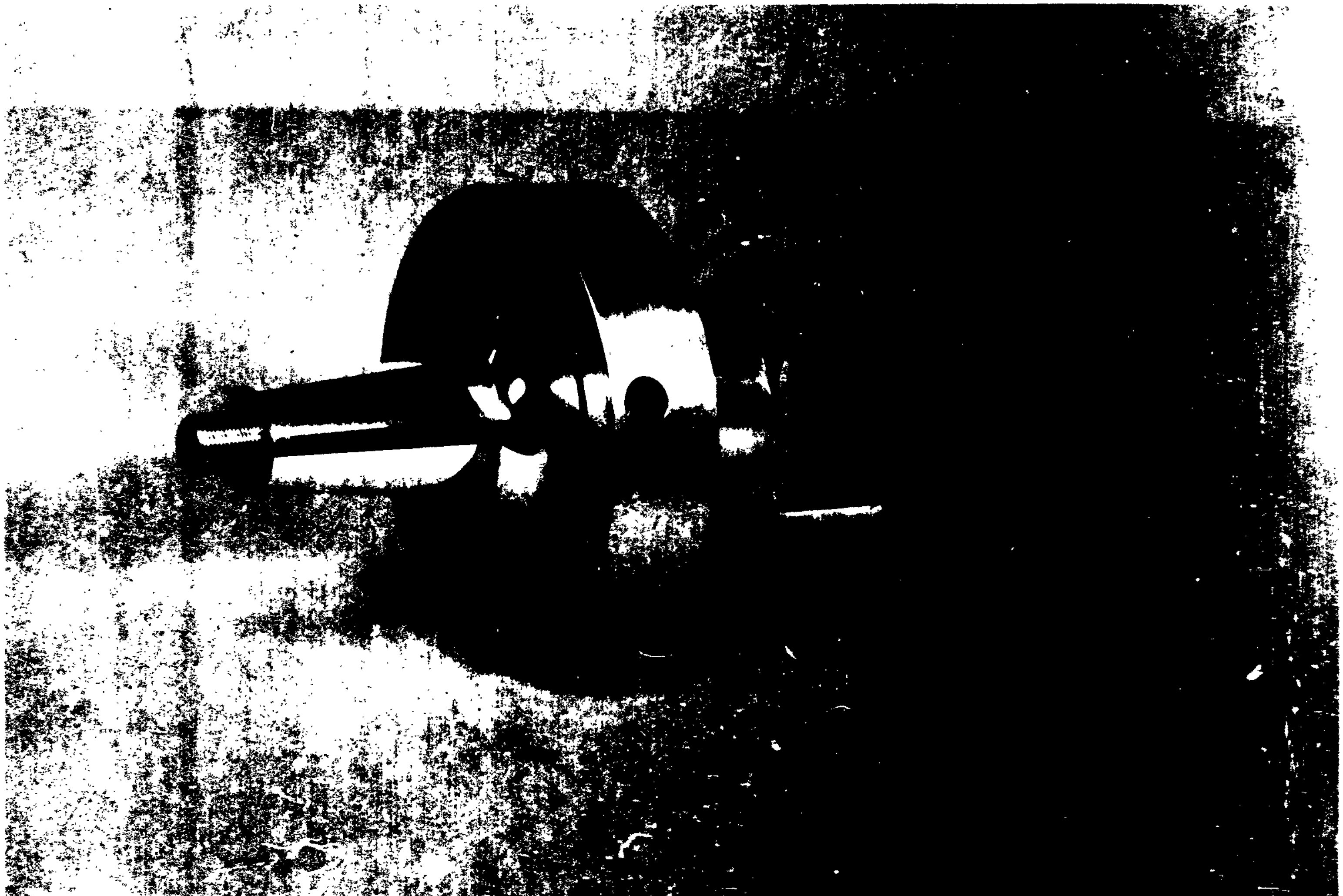
All test specimens used were processed by the Met-Cut Research Associates Inc., 3980 Rosslyn Drive, Cincinnati 9, Ohio. Two different sizes were used. Runs 200-320 (runs involving part vibration as well as wheel) were 7/16" wide by 3" long by 5/16" thick. Runs 400-496 were 2" wide by 4" long by 1/2" thick.

The Met-Cut Research Associates ground the specimens with the following conditions:

Downfeed	-	.001"/pass to the last .010" stock 2 passes at .0005" 2 passes at .0004" 6 passes at .0002" Spark out	
Table Speed	-	20' / minute	
Cross Feed	-	.050" / pass	
Coolant	-	Stuart Thread Cut #99, diluted 1:1 with paraffin oil	
Wheel	-	H-11; 15-7MO	32A46G12VBE - 6000 SFPM
		T16A1-4V	39C60J4VK - 3500 SFPM
		Rene 41	32A46G12VBE - 3500 SFPM

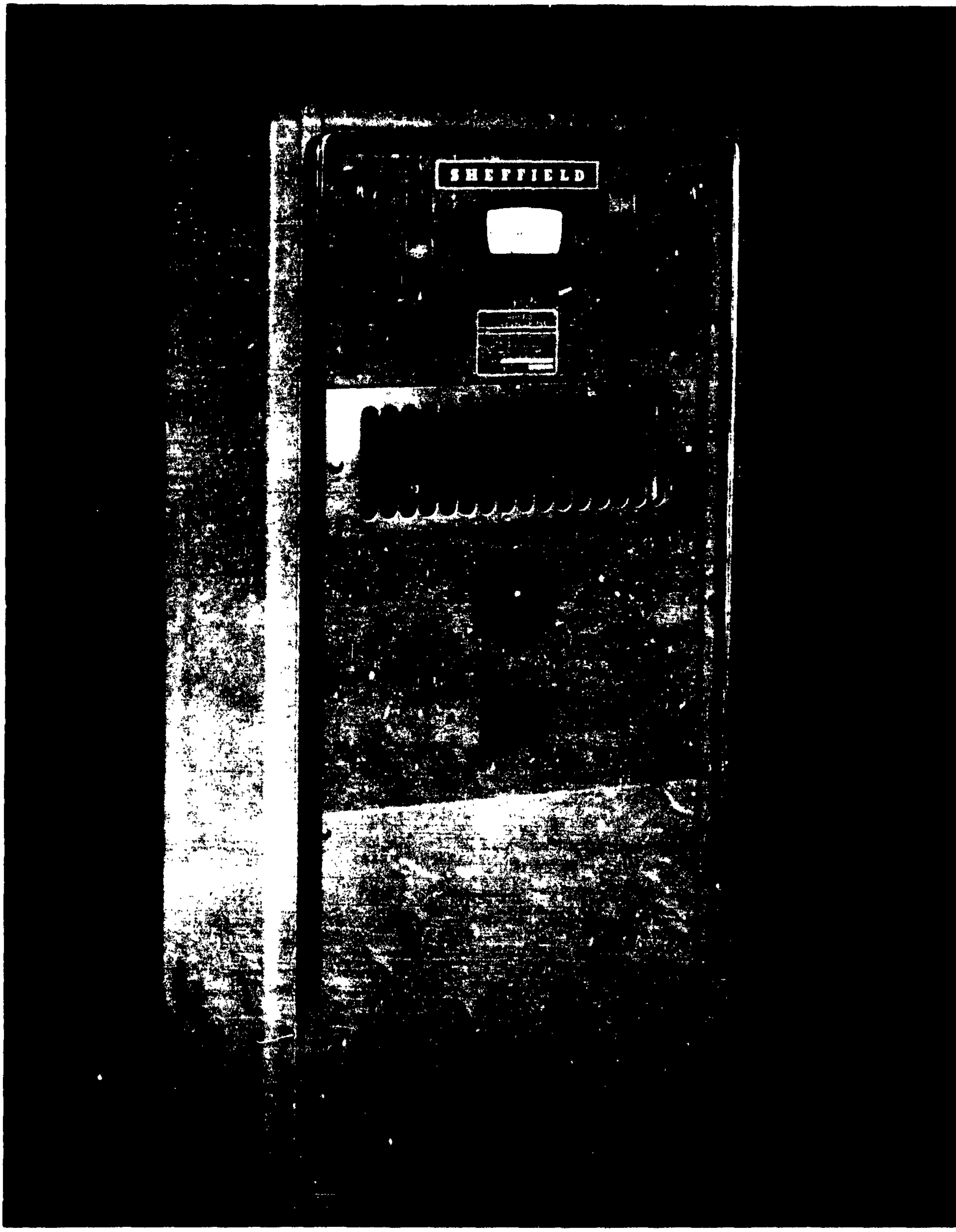
Physical Properties

Material	H-11	T16A1-4V	Rene 41	15-7MO
Supplier	Vanadium Alloys	Reactive Metals	Allegheny Ludlum	Armco Steel
Heat Treatment #	29147	29186	W22490	57968
Ultimate Tensile Strength	305	140	195	240
.2% Yield KPSI	255	130	160	215
% Elongations	8.5	8	31	6
Hardness Rockwell C	55-56	37	42-43	47-49



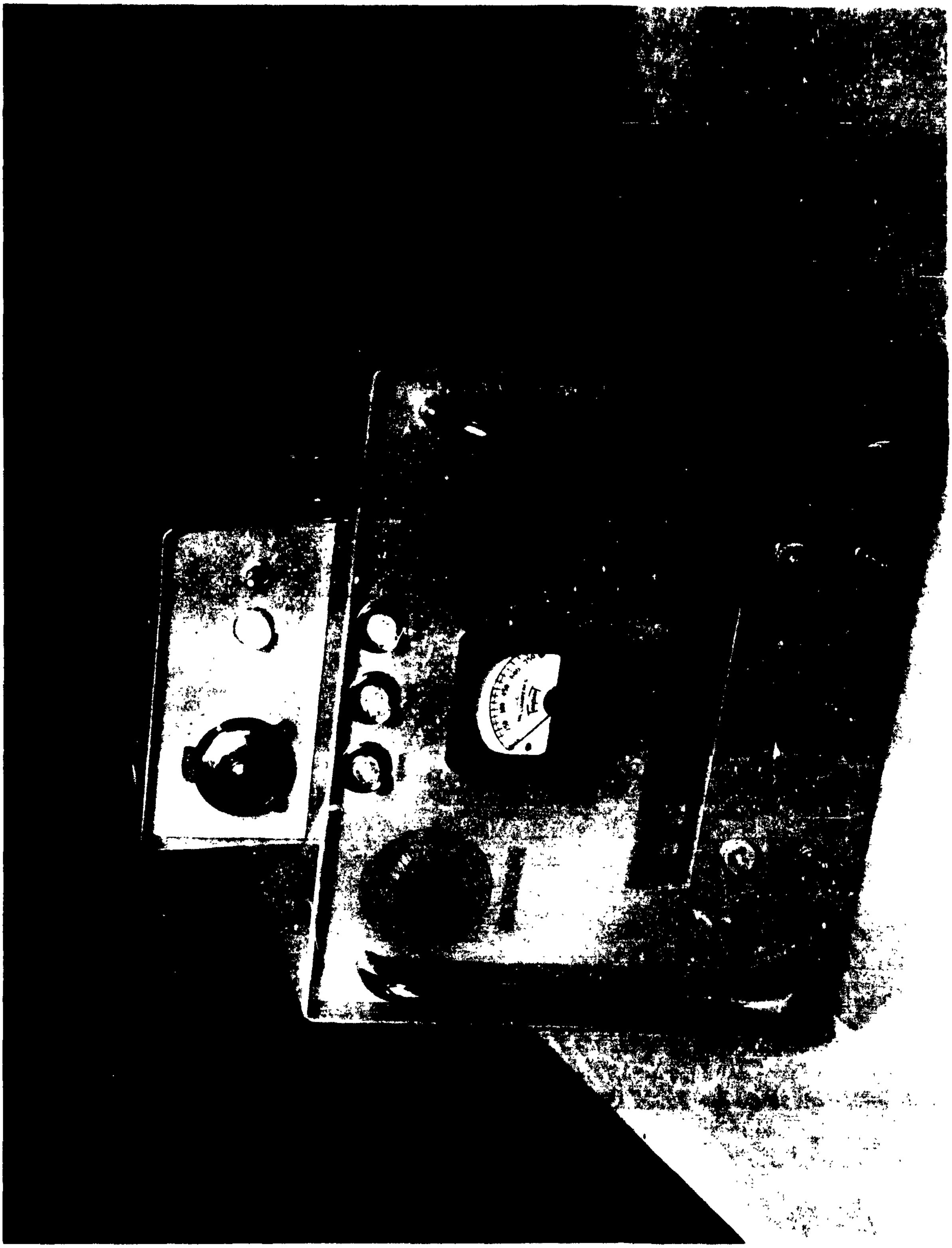
1000 WATT MAGNETOSTRICTIVE TRANSDUCER
(Type employed on experimental tests)

Figure 109



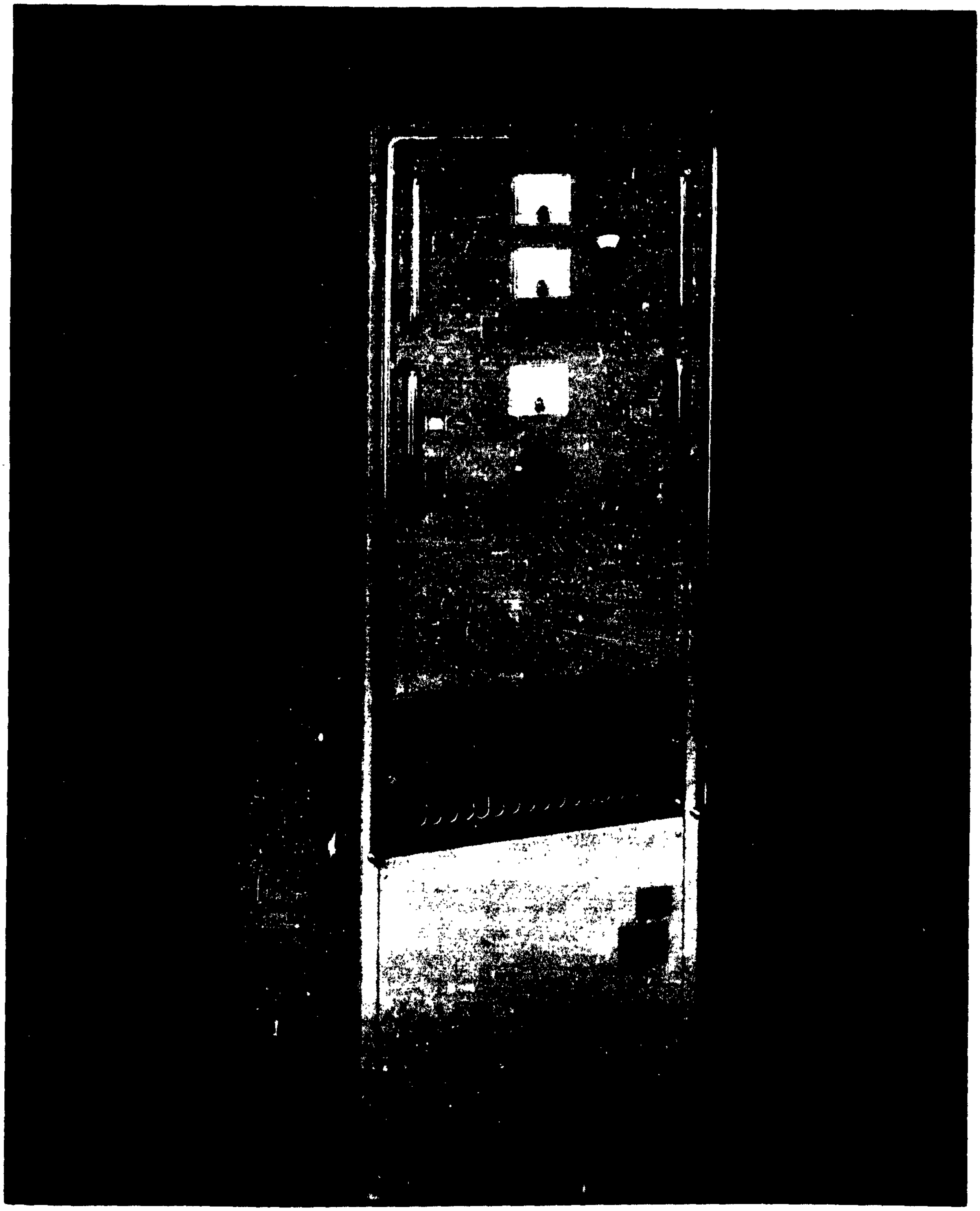
1000 WATT HIGH FREQUENCY ULTRASONIC GENERATOR

Figure 110



200 WATT HIGH FREQUENCY ULTRASONIC GENERATOR
(For Specifications see Sec. 7.4.3)

Figure 111



2400 WATT HIGH FREQUENCY ULTRASONIC GENERATOR

Figure 112

SPECIAL GRINDING RUNS

SPECIAL TEST RUNS
RUNS 1-16

GENERAL:

GRINDER -	Modified Brown & Sharpe #13 Ultrasonic Surface Grinder
SPINDLE -	Ultrasonic spindle incorporating antifriction bearings to eliminate bearing failures and loading changes due to heat expansion.
WHEELS -	Carborundum Company - Laboratory monitored to assure uniformity as to grit, density, bond and hardness.
WHEEL HUBS-	All runs, conventional and ultrasonic employed the ultrasonic hub assembly entailing a wheel epoxy resin bonded to the hub.
CHUCKING -	All parts were clamped to the table by means of a grinding vise so oriented to grind the 2 X 4 workpiece in the 4 inch direction. Workpiece was leveled within .001 TIR to the table travel.
WHEEL DRESSING -	A special dressing technique was employed for the different types of wheels used.

1. R & L grade grinding wheels employed diamond dressing before starting to grind each sample 2 passes at .008"/pass using 20"/minute cross feed, followed by one finish pass of .002"/pass using 20"/minute cross feed.

2. I grade grinding wheels employed diamond dressing before grinding each sample. 2 passes at .002" /pass with crossfeed of 40"/minute. Followed by 2 passes of .001"/pass with 20"/minute crossfeed. Finished with two passes of .001"/pass with diamond mounted with a negative rake and 10"/minute cross feed.

3. All H-11 and ti-6Al-4v runs were made with 40-80 downfeed passes across work with just the initial dressing at the start of the runs. The number of passes depended upon the wheel wear occurring in order to obtain 10% accuracy or better on the grinding ratios.

COOLANT - Coolants (Sulfurized oil - H-11) (Chlorinated oil - Ti-6Al-4V) were supplied by a centrifugal pump through a manifold at the wheel periphery, oil volume approximately 3 quarts/minute.

Provision was made for oil changes on each run to facilitate swarf collection and inspection. Recycling of swarf was restrained by filter collection.

A. Spindle Speed

1. Spindle speed was continuously monitored using an Electro Transducer model #3015A in conjunction with an Erie Counter model #400, set to read out once every 10 seconds. Signal to the Electro Transducer was produced by a single point steel block mounted on the end of the spindle.

B. Power Monitoring

1. A single phase of the 3 phase spindle motor was fed into a John Fluke VAW Meter model 101 and monitored during the 20th through 25th infeed passes of the total of 50 infeed passes of the grinding wheel. VAW meter was "zeroed" with machine idling so that power readings indicate the rate of work the grinding wheel does.

2. As the VAW meter is highly damped, the input to the VAW meter indicating meter was fed into a Tektronix Oscilloscope type 551 (network was employed to remove all AC current) and the oscilloscope calibrated. Peak power readings were averaged over the 20th through 25th infeed passes.

C. Vibration Testing

1. Model 545 vibration pick up of an International Research and Development Corporation model 311 vibration analyzer was mounted at the top center of the main bearing housing, the meter was continuously monitored during grinding.

2. A B&K Accelerometer type 4329 was mounted in the same relative position as the model 545 vibration pick up, on the main bearing housing. Its signal was fed into a B&K Audio Frequency Spectrometer type 2110. A complete spectro-analysis was made during grinding and the full spectrum was monitored throughout the runs.

3. B & K level Recorder type 2304 was employed to make a chart record of the spectro-analysis during grinding on original set-up.

D. Ultrasonic Vibration Measurement

1. With grinding wheel stopped the amplitude of ultrasonic vibration was measured with a National Scientific Instrument Company microscope type 4015, 600X power with a calibrated graduated reticle.

2. A B & K Accelerometer type 4329 was mounted on the spindle bracket within .005" of the end of the ultrasonic wheel hub. The output of the accelerometer was fed into the second channel of the Tektronix oscilloscope type 551 and calibrated against the NSIC type 4015 microscope. In this manner the wheel vibration was monitored on all ultrasonic runs.

E. <u>Grinding Wheel Measurement</u>

1. With Workpiece mounted in chuck and leveled, 10 grinding passes were made when using R & L wheels and 2 passes were made with I wheels, after the wheels were dressed per wheel dressing procedures outlined. Workpiece was then measured with micrometers within $\pm.0001$.

2. After dressing wheels per wheel dressing procedures, and making leveling passes on workpiece per item 1 above, wheel and hub temperatures were measured with HB engraved stem thermometer CSPLF 70° to 78° F.

3. Wheel OD was measured at 5 positions 40° apart with 5-6" or 6-7" micrometers and readings were averaged. All micrometers were read to $\pm.0001$.

4.. Wheel OD was again measured with a Sheffield Model 7 Dial Indicator snap gage, when wheel, hub, and snap gage were same temperature within $+1^{\circ}$F. (Snap gage temperature checked with permanently mounted Weston model 2261 dial thermometer). This measurement is taken at 5 points on the wheel diameter 40° apart and average diameter recorded, measurement accurate to within $\pm.00005$.

5. After completing set number of downfeed grinding passes, wheel, hub, and workpiece was allowed to cool down to original measuring temperature and again measured in accordance with above technique.

F. <u>Work Finish</u>

1. Finish on all workpieces was measured on a model 741 Profilometer manufactured by Micrometrical Manufacturing Company. A type QA profilometer Amplifier was employed. Twenty RMS readings were made, ten in the direction of grind and ten at right angles to the direction of grind. Averages of these readings are recorded in this report.

Run #: 9 Sample # 1
Ti-6Al-4V Conventional
Wheel AA60L8V40
Coolant Vantrol 5456X-75%;5456A-25%

Depth of Cut	0.001"
Cross Feed	0.050"
Table Speed	35 F P M
Wheel Speed	2000 S F P M
Grinding Ratio	23.7
Finish	33 micro in. RMS
Power	126 Watts
Magnification	3.5X

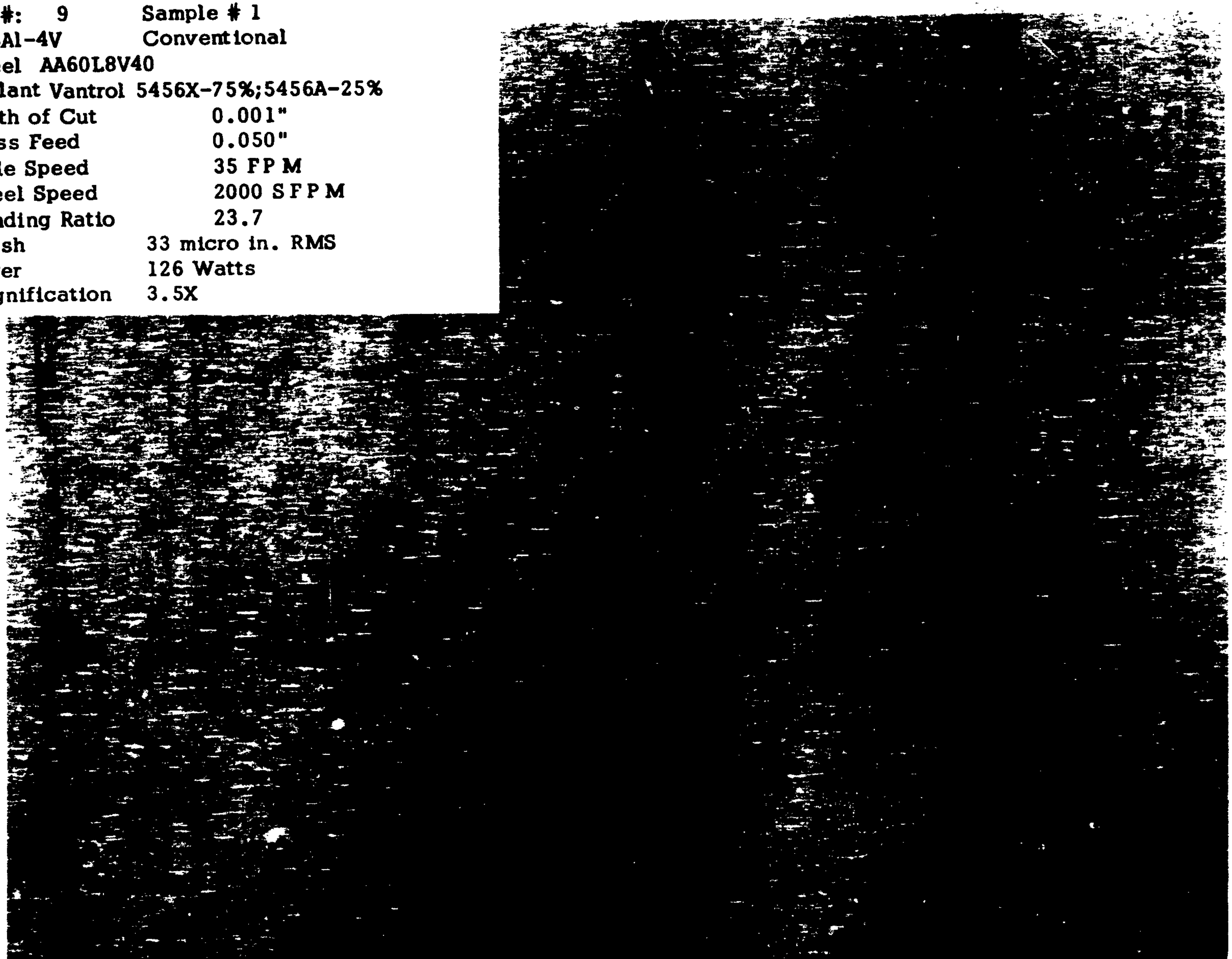


Figure 113

Run #: 10 Sample # 2
Ti-6Al-4V Ultrasonic 1 Div.
Wheel AA60L8V40
Coolant Vantrol 5456X-75%;5456A-25%

Depth of Cut	0.001"
Cross Feed	0.050"
Table Speed	35 FPM
Wheel Speed	1988 SFPM
Grinding Ratio	67.8
Finish	36 micro in. RMS
Power	72 Watts
Magnification	3.5X

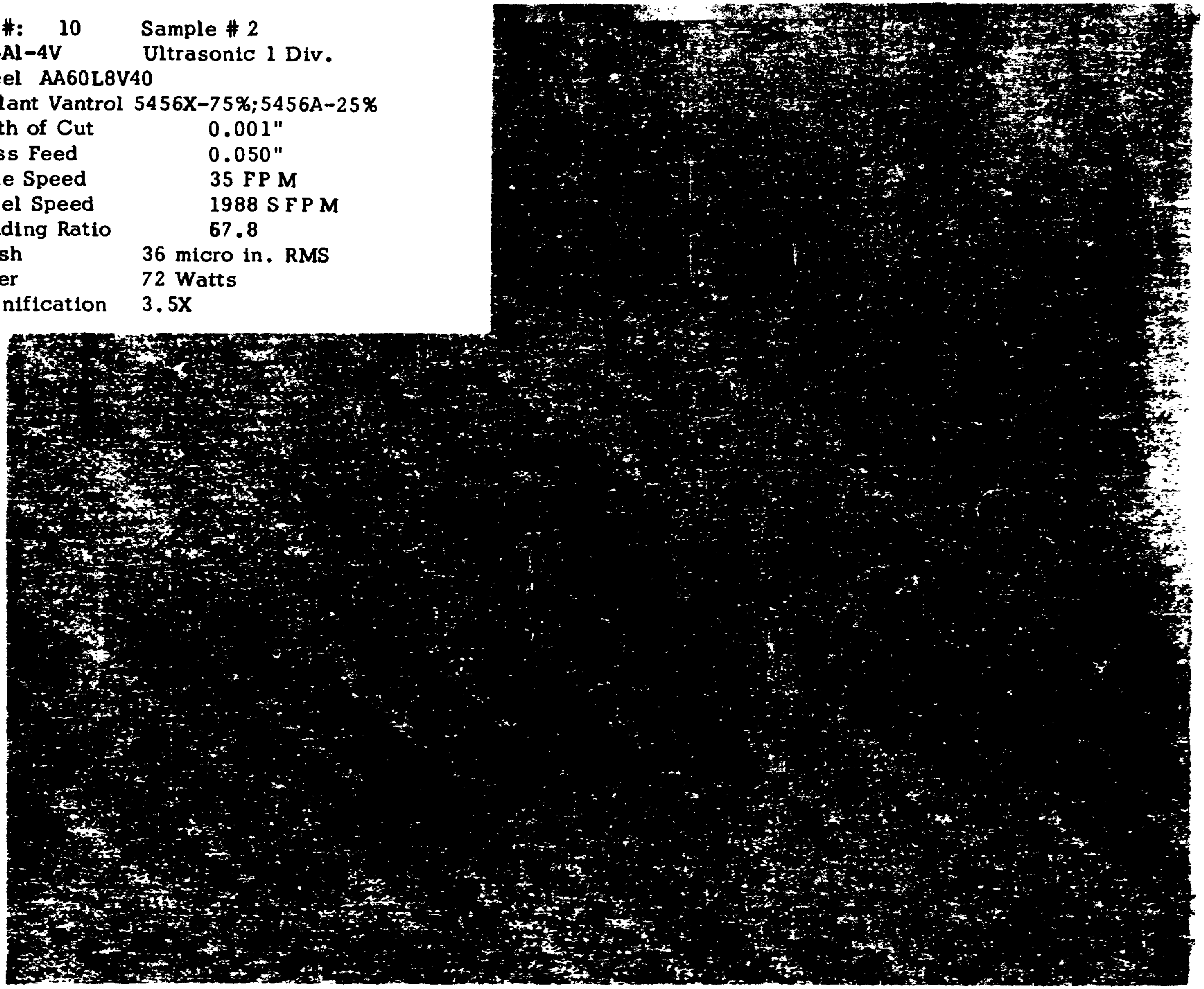


Figure 114

Run #: 11 Sample # 3
Ti-6Al-4V Ultrasonic 2 Div.
Wheel AA60L8V40
Coolant Vantrol 5456X-75%;5456A-25%

Depth of Cut	0.001"
Cross Feed	0.050"
Table Speed	35 FPM
Wheel Speed	1995 SFPM
Grinding Ratio	58.0
Finish	39 micro in. RMS
Power	49.5 Watts
Magnification	3.5X

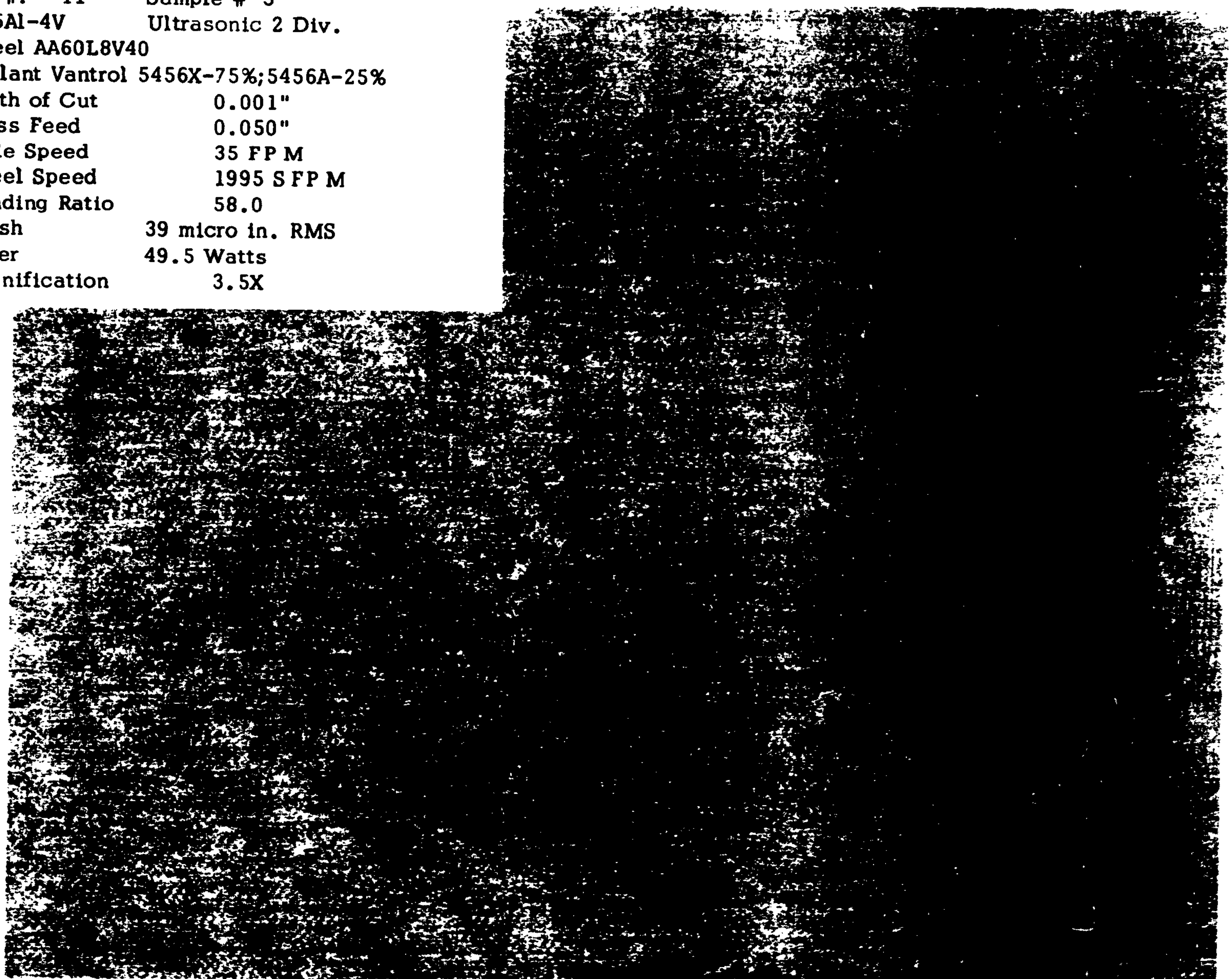
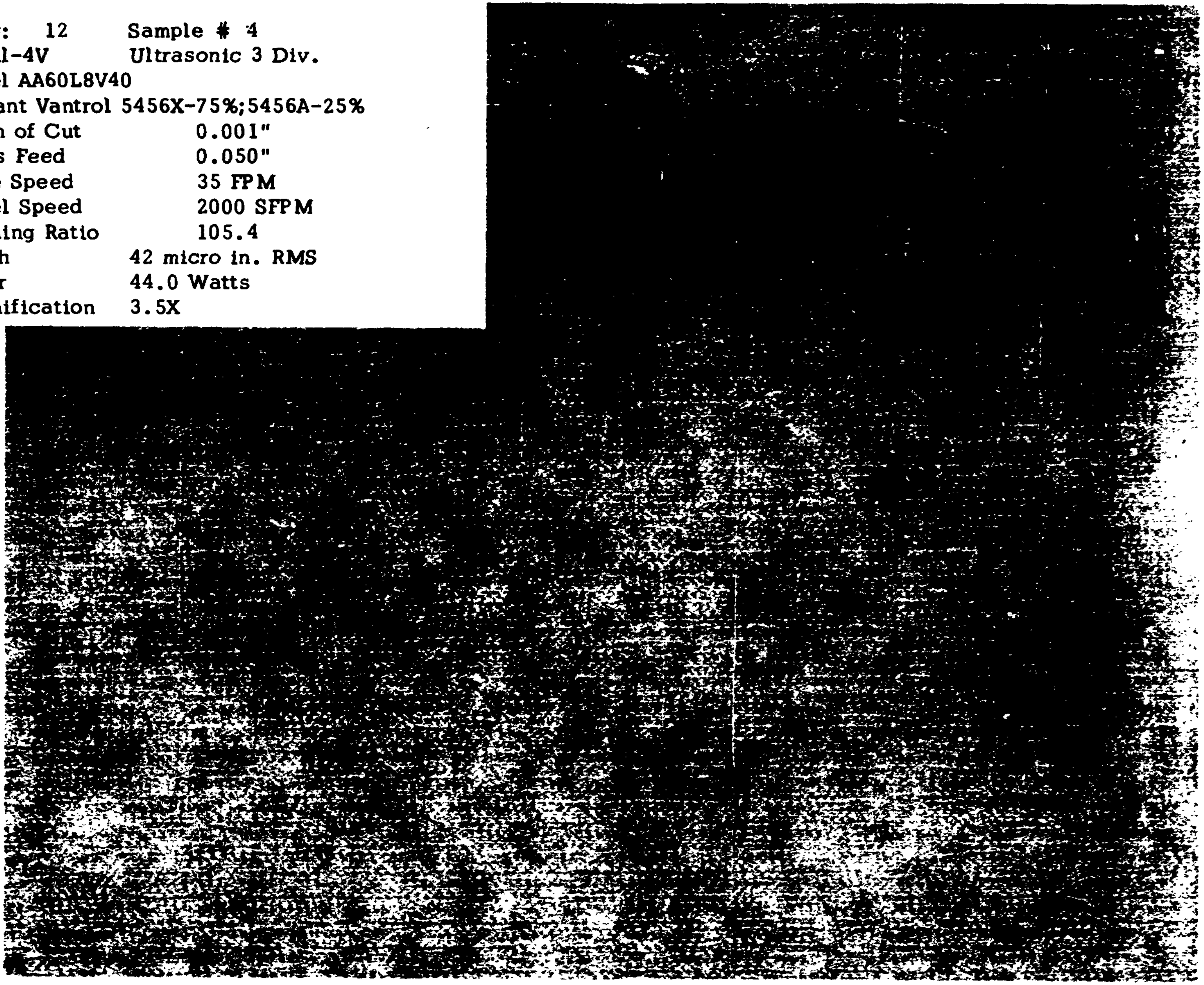


Figure 115



Run #: 12	Sample # 4	
Ti-6Al-4V	Ultrasonic 3 Div.	
Wheel AA60L8V40		
Coolant Vantrol	5456X-75%;5456A-25%	
Depth of Cut		0.001"
Cross Feed		0.050"
Table Speed		35 FPM
Wheel Speed		2000 SFPM
Grinding Ratio		105.4
Finish	42 micro in. RMS	
Power	44.0 Watts	
Magnification	3.5X	

Figure 116

Run #:	13	Sample # 8
Ti-6Al-4V		Conventional
Wheel	AA60R8V40	
Coolant Vantrol	5456X-75%;5456A-25%	
Depth of Cut		0.001"
Cross Feed		0.050"
Table Speed		35 FPM
Wheel Speed		1983 SFPM
Grinding Ratio		26.36
Finish	32 micro in. RMS	
Power	171 Watts	
Magnification	3.5X	

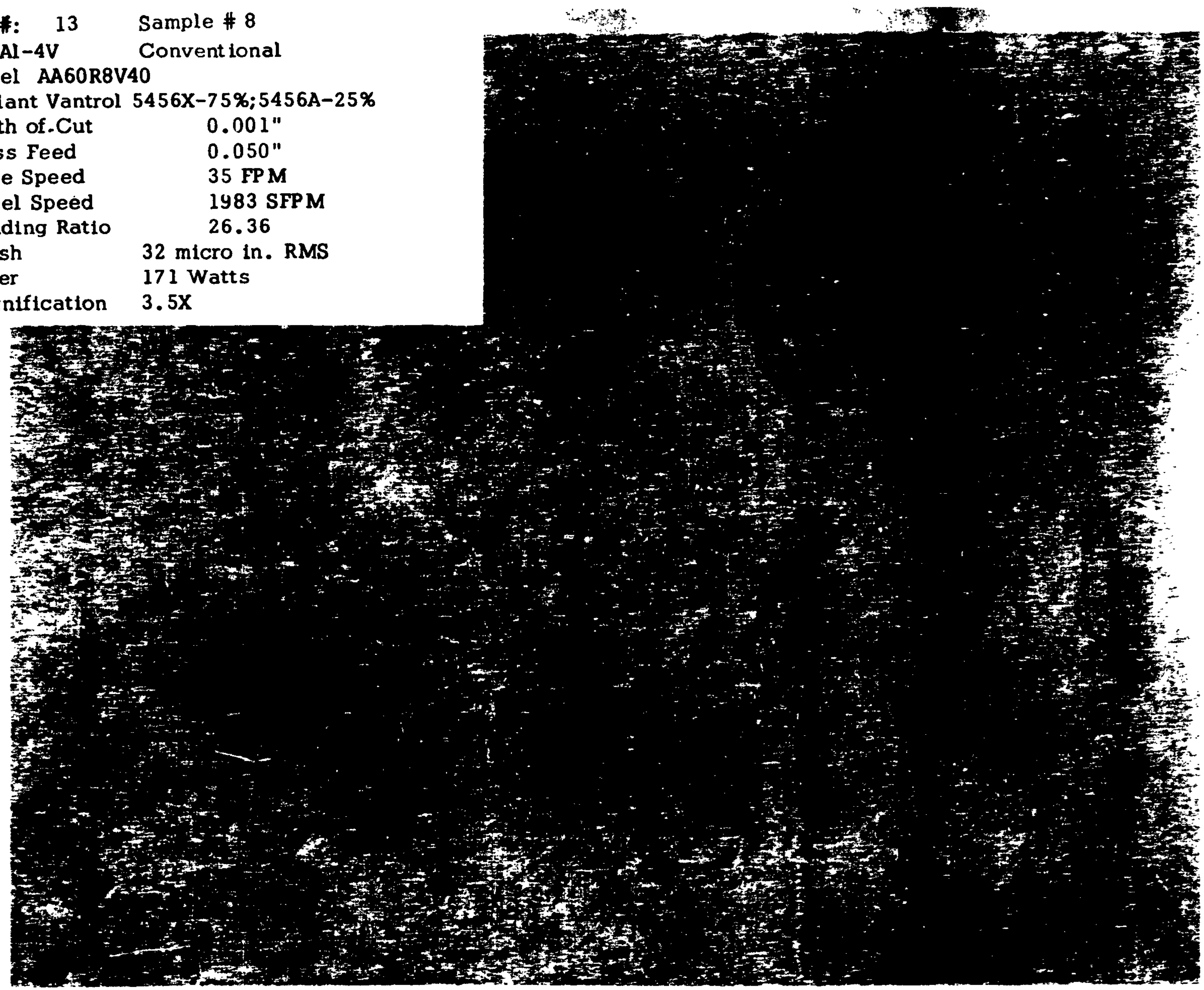


Figure 117

Run #: 14	Sample # 6
Ti-6Al-4V	Ultrasonic 1 Div.
Wheel AA60R8V40	
Coolant 5456X-75%;5456A-25% Vantrol	
Depth of Cut	0.001"
Cross Feed	0.050"
Table Speed	35 FPM
Wheel Speed	1989 SFPM
Grinding Ratio	41.7
Finish	30 micro in. RMS
Power	112.5 Watts
Magnification	3.5X

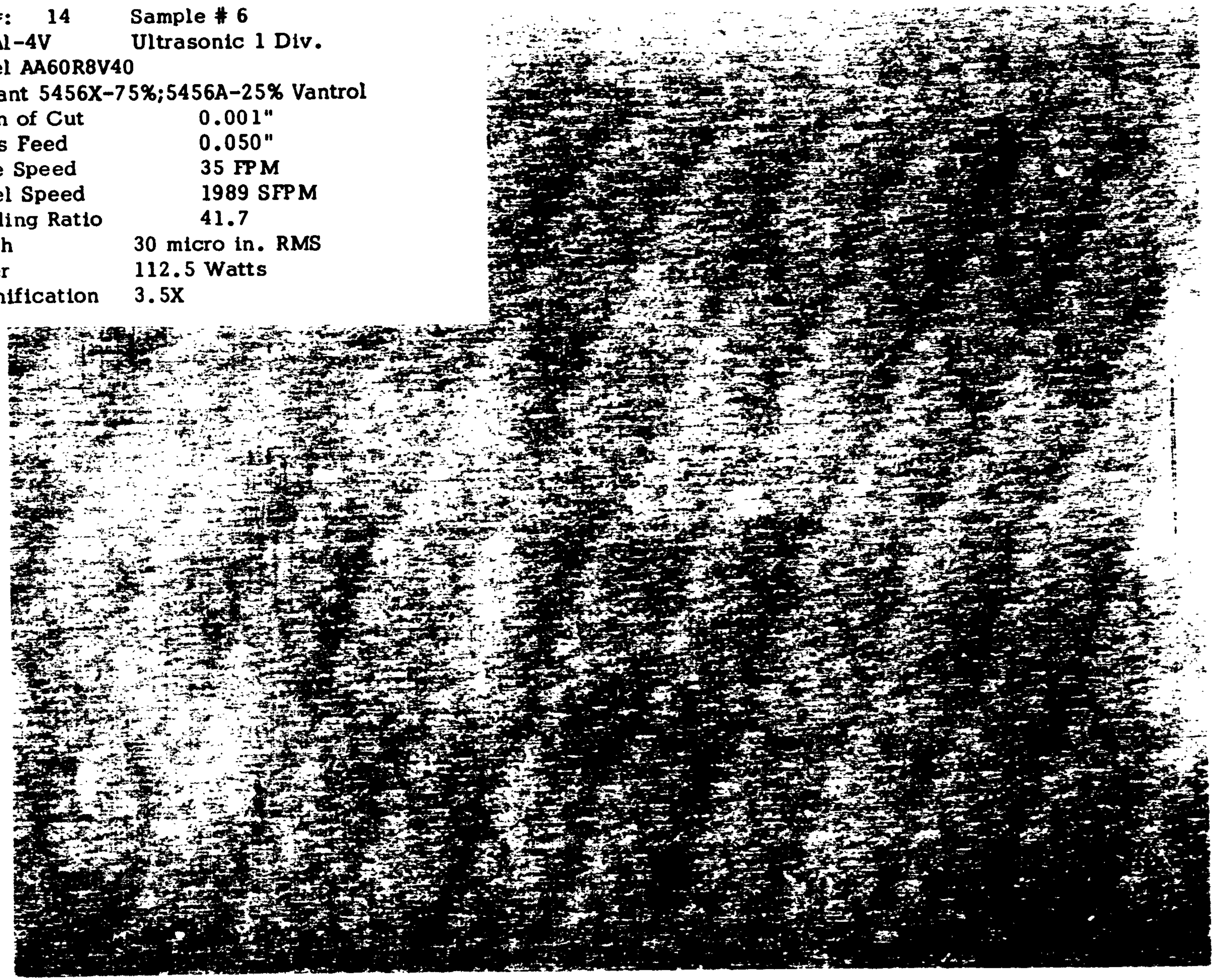
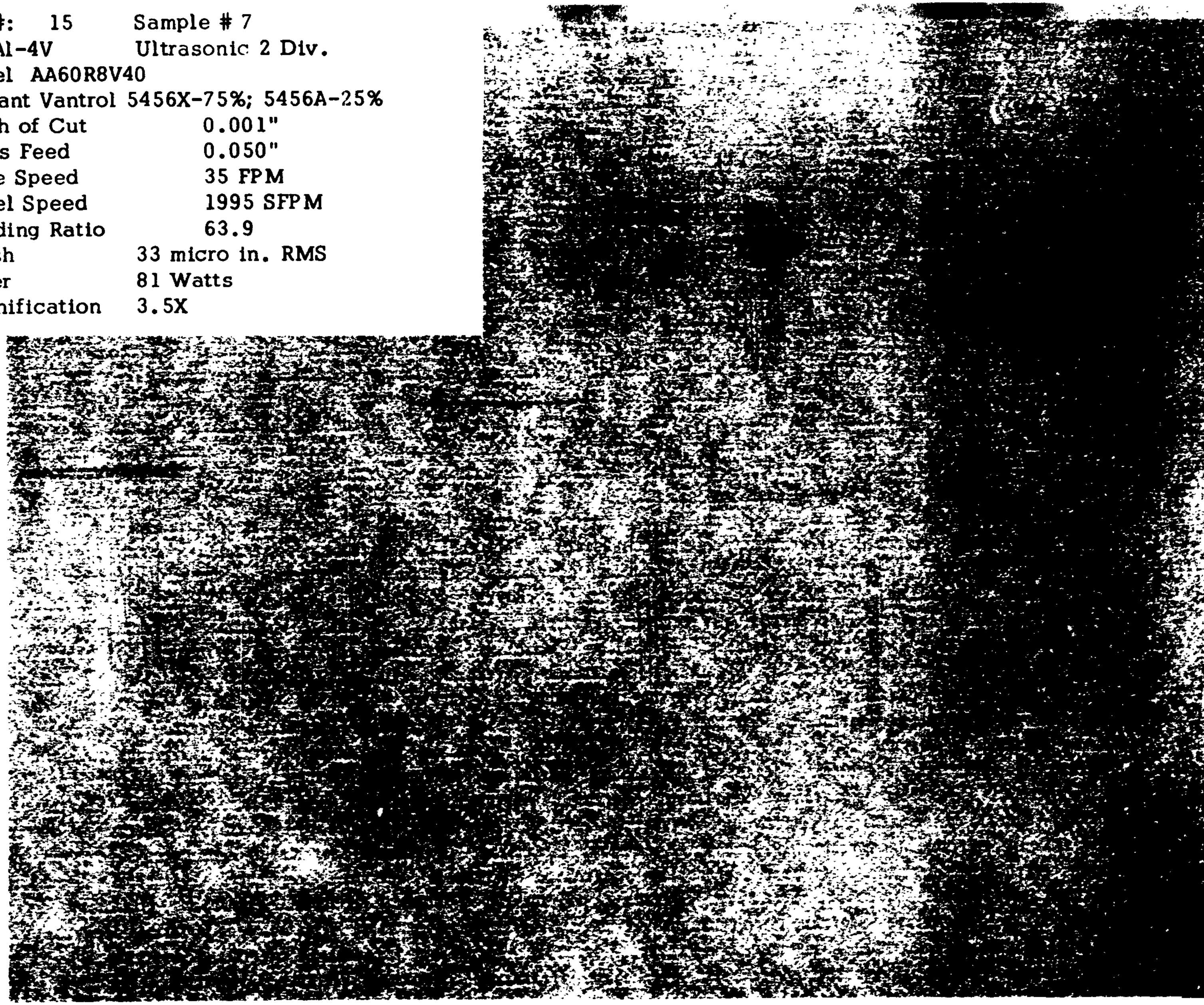


Figure 118



Run #: 15 Sample # 7
Ti-6Al-4V Ultrasonic 2 Div.
Wheel AA60R8V40
Coolant Vantrol 5456X-75%; 5456A-25%

Depth of Cut	0.001"
Cross Feed	0.050"
Table Speed	35 FPM
Wheel Speed	1995 SFPM
Grinding Ratio	63.9
Finish	33 micro in. RMS
Power	81 Watts
Magnification	3.5X

Figure 119

Run #: 16 Sample # 5
Ti-6Al-4V Ultrasonic 3 Div.
Wheel AA60R8V40
Coolant Vantrol 5456X-75%; 5456A-25%

Depth of Cut	0.001"
Cross Feed	0.050"
Table Speed	35 FPM
Wheel Speed	1998 SFPM
Grinding Ratio	69.8
Finish	35 micro in. RMS
Power	61.5 Watts
Magnification	3.5X

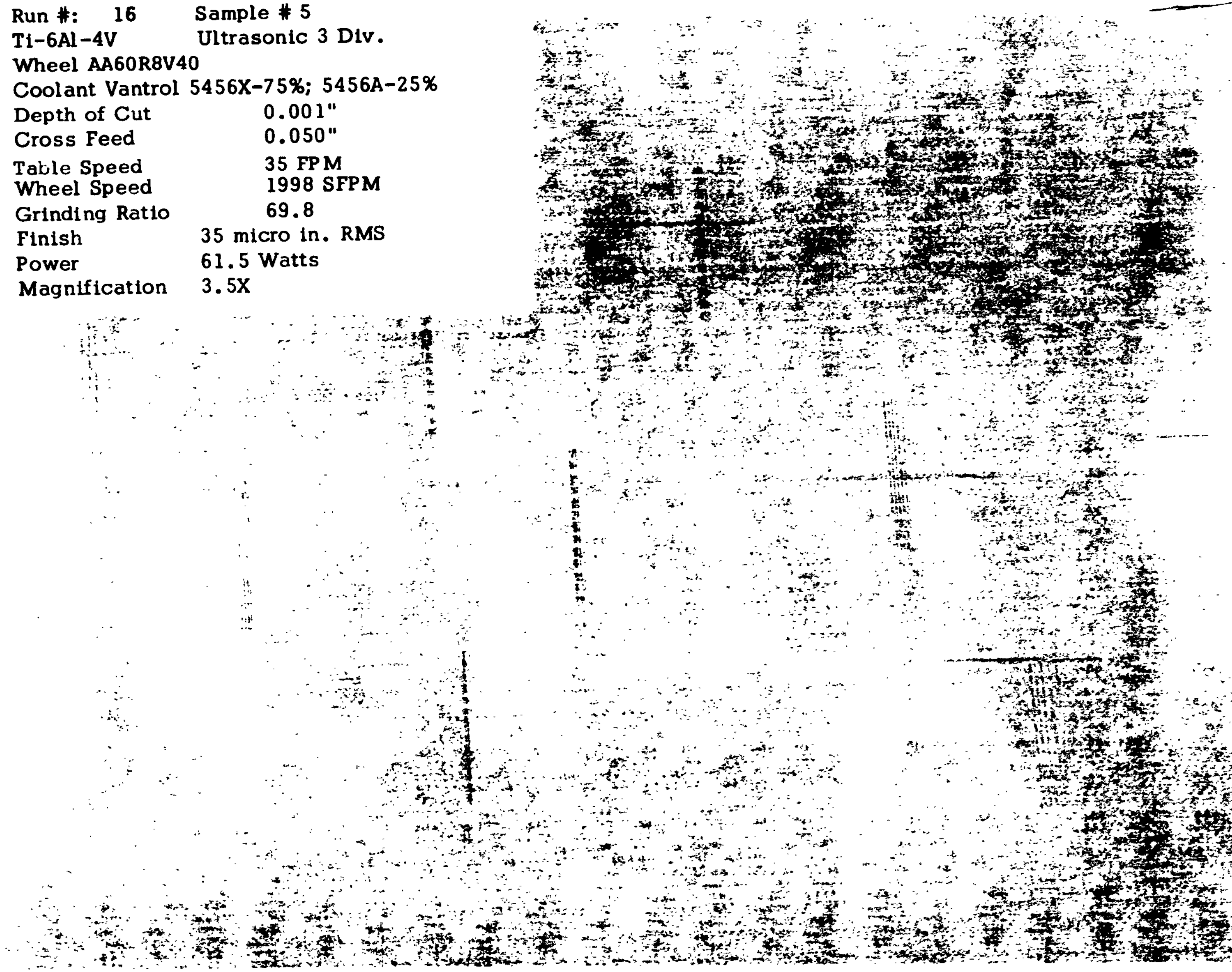


Figure 120

Run #: 8 Sample # 8
H-11 Ultrasonic 3 Div.
Wheel AA60R8V40

Coolant	Sultran 176M
Depth of Cut	0.001"
Cross Feed	0.050"
Table Speed	35 FP M
Wheel Speed	4951 S F P M
Grinding Ratio	426
Finish	38 micro in. RMS
Power	68 Watts
Magnification	3.5X

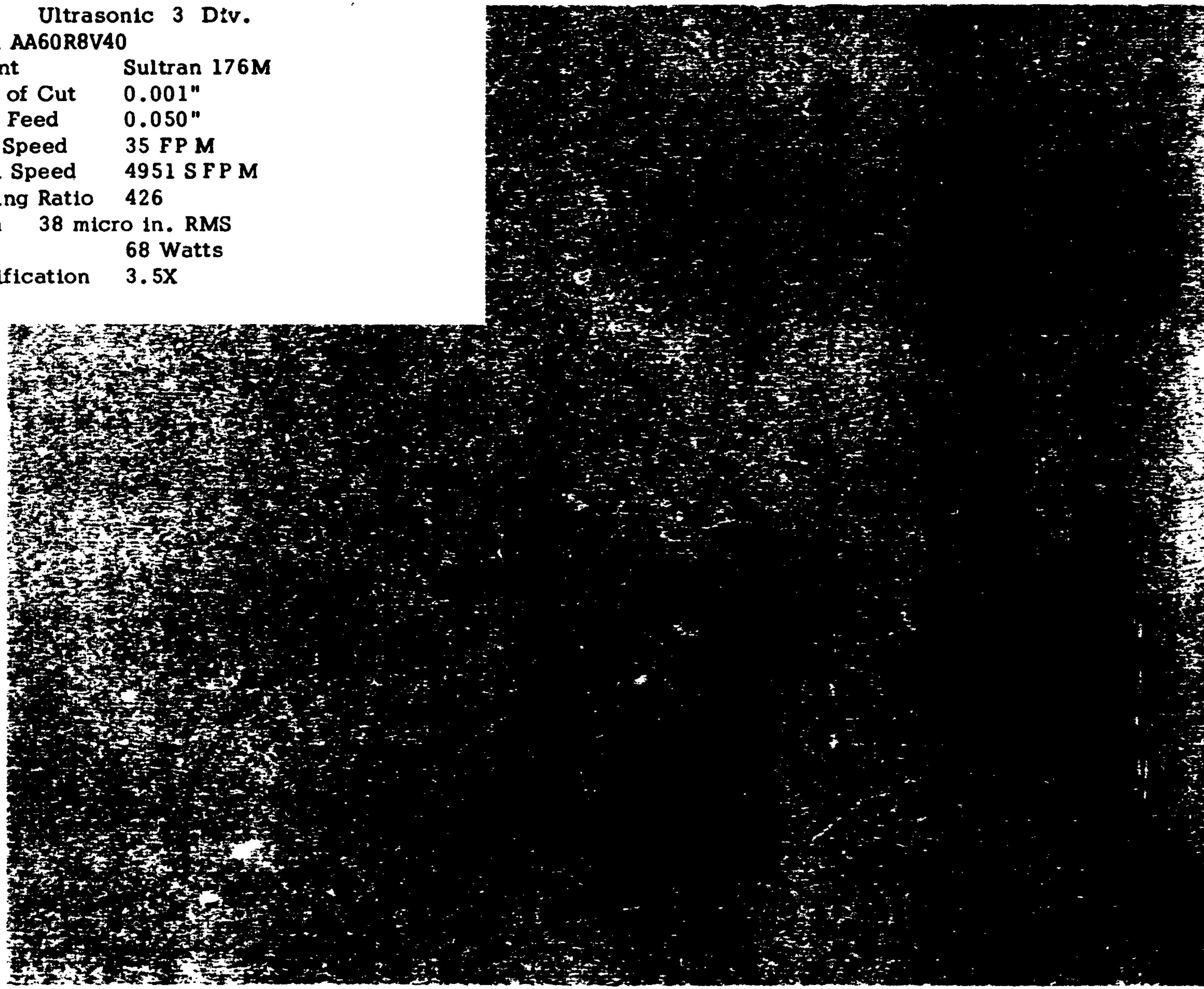
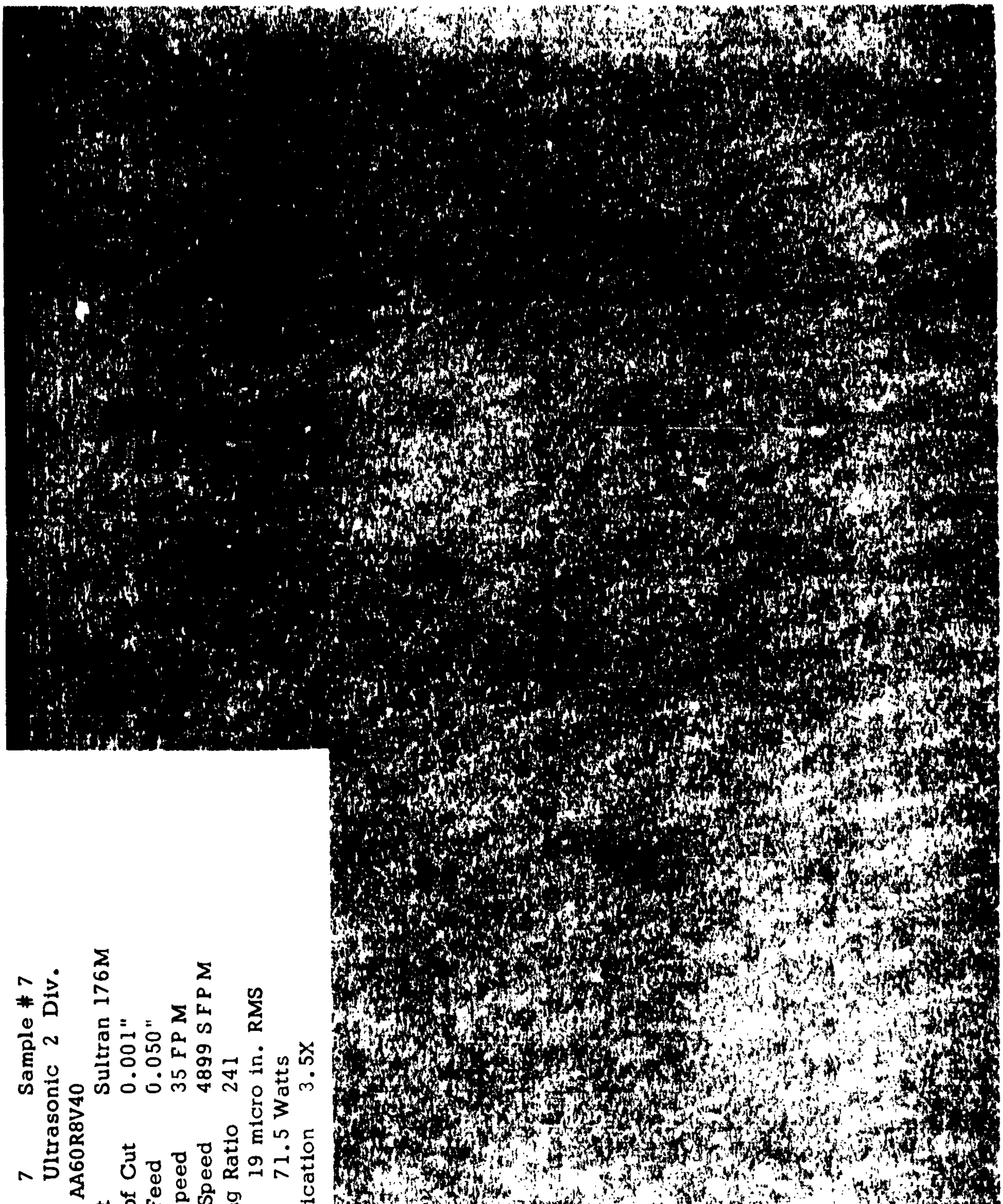


Figure 121



Run #: 7 Sample # 7
H-11 Ultrasonic 2 Div.
Wheel AA60R8V40
Coolant Sultran 176M
Depth of Cut 0.001"
Cross Feed 0.050"
Table Speed 35 F P M
Wheel Speed 4899 S F P M
Grinding Ratio 241
Finish 19 micro in. RMS
Power 71.5 Watts
Magnification 3.5X

Figure 122

Run #: 6 Sample # 6
H-11 Ultrasonic 1 Div.
Wheel AA60R8V40
Coolant Sultran 176M
Depth of Cut 0.001"
Cross Feed 0.050"
Table Speed 35 FP M
Wheel Speed 4905 S FP M
Grinding Ratio 173
Finish 18 micro in. RMS
Power 81.9 Watts
Magnification 3.5X

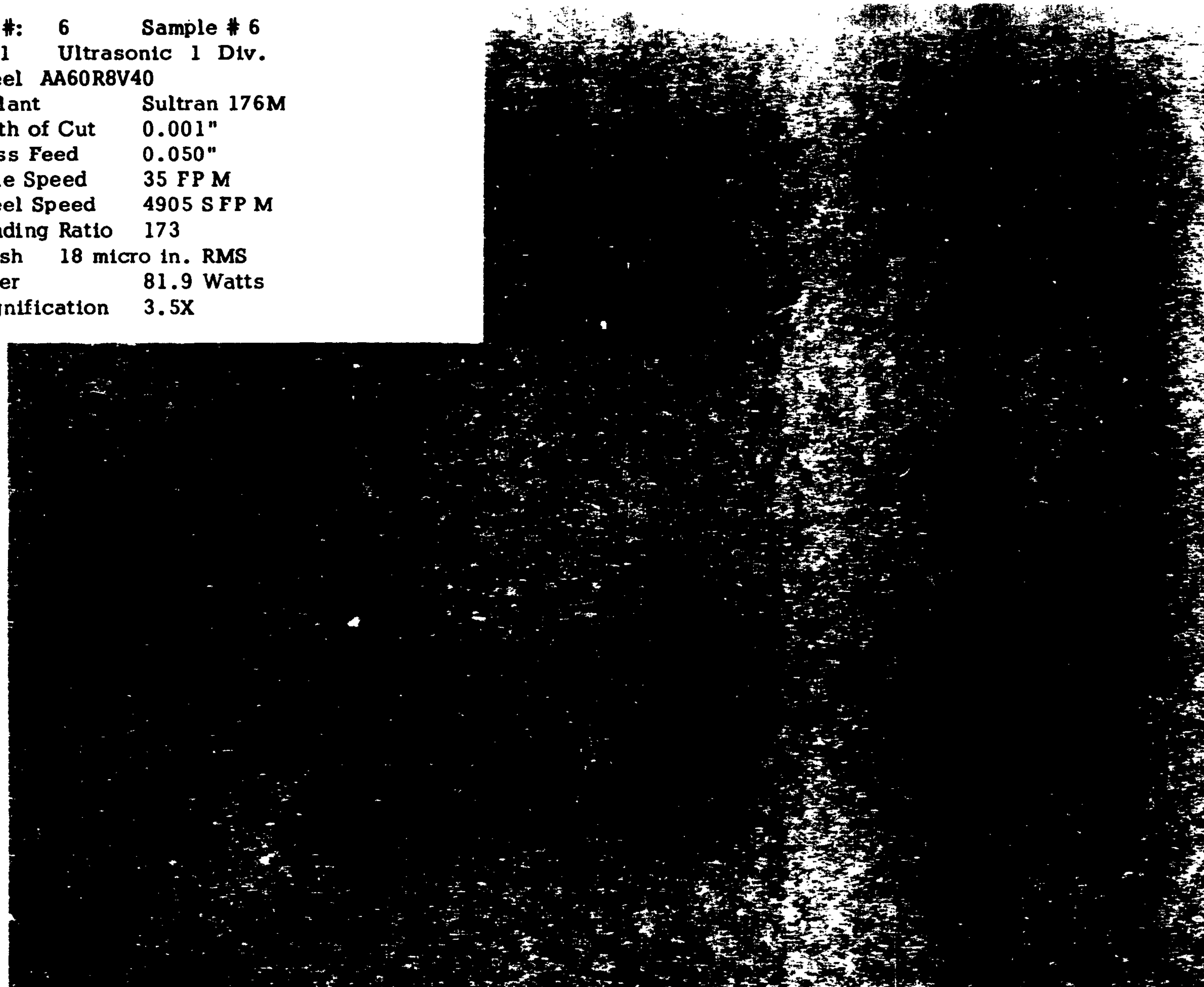


Figure 123

Run #: 5	Sample # 5
H-11	Conventional
Wheel AA60R8V40	
Coolant	Sultran 176M
Depth of Cut	0.001"
Cross Feed	0.050"
Table Speed	35 FPM
Wheel Speed	4947 SFPM
Grinding Ratio	69.5
Finish 19 micro in. RMS	
Power	105 Watts
Magnification	3.5X

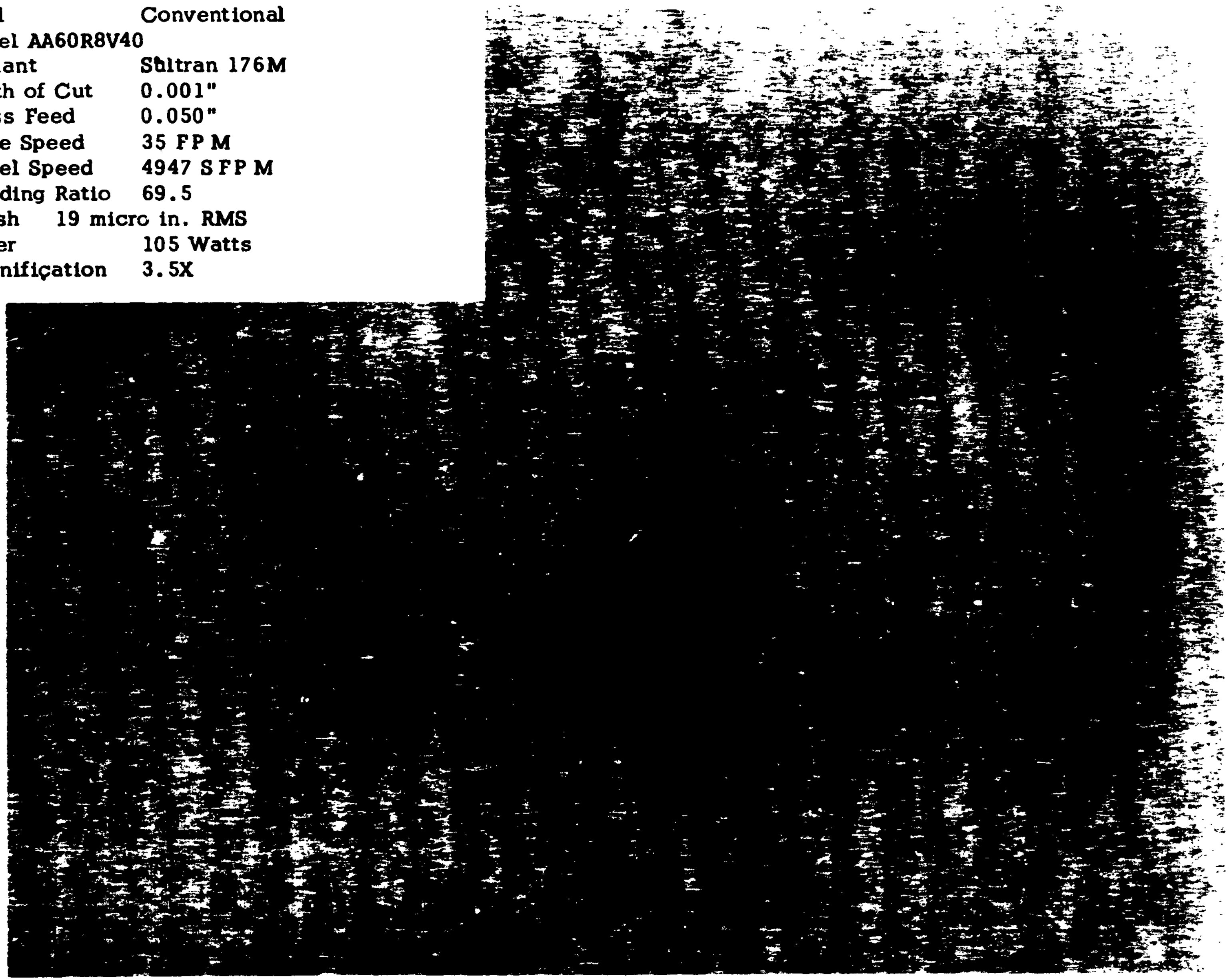


Figure 124

Run #: 4 Sample # 4
H-11 Ultrasonic 1/4 Div.
Wheel AA46I8V40

Coolant	Sultran 176M
Depth of Cut	0.001"
Cross Feed	0.050"
Table Speed	35 FPM
Wheel Speed	
Grinding Ratio	309
Finish	20 micro in. RMS
Power	72.8 Watts
Magnification	3.5X

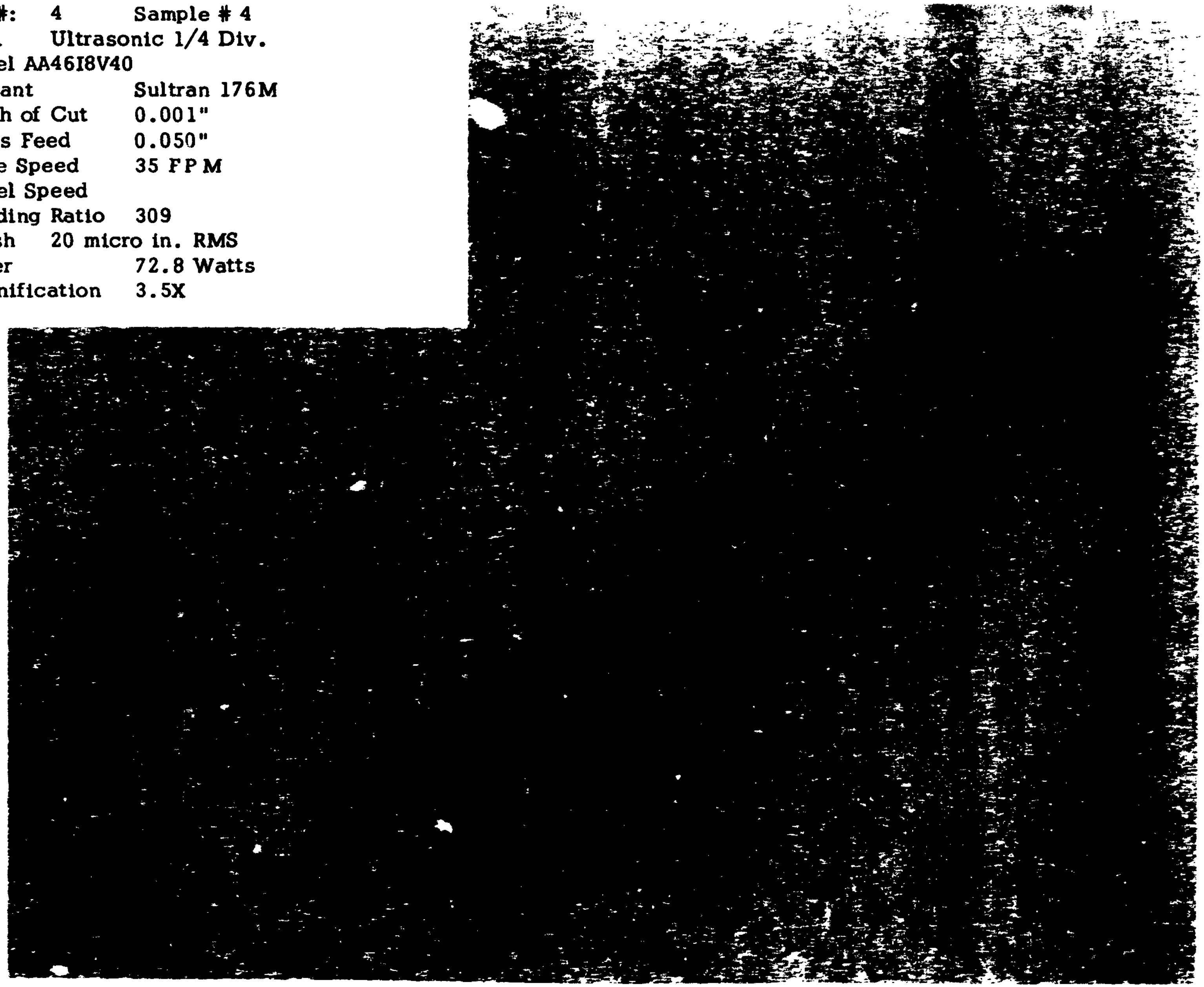
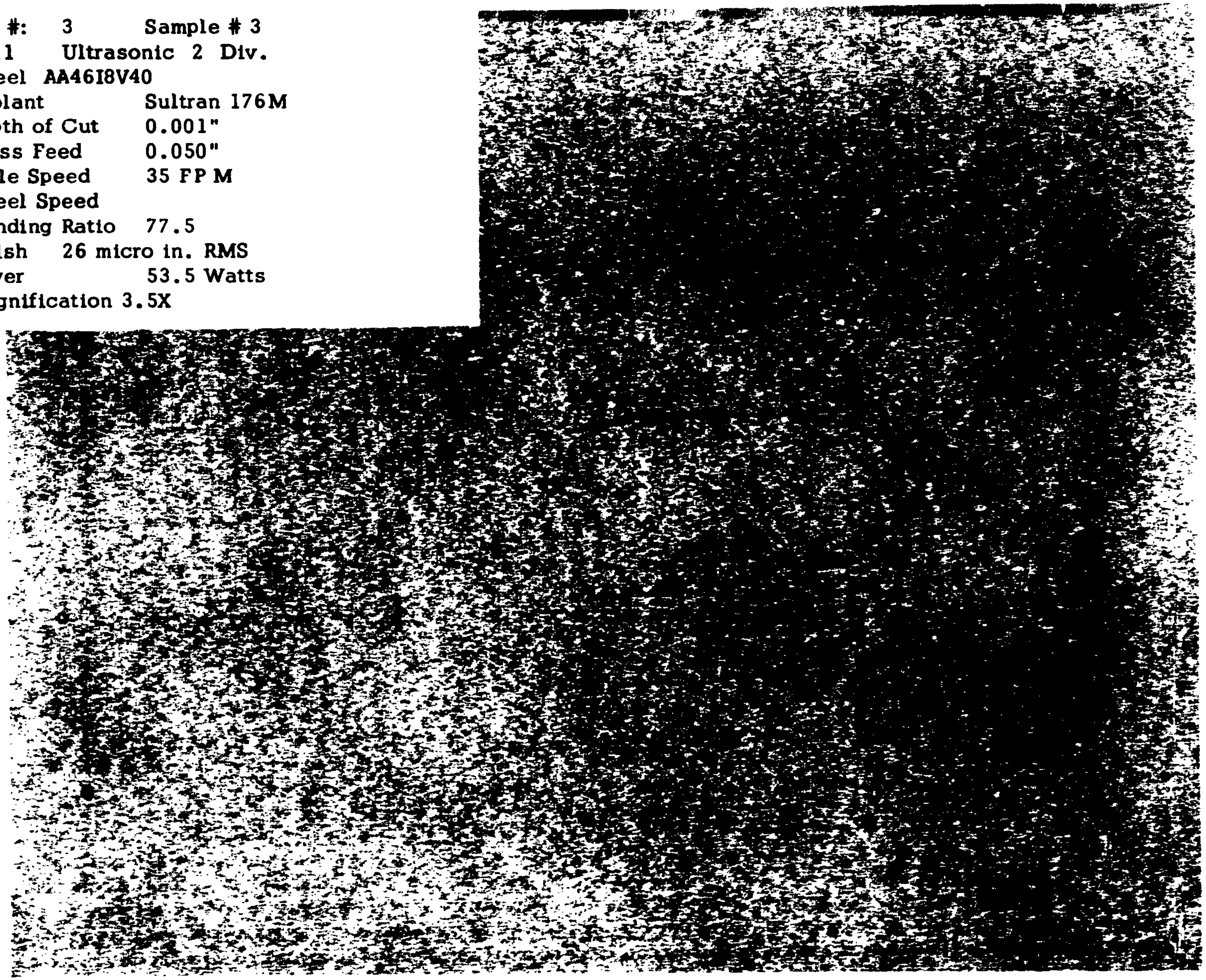


Figure 125



Run #: 3 Sample # 3
H-11 Ultrasonic 2 Div.
Wheel AA46I8V40
Coolant Sultran 176M
Depth of Cut 0.001"
Cross Feed 0.050"
Table Speed 35 FP M
Wheel Speed
Grinding Ratio 77.5
Finish 26 micro in. RMS
Power 53.5 Watts
Magnification 3.5X

Figure 126

Run #: 2 Sample # 2
H-11 Ultrasonic 1 Div.
Wheel AA46I8V40

Coolant	Sultran 176M
Depth of Cut	0.001"
Cross Feed	0.050"
Table Speed	35 FPM
Wheel Speed	4870 SFPM
Grinding Ratio	85
Finish	23 micro in. RMS
Power	68 Watts
Magnification	3.5X

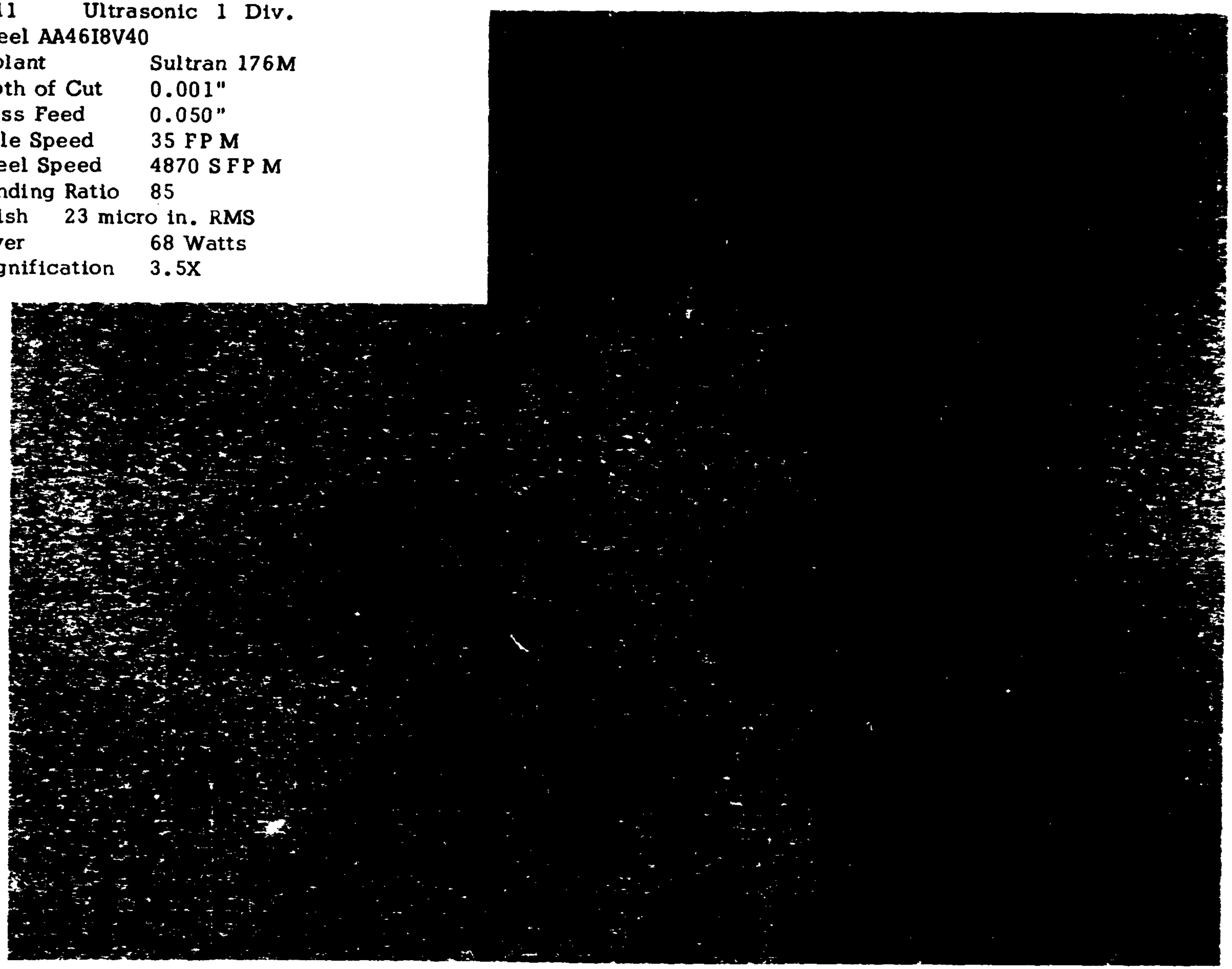


Figure 127

Run #: 1	Sample #1
H-11	Conventional
Wheel AA46I8V40	
Coolant	Sultran 176M
Depth of Cut	0.001"
Cross Feed	0.050"
Table Speed	35 FPM
Wheel Speed	4876 SFPM
Grinding Ratio	144
Finish	17 micro in. RMS
Power	85 Watts
Magnification	3.5X

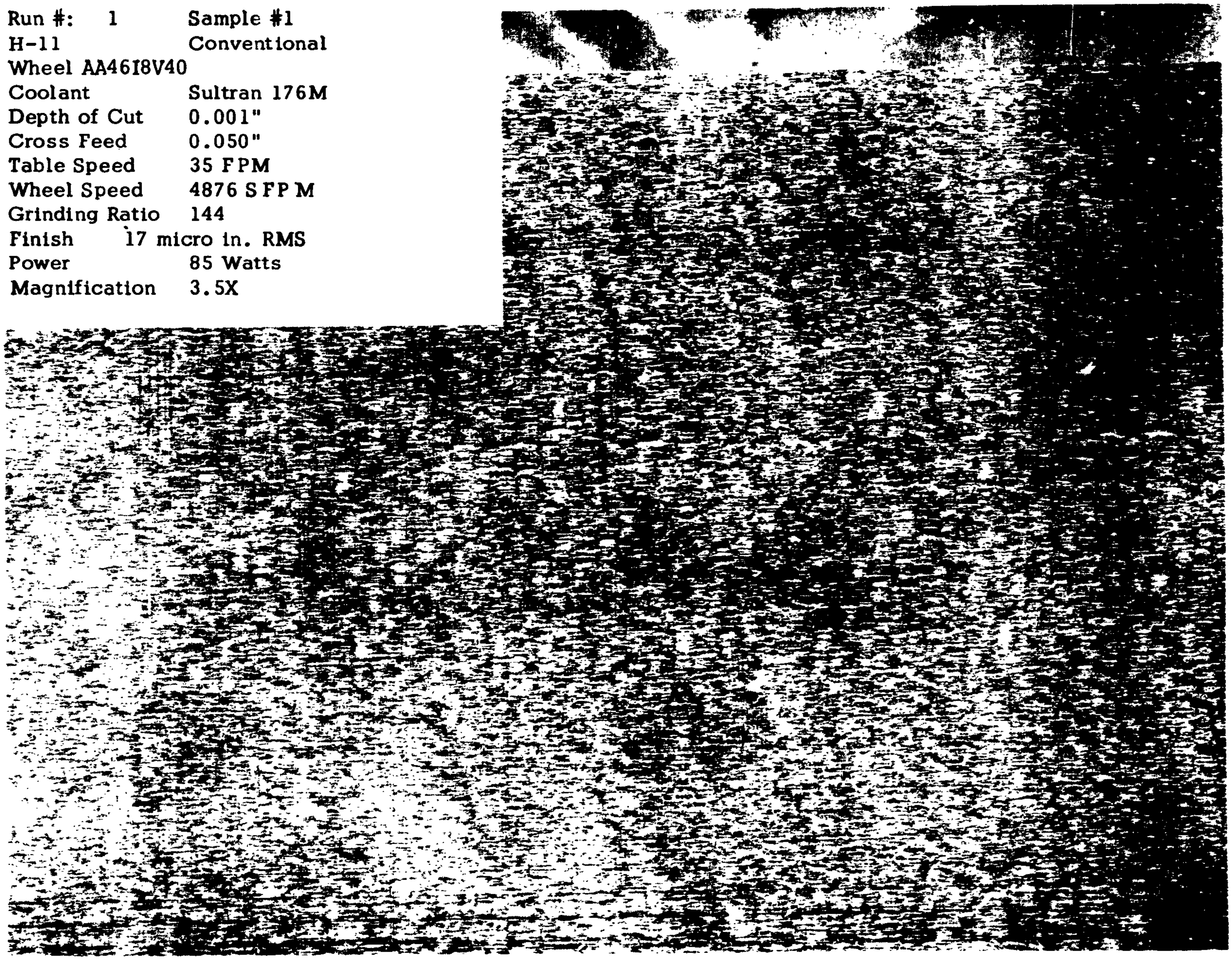


Figure 128

MATERIAL H-11 DATE May 22, 1961

RUN #: 1 SAMPLE # 1 TYPE Conventional

Wheel AA46 I8V40

Downfeed 0.001"

Crossfeed 0.050"

Spindle RPM 2778

SFPM 4876

Table Speed 35 FPM

Coolant Sultran 176M

Spindle vibration as measured from Bearing Journal 0.0001" - 0.0003"

Volume of work removed 0.320 in^3

(d_1) Wheel diameter before 6.70473 ± .00005"

(d_2) Wheel diameter after 6.70431 ± .00005"

Total number of passes 40

Part dimensions 2 x 4 x 1/2

Profilometer Used 17 across; 7 with Micrometric 741; QA Amplifier

Part Hardness After 672 ± 16 Vickers

Wheel condition after dirty, unglazed, sharp edges

Wheel dressing used diamond* - see under wheel dressing

Average Relative Spindle Power 85 Watts

$$\text{Grinding Ratio} = \frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} = 144$$

B.& K. Spectrometer:
Meter 9.8 MV Av. RMS - Fast Meter
Meter Range 10 MV
Meter Range Multiplier X 1.0
Filter Linear
Accelerometer B.& K. #41369 - 11.8MV/G

Comments on run Sparking heavy; sounds good

Figure 129

MATERIAL H-11 DATE May 25, 1961

RUN 2 SAMPLE 2 TYPE Ultrasonic 1 div. (50×10^{-6} in.)

Wheel AA46I8V40

Downfeed 0.001"

Crossfeed 0.050"

Spindle RPM 2826

SFPM of Wheel 4870

Table Speed 35 FPM

Coolant Sultran 176M

Spindle vibration as measured from Bearing Journal 0.0002" - 0.0004"

(d_1) Wheel diameter before 6.58403 ± .00005"

(d_2) Wheel diameter after 6.58329 ± .00005"

Total number of passes 40

Part dimensions 2 X 4 X 1/2

Profilometer Used 23 across; 11 with Micrometric 741; QA amplifier

Part Hardness After 628 ± 15 Vickers

Wheel Condition After Clean, sharp, no glaze

Wheel Dressing Used diamond* - see under wheel dressing

Volume of work removed 0.325 in.^{3}

Average Relative Spindle Power 68 ± 5 Watts

$$\text{Grinding Ratio} = \frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} = 85$$

B. & K. Spectrometer:

Meter 23 MV Av. RMS - Fast Meter

Meter Range 100 M V

Meter Range Multiplier X 1.0

Filter Linear

Accelerometer B. & K. #41369 ; 11.8MV/G

Comments on Run Sparking medium; sounds good

Figure 130

MATERIAL H-11 DATE May 26, 1961

RUN 3 SAMPLE 3 TYPE Ultrasonic 2 div. (100 X 10^{-6} in.)

Wheel AA46I8V40

(d_1) Wheel diameter before 6.56657 ± .00005"

Downfeed 0.001"

(d_2) Wheel diameter after 6.56576 ± .00005"

Crossfeed 0.050"

Total number of passes 40

Spindle RPM 2826

Part dimensions 2 X 4 X 1/2

SFPM of Wheel

Profilometer Used 26 across, 12 with Micrometric 741:OA amplifier

Table Speed 35 FPM

Part Hardness After 649 ± 11 Vickers

Coolant Sultran 176 M

Wheel Condition After Clean, clear, sharp

Spindle vibration as measured from Bearing Journal 0.0002" - 0.0004"

Wheel Dressing Used diamond* see under wheel dressing

Volume of work removed 0.320 in.^{3}

Average Relative Spindle Power 53.5 Watts ± 5

$$\text{Grinding Ratio} = \frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} = 77.5$$

B. & K. Spectrometer: Meter 32 MV Av. RMS - Fast Meter

Meter Range 100 MV

Meter Range Multiplier X 1.0

Filter Linear

Accelerometer B. & K.# 41369 - 11.8 MV/G

Comments on Run Very slight sparking; grinding noise barely detectable

Figure 131

MATERIAL H-11 DATE May , 1961

RUN 4 SAMPLE 4 TYPE Ultrasonic 1/4 div. (12.5 X 10^{-6} in.)

Wheel AA46 I8V40

(d1) Wheel diameter before 6.55001 ± .00005"

Downfeed 0.001"

(d2) Wheel diameter after 6.54978 ± .00005"

Crossfeed 0.050"

Total number of passes 40

Spindle RPM 2802

Part dimensions 2 X 4 X 1/2

SFPM of wheel

Profilometer used 20 across; 7 with Micrometric 741; QA amplifier

Table Speed 35 FPM

Part Hardness after 649 ± 10 Vickers

Coolant Sultran 176 M

Wheel condition after dirty, sharp and clear

Spindle vibration as measured from Bearing journal 0.0002" - .0004"

Wheel dressing used diamond* - see dressing method

Volume of work removed 0.318 in^3

Average Relative Spindle Power 72.8 Watts ± 5

Grinding Ratio = $\frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}}$ = 309

B. & K. Spectrometer

Meter Unrecorded MV Av. RMS - Fast Meter

Meter Range 10 MV

Meter Range Multiplier X 1.0

Filter Linear

Accelerometer B. & K. #41369 - 11.8 MV/G

Comments on run light sparking, sounds good

Figure 132

MATERIAL H-11 DATE May 5, 1961

RUN 5 SAMPLE 5 TYPE Conventional

Wheel AA60R8V40

Downfeed 0.001"

Crossfeed 0.050"

Spindle RPM 2813

SFPM of Wheel 4947

Table Speed 35 FPM

Coolant Sultran 176 M

Spindle vibration as measured from Bearing Journal 0.0001" - .0003"

(d_1) Wheel diameter before 6.71804 ± .00005"

(d_2) Wheel diameter after 6.71623 ± .00005"

Total number of passes 80 (one pass at .002" in error

Part dimensions 2 X 4 X 1/2

Profilometer Used 19 across; 6 with Micrometric 741:OA amplifier

Part Hardness After 672 ± 12 Vickers

Wheel Condition After dirty, glazed but no loading

Wheel Dressing Used diamond* - see under wheel dressing

Volume of work removed 0.660 in.^{3}

Average Relative Spindle Power 105 Watts ± 5

$$\text{Grinding Ratio} = \frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} = 69.5$$

B. & K. Spectrometer: Meter 8.5 MV Av. RMS - Fast Meter

Meter Range 10 MV

Meter Range Multiplier X1.0

Filter Linear

Accelerometer B. & K. #41369 - 11.8MV/G

Comments on Run Sparking heavy, sounds good

Figure 133

MATERIAL H-11 DATE May 11, 1961

RUN 6 SAMPLE 6 TYPE Ultrasonic 1 div. (50 X 10^{-6} in.)

Wheel AA60R8V40

(d_1) Wheel diameter before 6.65981 ± .00005"

Downfeed 0.001"

(d_2) Wheel diameter after 6.65910 ± .00005"

Crossfeed 0.050"

Total number of passes 80

Spindle RPM 2813

Part dimensions 2 X 4 X 1/2

SFPM of Wheel 4905

Profilometer Used 18 across; 8 with Micrometric:QA amplifier

Table Speed 35 F P M

Part Hardness After 651 ± 11 Vickers

Coolant Sultran 176 M

Wheel Condition After Sharp, clean, v.s. glaze

Spindle vibration as measured from Bearing Journal .0002" - 0.0004"

Wheel Dressing Used diamond* - see under wheel dressing

Volume of work removed 0.642 in.^{3}

Average Relative Spindle Power 81.9 Watts ± 5

Grinding Ratio = $\frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}}$ = 173

B. & K. Spectrometer: Meter 34 MV Av. RMS - Fast Meter

Meter Range 100 MV

Meter Range Multiplier X 1.0

Filter Linear

Accelerometer B. & K. #41369 - 11.8 MV/G

Comments on Run Little or no sparking, sounds good

Figure 124

MATERIAL H-11 DATE May 12, 1961

RUN 7 SAMPLE 7 TYPE Ultrasonic 2 div. (100 X 10^{-6} in.)

Wheel AA60R8V40

Downfeed 0.001"

Crossfeed 0.050"

Spindle RPM 2813

SFPM of Wheel 4899

Table Speed 35 F P M

Coolant Sultran 176M

Spindle vibration as measured from Bearing Journal 0.0002" - 0.0006"

(d_1) Wheel diameter before 6.65204" ± .00005"

(d_2) Wheel diameter after 6.65153" ± .00005"

Total number of passes 80

Part dimensions 2 X 4 X 1/2

Profilometer Used 19 across, 10 with Micrometric 741; QA amplifier

Part Hardness After 660 ± 12 Vickers

Wheel Condition After Sharp, no glaze, clean

Wheel Dressing Used diamond* - see under wheel dressing

Volume of work removed 0.642 in.^{3}

Average Relative Spindle Power 71.5 Watts ± 5

Grinding Ratio = $\frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}}$ = 241

B. & K. Spectrometer: Meter 24 MV Av. RMS - Fast Meter

Meter Range 100 MV

Meter Range Multiplier X 1.0

Filter Linear

Accelerometer B. & K. # 41369 - 11.8 MV/G

Comments on Run No sparking - sound of grinding difficult to hear

Figure 135

MATERIAL H-11 DATE May 8, 1961

RUN 8 SAMPLE 8 TYPE Ultrasonic 3 div. (150 X 10^{-6} in.)

Wheel AA60R8V40

(d_1) Wheel diameter before 6.70659 ± .00005"

Downfeed 0.001"

(d_2) Wheel diameter after 6.70629 ± .00005"

Crossfeed 0.050"

Total number of passes 84

Spindle RPM 2820

Part dimensions 2 X 4 X 1/2

SFPM of Wheel 4951

Profilometer Used 38 across; 13 with Micrometric 741;QA amplifier

Table Speed 35 FPM

Part Hardness After 672 ± 12 Vickers

Coolant Sultran 176M

Wheel Condition After clean, sharp, no loading

Spindle vibration as measured from Bearing Journal 0.0001" - 0.0003"

Wheel Dressing Used diamond * - see under wheel dressing

Volume of work removed 0.674 in.^{3}

Average Relative Spindle Power 68 Watts ± 5

$$\text{Grinding Ratio} = \frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} = 426$$

B. & K. Spectrometer: Meter 40-78 MV Av. RMS - Fast Meter

Meter Range 100 MV

Meter Range Multiplier X 1.0

Filter Linear

Accelerometer B. & K.# 41369 - 11.8 MV/G

Comments on Run No sparking - no grinding noise - quiet A. C. M.

Figure 136

MATERIAL Ti-6Al-4V DATE May 18, 1961

RUN 9 SAMPLE 1 TYPE Conventional

Wheel AA60L8V40

Downfeed 0.001"

Crossfeed 0.050"

Spindle RPM 1314

SFPM of Wheel 2000

Table Speed 35 F P M

Coolant Vantrol 5456X-75%; 5456A-25%

Spindle vibration as measured from Bearing Journal 0.0002"

(d_1) Wheel diameter before 5.81406 ± .00005"

(d_2) Wheel diameter after 5.81112 ± .00005"

Total number of passes 40

Part dimensions 2 X 4 X 1/2

Profilometer Used Micrometric 741; QA amplifier 33 across, 16 with

Part Hardness After 369 ± 7 Vickers

Wheel Condition After dirty, edges sharp, glazed slightly load

Wheel Dressing Used diamond* - See under wheel dressing

Volume of work removed 0.315 in.^{3}

Average Relative Spindle Power 126 Watts ± 5

$$\text{Grinding Ratio} = \frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} = 23.7 \pm 2\%$$

B. & K. Spectrometer: Meter 5.5 MV Av. RMS - Fast Meter

Meter Range 10 MV

Meter Range Multiplier X 1.0

Filter Linear

Accelerometer B. & K. # 41369 - 11.8 MV/G

Comments on Run Some sparking, sounds good - noisy toward end

Figure 137

MATERIAL Ti-6Al-4V DATE May 19, 1961

RUN 10 SAMPLE 2 TYPE Ultrasonic 1 div. (50×10^{-6} in.)

Wheel AA60L8V40	(d_1) Wheel diameter before 5.78020 $\pm$ .00005"
Downfeed 0.001"	(d_2) Wheel diameter after 5.77916 $\pm$ .00005"
Crossfeed 0.050"	Total number of passes 40
Spindle RPM 1314	Part dimensions 2 X 4 X 1/2
SFPM of Wheel 1988	Profilometer Used 36 across, 19 with Micrometric 741:OA amplifier
Table Speed 35 F P M	Part Hardness After 369 $\pm$ 7 Vickers
Coolant Vantrol 5456X-75%; 5456A-25%	Wheel Condition After no load, no glaze dirty, sharpedges.
Spindle vibration as measured from Bearing Journal 0.0002"	Wheel Dressing Used diamond* - see under wheel dressing

Volume of work removed 0.320 in.^{3}

Average Relative Spindle Power 72 Watts $\pm$ 3

$$\text{Grinding Ratio} = \frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} = 67.8 \pm 5\%$$

B. & K. Spectrometer: Meter 36 MV Av. RMS - Fast Meter

Meter Range 100 MV

Meter Range Multiplier X 0.3

Filter Linear

Accelerometer B. & K.# 41369 - 11.8 MV/G

Comments on Run No sparks, quiet

Figure 138

MATERIAL Ti-6Al-4V   DATE May 18, 1961

RUN 11   SAMPLE 3   TYPE Ultrasonic 2 div. (100 X 10^{-6} in.)

Wheel AA60L8V40

(d_1) Wheel diameter before 5.79944 $\pm$ .00005"

Downfeed 0.001"

(d_2) Wheel diameter after 5.79822 $\pm$ .00005"

Crossfeed 0.050"

Total number of passes 40

Spindle RPM 1314

Part dimensions 2 X 4 X 1/2

SFPM of Wheel 1995

Profilometer Used Micrometric 741; QA amplifier 39 across; 26 with

Table Speed 35 F P M

Part Hardness After 394 $\pm$ 8 Vickers

Coolant Vantrol 5456X-75%; 5456A-25%

Wheel Condition After clean, sharp, no glaze, no loading

Spindle vibration as measured from Bearing Journal 0.0002"

Wheel Dressing Used diamond* - see under wheel dressing

Volume of work removed 0.3224 $in.^3$

Average Relative Spindle Power 49.5 Watts $\pm$ 3

Grinding Ratio $= \dfrac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} =$ 58.0

B. & K. Spectrometer: Meter 60-80 MV Av. RMS - Fast Meter

Meter Range 100 MV

Meter Range Multiplier X 0.3

Filter Linear

Accelerometer B. & K.# 41369 - 11.8 MV/G

Comments on Run Extremely quiet grinding, no sparks visible throughout run

Figure 139

MATERIAL Ti-6Al-4V DATE May 19, 1961

RUN 12 SAMPLE 4 TYPE Ultrasonic 3 div. (150 X 10^{-6} in.)

Wheel AA60L8V40

Downfeed 0.001"

Crossfeed 0.050"

Spindle RPM 1314

SFPM of Wheel

Table Speed 35 F P M

Coolant Vantrol 5456X-75%; 5456A-25%

Spindle vibration as measured from Bearing Journal 0.0002"

(d_1) Wheel diameter before 5.76546 $\pm$ .00005"

(d_2) Wheel diameter after 5.76578 $\pm$ .00005"

Total number of passes 40

Part dimensions 2 X 4 X 1/2

Profilometer Used Micrometric 741; QA amplifier 42 across; 28 with

Part Hardness After 382 $\pm$ 10 Vickers

Wheel Condition After clean, clear, sharp no dulling, no load

Wheel Dressing Used diamond* - see under wheel dressing

Volume of work removed 0.3248 in.^{3}

Average Relative Spindle Power 44.0 Watts $\pm$ 5

Grinding Ratio $= \frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} =$ 105.4

B. & K. Spectrometer: Meter 70 MV Av. RMS - Fast Meter

Meter Range 100 MV

Meter Range Multiplier X 1. 0

Filter Linear

Accelerometer B. & K. # 41369 - 11.8 MV/G

Comments on Run Extremely quiet, absolutely no sparks

Figure 140

MATERIAL Ti-6Al-4V

DATE May 16, 1961

RUN 13 SAMPLE 8 TYPE Conventional

Wheel AA60R8V40

Downfeed 0.001"

Crossfeed 0.050"

Spindle RPM 1314

SFPM of Wheel 1983

Table Speed 35 F P M

Coolant Vantrol 5456X-75%;5456A-25%

Spindle vibration as measured from Bearing Journal 0.0002"

(d_1) Wheel diameter before 5.76725 ± .00005"

(d_2) Wheel diameter after 5.76457 ± .00005"

Total number of passes 40

Part dimensions 2 X 4X 1/2

Profilometer Used Micrometric 741;QA amplifier 32 across; 16 with

Part Hardness After 370 ± 7 Vickers

Wheel Condition After loaded severe, glazed dirty, edges broken,

Wheel Dressing Used diamond* - see under wheel dressing

Volume of work removed 0.320 in.^{3}

Average Relative Spindle Power 171 Watts ± 5

$$\text{Grinding Ratio} = \frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} = 26.36$$

B. & K. Spectrometer: Meter 5 MV MV Av. RMS - Fast Meter

Meter Range 100 MV

Meter Range Multiplier X 1.0

Filter Linear

Accelerometer B. & K.# 41369 - 11.8 MV/G

Comments on Run Extremely noisy - lots of sparks

Figure 141

MATERIAL Ti-6Al-4V DATE May 17, 1961

RUN 14 SAMPLE 6 TYPE Ultrasonic 1 div. (50 X 10^{-6} in.)

Wheel AA60R8V40

Downfeed 0.001"

Crossfeed 0.050"

Spindle RPM 1314

SFPM of Wheel 1989

Table Speed 35 F P M

Coolant Vantrol 5456X-75%;5456A-25%

Spindle vibration as measured from Bearing Journal 0.0002"

(d_1) Wheel diameter before 5.78202" $\pm$ .00005"

(d_2) Wheel diameter after 5.78031" $\pm$ .00005"

Total number of passes 40

Part dimensions 2 X 4 X 1/2

Profilometer Used 30 across; 12 with Micrometric 741;QA amplifier

Part Hardness After 384 $\pm$ 8 Vickers

Wheel Condition After starting to load edges dull, glazed

Wheel Dressing Used diamond* - see under wheel dressing

Volume of work removed 0.324 in.^{3}

Average Relative Spindle Power 112.5 Watts $\pm$ 5

Grinding Ratio $= \frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} =$ 41.7

B. & K. Spectrometer: Meter ____ MV Av. RMS - Fast Meter

Meter Range ____

Meter Range Multiplier ____

Filter ____

Accelerometer B. & K. ____

Comments on Run Pass 1 - 25 Light sparking - noisy
Pass 25-40 more sparking - more noisy

Figure 142

MATERIAL Ti-6Al-4V | DATE May 16, 1961

RUN 15 | SAMPLE 7 | TYPE Ultrasonic 2 div. (100×10^{-6} in.)

Wheel AA60R8V40

Downfeed 0.001"

Crossfeed 0.050"

Spindle RPM 1314

SFPM of Wheel 1995

Table Speed 35 F P M

Coolant Vantrol 5456X-75%; 5456A-25%

Spindle vibration as measured from Bearing Journal 0.0002"

(d_1) Wheel diameter before 5.80051 ± .00005"

(d_2) Wheel diameter after 5.79941 ± .00005"

Total number of passes 40

Part dimensions 2 X 4 X 1/2

Profilometer Used 33 across, 20 with Micrometric 741/QA amplifier

Part Hardness After 373 ± 7 Vickers

Wheel Condition After clean, sharp, no loading

Wheel Dressing Used diamond* - see under wheel dressing

Volume of work removed 0.320 in.^{3}

Average Relative Spindle Power 81 Watts ± 5

$$\text{Grinding Ratio} = \frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} = 63.9$$

B. & K. Spectrometer:

- Meter 35 MV Av. RMS - Fast Meter
- Meter Range 1 V
- Meter Range Multiplier X 1.0
- Filter Linear
- Accelerometer B. & K. # 41369 - 11.8 MV/G

Comments on Run Sparking absent except on climb

Figure 143

MATERIAL Ti-6Al-4V　　DATE May 15, 1961

RUN 16　　SAMPLE 5　　TYPE Ultrasonic 3 div. (150 X 10^{-6} in.)

Wheel AA60R8V40

(d_1) Wheel diameter before 5.80903 ± .00005"

Downfeed 0.001

(d_2) Wheel diameter after 5.80801 ± .00005"

Crossfeed 0.050

Total number of passes 40

Spindle RPM 1314

Part dimensions 2 X 4 X 1/2

SFPM of Wheel 1998

Profilometer Used Micrometric 741:OA amplifier 35 across, 25 with

Table Speed 35 F P M

Part Hardness After 367 ± 7 Vickers

Coolant Vantrol 5456X-75%;5456A-25%

Wheel Condition After clean, sharp, no loading

Spindle vibration as measured from Bearing Journal 0.0002" - 0.0003"

Wheel Dressing Used diamond* - see under wheel dressing

Volume of work removed 0.3248

Average Relative Spindle Power 61.5 Watts ± 5

Grinding Ratio $= \frac{\text{Vol. Metal Removed}}{\text{Vol. Wheel lost}} =$ 69.8

B. & K. Spectrometer: Meter 50.0 - 80.0 MV Av. RMS - Fast Meter

Meter Range 1 V

Meter Range Multiplier X 0.3

Filter Linear

Accelerometer B. & K. # 41369 - 11.8 MV/G

Comments on Run Little or no sparks in swarf stream observed. Noise in grinding very slight.

Figure 144

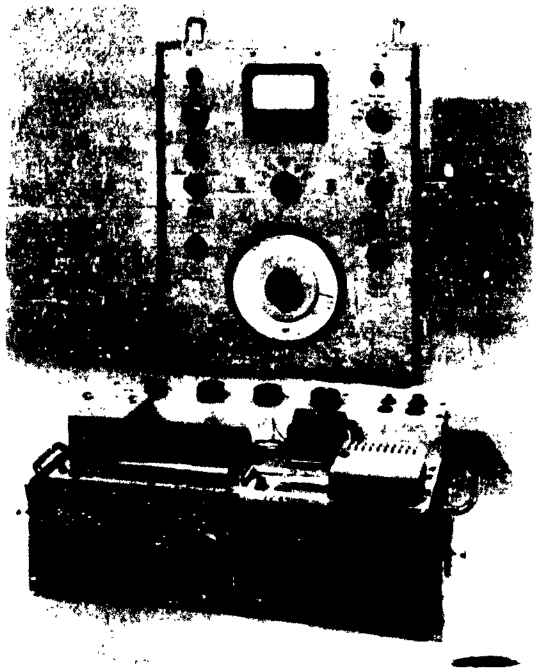


Figure 145 LEVEL RECORDER AND FREQUENCY SPECTROMETER

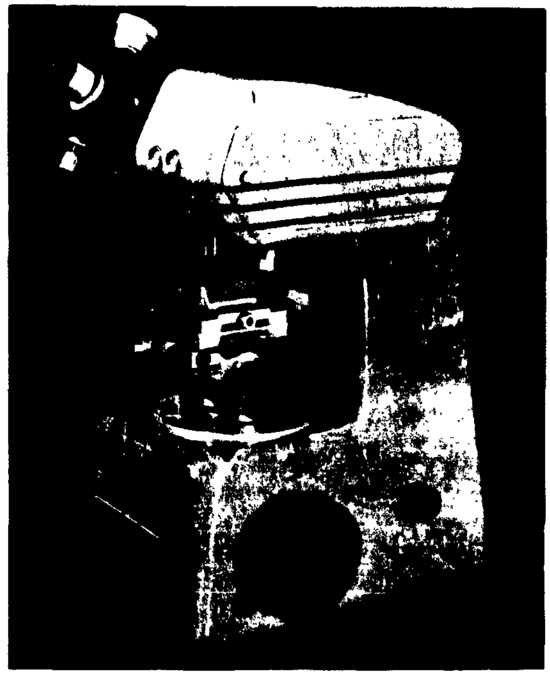


Figure 146 MICROHARDNESS TESTER

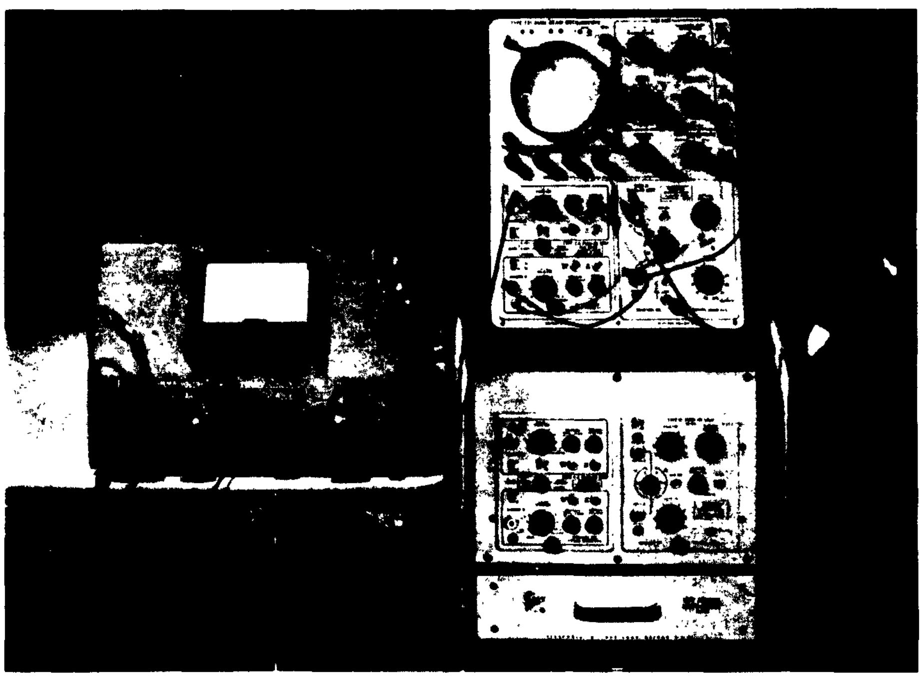
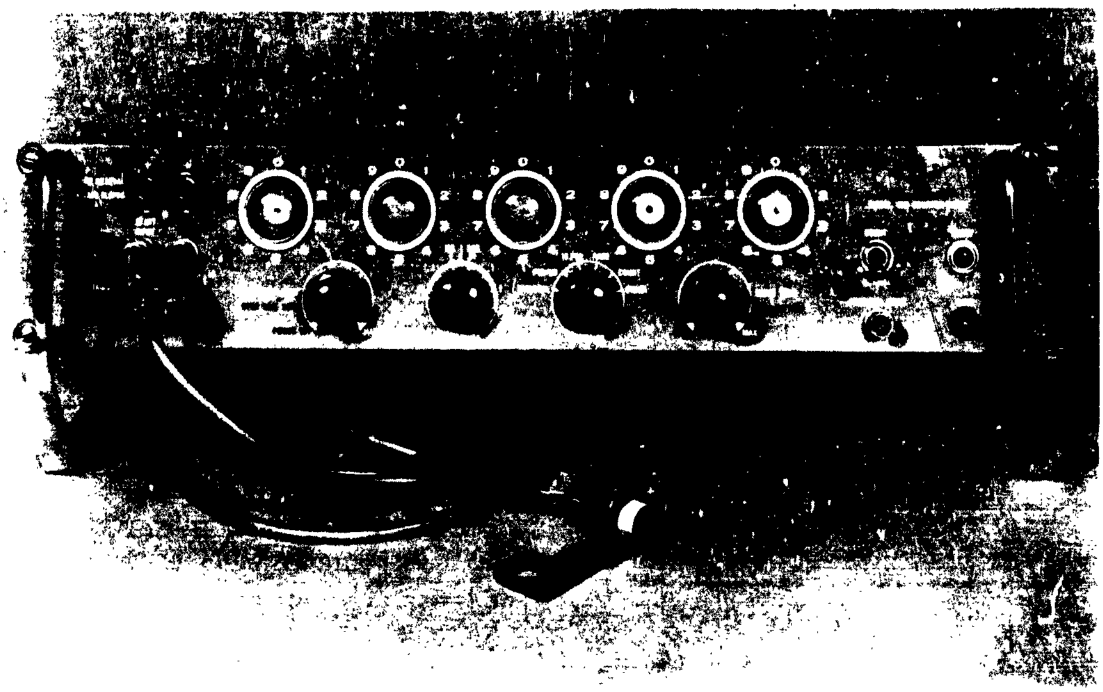
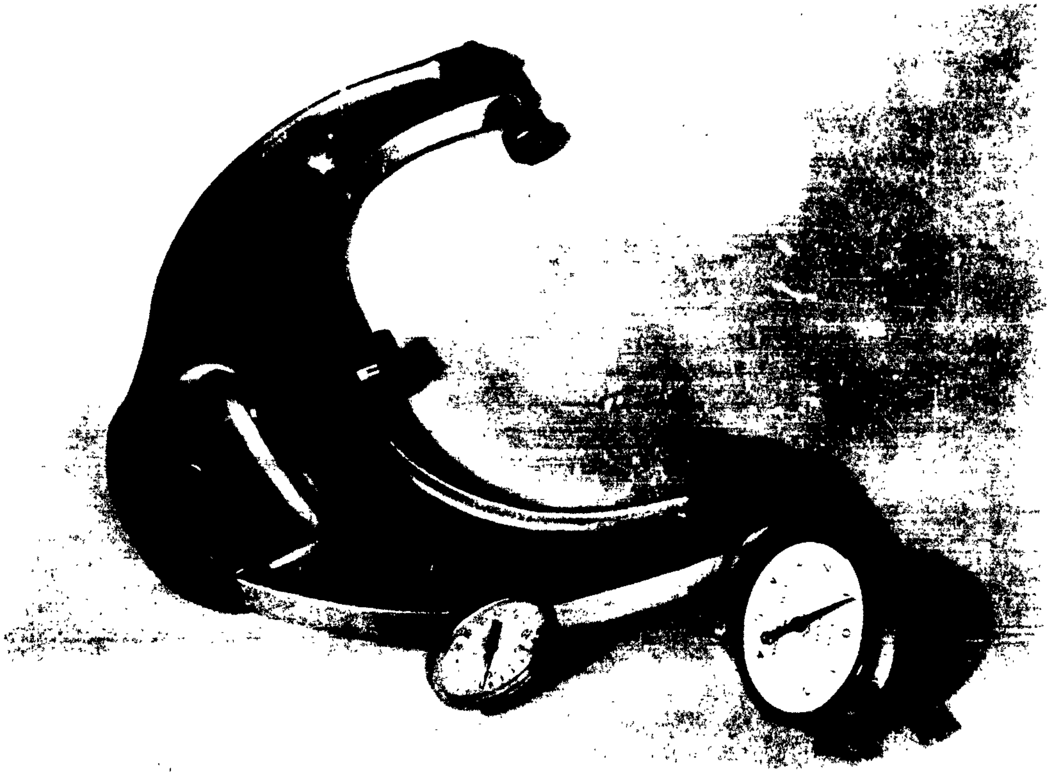


Figure 147 TEKTRONIX OSCILLOSCOPE WITH RF WATT METER



ERIE COUNTER FOR FREQUENCY AND RPM COUNT
Figure 148



WHEEL DIAMETER SNAP GAGE
Figure 149

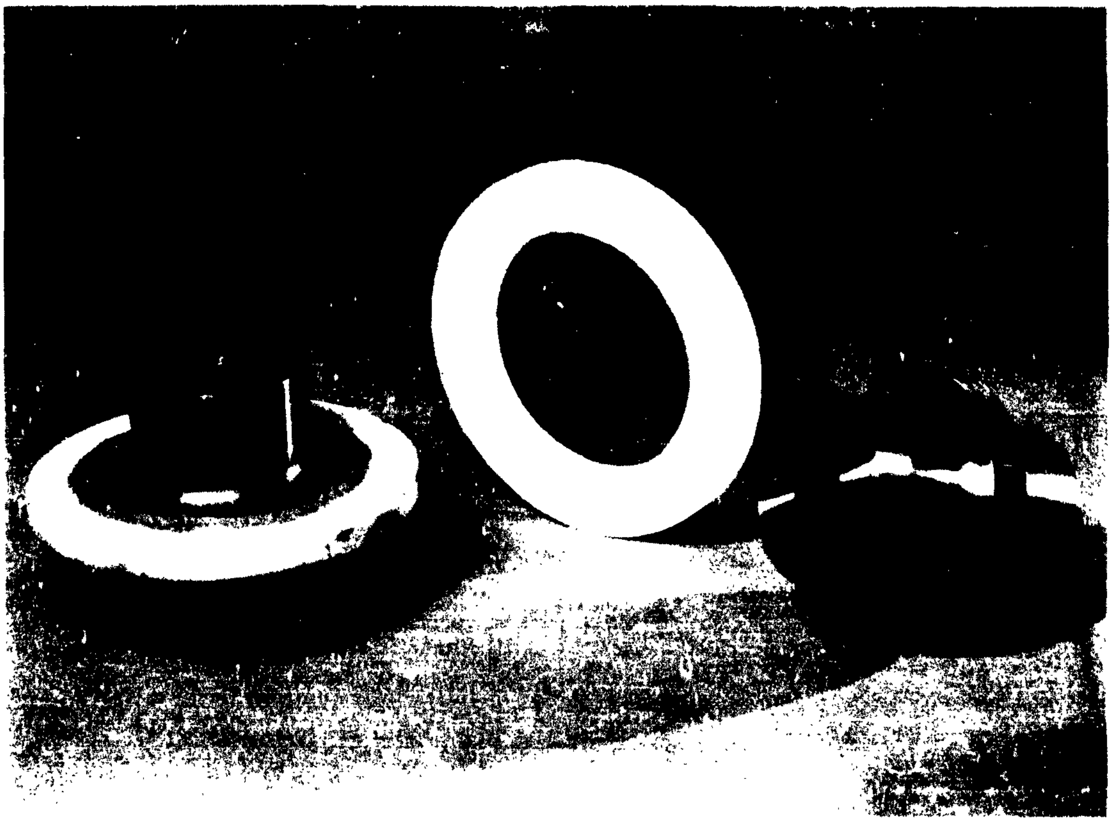


Figure 150 ULTRASONIC HUB AND WHEEL ASSEMBLY

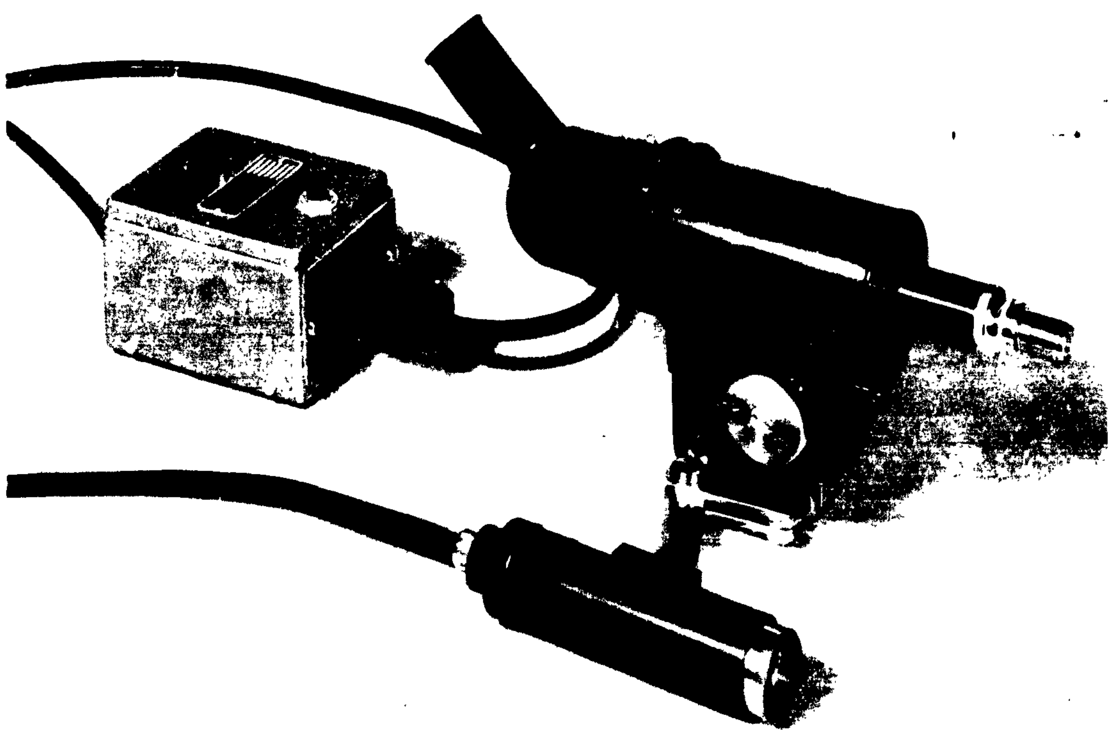


Figure 151 MICROSCOPE AND LIGHT ASSEMBLY FOR ULTRASONIC STROKE ANALYSIS

PHASE II

SECTION 8

8.0 Mechanical Property Tests

8.1 Testing Program

A fatigue, tensile testing and crack inspection program was conducted in order to determine what effect if any that ultrasonic assisted grinding had in comparison to conventional grinding.

It was decided, that if benefits from ultrasonic assisted grinding are to be most apparent that the grinding of specimens for fatigue, tensile and crack inspection with ultrasonics should be with wheels much harder in grade than those grades most commonly used in conventional grinding.

Further, the selection of wheel speeds, table speed, infeed per pass, downfeed and coolant were obtained from a variety of recommendations from papers and from discussions with Metcut Research Associates and others.

8.2 Grinding Conditions for Mechanical Property Tests

The test specimens for fatigue, tensile and crack inspection were ground under the following carefully adjusted conditions:

	ULTRASONIC		CONVENTIONAL	
	Ti6Al-4V	H-11	Ti6Al-4V	H - 11
Wheel	AA60-R8V40	AA60R8-V40	AA60L8-V40	AA46I8-V40
Wheel Speed SFPM	2000	5000	2000	5000
Cross Feed in/pass	0.050	0.050	0.050	0.050
Table Speed FPM	35	35	35	35
Down Feed in/pass	0.001"	0.001"	0.001"	0.001"
Ultrasonic Vibration Amplitude of Wheel	3 div 150×10^{-6} in P - P	3 div 150×10^{-6} in P - P	----	-----
Grinding Coolant	Vantrol 5456 M	Sultran 176 M	Vantrol 5456 M	Sultran 176 M

8.3 Grinding Procedure for Fatigue Specimens

8.3.1. The fatigue specimens as received from the Metcut Research Associates were designed for a Cantilever beam deflection. Approximately .010" of stock was left on each side for finish grind using test conditions in section 8.2.

These specimens were designed with means of fastening them to a rectangular fixture on the modified Brown & Sharpe #13 grinder. This fixture permitted grinding the one side of 3 specimens at one time. Then after turning specimens over the other side was ground.

8.3.2 Specimen Number and Grouping

The specimens were divided into 2 groups of forty (40) each of H-11 and Ti6Al-4V. Twenty specimens of H-11 were ground conventionally and twenty ground with ultrasonics. The same applied to the Ti6Al-4V. Specimens were ground in numerical order, 3 at a time for each specie group of 20.

8.3.3 Wheel Dressing

Wheel was dressed at the beginning (see section 7, page 128) of each fresh unground group and was not redressed before grinding other side. At the finish of one side, an accurate measurement with depth micrometer was taken to determine the number of 0.001" down-feed increments necessary to achieve part thickness within ± 0.001". This was done in order to avoid the uncertainty of thickness due to initial pass on the work which may remove more or less than 0.001", depending on manner of sparking and wheel diameter change due to previous mentioned dressing procedure.

8.3.4 Coolant Supply

During grinding, coolant supply, position and amount was constantly monitored to assure uniformity during all fatigue as well as tensile and crack test specimens.

8.3.5 Daily Grinder Set-up Verifications

At the beginning of each days run, the grinder set-up was verified to assure uniform conditions. Particular attention was given to uniform downfeed, wheel speed and ultrasonic wheel vibration which was constantly monitored by meter when running.

8.4 <u>Grinding Procedures for Tensile and Crack Inspection Specimens</u>

8.4.1 Grinding procedure for tensile and crack inspection specimens were the same as for fatigue except for the following:

1. Tensile specimens were divided into 3 groups of 6 each for Ti6Al-4V, H-11 and Rene 41 and numbered. Half (3) of each group were ground conventionally and half (3) were ground with ultrasonic wheel vibration.

Only two (2) tensile specimens were ground at one time. The groups therefore had 2 specimens for one run, one specimen for the second run.

2. All crack inspection specimens were ground on one side only and one at a time.

8.5 <u>Machine Status for Specimen Grinding</u>

8.5.1 The following changes in conditions existed on the ultrasonic modified Brown & Sharpe #13 grinder for all fatigue, tensile and crack inspection specimen grinding.

1. Infeed mechanism was modified to be completely automatic in operation. This repeatability of infeed was better than 0.001".

2. The table stops and table reversal mechanism were neutralized and micro switches and other circuitry incorporated to use the table motor for reciprocating table at a uniform rate. This alleviated some vibration on the table due to the 35 FPM table speed necessary.

3. A flow switch on coolant was incorporated to serve as a safety device in event coolant supply to wheel was starved.

4. An accelerometer (B&K 4329) was incorporated to monitor ultrasonic vibration amplitude of grinding wheel hub.

5. A counter was incorporated to keep track of the number of downfeed passes.

FATIGUE STUDIES RELATING TO ULTRASONICALLY GROUND SURFACES

METCUT RESEARCH ASSOCIATES INC.

FATIGUE STUDIES RELATING TO
ULTRASONICALLY GROUND SURFACES

Report No. 430-3550-2

for

The Sheffield Corporation
Dayton 1, Ohio

Purchase Order No. 34246-M

METCUT RESEARCH ASSOCIATES INC.

November 2, 1961

Peter R. Arzt

Peter R. Arzt, Project Engineer

Approved:

Michael Field

Michael Field, Research Director

INTRODUCTION

A fatigue test program was performed by Metcut Research Associates Inc. to evaluate the effect produced by the ultrasonic grinding process developed by The Sheffield Corporation,on the fatigue characteristics of two high strength thermal resistant alloys. The two alloys selected for these tests were:

H11 Steel, Quenched and Tempered to 56 R_c
6Al-4V-Titanium, Solution Treated and Aged to 40 R_c

An S-N curve was produced for each of these two materials for both conventional and ultrasonically ground surfaces. The mean endurance limit and standard deviation of each group of specimens was determined by statistical methods and conventional versus ultrasonic grinding was compared.

All fatigue tests were performed at room temperature, in cantilever bending with a mean stress = 0.

CONCLUSIONS

The fatigue test data was analyzed statistically to determine the mean endurance limit (S_E) and standard deviation (σ) of the data. The standard deviation is a measure of the scatter, or normal variability of the data around the mean. The results of the analysis of this data are as follows:

	H11 Steel, Q&T-56 R_c		6Al-4V-Ti, STA-40 R_c	
	S_E (psi)	σ (psi)	S_E (psi)	σ (psi)
Conventional Grind	89,750	$\pm$2,710	39,000	*
Ultrasonic Grind	89,370	$\pm$4,980	43,740	$\pm$ 605

* Not determined due to extreme variation in test results

The following conclusions can be drawn from these test results:

1. The endurance limits are essentially equal for conventionally or ultrasonically ground H11 steel. Somewhat more scatter was produced by the ultrasonic compared to the conventional grind, as evidenced by the larger standard deviation for the ultrasonic grind.

2. The endurance limit for ultrasonically ground 6Al-4V-Ti is approximately 12% (5,000 psi) higher than that for the conventional grind. The ultrasonically ground specimens exhibited a very high degree of uniformity in fatigue properties, while extreme variation was produced by the conventional grind.

3. The extreme variation in the fatigue data for the conventionally ground titanium seems to indicate that some change in grinding conditions may have occurred during test grinding of the specimen lot.

DISCUSSION

Test Program

S-N curves in cantilever bending at room temperature were developed for both ultrasonically and conventionally ground specimens of H11 steel, quenched and tempered to 56 R_c and 6Al-4V-Titanium, solution treated and aged to 40 R_c. A total of 15 to 20 tests were performed for each combination of material and grinding method. The majority of these tests were performed at a stress level near the endurance limit of the specimen group, according to a predetermined testing schedule. The mean endurance limit (S_E) and the standard deviation (σ) of each group of specimens was determined by a statistical analysis of the test data. The endurance limit for these tests was based on a fatigue life of 10^7 cycles.

Test Specimens

a. Materials and Heat Treatment

The H11 steel was procured from Vanadium Alloys Steel Company. This material was their alloy Hotform No. 2 and was supplied as annealed plate 4-3/4" wide x 3/8" thick x 100" long. The heat number of this material was 32057. Specimen blanks were cut from this plate with the longitudinal dimension parallel to the direction of rolling.

The following heat treatment was performed on the specimen blanks between rough milling and rough grinding operations:

Harden: 1850°F/1 hour in neutral salt, air cool
Temper: 950°F/1 hour, air cool
Final Hardness: 56-56.5 R_c

a. Materials and Heat Treatment (continued)

The 6Al-4V-Titanium was supplied by Reactive Metals Inc. The material was hot rolled and annealed plate .280" thick x 36" x 21" from heat number 29225. Specimen blanks were cut from the plate with the longitudinal dimension parallel to the direction of rolling.

The following heat treatment was performed on the specimen blanks between rough milling and grinding operations:

Solution Treat: 1700°F/1 hour, water quench
Age: 1000°F/8 hours, air cool
Final Hardness: 39-40 R_c

b. Manufacture

All specimens were manufactured in accordance with the specimen drawing, No. 601130-2, shown in Figure 1. A precise manufacturing procedure was used for preparing the test specimens, in order to insure that the specimen groups would be as uniform as possible. A condensed schedule of these manufacturing operations is as follows:

1. Rough mill contour and faces of specimens, leaving .030" stock on all sides for grinding.
2. Drill all holes in drill jig.
3. Heat treat.
4. Rough grind faces to .170"-.175" thickness.
5. Countersink holes.
6. Grind 1/2" radius to size.
7. Send to Sheffield Corporation for test grinding of faces to .150" thickness.
8. Grind off hold down lugs.
9. Polish edges in 1/2" radius and break corners .010" to .015".
10. Shot peen stationary grip section and edges of 1/2" radius.

b. Manufacture (continued)

The lugs and countersunk holes provided in the test specimens were for the purpose of holding the specimen to a flat fixture during grinding operations.

The stationary grip section of the specimen was shot peened prior to testing to prevent failure in this area due to the fretting corrosion which always occurs on these contact surfaces. The edges of the 1/2" radius in the test section of the specimen were also shot peened to insure that the fatigue failure would originate on the ground surface and not on an edge of the specimen [1]. This extra precaution was necessary, since the effects produced by the ground surface could not be determined unless the fatigue failures originated in this surface. The test surfaces of the specimens were protected with heavy masking tape during the shot peening operation.

c. Test Grinding

The final grinding of the faces of the fatigue specimens was performed by The Sheffield Corp. Twenty specimens of each material were ground "conventionally" and twenty were ground "ultrasonically". Approximately .010" of stock was removed from each surface of the specimens to bring them to a final thickness of .150". The specimens were ground in groups of three consecutively numbered specimens.

(1) Reference 1

c. Test Grinding (continued)

Grinding conditions used were as follows:

	Conventional		Ultrasonic	
	H11	6Al-4V-Ti	H11	6Al-4V-Ti
Wheel Grade	AA46I8V40	AA60L8V40	AA60R8V40	AA60R8V40
Wheel Speed-sfpm	5000	2000	5000	2000
Down Feed-in/pass	.001	.001	.001	.001
Cross Feed-in/pass	.050	.050	.050	.050
Table Speed-fpm	35	35	35	35
Grinding Fluid	(1) Sultran 176M	(2) Vantrol 5456M	Sultran 176M	Vantrol 5456M
Vibration Amplitude	–	–	3 div. (150" x 10^{-6})	3 div. (150" x 10^{-6}

Test Setup and Procedure

The fatigue tests were performed on three Baldwin-Lima-Hamilton SF1-U fatigue testing machines, operating at 1800 cycles per minute. A schematic sketch of a cantilever fatigue test setup is shown in Figure 2. A photograph of the actual test setup, showing a specimen in place, is shown in Figure 3.

The S-N (Stress versus Number of test cycles) curves were developed by running the initial test of each specimen group at a stress level higher than the anticipated endurance limit, then decreasing the stress for each successive test until run-out (no failure after 10^7 cycles) was obtained. After the first run-out was obtained, the remainder of the tests for that group were run using the "stairstep" loading sequence. To use this stairstep method, a stress increment (the amount by which the stress level of

(1) Highly Sulphurized Oil

(2) Highly Chlorinated Oil

Test Setup and Procedure (continued)

successive tests is to be changed) is first selected. Then if a test runs out, successive tests are run at intervals of one stress increment higher until a specimen failure occurs. After a failure occurs, the stress level is lowered one stress increment at a time until run-out again occurs. This test schedule is continued until a sufficient number of failures and run-outs is obtained to provide an accurate data analysis.

The stress increment selected for the titanium specimens was 1,500 psi, or about 3.5% of the expected endurance limit of 45,000 psi. This selection was based on the minimum increment of load adjustment available on the SF1-U machine.

The increment selected for the H11 specimens was 2,500 psi, or about 2.5% of the expected endurance limit of 100,000 psi.

Test Results

The S-N curves for each combination of material and grinding method are shown in Figures 4 through 7. Stairstep plots and calculations involved in the statistical analysis of the data are given in Figures 8 through 10. Complete tabulated test data are shown in Tables 1 and 2.

The S-N curve for conventionally ground H11 steel, quenched and tempered to 56 R_C, is shown in Figure 4. The average endurance limit for this group of specimens, as determined statistically, was 89,750 psi, and the standard deviation about this mean was $\pm$ 2,710 psi. The highest stress at which a

Test Results (continued)

10^7 cycle run-out occurred for this group of specimens was 90,000 psi, and the lowest stress at which failure occurred was 87,500 psi.

The S-N curve for ultrasonically ground H11 steel is shown in Figure 5. The mean endurance limit for this group of specimens was 89,370 psi, or very nearly equal to that for the conventionally ground specimens. The standard deviation of $\pm$ 4,980 psi, however, indicates a greater amount of variability was produced by the ultrasonically ground specimens. The highest stress at which a 10^7 cycle run-out occurred was 92,500 psi, and the lowest stress at which failure occurred was 87,500 psi.

Complete test data showing specimen numbers and number of test cycles for the H11 specimens is given in Table 1.

The S-N curve for conventionally ground 6Al-4V Titanium is shown in Figure 6. This group of specimens exhibited such a great amount of variability that a statistical analysis could not be performed without running additional tests. Since additional specimens were not available, the endurance limit of this group of specimens was estimated from the S-N curve as approximately 39,000 psi. Also, the width of the scatter band is probably in excess of $\pm$ 1,500 psi. The numbers shown adjacent to each test data point in Figure 6 are test specimen numbers. From a close examination of this data it can be seen that most of the test points above the curve are for specimens 21 through 30, while most of the test data points on or below the curve are for specimens 31 through 39. In view

Test Results (continued)

of the fact that these specimens were ground in groups of three in consecutive numerical order, the data seems to indicate that some detrimental change may have occurred in the grinding process about midway through the group of specimens. The highest stress at which a run-out occurred in these specimens was 40,500 psi, and the lowest stress at which a failure occurred was 37,500 psi.

The S-N curve for ultrasonically ground 6Al-4V Titanium, solution treated and aged to 40 R_C, is shown in Figure 7. The mean endurance limit for this group of specimens, as determined statistically, was 43,740 psi, or about 5,000 psi higher than the endurance limit of the conventionally ground specimens. The standard deviation for the ultrasonically ground specimens was only $\pm$ 605 psi, which indicates a very low degree of variability in fatigue properties. The highest stress at which a run-out occurred in this group of specimens was 43,500 psi. The lowest stress at which a failure occurred was also 43,500 psi.

Complete test data, showing specimen numbers and number of test cycles for the titanium specimens, is given in Table 2.

Statistical Analysis of Test Data

The statistical testing program and data analysis methods used for this fatigue testing study were researched by Mr. Robert Fopma of the Engineering Mathematics Department, University of Cincinnati. The source of the statistical methods equations used can be found in References 2, 3 and 4 at the end of this report.

Statistical Analysis of Test Data (continued)

Figures 8, 9 and 10 show the stairstep testing plots and the calculations for determining the mean endurance limit (S_E) and standard deviation (σ) for H11 and titanium ultrasonically ground, and for H11 conventionally ground. As stated previously, too much variability was produced by the conventionally ground titanium specimens to perform a statistical analysis on this group.

The Dixon-Mood* equations used for analyzing the data and the meaning of the sumbols are as follows:

Determination of mean endurance limit (S_E):

$$S_E = Y' + d\left(\frac{A}{N} + \frac{1}{2}\right)$$

Determination of standard deviation (σ):

$$\sigma = 1.62\, d\left(\frac{NB - A^2}{N^2} + .029\right)$$

Explanation of symbols:

S_E = Mean endurance limit of specimen group - psi

σ = Standard deviation - $\pm$ psi

Y' = Lowest stress level at which run-out occurs - psi

d = Stress increment (2,500 psi for H11) (1,500 psi for titanium)

$$A = \sum_{i=0}^{k} in, \qquad B = \sum_{i=0}^{k} i^2 n$$

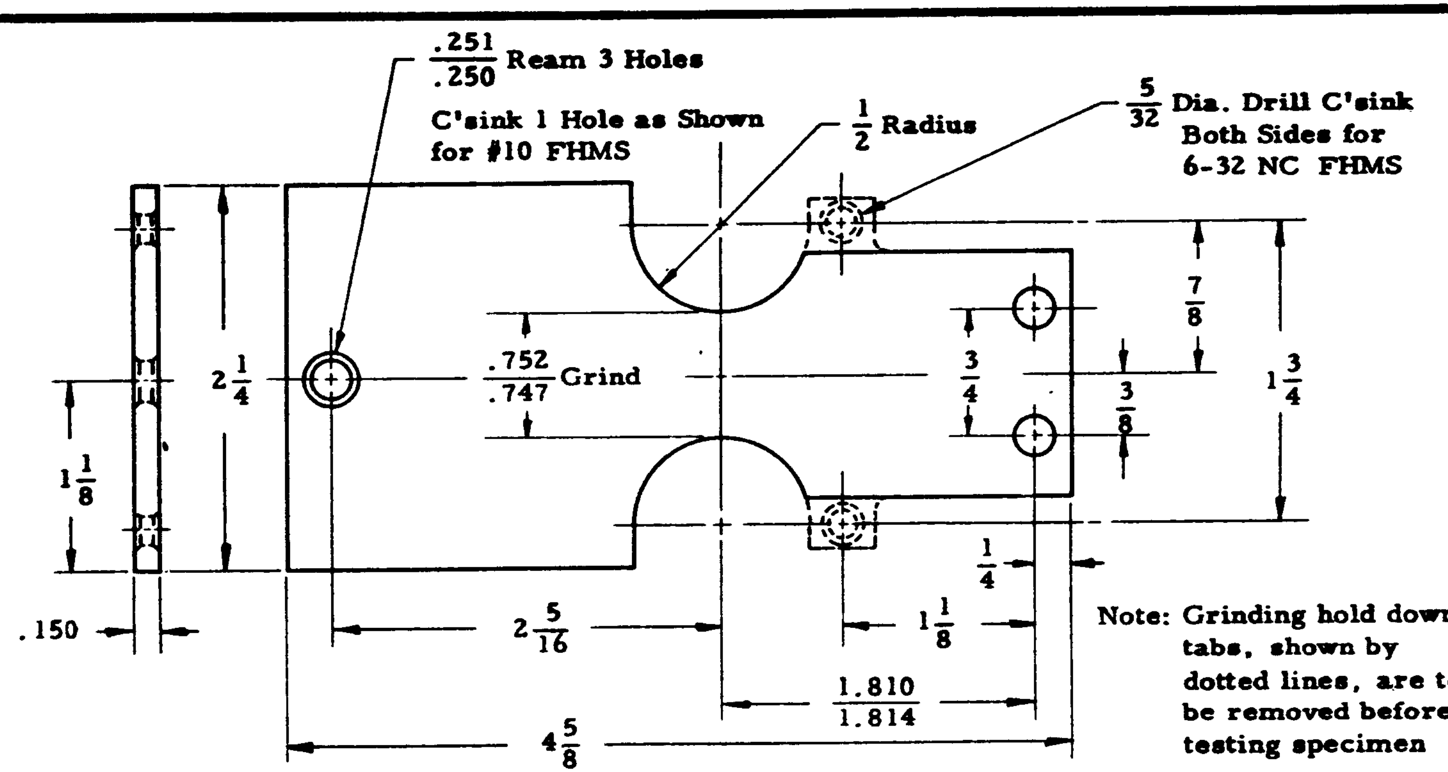
N = Total number of run-outs obtained

i = Number of stress increments above Y'

n_i = Number of run-outs at an incremental stress level

These equations and calculations are shown on the individual analysis charts.

*Reference 4



MATERIAL:

H-11 Quenched and Tempered to 56 R_c

6Al-4V Titanium Solution Treated and Aged to 35-40 R_c

Thickness:
Before Test Grinding: .170"-.175"
After Test Grinding: .149"-.150"

CANTILEVER FATIGUE SPECIMEN

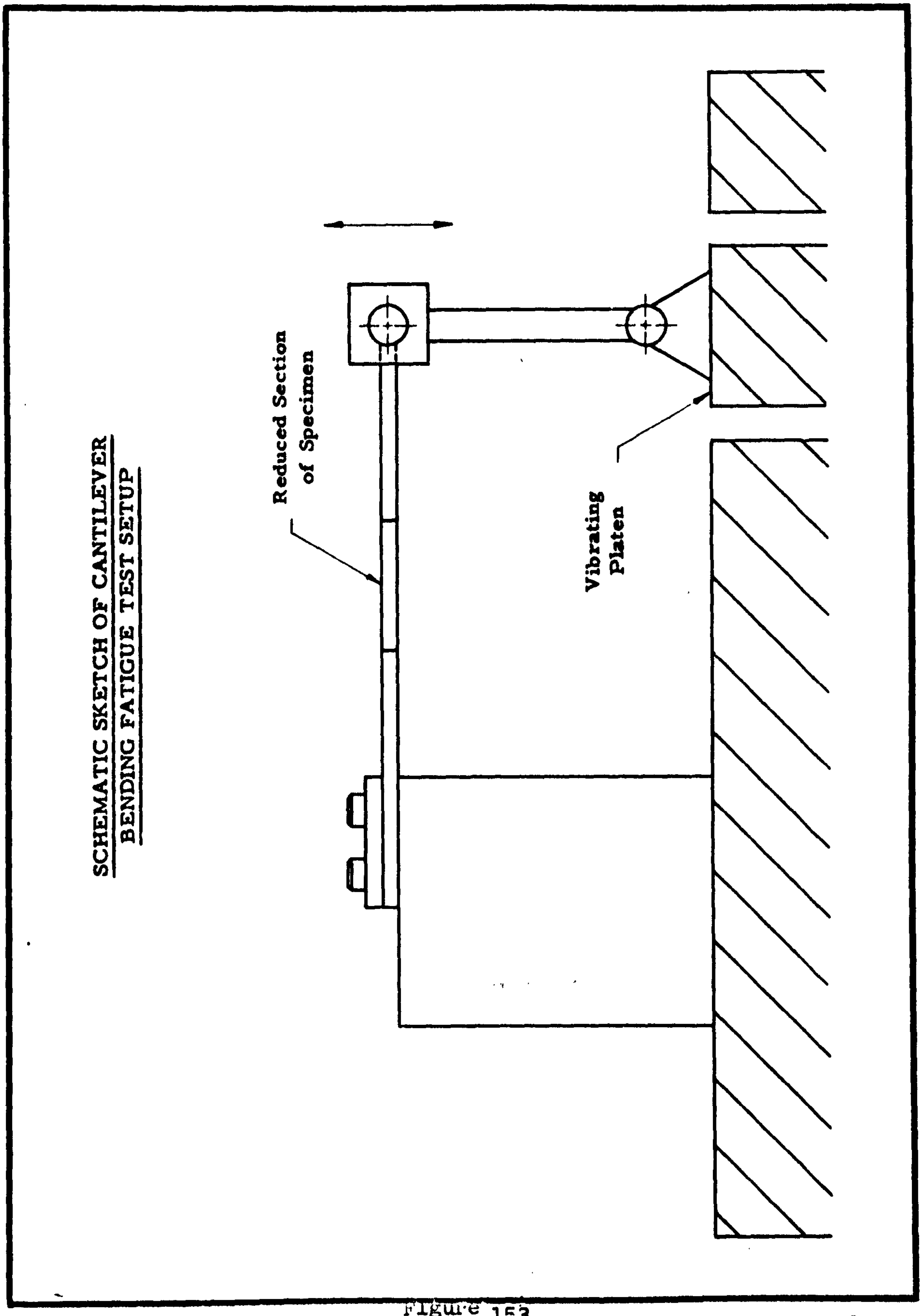
Use Drill Jig 430-3550 U-2 For All Holes

METCUT RESEARCH ASSOCIATES INC.
CINCINNATI 9, OHIO

DRAWING NO. 601130-2

Figure 152

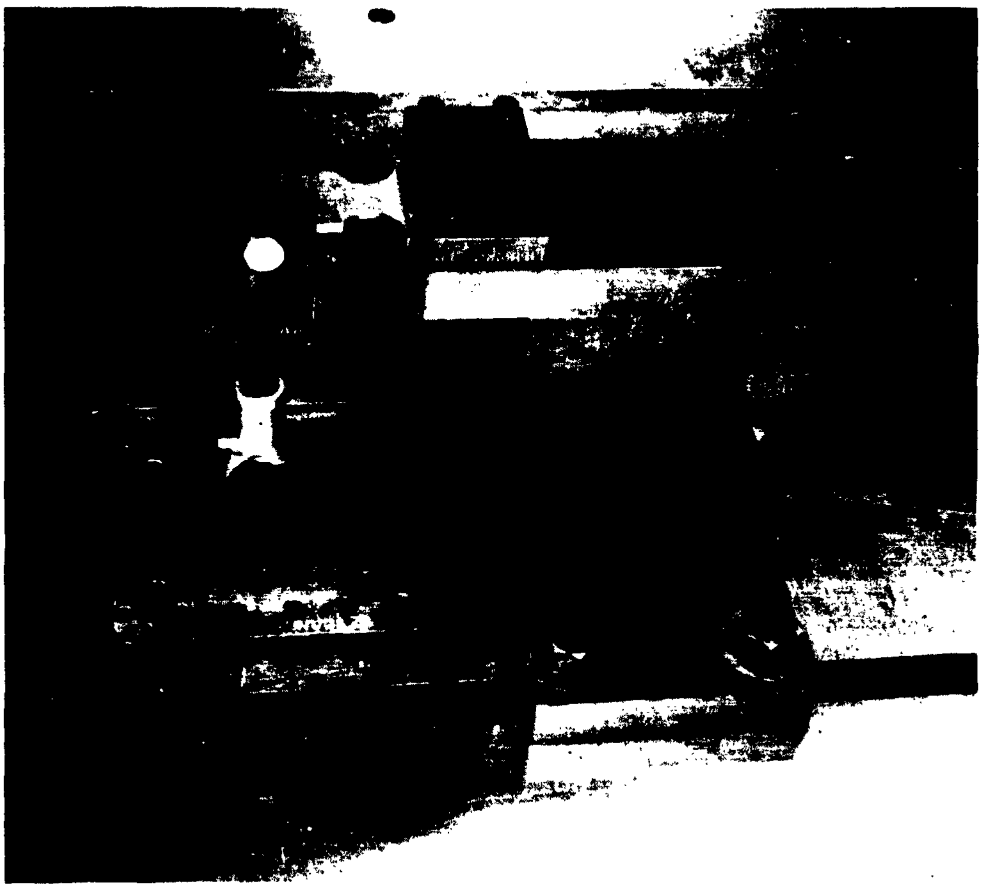
Figure 1
(Metcut)



SCHEMATIC SKETCH OF CANTILEVER BENDING FATIGUE TEST SETUP

Figure 153

Figure 2
(Metcut)



Cantilever Bending Fatigue Test Setup Showing Specimen in Place

Figure 3
(Metcut)

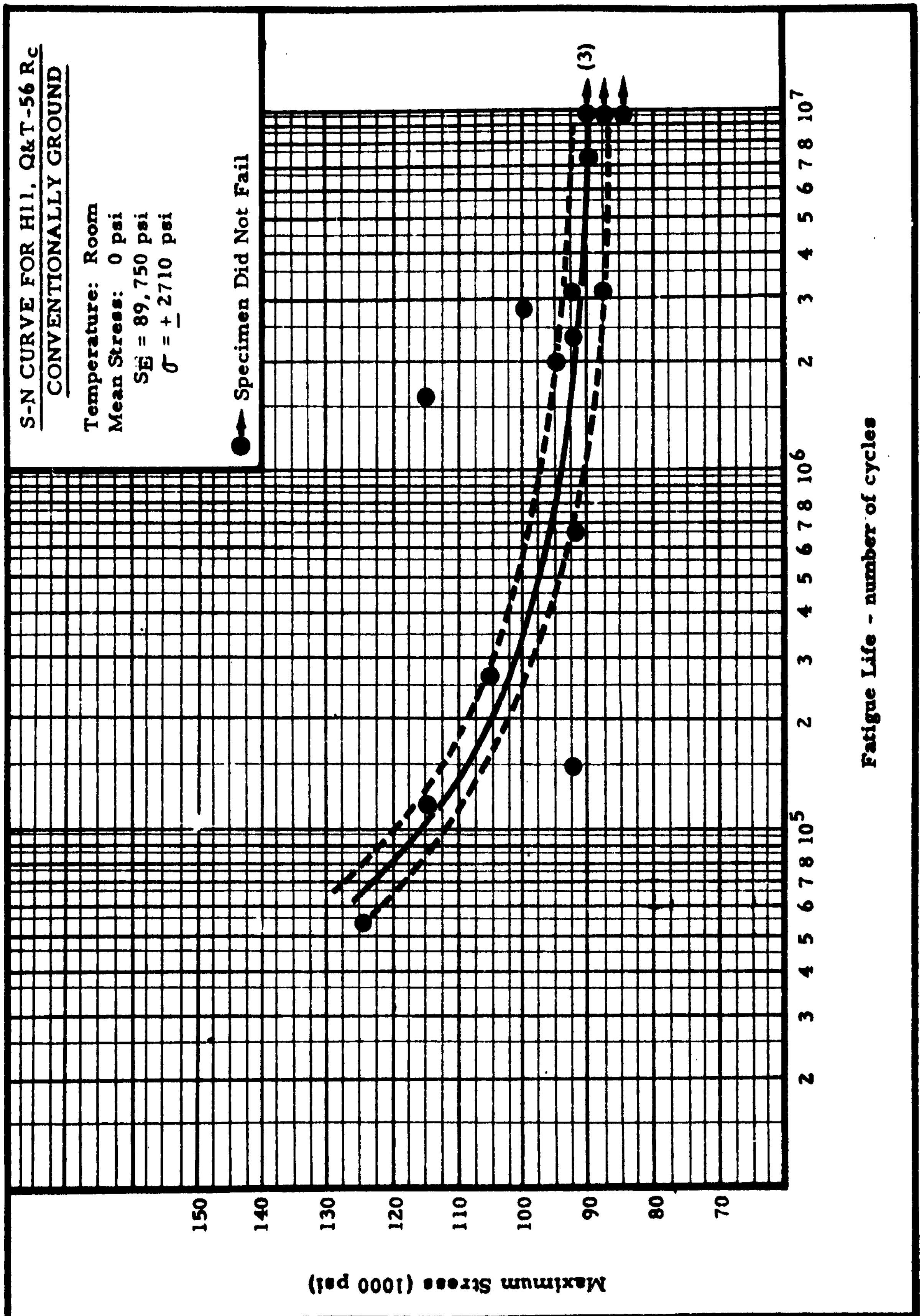


Figure 155

Figure 4
(Metcut)

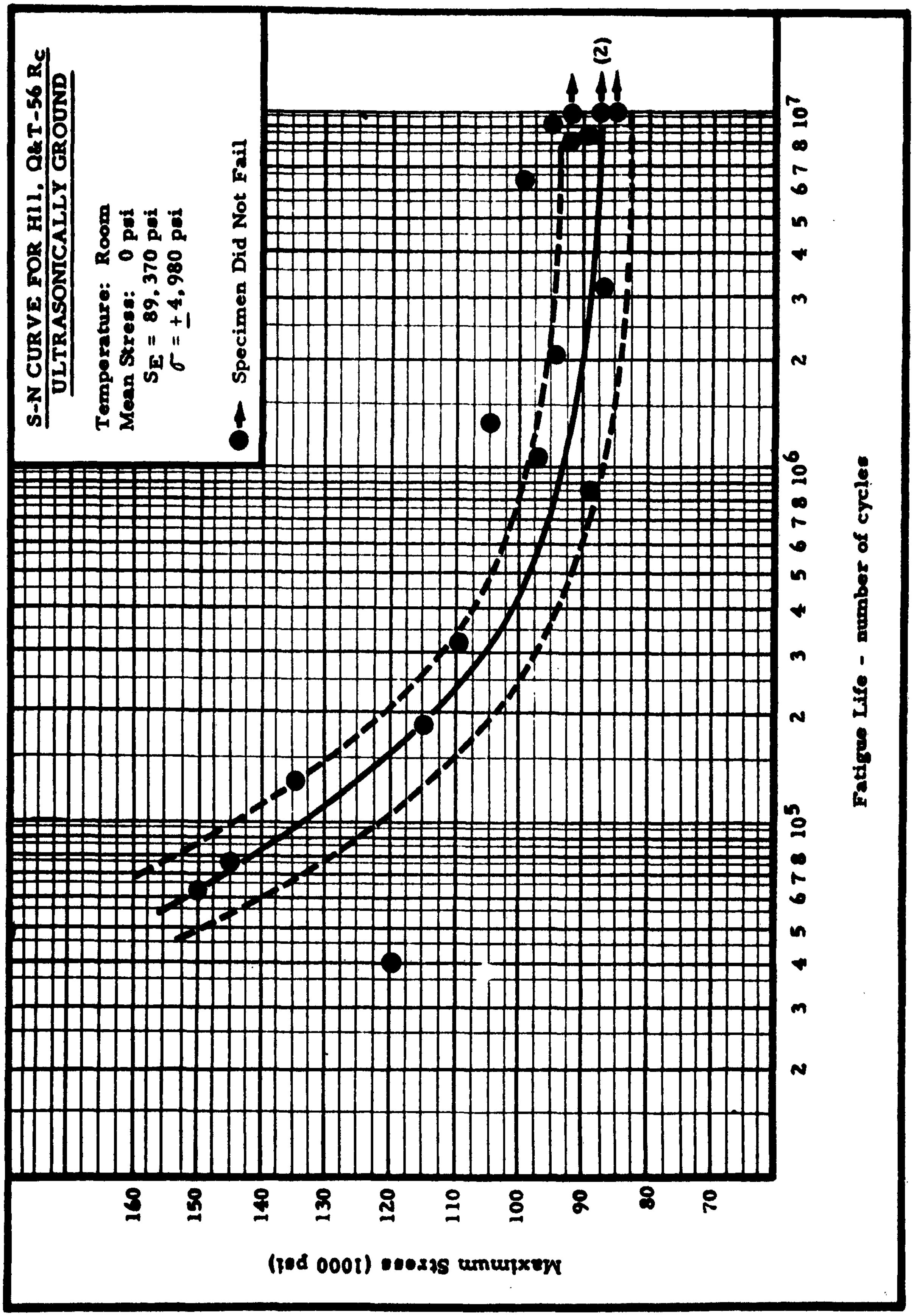


Figure 156

Figure 5
(Metcut)

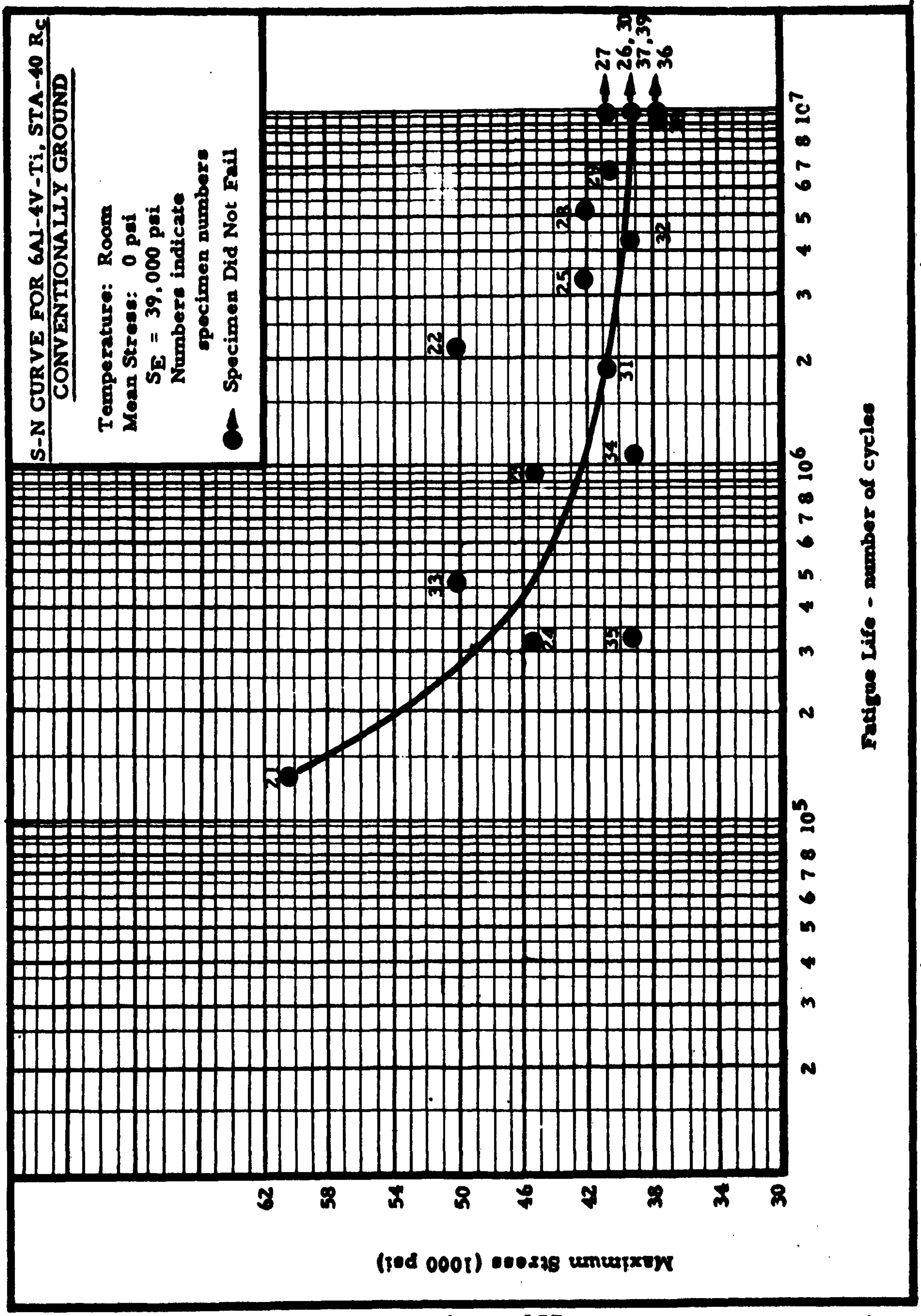


Figure 157

Figure 6
(Metcut)

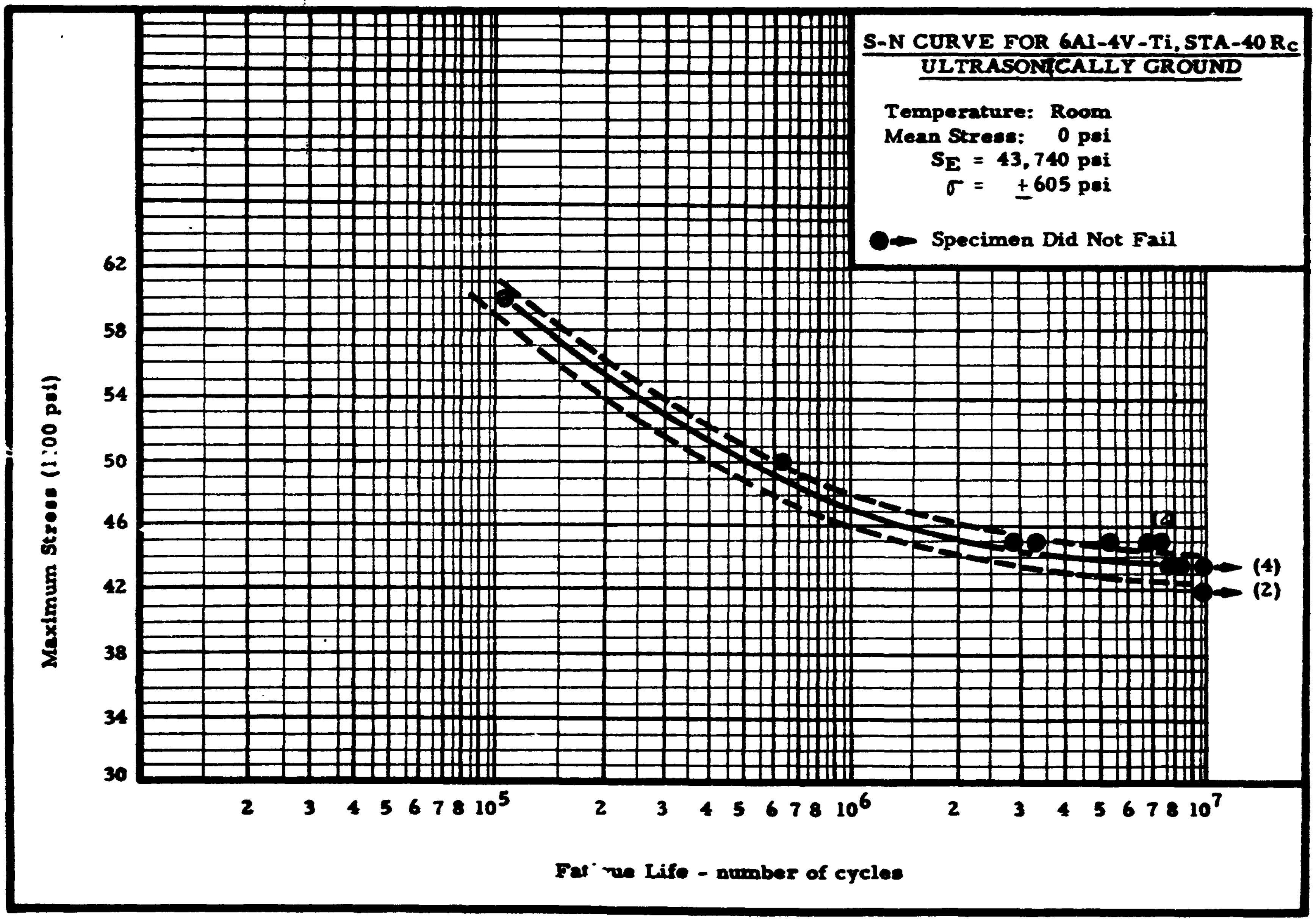


Figure 7
(Metcut)

Figure 158

STATISTICAL ANALYSIS OF DATA FOR H11 STEEL, Q & T - 56 R_C - CONVENTIONALLY GROUND

Summation

Stress	i	n_i	in_i	i^2n_i
95.0	4	0	0	0
92.5	3	0	0	0
90.0	2	3	6	12
87.5	1	1	1	1
85.0	0	1	0	0
		N = 5	A = 7	B = 13

Calculations for S_E and σ

$$S_E = Y' + d\left(\frac{A}{N} + \frac{1}{2}\right)$$

$$S_E = 85{,}000 + 2{,}500\left(\frac{7}{5} + \frac{1}{2}\right) = \underline{89{,}750 \text{ psi}}$$

$$\sigma = 1.62\, d\left(\frac{NB - A^2}{N^2} + .029\right)$$

$$\sigma = 1.62 \times 2{,}500\left(\frac{5 \times 13 - 49}{25} + .029\right) = \underline{\pm\, 2{,}710 \text{ psi}}$$

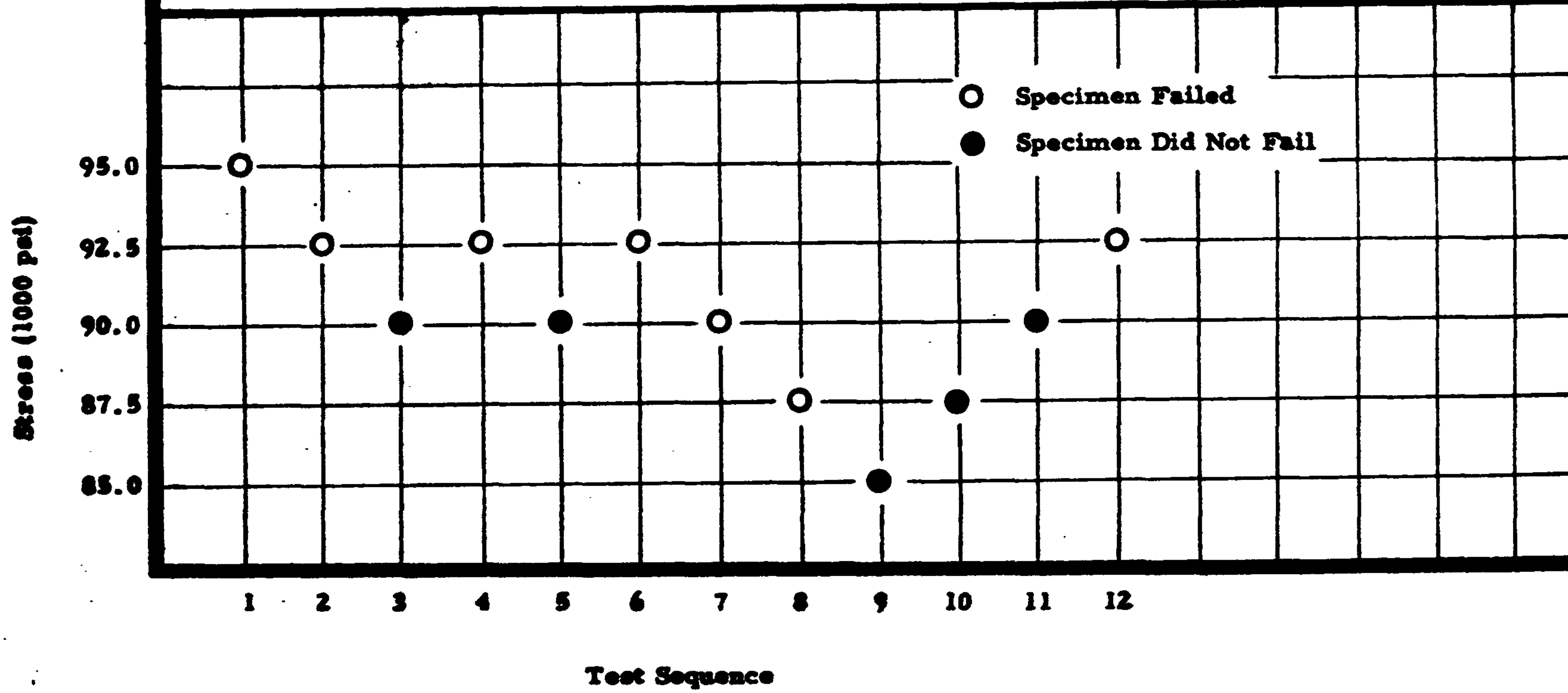


Figure 159

Figure 8
(Metcut)

STATISTICAL ANALYSIS OF DATA FOR H11 STEEL, Q & T - 56 R_C - ULTRASONICALLY GROUND

Summation

Stress	i	n_i	in_i	$i^2 n_i$
95.0	4	0	0	0
92.5	3	1	3	9
90.0	2	0	0	0
87.5	1	2	2	2
85.0	0	1	0	0
		N = 4	A = 5	B = 11

Calculations for S_E and σ

$$S_E = Y' + d\left(\frac{A}{N} + \frac{1}{2}\right)$$

$$S_E = 85{,}000 + 2{,}500\left(\frac{5}{4} + \frac{1}{2}\right) = \underline{89{,}370 \text{ psi}}$$

$$\sigma = 1.62\ d\left(\frac{NB - A^2}{N^2} + .029\right)$$

$$\sigma = 1.62 \times 2{,}500\left(\frac{4 \times 11 - 25}{16} + .029\right) = \underline{\pm\ 4{,}980 \text{ psi}}$$

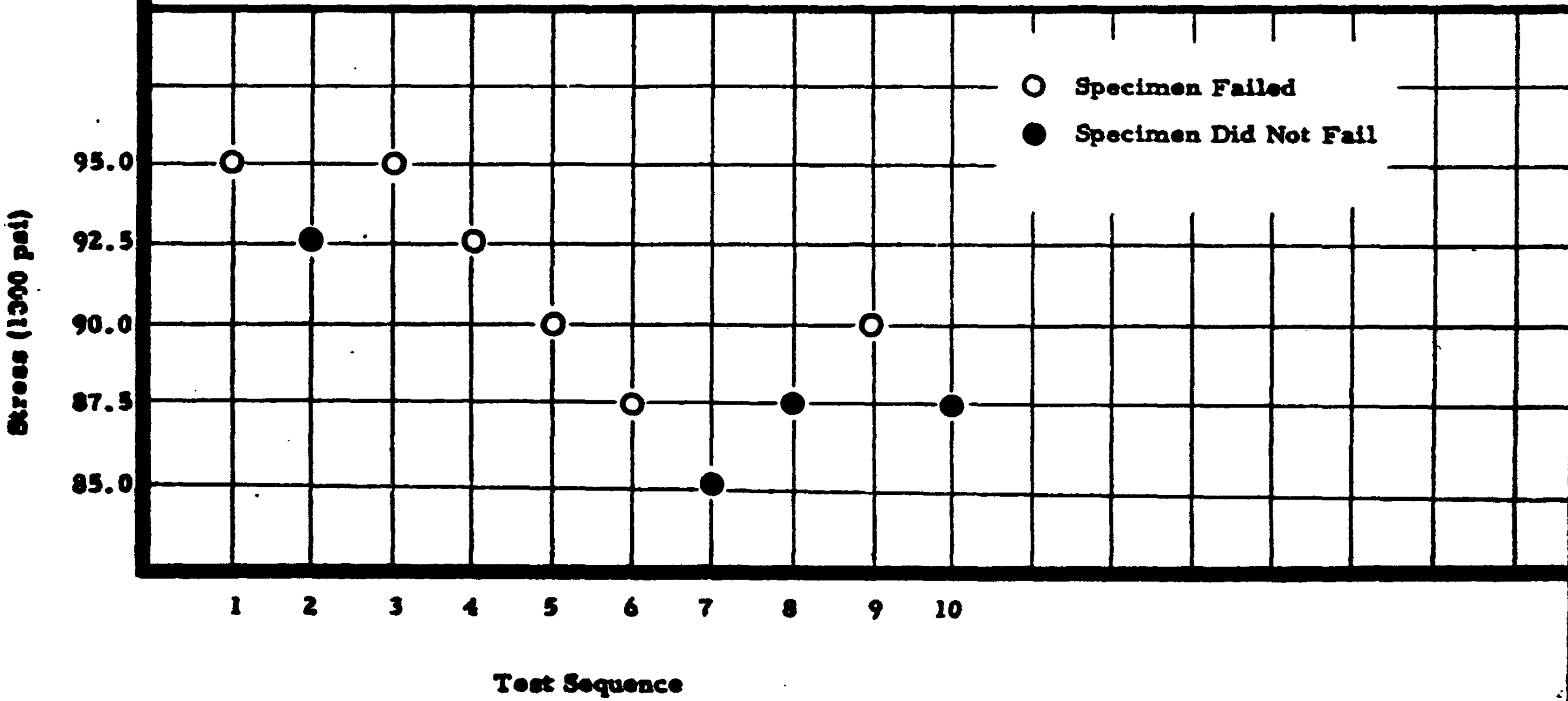


Figure 9
(Metcut)

Figure 160

STATISTICAL ANALYSIS OF DATA FOR 6Al-4V-TITANIUM, STA - 40 R_c - ULTRASONICALLY GROUND

Summation

Stress	i	n_i	in_i	i^2n_i
45.0	2	0	0	0
43.5	1	4	4	4
42.0	0	2	0	0
		N = 6	A = 4	B = 4

Calculations for S_E and σ

$$S_E = Y' + d\left(\frac{A}{N} + \frac{1}{2}\right)$$

$$S_E = 42,000 + 1,500\left(\frac{4}{6} + \frac{1}{2}\right) = \underline{43,740 \text{ psi}}$$

$$\sigma = 1.62\, d\left(\frac{NB - A^2}{N^2} + .029\right)$$

$$\sigma = 1.62 \times 1,500\left(\frac{24-16}{36} + .029\right) = \underline{\pm 605 \text{ psi}}$$

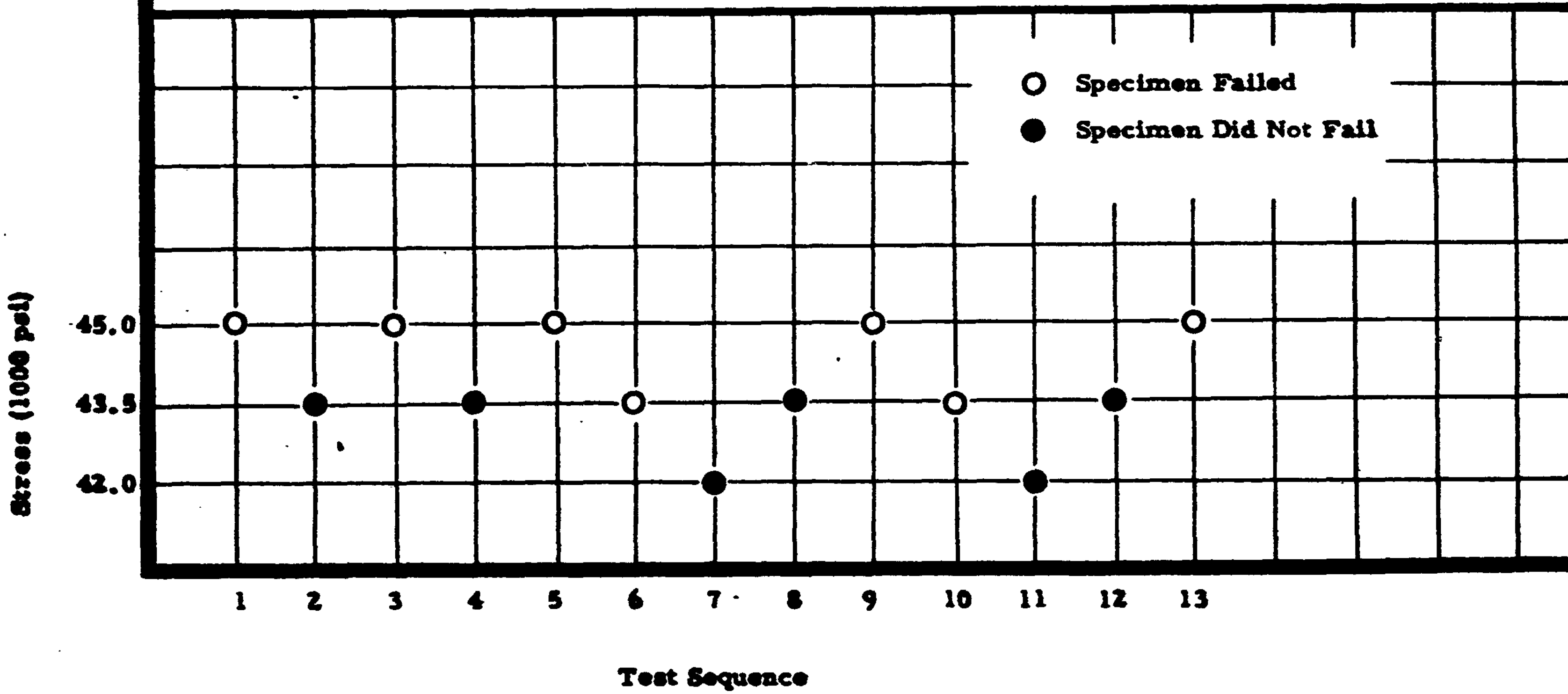


Figure 161

Figure 10
(Metcut)

TABLE 1

FATIGUE TEST DATA

H11 SPECIMENS

Type of Test: Cantilever Bending — **Machine:** SF1-U

Test Temperature: Room — **Mean Stress:** 0 psi

Ultrasonically Ground			Conventionally Ground		
Specimen No.	Test Stress psi	No. of Cycles to Failure	Specimen No.	Test Stress psi	No. of Cycles to Failure
HX1	150,000	62,000	H34	125,000	55,000
H1	145,000	71,000	H20	115,000	1,607,000
H2	135,000	142,000	H36	↓	124,000
H3	120,000	40,000	H21	105,000	263,000
H4	115,000	180,000	H22	100,000	2,854,000
H6	110,000	320,000	H23	95,000	1,985,000
H7	105,000	1,335,000	H25	92,500	3,037,000
H5	100,000	6,357,000	H27	↓	2,369,000
H8	97,500	1,019,000	H31	↓	671,000
H9	95,000	9,155,000	H37	↓	143,000
H13	↓	2,042,000	H24	90,000	10,291,000*
H10	92,500	10,215,000*	H28	↓	10,081,000*
H14	↓	7,758,000	H31	↓	10,400,000*
H11	90,000	8,193,000	H29	↓	7,484,000
H19	↓	840,000	H26	87,500	10,000,000*
H12	87,500	10,248,000*	H32	↓	3,179,000
H17	↓	10,237,000*	H33	85,000	10,012,000*
H15	↓	3,785,000			
H16	85,000	10,269,000*			

* Specimen did not fail - test discontinued

Figure 162

TABLE 2

FATIGUE TEST DATA

TITANIUM-6Al-4V SPECIMENS

Type of Test: Cantilever Bending **Machine:** SF1-U

Test Temperature: Room **Mean Stress:** 0 psi

Ultrasonically Ground			Conventionally Ground		
Specimen No.	Test Stress psi	No. of Cycles to Failure	Specimen No.	Test Stress psi	No. of Cycles to Failure
T1	60,000	104,000	T21	60,000	129,000
T2	50,000	629,000	T22	50,000	2,087,000
T14	45,000	7,360,000	T33		474,000
T8		7,043,000	T23	45,000	932,000
T11		6,600,000	T24		309,000
T6		5,217,000	T28	42,000	5,027,000
T3		3,262,000	T25		3,277,000
T10		2,961,000	T27	40,500	10,336,000*
T5	43,500	10,257,000*	T29		6,925,000
T7		10,295,000*	T31		1,924,000
T13		10,035,000*	T26	39,000	10,187,000*
T17		10,220,000*	T30		10,089,000*
T9		7,920,000	T37		10,020,000*
T15		7,471,000	T39		10,000,000*
T4	42,000	10,666,000*	T32		4,366,000
T16		10,020,000*	T34		1,153,000
			T35		408,000
			T36	37,500	10,040,000*
			T38		9,833,000

*Specimen did not fail - test discontinued

REFERENCES

1 E. C. Reed, J. A. Viens - "The Influence of Surface Residual Stresses on Fatigue Limit of Titanium" Transactions of The ASME, Journal of Engineering for Industry, February 1960, p 76

2 Dixon & Massey - "Introduction to Statistical Analysis" Second Edition (1957), Chapter 19 (pg 318-327)

3 Brownlee, Hodges, Rosenblatt - "The Up and Down Method With Small Samples" Journal of the American Statistical Association Vol. 48 (1953) - pg 262

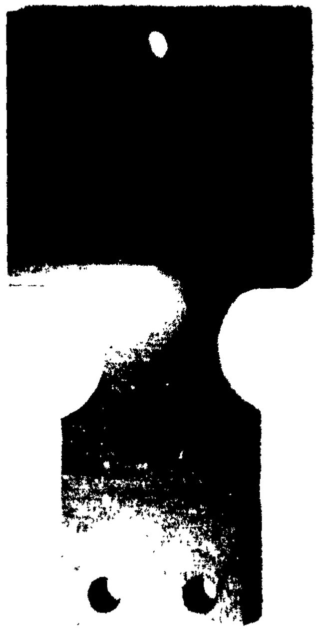
4 Dixon & Mood - "A Method for Obtaining and Analysing Sensitivity Data" Journal of the American Statistical Association Vol. 43 (1948) - pg 109

Reference 2 is basically a resume of the paper presented in Reference 4, which mentioned two important restrictions:

1. Trials must be made sequentially
2. The measures of reliability may be very misleading if the sample size is less than 40 or 50.

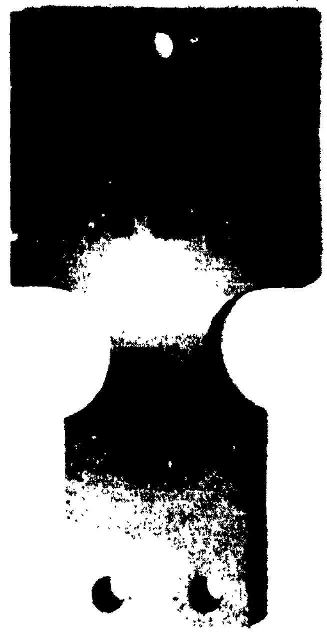
However, Reference 3 found that the Dixon-Mood technique is reasonably accurate even in samples as small as 5 to 10. It was found that reliable estimate for the mean can be obtained provided the experimenter can start the process within two testing intervals of the mean.

8.6.1 Representative Photographs of Fatigue Specimens Showing Fracture and Fracture Face



Ti6Al-4V Ultrasonic Ground Specimen
Stress 45,000 psi
Cycles 3,262,000

Figure 164

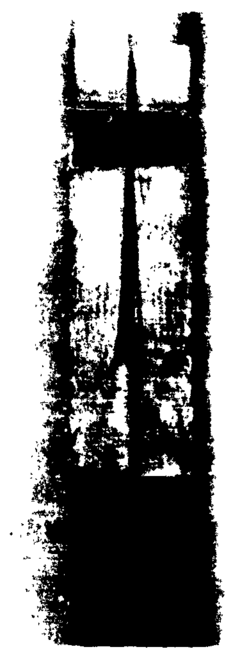


Ti6Al-4V Conventional Ground Specimen
Stress 43,000 psi
Cycles 5,027,000

Figure 165

Ti6Al-4V Ultrasonic Ground Specimen
Stress 45,000 psi
Cycles 6,600,000

Figure 166

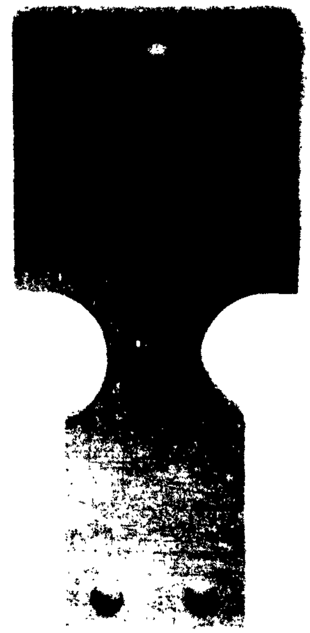


Ti6Al-4V Conventional Ground Specimen
Stress 37,500 psi
Cycles 9,833,000

Figure 167

H-11 Ultrasonic Ground Specimen
Stress 87,500 psi
Cycles 3,785,000

Figure 168



H-11 Conventional Ground Specimen
Stress 93,500 psi
Cycles 671,000

Figure 169

H-11 Ultrasonic Ground Specimen
Stress 95,000 psi
Cycles 2,042,000

Figure 170

H-11 Conventional Ground Specimen
Stress 87,500 psi
Cycles 3,179,000

Figure 171

8.7 Tensile Testing and Crack Inspection Results Performed by Metcut Research Associates on Ultrasonic vs. Conventional Specimens

METCUT RESEARCH ASSOCIATES INC.

3980 Rosslyn Drive — Cincinnati 9, Ohio

BRamble 1-6100

LABORATORY REPORT

DATE November 2, 1961 — NUMBER 430-3574-1

CLIENT	%
The Sheffield Corporation	Mr. Richard N. Roney
ADDRESS 721 Springfield Avenue Dayton 1, Ohio	AUTHORIZATION 35121-M

PROJECT Tensile Testing and Zyglo Plus Deep Etch Inspection of Three Alloys Ground by Conventional and Ultrasonic Methods

CONCLUSIONS

Deep etch and Zyglo specimens were prepared by Sheffield as follows:

Material	Type Grinding	Number	Wheel
Rene 41	Conventional	B	AA46I8-V40
Rene 41	Ultrasonic	H	AA60R8-V40
H11	Conventional	1	AA46I8-V40
H11	Ultrasonic	8	AA60R8-V40
Ti-6Al-4V	Conventional	1	AA60L8-V40
Ti-6Al-4V	Ultrasonic	7	AA60R8-V40

Zyglo inspection did not reveal any cracks in the ground surfaces.

After Zyglo inspection, the specimens were deep etched as follows:

Rene 41	RT Superoxal in HCl
H11	Hot 50% HCl - 50% H_2O
Ti-6Al-4V	RT Vilella's Etchant

Deep etching did not reveal any cracks in the ground surfaces.

Sheet 1 of 4 — APPROVED — BY

METCUT RESEARCH ASSOCIATES INC.

3980 Rosslyn Drive — Cincinnati 9, Ohio
BRamble 1-6100

LABORATORY REPORT

DATE: November 2, 1961 — NUMBER: 430-3574-1

CLIENT: The Sheffield Corporation — %: Mr. Richard N. Roney

ADDRESS: 721 Springfield Avenue, Dayton 1, Ohio — AUTHORIZATION: 35121-M

PROJECT: Tensile Testing of Six (6) Titanium 6Al-4V Sheet Specimens
Manufactured to Metcut Drawing No. 600106-1
Nom. Gage Section: .100" x .500" x 2.00" Temperature: Room
Strain Rate: .005 in./in./min. thru .2% Y.S.
Head Rate: .05 in./min. thence to failure

CONCLUSIONS

MRAI No.	Spec. No.	Type of Surface Grind	U.T.S. (ksi)	.2% Y.S. (ksi)	Elong. %	Wheel
T-9402	1	Conventional	168	155	8	AA60L8-V40
T-9404	2	Conventional	170	159	6	AA60L8-V40
T-9403	3	Conventional	169	157	8	AA60L8-V40
T-9405	4	Ultrasonic	168	157	10	AA60R8-V40
T-9406	5	Ultrasonic	172	160	6	AA60R8-V40
T-9407	6	Ultrasonic	170	157	7	AA60R8-V40

Notes: (1) Specimens 1 and 2 were ground together
(2) Specimens 4 and 5 were ground together

Specimen blanks were heat treated by Metcut as follows:

$1700 \pm 15^\circ F$/1 hour/water quench
$1000 \pm 15^\circ F$/8 hours/air cool

Sheet 2 of 4

APPROVED

BY

METCUT RESEARCH ASSOCIATES INC.

3980 Rosslyn Drive Cincinnati 9, Ohio

BRamble 1-5100

LABORATORY REPORT

DATE November 2, 1961 NUMBER 430-3574-1

CLIENT The Sheffield Corporation

% Mr. Richard N. Roney

ADDRESS 721 Springfield Avenue
Dayton 1, Ohio

AUTHORIZATION 35121-M

PROJECT **Tensile Testing of Six (6) Rene 41 Sheet Specimens Manufactured to Metcut Drawing No. 600106-1**
Nom. Gage Section: .100" x .500" x 2.00" **Temperature: Room**
Strain Rate: .005 in./in./min. thru .2% Y.S.
Head Rate: .05 in./min. thence to failure

CONCLUSIONS

MRAI No.	Spec. No.	Type of Surface Grind	U.T.S. (ksi)	.2% Y.S. (ksi)	Elong. %	Wheel
T-9408	1	Conventional	188	132	16	AA46I8-V40
T-9409	2	Conventional	191	133	18	AA46I8-V40
T-9410	3	Conventional	193	136	17	AA46I8-V40
T-9411	4	Ultrasonic	190	132	18	AA60R8-V40
T-9412	5	Ultrasonic	191	134	17	AA60R8-V40
T-9413	6	Ultrasonic	192	133	18	AA60R8-V40

Notes: (1) Specimens 1 and 2 were ground together
(2) Specimens 4 and 5 were ground together

Specimen blanks were heat treated by Metcut as follows:

$1950 \pm 25^{\circ}$F/1/2 hour/air cool
$1400 \pm 25^{\circ}$F/16 hours/air cool

Sheet 3 of 4	APPROVED	BY

METCUT RESEARCH ASSOCIATES INC.

3980 Rosslyn Drive — Cincinnati 9, Ohio

BRamble 1-6100

LABORATORY REPORT

DATE **November 2, 1961** NUMBER **430-3574-1**

CLIENT **The Sheffield Corporation**

% **Mr. Richard N. Roney**

ADDRESS **721 Springfield Avenue**
Dayton 1, Ohio

AUTHORIZATION **35121-M**

PROJECT **Tensile Testing of Six (6) H-11 Sheet Specimens Manufactured to Metcut Drawing No. 600106-1**
Nom. Gage Section: .100"x.500"x 2.00" **Temperature: Room**
Strain Rate: .005 in./in./min. thru .2% Y.S.
Head Rate: .05 in./min. thence to failure

CONCLUSIONS

MRAI No.	Spec. No.	Type of Surface Grind	U.T.S. (ksi)	.2% Y.S. (ksi)	Elong. %	Wheel
T-9416	3	Conventional	314	224	8	AA46I8-V40
T-9417	4	Conventional	314	223	5	AA46I8-V40
T-9418	5	Conventional	313	220	6	AA46I8-V40
T-9414	1	Ultrasonic	318	220	6	AA60R8-V40
T-9415	2	Ultrasonic	312	208	7	AA60R8-V40
T-9419	6	Ultrasonic	306	203	5	AA60R8-V40

Notes: (1) Specimens 3 and 4 were ground together
(2) Specimens 1 and 2 were ground together

Specimen blanks were heat treated by Metal Treating, Inc. as follows:

$1850 \pm 25^\circ F$/1 hour in neutral salt/air cool
$950 \pm 25^\circ F$/1 hour/air cool
$950 \pm 25^\circ F$/1 hour/air cool

Sheet 4 of 4

APPROVED

Elwood B. Norris, Supervisor
Mechanical Testing

BY

Edward Slattery,
Senior Laboratory Technician

PHASE II

SECTION 9

RESIDUAL STRESS TESTS

METCUT RESEARCH ASSOCIATES INC.

METALLURGY . MECHANICAL ENGINEERING . MACHINABILITY
RESEARCH . DEVELOPMENT . TESTING

MAIN OFFICE AND LABORATORIES AT
3980 Rosslyn Drive
Cincinnati 9, Ohio

BRamble 1-5100

November 11, 1960

Mr. Dan Giardini
The Sheffield Corporation
721 Springfield Avenue
Dayton 1, Ohio

Dear Mr. Giardini:

Enclosed are three copies of the graphs showing the nature of the residual stress distribution in the surface of the ground PH 15-7 MO stainless steel specimens.

The area under the curve in each case indicates the magnitude of the residual stress induced as a result of grinding. The magnitude of the residual stress is approximately the same for both specimens, MO-6 and MO-7. The residual stress is tensile in nature in both specimens.

The residual stress at the surface of specimen MO-6 was low, approximately 10,000 psi, and increased to a peak stress of 116,000 psi at a depth of .002" below the surface. The stress diminished rapidly and no appreciable stress was noted at a depth of .004" below the ground surface.

On specimen MO-7 the peak stress, 120,000 psi, was noted immediately at the ground surface. The residual stress diminished rapidly and no appreciable residual stress could be noted at a depth of .004" below the ground surface.

We are completing the work on the titanium specimens and should have the results to you Monday, November 14, 1960.

Should there be any questions please do not hesitate to call me. I am enclosing both of the specimens supplied to us for analysis.

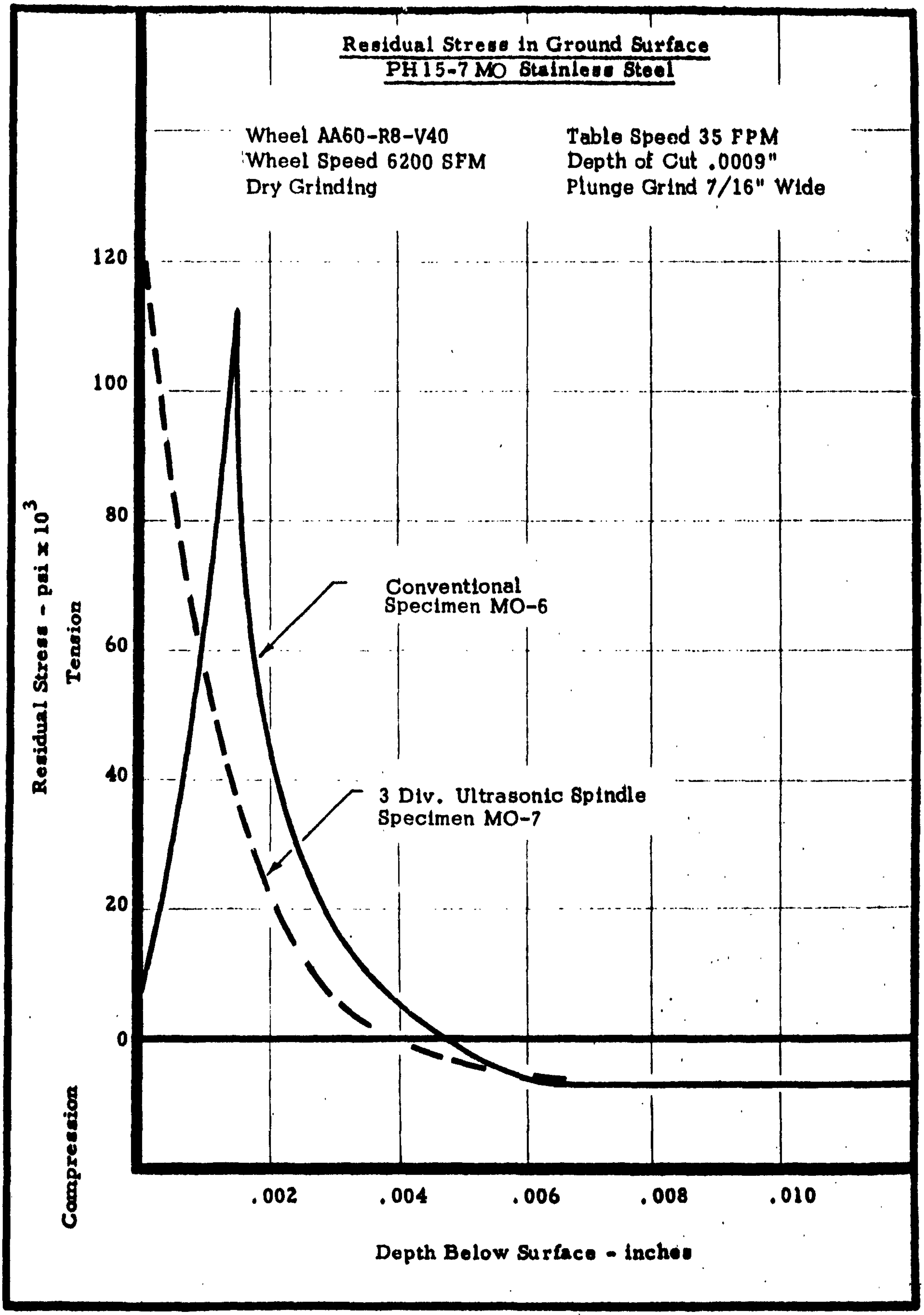
Very truly yours,

METCUT RESEARCH ASSOCIATES INC.

L J Nowikowski

L. J. Nowikowski, Director,
Manufacturing Research

LJN:jk
Enc.



Residual Stress in Ground Surface
PH 15-7 MO Stainless Steel
Wheel AA60-R8-V40
Wheel Speed 6200 SFM
Dry Grinding
Table Speed 35 FPM
Depth of Cut .0009"
Plunge Grind 7/16" Wide
120
100
80
60
40
20
0
Residual Stress - psi x 10^3
Tension
Compression
Conventional
Specimen MO-6
3 Div. Ultrasonic Spindle
Specimen MO-7
.002
.004
.006
.008
.010
Depth Below Surface - inches

Figure 172

METCUT RESEARCH ASSOCIATES INC.

METALLURGY . MECHANICAL ENGINEERING . MACHINABILITY
RESEARCH . DEVELOPMENT . TESTING

MAIN OFFICE AND LABORATORIES AT
3980 Rosslyn Drive
Cincinnati 9, Ohio

BRamble 1-5100

November 14, 1960

Mr. Dan Giardini
The Sheffield Corporation
721 Springfield Avenue
Dayton 1, Ohio

Metcut Project 430-3206

Dear Mr. Giardini:

Enclosed are three copies of the graphs showing the nature of the residual stress distribution in the surface of the ground 6Al-4V titanium specimens.

The area beneath the curves for both specimens, Ti-6 and Ti-7, indicates the magnitude of the total stress is approximately the same. The residual stress is tensile in nature in both specimens.

Specimen Ti-6 showed a peak stress of 174,000 psi immediately at the ground surface. The stress decreased rapidly, 40,000 psi at a depth of .0005" below the surface, and no appreciable stress was noted at a depth of .002" below the ground surface.

On specimen Ti-7, a peak stress of 91,000 psi was evident immediately at the ground surface. The residual stress diminished rapidly, 40,000 psi at a depth of .0006" below the surface, and no appreciable residual stress was noted at a depth of .002" below the ground surface.

Should there be any questions concerning the results of the stress analyses on the PH 15-7 MO and 6Al-4V specimens, please do not hesitate to call me. I would like to apologize for the slight delay in getting the results to you.

The samples supplied to us for analysis are enclosed.

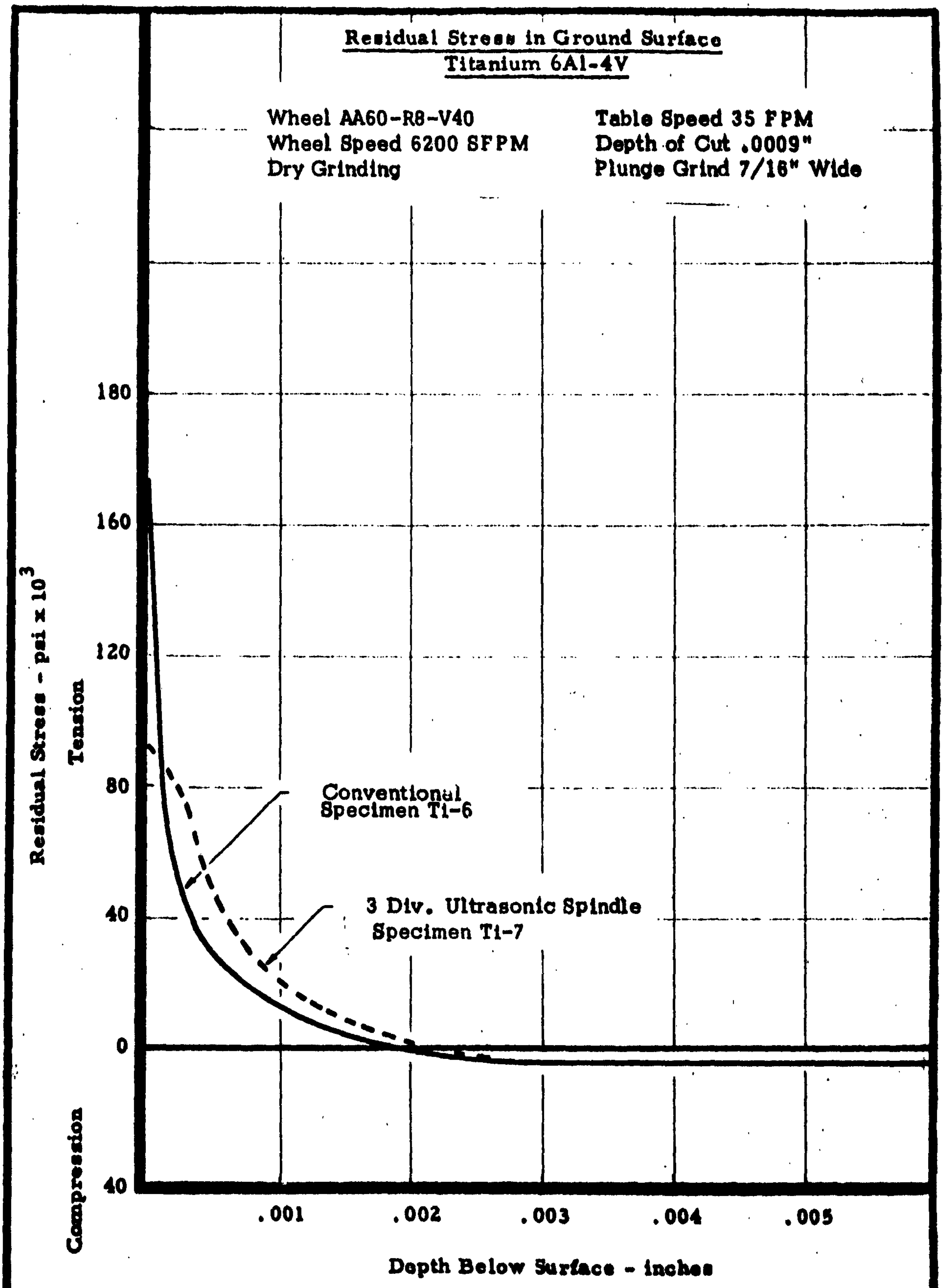
Very truly yours,

METCUT RESEARCH ASSOCIATES INC.

L. J. Nowikowski

L. J. Nowikowski, Vice-President
Manufacturing Research

j
enc.



Residual Stress in Ground Surface
Titanium 6Al-4V
Wheel AA60-R8-V40
Wheel Speed 6200 SFPM
Dry Grinding
Table Speed 35 FPM
Depth of Cut .0009"
Plunge Grind 7/16" Wide
Residual Stress - psi x 10^3
Tension
Compression
180
160
120
80
40
0
40
Conventional Specimen Ti-6
3 Div. Ultrasonic Spindle Specimen Ti-7
.001
.002
.003
.004
.005
Depth Below Surface - inches

Figure 173

The etchants used for the PH 15-7 MO stainless and the 6Al-4V titanium specimens were as follows:

PH 15-7 MO Stainless Steel Etchant

50% H_2O + 40% HCl + 10% HNO_3 (by volume) heated to 150° F.

Specimen etched by immersion using an agitator in the bath to obtain uniform etching. No undesirable effect was produced by the etchant used on the 15-7 MO test specimens.

6Al-4V Titanium Etchant

68% H_2O + 30% HNO_3 + 2% HF (by volume) at room temperature.

Specimen etched by immersion using an agitator in the bath to obtain uniform etching. Each sample was given a heat treatment of 200°F/2 hours after each etching to remove any effect produced by etching. Heat treatment did not reduce hardness level or cause stress relief. Previous experience with stress analysis of titanium has shown this treatment is necessary to obtain valid, consistent data.

The stress analysis was performed as outlined in the procedure shown in Table II. Deflection measurements, to note the change in curvature of the specimen as the test surface was etched away, were made on the fixture sketched in Figure 3. A sample of a typical deflection versus stock removed curve used to obtain the slope data for calculation purposes is shown in Figure 5. The equation used for calculation of the residual stress at any depth is given in Table V. The integral noted in the equation is obtained by performing a mechanical integration on the deflection versus stock removed curve to the desired depth. The modulus of elasticity used on the test samples was as follows.

Ti 6Al-4V	E	$= 16 \times 10^6$ psi
PH 15-7MO	E	$= 16 \times 10^6$ psi

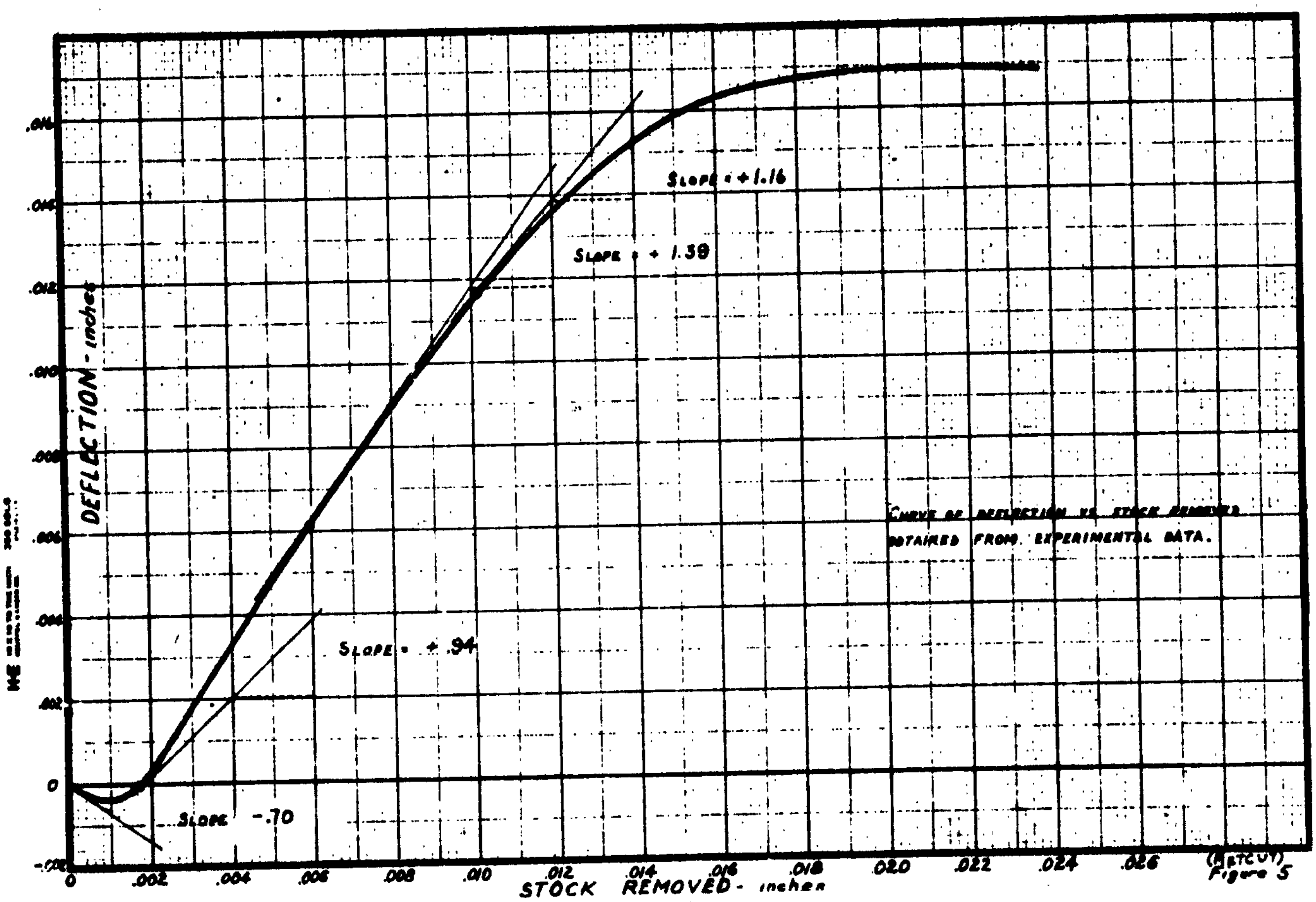

DEFLECTION - inches
STOCK REMOVED - inches
SLOPE = +1.16
SLOPE = + 1.39
SLOPE = + .94
SLOPE -.70
0
.002
.004
.006
.008
.010
.012
.014
.016
.018
.020
.022
.024
.026
Figure 5

Figure 174

TABLE V

BASED ON EQUATION FROM F. STABLEIN

$$S_n = \frac{E}{3\,L^2}\left[(H-h_n)^2\left(\frac{df}{dh}\right)_n - 4\,(H-h_n)\,(f_n) - 2\left(h_n\,f_o\right) - 2\int_o^h f\,dh\right]$$

Where:

S_n	=	Residual stress, pounds/square inch
H	=	Initial thickness of the test specimen, inches
h	=	Stock removed to any depth, inches
f	=	Deflection of specimen at any depth, inches
f_o	=	Initial deflection of the test bar, inches
L	=	One-half gage length, inches
E	=	Modulus of elasticity, pounds/square inch
$\frac{df}{dh}$	=	Slope at any point on deflection versus stock removed curve

TABLE V (continued)

Breakdown of equation for calculation:

$\mathrm{I} = h_n =$ Stock removed, inches

$\mathrm{II} = f_n =$ Change in deflection of specimen at any depth, inches

$\mathrm{III} = \left(\frac{df}{dh}\right)_n =$ Slope at any point on deflection versus stock removed curve

$\mathrm{IV} = (\mathrm{H}) - (\mathrm{I})$

$\mathrm{V} = (\mathrm{III}) \times (\mathrm{IV})^2$

$\mathrm{VI} = 4\,(\mathrm{IV})\,(\mathrm{II})$

$\mathrm{VII} = 2\,(f_o)\,(\mathrm{I})$

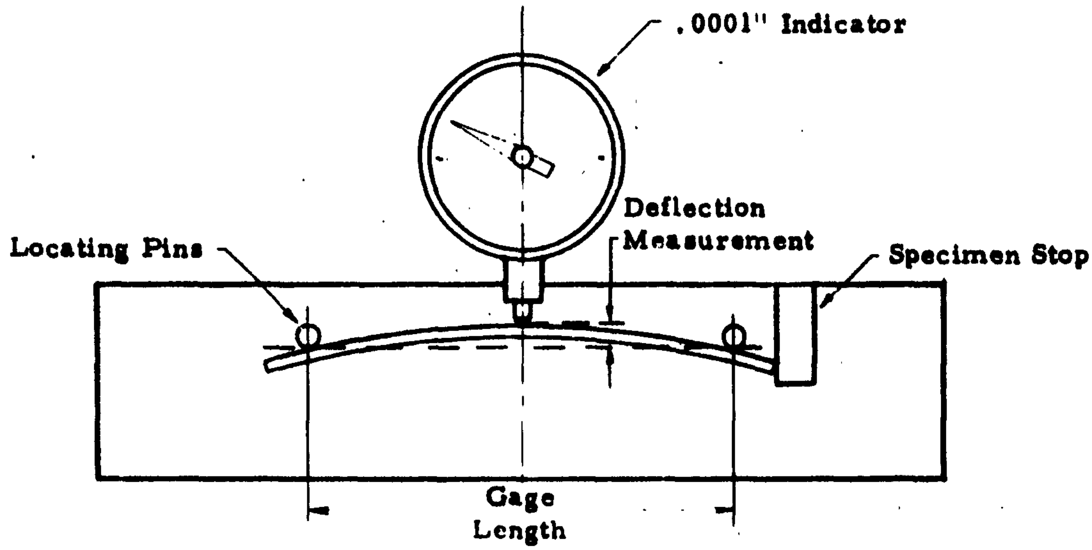
$\mathrm{VIII} = 2 \int_o^h f\,dh$

$K = \frac{E}{3L^2}$

$$\text{Residual Stress} = S_n = K \left[(\mathrm{V}) - (\mathrm{VI}) - (\mathrm{VII}) - (\mathrm{VIII}) \right]$$

Note: Term VIII can be omitted from the calculation without significantly affecting the stress calculation.

DEFLECTION MEASUREMENT



1. Position indicator to 0 using flat gage block of same length as specimen before making deflection measurements.

2. In making deflection measurements, locate the specimen in the same position on the fixture each time.

3. Measure deflection from the back side of the specimen, <u>NOT</u> the test surface, to insure having a smooth surface for indicator contact.

4. Obtain deflection by gently pushing the specimen against the locating pins making sure that no additional bending is produced when making the measurement.

NOTE:

Concave surface on above specimen is the test surface and deflection measurement is being made from the opposite side as outlined above.

Figure 175

Figure 3
(Metcut)

TABLE II

EXPERIMENTAL PROCEDURE FOR STRESS ANALYSIS

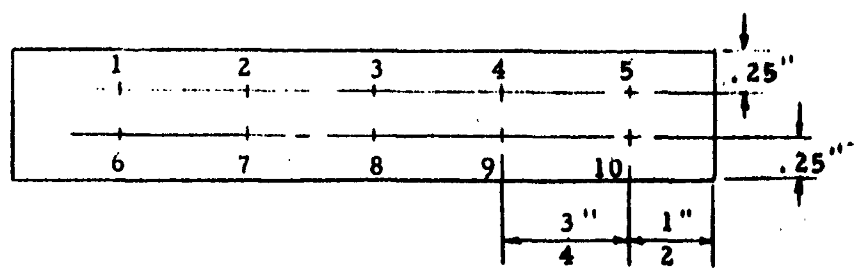
General:

1. Measure deflection by placing indicator button against side opposite to test surface (surface being etched).

2. Position test specimen with number side to left on deflection fixture for each deflection measurement.

3. Lay out 10 equally spaced points for thickness measurement on side opposite to test surface. Use soft lead pencil. Measure thickness using indicating .0001" micrometer in numbered sequence as shown:

Numbered Side



Experimental Technique:

1. Use flat gage block to obtain 0 position on .0001" indicator on fixture.

2. Measure deflection of test specimen. Indicate whether test surface is concave or convex. Deflection is negative (-) if test surface is concave, positive (+) if test surface is convex. Record deflection.

3. Measure thickness of test specimen to obtain initial average thickness of the specimen. Record thickness.

4. Coat back of test specimen with stop-off lacquer to prevent etching of this surface.

TABLE II (continued)

EXPERIMENTAL PROCEDURE FOR STRESS ANALYSIS

Experimental Technique: (continued)

5. Etch test surface removing stock uniformly.

6. After etching dip in bicarbonate of soda solution to neutralize and, then water rinse, dry specimen. Peel off protective coating from back of specimen.

7. Measure thickness in 10 locations. If stock removal is not uniform, preferentially etch high spots by localised swabbing to get uniform stock removal. Record average thickness and stock removed.

8. Measure deflection and record. Be sure that sign (+ or -) for deflection is correct.

9. Coat back of specimen again and repeat etching procedure, thickness and deflection measurements outlined in Items 5, 6, 7 and 8.

   NOTE: Stock removal by etching to be performed in steps as follows:

   a. .0001" steps (approx.) to .0005" stock removed.
   b. .0002" steps (approx.) to .0015" stock removed.
   c. .0005" steps (approx.) to .003" stock removed.
   d. .001" steps (approx.) to .008" stock removed.
   e. .002" to .003" steps (approx.) to finish.

10. Experimental procedure is stopped when no significant change is noted in deflection after two successive steps in stock removal. A minimum of .008" to .010" metal must be removed from the surface of the specimen even though no significant change in deflection is noted at lesser depths.

TABLE II (continued)

EXPERIMENTAL PROCEDURE FOR STRESS ANALYSIS

Experimental Technique: (continued)

11. Plot curve of deflection versus stock removed. Draw smooth curve through experimental points. Positive deflection plotted in first quadrant, negative deflection in fourth quadrant.

12. Physically measure slope of curve for each specific depth. Use algebraic procedure for sign of slope.

13. Record stock removed, deflection and slope information on data sheet for calculation.

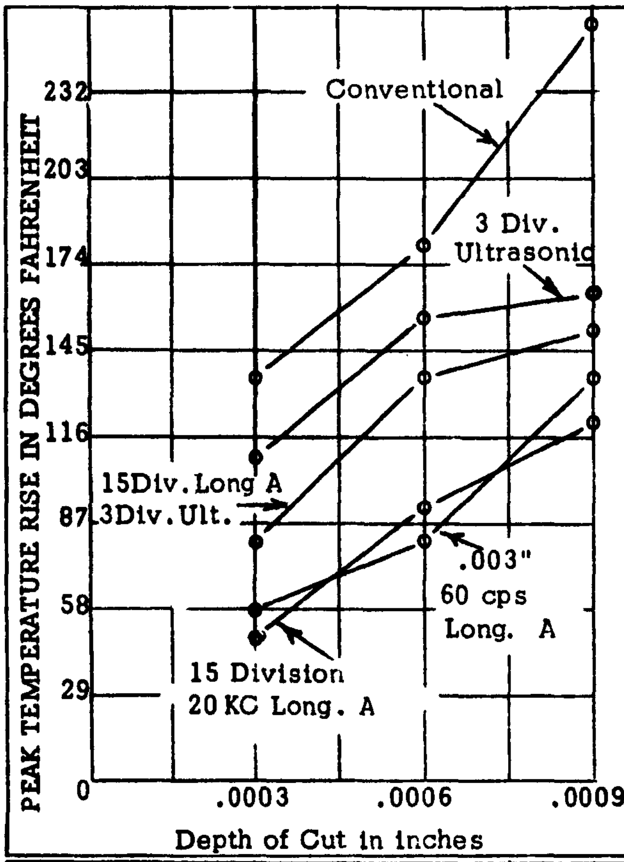
14. Calculate residual stress for each depth.

15. Plot stress distribution curve.

PHASE II

SECTION 10

TEST DATA



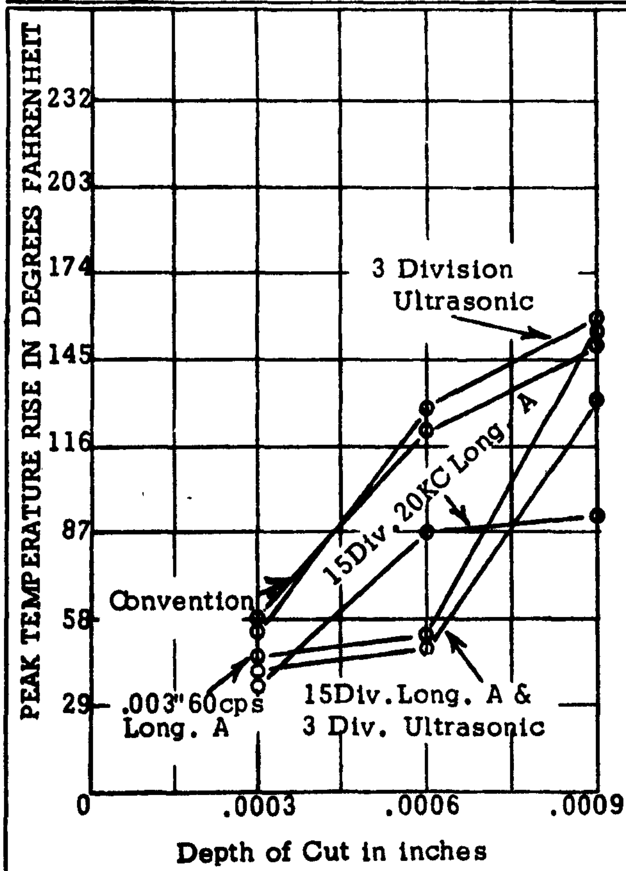
SURFACE GRINDING

PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Rene 41
Wheel	AA60L8-V40
Wheel Speed SFPM	6200
Table Speed	35 FPM

Run Numbers: II- 306 - 320

Figure 176



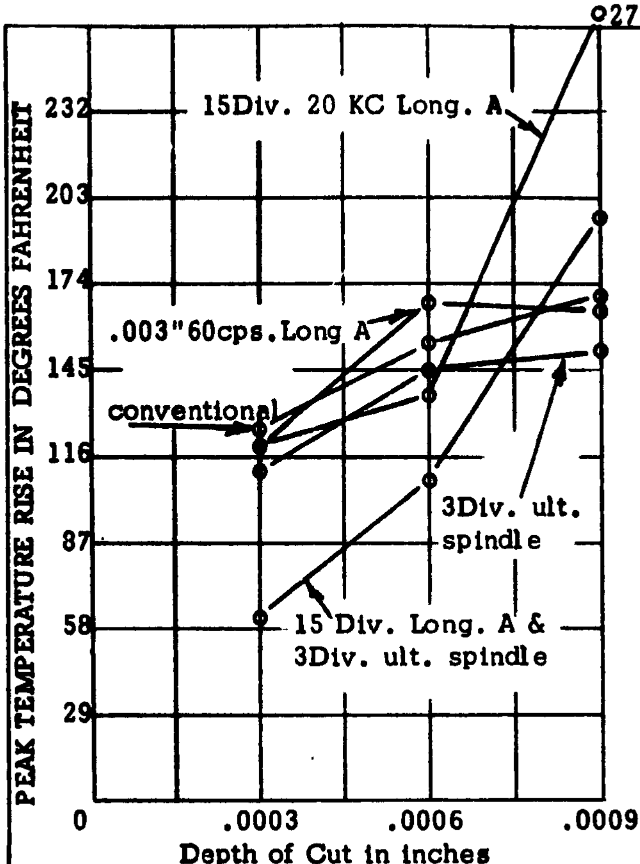
SURFACE GRINDING

PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Rene 41
Wheel	AA60R8-V40
Wheel Speed SFPM	6200
Table Speed	35 FPM

Run Numbers: II- 291 - 305

Figure 177



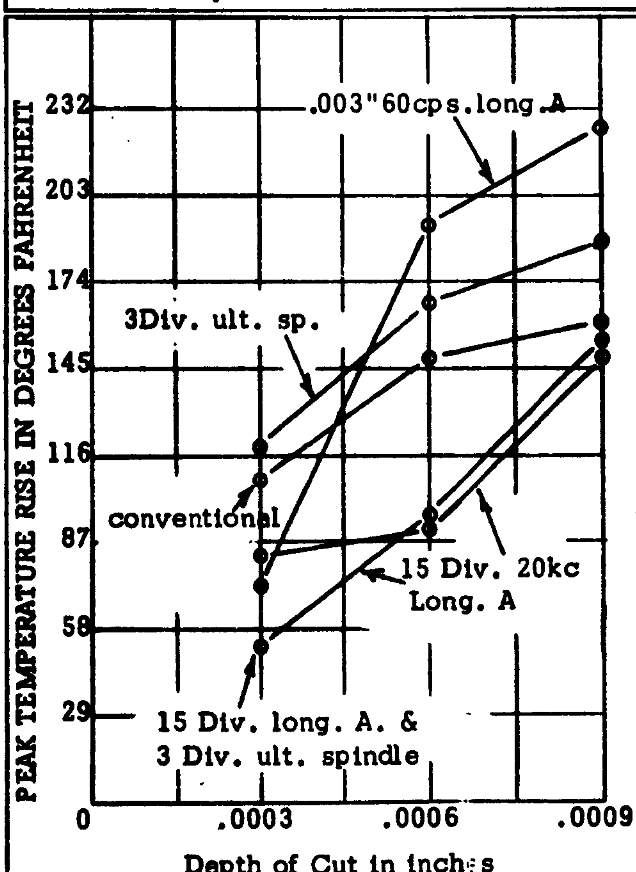
SURFACE GRINDING

<u>**PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER**</u>

Material	**15-7 MO**
Wheel	**AA60L8-V40**
Wheel Speed SFPM	**6200 SFM**
Table Speed	**35 FPM**

Run Numbers: II- 201 - 215

Figure 178



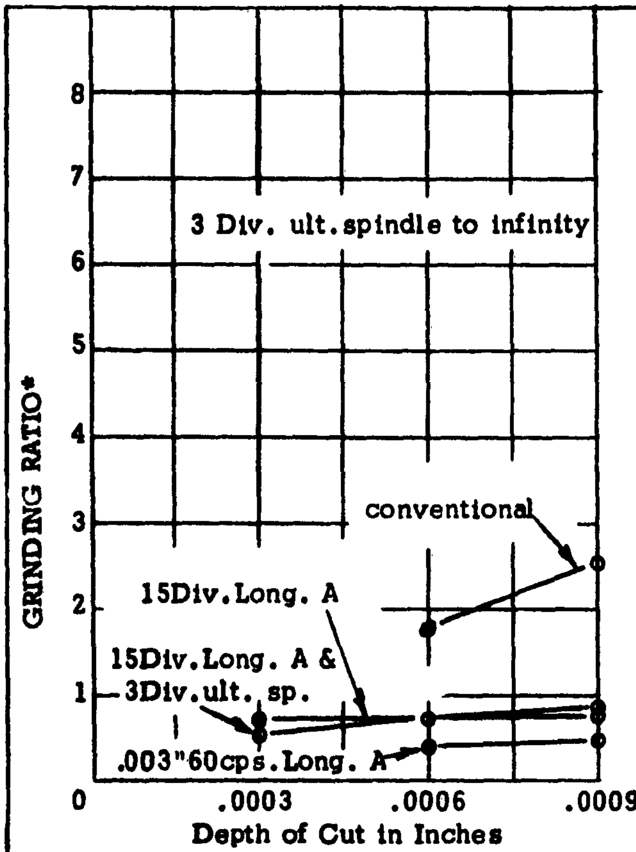
SURFACE GRINDING

<u>**PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER**</u>

Material	**15-7 MO**
Wheel	**AA60R8-V40**
Wheel Speed SFPM	**6200**
Table Speed	**35 FPM**

Run Numbers: II-216 - 230

Figure 179



SURFACE GRINDING

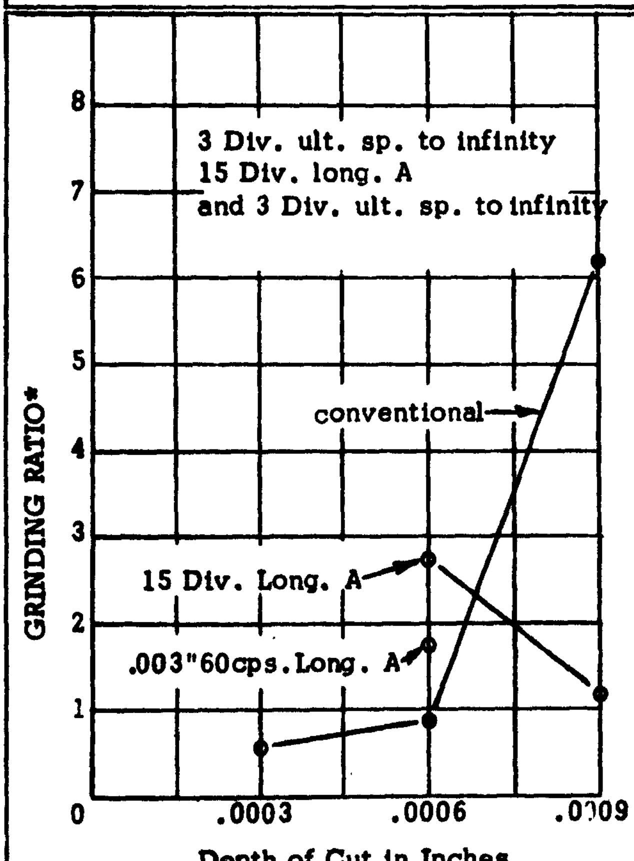
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Ti6Al-4V
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: II-261 - 275

Figure 180



SURFACE GRINDING

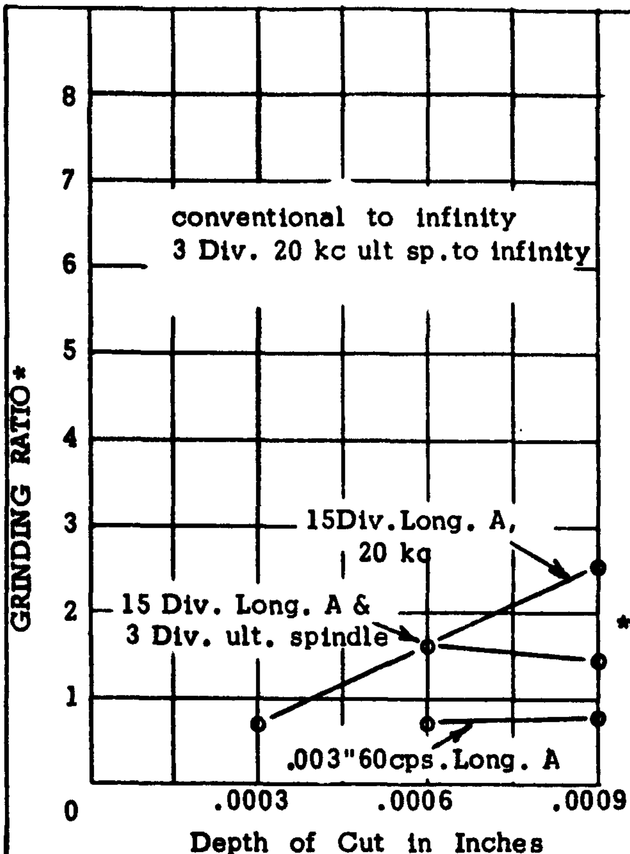
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Ti6Al-4V
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: II- 276 - 290

Figure 181



SURFACE GRINDING

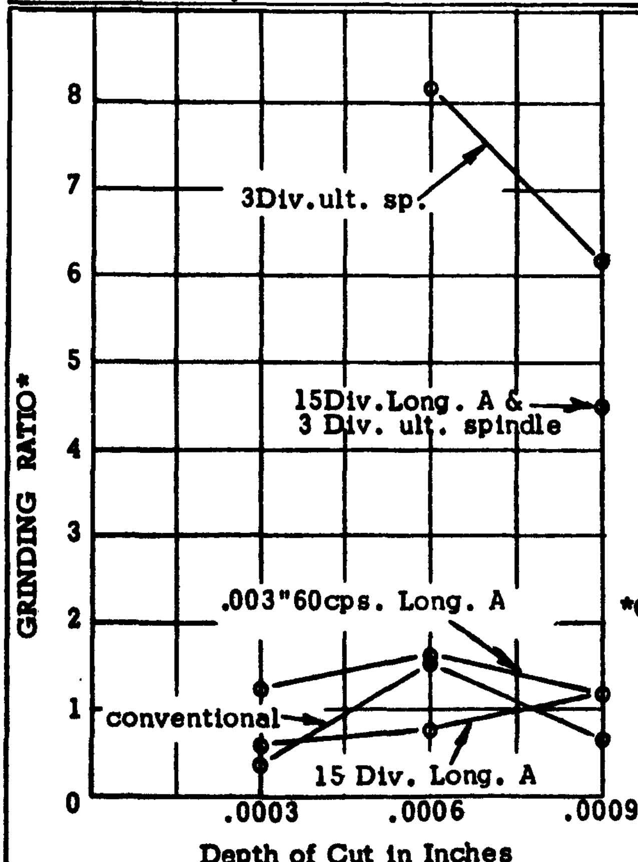
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	H - 11
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: II-231 - 245

Figure 182



SURFACE GRINDING

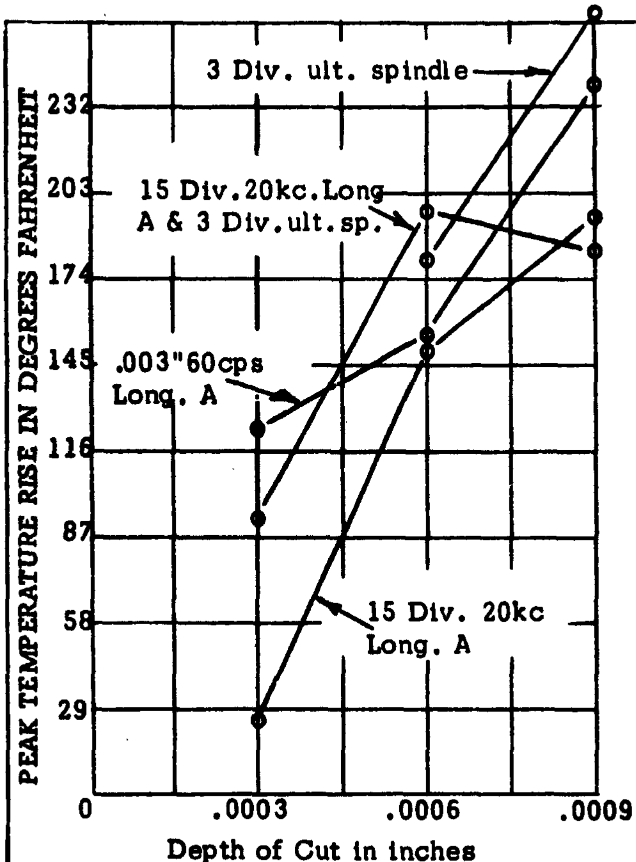
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	H - 11
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: II-246 - 260

Figure 183



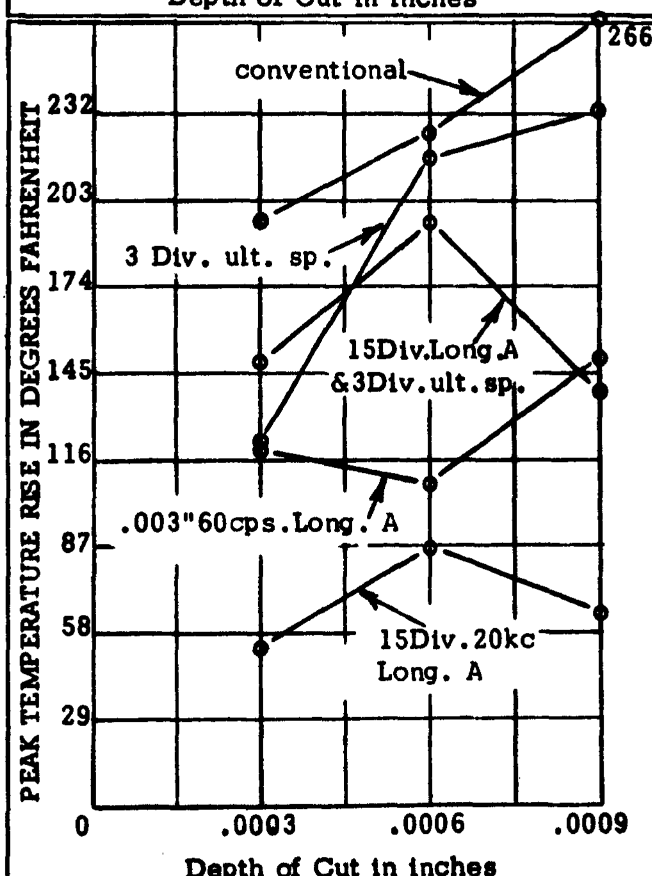
SURFACE GRINDING

<u>PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER</u>

Material	Ti6Al-4V
Wheel	AA60L8-V40
Wheel Speed SFPM	6200
Table Speed	35 FPM

Run Numbers: II-261 - 275

Figure 184



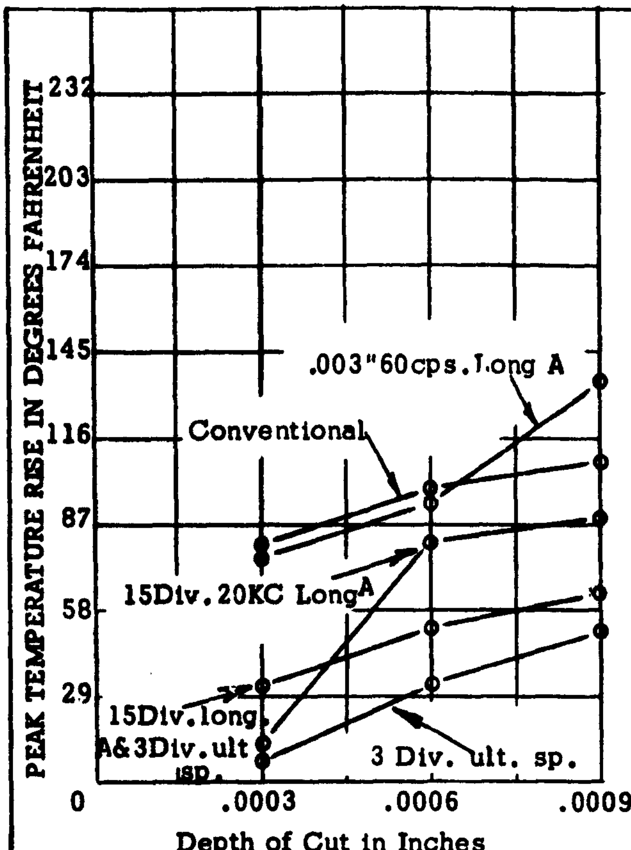
SURFACE GRINDING

<u>PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER</u>

Material	Ti6Al-4V
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Run Numbers: II-276-290

Figure 185



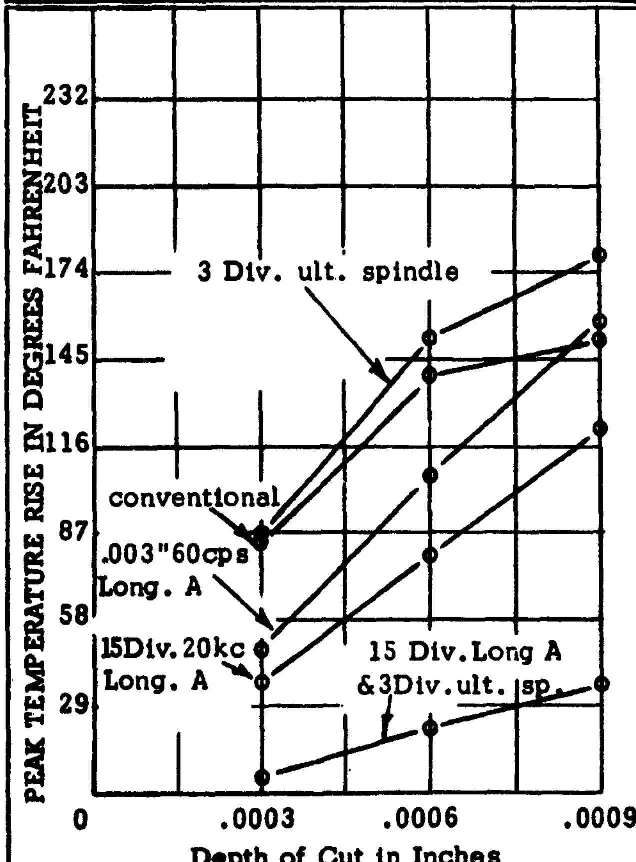
SURFACE GRINDING

PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	H-11
Wheel	AA60L8-V40
Wheel Speed SFPM	6200
Table Speed	35 FPM

Run Numbers: II- 231 - 245

Figure 186



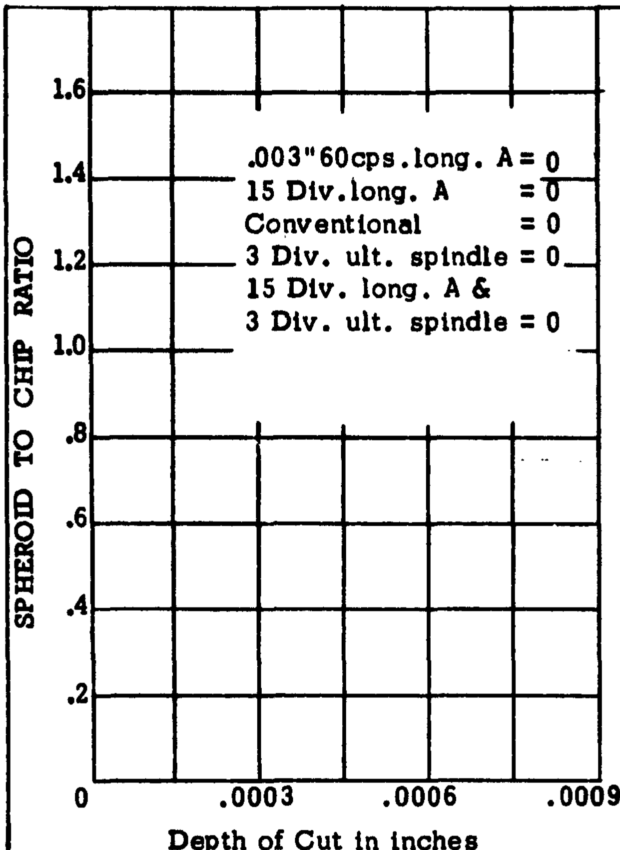
SURFACE GRINDING

PEAK TEMPERATURE RISE AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	H-11
Wheel	AA60R8-V40
Wheel Speed SFPM	6200
Table Speed	35 FPM

Run Numbers: II - 246 - 260

Figure 187



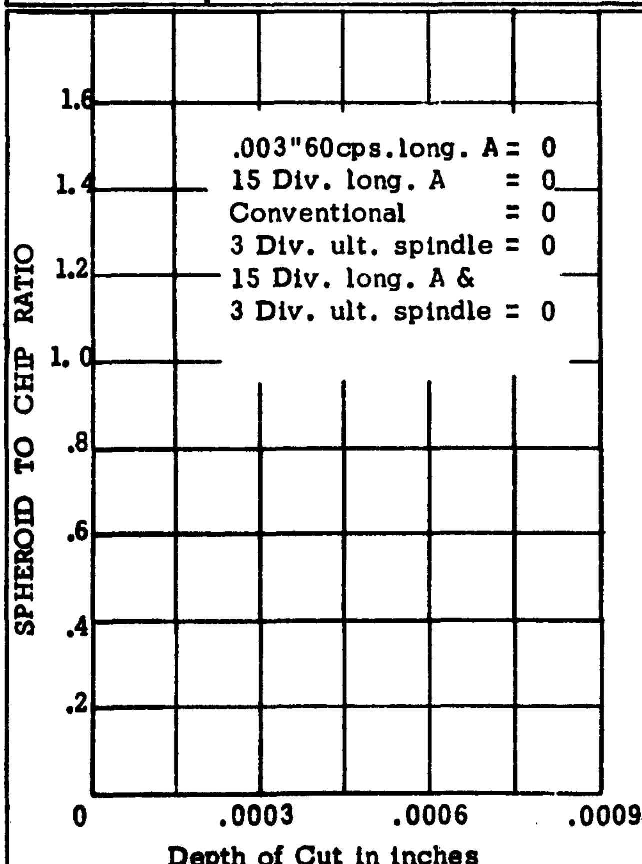
SURFACE GRINDING

SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material Rene 41
Wheel AA60L8-V40
Wheel Speed SFPM 6200
Table Speed 35 FPM

Run Numbers: II-291 - 305

Figure 188



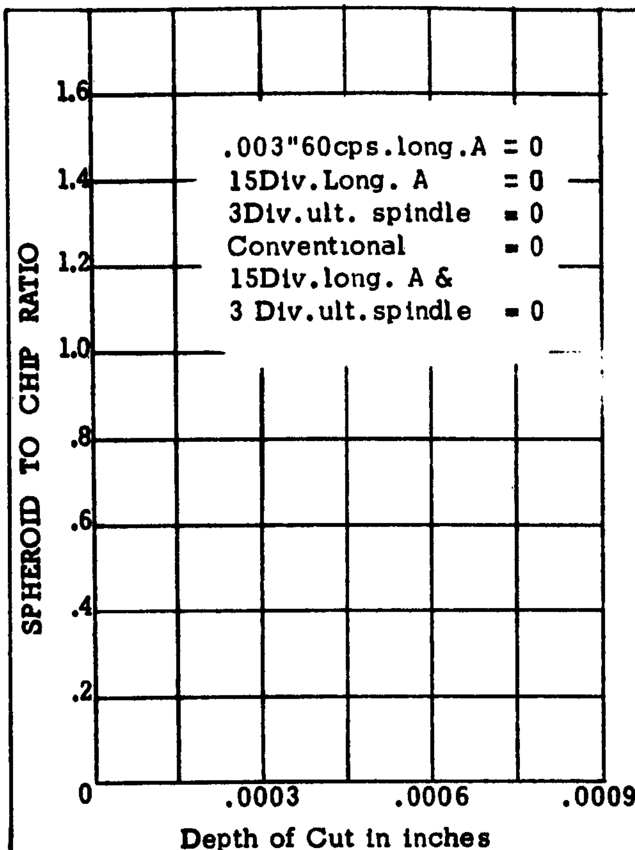
SURFACE GRINDING

SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material Rene 41
Wheel AA60R8-V40
Wheel Speed SFPM 6200
Table Speed 35 FPM

Run Numbers: II-306 - 320

Figure 189



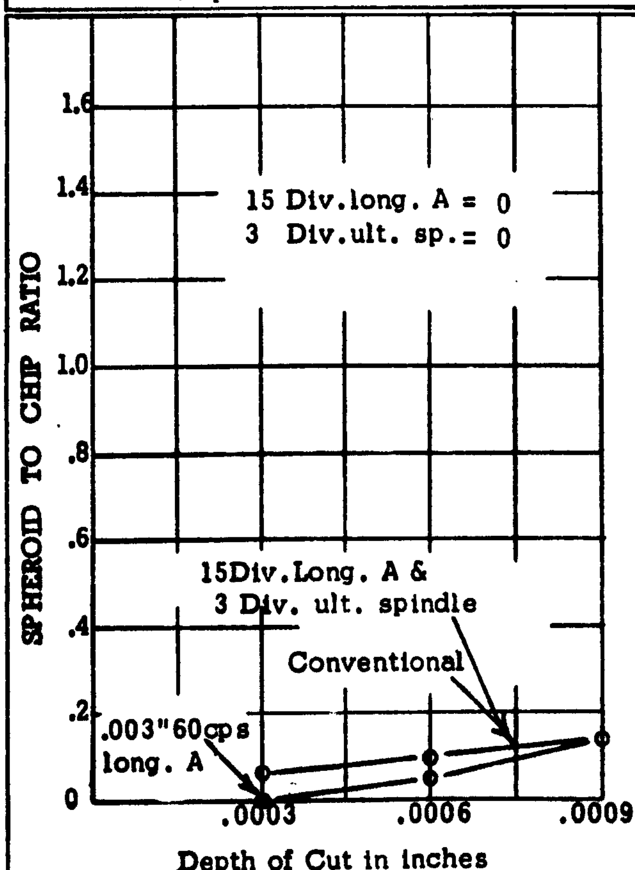
SURFACE GRINDING

SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	AA60L8-V40
Wheel Speed SFPM	6200
Table Speed	35 FPM

Run Numbers:II-201 - 215

Figure 190



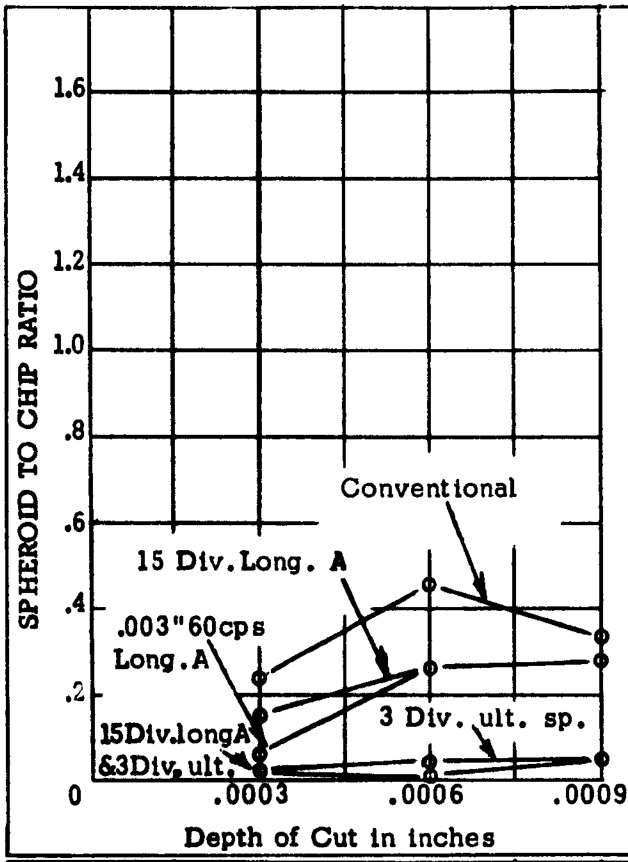
SURFACE GRINDING

SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	AA60R8-V40
Wheel Speed SFPM	6200
Table Speed	35 FPM

Run Numbers:II -216 - 230

Figure 191



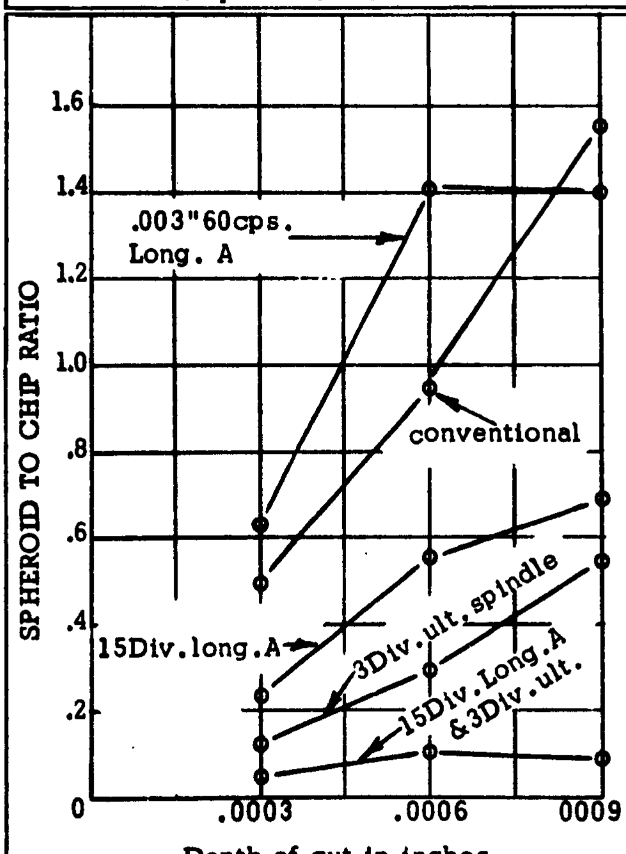
SURFACE GRINDING

SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	H-11
Wheel	AA60L8-V40
Wheel Speed SFPM	6200
Table Speed	35 FPM

Run Numbers: II-231 - 245

Figure 192



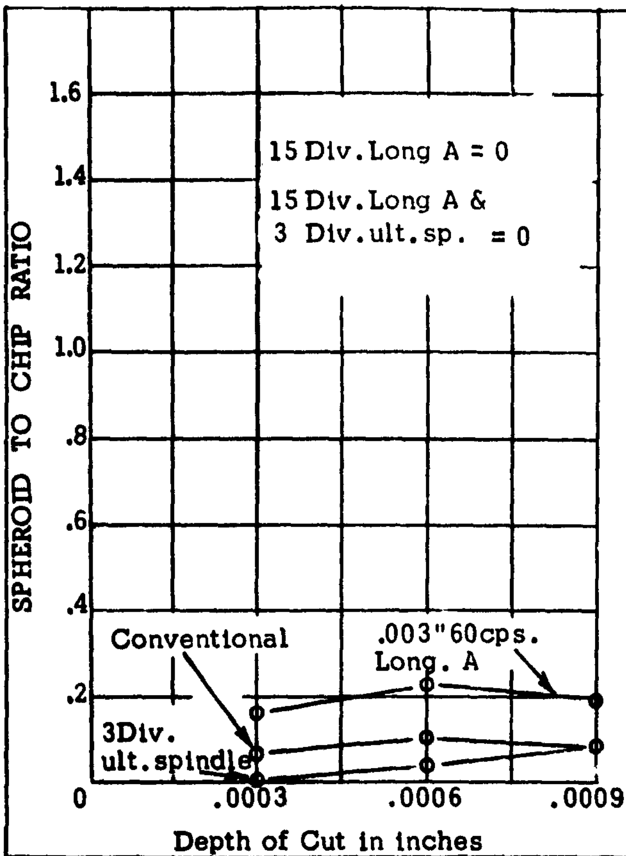
SURFACE GRINDING

SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	H-11
Wheel	AA60R8-V40
Wheel Speed SFPM	6200
Table Speed	35 FPM

Run Numbers: II-246 - 260

Figure 193



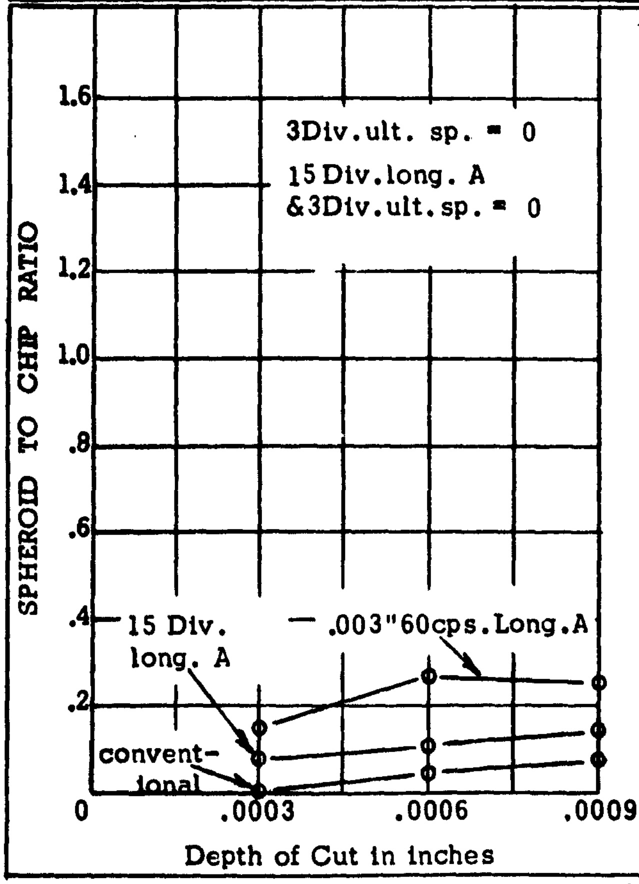
SURFACE GRINDING

<u>SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER</u>

Material	Ti6Al-4V
Wheel	AA60L8-V40
Wheel Speed SFPM	6200
Table Speed	35 FPM

Run Numbers: II-261 - 275

Figure 194



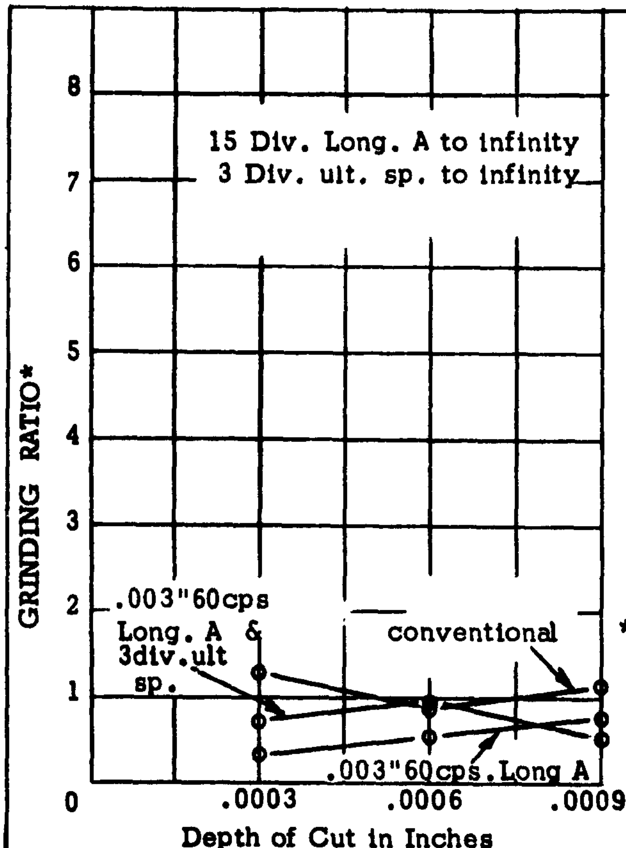
SURFACE GRINDING

<u>SPHEROID TO CHIP RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER</u>

Material	Ti6Al-4V
Wheel	AA60R8-V40
Wheel Speed SFPM	6200
Table Speed	35 FPM

Run Numbers: II-276 - 290

Figure 195



SURFACE GRINDING

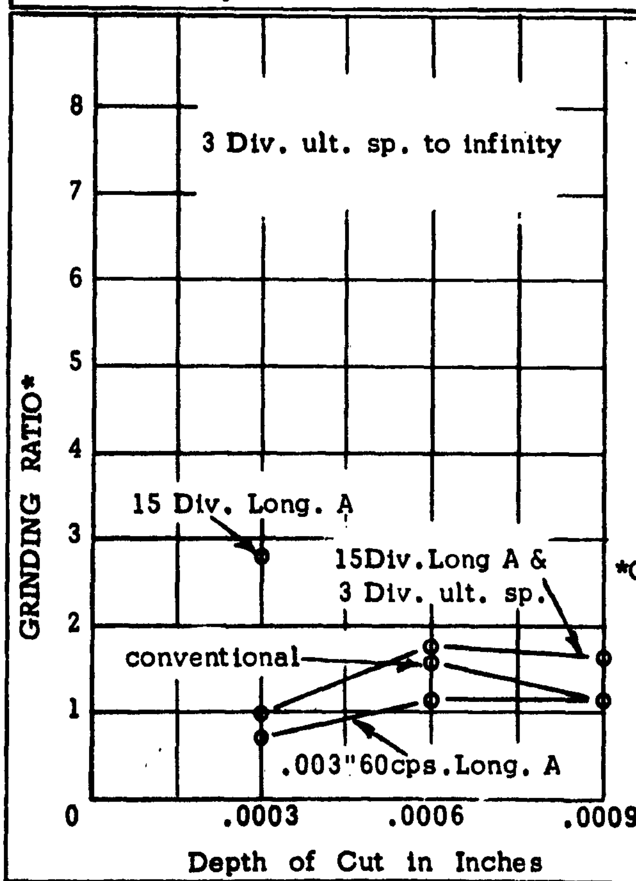
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Rene 41
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: II-291 - 305

Figure 196



SURFACE GRINDING

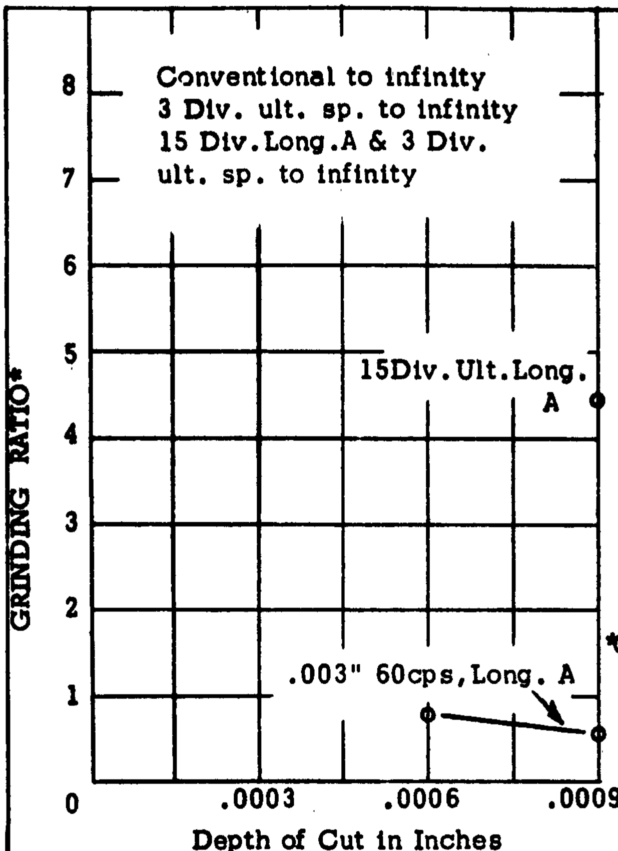
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Rene 41
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: II-306 - 320

Figure 197



SURFACE GRINDING

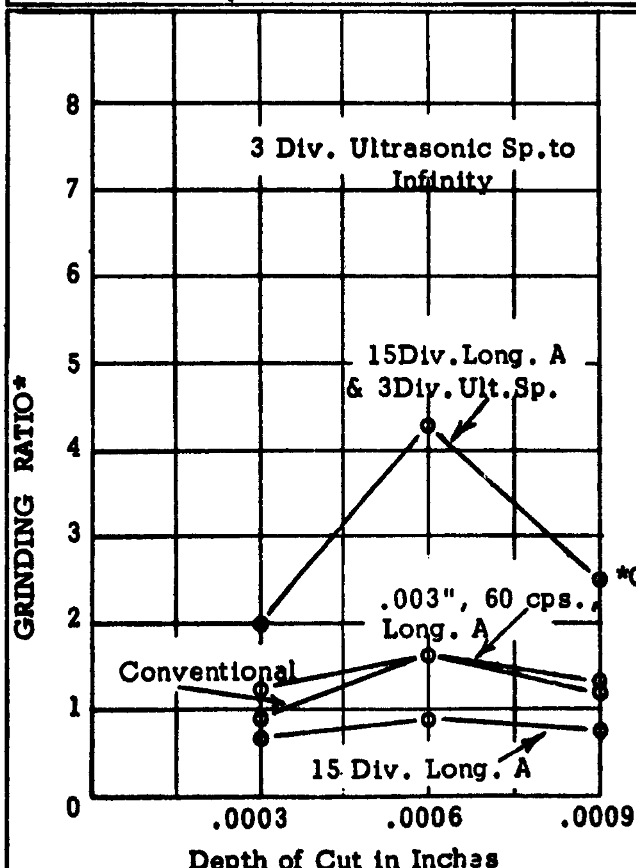
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15 - 7 MO
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: II-201 - 215

Figure 198



SURFACE GRINDING

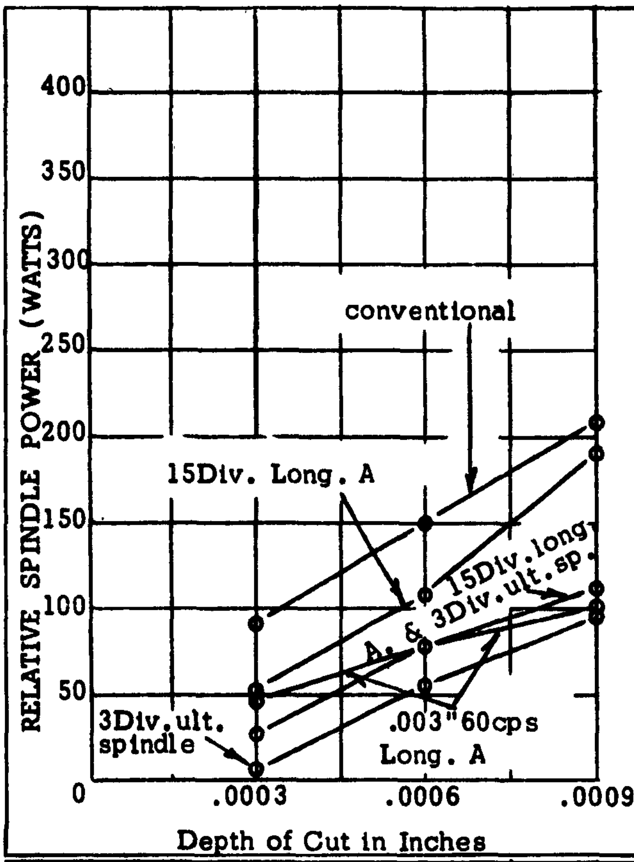
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: II-216 - 230

Figure 199



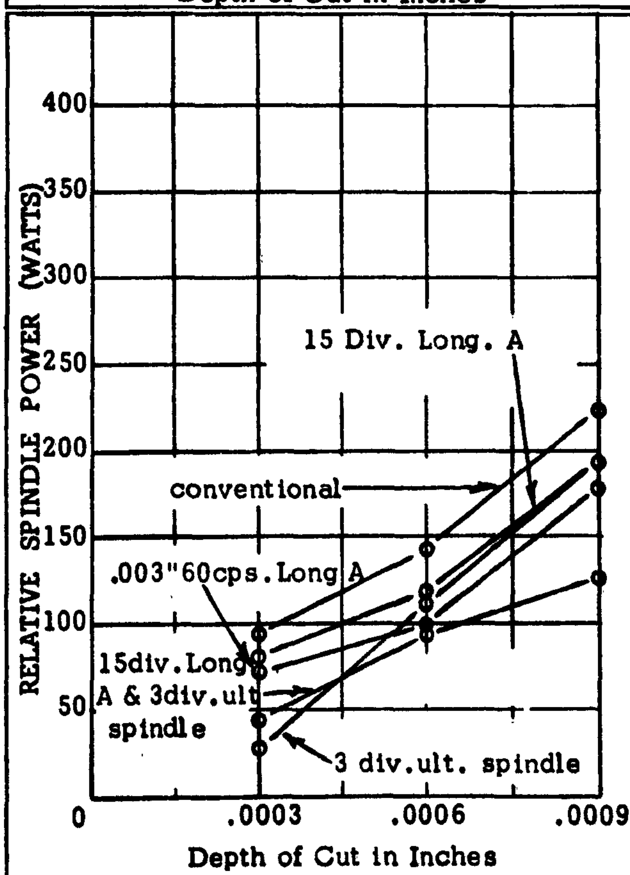
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	H-11
Wheel	AA60L8-V40
WheelSpeed	6200 SFPM
Table Speed	35 FPM

Run Numbers: II-231 - 245

Figure 200



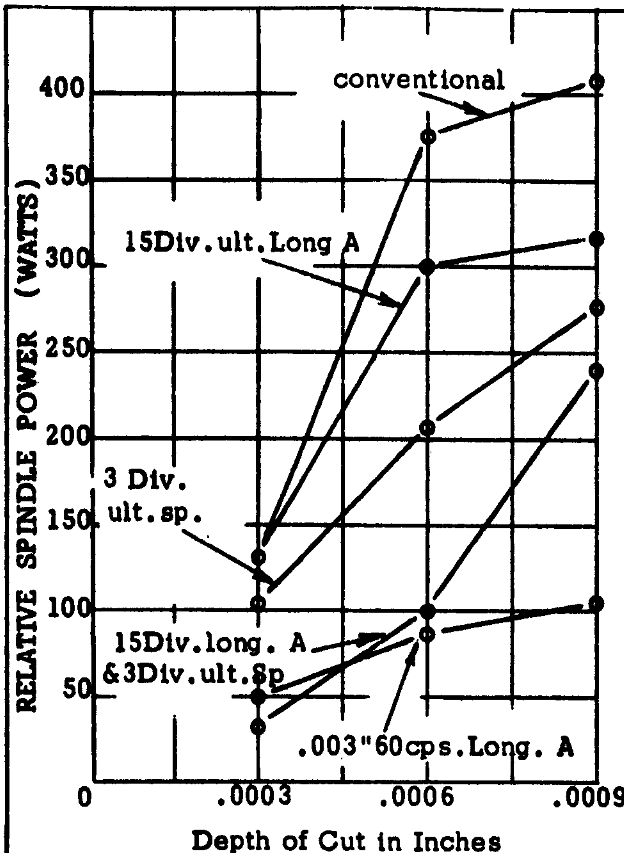
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	H-11
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Run Numbers:II- 246 - 260

Figure 201



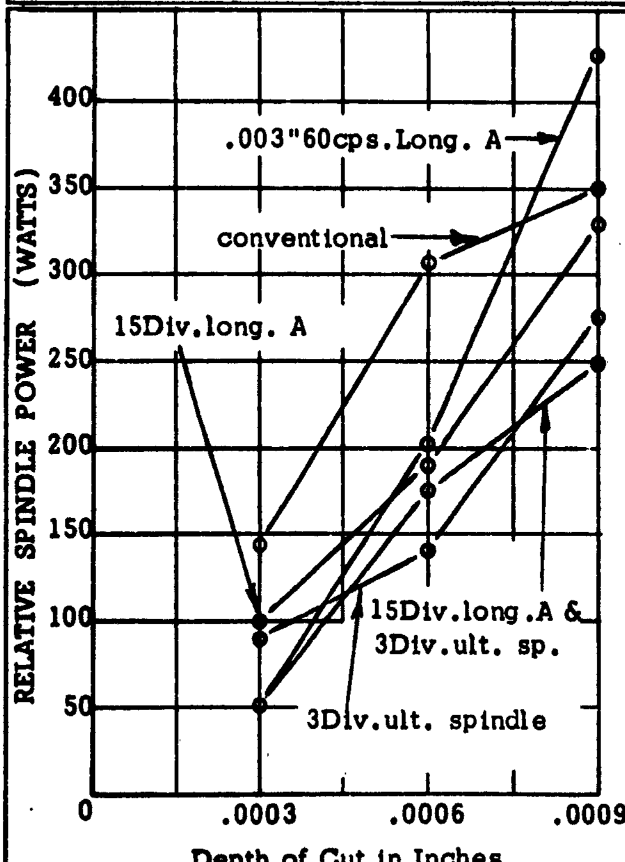
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Run Numbers: II- 201 - 215

Figure 202



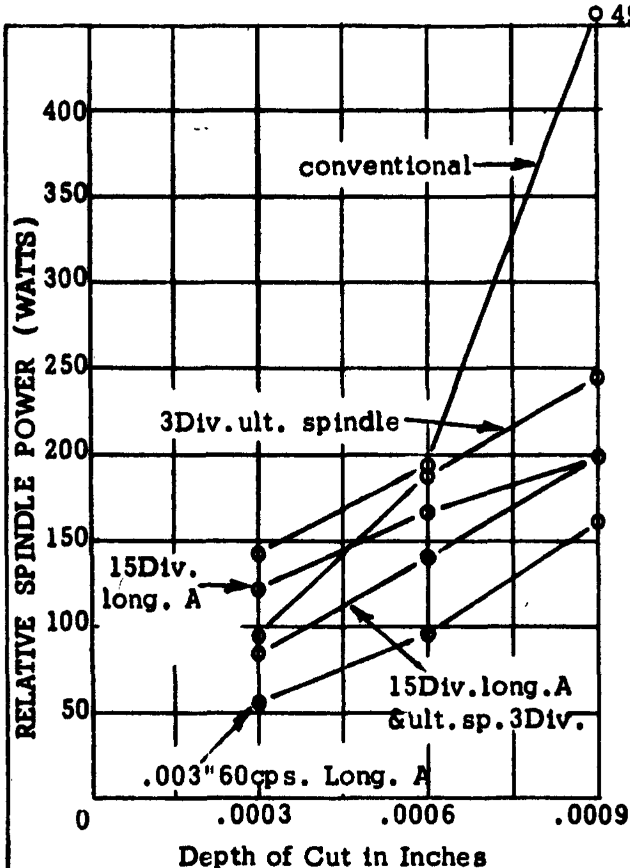
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15 - 7 MO
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Run Numbers: II- 216 - 230

Figure 203



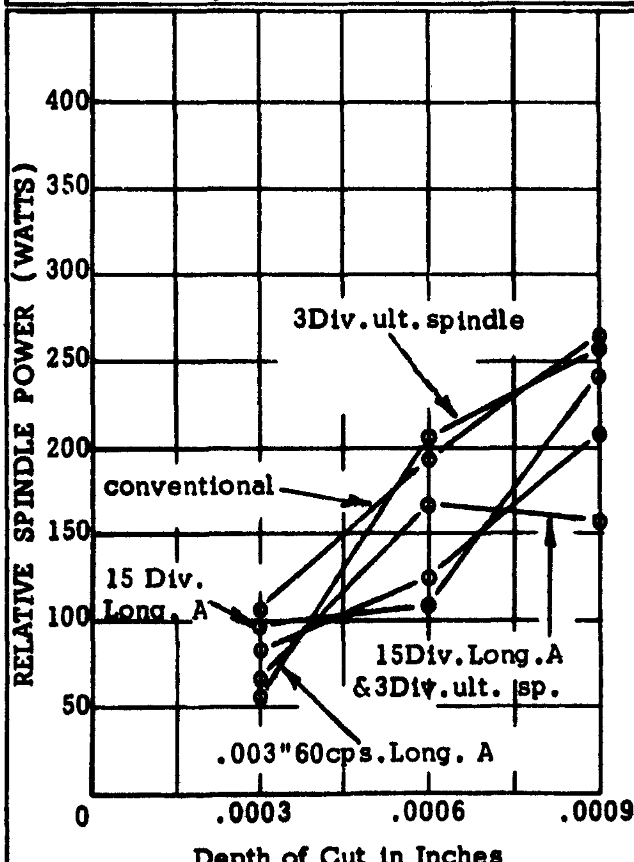
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Rene 41
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Run Numbers:II - 291 - 305

Figure 204



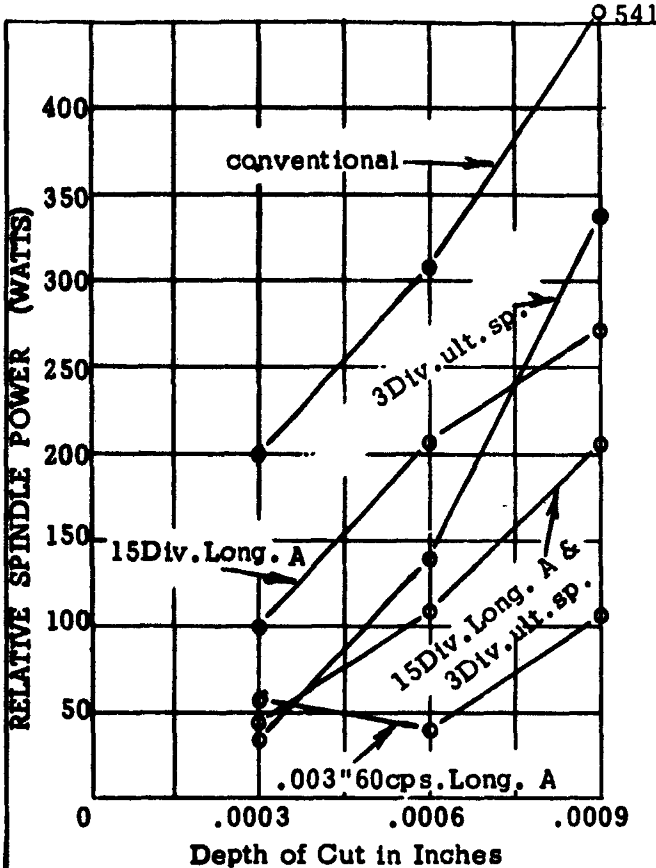
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Rene 41
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Run Numbers: II- 306 - 320

Figure 205



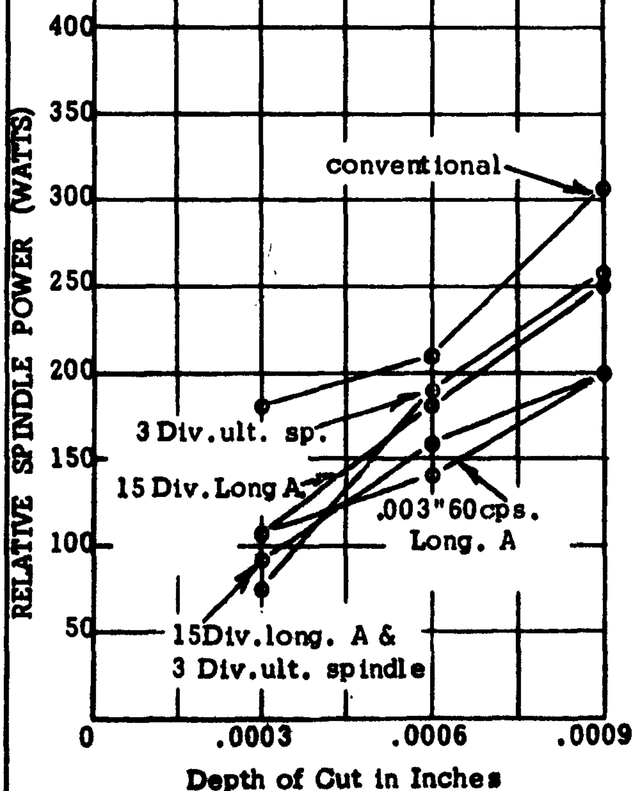
SURFACE GRINDING

<u>SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER</u>

Material	Ti6Al-4V
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Run Numbers: II-261 - 275

Figure 206



SURFACE GRINDING

<u>SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER</u>

Material	Ti6Al-4V
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Run Numbers: II-276 - 290

Figure 207

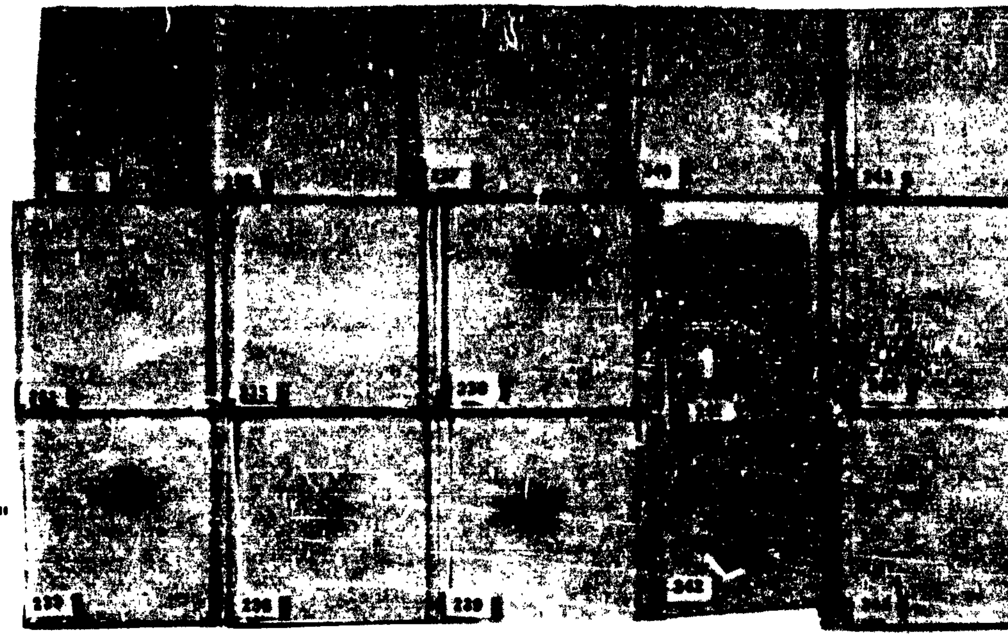
Material H-11 Wheel AA60-L8-V40

Conv. | 3Div.Ult.Sp. | 15Div.Long A | .003"60cps. Long. A | 15Div.Long A & 3Div.Ult.S

.0003"

.0006"

.0009"



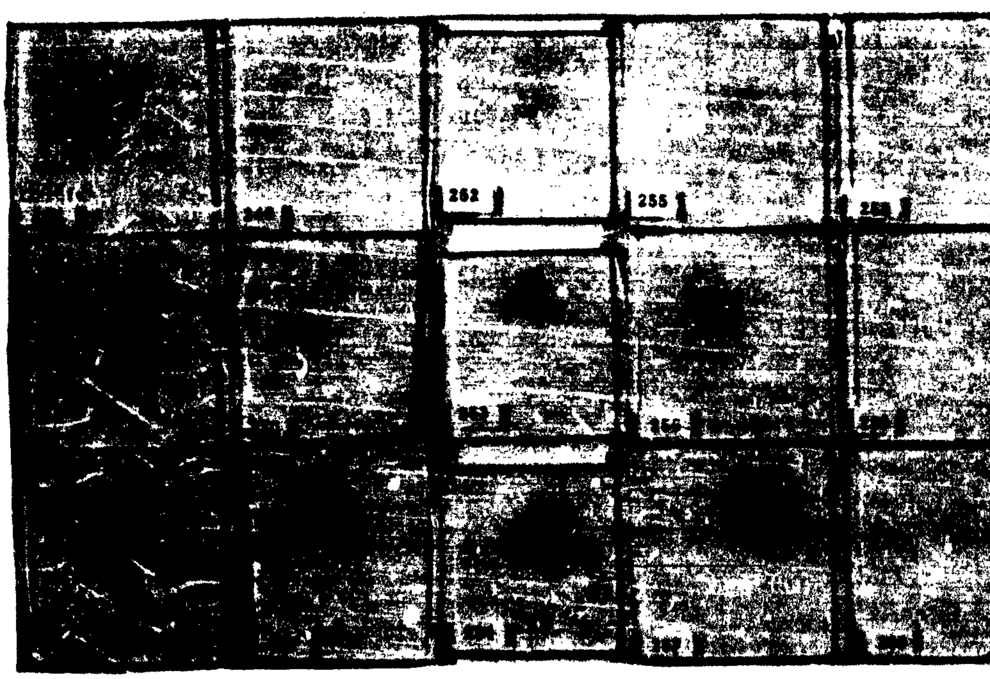
Material H-11 Wheel AA60-R8-V40

Conv. | 3Div.Ult.Sp. | 15Div.Long A | .003"60cps Long. A | 15Div.Long &3Div.Ult.

.0003"

.0006"

.0009"

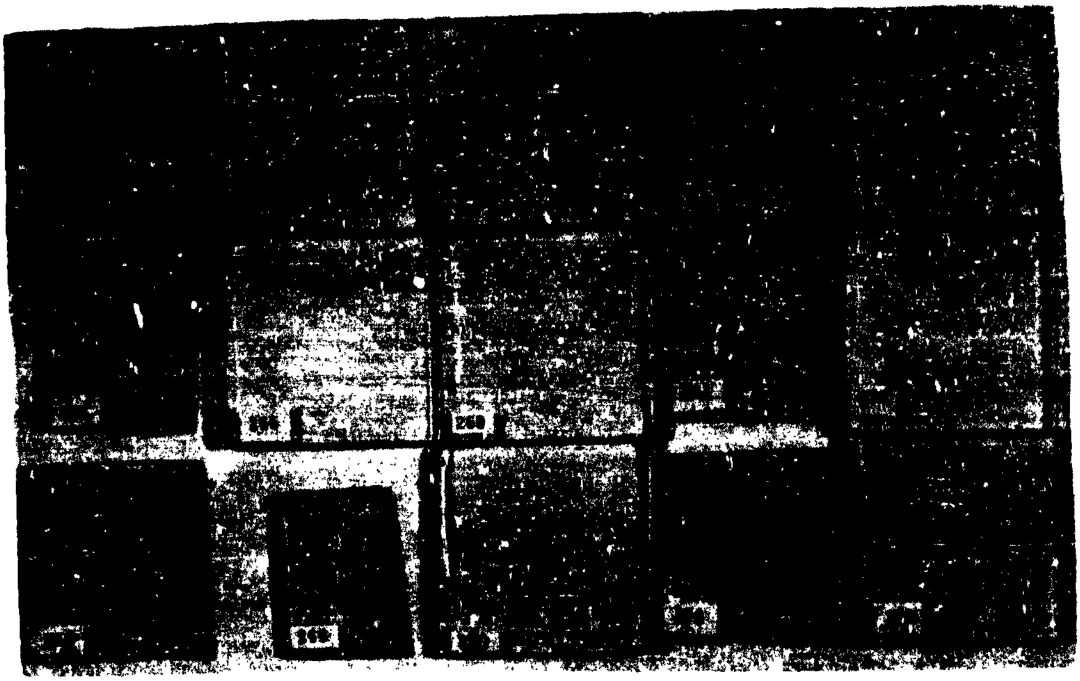


Figure

Material Ti6Al-4V Wheel AA60-L8-V40

Conv. 3Div.Ult.Sp. 15Div.Long.A .003"60cps. Long.A 15Div.Long.A &3Div.Ult.Sp.

.0003"
.0006"
.0009"



Material Ti6Al-4V Wheel AA60-R8-V40

Conv. 3Div.Ult.Sp. 15Div.Long.A .003"60cps. Long.A 15Div.Long.A &3Div.Ult.Sp.

.0003"
.0006"
.0009"

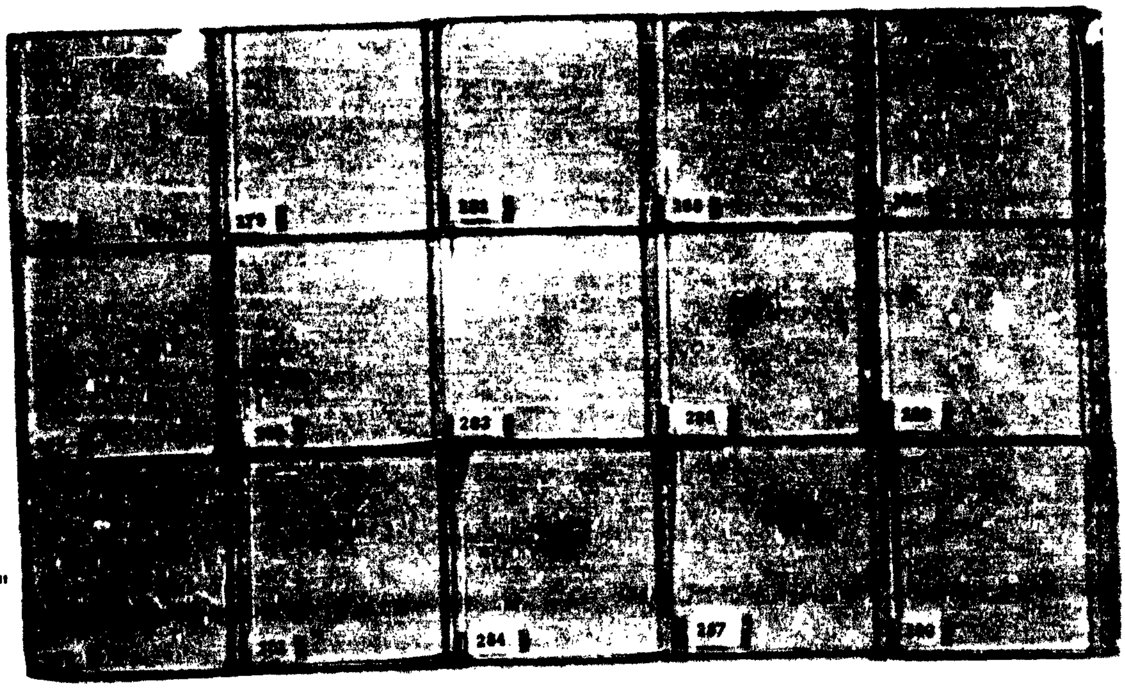


Figure 209

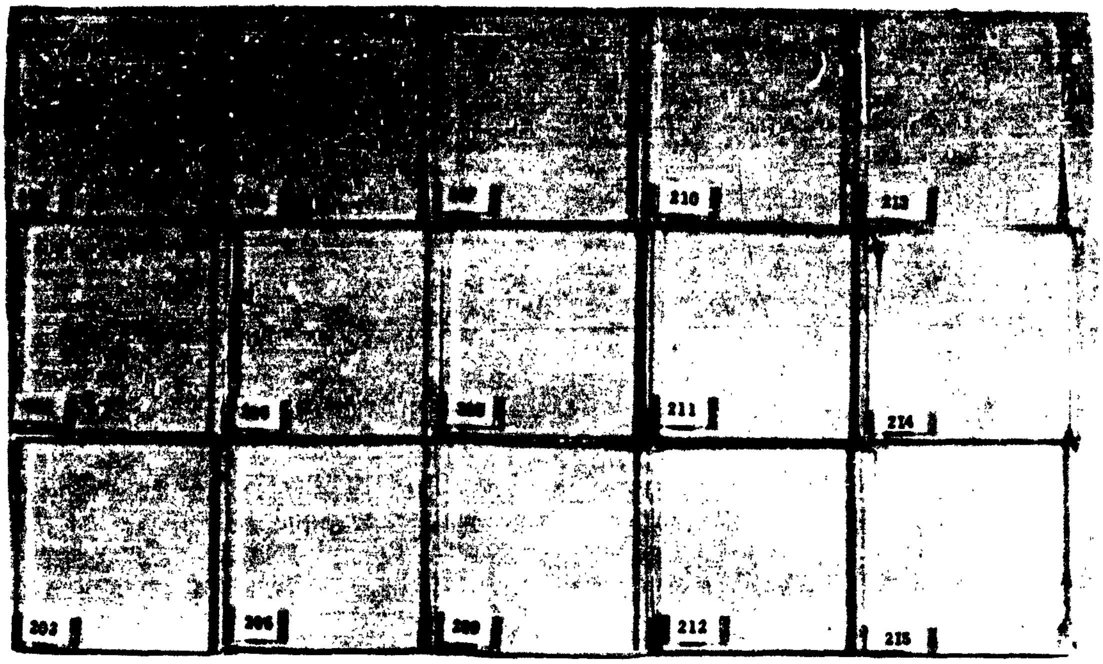
Material 15-7MO Wheel AA60-L8-V40

Conv. | 3Div.Ult.Sp. | 15Div.Long.A | .003"60cps. Long. A | 15Div.Long.A &3Div.Ult.Sp.

.0003"

.0006"

.0009"



Material 15-7MO Wheel AA60-R8-V40

Conv. | 3Div.Ult.Sp. | 15Div.Long.A | .003"60cps. Long. A | 15Div.Long.A &3Div.Ult.Sp.

.0003"

.0006"

.0009"

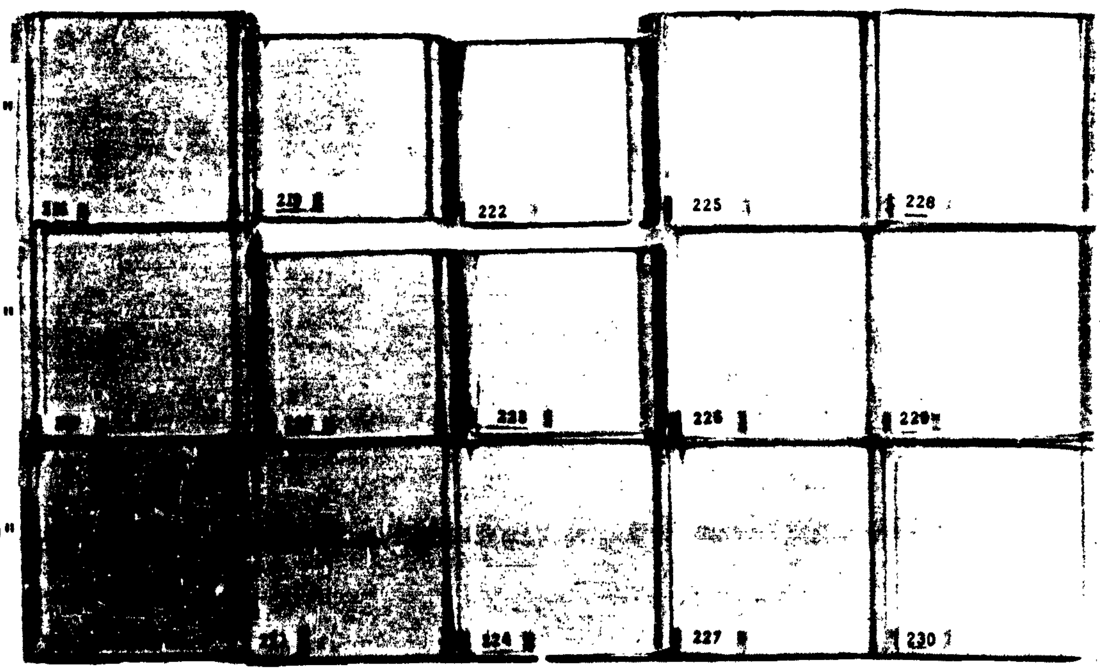
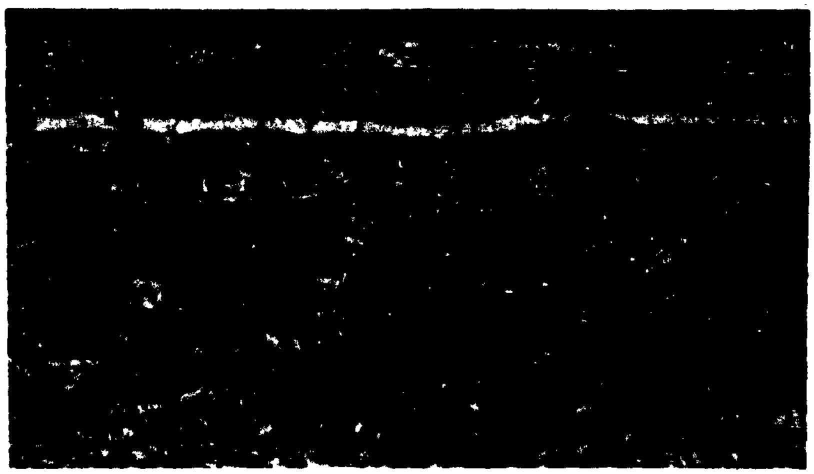


Figure 210

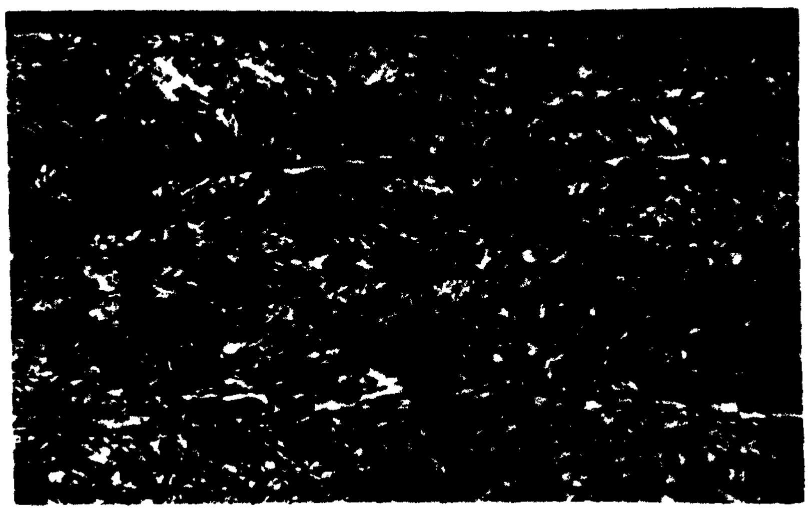
PHOTOMICROGRAPHS*

Note Surface Working

Material 15-7MO
Wheel AA60-L8-V40
Table Speed 35 FPM
Wheel Speed 6200 SFPM
Conventional .0009"Cut
Surface Micro-Hardness
Before Grind - Vickers 575
After Grind - Vickers 393



Material 15-7MO
Wheel AA60-L8-V40
Table Speed 35 FPM
Wheel Speed 6200 SFPM
Longitudinal .0009"Cut
15 Division Amplitude
Surface Micro-Hardness
Before Grind - Vickers 558
After Grind - Vickers 370



Material 15-7MO
Wheel AA60-L8-V40
Table Speed 35 FPM
Wheel Speed 6200 SFPM
Ult. Spindle 3 Div. Amp.
.0009" Cut
Surface Micro-Hardness
Before Grind - Vickers 532
After Grind - Vickers 509

*All photomicrographs were taken at the ground surface of a longitudinal cross section through the center of the samples. They are enlarged 500 times.

Figure 211

PHOTOMICROGRAPHS

Material Ti6Al-4V
Table Speed 35 FPM
Wheel AA60-L8-V40
Wheel Speed 6200 SFPM
Conventional .0009" Cut
Surface Micro-Hardness
Before Grind - Vickers 502
After Grind - Vickers 558

Material Ti6Al-4V
Table Speed 35 FPM
Wheel AA60-L8-V40
Wheel Speed 6200 SFPM
Longitudinal .0009" Cut
15 Division Amplitude
Surface Micro-Hardness
Before Grind - Vickers 627
After Grind - Vickers 604

Material Ti6Al-4V
Table Speed 35 FPM
Wheel AA60-L8-V40
Wheel Speed 6200 SFPM
Ult. Spindle 3 Div. Amp.
.0009" Cut
Surface Micro-Hardness
Before Grind - Vickers 558
After Grind - Vickers 619

*All photomicrographs were taken at the ground surface of a longitudinal cross section through the center of the samples. They are enlarged 500 times.

Figure 212

GRINDING RATIOS

Wheel AA60-R8-V40
Wheel Speed 4000 SFPM

Depth of Cut .0006" plunge cut
Table Speed 35 FPM

Type of Grind*	H-11	Ti6Al-4V	Rene 41	15-7 MO
Conventional	9.34	.53	.58	.81
3 Div. Ult. Spindle	70.86	4.60	.72	1.34
15 Div. Long. A	9.37	.88	.46	.54
15 Div. Long. A and 3 Div. Ult. Spindle	5.58	.57	.43	.50

Figure 213

* All Runs for these grinding ratios were made with 50 to 75 passes

GRINDING RATIOS

Wheel AA60-L8-V40
Wheel Speed 4000 SFPM

Depth of Cut .0006" plunge cut
Table Speed 35 FPM

Type of Grind*	H-11	Ti6Al-4V	Rene 41	15-7 MO
Conventional	.34	.31	1.04	.62
3 Div. Ult. Spindle	4.89	.59	1.53	.95
15 Div. Long. A	1.81	.39	.33	.35
15 Div. Long. A and 3 Div. Ult. Spindle	1.29	.36	.28	.32

Figure 214

* All Runs for these grinding ratios were made with 50 to 75 passes

MICRO-HARDNESS CHECKS* ON TEST SPECIMENS

Material Ti-6Al-4V
Depth of Cut .0009" plunge cut

Wheel Speed 6200 SFPM
Table Speed 35 F P M

Type of Grind	Wheel AA60-L8-V40		Wheel AA60-R8-V40	
	Before	After	Before	After
Conventional	502	558	494	492
15 Div. Long. A	627	604	502	549
.003" 60 cps. Long. A	502	501	473	501
3 Div. Ultrasonic Spindle	558	611	519	528
15 Div. Long. A & 3 Div. Ultrasonic Spindle	460	482	516	518

Figure 215

Material H-11
Depth of Cut .0009" plunge cut

Wheel Speed 6200 SFPM
Table Speed 35 F P M

Type of Grind	Wheel AA60-L8-V40		Wheel AA60-R8-V40	
	Before	After	Before	After
Conventional	795	842	776	771
15 Div. Long. A	820	826	781	1261
.003" 60 cps. Long. A	836	839	831	1074
3 Div. Ultrasonic Spindle	785	863	885	927
15 Div. Long. A & 3 Div. Ultrasonic Spindle	868	880	810	868

Figure 216

* Using Sheffield Micro Hardness Tester - All Values Vickers - Average 3 Tests

MICRO - HARDNESS CHECKS* ON TEST SPECIMENS

Material 15-7 MO
Depth of Cut .0009" plunge cut

Wheel Speed 6200 SFPM
Table Speed 35 F P M

Type of Grind	Wheel AA60-L8-V40		Wheel AA60-R8-V40	
	Before	After	Before	After
Conventional	575	393**	521	535
15 Div. Long. A	532	509	494	516
.003" 60 cps. Long. A	509	546	518	663
3 Div. Ultrasonic Spindle	558	370	516	490
15 Div. Long. A & 3 Div. Ultrasonic Spindle	516	483	514	540

Figure 217

Material Rene 41
Depth of Cut .0009" plunge cut

Wheel Speed 6200 SFPM
Table Speed 35 F P M

Type of Grind	Wheel AA60-L8-V40		Wheel AA60-R8-V40	
	Before	After	Before	After
Conventional	666	464**	637	608
15 Div. Long. A	633	615	613	558
.003" 60 cps. Long. A	627	555	613	573
3 Div. Ultrasonic Spindle	644	613	603	600
15 Div. Long. A & 3 Div. Ultrasonic Spindle	593	593	644	613

Figure 218

*Using Sheffield Micro Hardness Tester - All Values Vickers - Average 3 Tests

**Conventional Grinding conditions apparently have made a decrease in the hardness of the specimen.

SURFACE FINISHES

Material Ti6Al-4V
Depth of Cut .0009" plunge cut

Wheel Speed 6200 SFPM
Table Speed 35 FPM

R M S VALUE IN MICRO INCHES

Type of Grind	Wheel AA60L8-V40	Wheel AA60R8-V40
Conventional	32	130
15 Div. Long. A	28	55
3 Div. Ult. Spindle	32	90
.003" 60 cps Long. A	60	52
15 Div. Long. A and 3 Div. Ult. Spindle	80	110

Figure 219

Material H-11
Depth of Cut .0009" plunge cut

Wheel Speed 6200 SFPM
Table Speed 35 F P M

R M S VALUE IN MICRO INCHES

Type of Grind	Wheel AA60L8-V40	Wheel AA60R8-V40
Conventional	30	60
15 Div. Long. A	42	65
3 Div. Ult. Spindle	55	52
.003" 60 cps Long. A	115	115
15 Div. Long. A and 3 Div. Ult. Spindle	105	67

Figure 220

SURFACE FINISHES

Material 15-7MO
Depth of Cut .0009" plunge cut

Wheel Speed 6200 SFPM
Table Speed 35 FPM

RMS VALUE IN MICRO INCHES

Type of Grind	Wheel AA60-L8-V40	Wheel AA60-R8-V40
Conventional	45	52
15 Div. Long. A	40	36
3 Div. Ult. Spindle	37	65
.003" 60 cps Long. A	40	40
15 Div. Long. A and 3 Div. Ult. Spindle	50	125

Figure 221

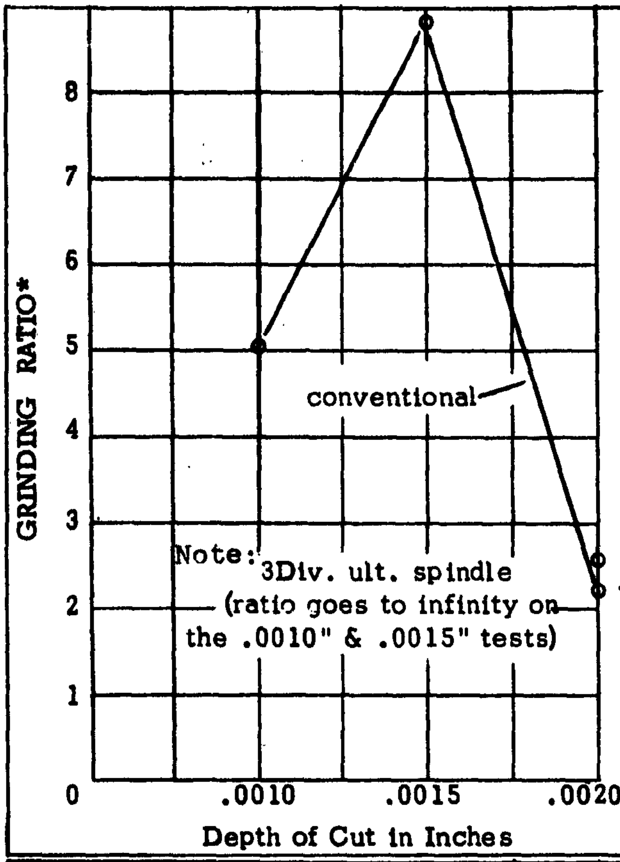
Material Rene 41
Depth of Cut .0009" plunge cut

Wheel Speed 6200 SFPM
Table Speed 35 FPM

RMS VALUE IN MICRO INCHES

Type of Grind	Wheel AA60-L8-V40	Wheel AA60-R8-V40
Conventional	26	47
15 Div. Long. A	40	40
3 Div. Ult. Spindle	50	50
.003" 60 cps Long. A	62	57
15 Div. Long. A and 3 Div. Ult. Spindle	115	200

Figure 222



SURFACE GRINDING

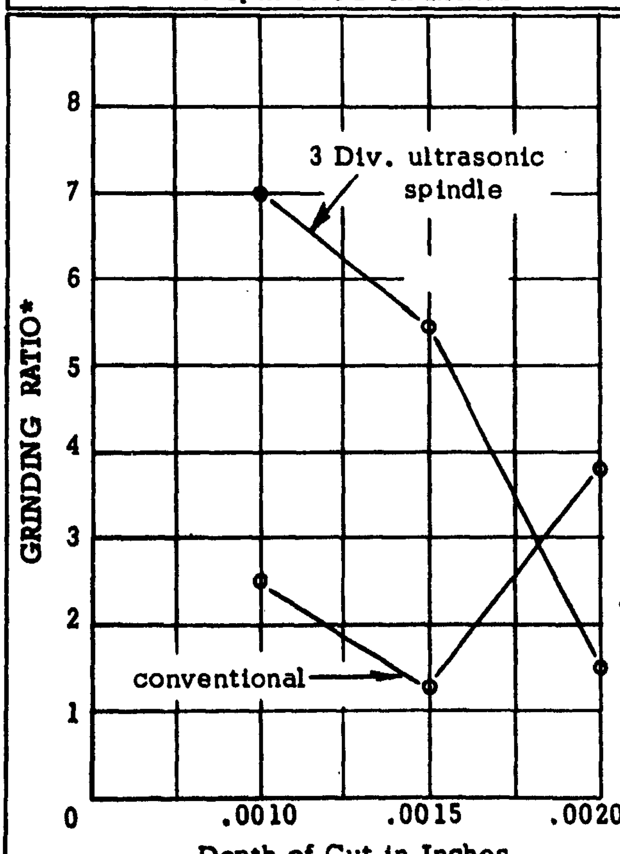
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7 MO
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
With Coolant	

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: II- 419 - 424

Figure 223



SURFACE GRINDING

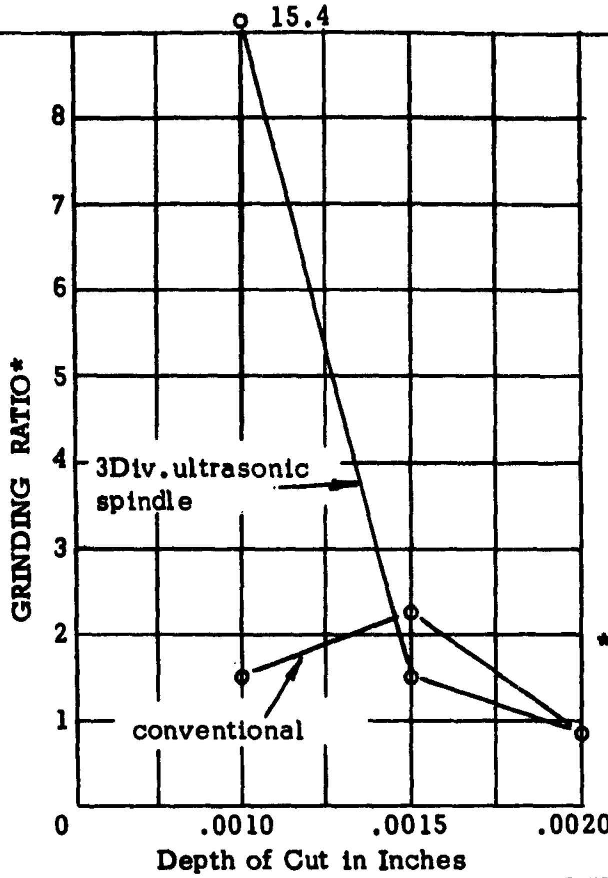
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15-7MO
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
With Coolant	

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: II- 413 - 418

Figure 224



SURFACE GRINDING

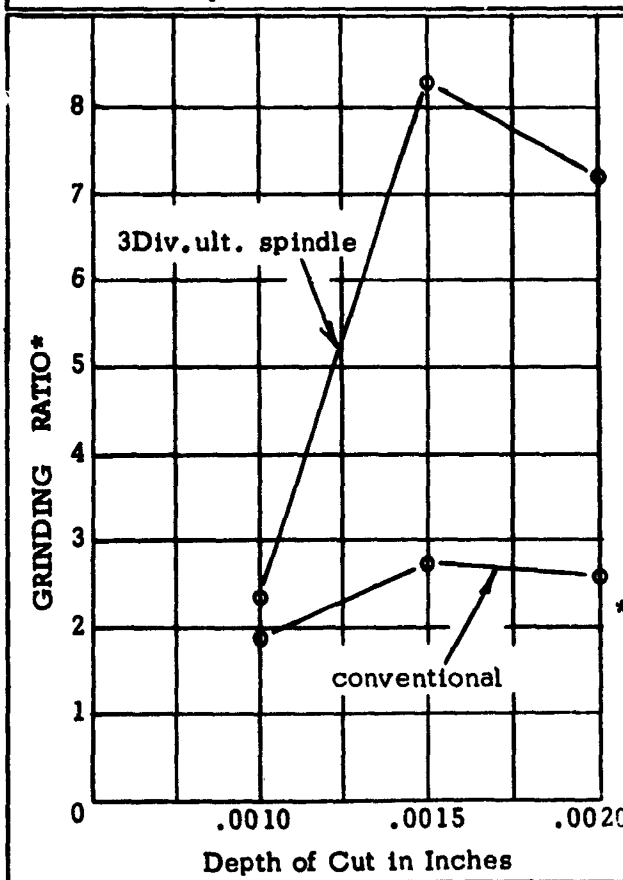
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Rene 41
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers:II-491 - 496

Figure 225



SURFACE GRINDING

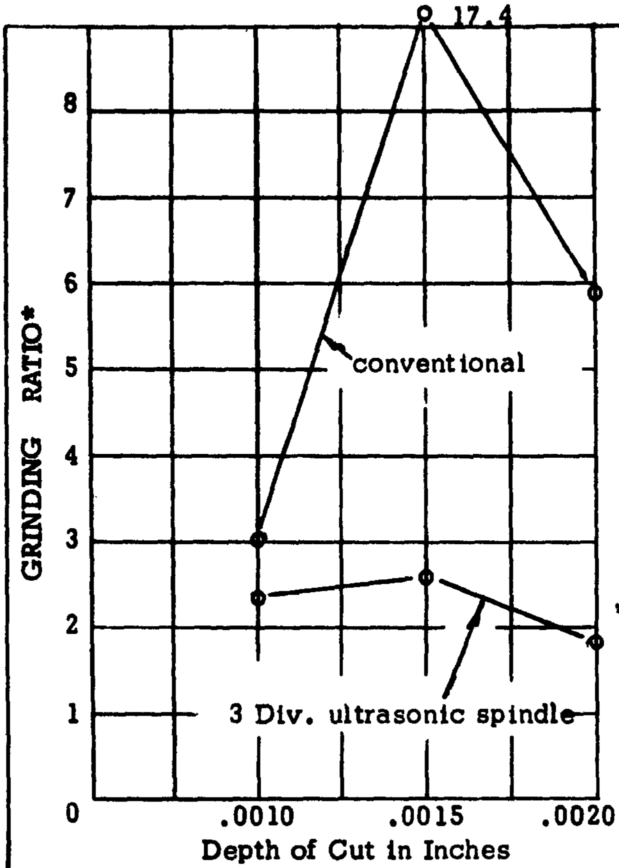
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Rene 41
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers:II-485 - 490

Figure 226



SURFACE GRINDING

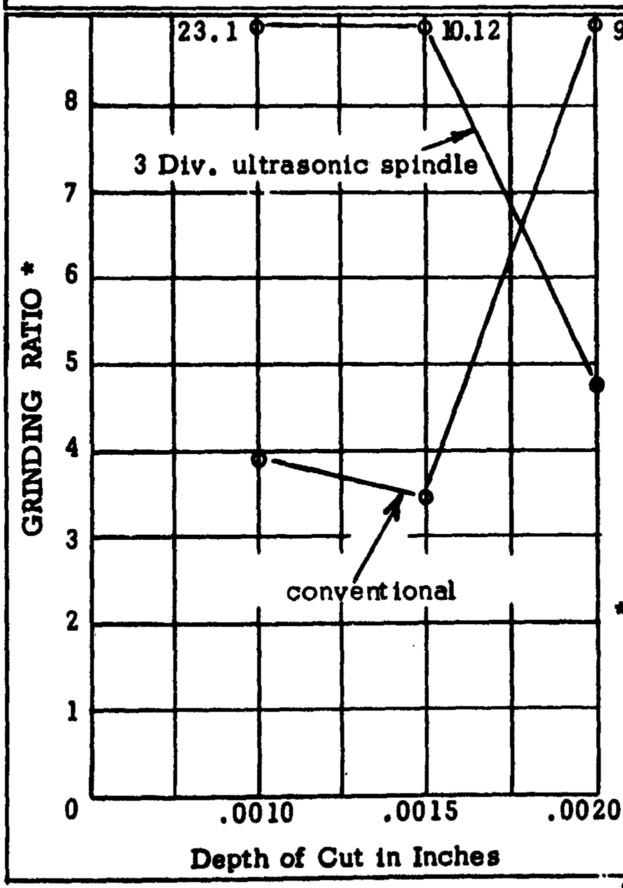
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	H - 11
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Without Coolant	

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers :II-431 - 436

Figure 227



SURFACE GRINDING

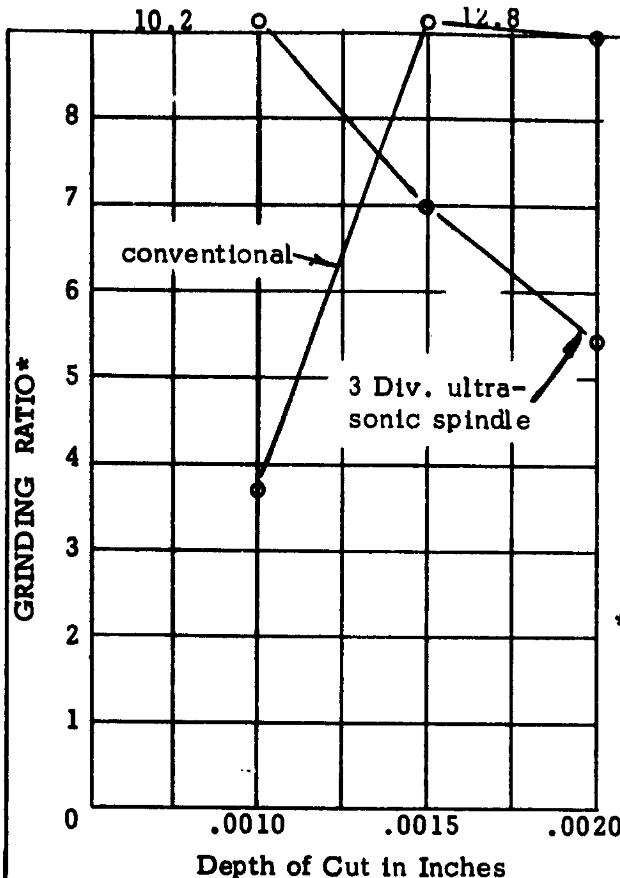
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	H-11
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Without Coolant	

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: II-425 - 430

Figure 228



SURFACE GRINDING

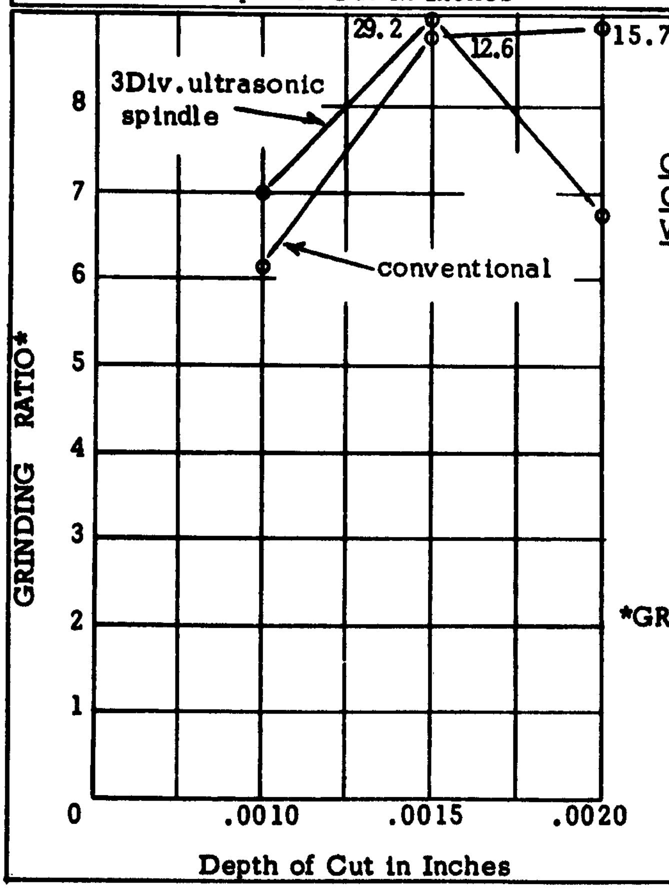
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	H - 11
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
With Coolant	

$$*\text{GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: II-443 - 448

Figure 229



SURFACE GRINDING

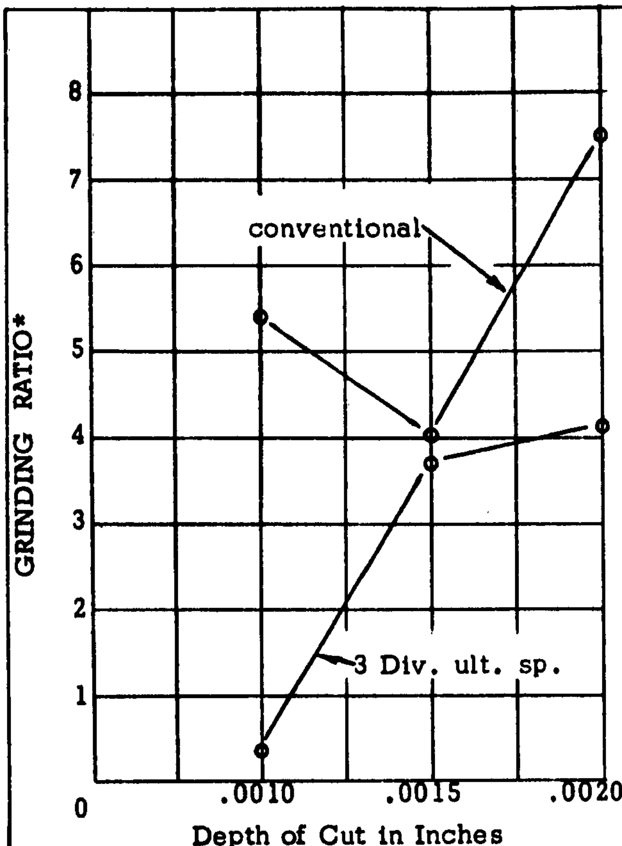
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	H - 11
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
With Coolant	

$$*\text{GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: II- 437 - 442

Figure 230



SURFACE GRINDING

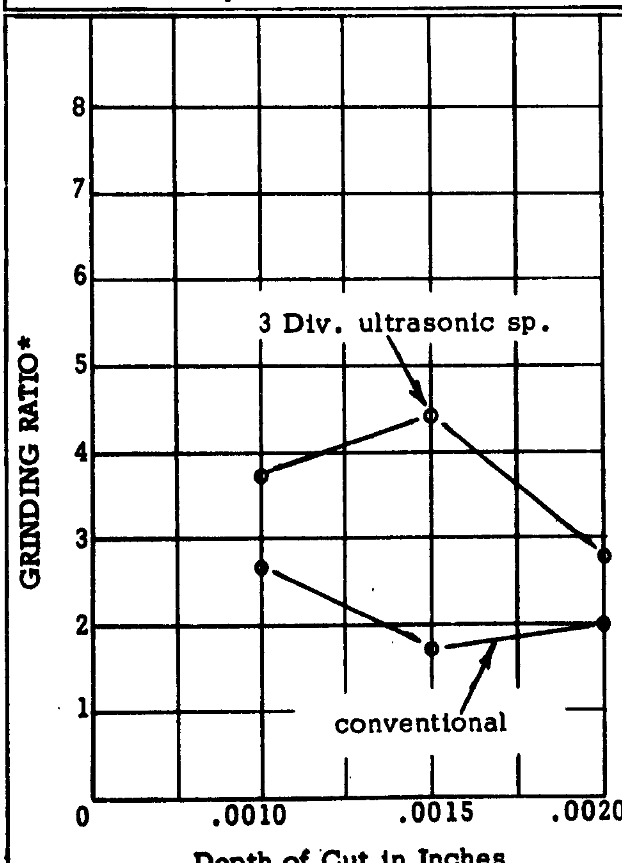
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15 - 7 MO
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Without Coolant	

$$*\text{GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: II-407 - 412

Figure 231



SURFACE GRINDING

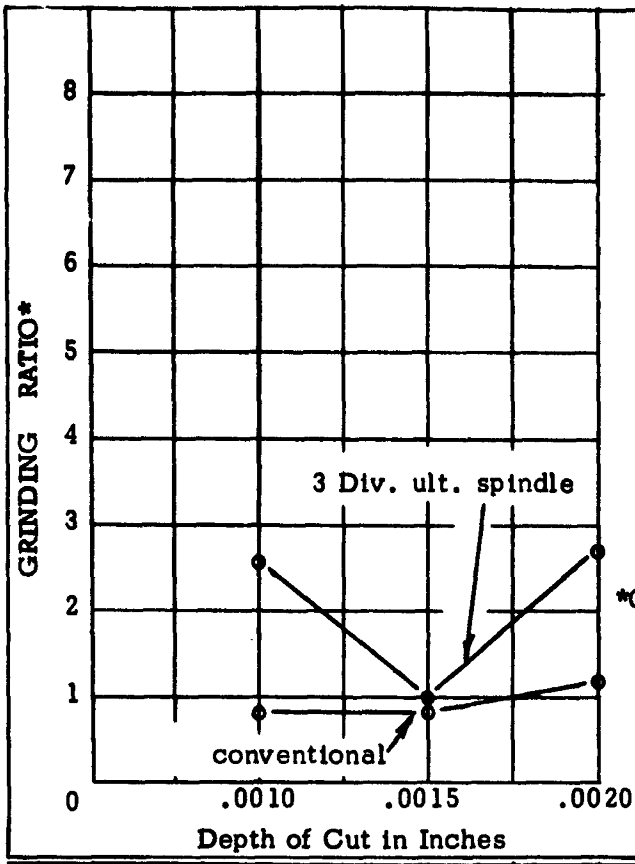
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	15 - 7 MO
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Without Coolant	

$$*\text{GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: II-401 - 406

Figure 232



SURFACE GRINDING

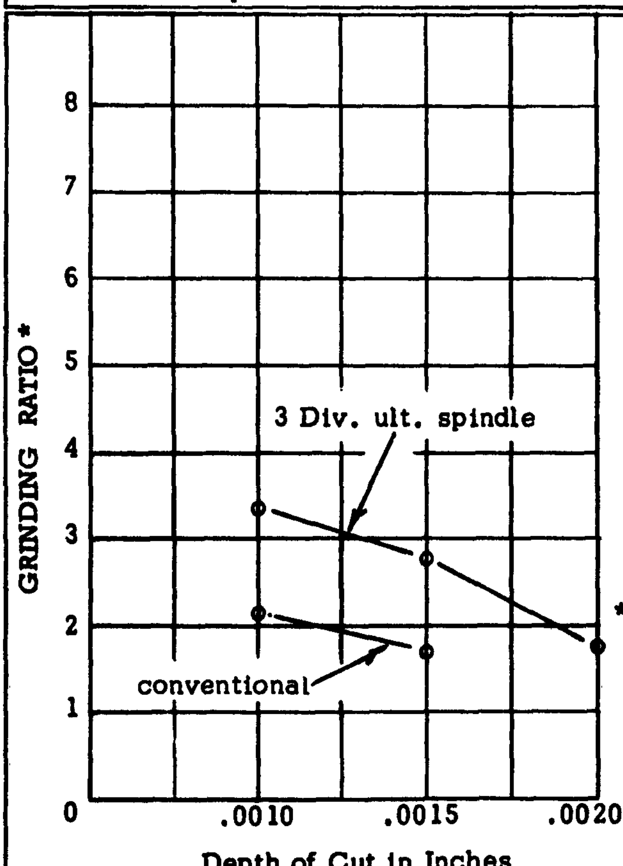
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Ti6Al-4V
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Without Coolant	

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: II- 455 - 460

Figure 233



SURFACE GRINDING

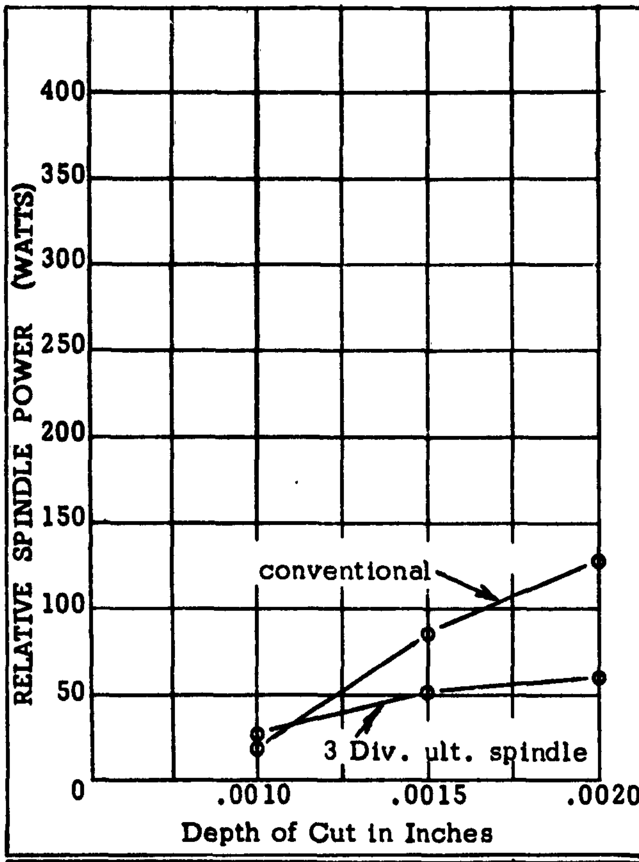
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Ti6Al-4V
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Without Coolant	

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: II - 449 - 454

Figure 234



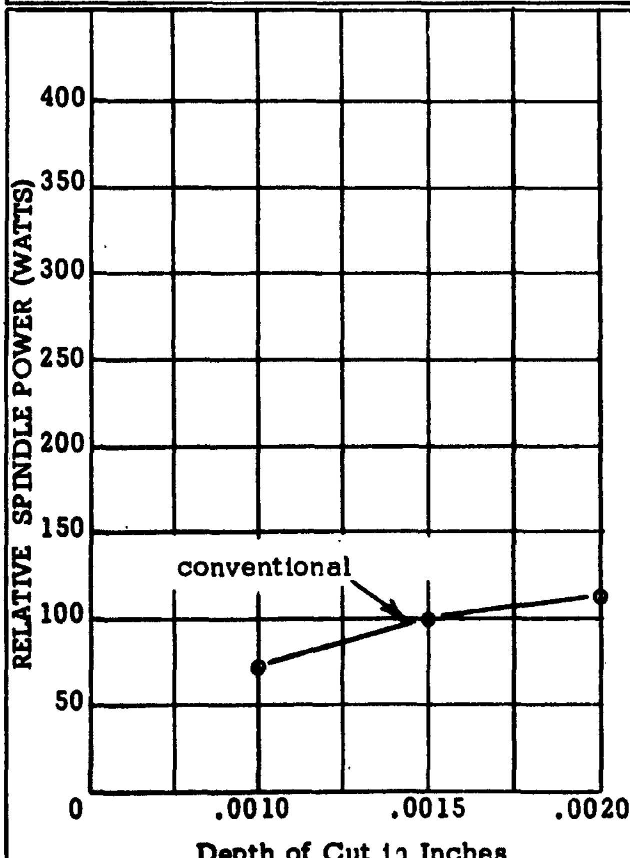
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Ti6Al-4V
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Run Numbers: II- 467 - 472

Figure 235



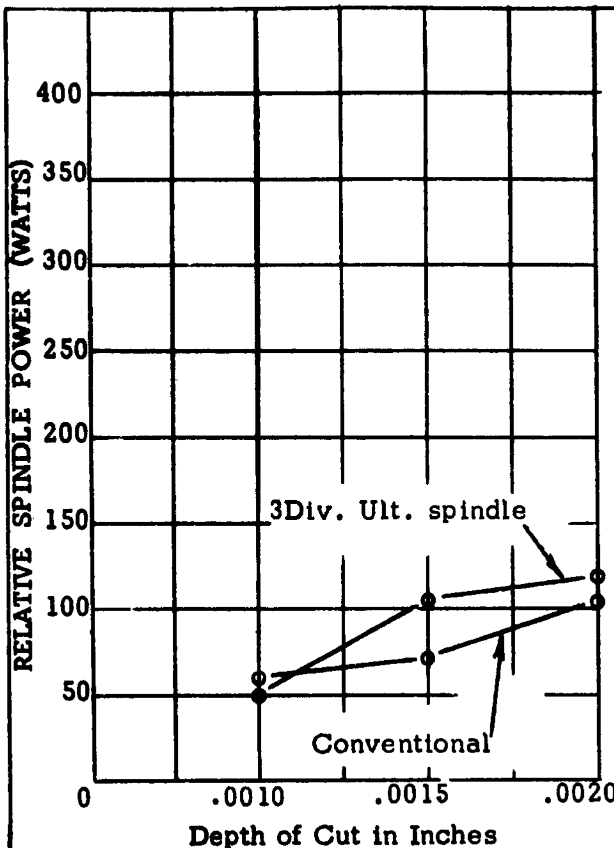
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Ti6Al-4V
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Run Numbers: II-461 - 466

Figure 236



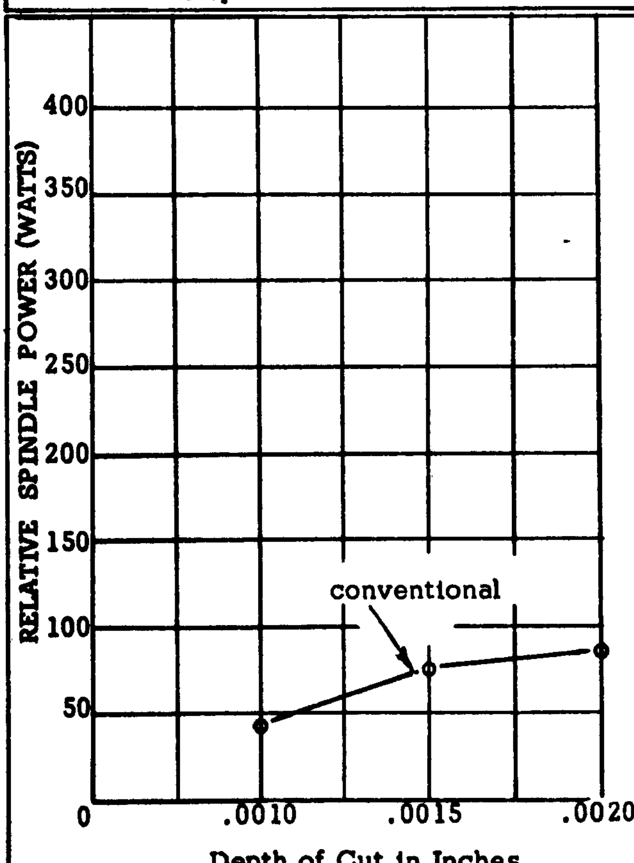
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	T16Al-4V
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Run Numbers: II- 455 - 460

Figure 237



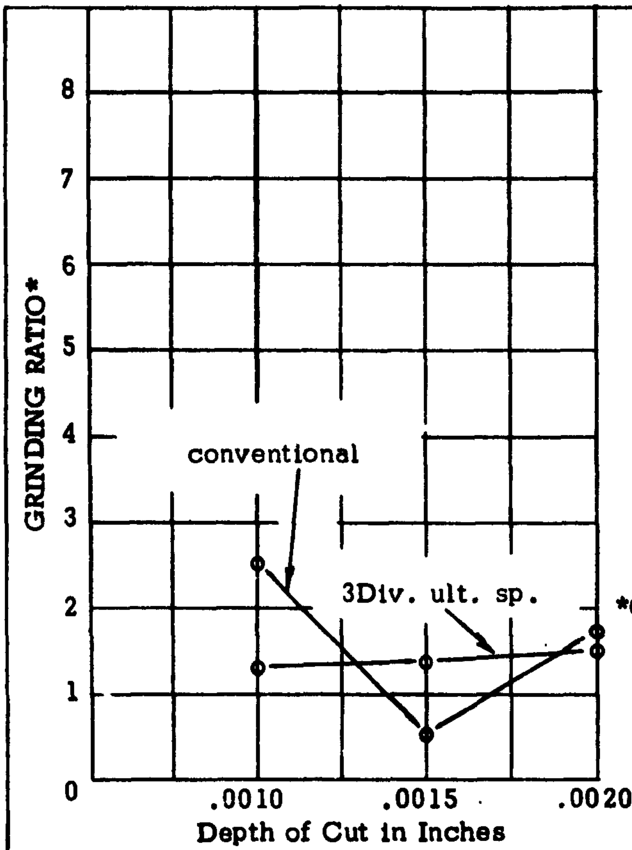
SURFACE GRINDING

SPINDLE POWER AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	T16Al-4V
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM

Run Numbers: II -449 - 454

Figure 238



SURFACE GRINDING

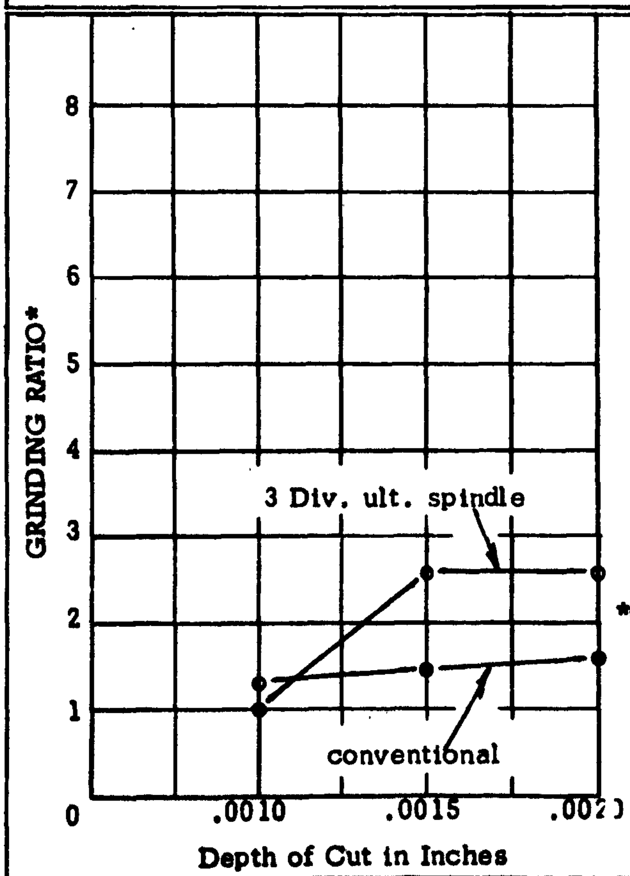
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Ti6Al-4V
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
With Coolant	

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: II-467 - 472

Figure 239



SURFACE GRINDING

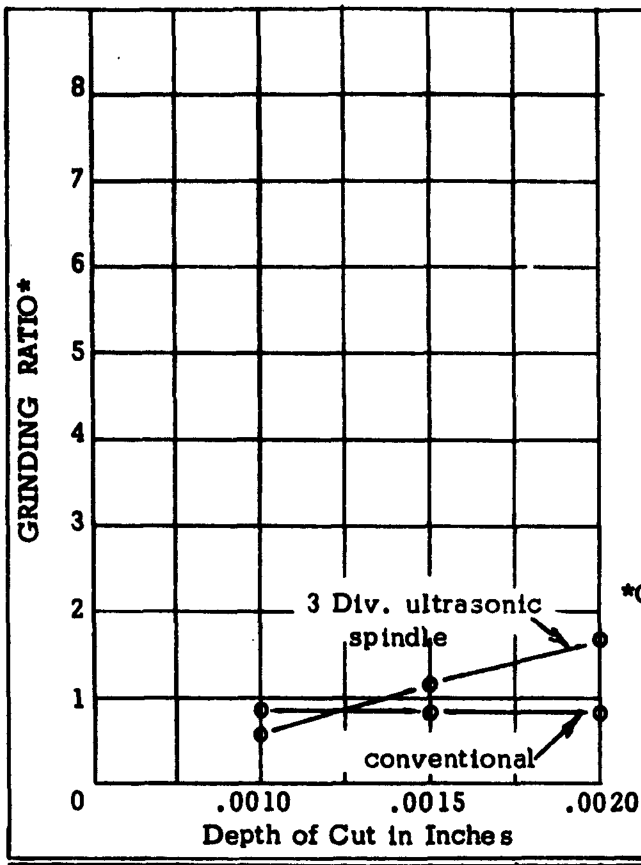
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Ti6Al-4V
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
With Coolant	

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: II-461 - 466

Figure 240



SURFACE GRINDING

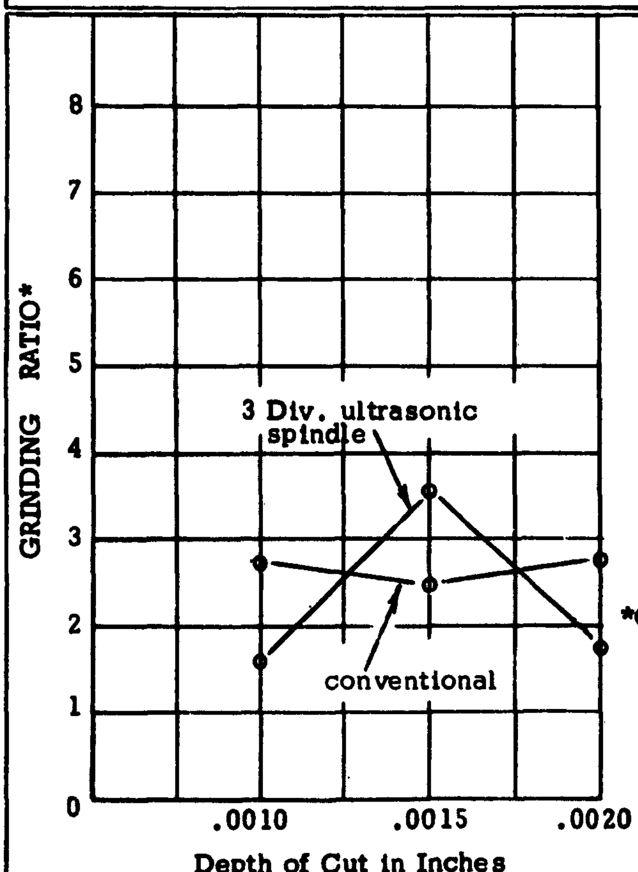
GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Rene 41
Wheel	AA60L8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Without Coolant	

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: II- 479 - 484

Figure 241



SURFACE GRINDING

GRINDING RATIO AS A FUNCTION OF THE DEPTH OF CUT WITH VIBRATION AS A PARAMETER

Material	Rene 41
Wheel	AA60R8-V40
Wheel Speed	6200 SFPM
Table Speed	35 FPM
Without Coolant	

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: II- 473 - 478

Figure 242

PHOTOGRAPHS OF THE WHEELS TAKEN IMMEDIATELY AFTER EACH RUN

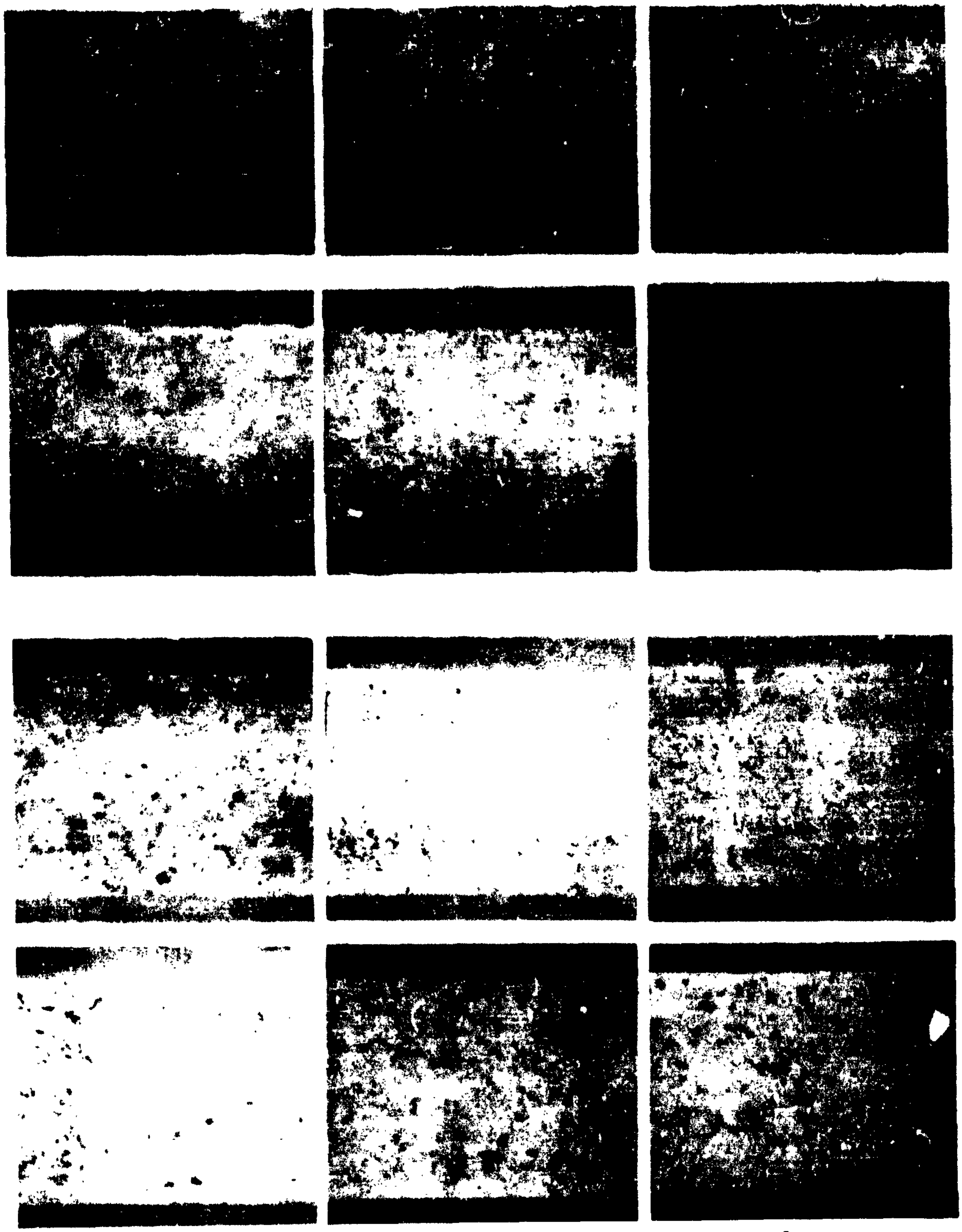
RUNS 400 to 496

WHEEL AA60-L8-V40

MATERIAL Ti6Al-4V

Conventional----DRY----Ultrasonic

Conventional----WET----Ultrasonic



Depth of Cut

.0010"

.0015"

.0020"

Magnification 3.5X

Figure 243

WHEEL AA60-L8-V40 MATERIAL 15-7MO

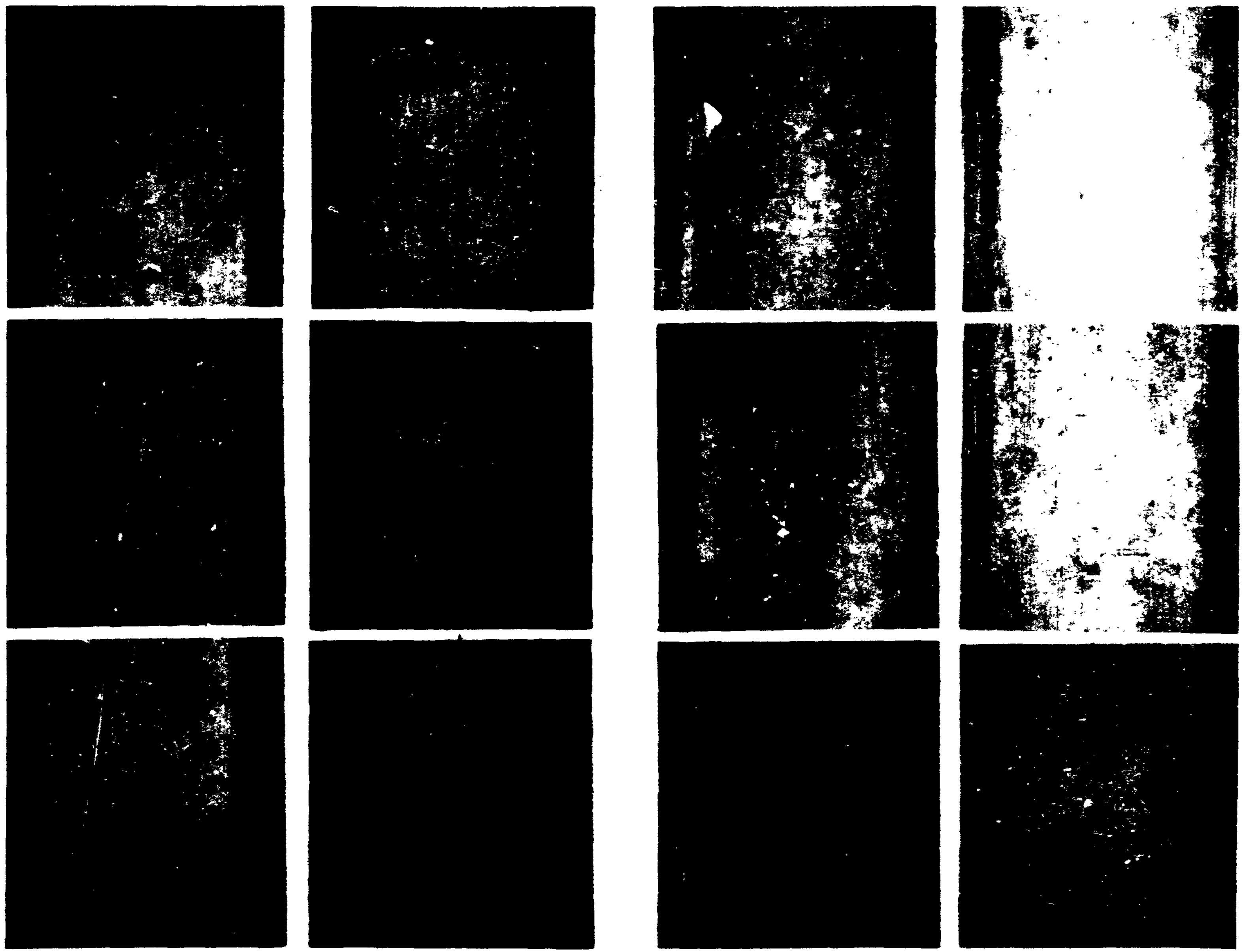
Conventional----DRY----Ultrasonic Conventional----WET----Ultrasonic

Depth of Cut

.0010"

.0015"

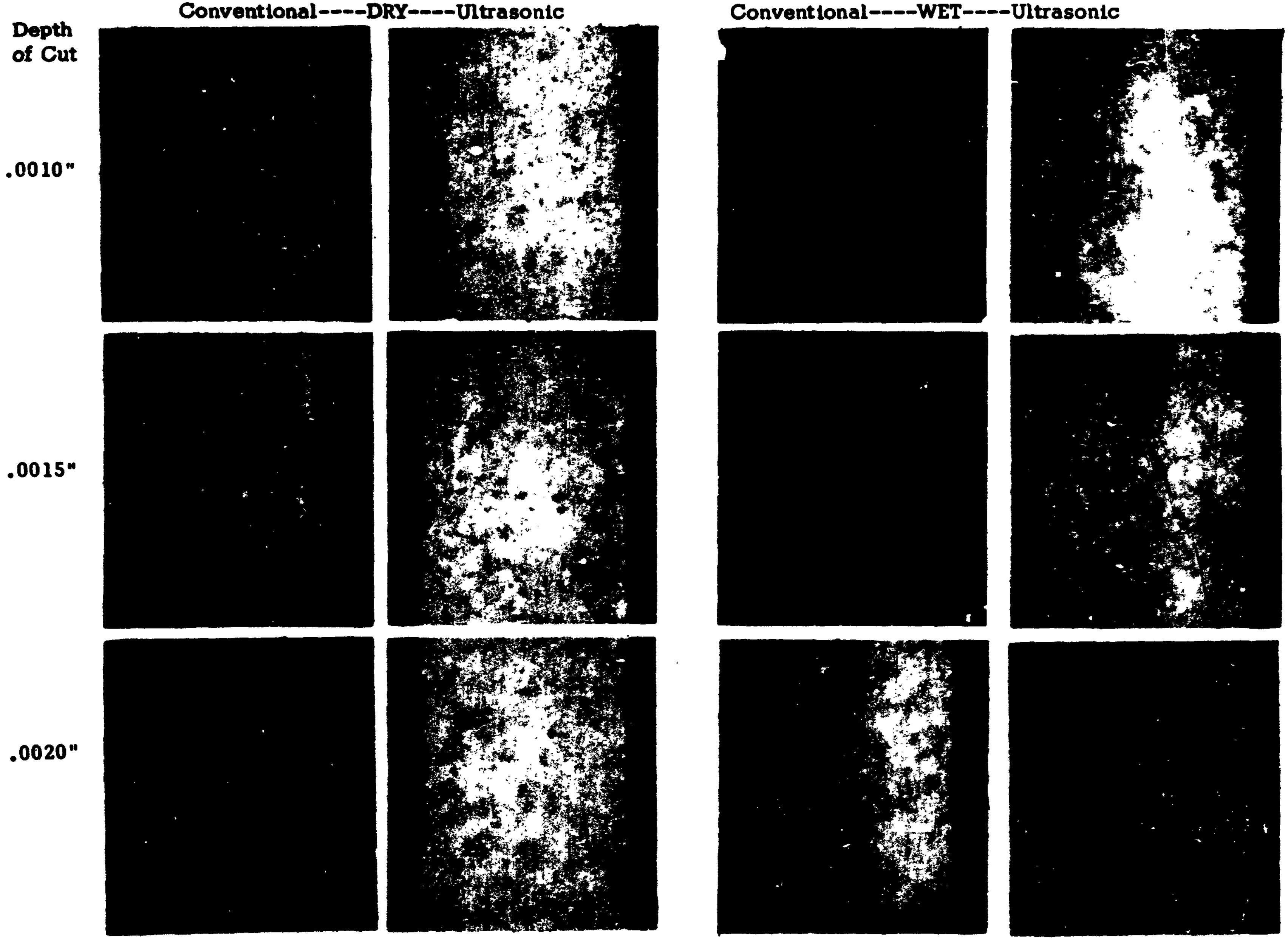
.0020"



Magnification 3.25X

Figure 244

WHEEL AA60-L8-V40 MATERIAL Rene 41



Magnification 3.25X
Figure 245

WHEEL AA60-R8-V40 MATERIAL H-11

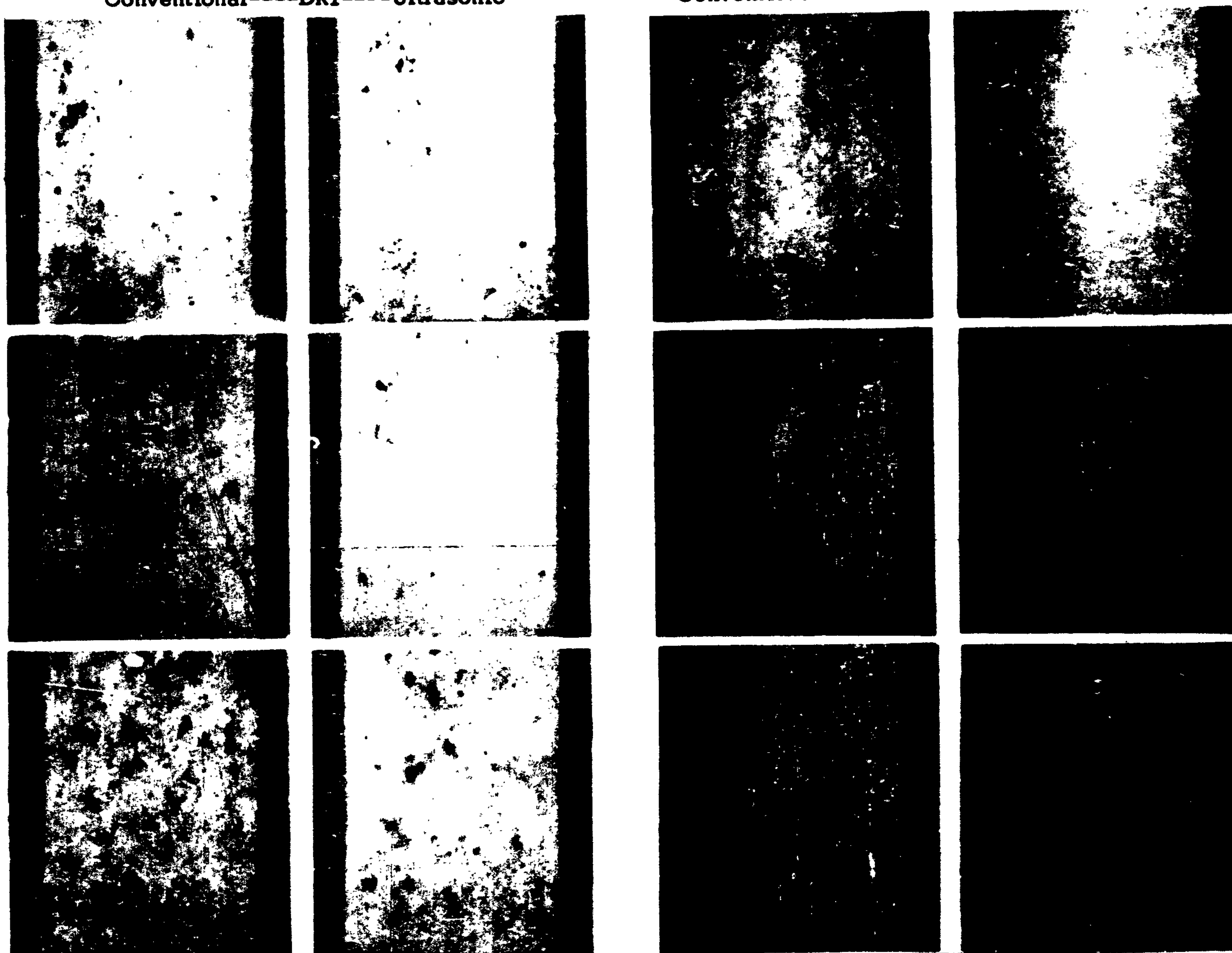
Conventional----DRY----Ultrasonic Conventional----WET----Ultrasonic

Depth of Cut

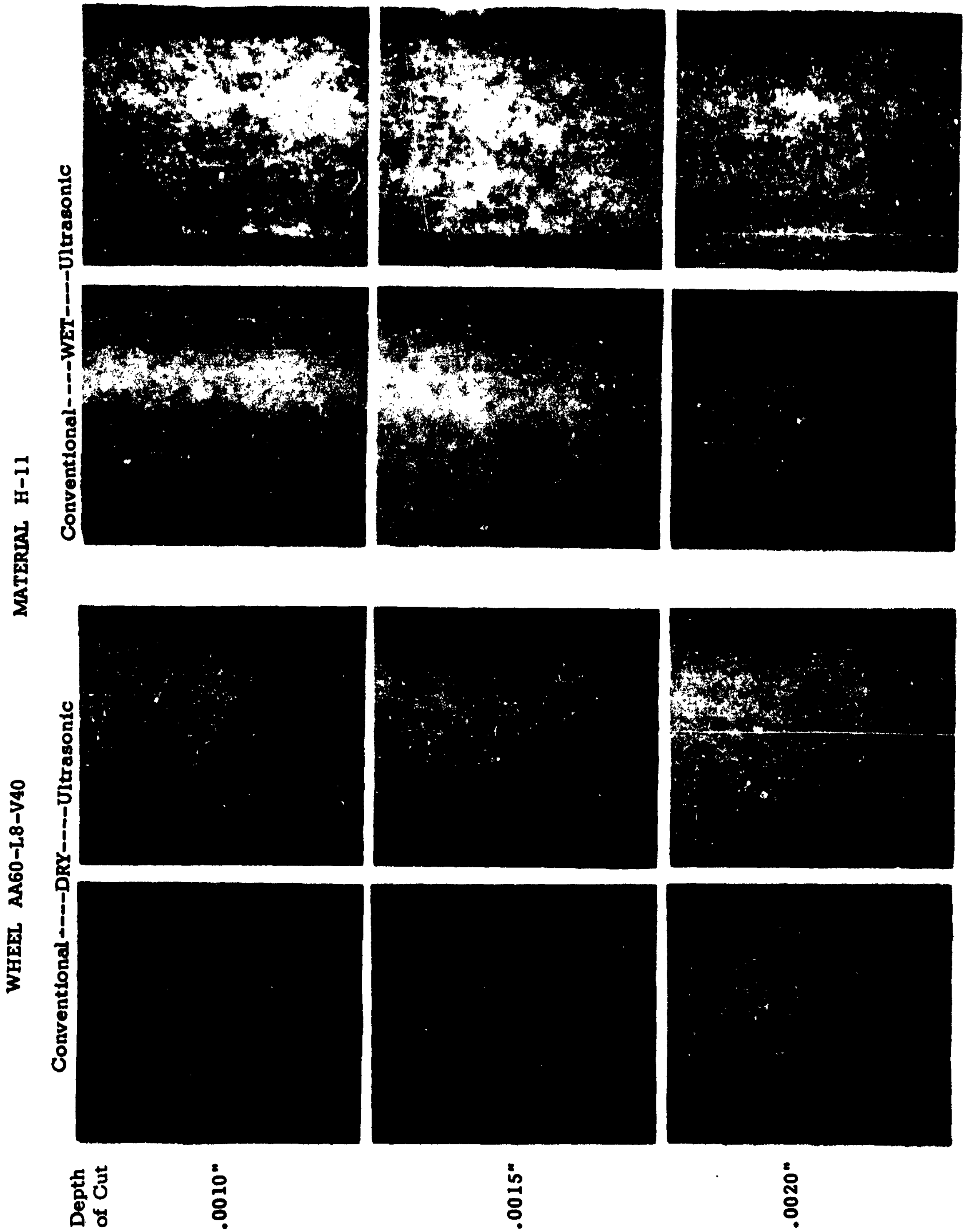
.0010"

.0015"

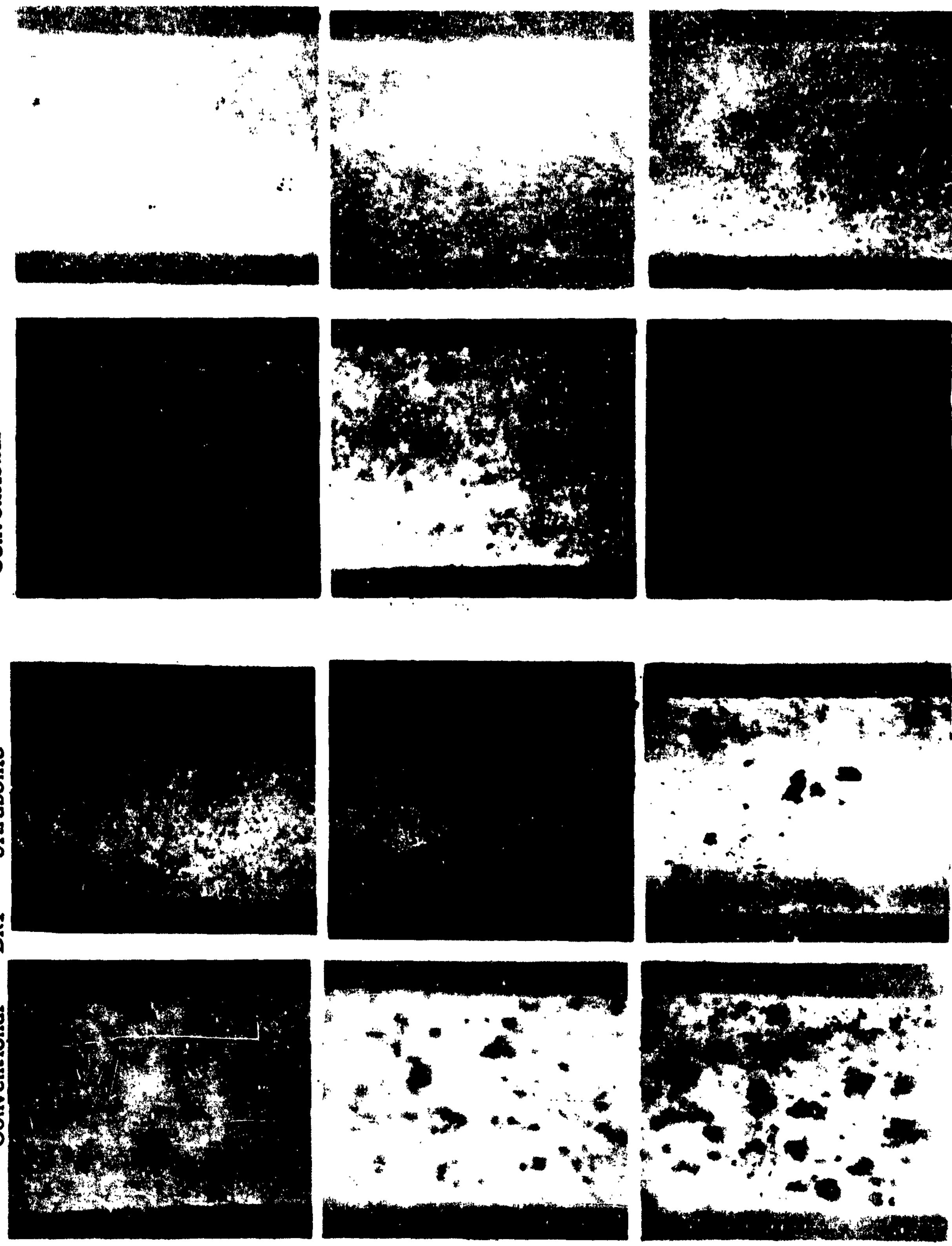
.0020"



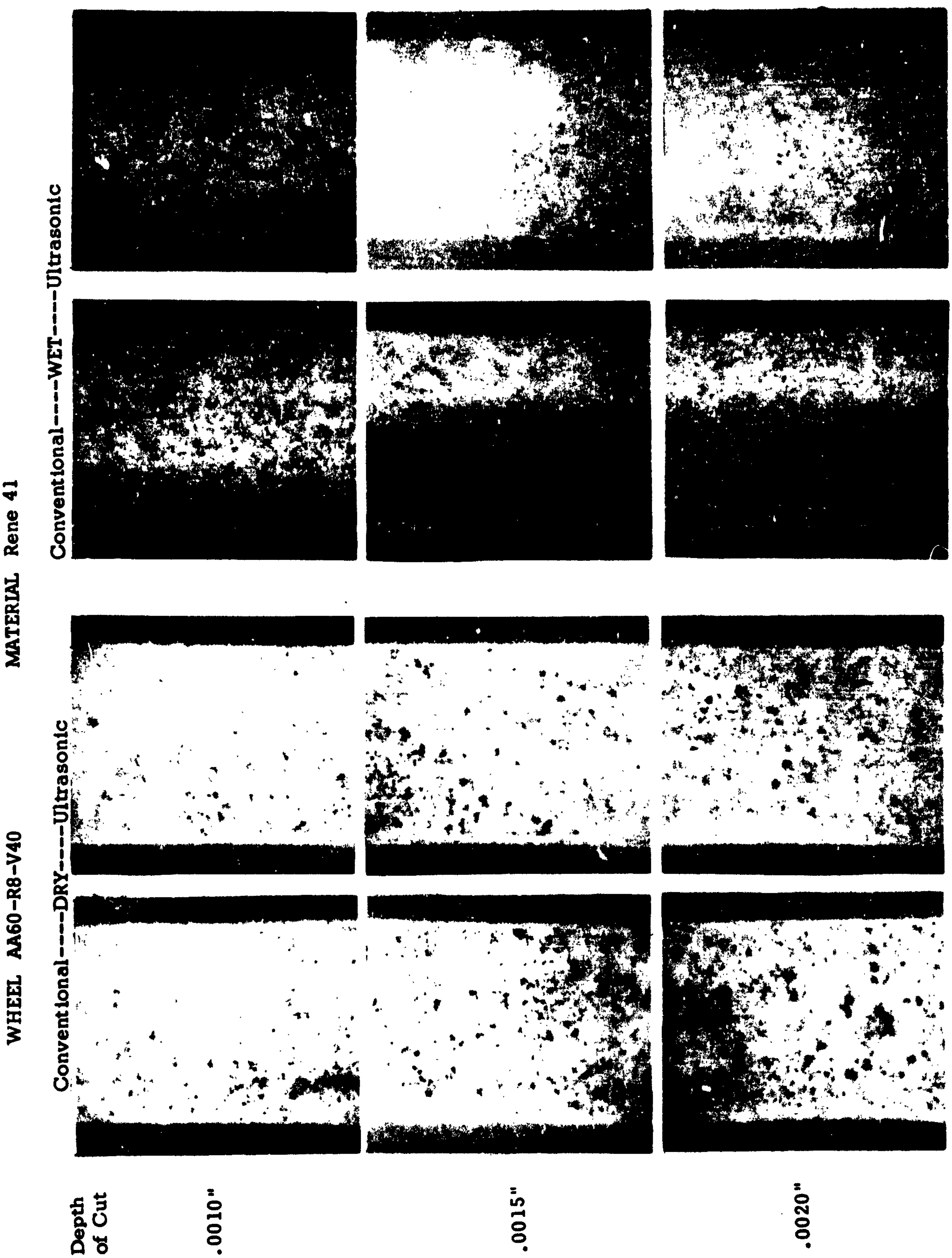
Magnicication 3.25X
Figure 246



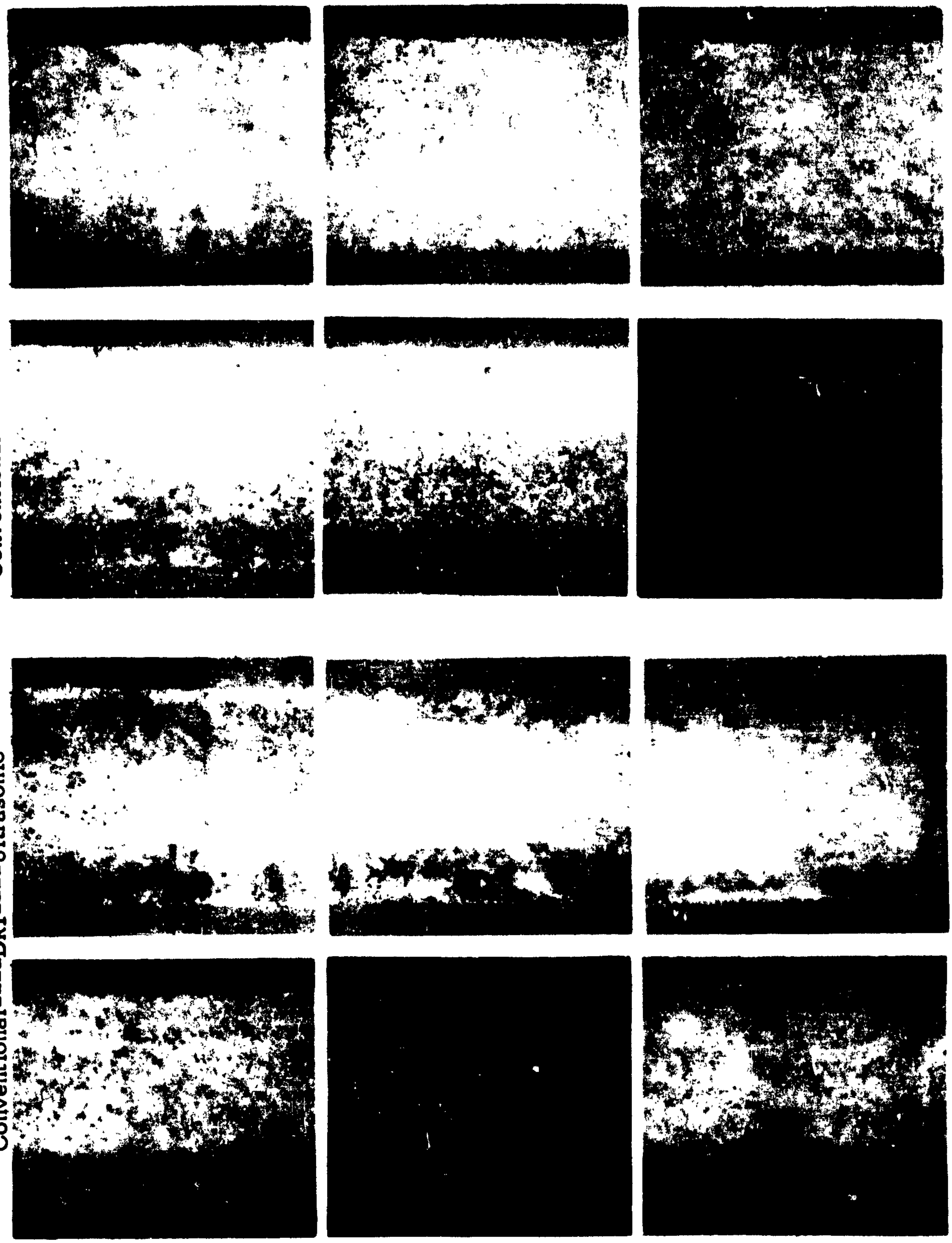
Magnification 3.25X
Figure 247



Magnification 3.25X
Figure 248



Magnification 3.25X
Figure 249



WHEEL AA60-R8-V40 MATERIAL Ti6Al-4V

Conventional----DRY----Ultrasonic Conventional----WET----Ultrasonic

Depth of Cut

.0010"

.0015"

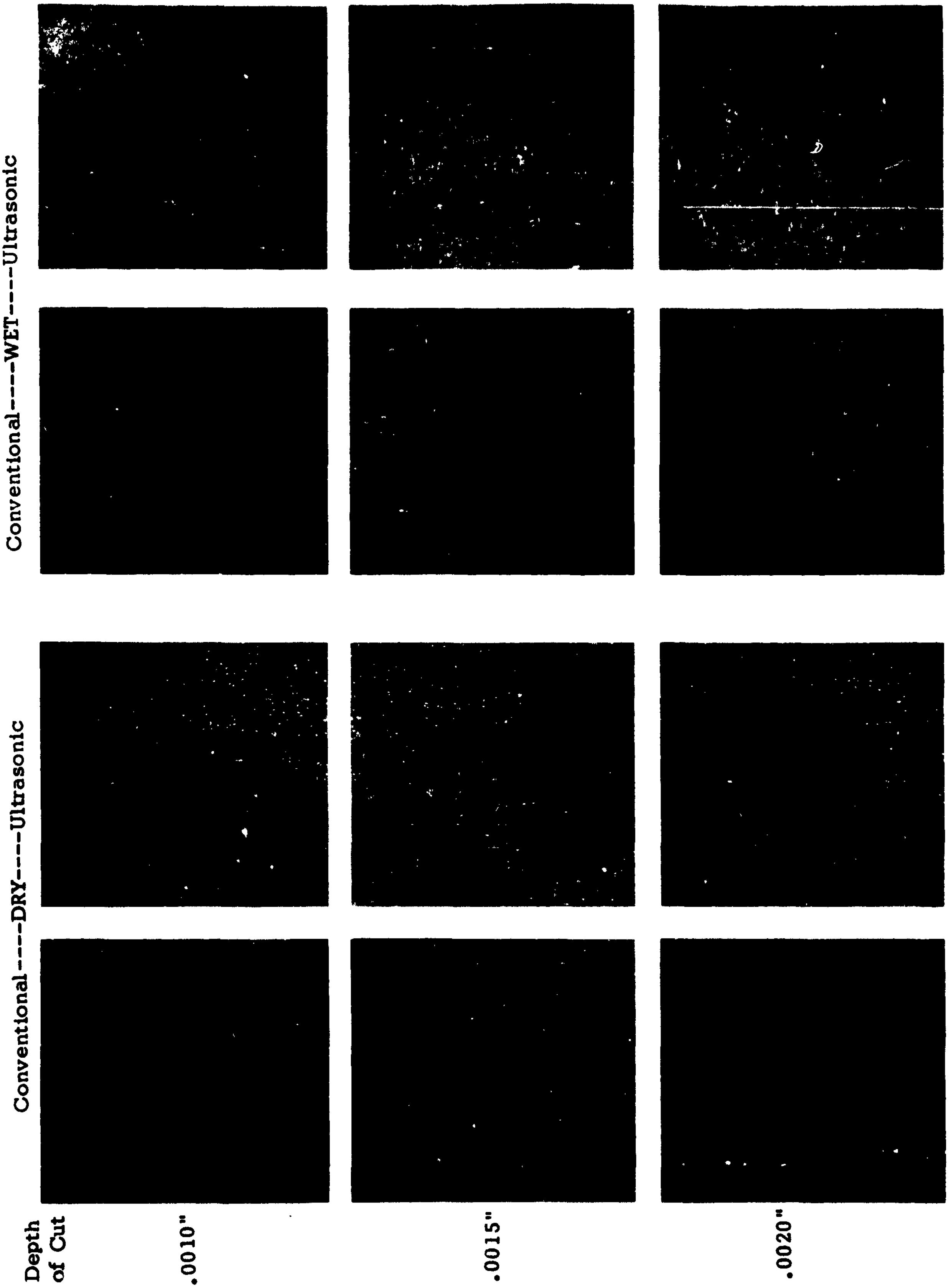
.0020"

Magnification 3.25X

Figure 250

PHOTOGRAPHS OF THE TEST SPECIMENS TAKEN IMMEDIATELY AFTER EACH RUN

RUNS 400 to 496



Magnification 3.25X

Figure 251

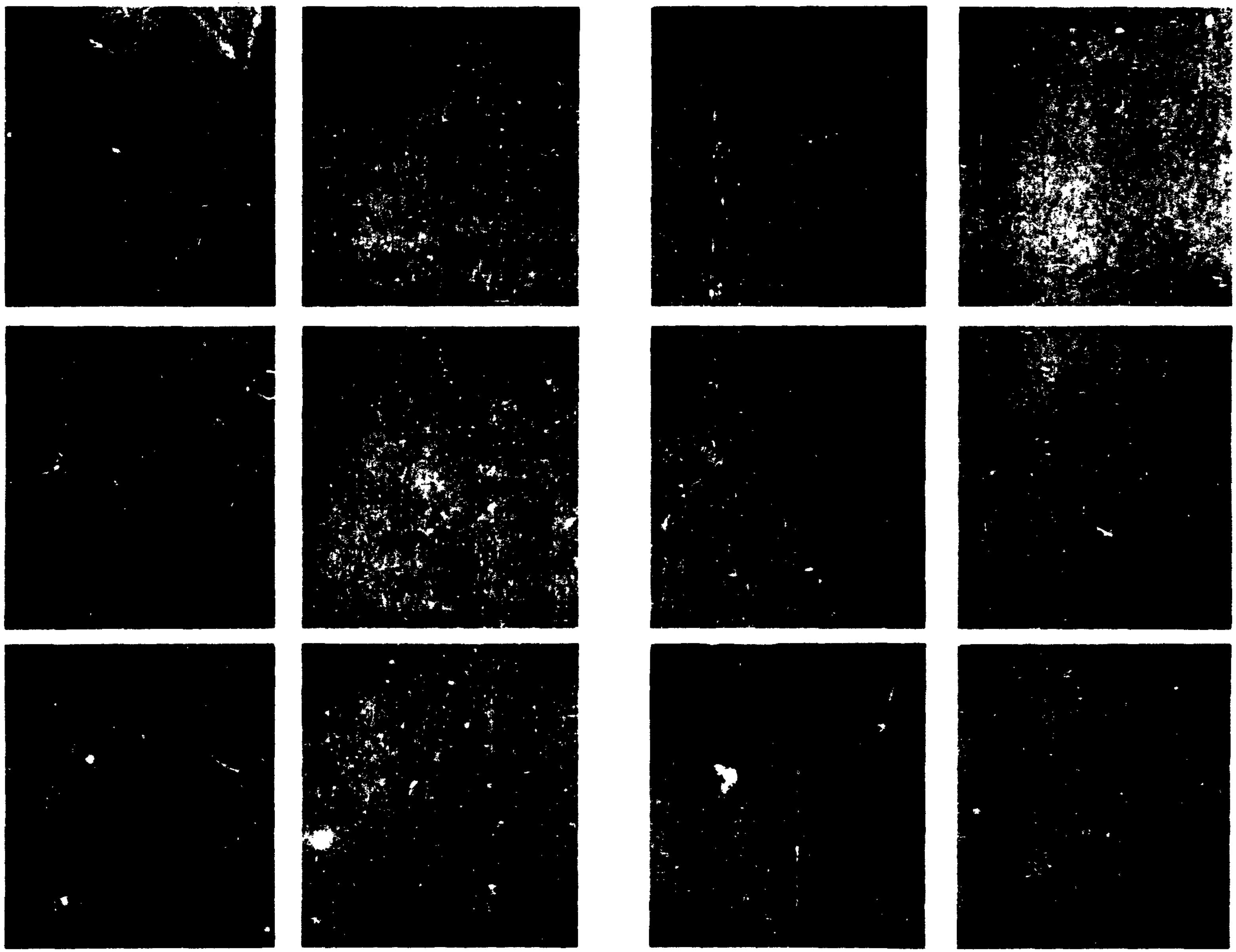
WHEEL AA60-L8-V40 MATERIAL H-11

Depth of Cut | Conventional----DRY----Ultrasonic | Conventional----WET----Ultrasonic

.0010"

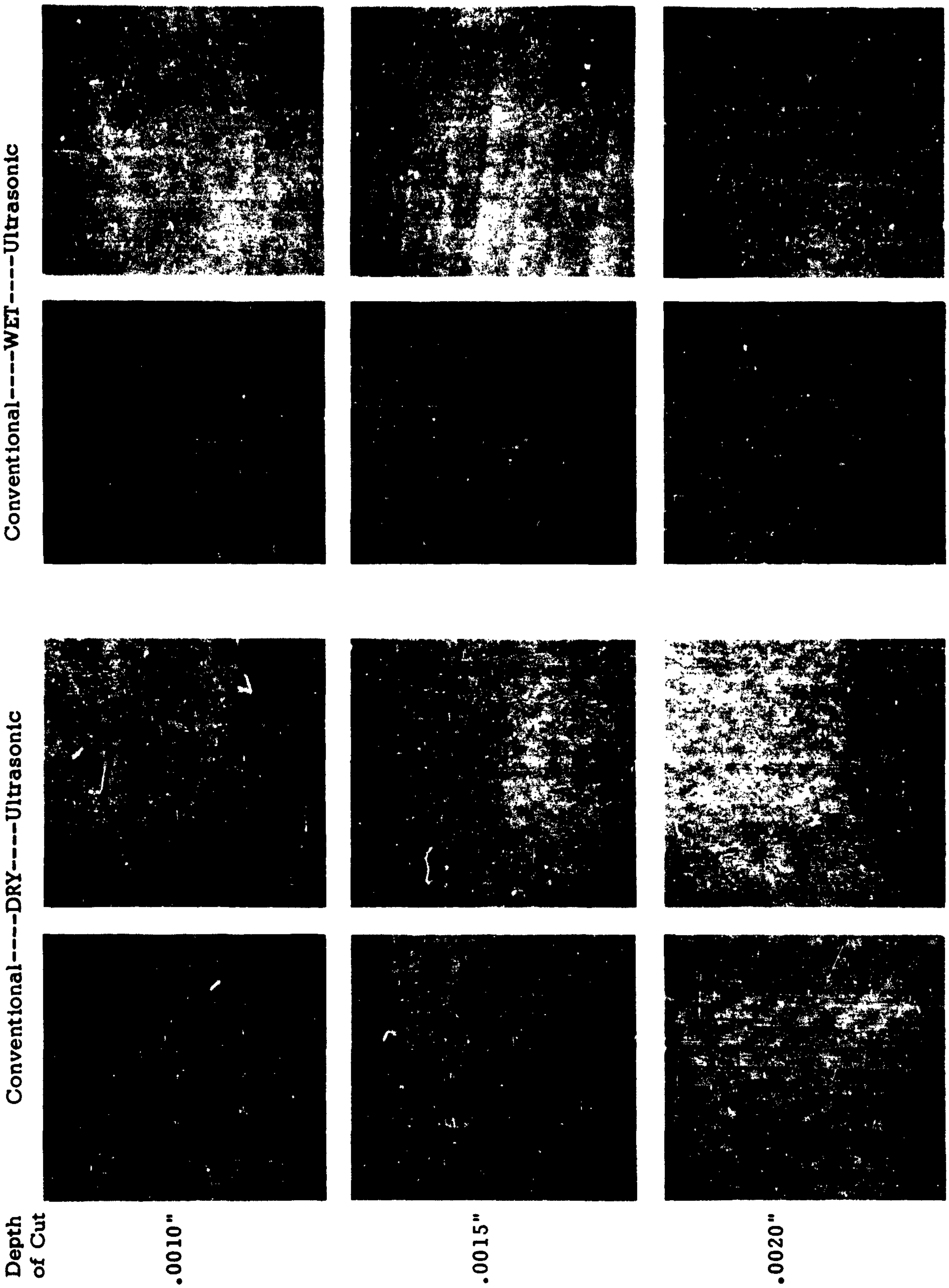
.0015"

.0020"



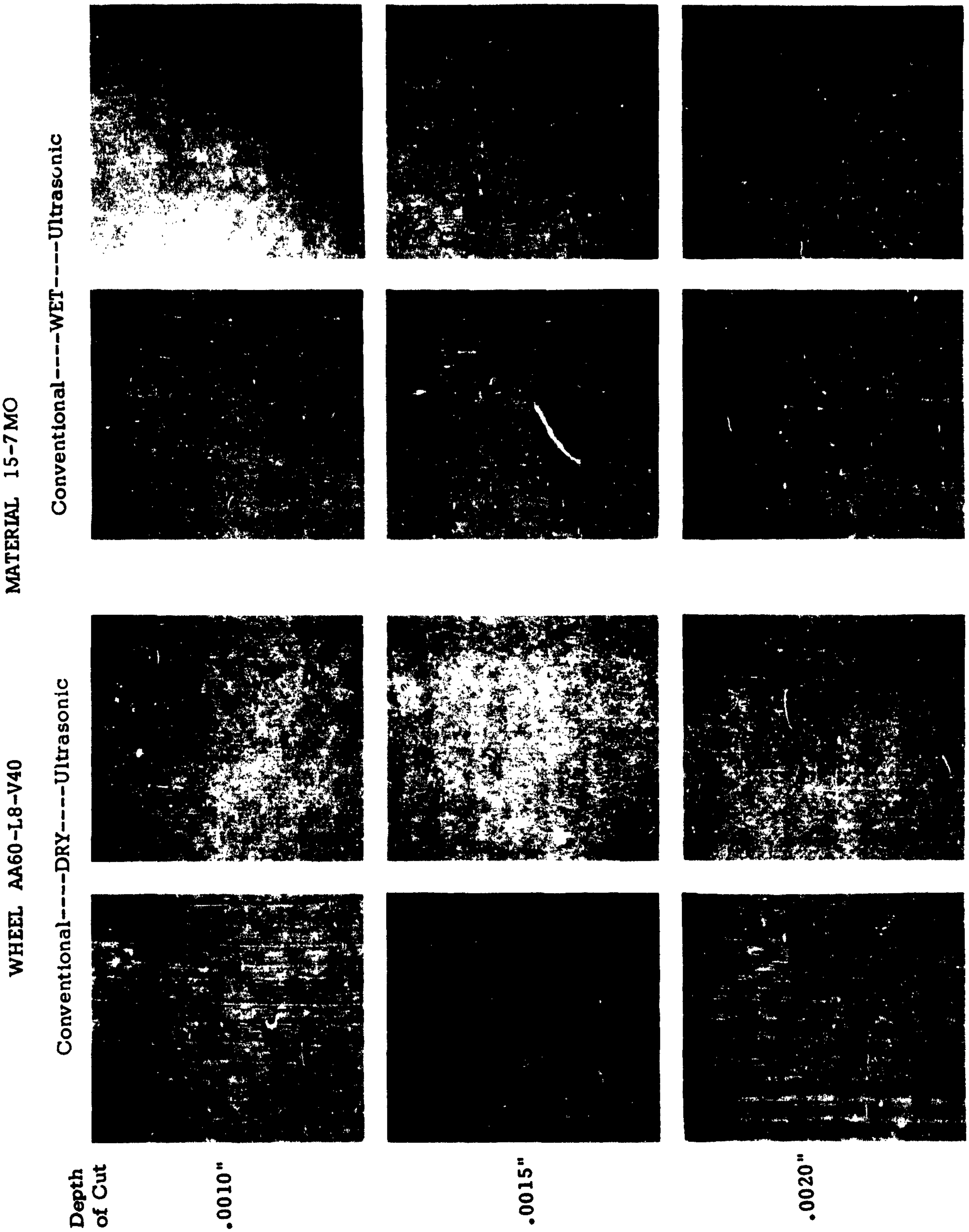
Magnification 3.25X

Figure 252



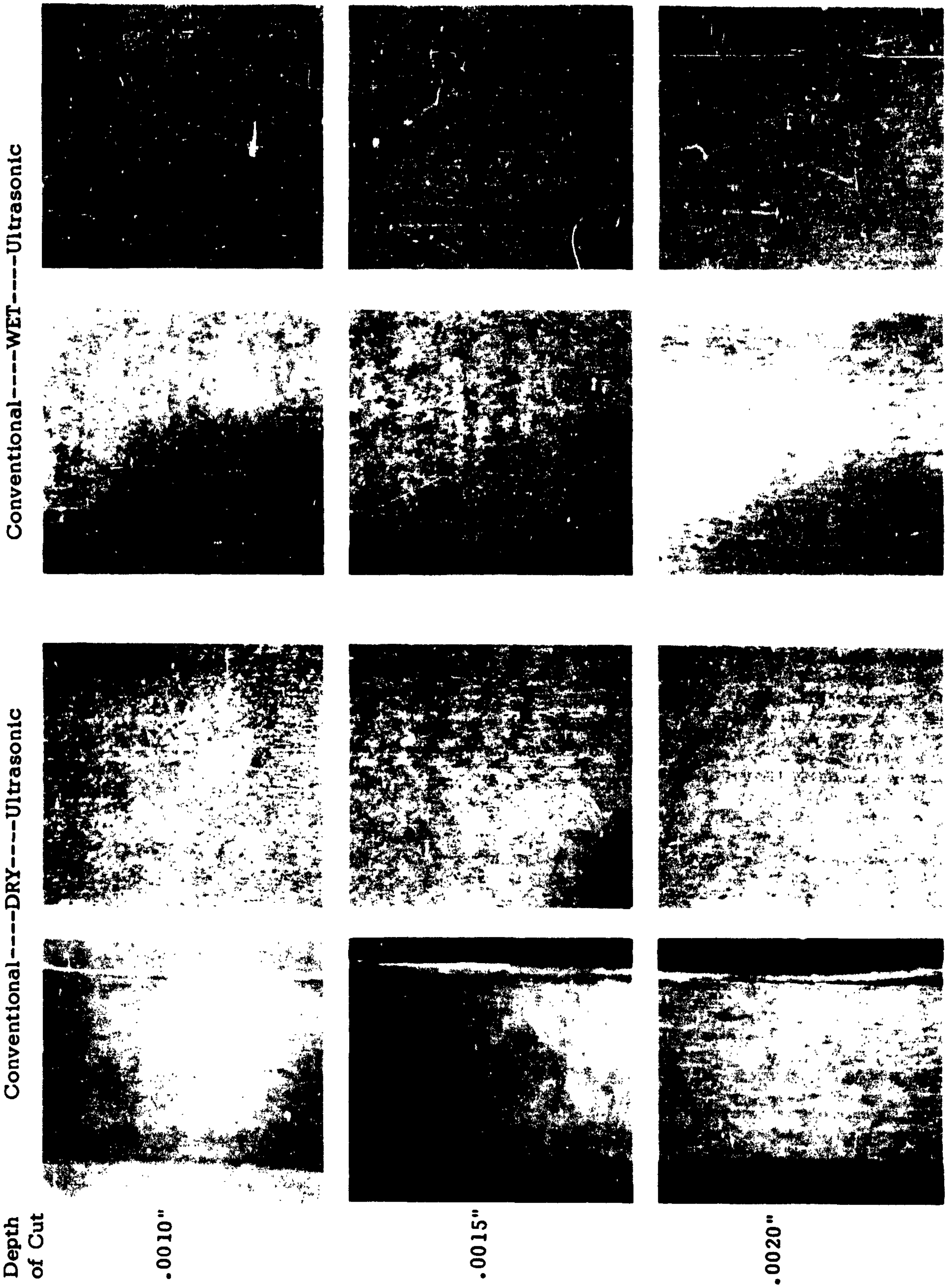
Magnification 3.25X

Figure 253



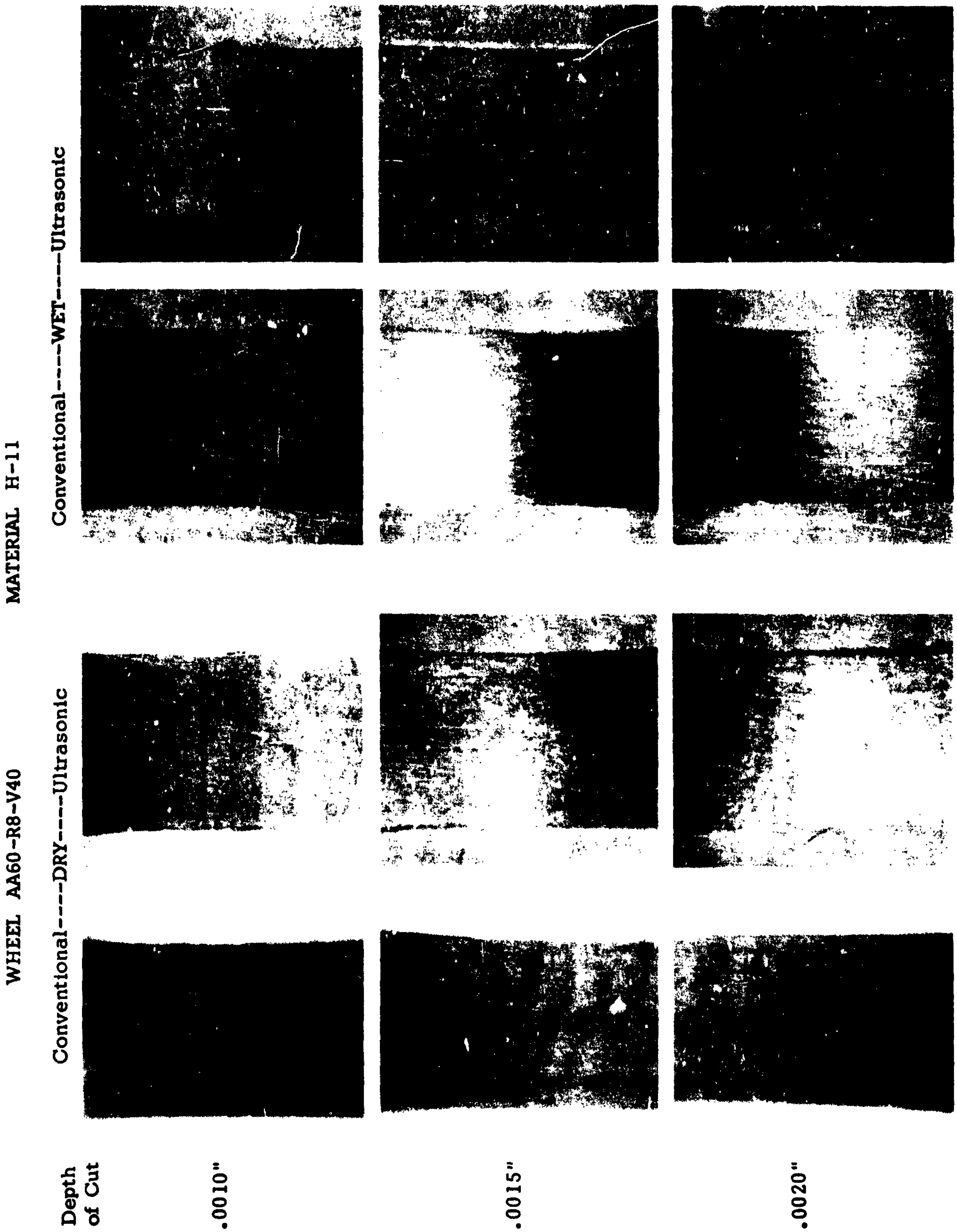
Magnification 3.25X

Figure 254



Magnification 3.25X

Figure 255



Magnification 3.25X

Figure 256

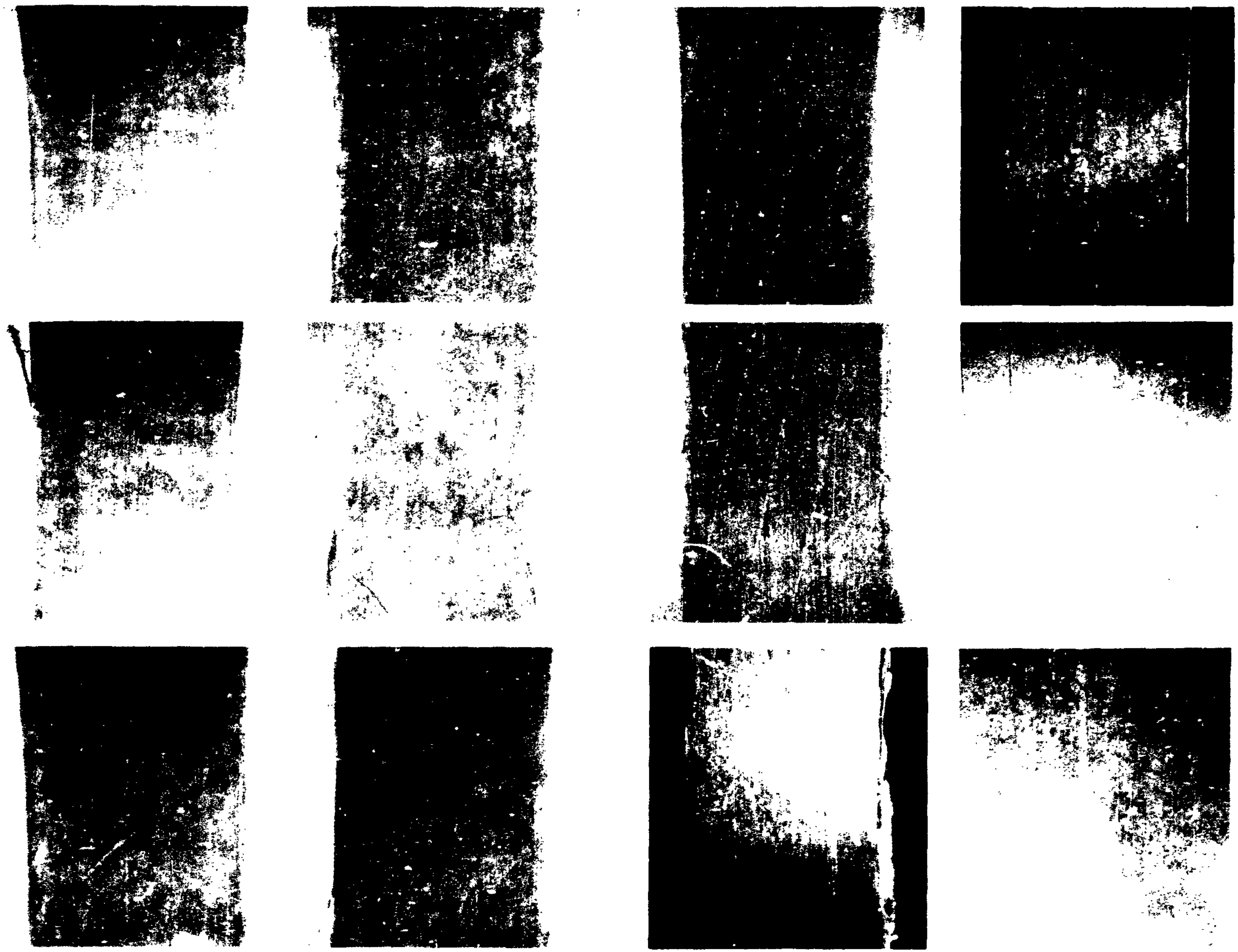
WHEEL AA60-R8-V40 MATERIAL Rene 41

Depth of Cut | Conventional----DRY----Ultrasonic | Conventional----WET----Ultrasonic

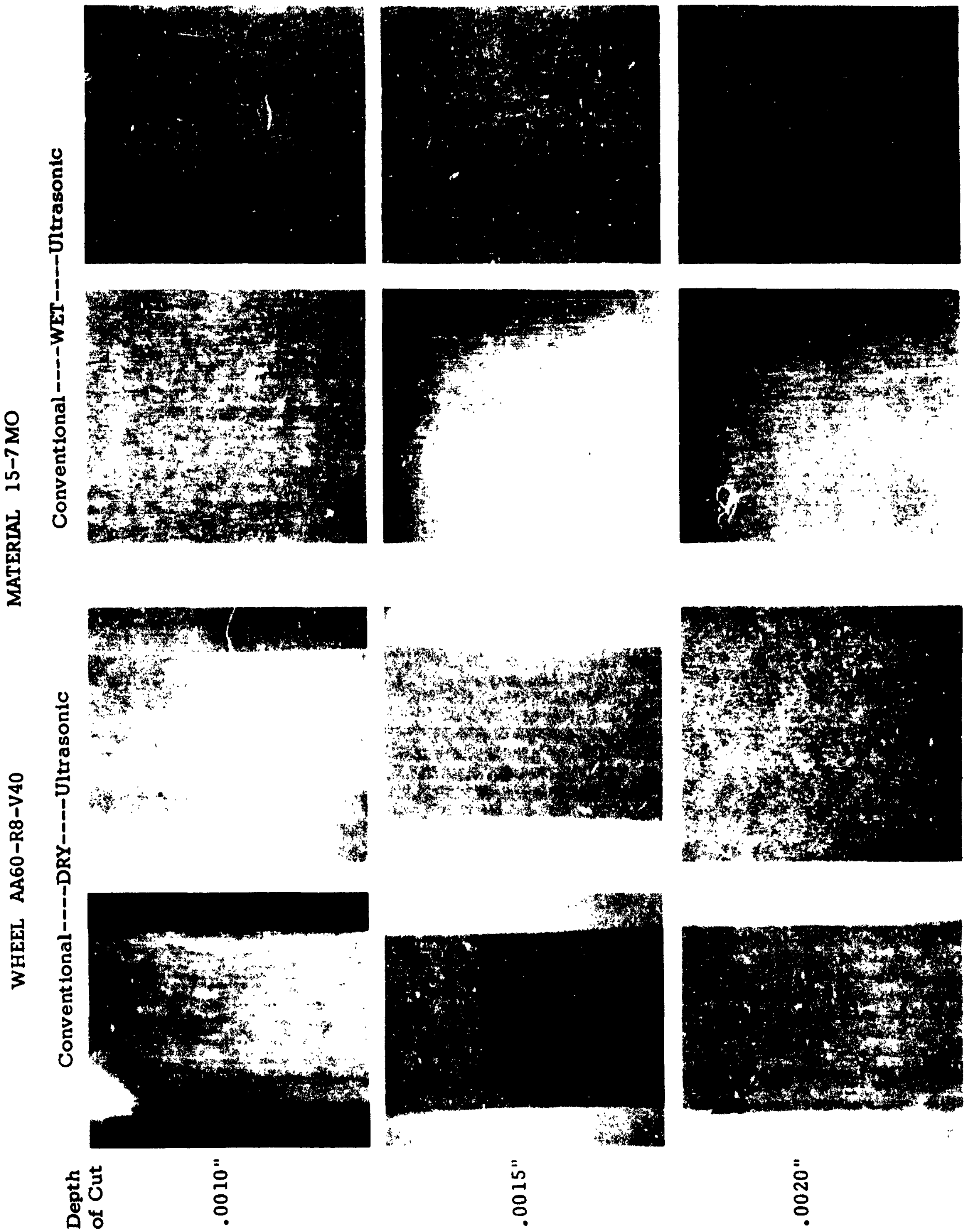
.0010"

.0015"

.0020"



Magnification 3.25X
Figure 257



Magnification 3.25X

Figure 258

PHOTOMICROGRAPHS OF THE TEST SPECIMENS

WHEEL AA60-L8-V40 MATERIAL 15-7MO

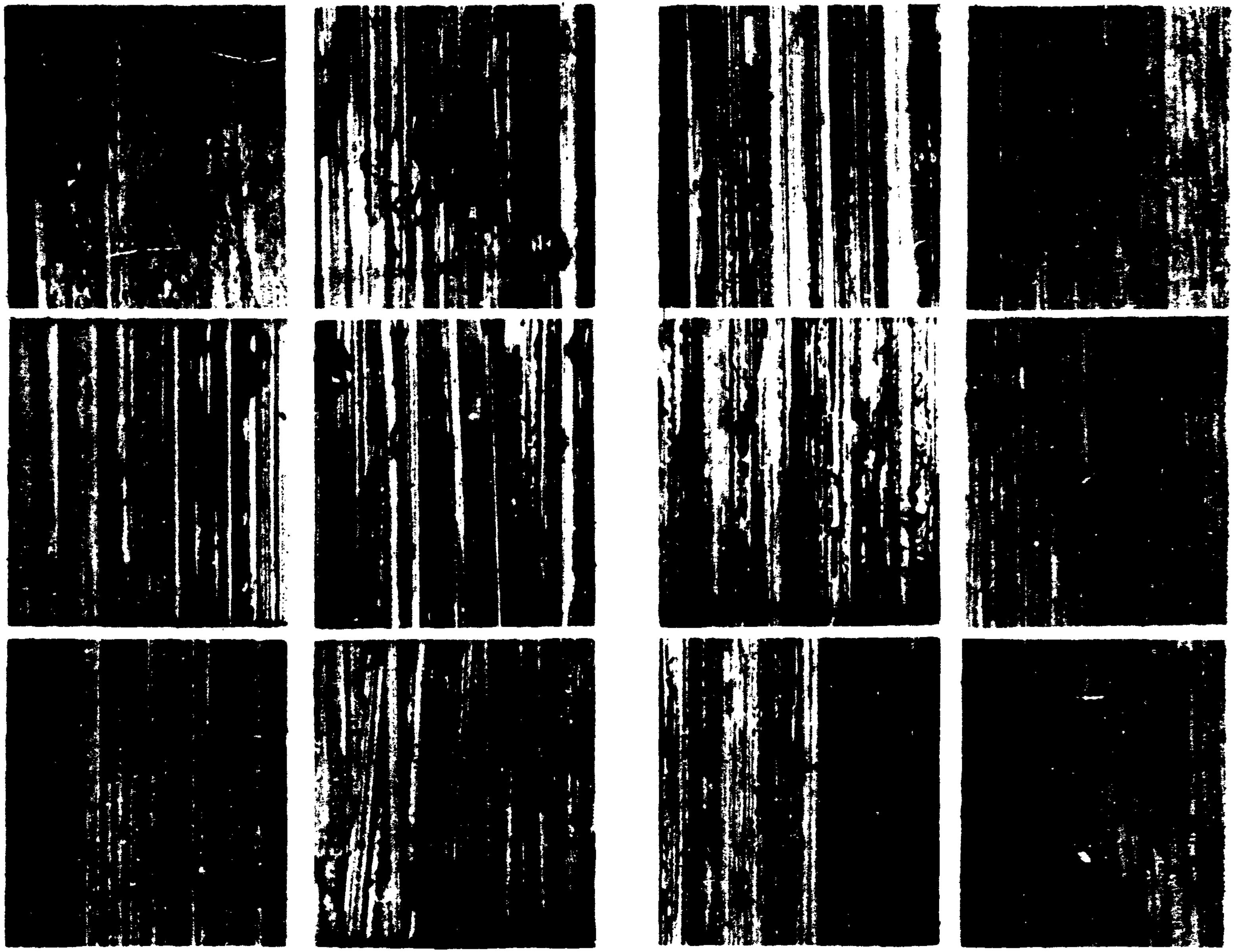
Depth of Cut

Conventional----DRY----Ultrasonic Conventional----WET----Ultrasonic

.0010"

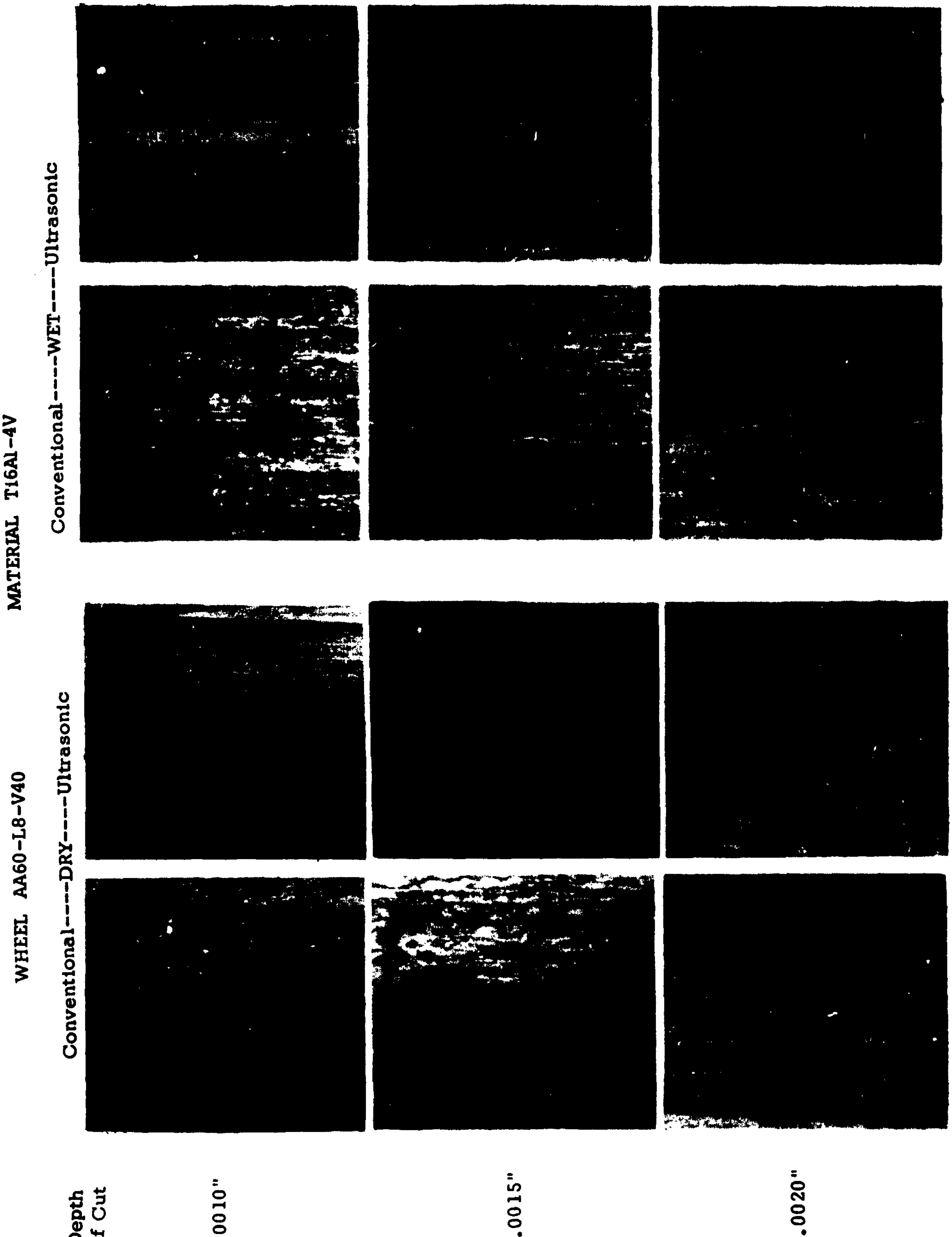
.0015"

.0020"



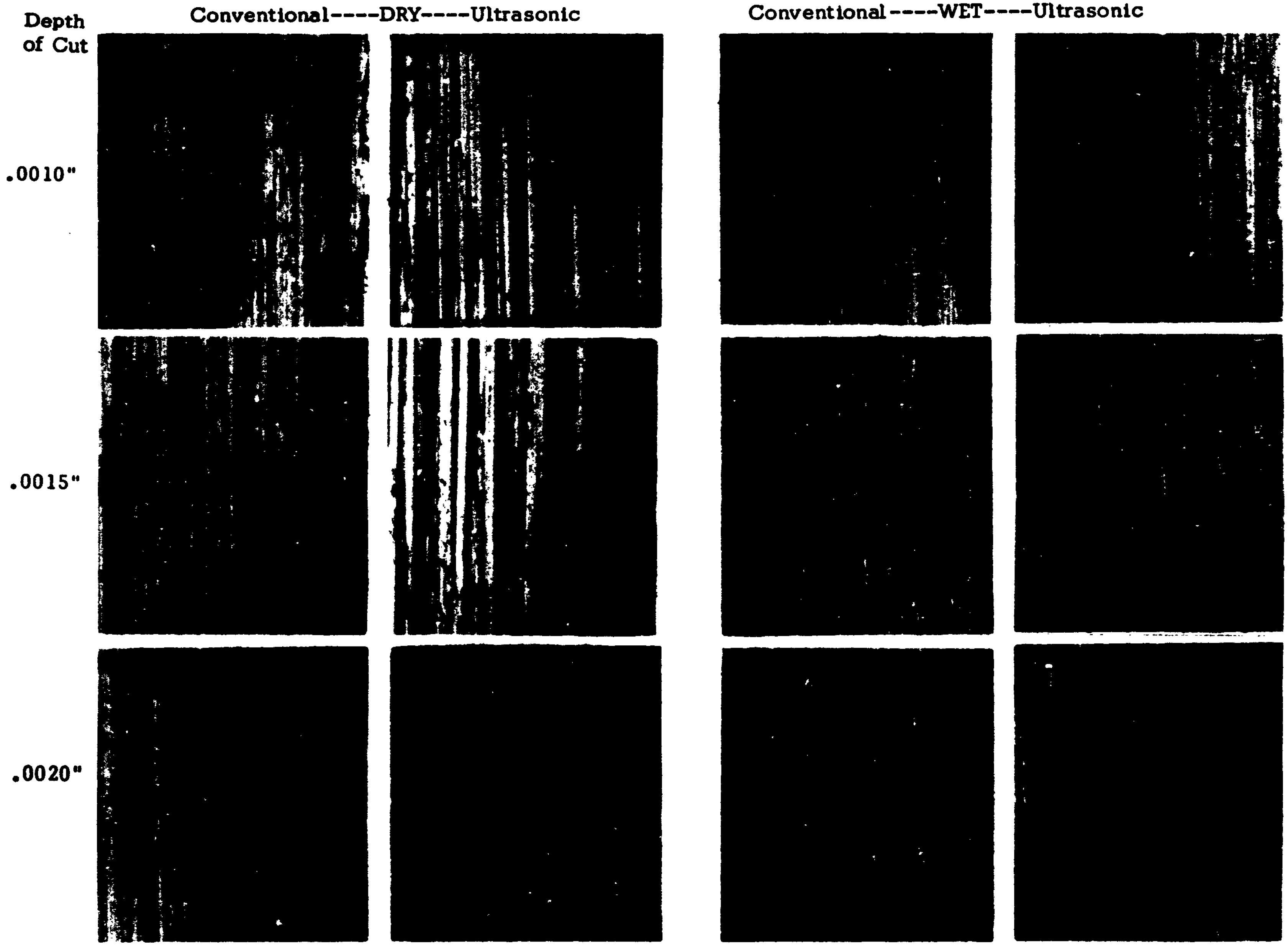
Magnification 3.25X

Figure 259



Magnification 3.25X
Figure 260

WHEEL AA60-L8-V40 MATERIAL Rene 41



Magnification .25X
Figure 26

WHEEL AA60-L8-V40 MATERIAL H-11

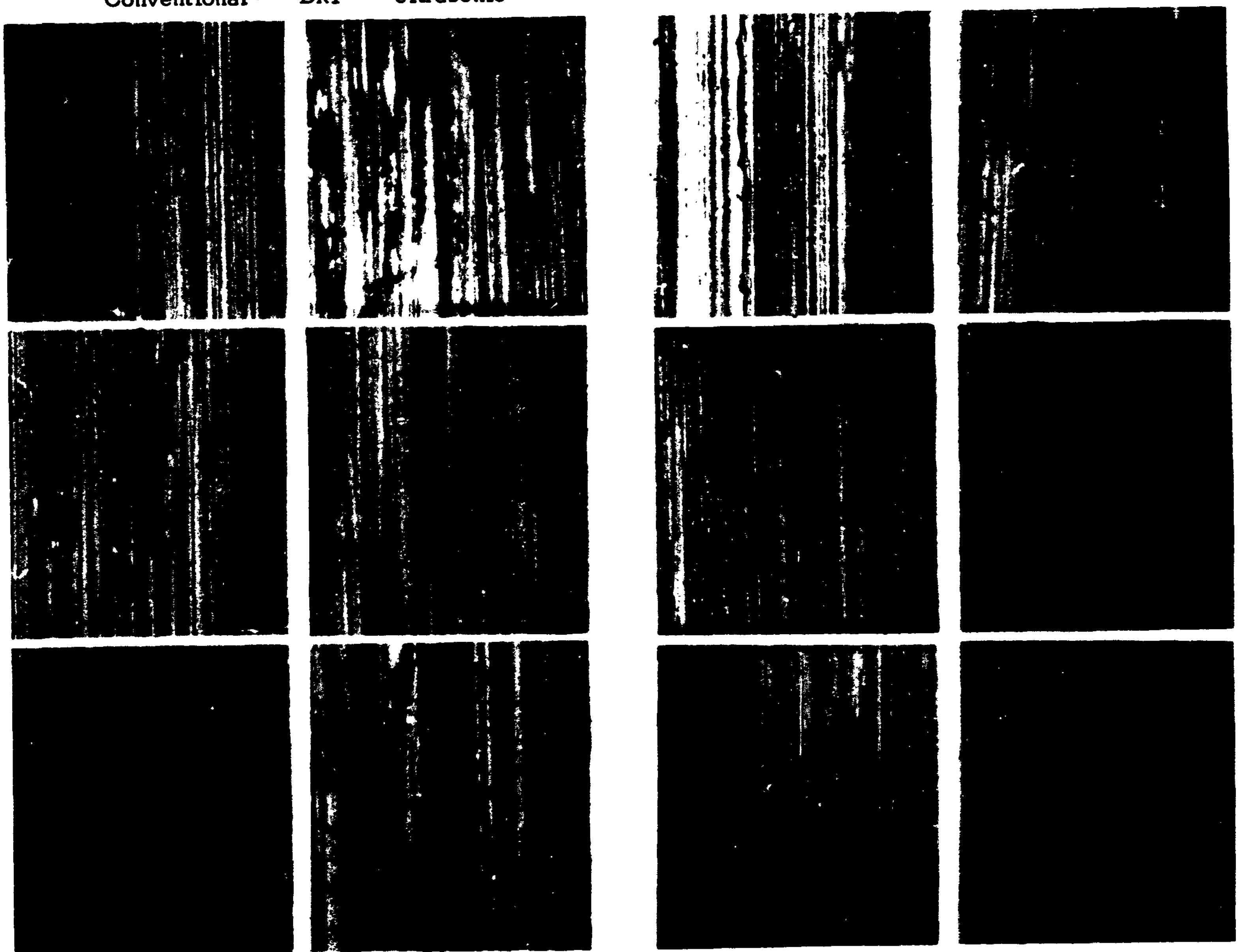
Conventional----DRY----Ultrasonic Conventional----WET----Ultrasonic

Depth of Cut

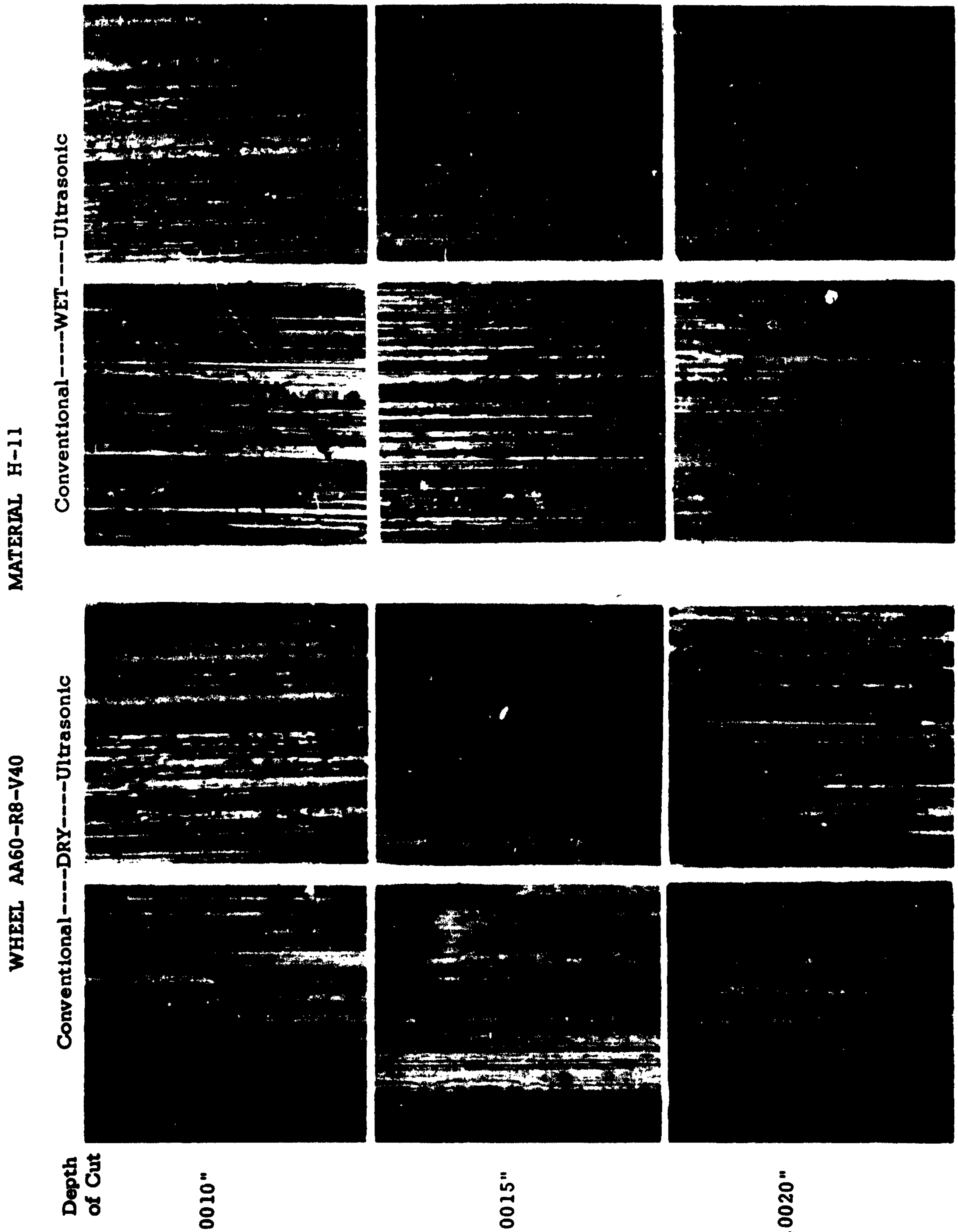
.0010"

.0015"

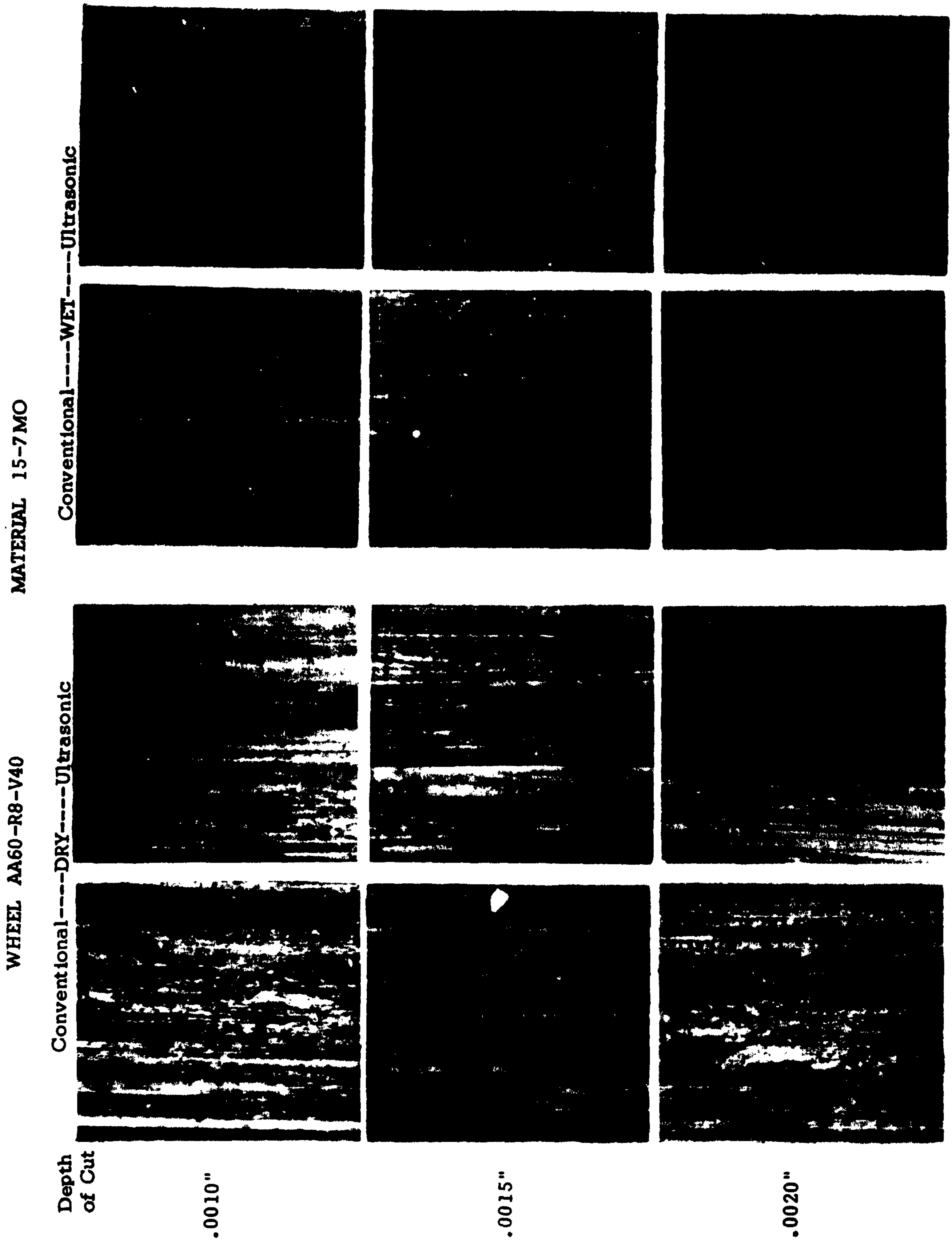
.0020"



Magnification 3.25X
Figure 262



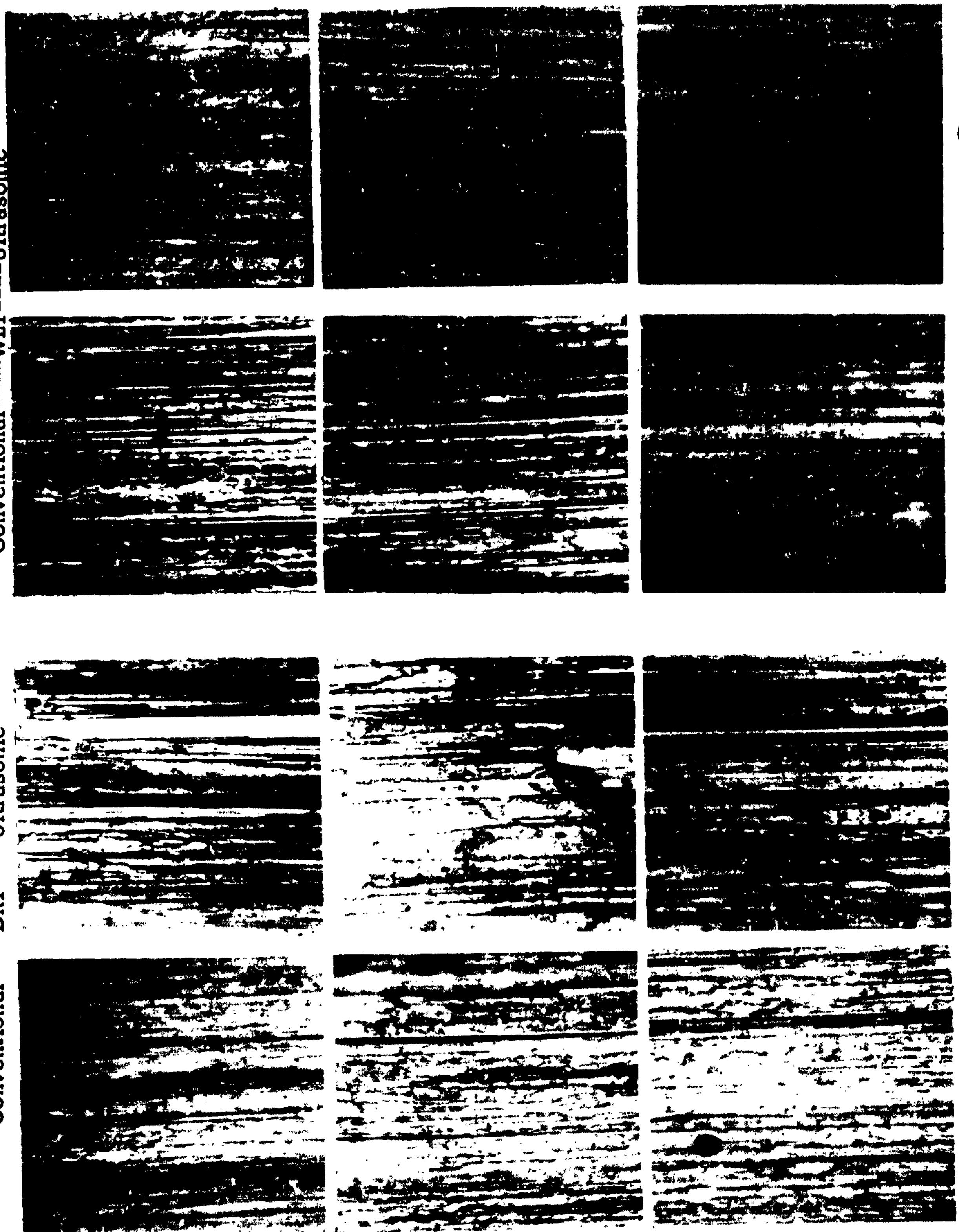
Magnification 3.25X
Figure 263



Magnification 3.25X
Figure 264

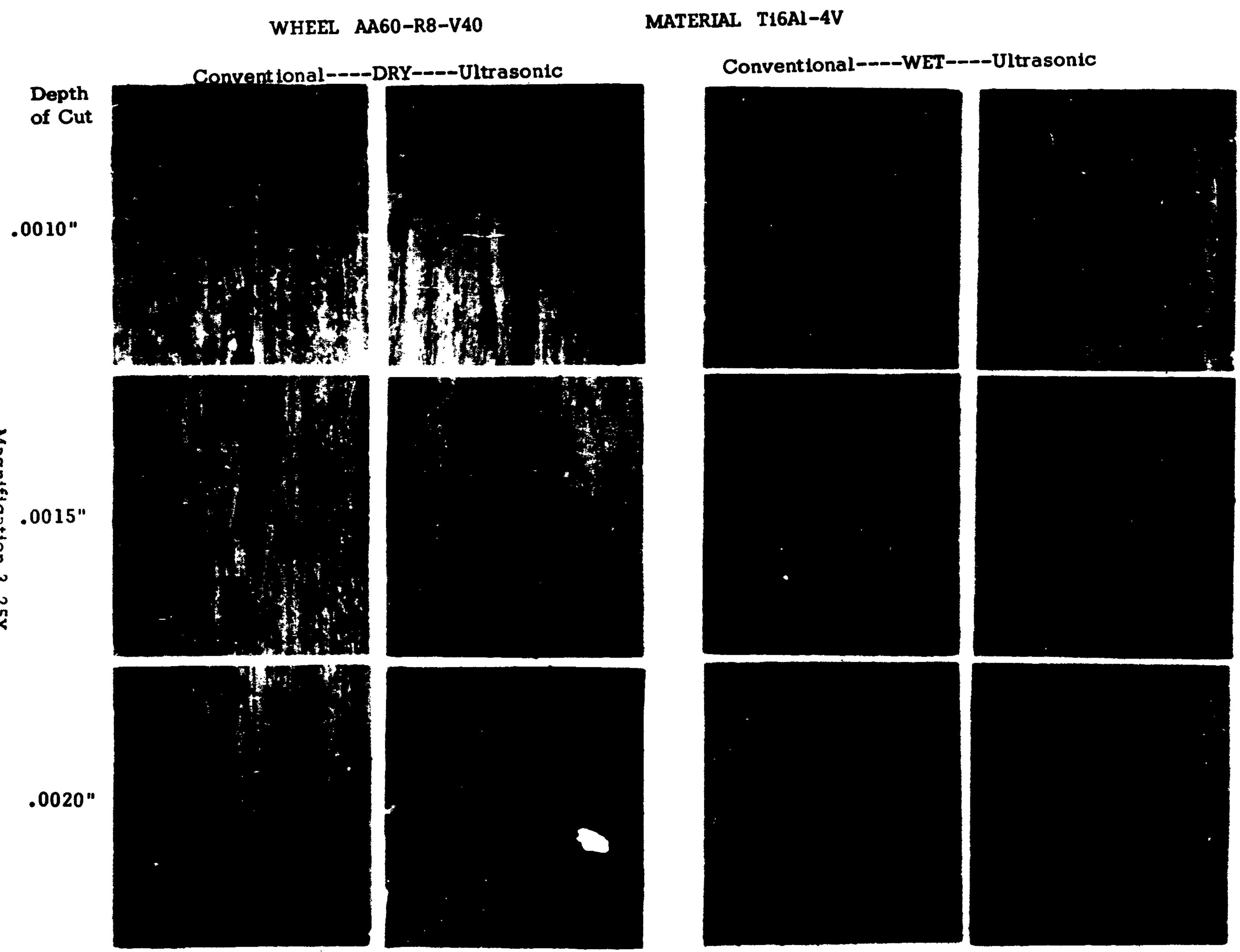
WHEEL AA60-R8-V40 MATERIAL Rene 41

Conventional----DRY----Ultrasonic Conventional----WET----Ultrasonic



Depth of Cut: .0010" .0015" .0020"

Magnification 3.25X
Figure 265



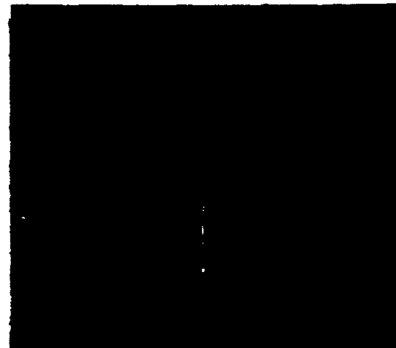
Magnification 3.25X
Figure 266

MISCELLANEOUS

RUNS 497 to 502

COMPARISON PHOTOMICROGRAPHS OF SPECIMEN SURFACE FINISHES

Magnification 3.25X
of Ti6Al-4V Steel



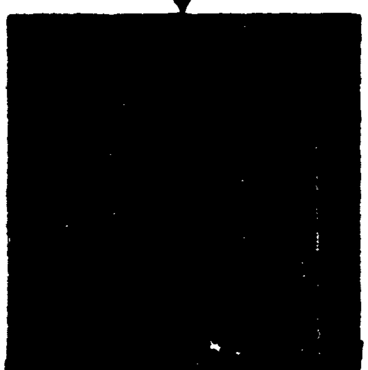
20 kc
Vibration
Assisted
Grind

Conventional
Grind

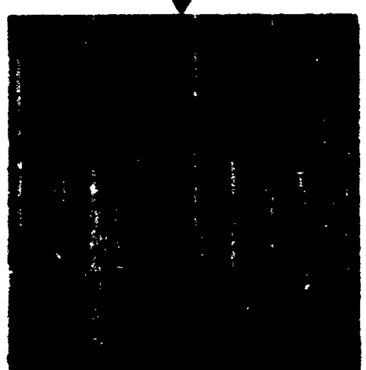
2 Specimens having the same wet Grinding Conditions:
(a) 2 passes .002" downfeed
(b) .050" cross feed
(c) Table travel 35' per minute
(d) Wheel Speed 6000 S.F.M.
(e) Grinding Wheel AA60R8-V40
(f) Cimco & Water Coolants(1:5)

Surface Photomicrographs of test specimens ground by Met-Cut Associates, Cincinnati, Ohio
All specimens were wet ground with down feed of .001" per pass with .050" cross feed. The depth of cut was then changed to: 2 passes at .0005" , 2 passes at .0004" , 6 passes at .0002" and finishing up by sparking out.

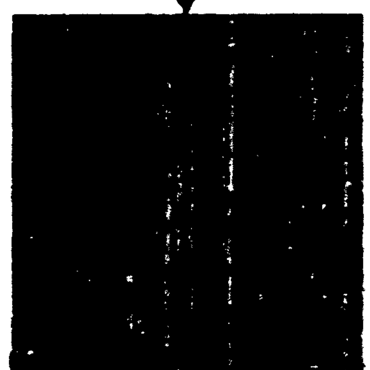
Table travel 20' per minute
Coolant: Fluid Stuart thread cut 99
Diluted 1:1 with paraffin oil



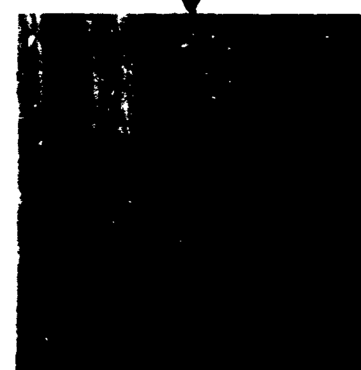
Magnification 200 X
of H-11 Die Steel
Wheel used
32A46G12 VBE at
6000 S.F.M.



Magnification 200 X
of Rene 41 Steel
Wheel used
32A46G12VBE at
3500 S.F.M.



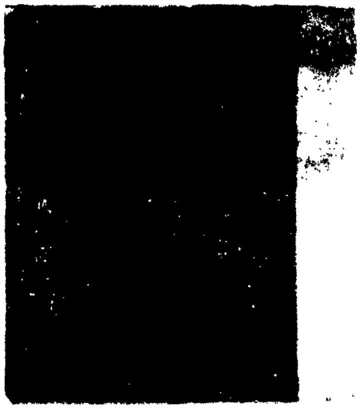
Magnification 200 X
of 15-7MO Stainless
Wheel used
32A46G12VBE at
6000 S.F.M.



Magnification 200 X
of Ti6Al-4V Steel
Wheel used
39 C 60J 4 V K at
3500 S.F.M

Figure 267

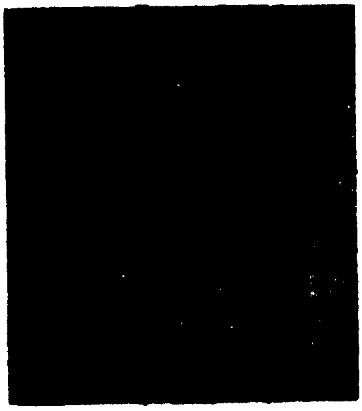
Wheel - - AA60-L8-V40
downfeed - .001
infeed - .100"/pass
table speed - 3'/minute
Ti6Al-4V
Cimco Coolant
5 Div. Spindle
Run 497



Wheel - AA60-L8-V40
downfeed - .004
infeed - .050"
table speed - 35'/minute
Ti6Al-4V
Cimco coolant
5 Div. Spindle
Run 498

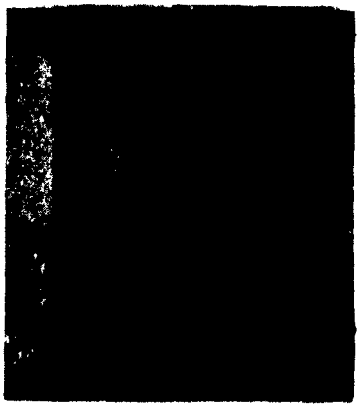
Grinding Ratio 1.83

Wheel - AA60-L8-V40
downfeed - .004
infeed - .050"
table speed - 35'/minute
Ti6Al-4V
Cimco Coolant
Conventional
Run 499



Grinding Ratio .61

Wheel - AA60-L8-V40
downfeed - .006"
infeed - .050"
table speed - 35'/minute
Ti6Al-4V
Dry
5 Div. Spindle
Run 500



Grinding Ratio 1.20

Figure 268

Wheel - AA60-L8-V40
downfeed - .006"
infeed - .050"
table speed - 35'/minute
Ti6Al-4V
Cimco Coolant
5 Div. Spindle
Run 501

Grinding Ratio .50

Wheel - AA60-L8-V40
downfeed - .008"
infeed - .050"
table speed - 35'/minute
Ti6Al-4V
Dry
7 Div. Ultrasonic Spindle - Approx.
Run 502

Grinding Ratio .41

Figure 269

SURFACE FINISHES

RUNS 400 to 496

SURFACE FINISHES

MATERIAL 15-7 MO   Wheel Speed 6200 SFPM   Table Speed 35 FPM

RMS VALUES IN MICRO INCHES

TYPE OF GRIND		WHEEL AA60-L8-V40	WHEEL AA60-R8-V40
		.050" Infeed .0010" Downfeed	
Wet	Conventional	25	20
	3 Div. Ult. Spindle	30	32
Dry	Conventional	Not Run	Not Run
	3 Div. Ult. Spindle	45	Not Run
		.050" Infeed .0015" Downfeed	
Wet	Conventional	25	25
	3 Div. Ult. Spindle	25	30
Dry	Conventional	75	Not Run
	3 Div. Ult. Spindle	Not Run	Not Run
		.050" Infeed .0020" Downfeed	
Wet	Conventional	25	28
	3 Div. Ult. Spindle	32	Not Run
Dry	Conventional	Not Run	Not Run
	3 Div. Ult. Spindle	Not Run	45

Figure 270

SURFACE FINISHES

MATERIAL Rene 41 — Wheel Speed 6200 S F P M — Table Speed 35 FPM

RMS VALUES IN MICRO INCHES

	TYPE OF GRIND	WHEEL AA60-L8-V40	WHEEL AA60-R8-V40
		.050" Infeed .0010" Downfeed	
Wet	Conventional	17	Not Run
	3 Div. Ult. Spindle	23	Not Run
Dry	Conventional	20	Not Run
	3 Div. Ult. Spindle	30	Not Run
		.050" Infeed .0015" Downfeed	
Wet	Conventional	15	Not Run
	3 Div. Ult. Spindle	16	20
Dry	Conventional	32	Not Run
	3 Div. Ult. Spindle	28	Not Run
		.050" Infeed .0020" Downfeed	
Wet	Conventional	18	Not Run
	3 Div. Ult. Spindle	20	25
Dry	Conventional	Not Run	Not Run
	3 Div. Ult. Spindle	Not Run	Not Run

Figure 271

SURFACE FINISHES

MATERIAL H-11 Wheel Speed 6200 SFPM Table Speed 35 FPM

RMS VALUES IN MICRO INCHES

	TYPE OF GRIND	WHEEL AA60-L8-V40	WHEEL AA60-R8-V40
		.050" Infeed .0010" Downfeed	
Wet	Conventional	40	Not Run
	3 Div. Ult. Spindle	38	Not Run
Dry	Conventional	25	Not Run
	3 Div. Ult. Spindle	45	Not Run
		.050" Infeed .0015" Downfeed	
Wet	Conventional	33	Not Run
	3 Div. Ult. Spindle	40	Not Run
Dry	Conventional	30	Not Run
	3 Div. Ult. Spindle	45	Not Run
		.050" Infeed .0020" Downfeed	
Wet	Conventional	27	Not Run
	3 Div. Ult. Spindle	40	Not Run
Dry	Conventional	Not Run	Not Run
	3 Div. Ult. Spindle	Not Run	Not Run

Figure 272

SURFACE FINISHES

MATERIAL Ti6Al-4V   Wheel Speed 6200 SFPM   Table Speed 35 FPM

RMS VALUES IN MICRO INCHES

	TYPE OF GRIND	WHEEL AA60-L8-V40	WHEEL AA60-R8-V40
		.050" Infeed	.0010" Downfeed
Wet	Conventional	23	23
	3 Div. Ult. Spindle	30	28
Dry	Conventional	Not Run	40
	3 Div. Ult. Spindle	38	Not Run
		.050" Infeed	.0015" Downfeed
Wet	Conventional	30	30
	3 Div. Ult. Spindle	34	38
Dry	Conventional	Not Run	Not Run
	3 Div. Ult. Spindle	33	48
		.050" Infeed	.0020" Downfeed
Wet	Conventional	29	45
	3 Div. Ult. Spindle	32	34
Dry	Conventional	Not Run	Not Run
	3 Div. Ult. Spindle	38	42

Figure 273

PHASE II

SECTION 11

Discussion of Phase II Results and Proposed Ultrasonic Vibrated Grinding Wheel System Modification and Specifications for PhaseIII.

11.1 Effectiveness of Vibration of the Grinding Wheel as opposed to Vibration of the Workpiece

Summary: Vibration of the grinding wheel was determined to be more effective in nearly every respect than vibration of the part. Far less amplitude of vibration of the wheel (.00015") is required to outperform the vibration of the workpiece (.00075"). Limitations of the wheel however are size and amplitude of vibration.

11.1.1. Previous Work

Exploratory work conducted in Phase I (October 2, 1959 to June 2, 1960) indicated that numerous advantages could be had by Ultrasonic vibration of a workpiece while grinding. A prototype Ultrasonic spindle had been completed during this period but insufficient runs were made in order to make comparisons.

Further, tests conducted at 60 cps on the workpiece were also insufficient to resolve differences even though there was some indication of improvement in the grinding.

11.1.2. Comparison Tests of Vibration Systems

In order to make the most favorable comparison between vibration assisted grinding and conventional grinding, it was decided in Phase II to determine which vibration system was the most effective.

Tests were conducted comparing conventional grinding with Ultrasonic workpiece vibration at 60 cps and 20,000 cps; and with Ultrasonic wheel vibration at 20,000 cps. The tests indicated that the wheel vibration was superior to all other forms tested.

In addition to improved performance of the Ultrasonic wheel, other advantages are in evidence. They are:

A. The workpiece may be as varied in geometry as is customarily found in industry. Vibration of the workpiece at effective amplitudes is extremely dependent on its mass, density, shape and ability to adhere to bonding agents sufficiently strong to withstand the high stress involved during vibration.

B. Adaptability. The Use of the Ultrasonic Wheel permits the application of Ultrasonic vibration assisted grinding on Internal, External and Centerless grinding as well. The problems associated with the vibration of workpieces supported on centers (External) or Centerless are numerous but the chief problem is basic and requires application of vibration to a workpiece essentially detached from any medium which could transmit the high energy level required.

C. The Wheel, while vibrated, is effectively cleaned of all broken grits, metal, etc., that would have normally remained if not vibrated. This provides a cleaner and freer cutting wheel.

11.1.3 Limitations of Wheel Vibration

A. Limited in the diameter and the thickness in which it may be vibrated for a given frequency. However, at 20 kc, a wheel 8" in diameter may still be effective down to 4" in diameter before replacement.

B. The amplitude of vibration tolerated by a standard vitrified wheel at high frequencies is much less than that which can be withstood by normal workpieces. However, the amplitude required by the wheel is much less to produce the same performance (not withstanding other wheel advantages per se) as the vibration of the part. (.00015" amplitude of the wheel is superior to .00075" amplitude of the workpiece).

C. Wheel Coupling. Simple mechanical attachment of wheels to the vibrating hub is not effective. The high vibration stresses and the resulting hammering due to ineffective attachment soon destroy the wheel. The soft paper pressure pads are a serious impediment to efficient vibration transfer. However, epoxy resin bonding of the wheel to the vibrating hub is quite effective in coupling the wheel to the hub. The resin, as well as the wheel, cannot tolerate the high stresses as in the case of the workpiece when vibrated. Nevertheless, the amplitude of vibration required of the wheel to do an effective job is within that amplitude range for which the endurance of the bond and the wheel is long lived.

D. Effective vibration isolation from the bearings in the spindle can be much more easily attained at high frequencies (20kc) than low (60 cps). If proper vibration isolation is not attained, undue bearing loads and bearing wear will follow.

11.2 Relationship of Frequency andAmplitude Variations in Grinding Tests

11.2.1. Amplitude Constant - Varying Frequency

For a given wheel, workpiece, depth of cut, table speed, and amplitude of vibration, the effect of changing the frequency of vibration is rather complex. At low frequencies (60-1000 cps) only spindle power reductions are found. High spheroids to chip ratios, high peak temperatures and low grinding ratios occur. At high frequencies (10-25kc), spindle power, peak temperature rise in grinding, and spheroid to chip ratios are low while grinding ratios are high-all in comparison to conventional grinding.

11.2.2. Frequency Constant - Varying Amplitude

For a given wheel, workpiece, depth of cut, table speed and frequency of vibration the effect of changing amplitude of vibration is as follows: at low frequencies (60-1000 cps), spindle power reductions increase as amplitude increases. However, spheroid to chip ratios and peak temperatures increase while grinding ratios decrease. In some cases (particularly soft grade wheels) the grinding ratio decrease is severe. At high frequencies (10-25kc) an increase in amplitude causes spindle power, peak temperature rise, and spheroid to chip ratio reductions while grinding ratios increase. These benefits do not increase without bounds, but are limited due to depth of cut, loading on the vibration system, wheel bond strength and grit fracture. In other words, there are optimum levels of amplitude, above or below which decreasing effects will occur.

11.3 Comparisons Between Vibration Assisted and Conventional Grinding

11.3.1 Surface Finish

With light cuts (.0003") Vibration of the wheel or the workpiece at high frequencies (20KC) while grinding gives surface finishes that are neither superior nor inferior to conventional grinding. However, the general visual appearance is superior for the ultrasonic vibrated ground condition. On heavier cuts (.0009") surface finish is generally superior on the vibration assisted grinds. Further, the surface ginish superiority is enhanced by decided chatter reduction. This can be borne out by comparing the photographs of the ultrasonic versus the conventional ground specimens.

11.3.2 Dimensional Changes

Under the test conditions conducted so far, no apparent dimensional differences have been noted between vibration assisted ground specimens and conventional ground specimens.

11.3.3 Surface Damage

To date, no checking or cracking of the vibration assisted or the conventional ground specimens have been observed. However, under the majority of the dry test runs conducted, a burned appearance occurs on the test specimens that have been conventionally ground. This burning is almost totally absent on the vibration assisted specimens. The H-11 seems most susceptible in burn indication. No burns were in evidence on specimens ground for mechanical property testing.

11.3.4 Residual Stresses

To date, no fundamental differences in the residual stress have been on the ground test specimens, either conventional or vibration assisted. However, the test conditions could be made more severe in order to determine if any change in differences occur. (pages 208-211).

Upon inspection of the curves on pages 208-211 it will be found that the areas under each curve are essentially equal and this of course relates the magnitude of stress.

11.3.5 Grinding Ratios

The grinding ratios attained by ultrasonic vibration assist of the grinding wheel are nearly always superior to any other method tried, regardless of wheel used. However, in the case of ultrasonic workpiece vibration while grinding, the grinding ratios are nearly the same as conventional but worse when ultrasonic wheel and part vibration are combined. This is indicative that the alternating forces due to vibration were sufficient to fracture the grits and more probably the grit post bonds. If grinding wheels could be made to withstand these forces, more certainly improved grinding ratios would prevail in addition to permitting greater stock removal rates.

In the case of Titanium and H-11 die steel (pages 196-209 & 243) the grinding ratios attained with theultrasonic vibrated wheel are truly significant in comparison to their conventional counterparts. A harder wheel suits vibration assisted grinding in this respect.

11.3.6 Fatigue Studies by Metcut Research - Section 8.6

After careful study of fabrication and grinding conditions, together with the results of the fatigue testing program previously discussed we can only conclude that the ultrasonic assisted grinding does not impair fatigue properties of the materials tested, even though under such severe grinding conditions as a much harder wheel.

Further, since the grinding of both ultrasonic and conventional specimens were very carefully made, we can offer no explanation at present as to the large scatter in data found on the conventionally ground titanium specimens.

We can only assume therefore that titanium, as conventional ground, might require more extensive fatigue testing in this area to elucidate the cause(s), if any. Further, fatigue testing of ultrasonic vs. conventional in which like grades of wheels as well as larger diameter wheels on other style surface grinders might be in order. It is commonly assumed that a hard wheel would normally produce lower endurance limits than soft wheels. Since hard wheels (R) produce equal or superior results with ultrasonics as opposed to conventional with soft wheels (I,L), it seems reasonable to assume that ultrasonics employing soft wheels might further improve fatigue properties.

One might still assume that "safe" grinding practice on certain critical components or materials might have an added safety factor by employing ultrasonics to the standard procedures. This might then prevent certain types of occasional defective specimens due to minor variation in standard procedures.

11.3.7 Tensile and Crack Inspecion Tests Results

As in the fatigue studies, results of ultrasonics, vs. conventional grinding are that ultrasonics using a hard (R) wheel does not impair the tensile or create cracks in ground specimens.

11.4 Grinder Vibration System Design Specifications for Operational Efficiency as applied to Reciprocating Surface Grinders

11.4.1 Wheels

Maximum diameter	-	8-16" - limited by style of surface grinder
Minimum diameter	-	5"
hardness	-	I to R (R is preferred for best g ratios)
grit	-	46 - 60 aluminum oxide
width of face	-	up to 1¼"
SFPM	-	2000 - 6200 depending on material ground
stroke of ultrasonic vibration	-	for an 8" wheel approximately 3 div. (150 X 10^{-6} in.) but not exceeding 5 div. (250 X 10^{-6} in.)
frequency range	-	18 - 25 kc
wheel to hub bonding	-	Armstrong's epoxy cement A-4

11.4.2 Hubs

Material	-	K or M monel annealed and stress relieved after machining
diameter	-	4-3/8" - 20 kc
length	-	4.33" - 20 kc

For optimum performance, all hubs should be carefully tuned to design frequency and be free of cracks, flaws and be of smooth finish free from tool marks.
The flange upon which the wheel is mounted should have a knurled surface to provide additional bonding area for the epoxy cement.(see page 165)

11.4.3 Ultrasonic Transducer

power rating -	300 - 1000 watts depending on wheel size
frequency range-	18 - 25 kc depending on hub design. However different transducers are required for frequency changes of equipment that is greater than 2 kc. This is done to avoid shifting nodal planes about which the plain or anti-friction bearings must mount to avoid abnormal bearing loading and wear.
output diameter (diameter to which wheel hub is attached) -	dependent on wheel diameter however an 8" wheel to 16" wheel should be 1-5/8" or greater if possible. This allows necessary spindle stiffness. A pilot in the hub to receive the output diameter helps concentricity.
Stud size -	½-28 UNF to 3/4-16 UNF depending on output diameter
cooling -	water sealed-air heat exchange on cooling fins. An open type air cooled system could be devised at lower transducer powers. Water cooling should be employed above 20 watts per cubic inch of transducer core material.
amplitude -	0 - 0.001" peak to peak
type -	nickel or vanadium permendur-magnetostrictive preferred, barium titanate types also show promise.
slip rings -	copper - carbon brushes. Slip rings should be used whenever window types of transducers are employed. Ordinary solenoid wound transducers do not require slip rings but necessitate greater d.c. currents to polarize.
input impedance -	Preferred magnetostrictive-8-16 ohms Electrostrictive-several hundred or more

11.4.4 Spindle

bearings	-	Anti-friction bearings double tapered loaded in front-rear in radial thrust

and floating to minimize changing bear-loads due to heating of spindle section housing transducer. Bearings must be mounted in such a manner as to be placed as nearly as possible to the nodal plane of the transducer. This will prevent undue vibration in the bearings. Present information on bearing and race wear on a spindle with over 200 hours ultrasonic grinding service indicates no visible wear. However, it is deemed a wise precaution to use bearings capable of handling much greater loads than normal and avoiding operation of the ultrasonic transducer in the spindle while not rotating. More efficient vibration mounts exist other than nodal plane mounting but all are deficient in not affording sufficient spindle and hub rigidity as well. Therefore-bearings and vibration damping are compromised somewhat in favor of stiffness and slight losses in mounting efficiency.

lubrication - oil mist
R.P.M. - 1500 - 3875 depending on material being ground (titanium - 2000 SFPM with an aluminum oxide wheel) and wheel diameter.
drive - belt - "V" type 3/4 - 1hp - 8" wheel

11.4.5 Generator

power output- 0 - 1000 watts
frequency - 18 - 25 kc frequency dependent on transducer's range of operation (2kc nominally)
tuning - manual and A.F.C.
input - 60 cycles - 220 V, 3 phase, 2.4 KVA
output impedance - 8 - 16 ohms

11.5 Design Variations of the Vibration System among the Various Grinders as planned for Phase III work: Surface, External, Internal and Centerless.

Section 11.4, page 304, previously covered design specifications for the operational efficiency of a surface grinder. The spindle assembly, wheel head and ultrasonic frequency generator are of such specifications as to permit the adaptation to other types of grinders. In fulfilling Phase III, we therefore will apply the ultrasonic vibrating spindle to the Universal Brown & Sharpe #13 converted to the different kinds of grinders. Page 311 shows a drawing of such a proposed assembly, whereas pages 307-310 depict the vibration assembly appropriately on the respective grinders.

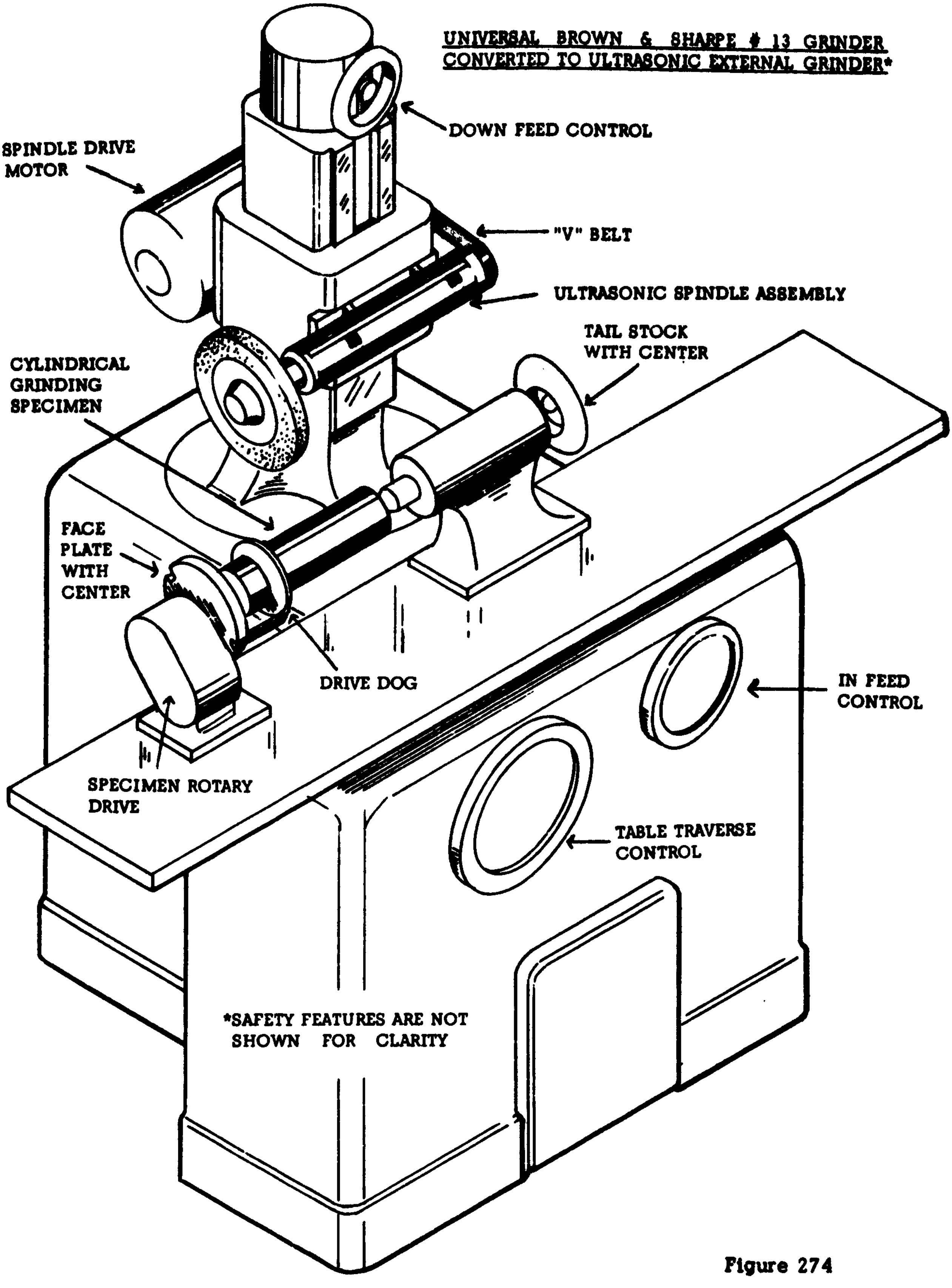

UNIVERSAL BROWN & SHARPE # 13 GRINDER
CONVERTED TO ULTRASONIC EXTERNAL GRINDER*
DOWN FEED CONTROL
SPINDLE DRIVE
MOTOR
"V" BELT
ULTRASONIC SPINDLE ASSEMBLY
TAIL STOCK
WITH CENTER
CYLINDRICAL
GRINDING
SPECIMEN
FACE
PLATE
WITH
CENTER
DRIVE DOG
IN FEED
CONTROL
SPECIMEN ROTARY
DRIVE
TABLE TRAVERSE
CONTROL
*SAFETY FEATURES ARE NOT
SHOWN FOR CLARITY

Figure 274

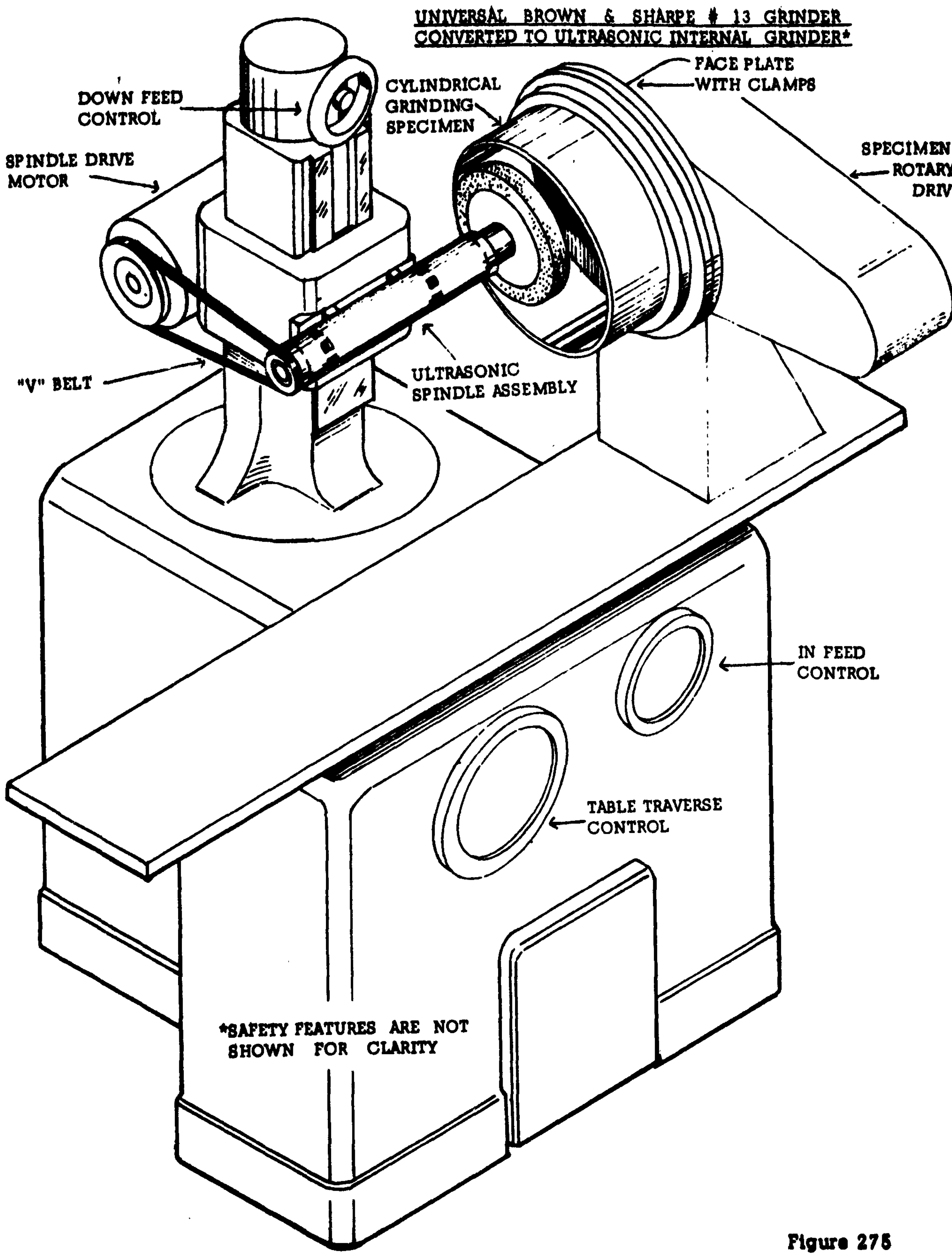

UNIVERSAL BROWN & SHARPE # 13 GRINDER
CONVERTED TO ULTRASONIC INTERNAL GRINDER*
FACE PLATE
WITH CLAMPS
CYLINDRICAL
GRINDING
SPECIMEN
DOWN FEED
CONTROL
SPINDLE DRIVE
MOTOR
SPECIMEN
ROTARY
DRIVE
"V" BELT
ULTRASONIC
SPINDLE ASSEMBLY
IN FEED
CONTROL
TABLE TRAVERSE
CONTROL
*SAFETY FEATURES ARE NOT
SHOWN FOR CLARITY

Figure 275

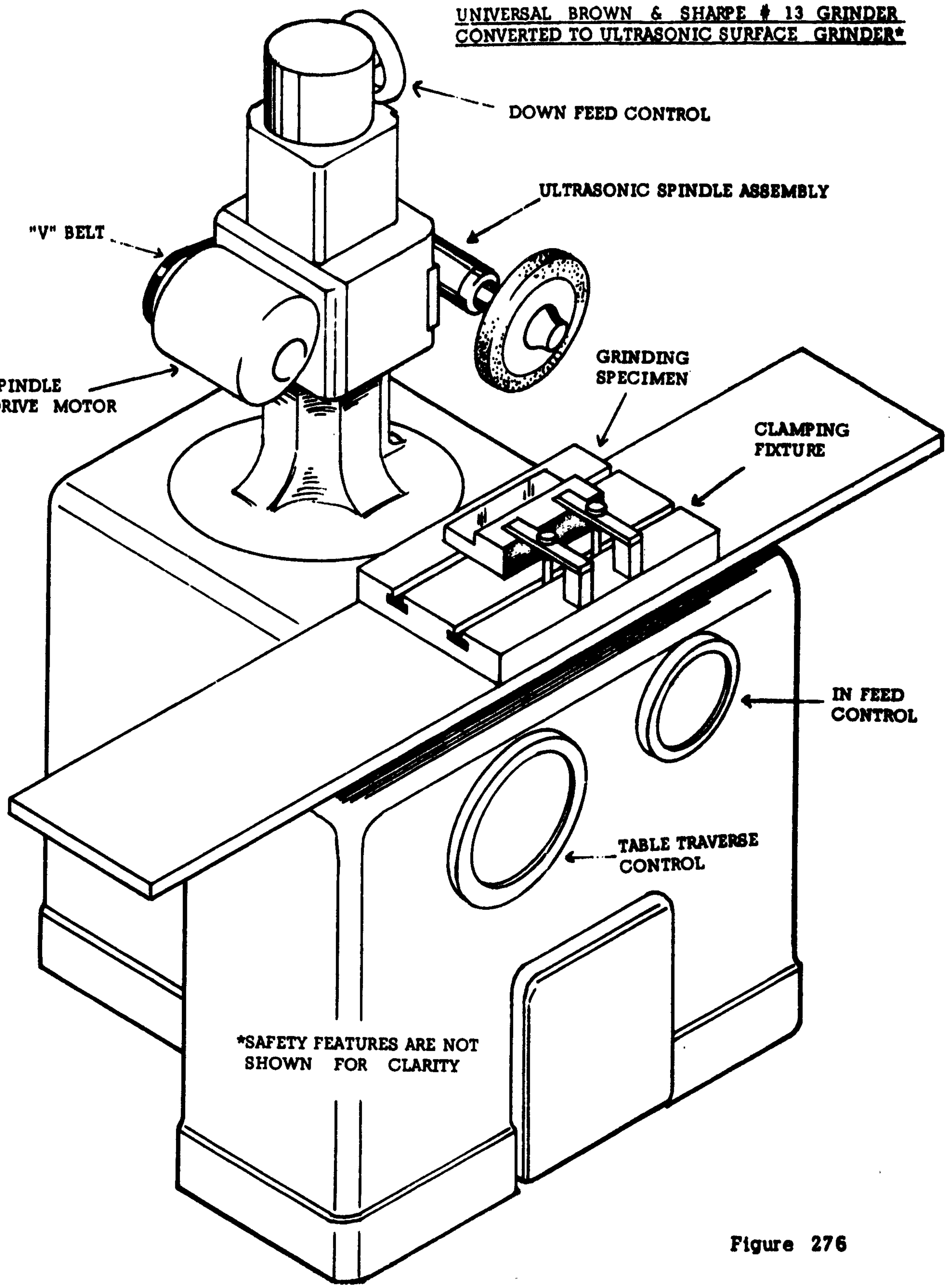

UNIVERSAL BROWN & SHARPE # 13 GRINDER CONVERTED TO ULTRASONIC SURFACE GRINDER*
DOWN FEED CONTROL
ULTRASONIC SPINDLE ASSEMBLY
"V" BELT
SPINDLE DRIVE MOTOR
GRINDING SPECIMEN
CLAMPING FIXTURE
IN FEED CONTROL
TABLE TRAVERSE CONTROL
*SAFETY FEATURES ARE NOT SHOWN FOR CLARITY

Figure 276

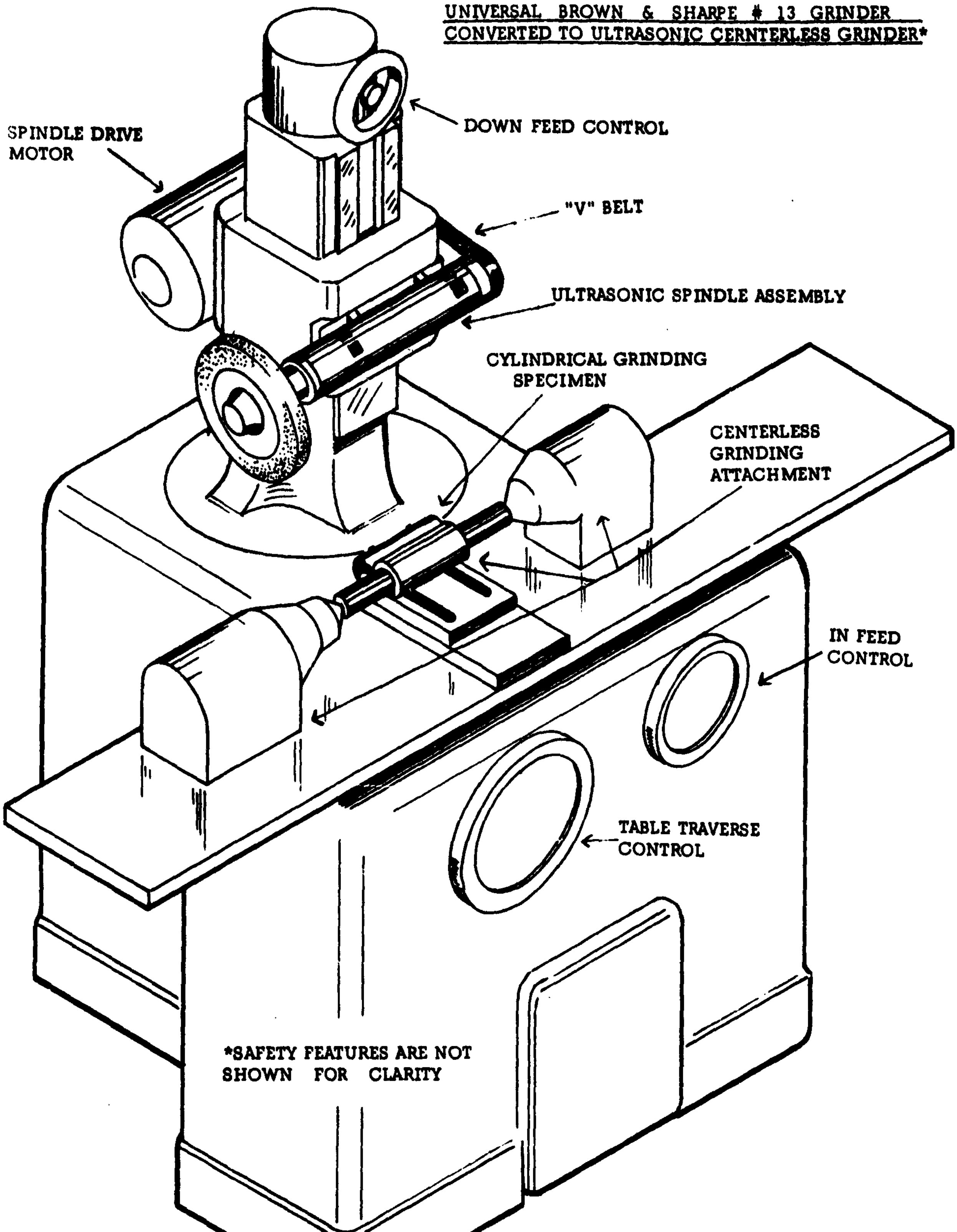
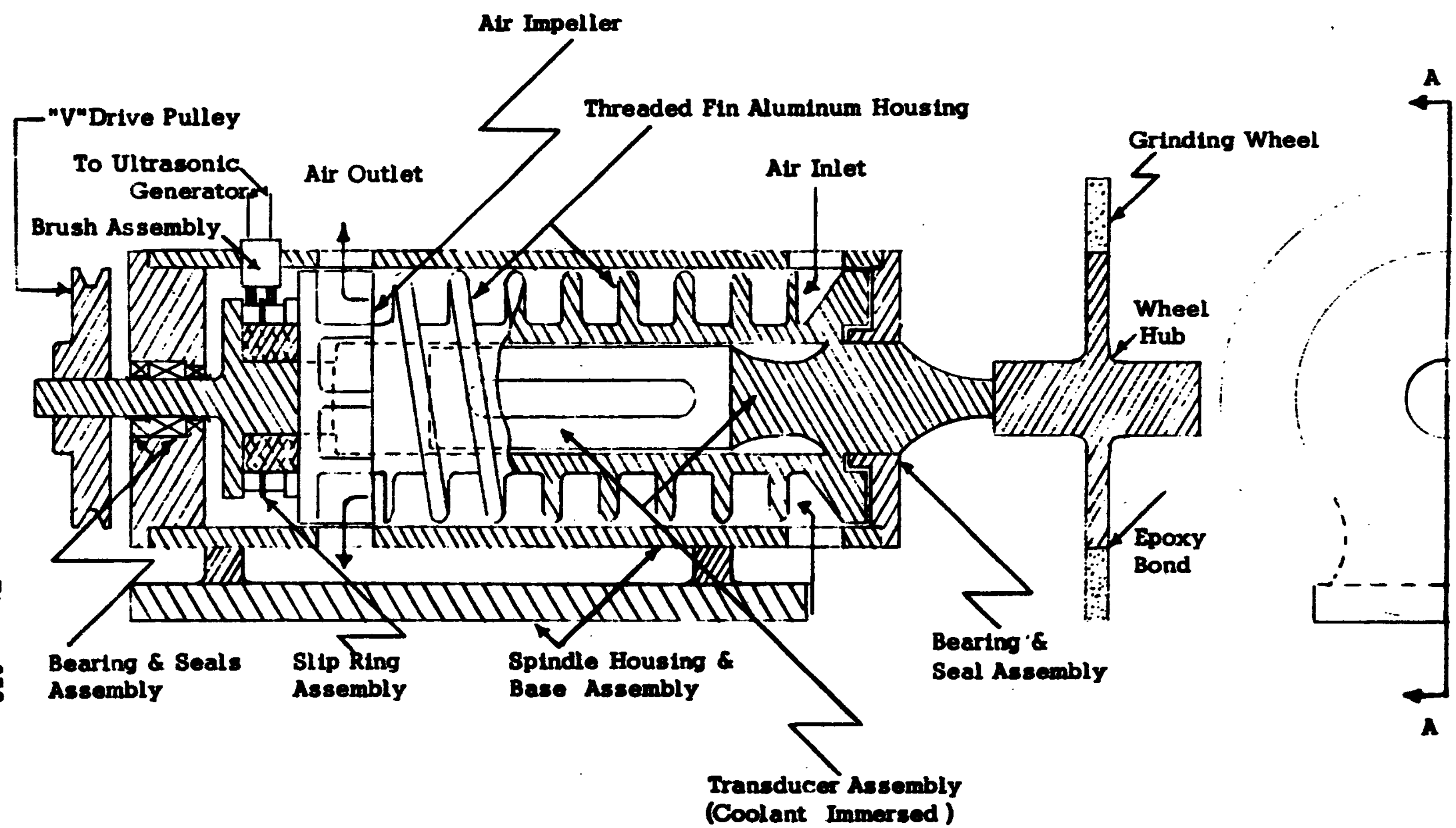

UNIVERSAL BROWN & SHARPE # 13 GRINDER
CONVERTED TO ULTRASONIC CERNTERLESS GRINDER*
SPINDLE DRIVE MOTOR
DOWN FEED CONTROL
"V" BELT
ULTRASONIC SPINDLE ASSEMBLY
CYLINDRICAL GRINDING SPECIMEN
CENTERLESS GRINDING ATTACHMENT
IN FEED CONTROL
TABLE TRAVERSE CONTROL
*SAFETY FEATURES ARE NOT SHOWN FOR CLARITY

Figure 277

PROPOSED ULTRASONIC VIBRATION SPINDLE SYSTEM DESIGN FOR PEAK OPERATIONAL EFFICIENCY



SECTION A - A

Figure 278

PHASE III

12 Work Summary

The Work performed in Phase III is best summarized as follows:

A specially designed ultrasonic assisted grinding spindle was made, tested and installed in each of three grinding modifications, namely, internal, external and surface.

Numerous grinding runs were made with each grinding modification on 15-7 MO, T16Al-4V, Rene 41 and H-11 die steel to establish grinding criteria for certain simulated production runs of ten specimens each.

Simulated production runs were made and through these runs, operational feasibility, adaptability, and portrayals of new grinder types of adaptations of existing grinders were made. Further, substantiation of phase II findings was made through these tests.

Finally, procurement specifications were drafted involving centerless type grinders as well as the above three types.

PHASE III

SECTION 13

13.1 Manufacturing of Ultrasonic Spindle

13.2 Test Specimens

13.3 Instrumentation

13.4 Test Criteria

13.1 Design, Manufacture and Testing of Ultrasonic Spindle

Figure (279) shows the ultrasonic spindle as designed in Phase III. This portrayal illustrates the arrangement of major components.

Studies were made of previous attempts and analyzed for incorporation into the final design. The entire spindle, from wheel and hub assembly to the driven pulley assembly was considered, step by step, for improvement.

Wheel and Hub Assembly

The wheel and hub designs used previously were considered carefully and it was decided to maintain the basic design of Phase II (see figure 280).

However, certain weaknesses such as concentricity and stiffness have been greatly improved upon in the new designs. It was decided to finish grind the hubs as well as provide a larger diameter pilot and stud system. This results in improved operation.

Further, provision in the hub design has been made in order to facilitate the use of 5.5" to 10" diameter wheels from ½" to 1" in width. Epoxy resin bonding to knurled hub flanges were maintained.

Ultrasonic Transducer

Based on the experience in Phase II, early in Phase III evaluation and preliminary design analysis, disclosed certain paths for improvement in the ultrasonic transducer. Since ultrasonic transducers normally are not tailored for rotating operations, especially at high spindle speeds, strict attention to concentricity is not normally given. In addition, the connecting body (see figure 279) usually employed has a lack of lateral rigidity due to a small diameter to length ratio.

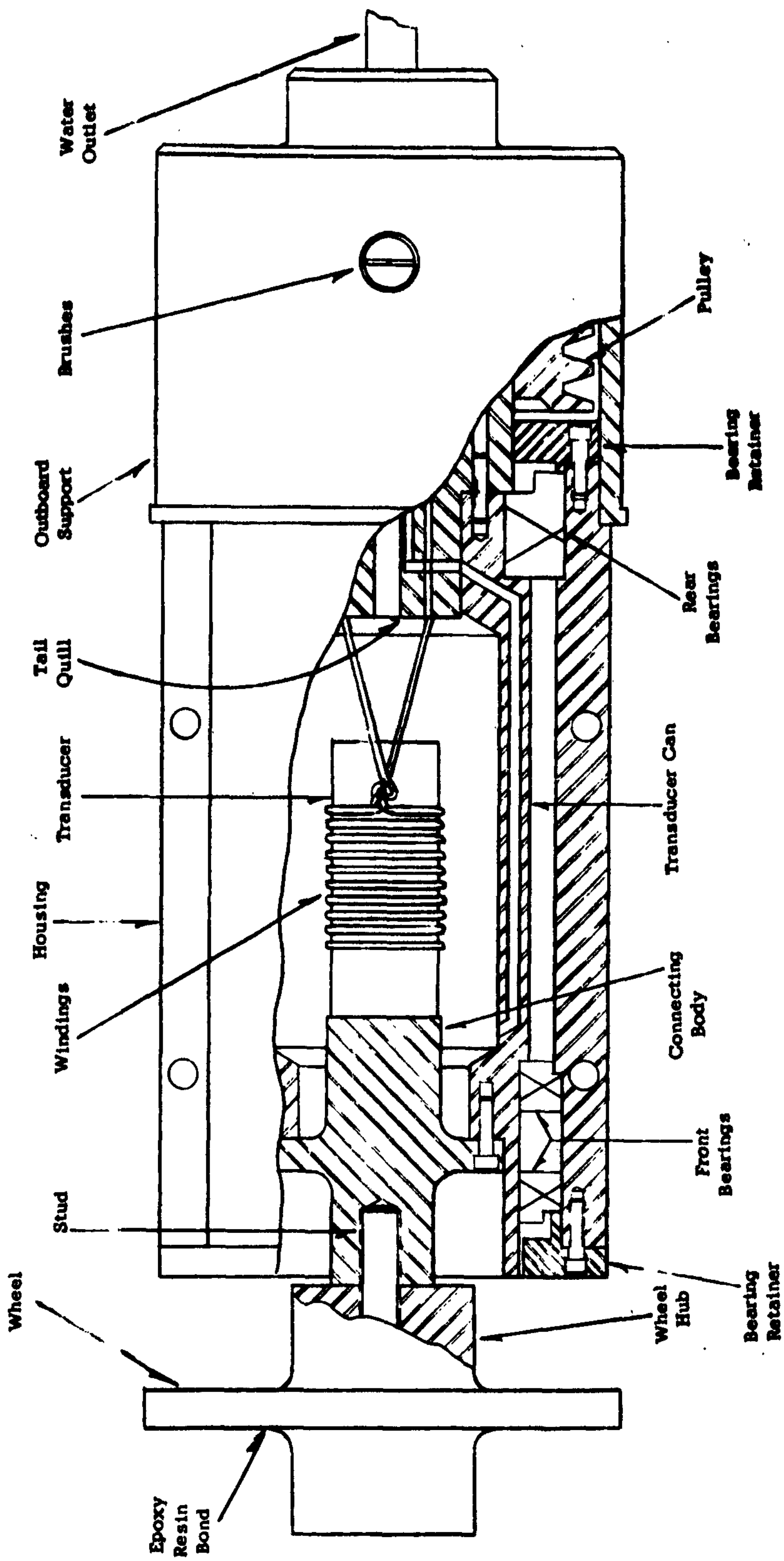
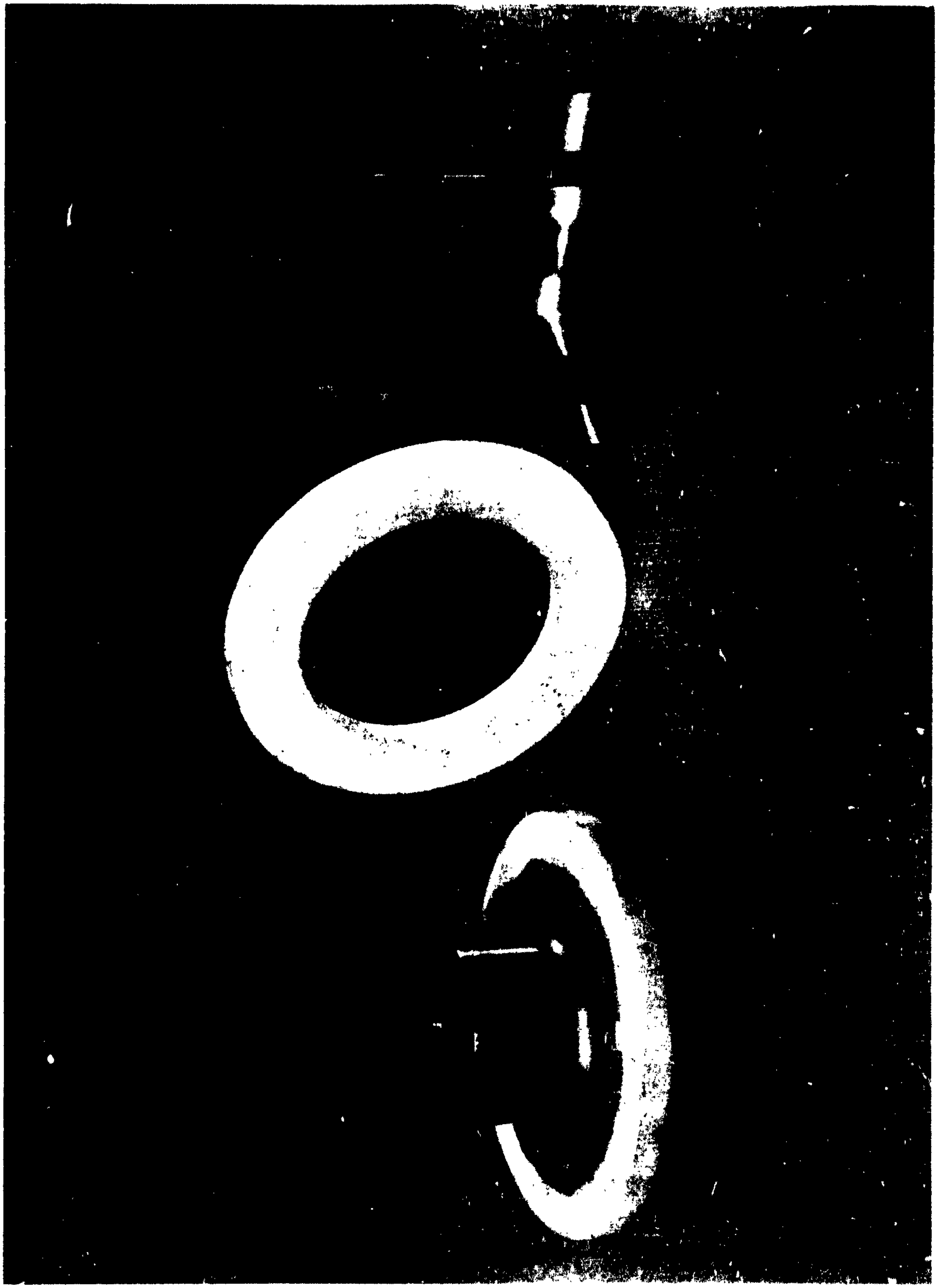

Water Outlet
Brushes
Outboard Support
Tail Quill
Transducer
Housing
Windings
Stud
Wheel
Epoxy Resin Bond
Pulley
Bearing Retainer
Rear Bearings
Transducer Can
Connecting Body
Front Bearings
Wheel Hub
Bearing Retainer

Figure 279



ULTRASONIC HUB-WHEEL ASSEMBLY

Figure 280

In consideration of above, the ultrasonic transducer was redesigned to maintain greater connecting body rigidity by enlarging the connecting body output end. To further insure all diameters being concentric, design provisions call for finish grinding the connecting body diameters on centers. Also, squareness of the output face of the connecting body is provided by finish grinding to insure proper squaring and piloting to the wheel hub assembly which attaches to this face by means of a redesigned threaded stud.

The ultrasonic transducer's electro-mechanical conditions as analyzed from previous work were found quite satisfactory. These were therefore maintained. The transducers resonant frequency of operation is from 19,000 to 21,500 cycles per second and its normal power input is 1000 Watts though its operating power was maintained lower to prevent over powering the somewhat vitrified grinding wheels.

Ultrasonic Transducer Coolant Supply

The coolant supply of the ultrasonic spindle in Phase II was obtained by jacketing the transducer in water and allowing for heat exchange with the jacket to the surrounding air. This worked rather well but the power input to the ultrasonic transducer was less than the present arrangements because the largest wheels used in Phase II were only 7" diameter by ½" face. This would be inadequate for wheels of 1" face and up to 10" diameter.

Further, the original design portrayal of the Phase II spindle (figure 278) as contemplated at the completion of Phase II was, after further study in Phase III, inadequate for the above reasons. The final coolant system is arranged as in Figure 279. There the cooling of the transducer is achieved by a continuous flow of water (about 1 quart/minute). Influx and efflux is accommodated by rotary water seals which are effective at high speeds and surface feet per minute.

Slip Rings and Brush Assembly

Slip rings and brushes, the means for delivering the high frequency alternating current from the generator to the transducer were previously used.

Though this system worked well, it was decided to insure more uniform and reliable contact between the brushes and the slip rings in addition to making them accessible for service if required.

The slip ring design was enhanced by proper care in truing their diameters during final grinding of all major spindle diameters. In addition, the brushes were increased from 2 to 4 to maintain greater possibility of continuous flow of high frequency alternating current.

Spindle Bearings

The early ultrasonic spindle used in a portion of Phase I and II used bronze bearings. Though they were effective for the purpose at hand, their short life and undue maintenance led to an early Phase II modification to antifriction bearings.

Therefore, considering past work, it was decided to maintain the use of antifriction bearings in order to assure long life and tool performance under the test runs of Phase III. Arrangements are as in figure 279.

Drive

The spindle is driven by a 1 h.p. matched twin "V" belt drive with various drive pulleys to achieve the full range of surface speeds dictated by the grinding conditions selected.

Fabrication, Assembly and Testing of Ultrasonic Spindle

Upon completion of all the manufactured spindle parts, the assembly was made. As shown in figure 279, the spindle package consists of three sub assemblies:

(a) Ultrasonic shaft(transducer assembly, transducer can and quill shaft)

(b) Shaft enclosure (housing with bearings and outboard support with its brushes and water seals)

(c) hub wheel assembly (grinding wheel bonded to 20 kc monel hub)

This spindle package was then installed on the Brown & Sharpe #13 grinder. Final installation of spindle consisted of:

(a) electrical attachment of ultrasonic generator

(b) "V" belt attachment of 1 h.p. drive motor

(c) plumbing hook-up of coolant water supply.

Testing of spindle consisted of running the spindle (ultrasonic vibration "ON" and water coolant flow adjusted) to maintain an operating temperature range of 130°F to 140°F on spindle bearings.

13.2 Test Specimens

The following grinding test specimens for surface, external and internal grinding tests, were prepared by Metcut Research Associates.

a. For Surface Grinding Tests:

(1) Samples of hot work H-11 die steel blanks cut to: 2" X 4" X ½" (leaving stock to finish grind after hardening) hardened to 56 Rockwell C.
Heat Treatment: 1850°F +25° F/1hour/air cool
First temper 950°F + 25° F/1hour
Second temper 950°F ± 25° F/1hour air cool

(2) Samples of 15-7MO Stainless Steel blanks cut to: 2" X 4" X ½" (leaving stock to finish grind after hardening) heat treated to RH950 condition - approximately 48 Rockwell C
Heat Treatment: 1750°F +10°minutes/air cool
950°F 7 1½ hours/air cool

(3) Samples of Rene 41 Steel Blanks, cut to 2" X 4" X ½" (leaving stock to finish grind after hardening) hardened to 40-42 Rockwell C.
Heat Treatment: 1950° F ± 25°F/½ hour/air cool
1400° F ± 25°F/16 hours/air cool

(4) Samples of 6Al-4V Titanium Blanks cut to 2" X 4" X ½" (leaving stock to finish grind after hardening) hardened to 35-40 Rockwell C.
Heat Treatment: 1700°F + 25°F/1 hour/water quench
1000°F ± 25°F/1 hour/ air cool

b. For External Grinding Tests:

(1) Samples of H-11 Die Steel Rods, cut to 2½" dia. X 5" long (leaving stock to finish grind after hardening) hardened to 56 Rockwell C.
Heat Treatment: 1850°F + 25° F/1hour/air cool
first temper 950°F ± 25° F/1hour/air cool
second temper 950°F ± 25° F/1hour/air cool

(2) Samples of 15-7Mo Stainless Steel Rods, cut to 2½" diameter X 5" long (leaving stock to finish grind after hardening) heat treated to RH950 condition 48 Rockwell C.
Heat Treatment: 1750° F ± 10° F/10minutes/air cool
-120° F /8 hours/air cool
950° F /1½ hours/air cool

(3) Samples of Rene 41 Steel Rods, cut to 2½" dia. X 5" long (leaving stock to finish grind after hardening)hardened to 40-42 Rockwell C.
Heat Treatment: 1950° F ± 25° F / ½hour/air cool
1400° F ± 25° F / 16 hours/air cool

(4) Samples of 6Al-4V Titanium Rods, cut to 2½" dia. X 5" long (leaving stock to finish grind after hardening) hardened to 35-40 Rockwell C.
Heat Treatment: 1700° F ± 25° F/1 hour/water quench
1000° F ± 25° F/1 hour/air cool

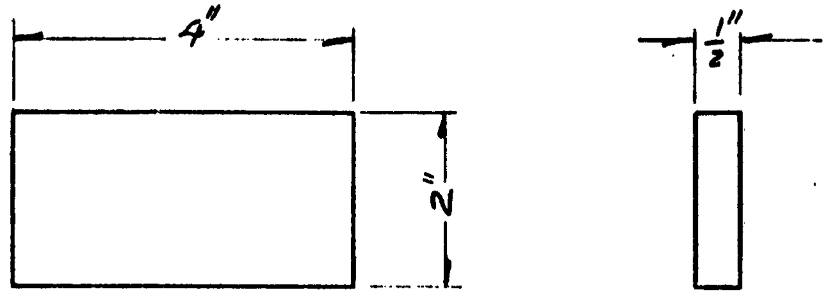
c. For Internal Grinding Tests:

(1) Samples of H-11 Die Steel blanks cut to 9" o.d. X 7" i.d. X ½" thick rings(leaving stock to finish grind after hardening) hardened to 56 Rockwell C.
Heat Treatment: 1850° F ± 25° F/1 hour/air cool
First Temper 950° F ± 25° F/1 hour/air cool
Second Temper 950° F ± 25° F/1 hour/air cool

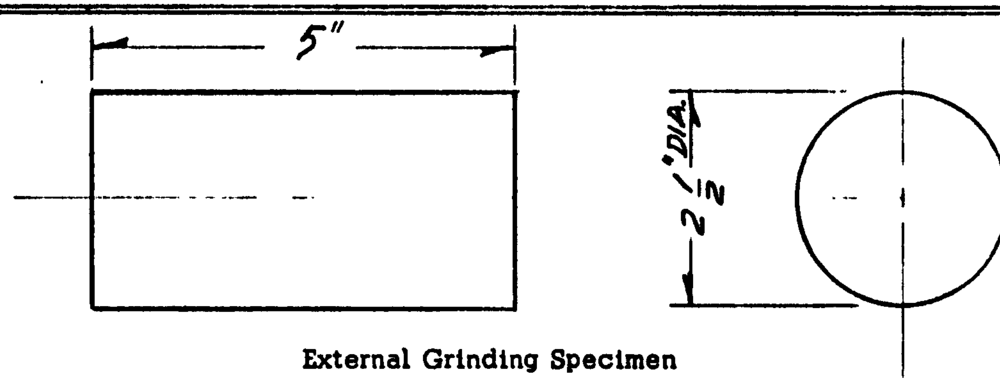
(2) Samples of 15-7 Mo Stainless Steel blanks cut to 9" X 7" i.d. X ½" thick rings (leaving stock to finish grind after hardening) heat treated to RH950 condition 48 Rockwell C.
Heat Treatment: 1750° F ± 10° F/10 minutes air cool
First Temper -120° F ± 8 hours/air cool
Second Temper 950° F 1½hours/air cool

(3) Samples of Rene 41 Steel blanks cut to 9"o.d. X 7" i.d. X ½" thick rings (leaving stock to finish grind after hardening) hardened to 40-42 Rockwell C.
Heat Treatment: 1950° F ± 25° F/½hour/air cool
1400° F ± 25° F/16 hous/air cool

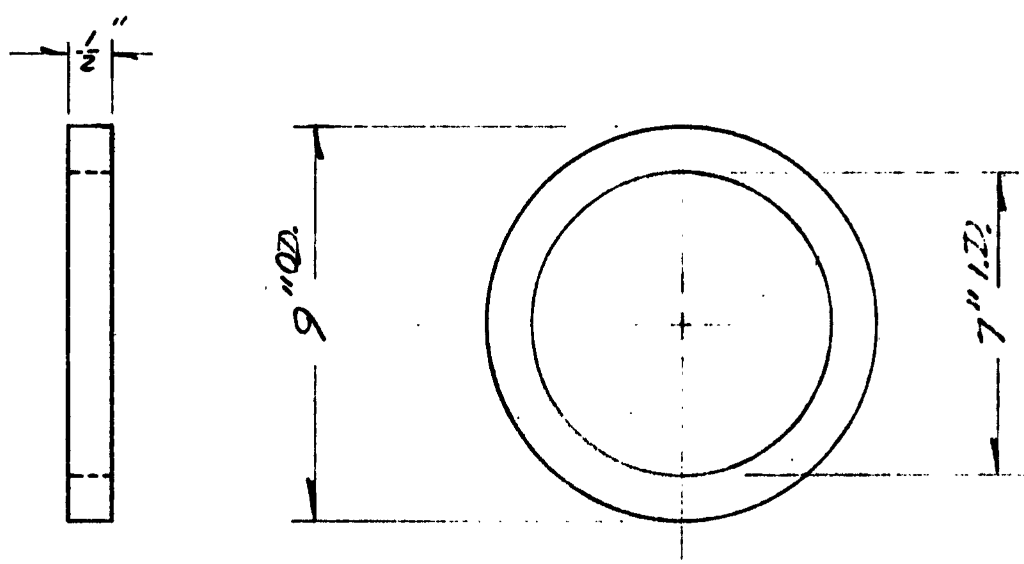
(4) Samples of 6Al-4V Titanium blanks cut to 9: o.d. X 7" i.d. X ½" thick rings (leaving stock to finish grind after hardening) harden to 35 - 40 RockwellC
Heat Treatment: 1700° F ± 25° F/1 hour/water quench
1000° F ± 25° F/1 hour/air cool



Surface Grinding Specimen



External Grinding Specimen



Internal Grinding Specimen

Figure 281

13.3 Instrumentation

Grinding Wheel Measurement

1. With workpiece mounted in workhead and i.d. ground concentric, six grinding passes were made with all wheels, after the wheels were dressed per wheel dressing procedures outlined. Workpiece was then measured with micrometers to within $\pm$.0001".

2. After dressing wheels per wheel dressing procedures, and making concentric passes on workpiece per item 1 above, wheel and hub temperatures were measured with HB engraved stem thermometer CSPF 70° to 78° F.

3. Wheel o.d. was measured at 5 positions 40° apart with 5-6" or 6-7" micrometers and readings were averaged. All micrometers were read to $\pm$ .0001".

4. Wheel o.d. was again measured with a Sheffield model 7 dial indicator snap gage, when wheel, hub, and snap gage were same temperature within $\pm$ 1° F. (Snap gage temperature checked with permanently mounted Weston model 2261 dial thermometer). This measurement is taken at 5 points on the wheel diameter 40° apart and an average diameter is recorded, measurement accurate within $\pm$ .00005".

5. After completing set number of infeed grinding passes, wheel, hub and workpiece were allowed to cool down to original measuring temperature and again measured in accordance with above technique.

Ultrasonic Vibration Measurement

1. With grinding wheel stopped the amplitude of ultrasonic vibration was measured with a National Scientific Instrument Company microscope type 4015, 600X power with a calibrated graduated reticle.

2. A B & K accelerometer type 4329 was mounted on the spindle bracket within $\pm$ .005" of the end of the ultrasonic wheel hub. The output of the accelerometer was fed into the second channel of the Tektronix oscilloscope type 551 and calibrated against the NSIC type 4015 microscope. In this manner the wheel vibration was monitored on all ultrasonic runs.

Wheel Dressing

A typical dressing technique was employed for the different types of wheels used:

1. R & K grade grinding wheels employed diamond dressing before starting to grind each sample. 2 passes at .008"/pass using 20"/minute cross feed, followed by one finish pass of .002"/pass using 20"/minute crossfeed.

2. All other grinding wheels employed diamond dressing before grinding each sample. Two passes at .002"/pass with cross feed of 40"/minute. Followed by 2 passes of .001"/minute with 20"/minute crossfeed. Finished with two passes of .001"/pass with diamond mounted with a negative rake and 10"/minute crossfeed.

Watt Hour Measurement

During the last 30% of the grinding test runs the V.A.W meter used to monitor spindle power failed and was replaced by a Westinghouse type TA, Industrial Analyzer.

PHASE III

SECTION 13:4

TEST CRITERIA

13.4 Test Criteria

Test Criteria were established in order that test conditions could be determined for the simulated production runs. The final selection of the conditions for grinding the simulated production runs, was made with operational efficiency and performance as prime considerations.

The simulated production runs were to be five ultrasonic and five conventional grinding runs on each of the three grinder types. (internal, external and surface) However, in the case of the internal grinding, we found it wise to make an additional five ultrasonic runs.

The grinding conditions forthe numerous grinding tests, leading up to the selection of those conditions for grinding the simulated production runs were generally similar to or about the same as the conditions recommended.

The Recommended conditions were selected from Scientific papers, Metcut Research Associates, Cincinnati; Carborundum Corporation, Ordnance Corps pamphlet #ORDP40-1, and our own staff.

The actual criteria for selection of these conditions were:

1. wheels
2. speeds
3. feeds
4. coolants
5. peak to peak amplitude of vibration
6. frequency of vibration
7. finish
8. surface checks or cracks
9. excessive part deflection or bowing
10. burns
11. grinding ratios
12. spindle power consumption increase during grind
13. test specimen type
14. test specimen geometry

The criteria for ultrasonic grinding conditions are rather limited. The frequency in the ultrasonic vibrated spindle can vary from 19 to 21.5 kc. Each wheel can be tuned at only a definite zone within this range.

Similarly, the level of stress attainable without fracture is limited in an ultrasonic vibrating wheel. The range of amplitude was from 50×10^{-6}" peak to peak to 150×10^{-6}" peak to peak. This is deemed to be well below what is thought to be the limiting amplitude for vitrified wheels of this diameter range. (5½"dia. to 10" dia. up to 350×10^{-6}" peak to peak). Further improvements by ultrasonics could be made if a greater amplitude of vibration, of the wheel, could be tolerated.

Frequencies below 18 kc would be audible and therefore be obnoxious from the standpoint of discomfort to personnel. (As sound intensities in the air would be very high). Frequencies above 25kc are extremely difficult to attain, but never the less, have a further disadvantage due to the much higher stresses for the amplitude of vibration, thus wheel life would be impaired. We believe the frequency range from 18 to 25 kc to be optimum.

PHASE III

SECTION 14

TEST DATA

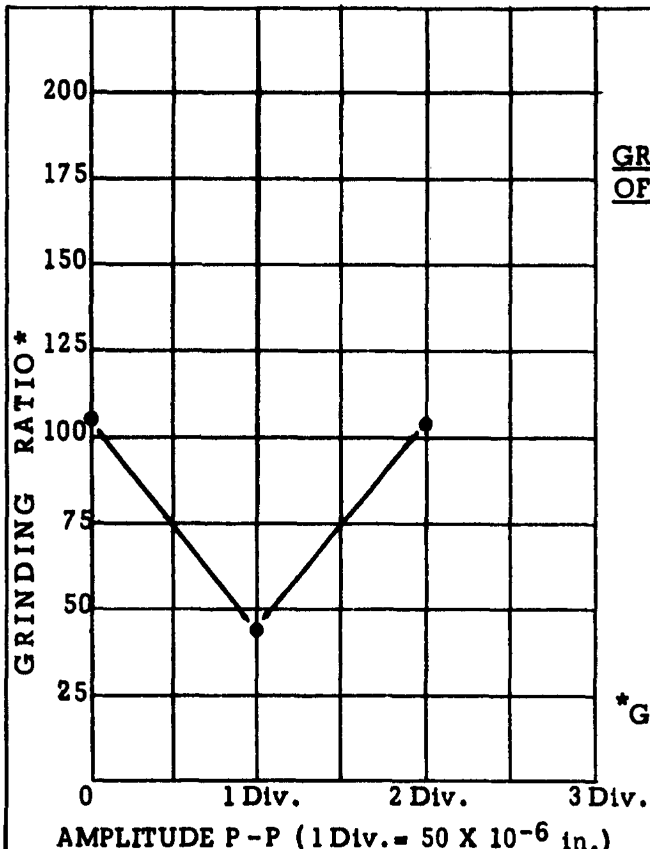
The following are the grinding tests made in order to determine the test conditions under which to make the Simulated Production Runs (Section 14.4).

14.1 Internal Grinding

14.2 External Grinding

14.3 Surface Grinding

14.4 Production Runs



INTERNAL GRINDING

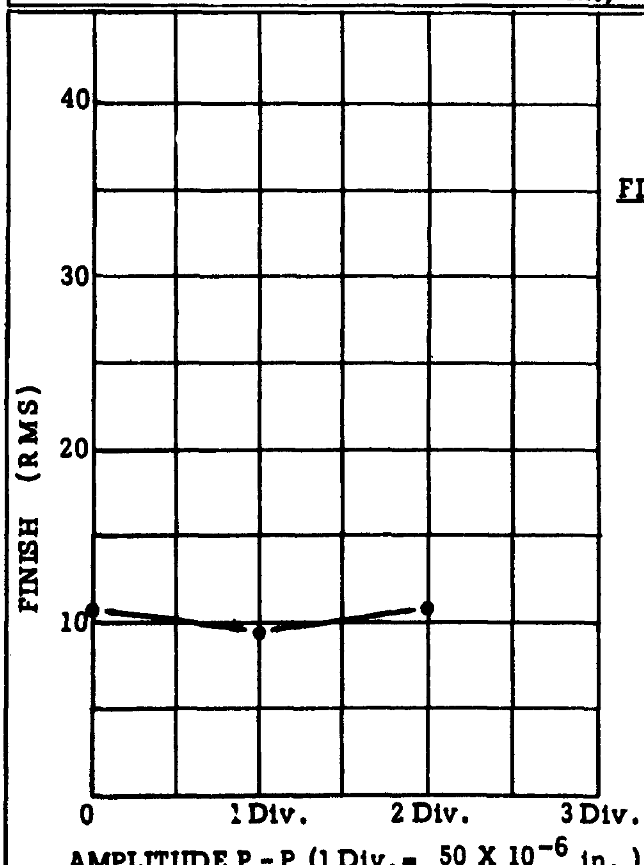
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	15-7 MO
Wheel	AA60-I8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: 30 - 33 - III

Figure 282



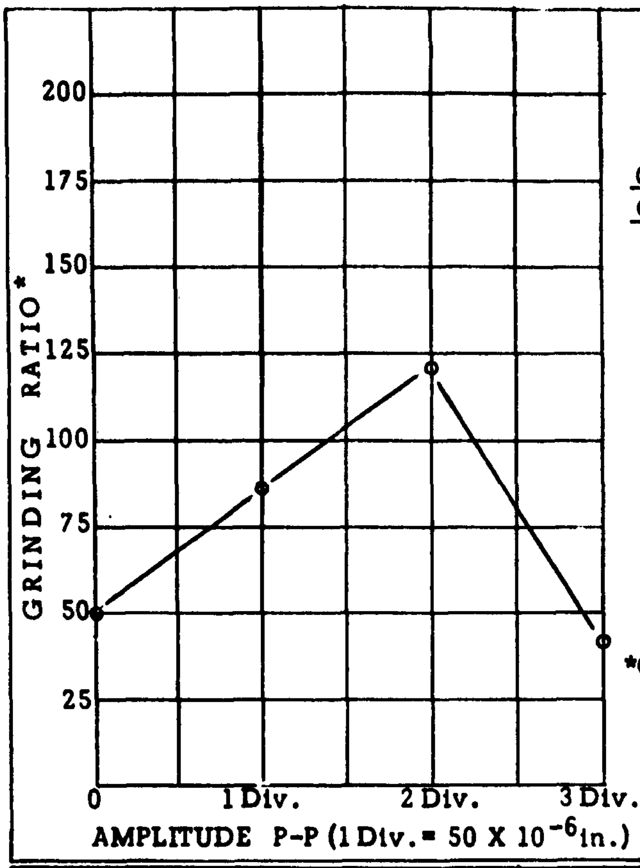
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	AA60-I8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 30 - 33 - III

Figure 283



INTERNAL GRINDING

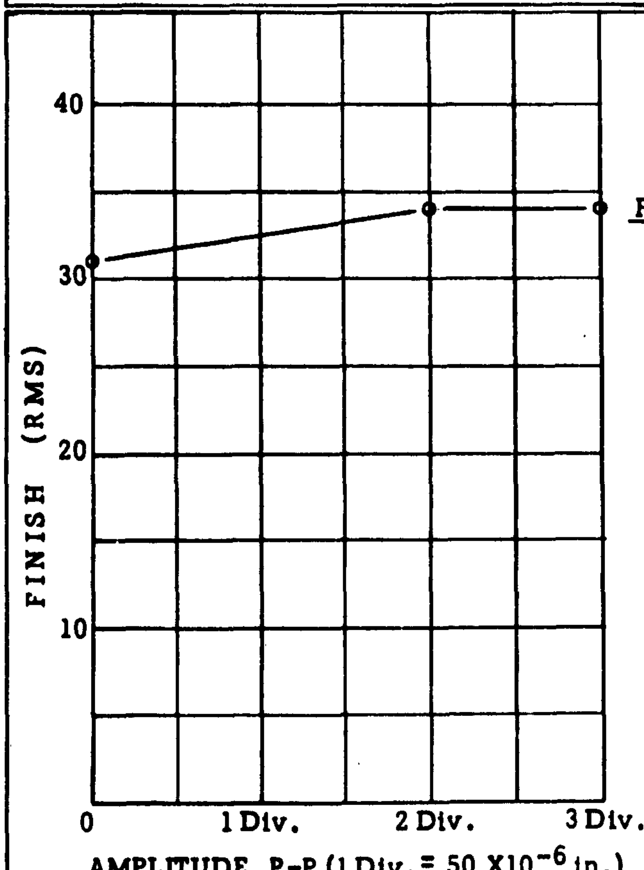
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	15 - 7 MO
Wheel	AA60-I8V40
Wheel Speed	4600 SFPM
Traverse Feed	13.5 in./min.
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 36, 35, 34, 33 - III

Figure 284



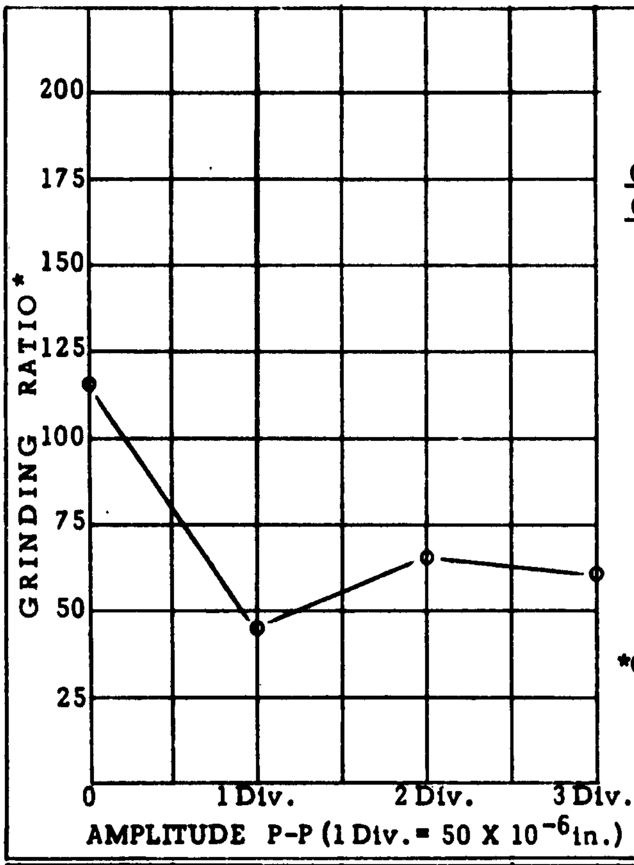
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	15 - 7 MO
Wheel	AA60-I8V40
Wheel Speed	4600 SFPM
Traverse Feed	13.5 in./min.
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 36, 35, 34, 33 - III

Figure 285



INTERNAL GRINDING

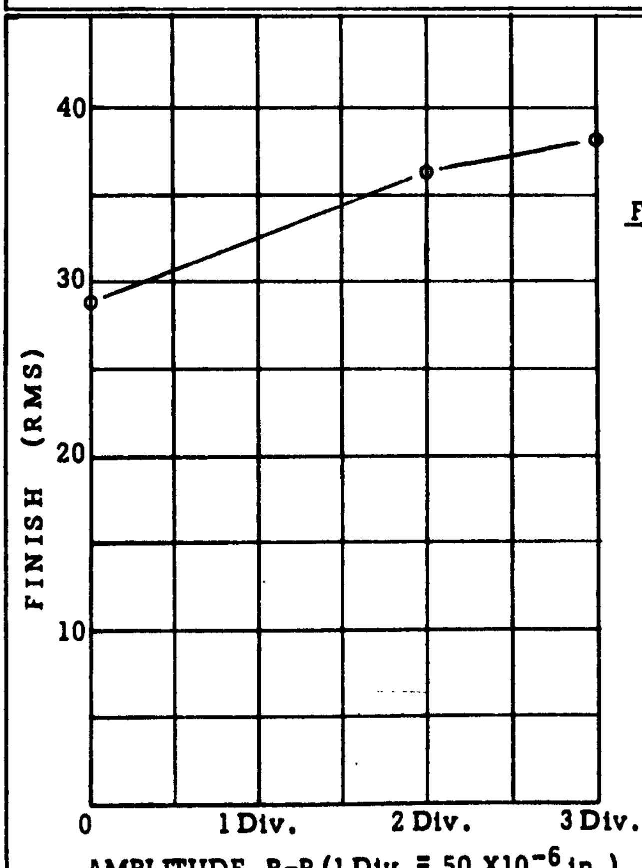
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	15 - 7 MO
Wheel	AA46-J8V40
Wheel Speed	4625 SFPM
Traverse Feed	13.5 in./min.
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 41 - 44 - III

Figure 286



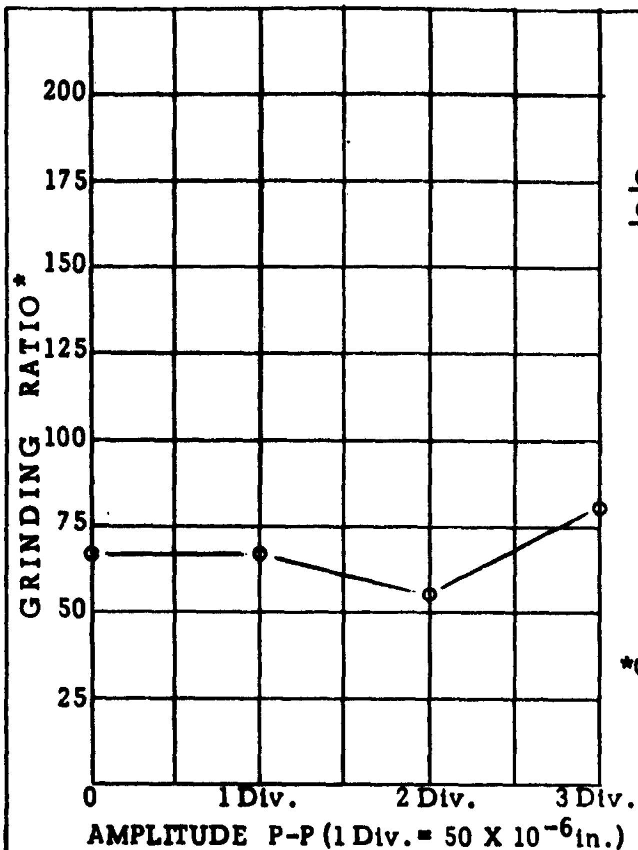
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	AA46-J8V40
Wheel Speed	4625 SFPM
Traverse Feed	13.5 in./min.
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 41 - 44 - III

Figure 287



INTERNAL GRINDING

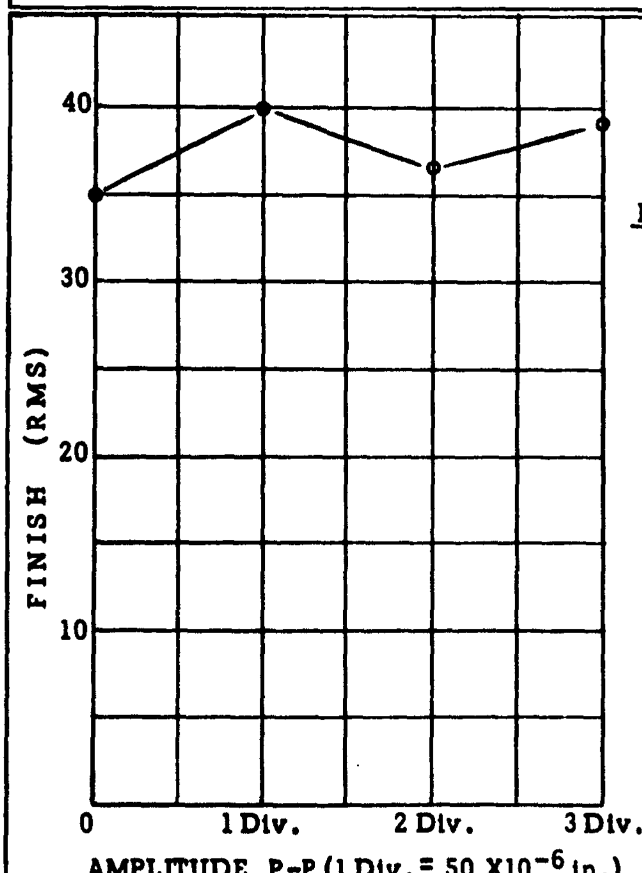
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	15 - 7 MO
Wheel	AA46-K8V40
Wheel Speed	4600 SFPM
Traverse Feed	13.5 in./min.
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: 58 - 61 - III

Figure 288



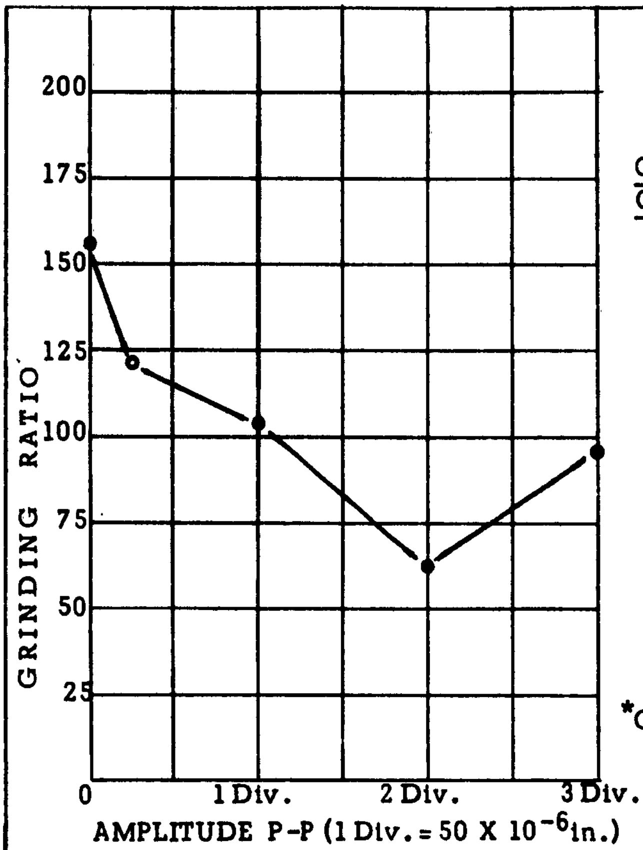
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	15 - 7 MO
Wheel	AA46-K8V40
Wheel Speed	4600 SFPM
Traverse Feed	13.5 in./min.
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 58 - 61 - III

Figure 289



INTERNAL GRINDING

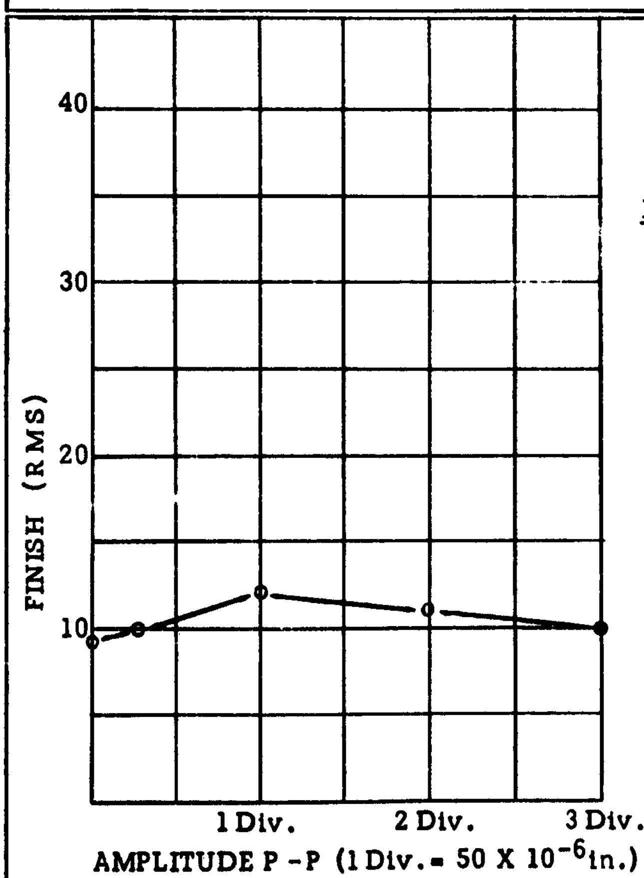
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	AA60R8-V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	135 to 145
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

$$^{*}\text{GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 1 - 4 - III

Figure 290



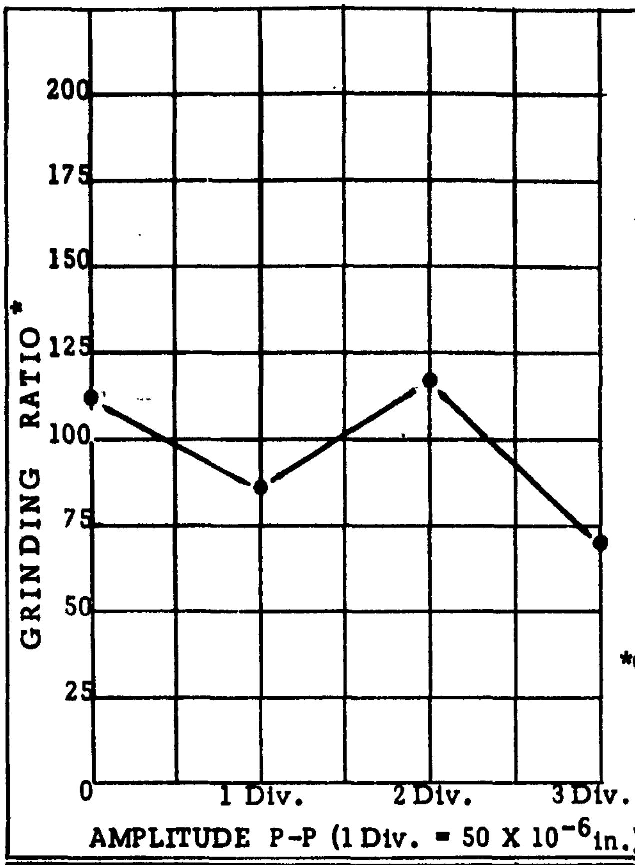
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H-11
Wheel	AA60R8-V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	135 to 145
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 1 - 4 - III

Figure 291



INTERNAL GRINDING

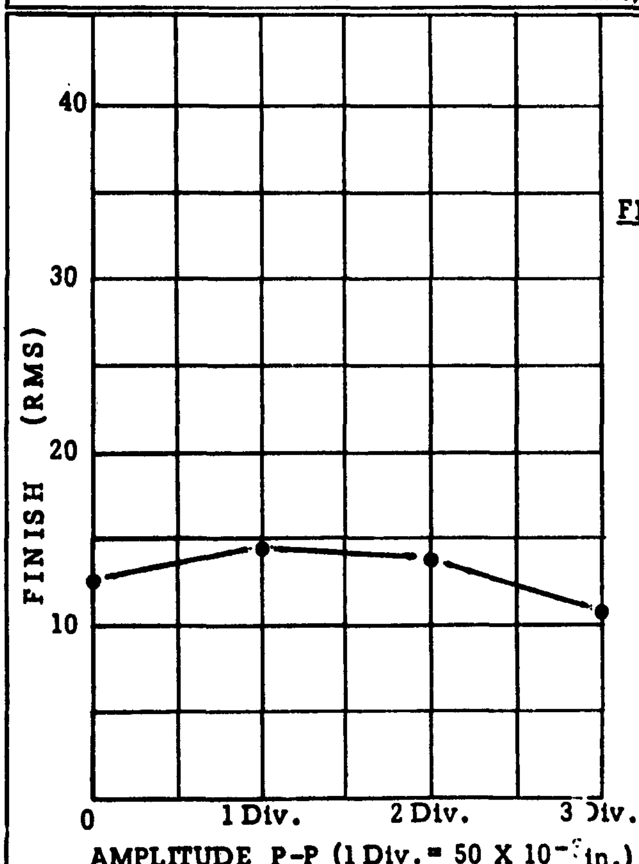
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H - 11
Wheel	AA46-K8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	135 to 145
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 10 - 13 - III

Figure 292



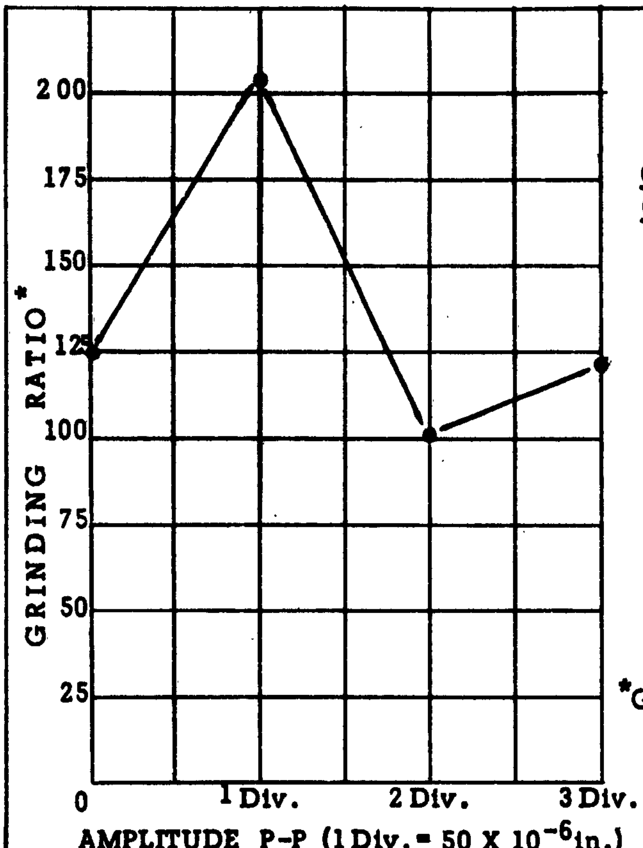
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H - 11
Wheel	AA46-K8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	135 to 145
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 10 - 13 - III

Figure 293



INTERNAL GRINDING

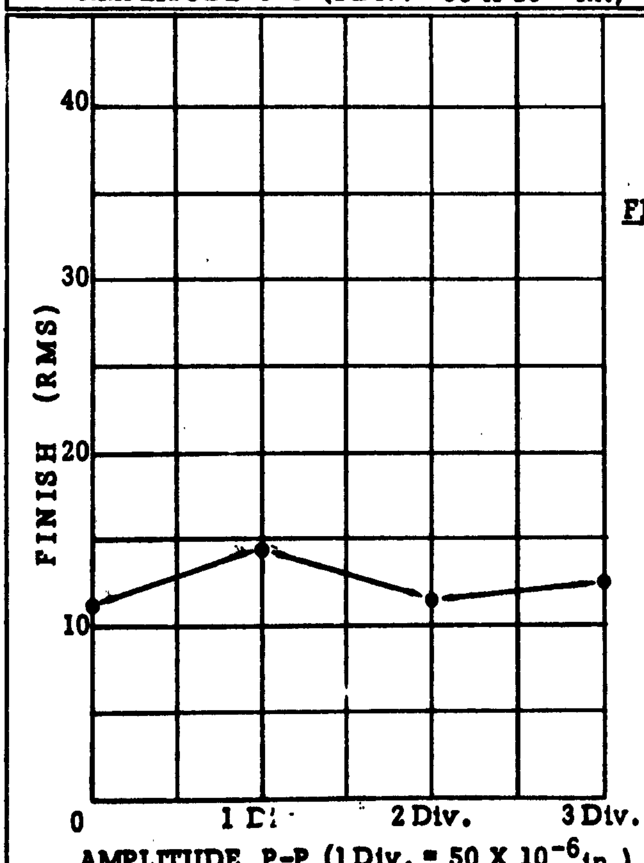
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H - 11
Wheel	AA60-I8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	150 to 160
Depth of Cut	0.0005"
Coolant	Sultran 176M

$$^{*}\text{GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 26 - 28 - III

Figure 294



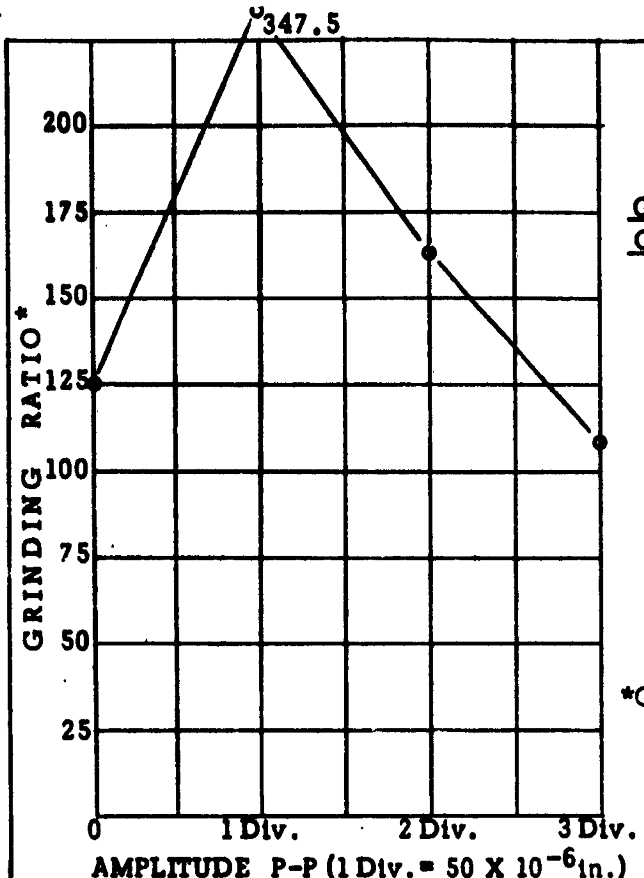
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H - 11
Wheel	AA60-I8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	150 to 160
Depth of Cut	0.0005"
Coolant	Sultran 176M

Run Numbers: 26 - 28 - III

Figure 295



INTERNAL GRINDING

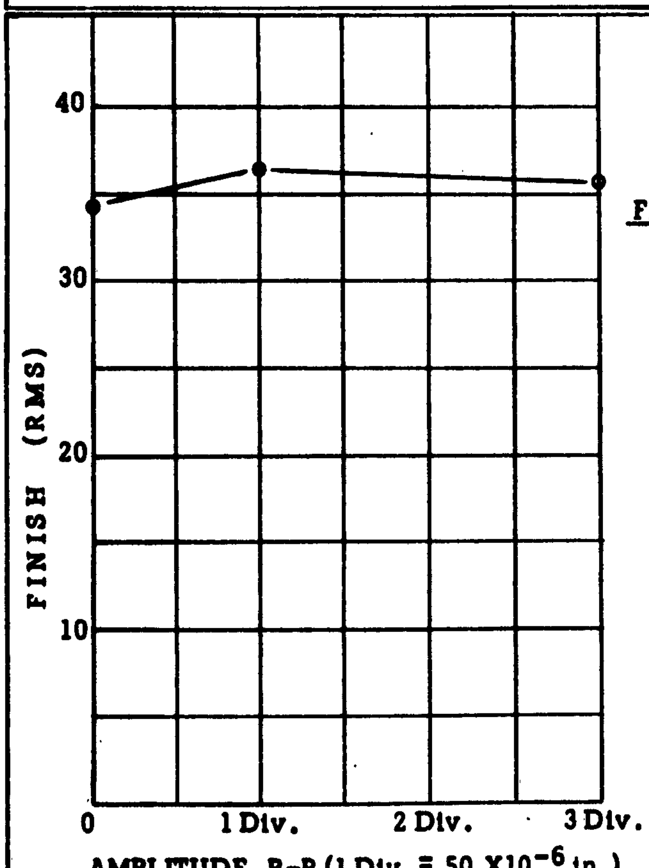
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	AA60-I8V40
Wheel Speed	4600 SFPM
Traverse Feed	13.5 in./min.
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: 37 - 40 - III

Figure 296



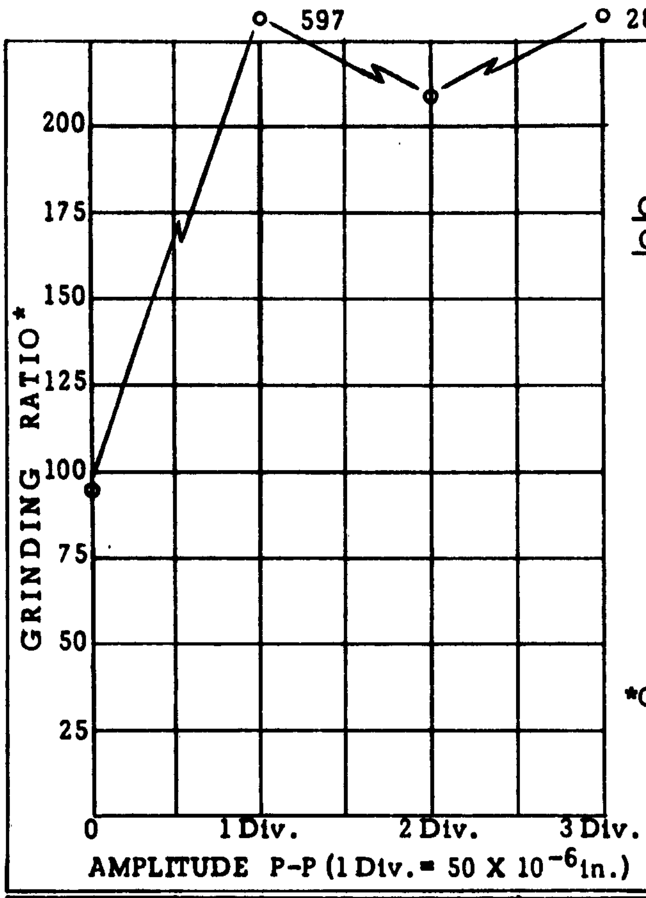
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H - 11
Wheel	AA60-I8V40
Wheel Speed	4600 SFPM
Traverse Feed	13.5 in./min.
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 37 -40 - III

Figure 297



INTERNAL GRINDING

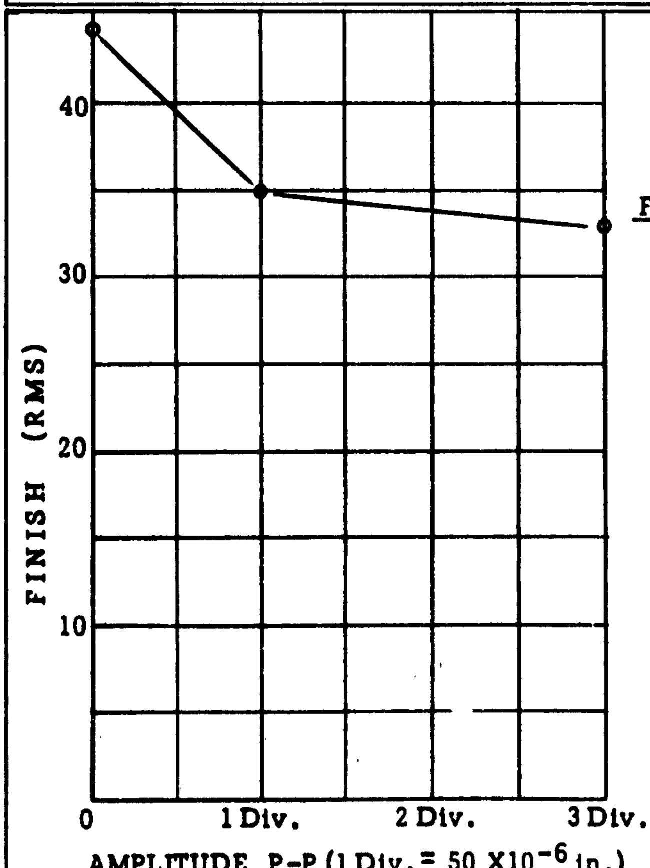
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H - 11
Wheel	GA60-J8V40
Wheel Speed	4600 SFPM
Traverse Feed	13.5 in./min.
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 54 - 57 - III

Figure 298



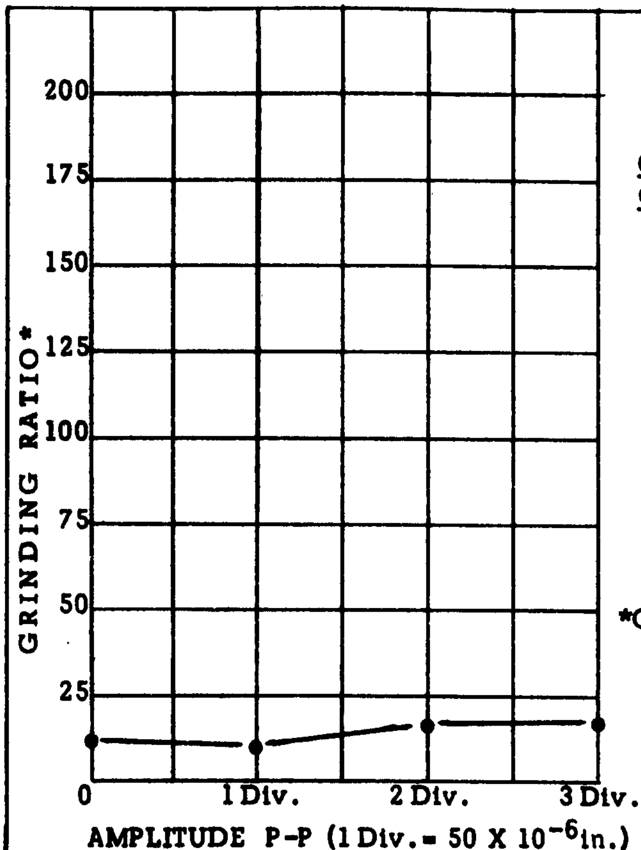
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H - 11
Wheel	GA60-J8V40
Wheel Speed	4600 SFPM
Traverse Feed	13.5 in./min.
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 54 - 57 - III

Figure 299



INTERNAL GRINDING

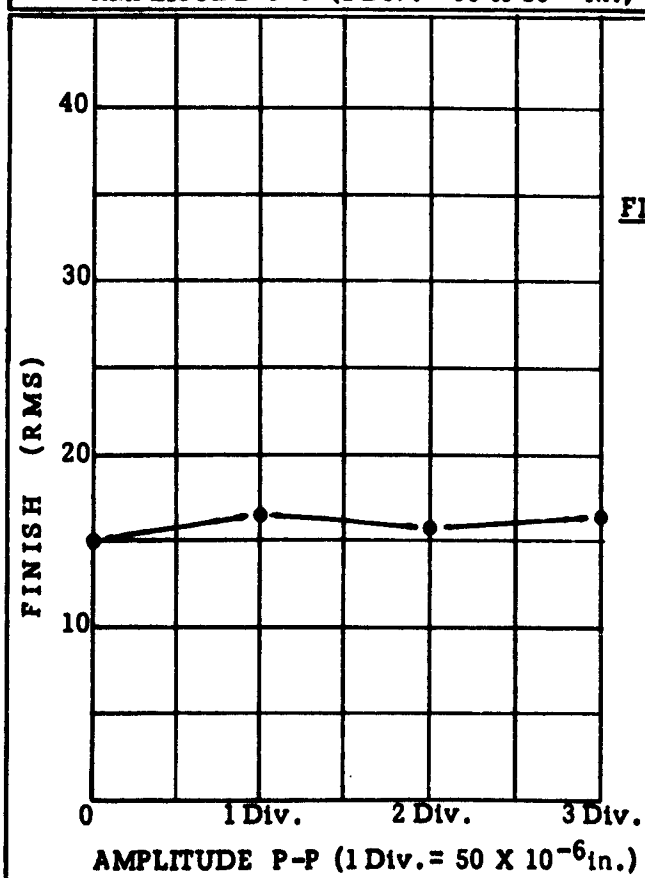
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	AA46-K8V40
Wheel Speed	4250 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	40 to 45
Depth of Cut	0.0006 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 22 - 25 - III

Figure 300



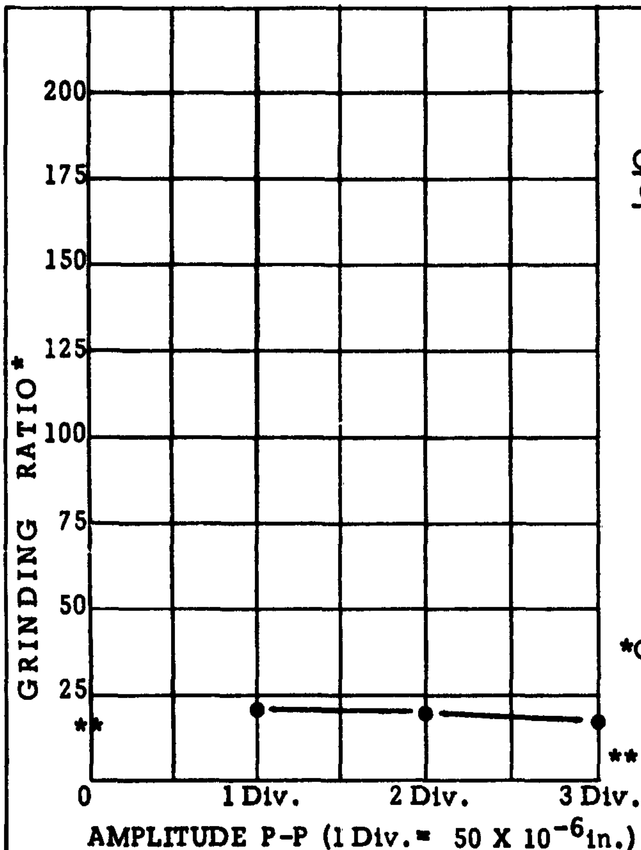
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	AA46-K8V40
Wheel Speed	4250 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	40 to 45
Depth of Cut	0.0006 inch
Coolant	Sultran 176M

Run Numbers: 22 - 25 - III

Figure 301



INTERNAL GRINDING

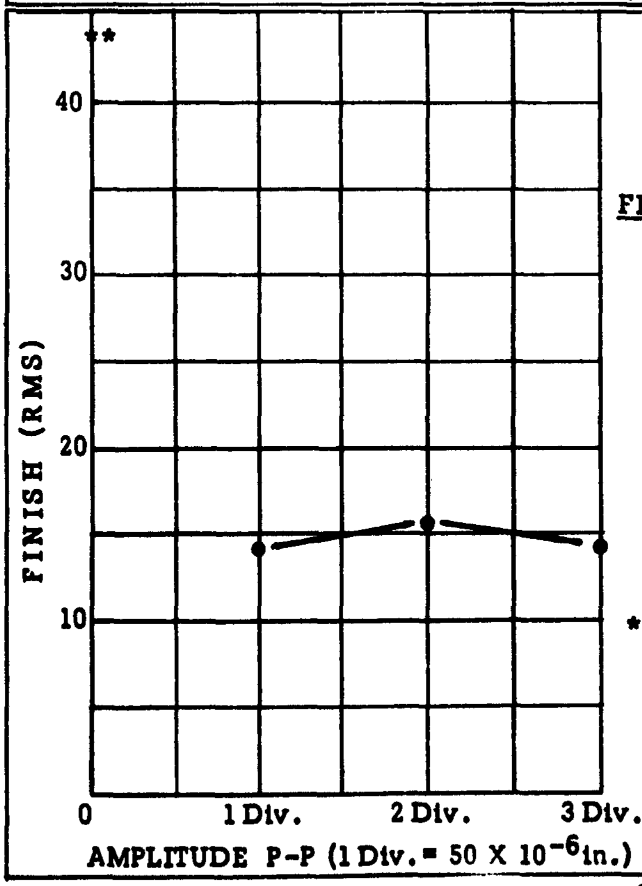
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	AA60-R8V40
Wheel Speed	4250 SFPM
Traverse Speed	1 in./minute
Workpiece SFPM	40 to 45
Depth of Cut	0.0006 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

** Unable to obtain a value excessive wheel wear and breaking.

Run Numbers: 18 - 22 -III Figure 302



INTERNAL GRINDING

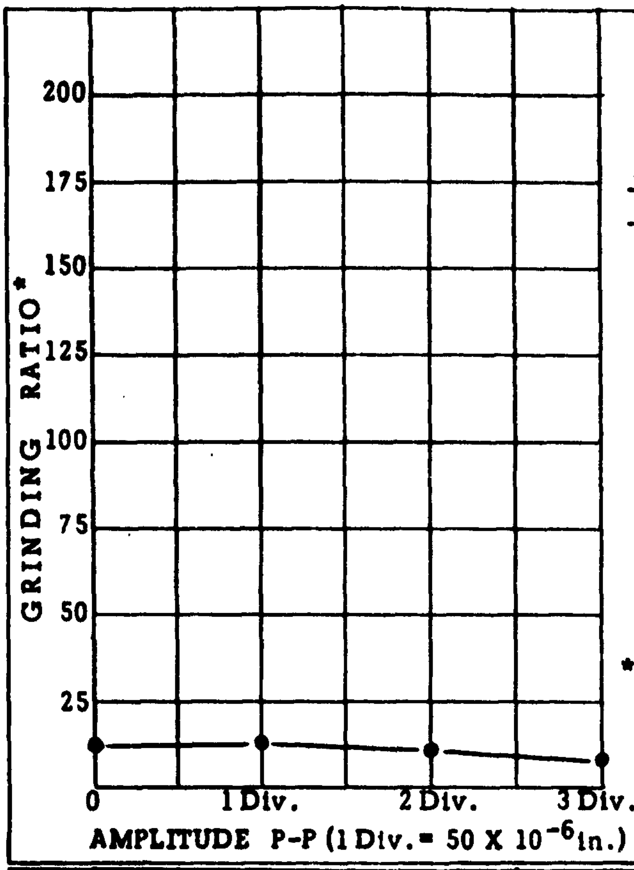
FINISH AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	AA60-R8V40
Wheel Speed	4250 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	40 to 45
Depth of Cut	0.0006
Coolant	Sultran 176M

** Burnt and Chattered

Run Numbers: 18 - 22 -III

Figure 303



INTERNAL GRINDING

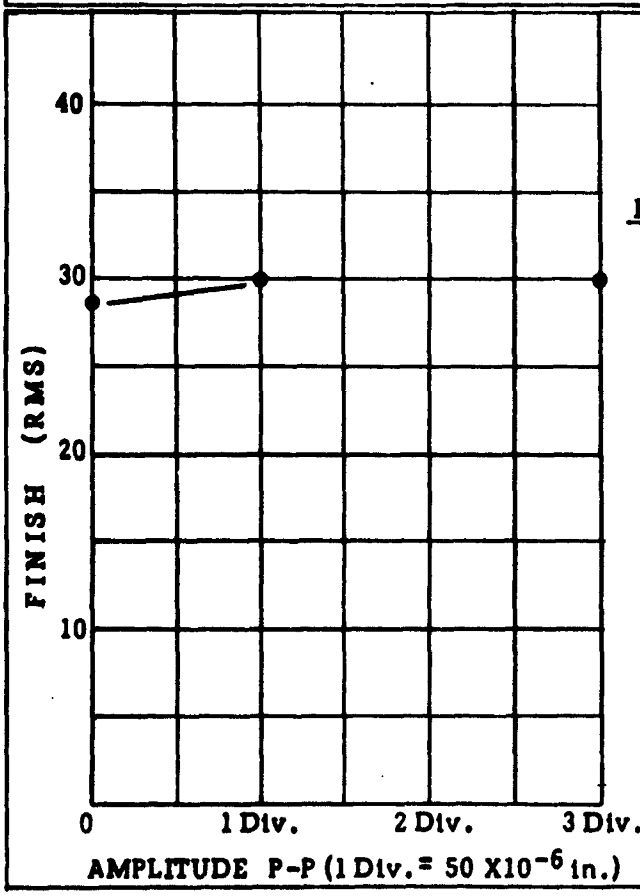
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	AA46-I8V40
Wheel Speed	3960 SFPM
Traverse Feed	4 in./min.
Workpiece SFPM	50 to 55
Depth of Cut	0.0006 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 52, 51, 50, 49 - III

Figure 304



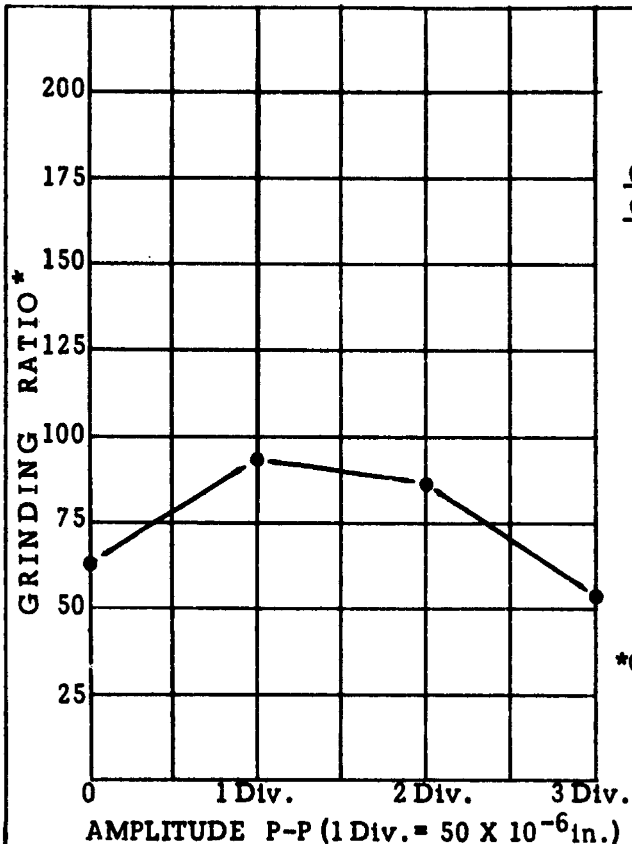
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	AA46-I8V40
Wheel Speed	3960 SFPM
Traverse Feed	4 in./min.
Workpiece SFPM	50 to 55
Depth of Cut	0.0006 inch
Coolant	Sultran 176M

Run Numbers: 52, 51, 50, 49 - III

Figure 305



INTERNAL GRINDING

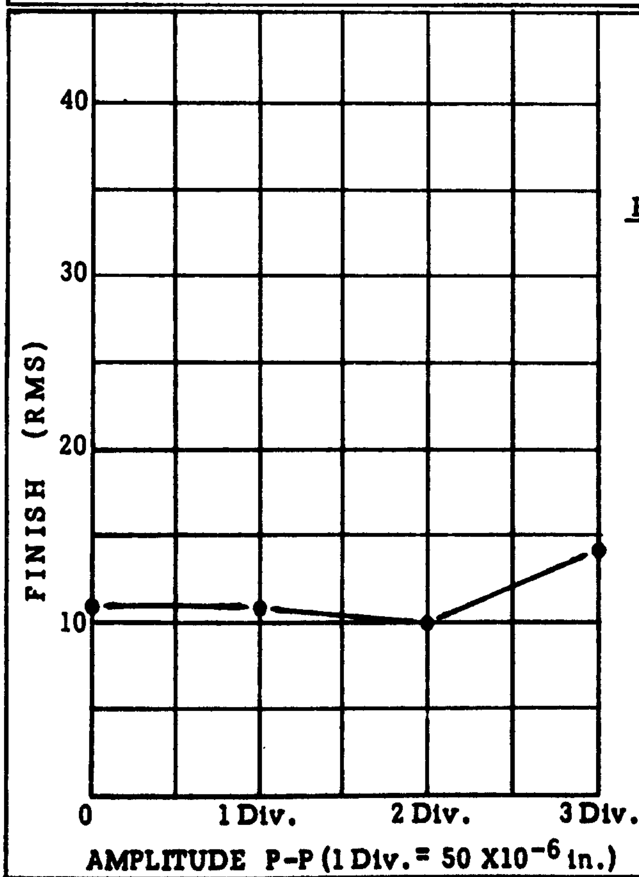
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	15-7 MO
Wheel	AA46-K8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	135 to 145
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: 14 - 17 - III

Figure 306



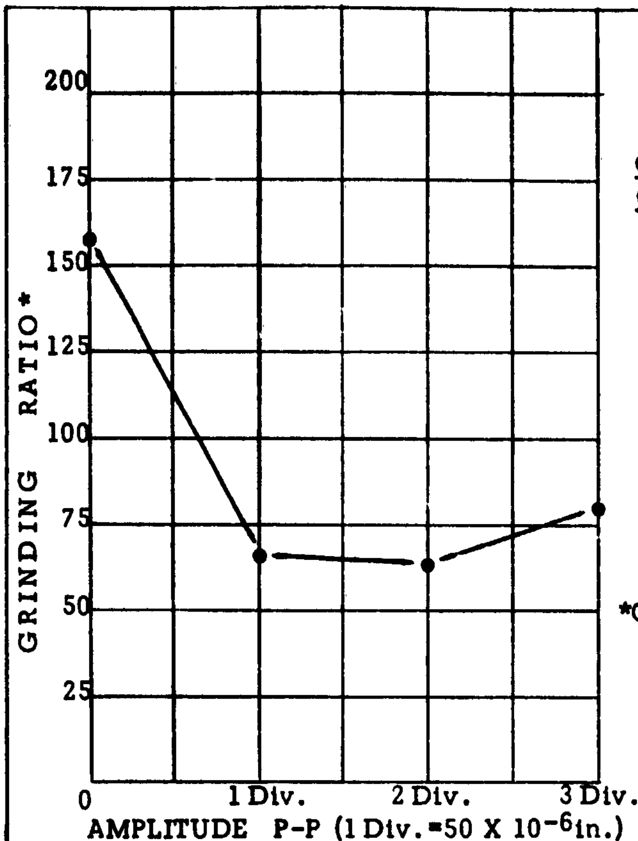
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	AA46-K8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	135 to 145
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 14 - 17 - III

Figure 307



INTERNAL GRINDING

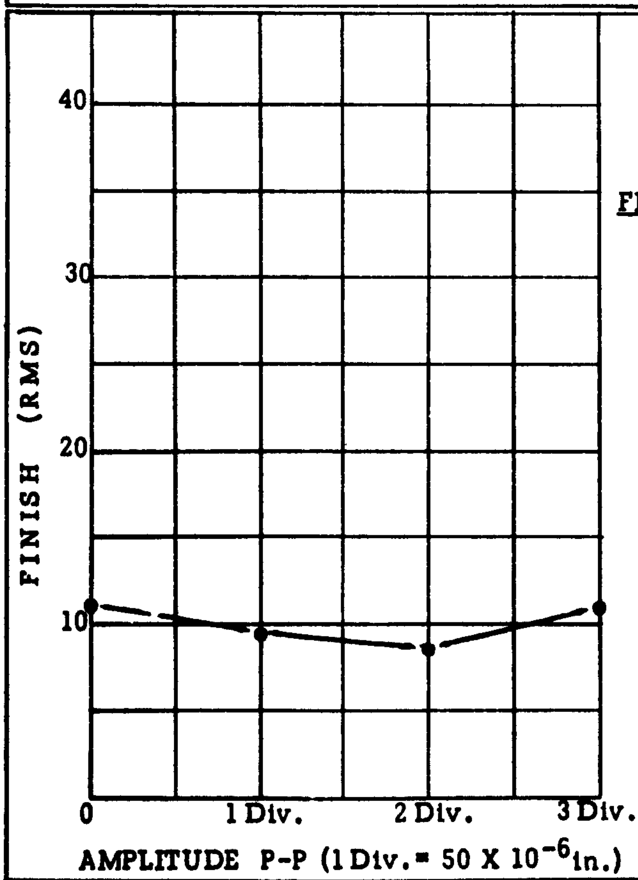
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	15-7 MO
Wheel	AA60-R8V40
Wheel Speed	4540 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	135 to 145
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 6 - 9 - III

Figure 308



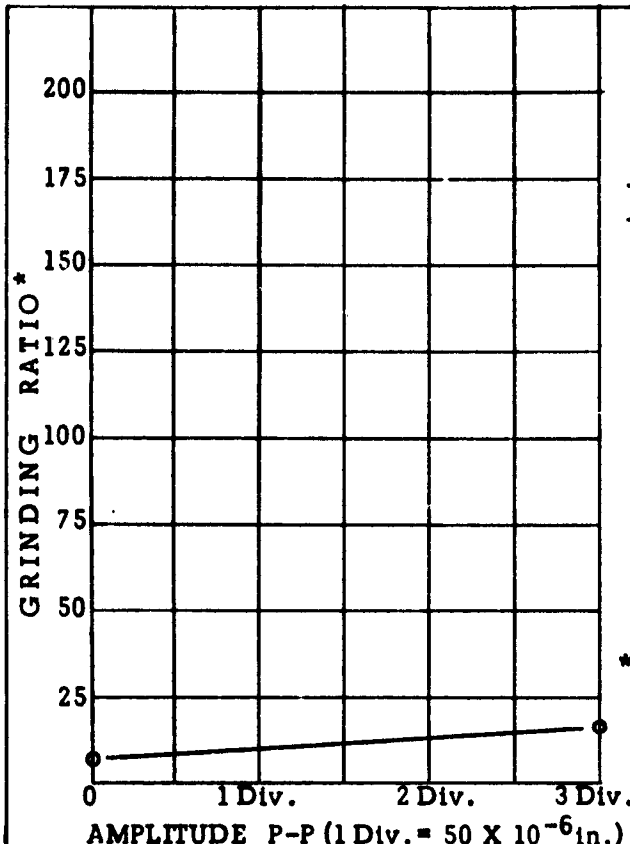
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	AA60-R8V40
Wheel Speed	4540 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	135 to 145
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 6 - 9 - III

Figure 309



INTERNAL GRINDING

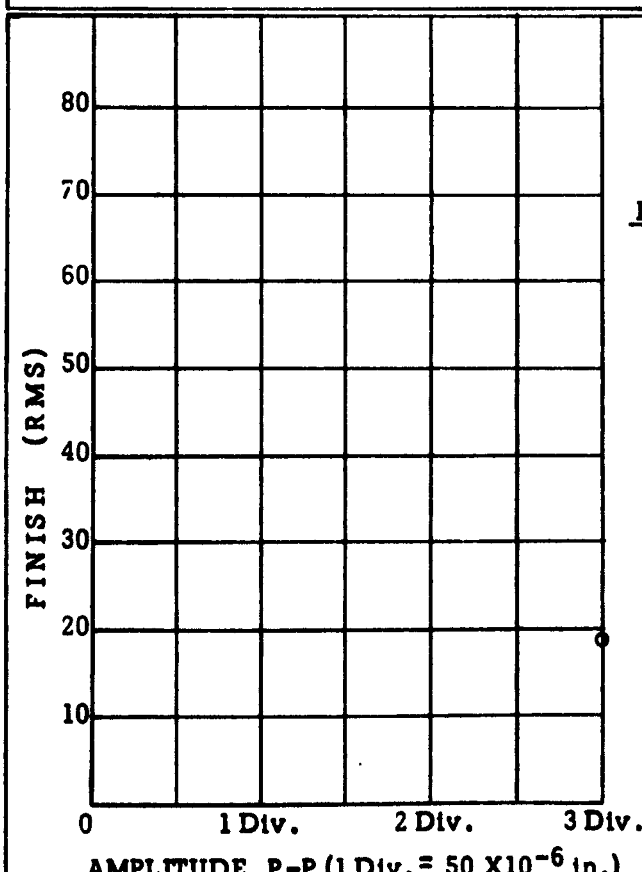
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60J6-V10
Wheel Speed	2870 SFPM
Traverse Feed	2 in/minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 112, 109 - III

Figure 310



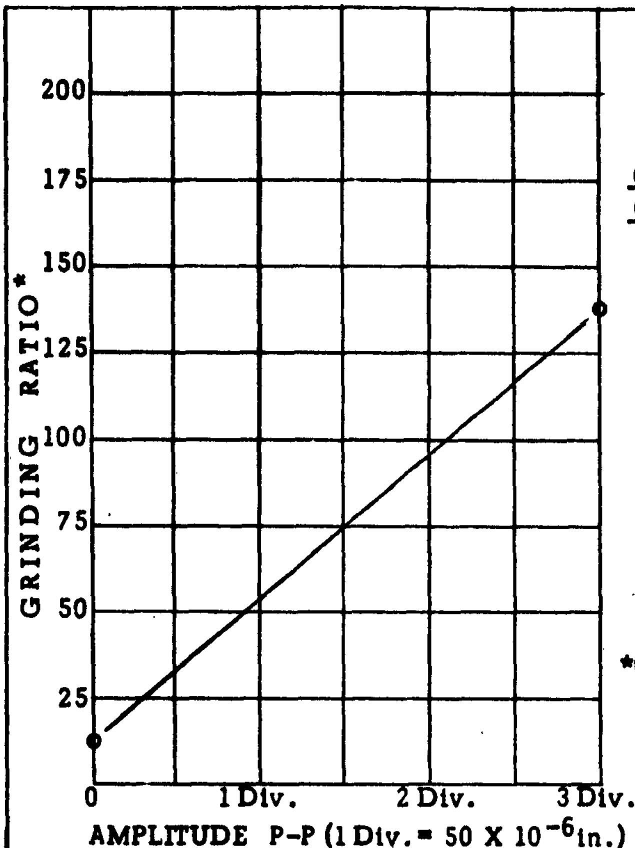
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	A60J6-V10
Wheel Speed	2870 SFPM
Traverse Feed	2 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 112, 109 - III

Figure 311



INTERNAL GRINDING

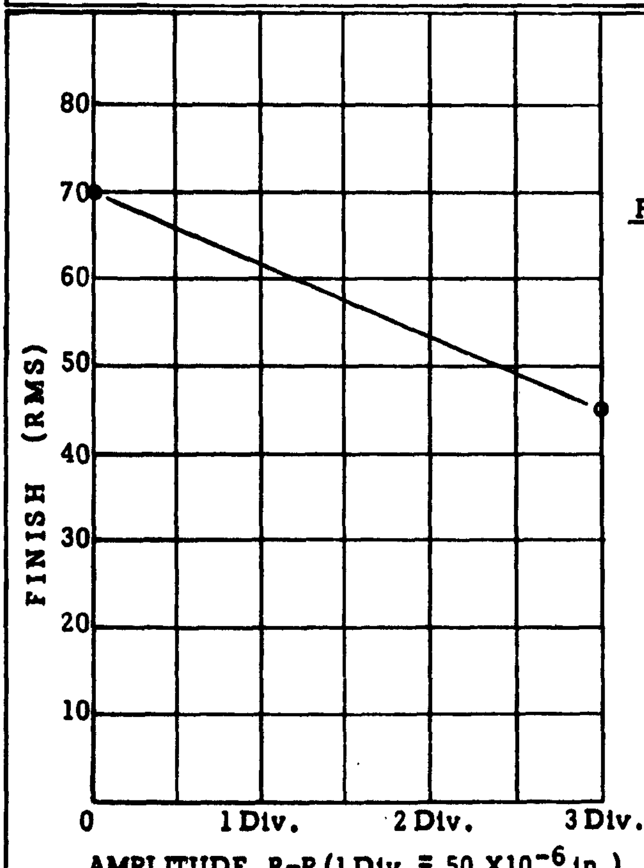
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	8 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 74 - 75 - III

Figure 312



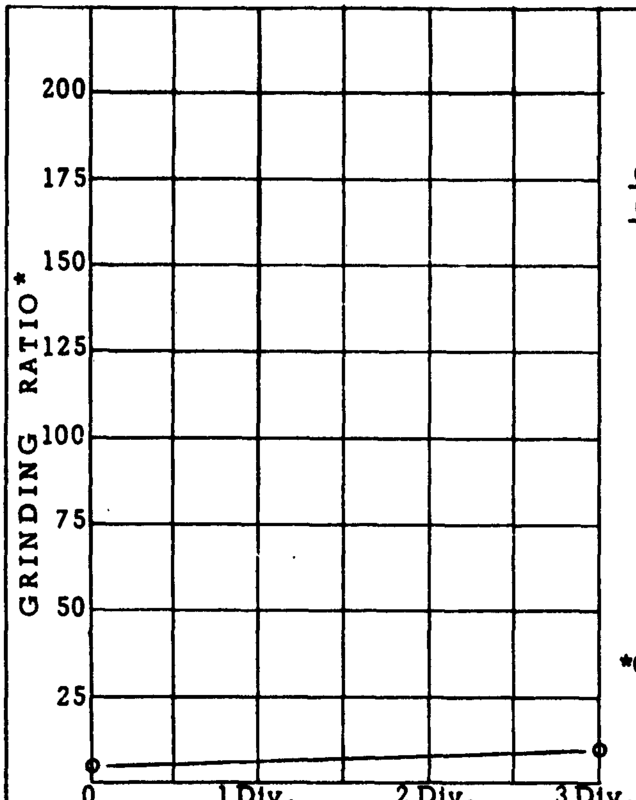
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	8 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

Run Numbers: 74, 75 - III

Figure 313



AMPLITUDE P-P (1 Div. = 50 X 10^{-6} in.)

INTERNAL GRINDING

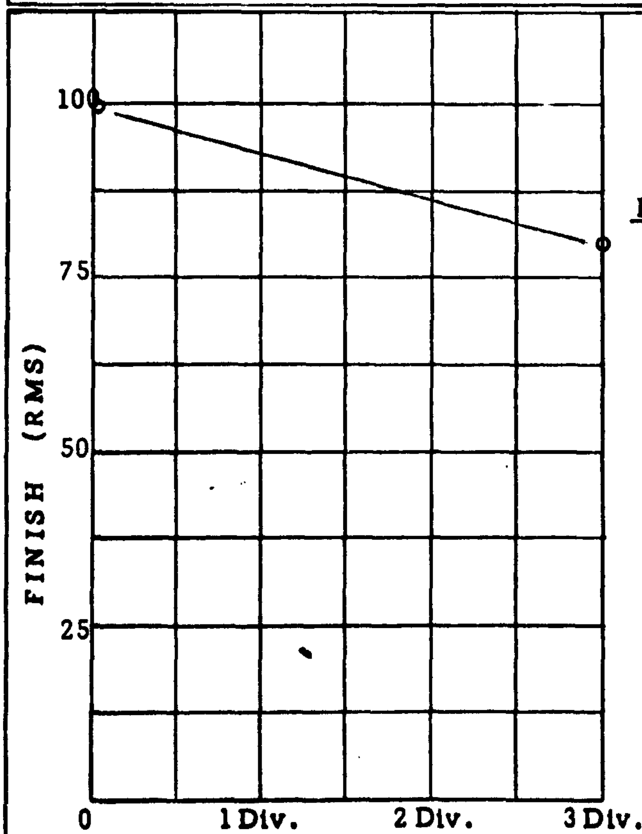
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	8 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 76, 77 - III

Figure 314



AMPLITUDE P-P (1 Div. = 50 X10^{-6} in.)

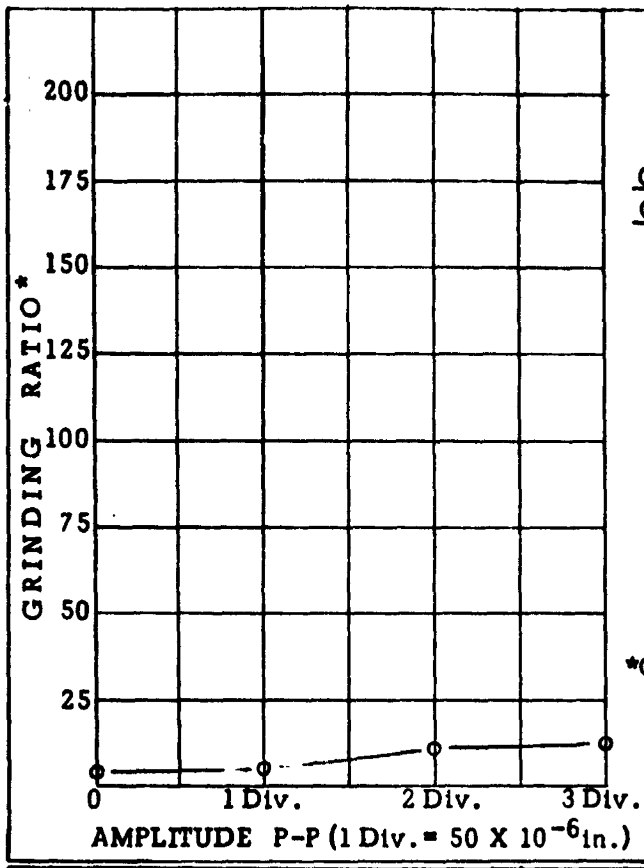
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	8 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 76, 77 - III

Figure 315



INTERNAL GRINDING

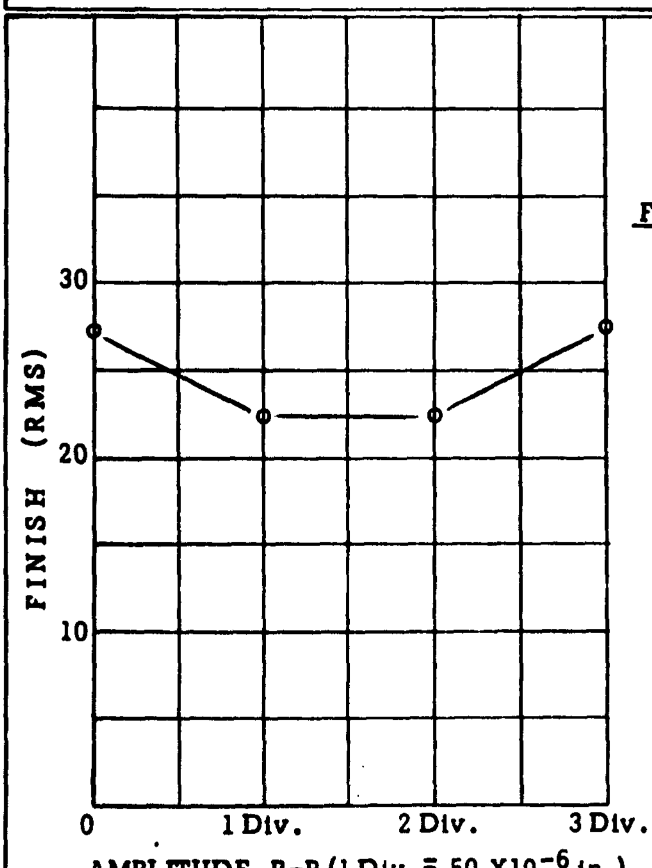
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	AA46K8-V40
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 78-81 - III

Figure 316



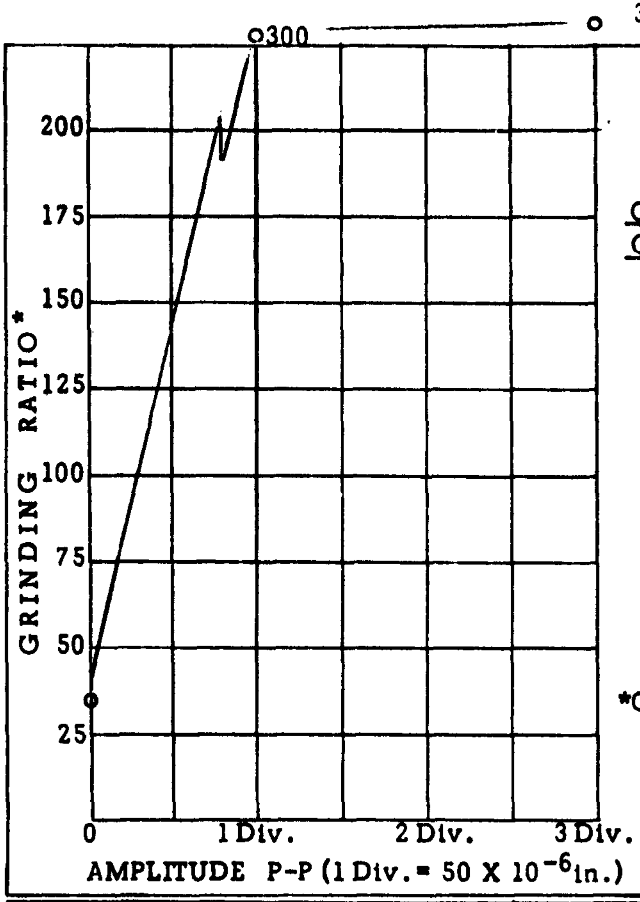
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	AA46K8-V40
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

Run Numbers: 78-81 - III

Figure 317



INTERNAL GRINDING

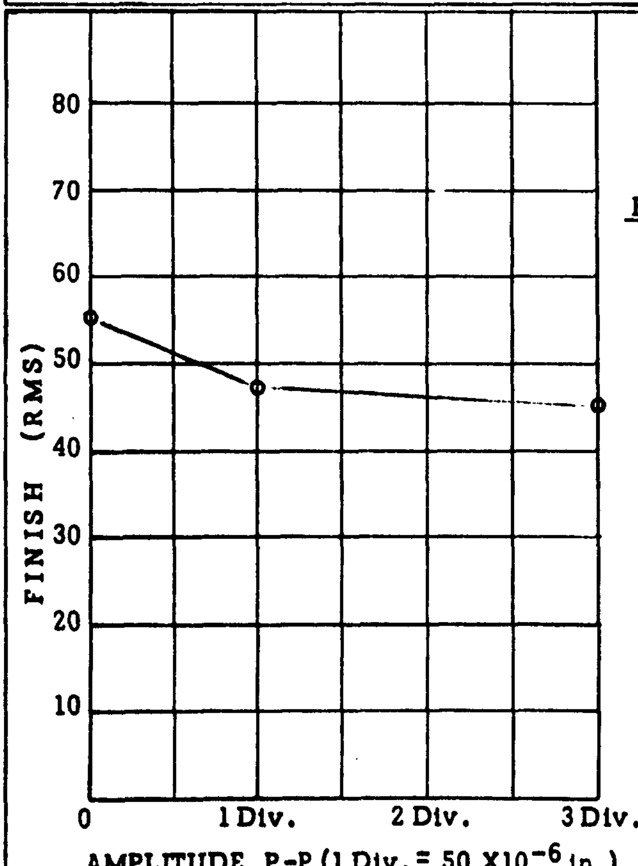
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 67, 68, 69 - III

Figure 318



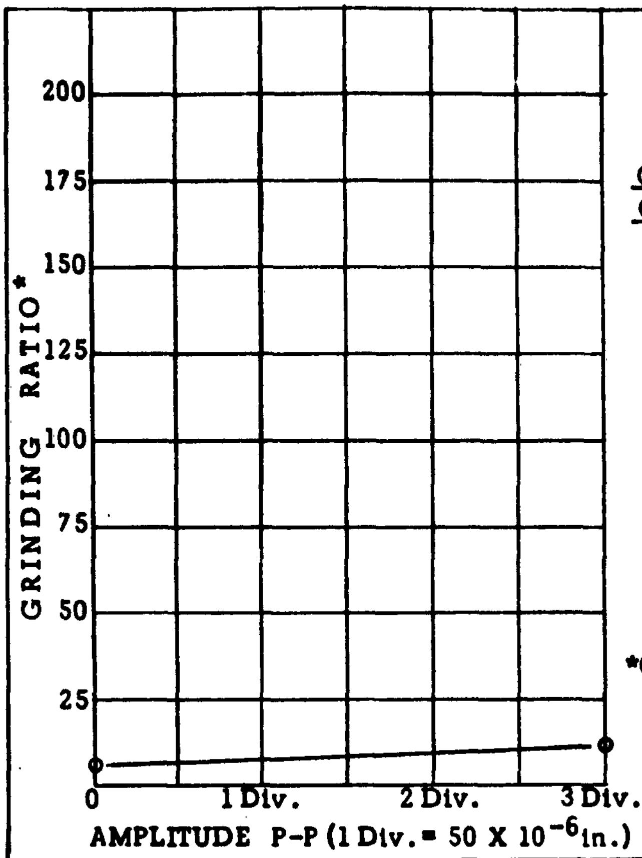
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

Run Numbers: 67, 68, 69 - III

Figure 319



INTERNAL GRINDING

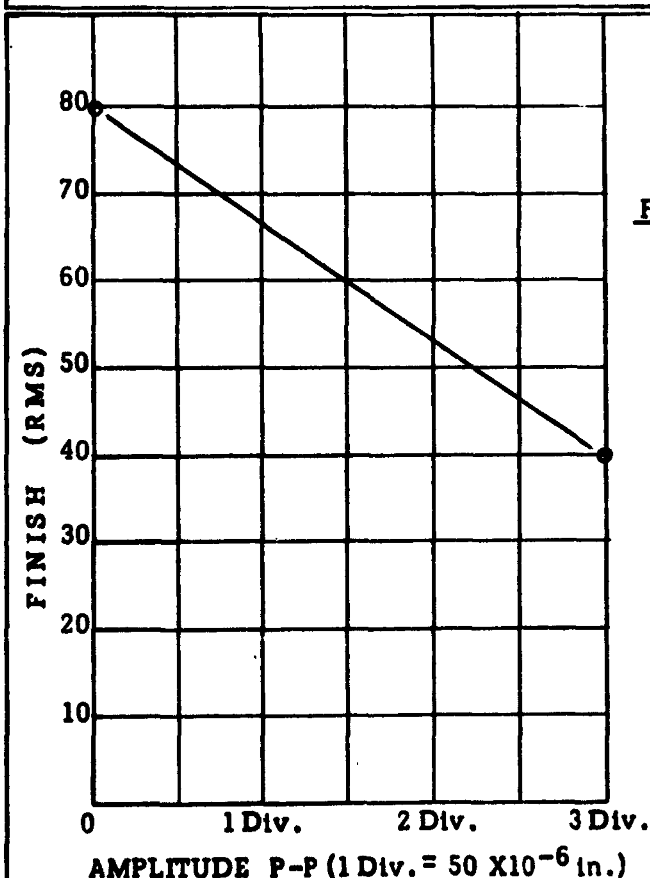
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.0015 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 70, 71 - III

Figure 320



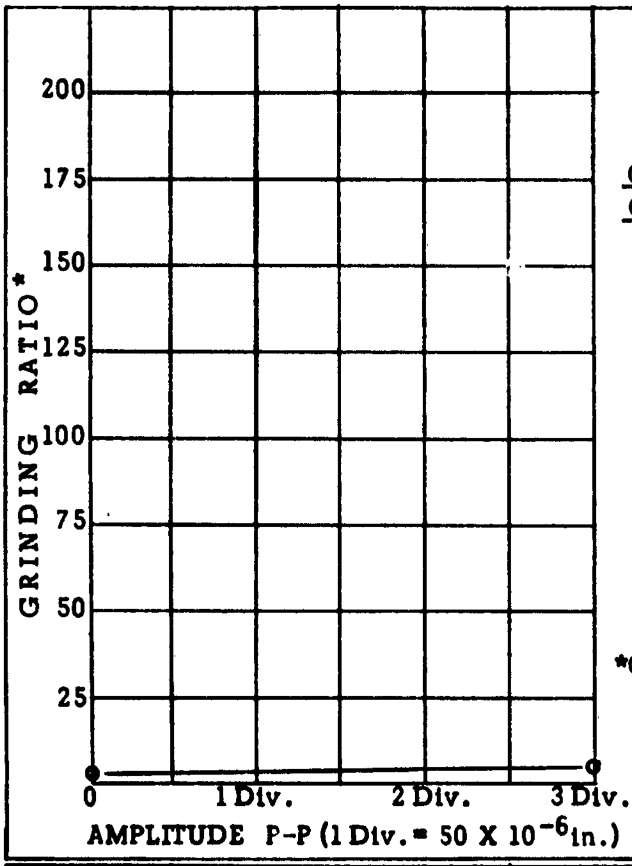
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.0015 in.
Coolant	Vantrol 5456M

Run Numbers: 70, 71 - III

Figure 321



INTERNAL GRINDING

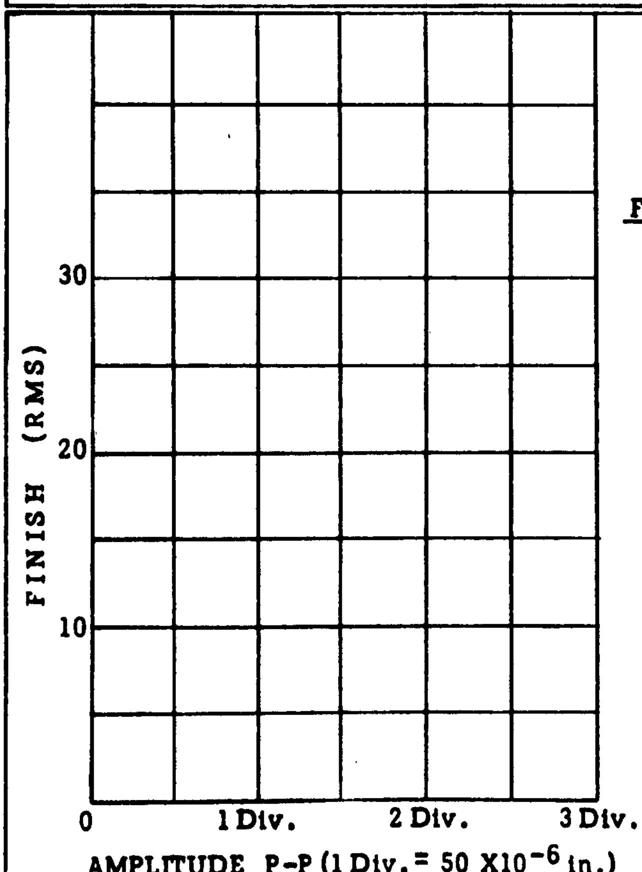
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: 72, 73 - III

Figure 322



INTERNAL GRINDING

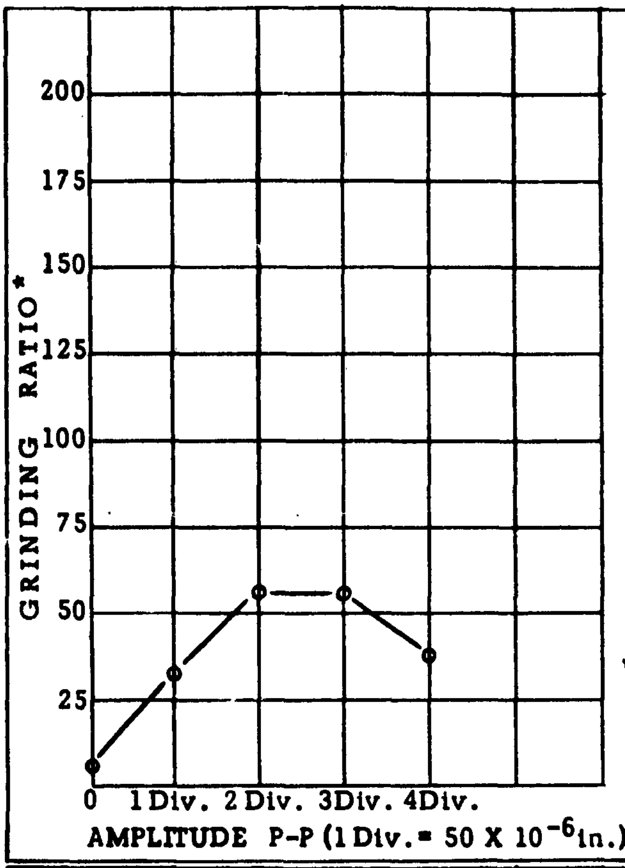
FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

Finish Burned and Chattered

Run Numbers: 72, 73 - III

Figure 323



INTERNAL GRINDING

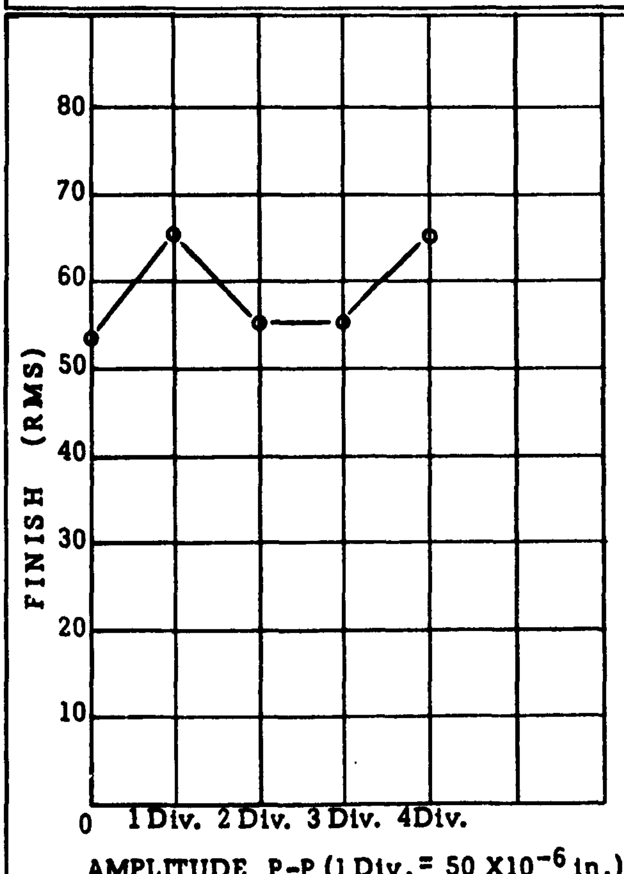
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 90A, 62, 63 - 66 - III

Figure 324



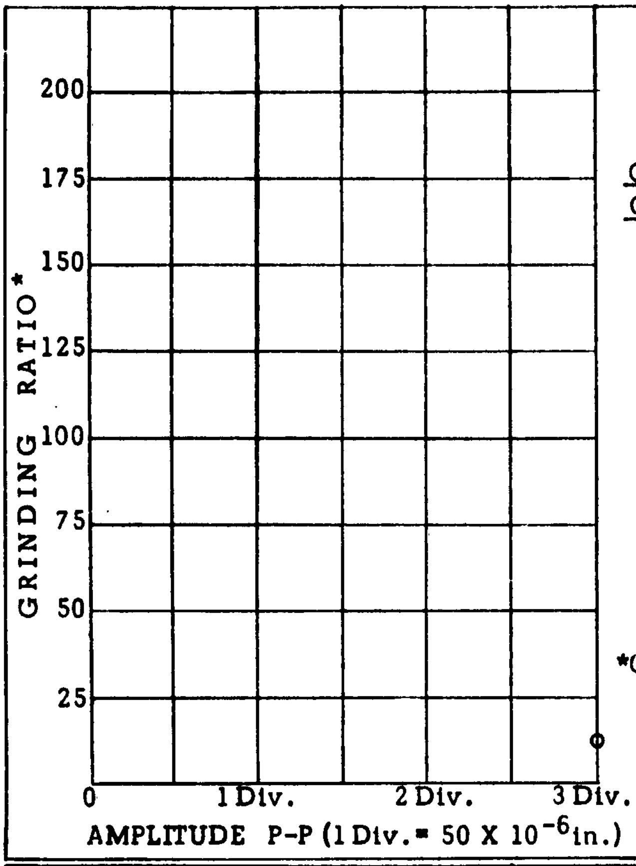
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 90A, 62 - 66 - III

Figure 325



INTERNAL GRINDING

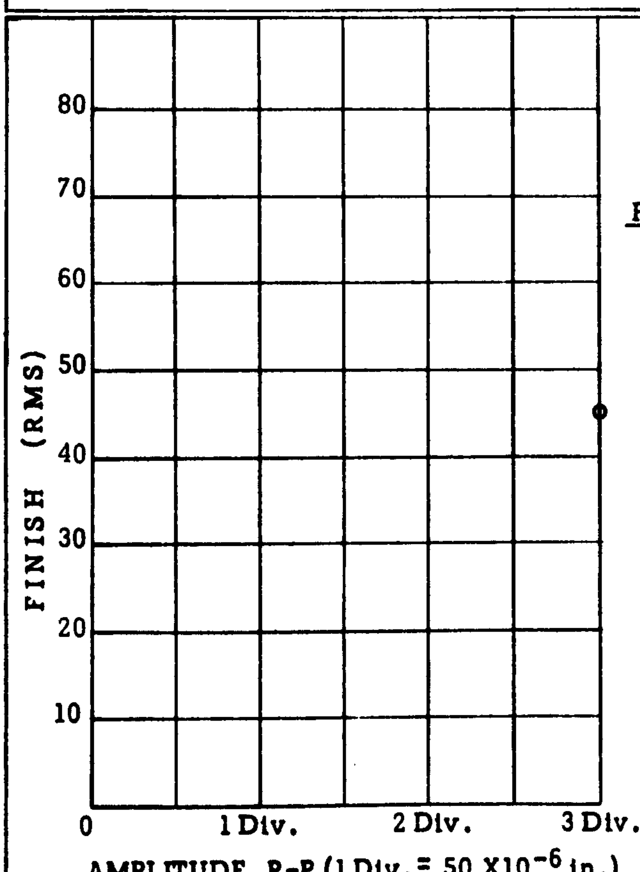
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.0015 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Number: 100A - III

Figure 326



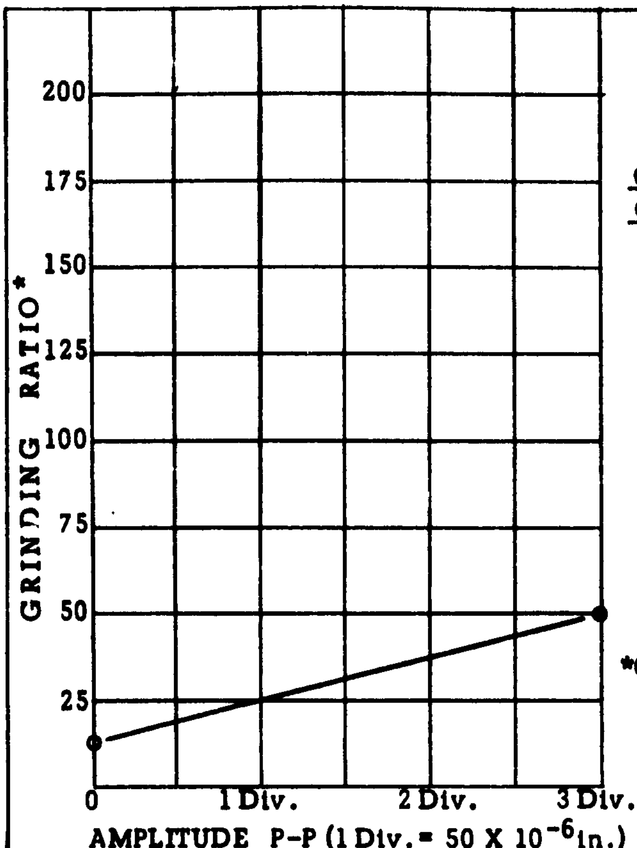
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.0015 in.
Coolant	Vantrol 5456M

Run Number: 100A - III

Figure 327



INTERNAL GRINDING

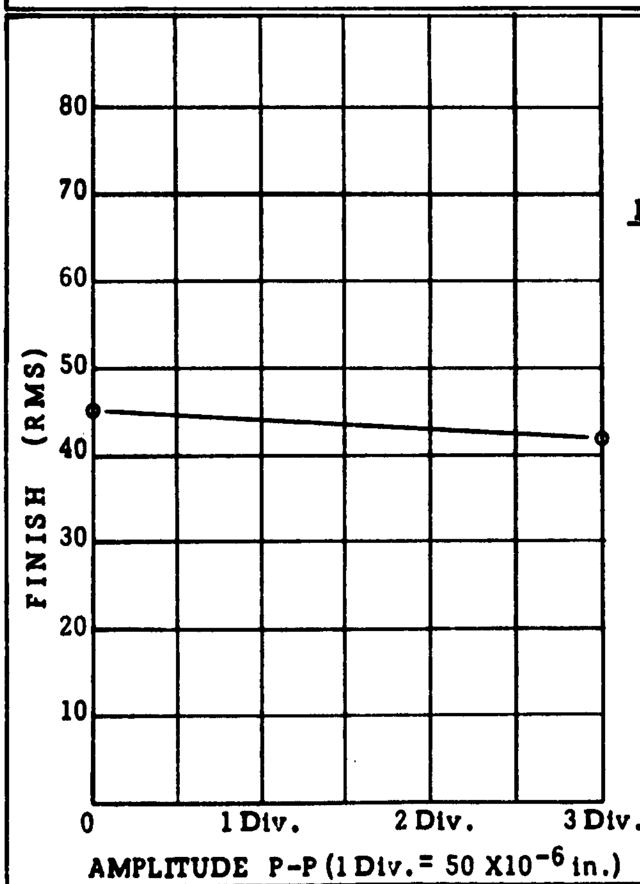
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 95, 131, 96, 115 - III

Figure 328



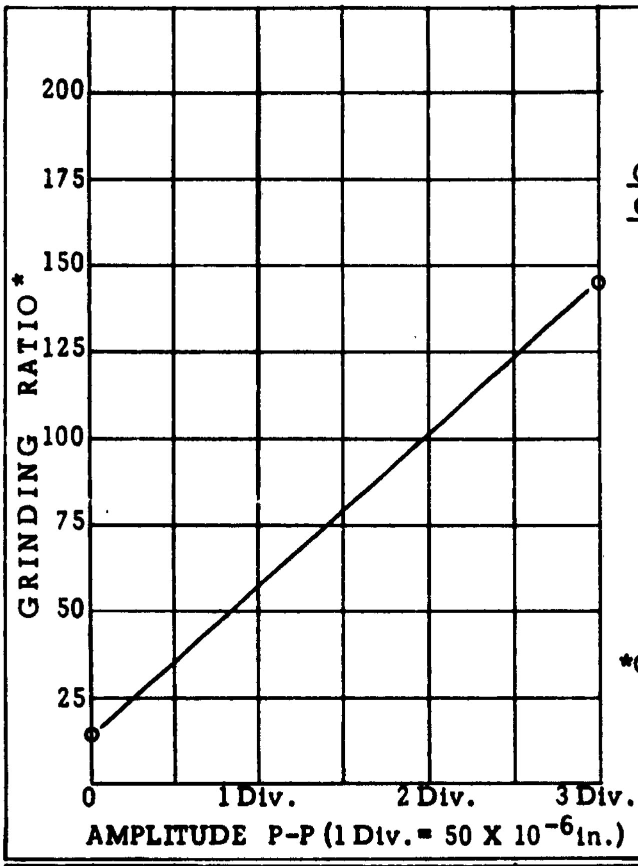
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 131, 96, 115 - III

Figure 329



INTERNAL GRINDING

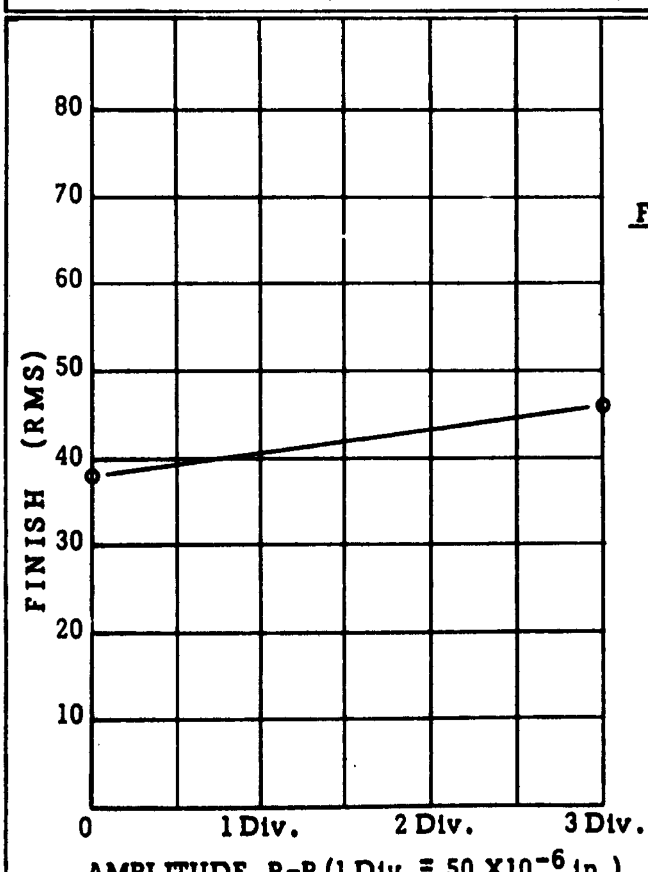
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	T16Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	3 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 92, 93, 127A, 116,-III
101, 121

Figure 330



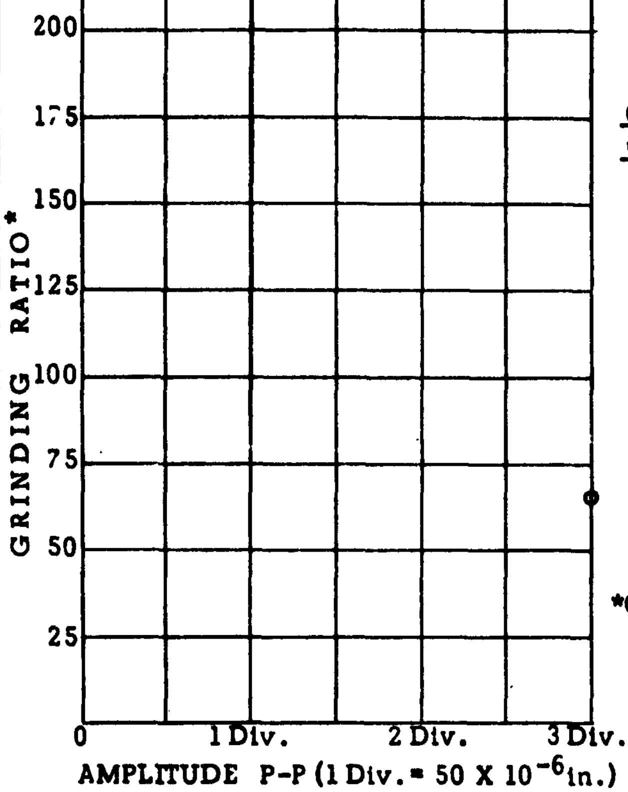
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	T16Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	3 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 92, 93, 127A, 116, 101
III

Figure 331



INTERNAL GRINDING

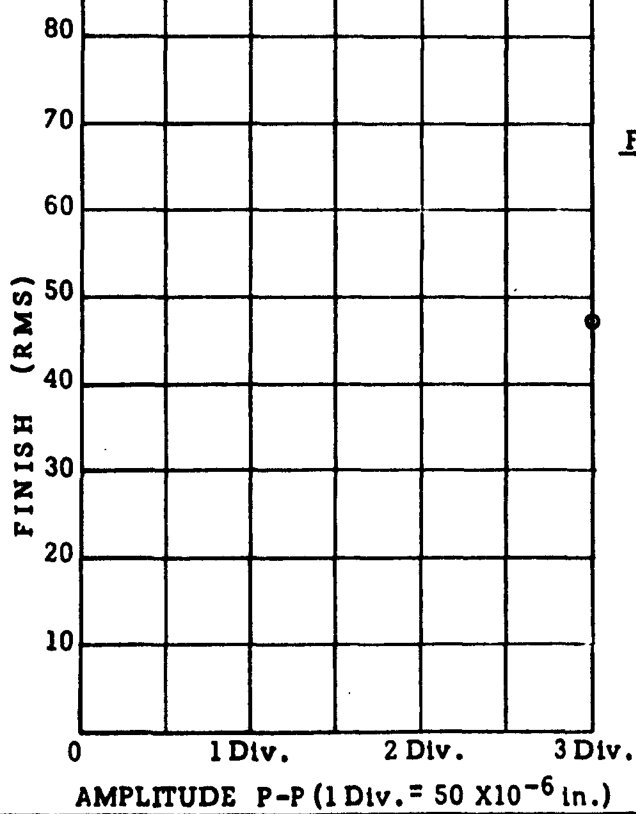
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	3 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.0015 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 104A, 104B, 102, 123, 122, 125, 127B, 129, 133 III

Figure 332



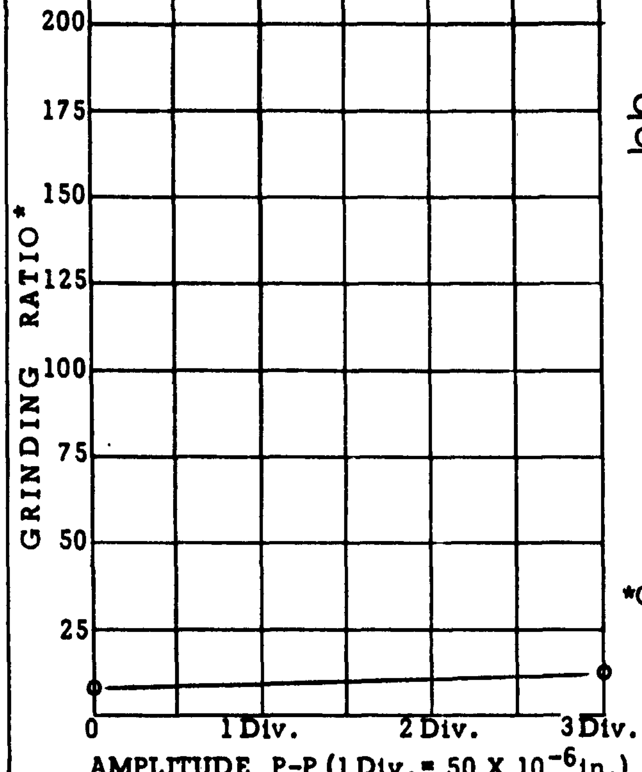
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	3 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.0015 in.
Coolant	Vantrol 5456M

Run Numbers: 104A, 104B, 102, 122, 123, 125, 127B - III

Figure 333



INTERNAL GRINDING

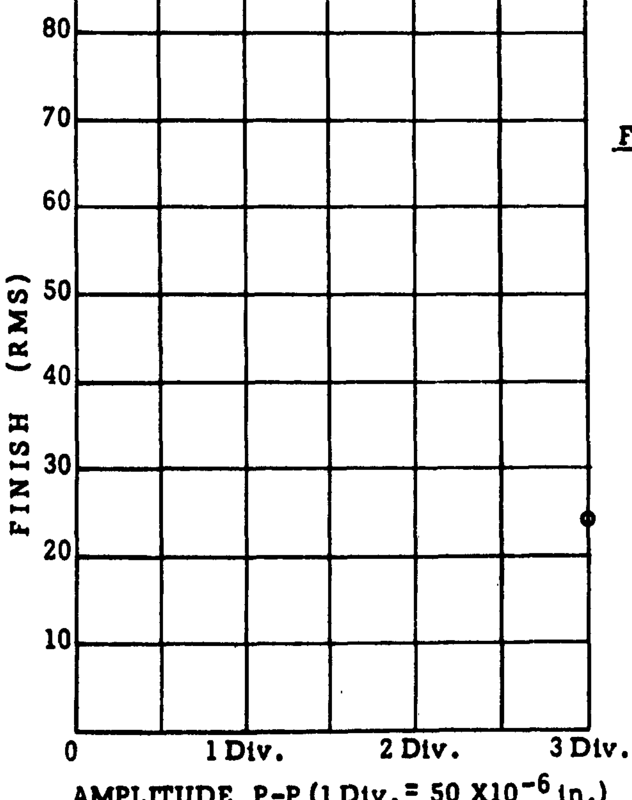
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60J6-V10
Wheel Speed	2870 SFPM
Traverse Feed	3 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Number: 113, 110 - III

Figure 334



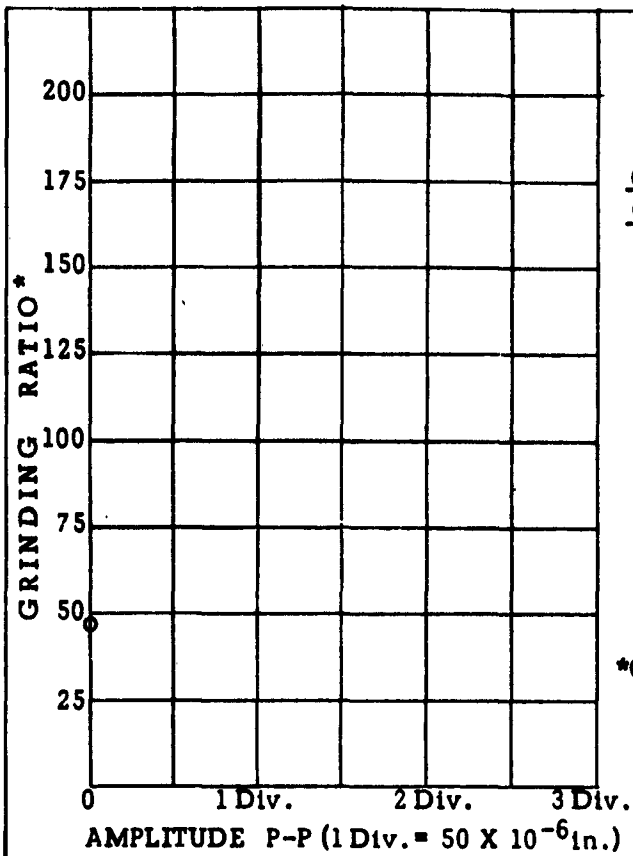
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	A60J6-V10
Wheel Speed	2870 SFPM
Traverse Feed	3 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 113, 110 - III

Figure 335



INTERNAL GRINDING

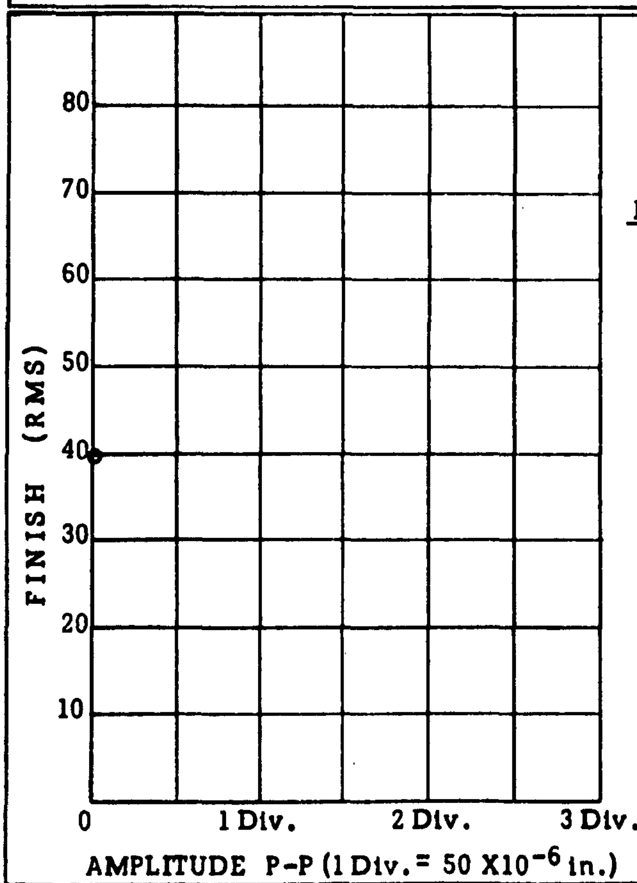
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	2 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Number: 90 - III

Figure 336



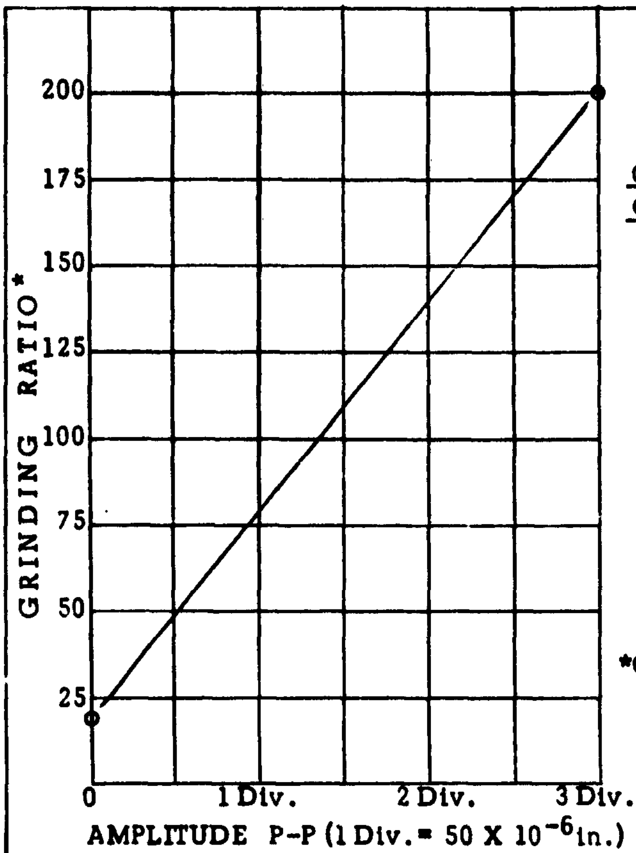
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	2 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 inch
Coolant	Vantrol 5456M

Run Number: 90 - III

Figure 337



INTERNAL GRINDING

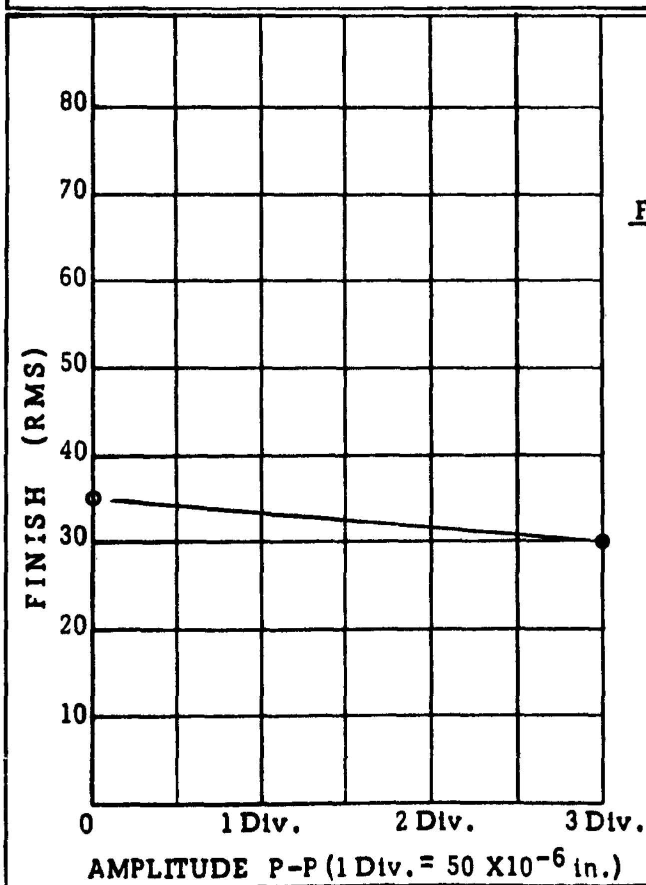
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	2 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 99, 94, 120, 132, 98, 119 - III

Figure 338



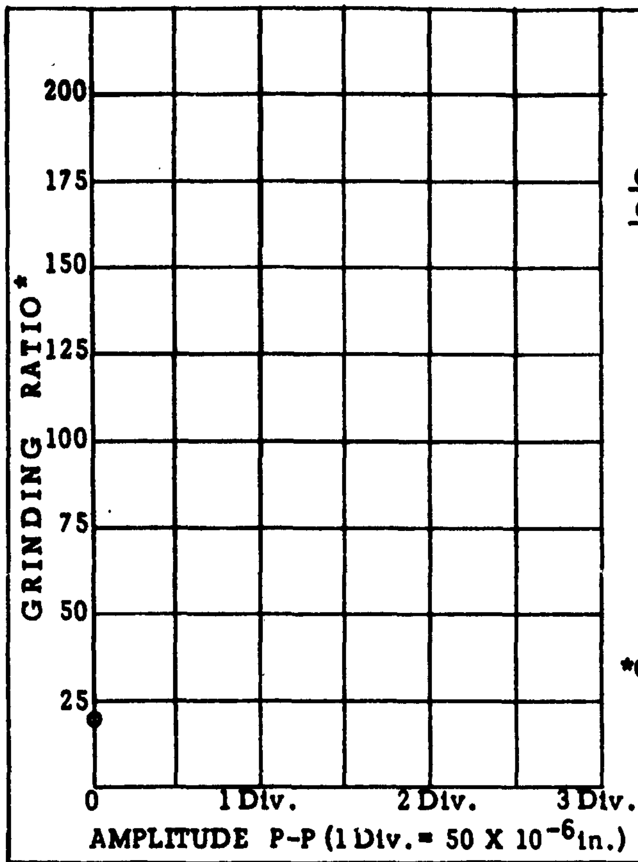
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	2 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 99, 94, 120, 132, 98, 119 - III

Figure 339



INTERNAL GRINDING

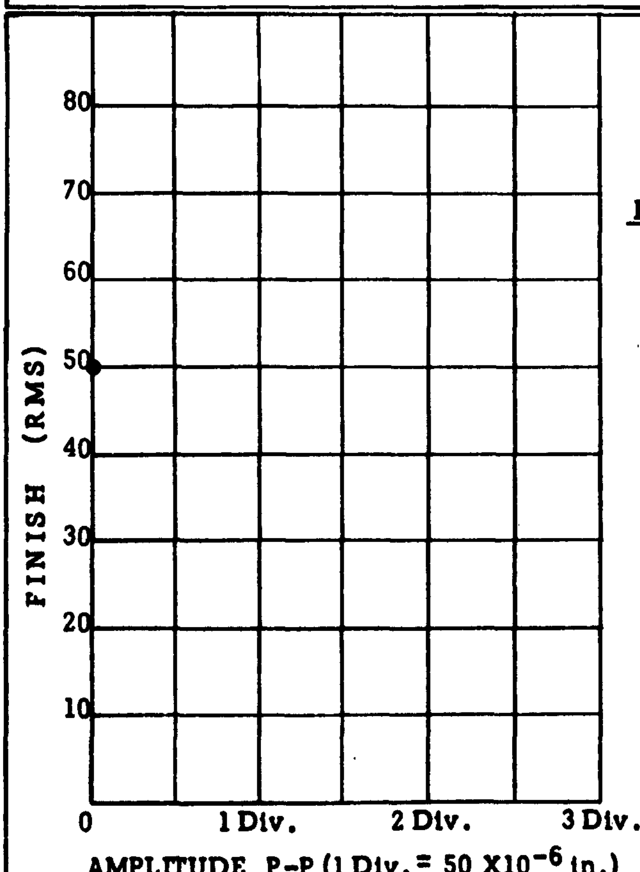
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	T16Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	3 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Number: 91 - III

Figure 340



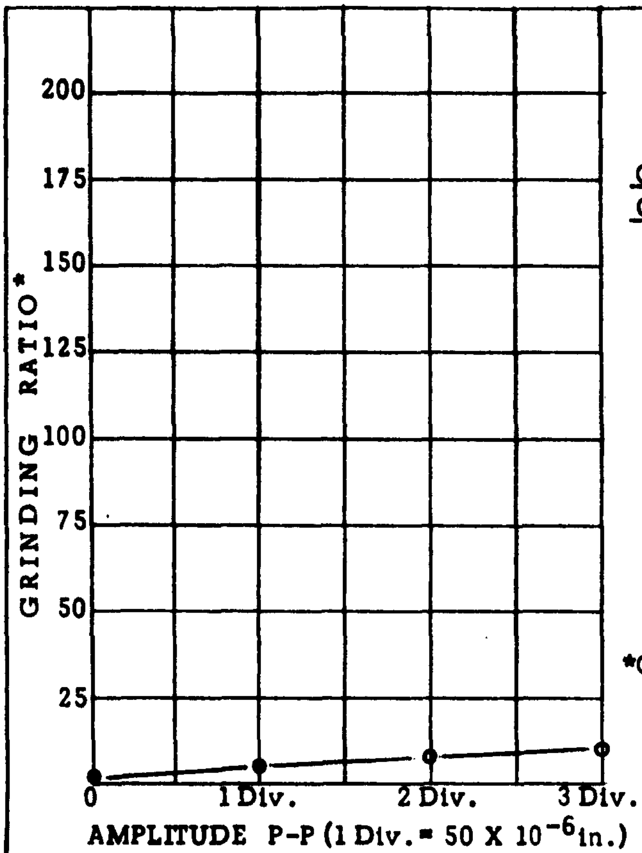
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	T16Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	3 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Number: 91 - III

Figure 341



INTERNAL GRINDING

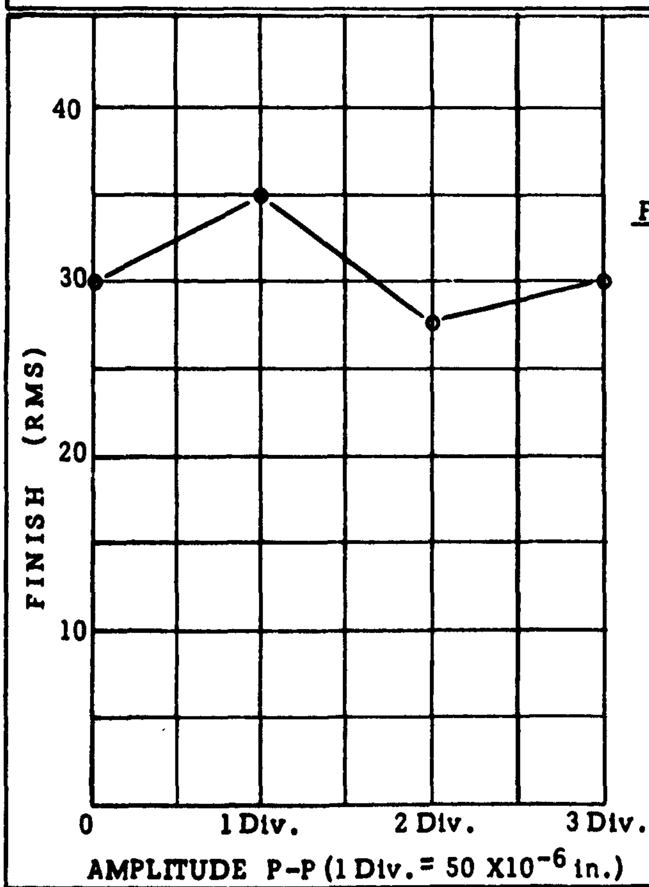
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	AA46K8-V40
Wheel Speed	2870 SFPM
Traverse Feed	4 in/minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 82 - 85 - III

Figure 342



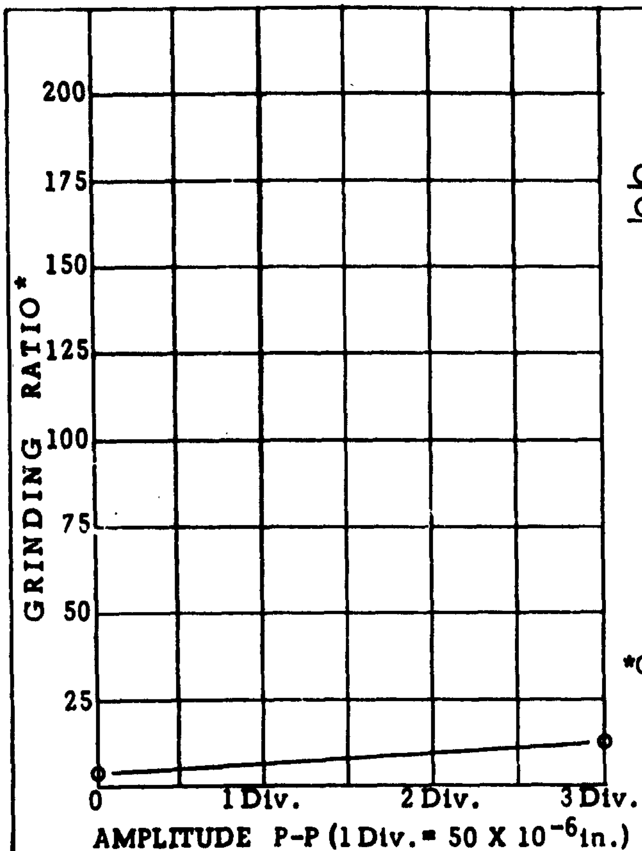
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	AA46K8-V40
Wheel Speed	2870 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 82 - 85 - III

Figure 343



INTERNAL GRINDING

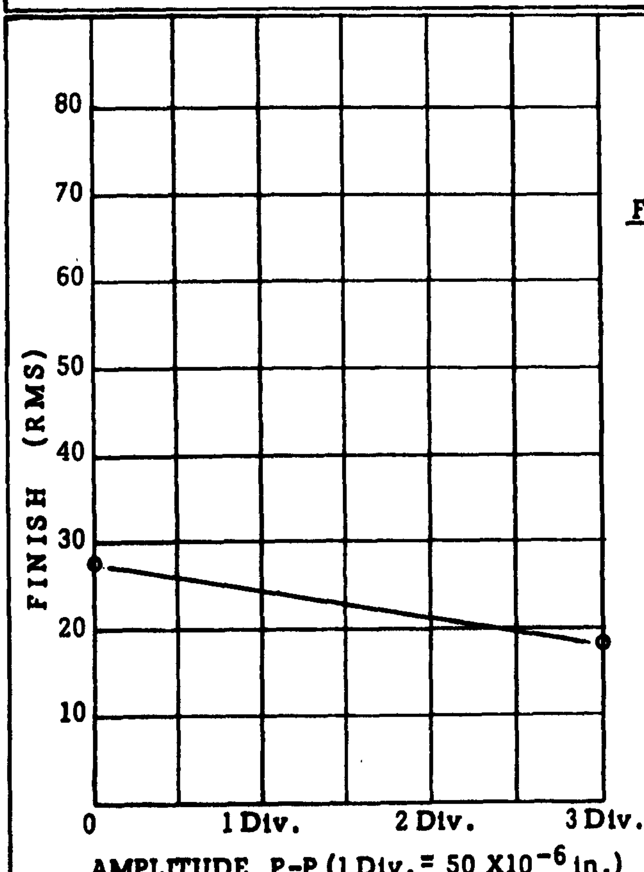
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	T16Al-4V
Wheel	AA46K8-V40
Wheel Speed	2870 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 86, 87 - III

Figure 344



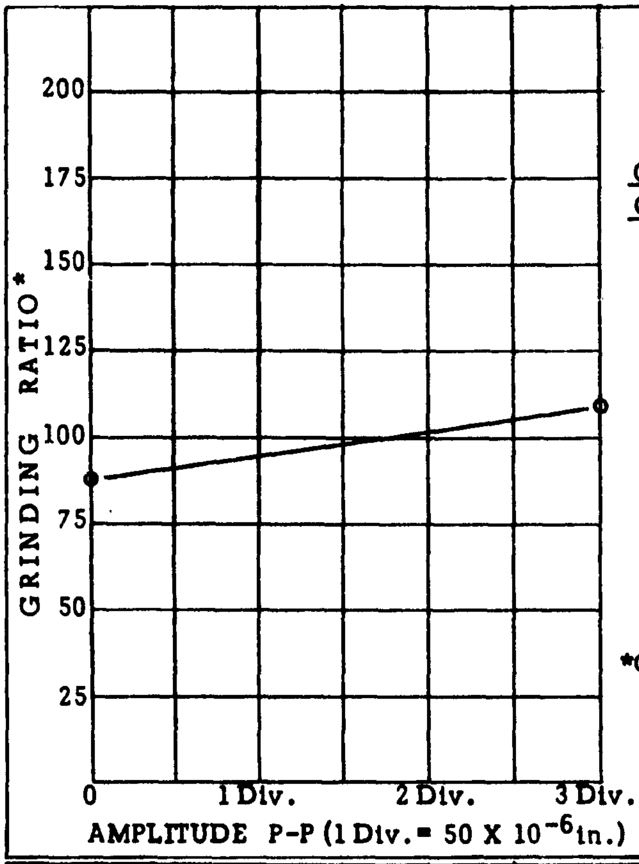
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	T16Al-4V
Wheel	AA46K8-V40
Wheel Speed	2870 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 86, 87 - III

Figure 345



INTERNAL GRINDING

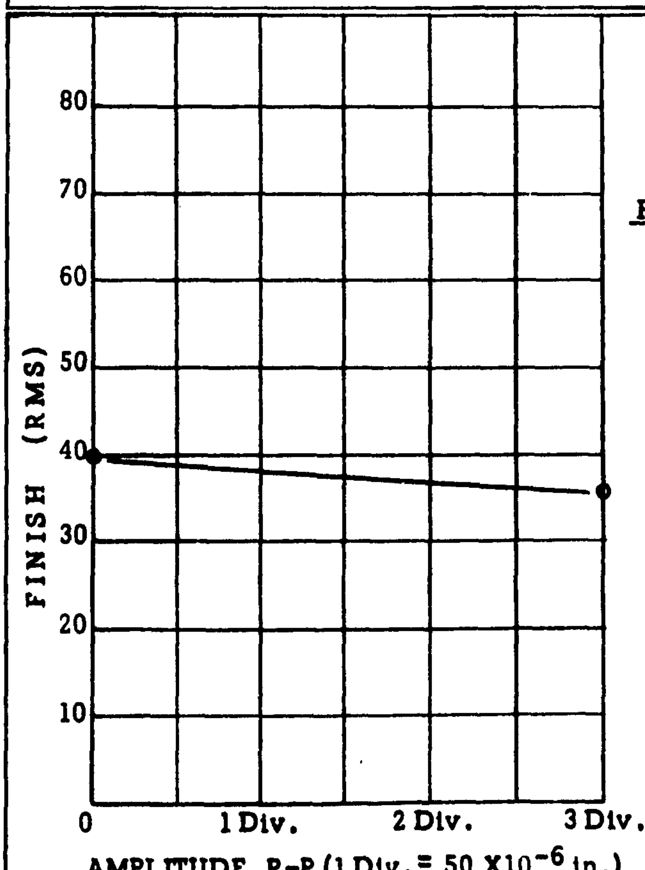
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	T16Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 87, 88 - III

Figure 346



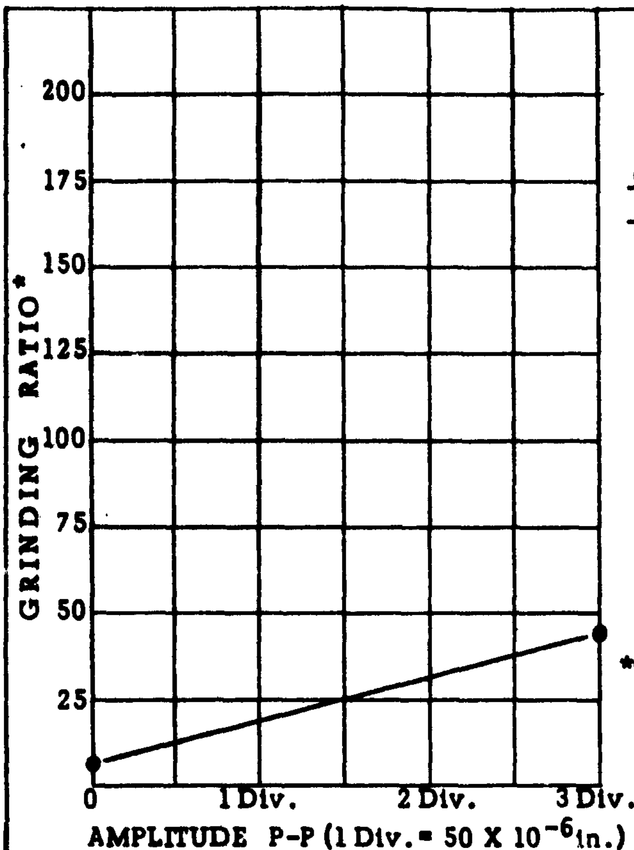
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	T16Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 87, 88 - III

Figure 347



INTERNAL GRINDING

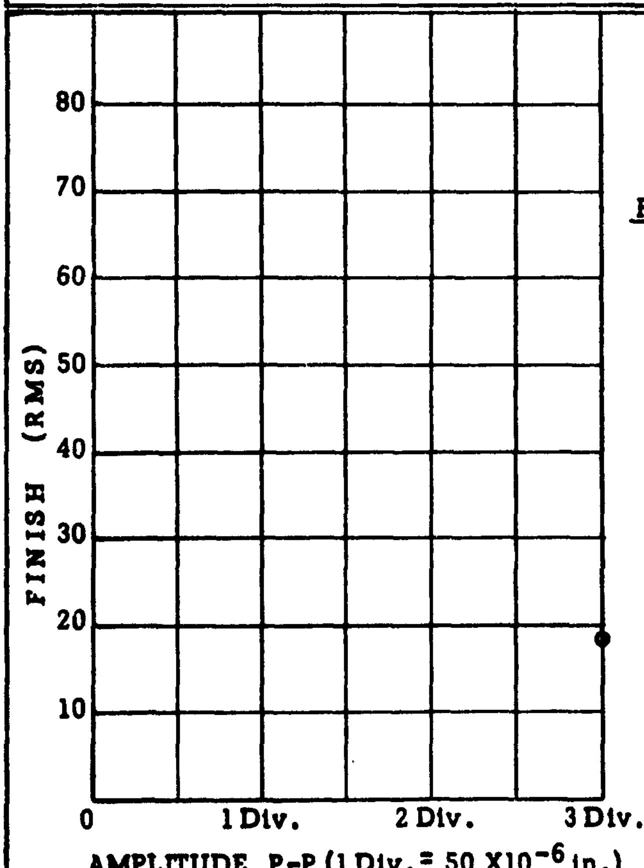
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60J6-V10
Wheel Speed	2870 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 111, 108 - III

Figure 348



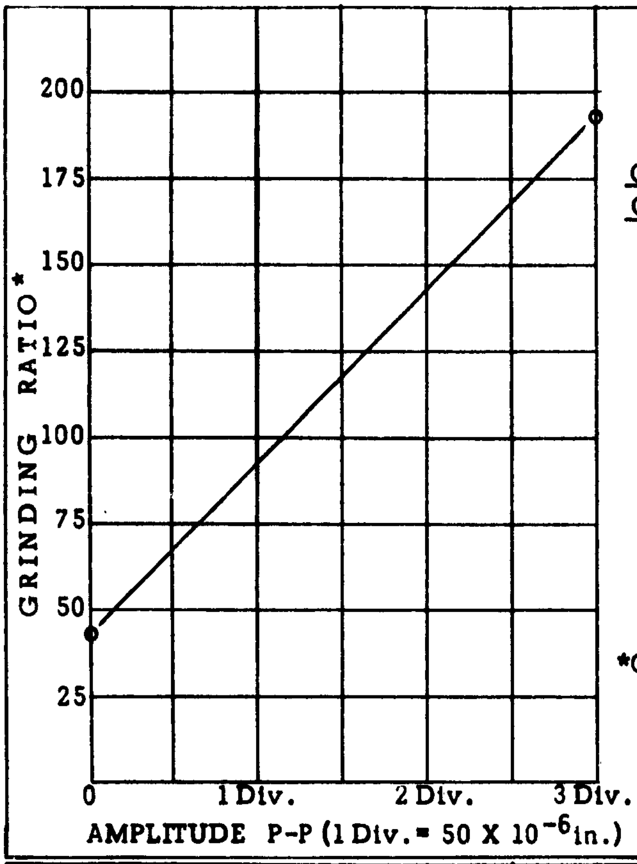
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	A60J6-V10
Wheel Speed	2870 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 111, 108 - III

Figure 349



INTERNAL GRINDING

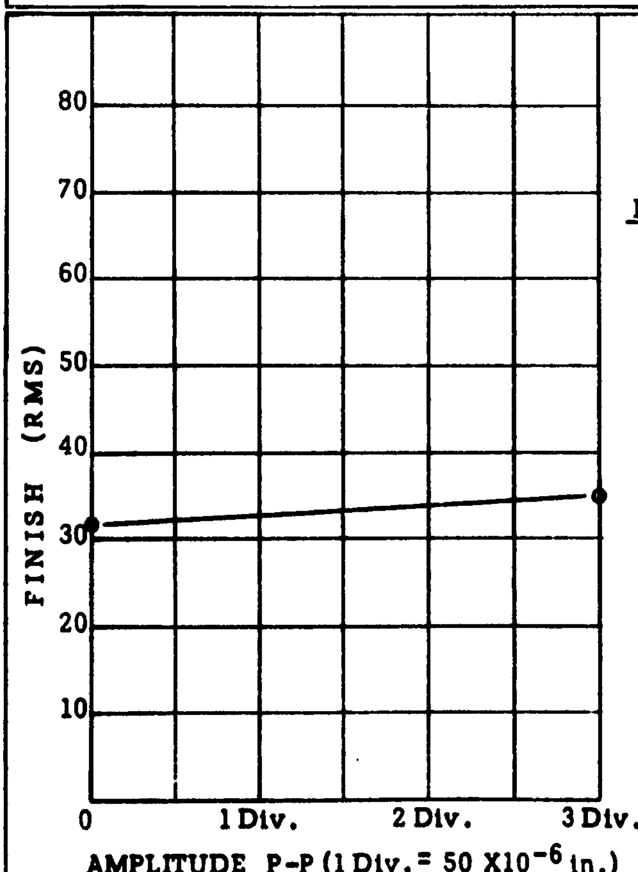
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 103A, 103B, 114, 117, 130, 97, 118 - III

Figure 350



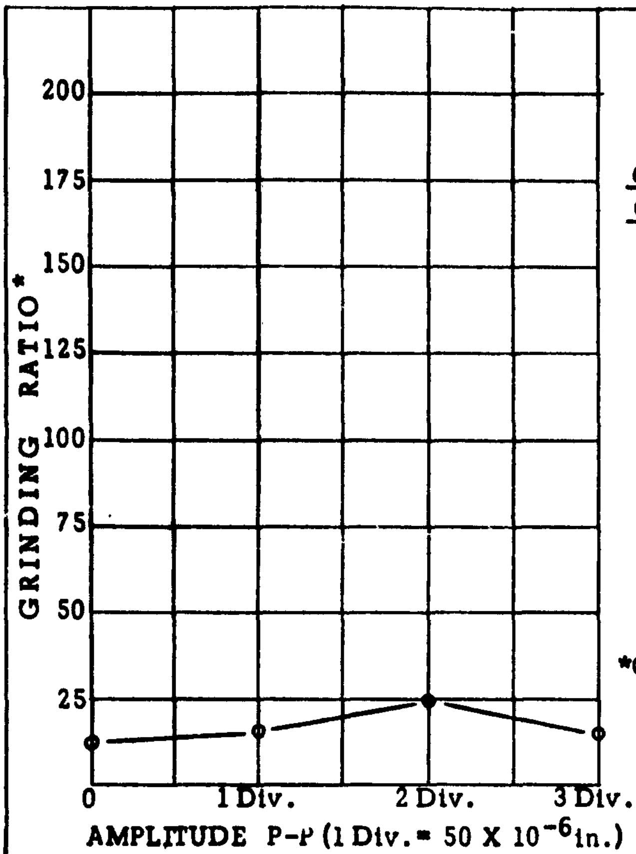
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 114, 117, 97, 118 -III

Figure 351



INTERNAL GRINDING

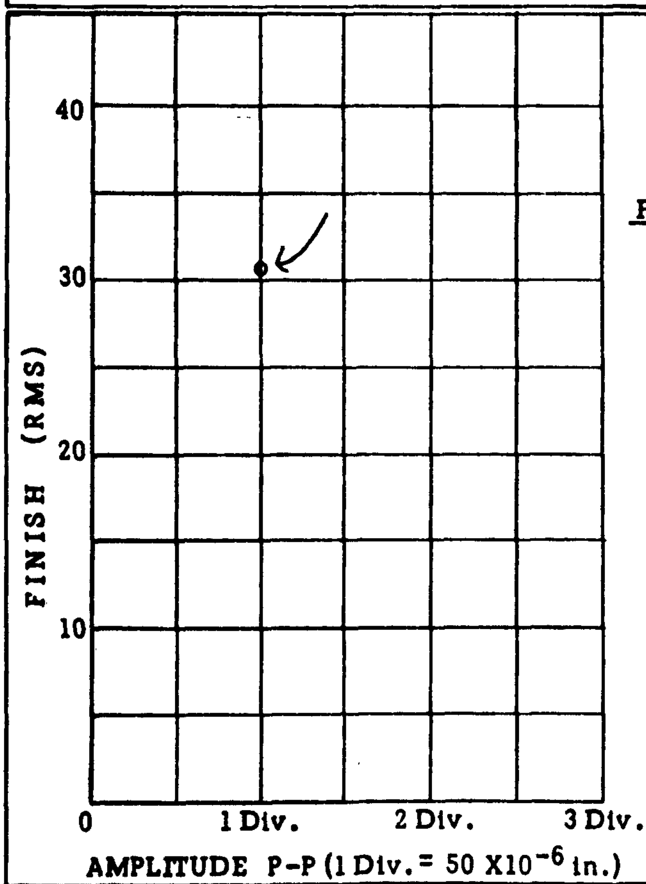
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	AA60-J8V40
Wheel Speed	3925 SFPM
Traverse Feed	4 in./min.
Workpiece SFPM	50 to 60
Depth of Cut	0.0006 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 45 - 48 - III

Figure 352



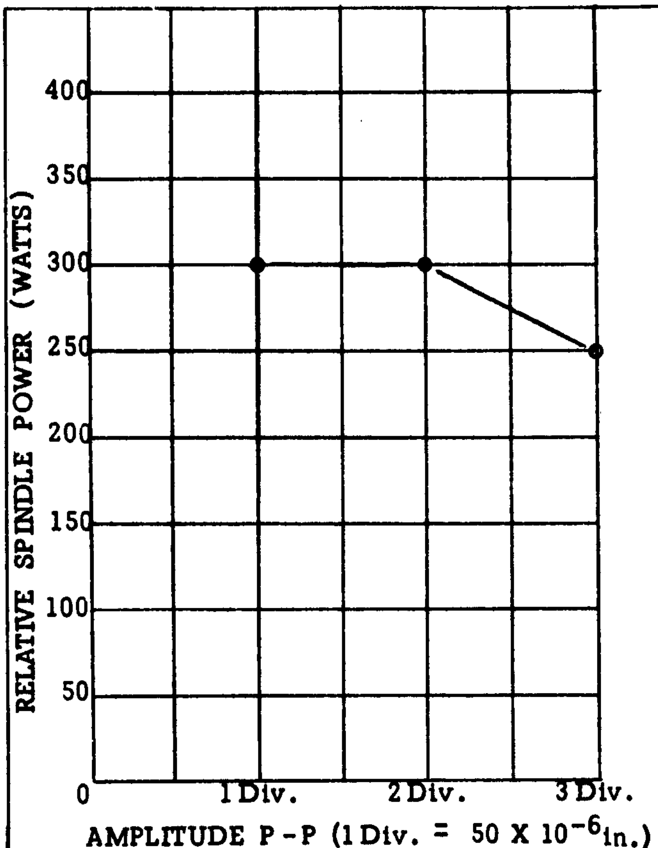
INTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	AA60-J8V40
Wheel Speed	3925 SFPM
Traverse Feed	4 in./min.
Workpiece SFPM	50 to 60
Depth of Cut	0.0006 inch
Coolant	Sultran 176M

Run Numbers: 45 - 48 - III

Figure 353



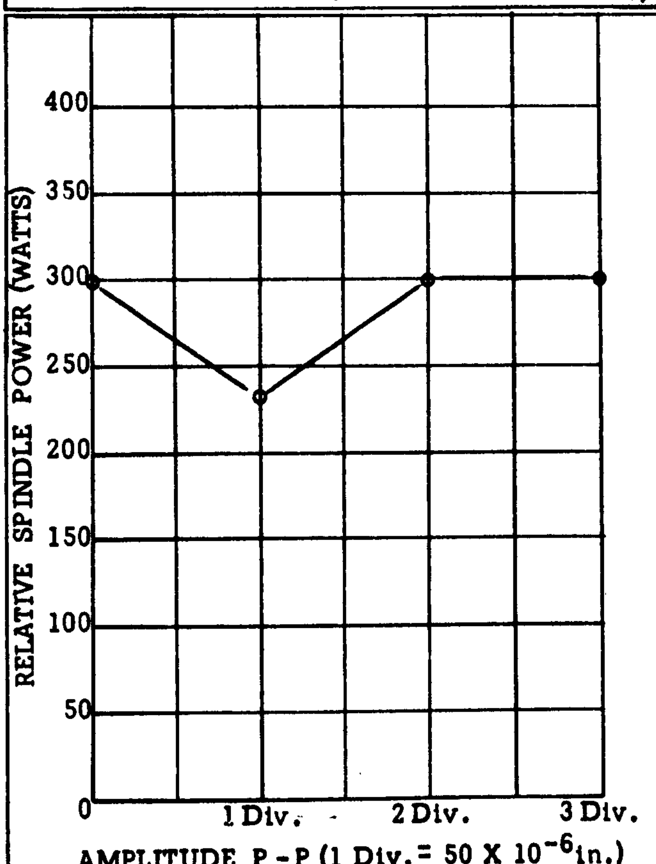
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	AA60-R8V40
Wheel Speed	4250 SFPM
Traverse Feed	1 in./minute
Workpiece (SFPM	40 to 45
Depth of Cut	0.0006 inch
Coolant	Sultran 176M

Run Numbers: 18 - 22 - III

Figure 354



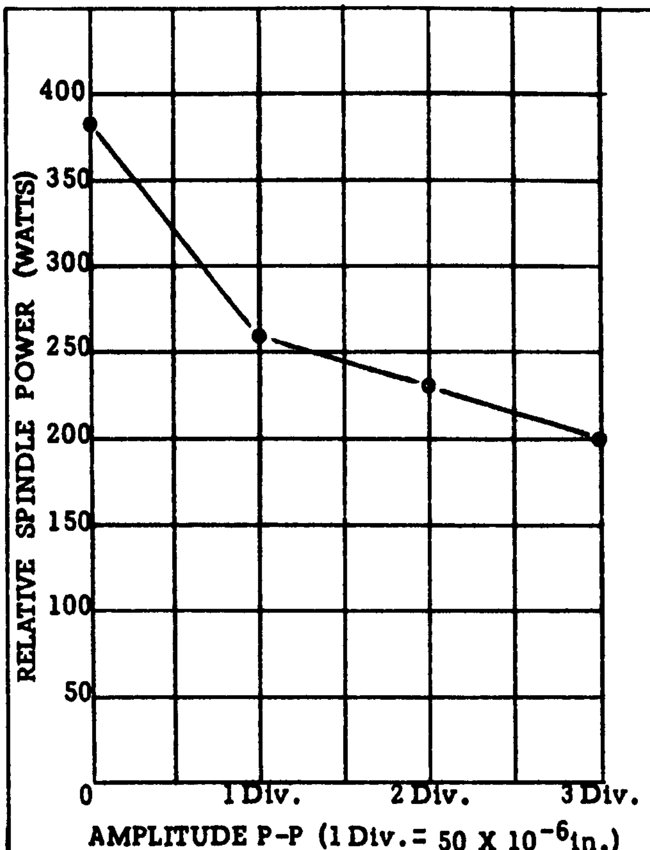
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	AA46-K8V40
Wheel Speed	4250 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	40 to 45
Depth of Cut	0.0006 inch
Coolant	Sultran 176M

Run Numbers: 22 - 25 - III

Figure 355



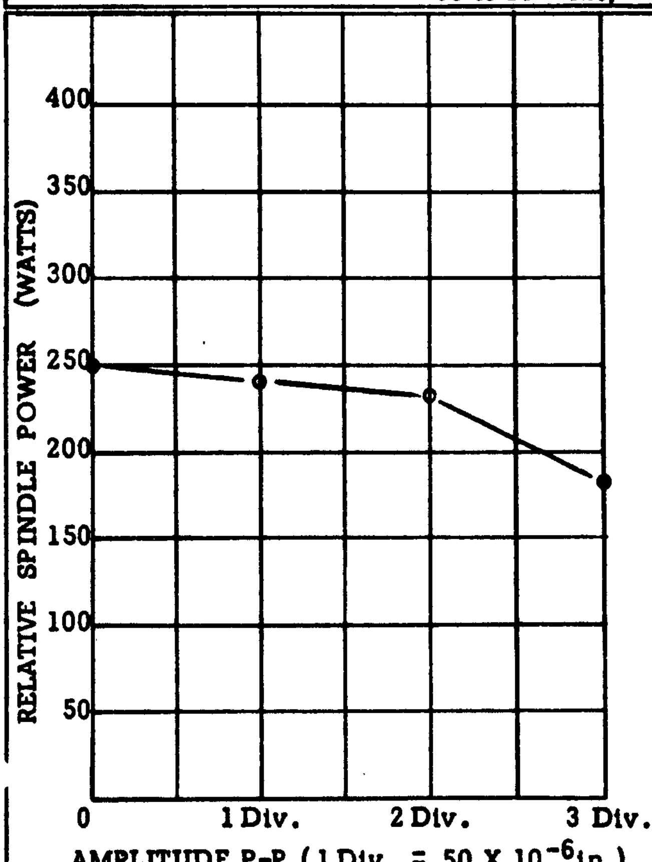
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	15-7MO
Wheel	AA46-J8V40
Wheel Speed	4625 SFPM
Traverse Feed	13.5 in./minute
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 41 - 44 - III

Figure 356



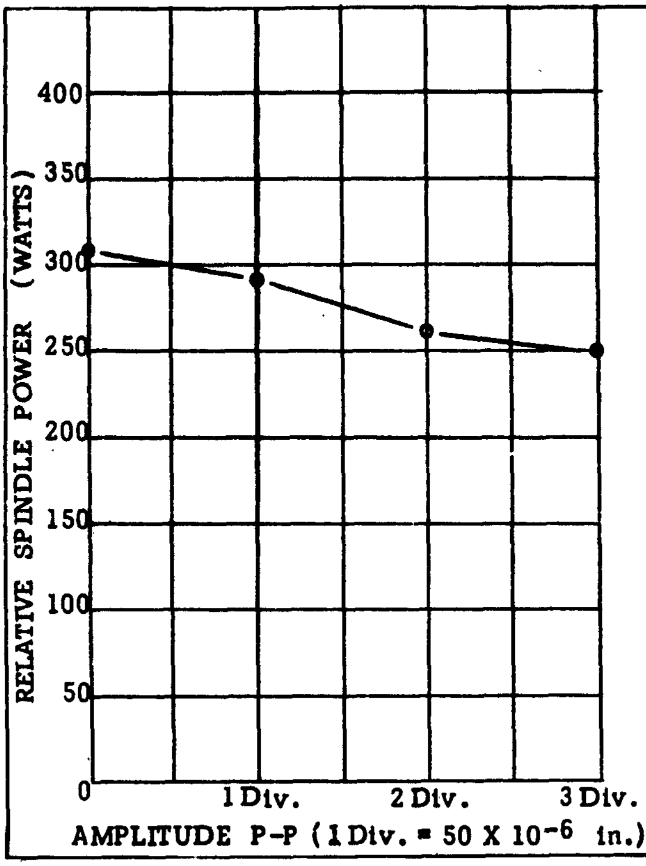
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	AA60-J8V40
Wheel Speed	3925 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	50 to 60
Depth of Cut	0.0006 inch
Coolant	Sultran 176M

Run Numbers: 45 - 48 - III

Figure 357



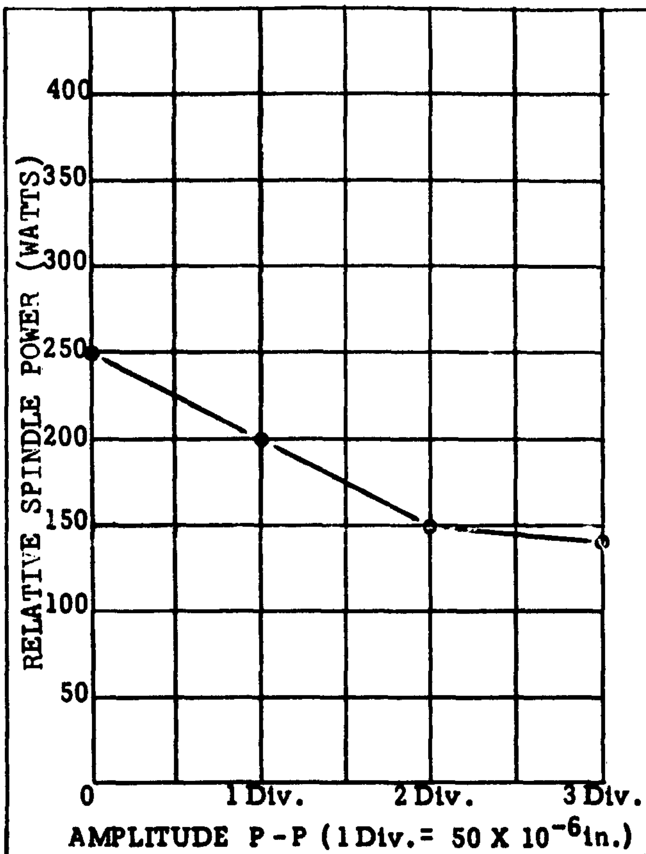
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	AA46-K8V40
Wheel Speed	4600 SFPM
Traverse Feed	13.5 in./minute
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 58 - 61 - III

Figure 358



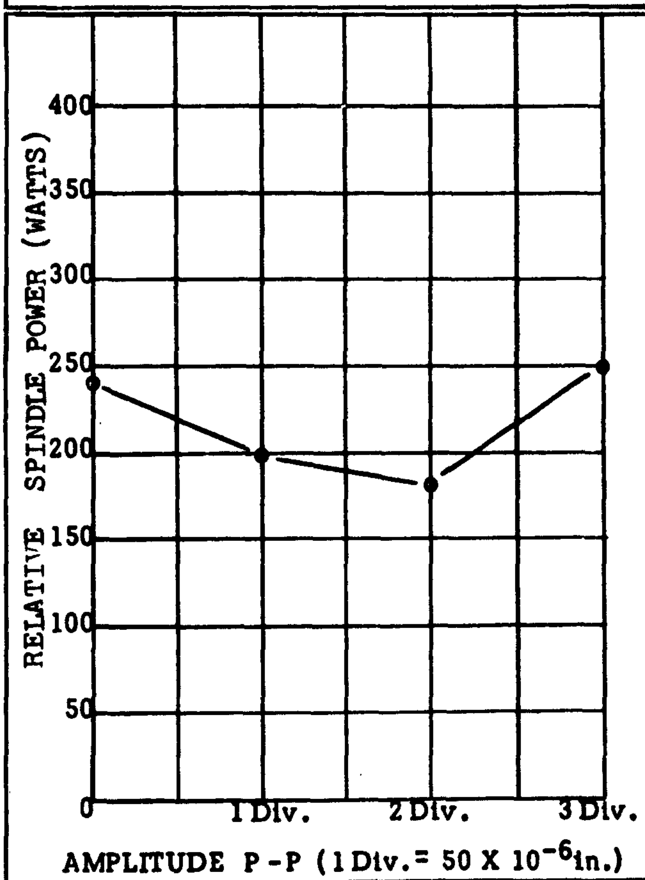
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	AA46-I8V40
Wheel Speed	3960 SFPM
Traverse Feed	4 in./minute
Workpiece SFPM	50 to 55
Depth of Cut	0.0006 inch
Coolant	Sultran 176M

Run Numbers: 52, 51, 50, 49 - III

Figure 359



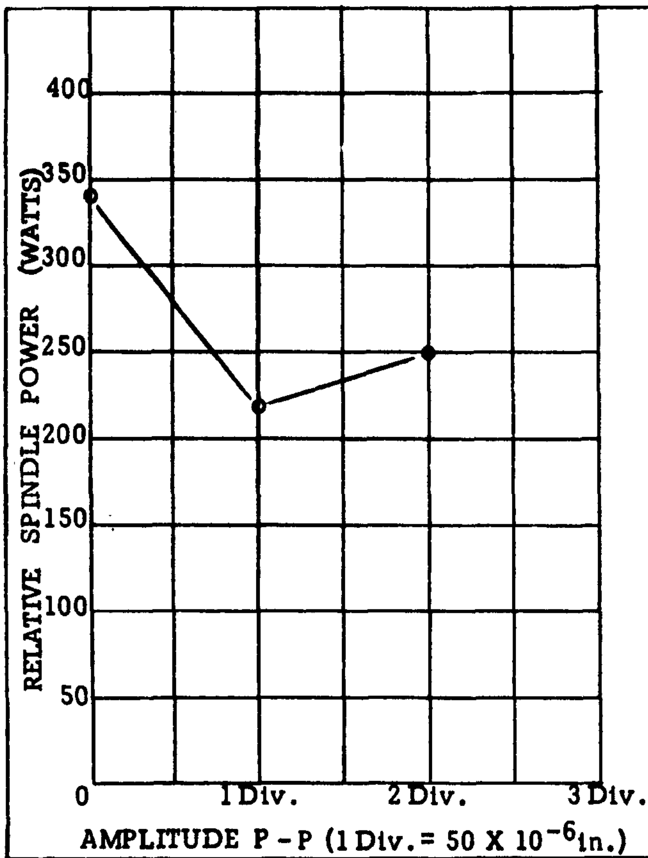
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	H - 11
Wheel	GA60-J8V40
Wheel Speed	4600 SFPM
Traverse Feed	13.5 in./minute
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 54 - 57 - III

Figure 360



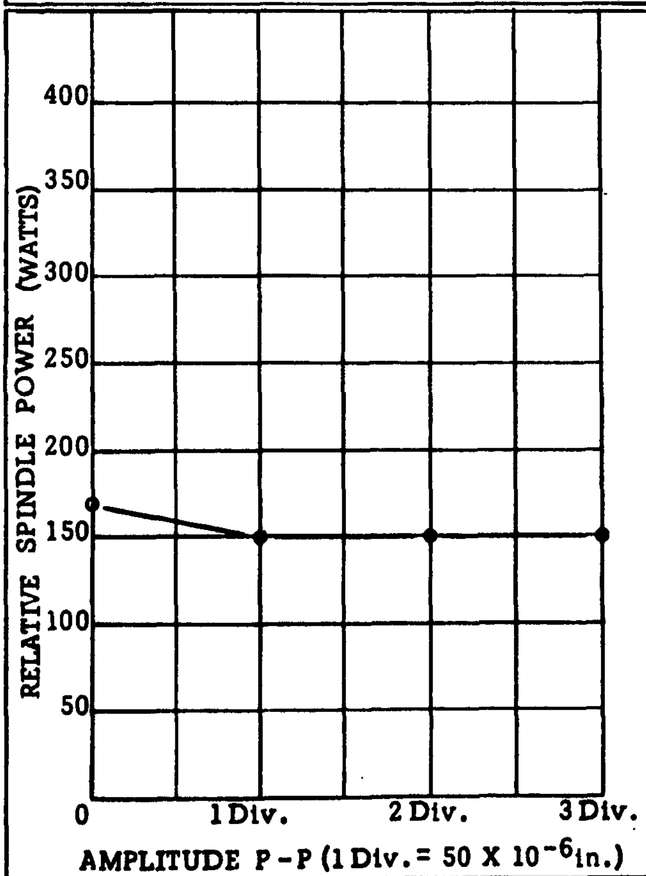
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	AA60-I8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 30 - 33 - III

Figure 361



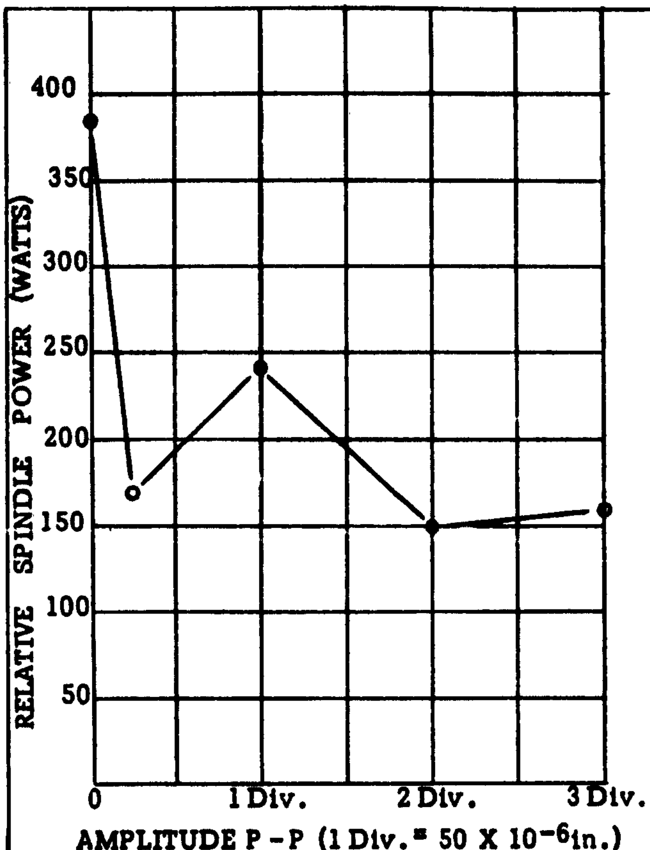
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	H - 11
Wheel	AA60-I8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 26 - 28 - III

Figure 362



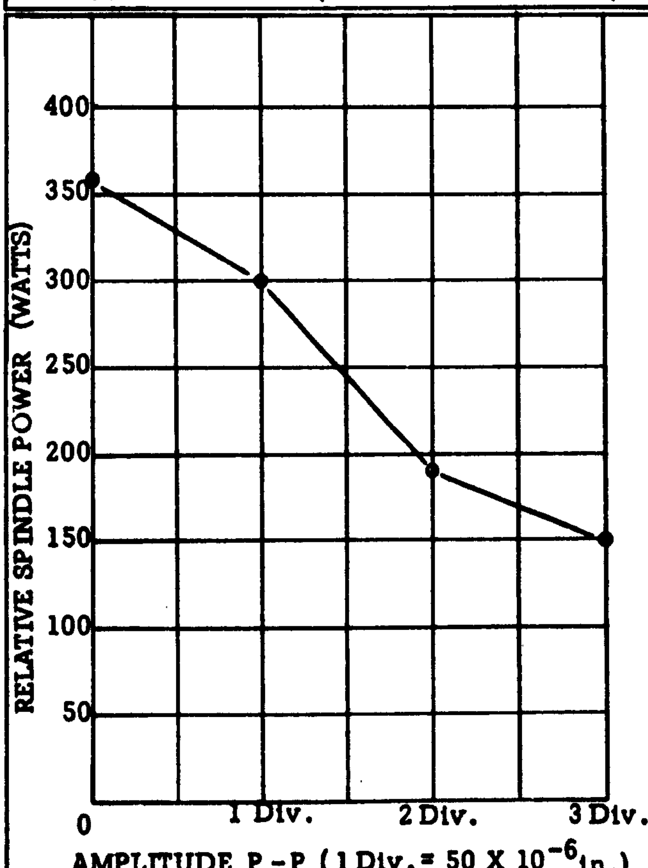
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	H - 11
Wheel	AA60-R8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	135 to 145
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 1 - 4 - III

Figure 363



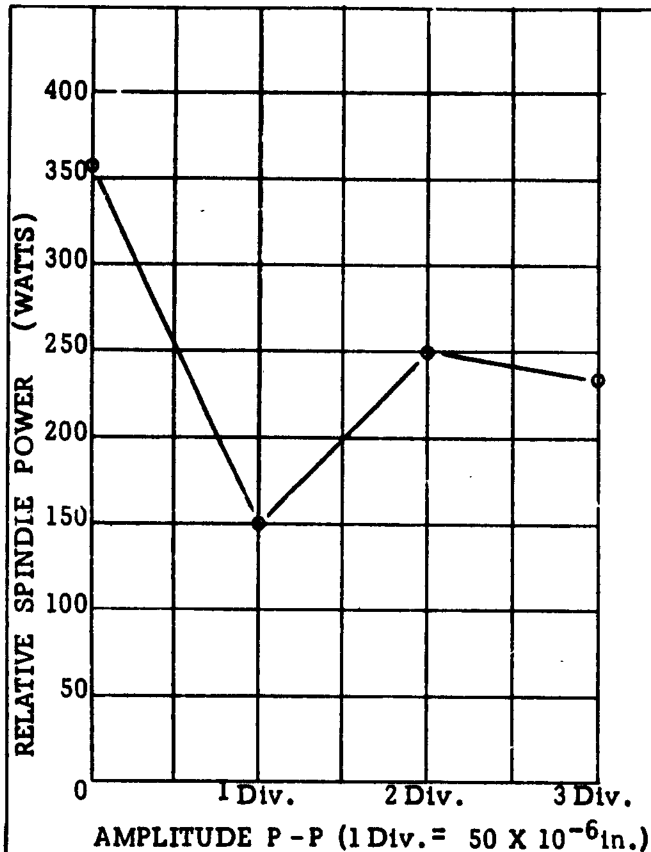
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	AA60-R8V40
Wheel Speed	4540 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	135 to 145
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 6 - 9 - III

Figure 364



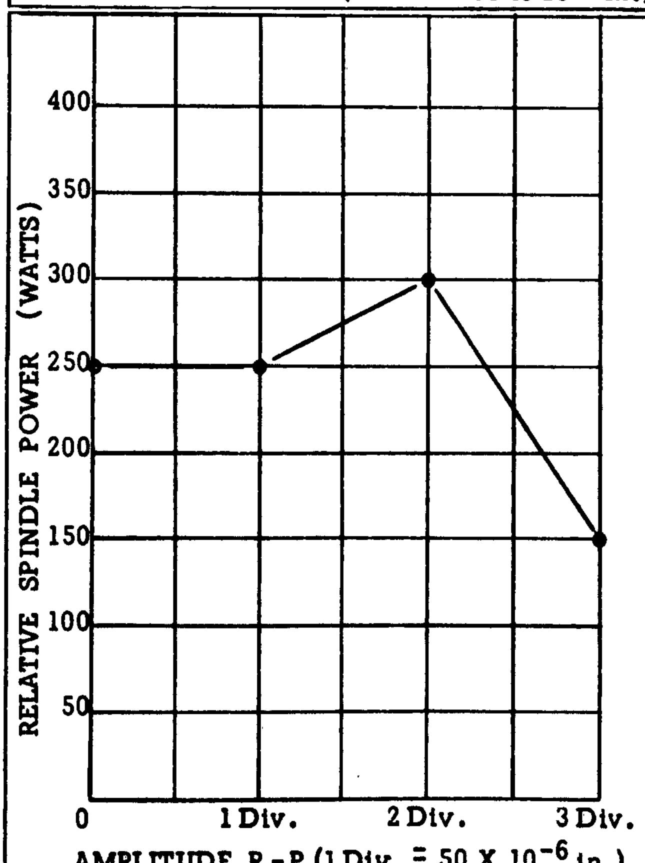
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	H - 11
Wheel	AA46-K8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	135 to 145
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 10 - 13 - III

Figure 365



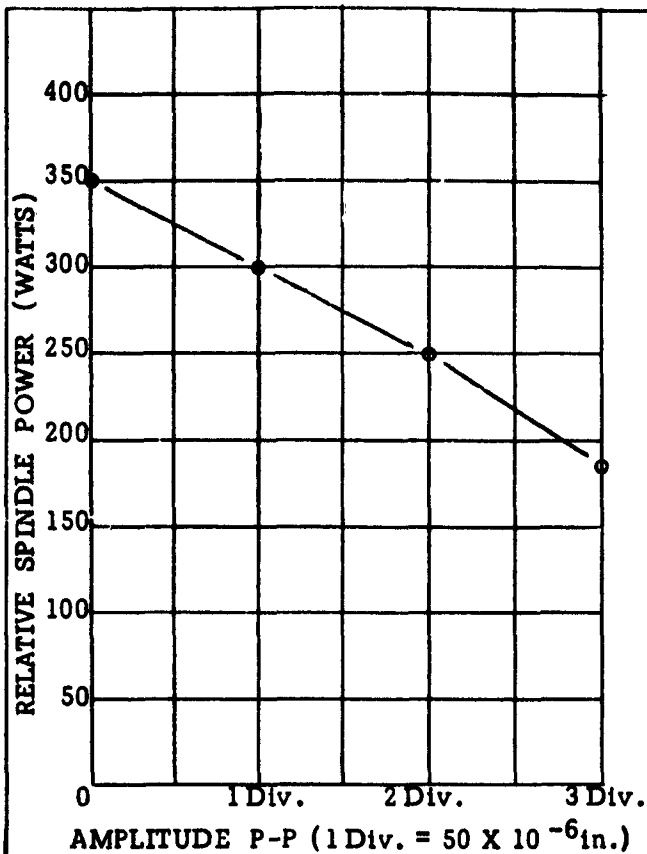
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	AA46-K8V40
Wheel Speed	4625 SFPM
Traverse Feed	1 in./minute
Workpiece SFPM	135 to 145
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 14 - 17 - III

Figure 366



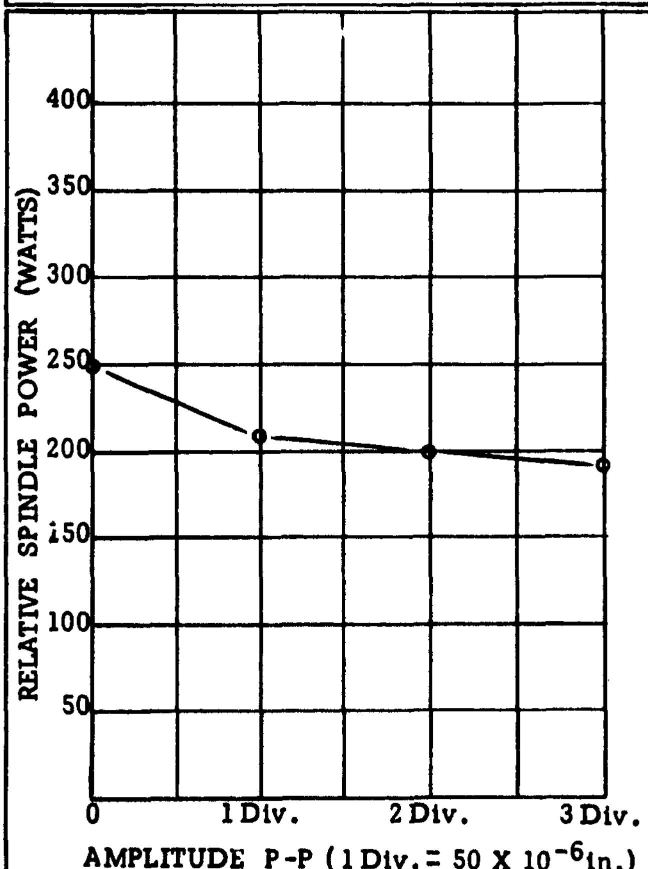
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	AA60-I8V40
Wheel Speed	4600 SFPM
Traverse Feed	13.5 in./minute
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 36, 35, 34, 33 - III

Figure 367



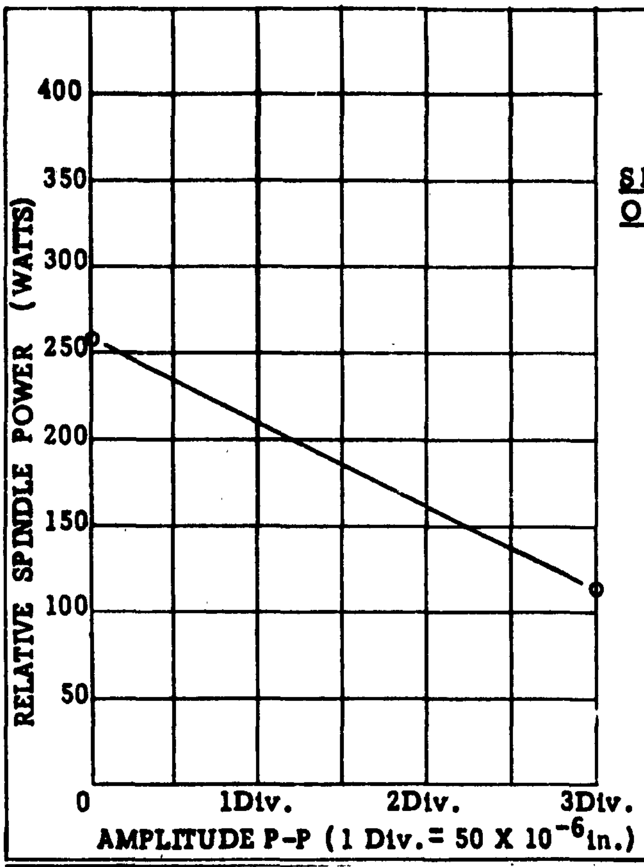
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE

Material	H - 11
Wheel	AA60-I8V40
Wheel Speed	4600 SFPM
Traverse Feed	13.5 in./minute
Workpiece SFPM	150 to 160
Depth of Cut	0.0005 inch
Coolant	Sultran 176M

Run Numbers: 37 - 40 - III

Figure 368



INTERNAL GRINDING

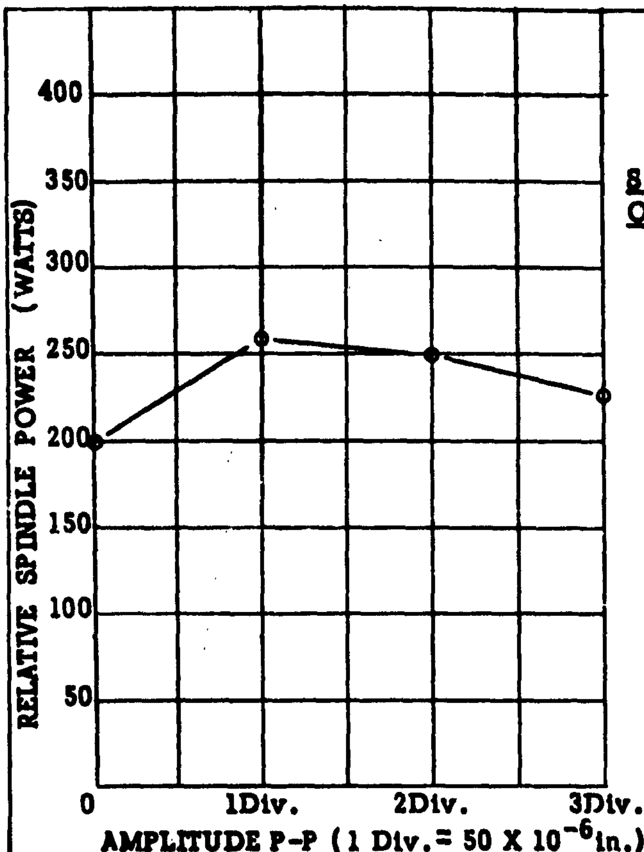
SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	2 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 94, 120, 132, 98, 119

III

Figure 369



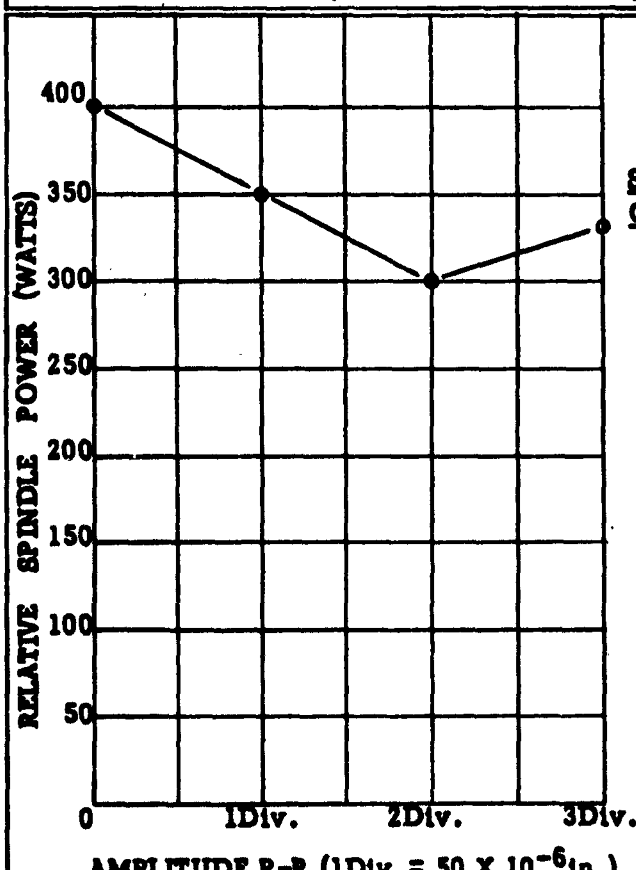
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	AA46K8-V40
Wheel Speed	2870 SFPM
Traverse Feed	4 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

Run Numbers: 78, 79, 80, 81 - III

Figure 370



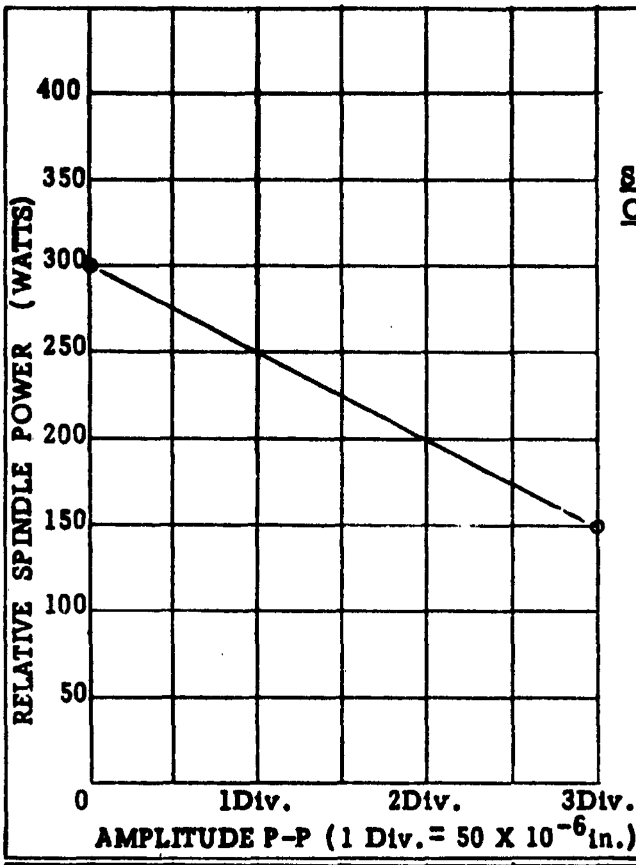
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	AA46K8-V40
Wheel Speed	2870 SFPM
Traverse Feed	4 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 82, 83, 84, 85 - III

Figure 371



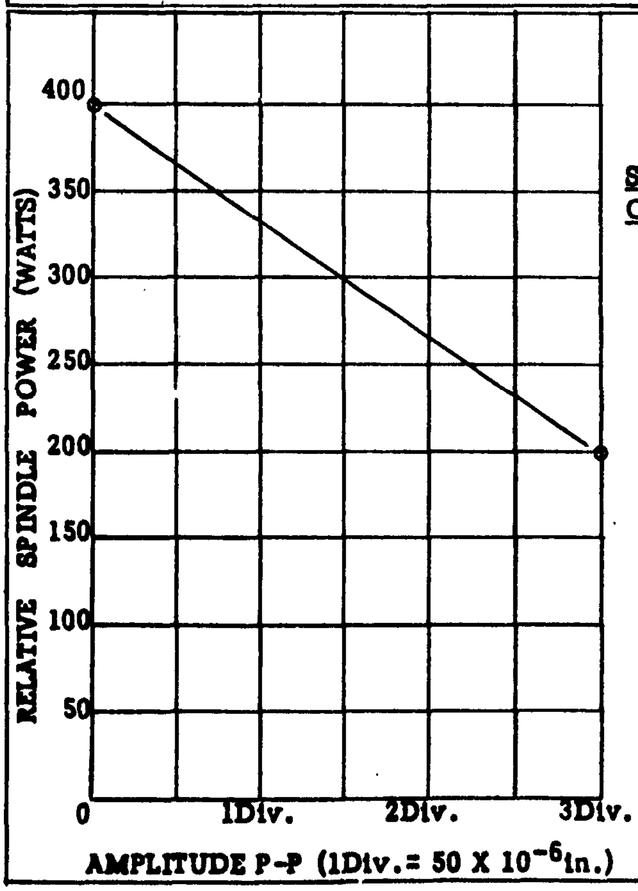
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	8 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

Run Numbers: 74, 75 - III

Figure 372



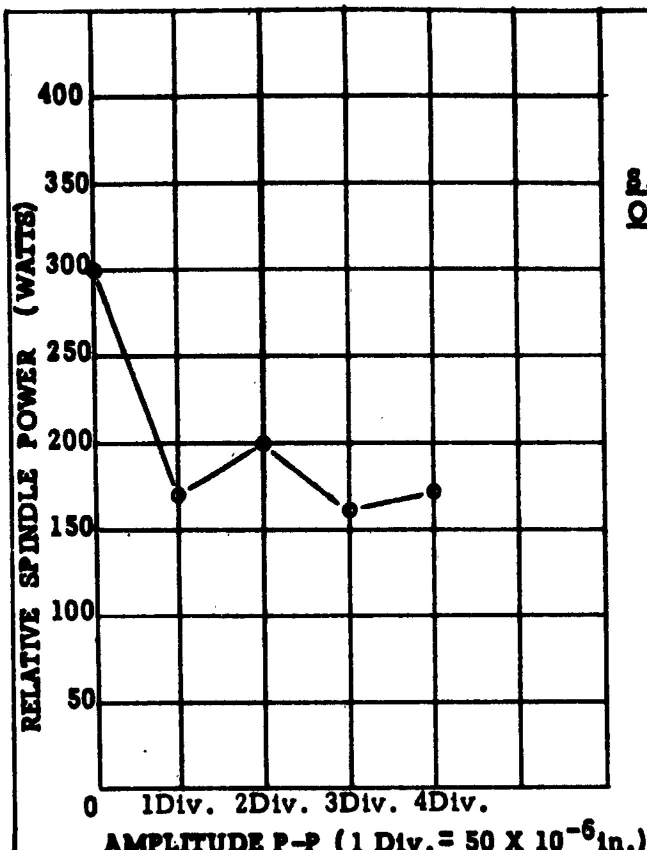
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	8 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 76, 77 - III

Figure 373



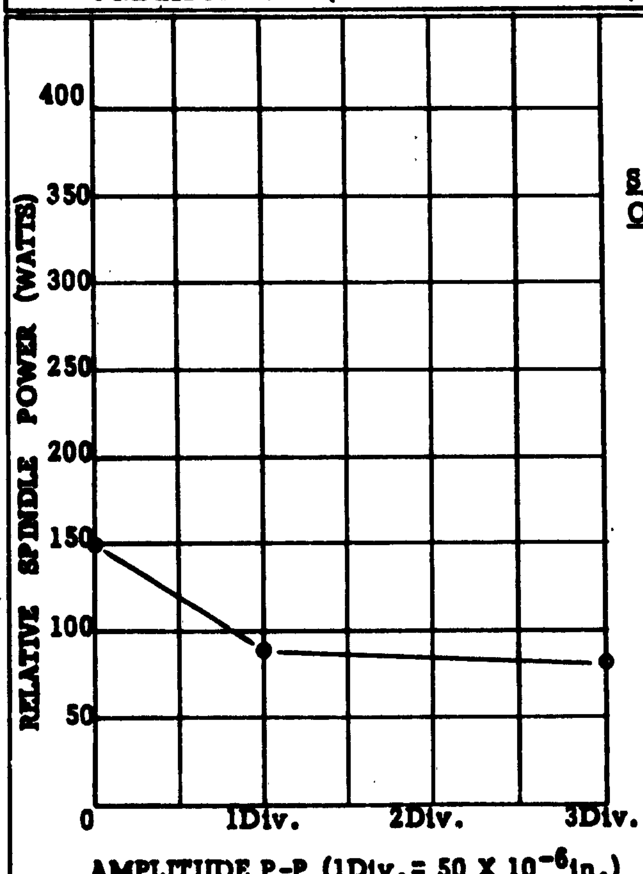
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 90, 62, 63, 64, 65, 66 - III

Figure 374



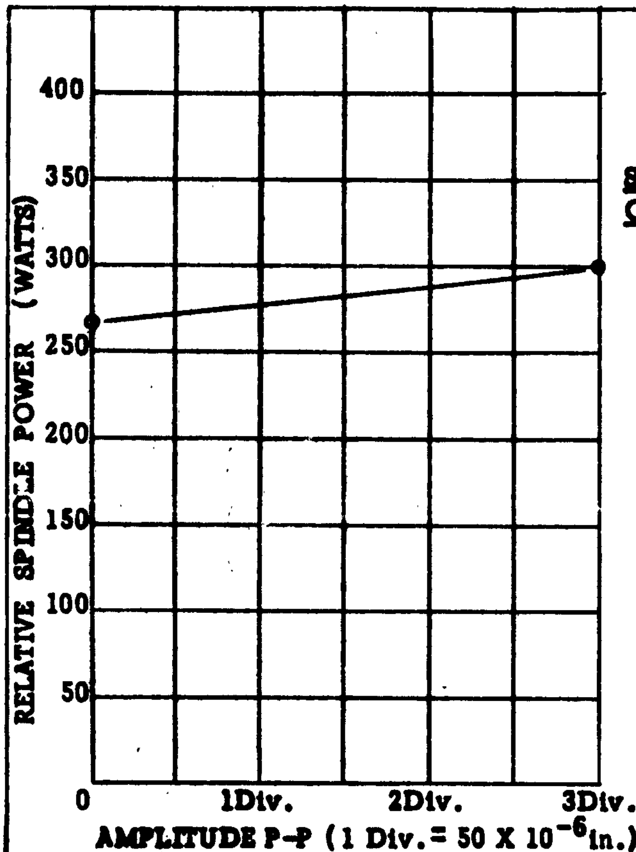
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

Run Numbers: 67, 68, 69 - III

Figure 375



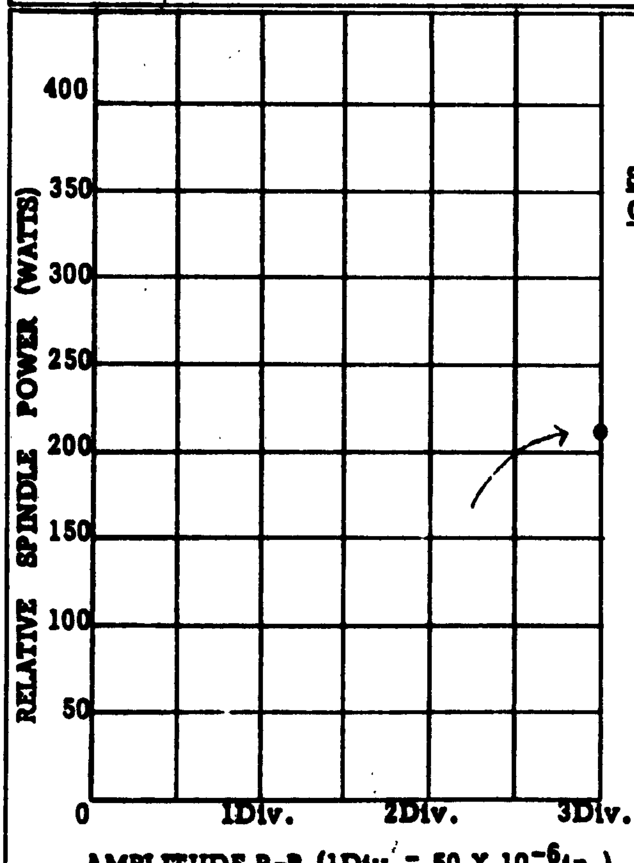
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60J6-V10
Wheel Speed	2870 SFPM
Traverse Feed	3 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 113, 110 - III

Figure 376



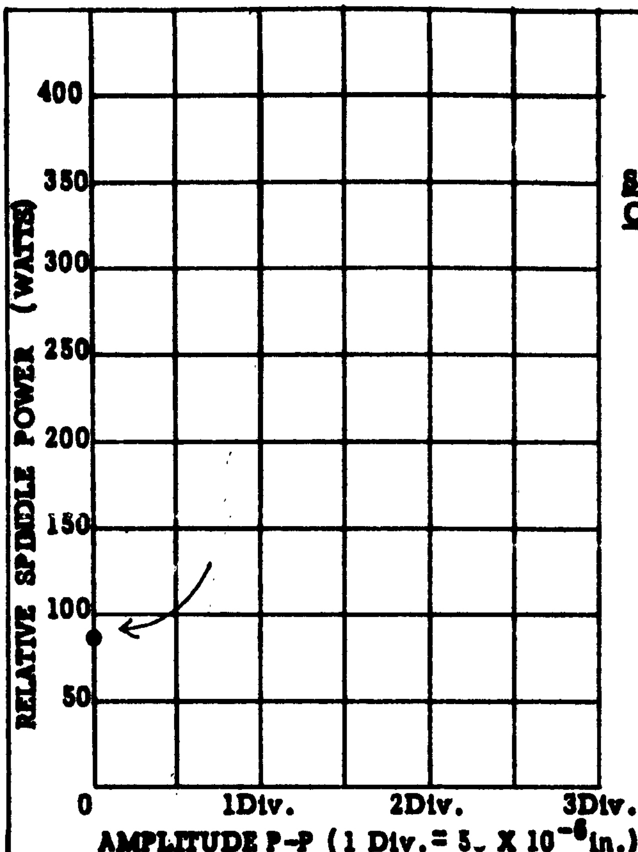
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	3 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.0015 in.
Coolant	Vantrol 5456M

Run Numbers: 102, 104A, 104B, 116, 122, 123, 125, 126, 127, 129, 133 - III

Figure 377



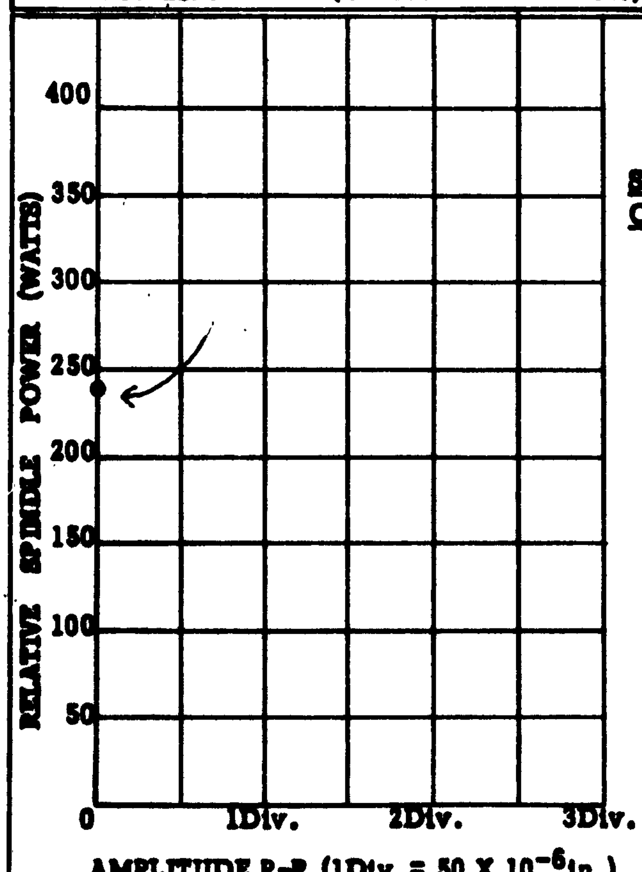
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	2 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Number: 90 - III

Figure 378



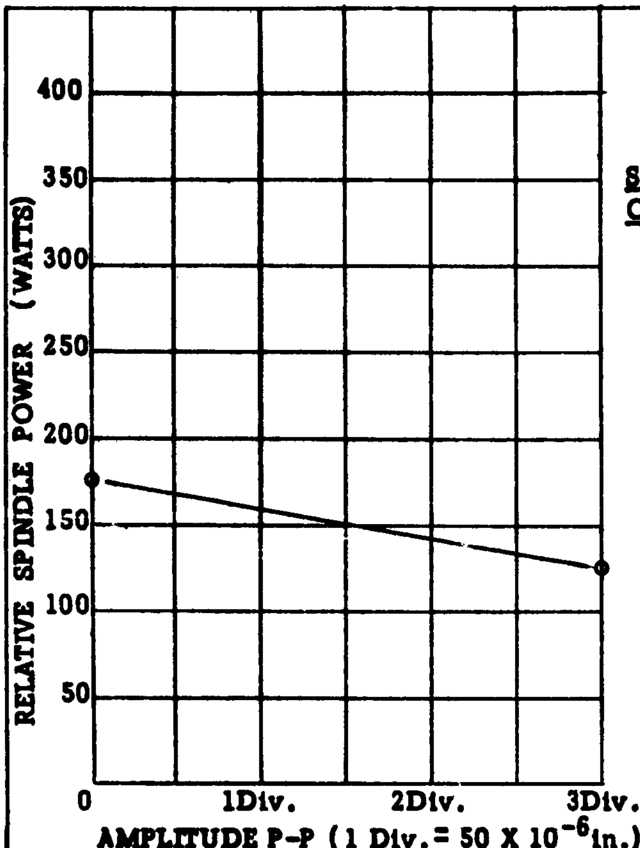
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	3 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Number: 91 - III

Figure 379



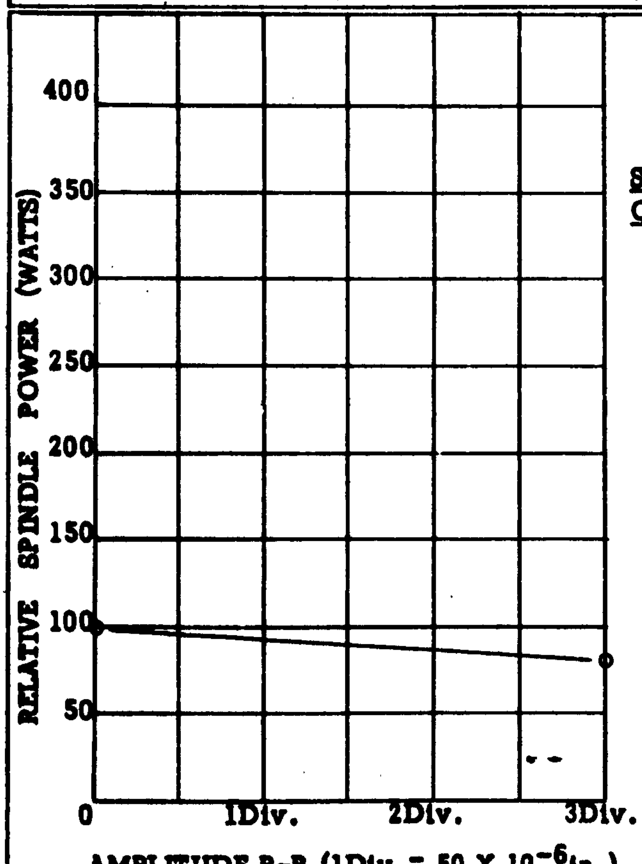
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	AA46K8-V40
Wheel Speed	2870 SFPM
Traverse Feed	1 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 86, 87 - III

Figure 380



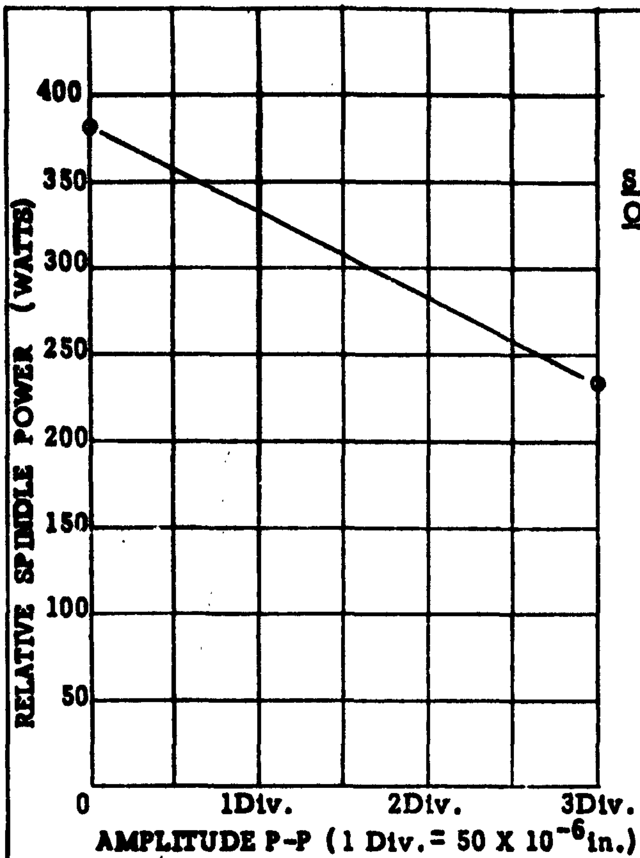
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	1 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 89, 88 - III

Figure 381



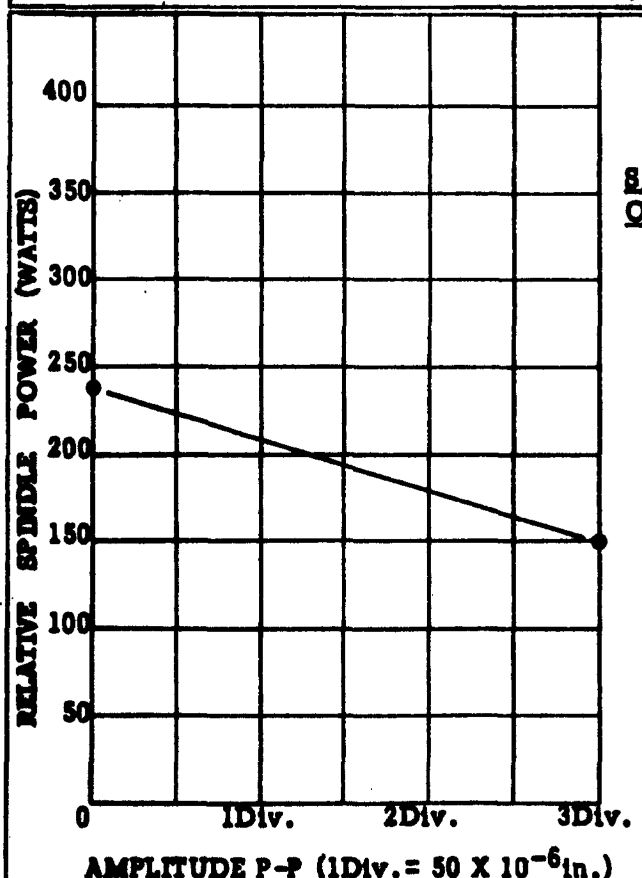
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 95, 131, 96, 115, 127
III

Figure 382



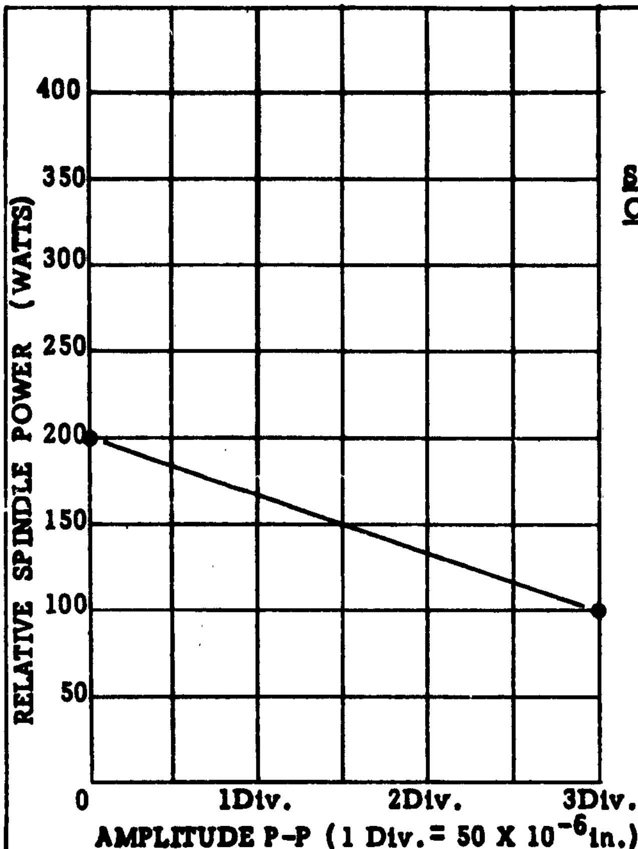
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	3 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 92, 99, 121 - III

Figure 383



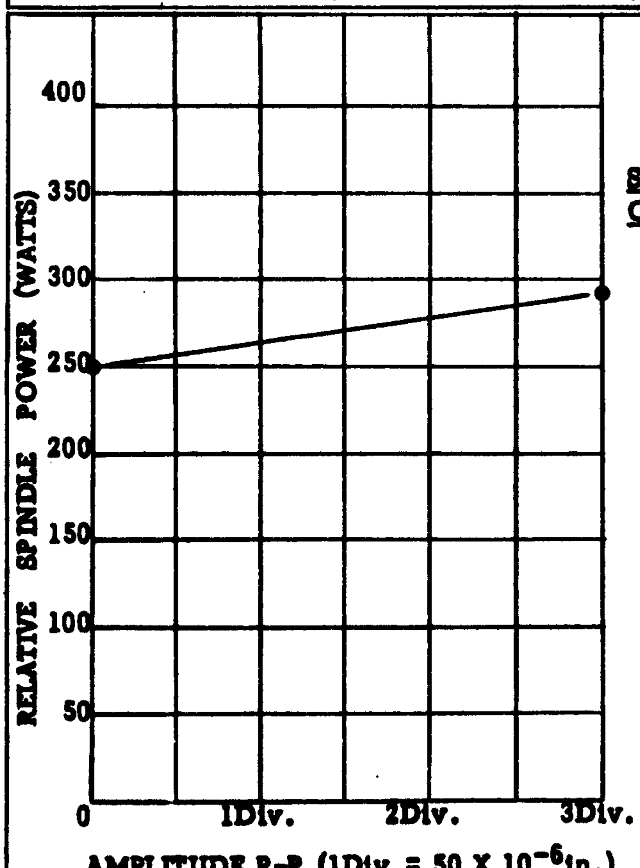
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	T16Al-4V
Wheel	A60J6-V10
Wheel Speed	2870 SFPM
Traverse Feed	1 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 111, 108 - III

Figure 384



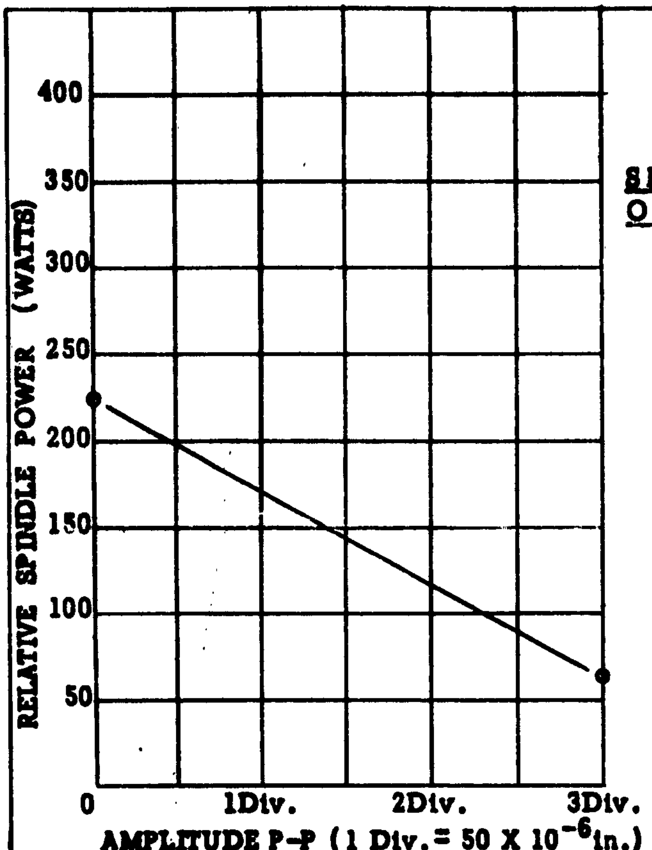
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	T16Al-4V
Wheel	A60J6-V10
Wheel Speed	2870 SFPM
Traverse Feed	2 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 112, 109 - III

Figure 385



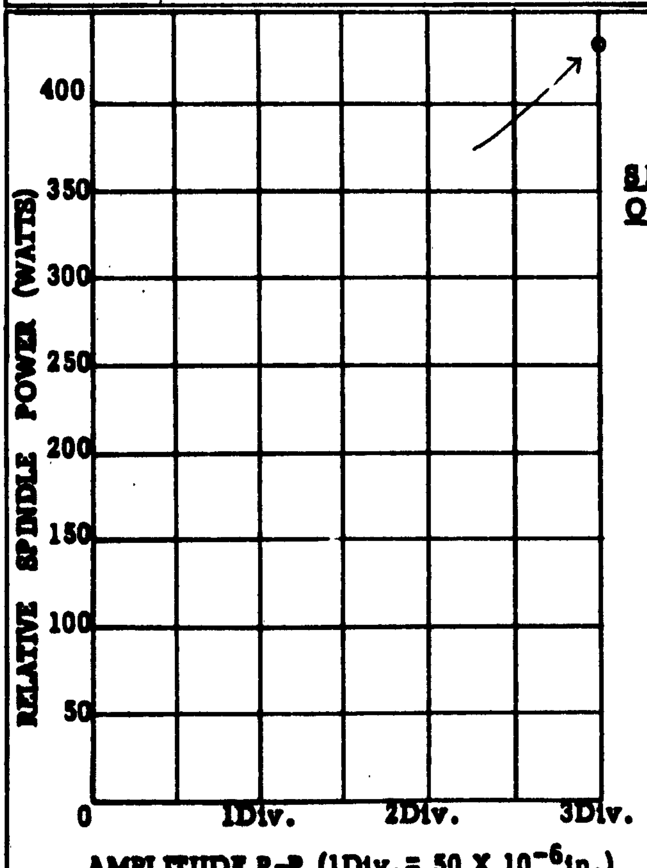
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	1 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 93, 103A, 103B, 114, 117, 130, 97, 118 - III

Figure 386



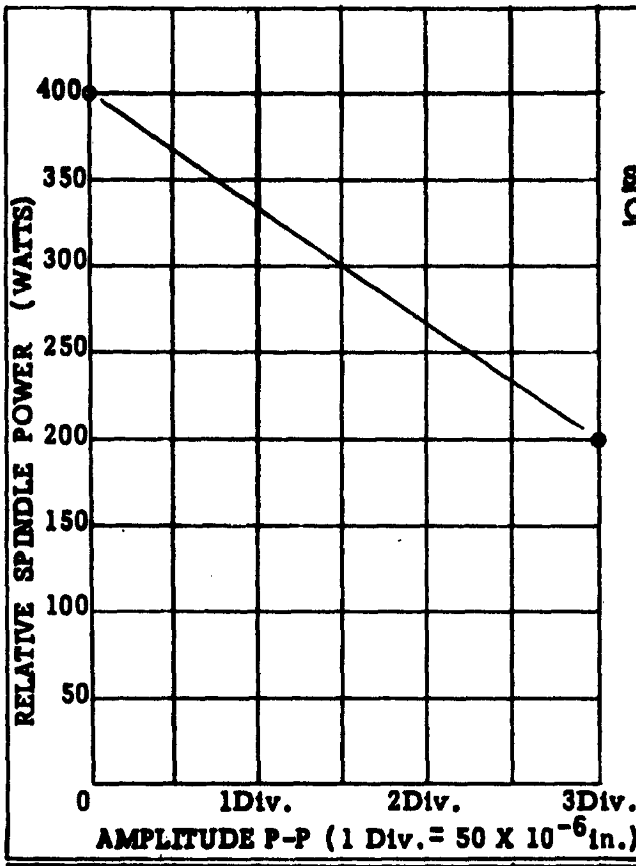
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60P5-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.0015 in.
Coolant	Vantrol 5456M

Run Numbers: 100, 100A - III

Figure 387



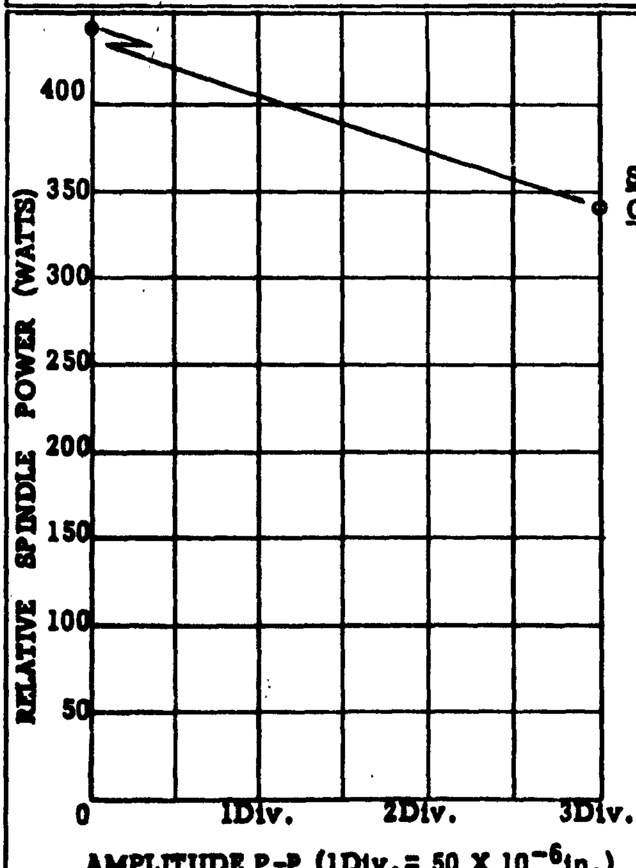
INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.0015 in.
Coolant	Vantrol 5456M

Run Numbers: 70, 71 - III

Figure 388



INTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	C60K4-VE
Wheel Speed	2870 SFPM
Traverse Feed	4 in./min.
Workpiece SFPM	38 to 40
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

Run Numbers: 72, 73 - III

Figure 389

RUN #	1	2	3	4	5	6	7	8
Material	H-11	H-11	H-11	H-11	H-11	15-7MO	15-7MO	15-7MO
Type of Grind	Internal Conv.	Internal 2 Division	Internal 1 Division	Internal 1/4 Division	Internal 3 Division	Internal Conventional	Internal 1 Division	Internal 2 Division
Wheel Used	AA60-R8V40	AA60-R8V40	AA60-R8V40	AA60-R8V40	AA60-R8V40	AA60-R8V40	AA60-R8V40	AA60-R8V40
Traverse Speed in./min.	1	1	1	1	1	1	1	1
SFPM of Wheel	4626	4626	4626	4626	4555	4540	4540	4540
Spindle R.P.M.	2850	2850	2850	2850	2850	2850	2850	2850
SFPM of Specimen	135-145	135-145	135-145	135-145	135-145	135-145	135-145	135-145
Number of Passes	57	57	57	57	57	57	57	57
Depth of Cut	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"
Coolant Used	Sultran176M	Sultran176M	Sultran176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M
Volume of Work Removed	0.311in.^{3}	0.312 in.^{3}	0.302 in.^{3}	0.296 in.^{3}	0.275 in.^{3}	0.308 in.^{3}	0.285 in^3	0.299 in.^{3}
Relative Spindle Power	380	150	290	170	154	364	300	190
Grinding Ratio	159.8	63	104	122.6	95.3	160.4	66.2	62.6
Wheel diameter Before Grind	6.2068"	6.1858"	6.1610"	6.1498"	6.1302"	6.1102"	6.0950"	6.0868"
Wheel diameter After Grind	6.2064"	6.1848"	6.1604"	6.1493"	6.1290"	6.1098"	6.0941"	6.0858"
Part Dimensions	6.998"i.d.	7.010"i.d.	6.990"i.d.	7.0564"i.d.	7.0656"i.d.	7.000"i.d.	6.9852"i.d.	6.9811"i.d.
Profilometer micro. in. (RMS)	8-10RMS	10-12 RMS	12 RMS	10 RMS	10 RMS	11 RMS	9-10 RMS	7-9 RMS
Wheel condition after grind	Primary load	primary load sharp edges good cond.	primary load sharp edges good cond.	light primary load	primary load sharp edges good cond.	primary load sharp edges good cond.	primary load slight glaze sharp edges	primary load sharp edges good cond.
Wheel dressing Used	1 -.008 1 -.002	1 - .008 1 - .002	1 - .008 1 - .002	1 - .008 1 - .002	1 - .008 1 - .002	1 - .008 1 - .002	1 - .008 1 - .002	1 - .008 1 - .002
Part condition after grind	no burn, no chatter, shiny fin.	no burn, satin finish, no chatter	no burn, satin finish, no chatter	no burn, satin finish, no chatter	no burn, satin finish, no chatter	burned in chatter marks shiny in part	no burn, satin finish, no chatter	no burn, satin finish, no chatter

Figure 390

RUN #	9	10	11	12	13	14	15	16
Material	15-7 MO	H-11	H - 11	H - 11	H - 11	15-7 MO	15 - 7 MO	15 - 7 MO
Type of Grind	Internal 3 Division	Internal Conventional	Internal 1 Division	Internal 2 Division	Internal 3 Division	Internal Conventional	Internal 1 Division	Internal 2 Division
Wheel Used	AA60-RV40	AA46-KV40	AA46-KV40	AA46-KV40	AA46-KV40	AA46-KV40	AA46-KV40	AA46-KV40
Traverse Speed in./min.	1	1	1	1	1	1	1	1
SFPM of Wheel	4540	4540	4540	4540	4540	4540	4540	4540
Spindle R.P.M.	2850	2850	2850	2850	2850	2850	2850	2850
SFPM of Specimen	150 - 160	135 - 145	135 - 145	135 - 145	135 - 145	150 - 160	150 - 160	150 - 160
Number of Passes	57	59	57	57	57	57	57	57
Depth of Cut	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"
Coolant Used	Sultran176M	Sultran176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran176M
Volume of Work Removed	0.299 in.^{3}	0.311 in.^{3}	0.3126 in.^{3}	0.3126 in.^{3}	0.296 in.^{3}	0.3055 in.^{3}	0.300 in.^{3}	0.3115 in.^{3}
Relative Spindle Power	150	360	150	250	230	250	250	300
Grinding Ratio	78.48	113.1	84	118.8	69.9	62.9	93.86	87.1
Wheel diameter Before Grind	6.0660"	6.25190"	6.2322"	6.20420"	6.1992"	6.1840"	6.16530"	6.1521"
Wheel diameter After Grind	6.0652"	6.25133"	6.23144"	6.20366"	6.19833"	6.1830"	6.16464"	6.15136"
Part Dimensions	7.052"i.d	7.1191" i.d.	7.1305"i.d.	7.080"i.d.	7.1166"i.d.	7.0452"i.d.	7.045"i.d.	7.106"i.d.
Profilometer micro.in.(RMS)	10-11	12	14-15	13 - 14	11	10 - 11	10 - 11	9 - 11
Wheel condition after grind	sharp edge exceptionally clean	sharp edges sl.dirty, no glaze,lt.pri.	prim.loading sharp edges exc. cond.	sharp edges good cond.	sharp edges dirty tertiary	sec. load.Sh. edges, glazed	tertiary load sharp edges good cond.	sharp edges clean slight glaze
Wheel dressing Used	1 - .008" 1 - .002"	1 - .008" 1 - .002"	1 - .008" 1 - .002"	1 - .008" 1 - .002"	1 - .008" 1 - .002"	1 - .008" 1 - .002"	1 - .008" 1 - .002"	1 - .008" 1 - .002"
Part condition after grind	no burn, no chatter, satin finish	light chatter no burn				lt. chatter, some lt.burn	no burns no chatter	very slt.burn no chatter

Figure 391

RUN #	17	18	19	20	21	22	23	24
Material	15 -7MO	Rene 41	Rene 41	Rene 41	Rene 41	Rene 41	Rene 41	Rene 41
Type of Grind	Internal 3 Division	Internal Conventional	Internal 1 Division	Internal 2 Division	Internal 3 Division	Internal Conventional	Internal 1 Division	Internal 2 Division
Wheel Used	AA46-K8V40	AA60-R8V40	AA60-R8V40	AA60-R8V40	AA60-R8V40	AA46-K8V40	AA46-K8V40	AA46-K8V40
Traverse Speed in./min.	1	1	1	1	1	1	1	1
SFPM of Wheel	4540	3960	3960	3960	3960	3960	3960	3960
Spindle R.P.M.	2850	2850	2850	2850	2850	2850	2850	2850
SFPM of Specimen	150-160	50 - 55	50 - 55	50 - 55	50 - 55	50 - 55	50 - 55	50 - 55
Number of Passes	57	47	47	48	47		47	47
Depth of Cut	0.0005"	0.0006"	0.0006"	0.0006"	0.0006"	0.0006"	0.0006"	0.0006"
Coolant Used	Sultran176M	Sultran176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M
Volume of Work Removed	0.299in.^{3}		0.297 in.^{3}	0.233 in.^{3}	0.276 in.^{3}	0.275 in.^{3}	0.272 in.^{3}	0.277 in.^{3}
Relative Spindle Power	150		300	300	250	300	230	300
Grinding Ratio	54.4		22.4	20.2	18.0	12.7	10.35	12.3
Wheel diameter Before Grind	6.1400"	5.5215"	5.4665"	5.4405"	5.4157"	5.5123"	5.4916"	5.47210"
Wheel diameter After Grind	6.13886"		5.4634"	5.4378"	5.4121"	5.5073"	5.4855"	5.46692"
Part Dimensions	7.1059"i.d.	6.9831"i.d.	6.985"i.d.	7.0182"i.d.	6.9821"i.d.	7.010" i.d.	7.0483"i.d.	7.0260"i.d.
Profilometer micro.in.(RMS)	13-14		14	15-16	13-14	15-16	16-17	15-16
Wheel condition after grind	dirty, some 1&2loading	exc.loading, chunks fr.wh.	sharp edges, tertiary load 20% shiny grit	prim.&sec.load sharp edges dirty	20% glazed, sharp edges, tertiary load.	40% glazed, secondary loading	Tertiary load clean, round edges	20% shiny gr. sharp edges, tertiary load
Wheel dressing Used	2 - .002" 2 - .001"	1 - .008" 1 - .002"	1 - .008" 1 - .002"	1 - .008" 1 - .002"		2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind		Burned and Chattered	very light chatter, no burn			chatter, light burn	light chatter	

Figure 392

RUN #	25	26	27	28	29	30	31	32
Material	Rene 41	H - 11	H - 11	H - 11	15 - 7 MO	15 - 7 MO	15 - 7 MO	15 - 7 MO
Type of Grind	Internal 3 Division	Internal Conventional	Internal 1 Division	Internal 2 Division	Internal Conventional	Internal 1 Division	Internal 2 Division	Internal 3 Division
Wheel Used	AA46-K8V40	AA60-I8V40	AA60-I8V40	AA60-I8V40	AA60-I8V40	AA60-I8V40	AA60-I8V40	AA60-I8V40
Traverse Speed in./min.	1	1	1	1	1	1	1	1
SFPM of Wheel	3960	4625	4625	4625	4625	4625	4625	4625
Spindle R.P.M.	2850	2850	2850	2850	2850	2850	2850	2850
SFPM of Specimen	50 - 55	135 - 145	135 - 145	135 - 145	150 - 160	150 - 160	150 - 160	150 - 160
Number of Passes	47	57	57		57	57	57	57
Depth of Cut	0.0006"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"
Coolant Used	Sultran176M	Sultran176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran176M
Volume of Work Removed	0.288 $in.^3$	0.309 $in.^3$	0.317 $in.^3$	0.292 $in.^3$	0.309 $in.^3$	0.328 $in.^3$	0.311 $in.^3$	0.353 $in.^3$
Relative Spindle Power	300	170	150	150	340	220	250	150
Grinding Ratio	15.68	125.75	208	99.7	105.7	42.2	107	121.9
Wheel diameter Before Grind	5.4432"	6.2613"	6.2505"	6.2280"	6.2085"	6.1938"	6.1572"	6.1437"
Wheel diameter After Grind	5.4389"	6.2608"	6.25019"	6.2274"	6.2079"	6.1922"	6.1566"	6.1431"
Part Dimensions	7.030"i.d.	7.1828"i.d.	7.182" i.d.	7.140" i.d.	7.150"i.d.	7.107" i.d.	7.169"i.d.	7.242"i.d.
Profilometer micro.in.(RMS)	15-17	10-11	13-14	11-12	10-11	8 - 9	10 - 11	12 - 13
Wheel condition after grind	5% glazed sharp edge clean surf.	prim. loading sharp edges fairly clean	primary load sharp edges clean	primary load sharp edges good cond.	primary load sharp edges, mod. dirty	primary load sharp edges fair cond.	Primary load sharp edges good cond.	dirty, sharp edges, prim. loading
Wheel dressing Used		2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"		2 - .002" 2 - .001"
Part condition after grind					slight burn, no chatter			

Figure 393

RUN #	33	34	35	36	37	38	39	40
Material	15 - 7MO	15 - 7MO	15 - 7 MO	15 - 7 MO	H - 11	H - 11	H - 11	H - 11
Type of Grind	Internal 3 Division	Internal 2 Division	Internal 1 Division	Internal Conventional	Internal conventional	Internal 2 Division	Internal 1 Division	Internal 3 Division
Wheel Used	AA60-I8V40	AA60-I8V40	AA60-I8V40	AA60-I8V40	AA60-I8V40	AA60-I8V40	AA 60-I8 V40	AA60-I8V40
Traverse Speed in./min.	13.5"	13.5"	13.5"	13.5"	13.5"	13.5"	13.5"	13.5"
SFPM of Wheel	4625	4625	4625	4625	4625	4625	4625	4625
Spindle R.P.M.	2850	2850	2850	2850	2850	2850	2850	2850
SFPM of Specimen	150 - 160	150 - 160	150 - 160	150 - 160	135 - 145	135 - 145	135 - 145	135 - 145
Number of Passes	57	57	57	57	57		57	57
Depth of Cut	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"
Coolant Used	Sultran176M	Sultran176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M
Volume of Work Removed	0.305in.	0.321 in.	0.299 in.	0.286 in.	0.304 in.	0.3135 in.	0.3275 in.	0.3077 in.
Relative Spindle Power	180	250	300	350	250	200	210	190
Grinding Ratio	38.3	120	82.2	49.9	128.2	165.8	347.5	109
Wheel diameter Before Grind	6.1213"	6.0855"	6.0915"	6.0780"	6.0390"	6.0185"	6.0000"	5.9856"
Wheel diameter After Grind	6.12063"	6.08494"	6.09074"	6.0768"	6.0385"	6.0181"	5.9998"	5.9850"
Part Dimensions	7.174" i.d	7.2200" i.d	7.205" i.d.	7.2623" i.d.	7.2780" i.d.	7.2310 i.d.	7.2885" i.d.	7.228" i.d.
Profilometer micro.in.(RMS)	33 - 35	33 - 35		30 - 32	33 - 35		36 - 38	35 - 36
Wheel condition after grind	clean, sharp edges, lt. primary	primary load. sharp edges fair cond.	primary load. sharp edges	primary load. sharp edges glazed	tertiary load. sharp edges, good cond.	tertiary load. sharp edges, good cond.	tertiary load sharp edges good cond.	sl. prim. load very clean
Wheel dressing Used	2 - .002" 2 - .001"		2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"
Part condition after grind	no burn lt. chatter	chatter	light chatter	heavy chatter very bad burn	chatter, edges burned	free of chatter	no chatter	

Figure 394

RUN #	41	42	43	44	45	46	47	48
Material	15 - 7 MO	15 - 7 MO	15 - 7 MO	15 - 7 MO	Rene 41	Rene 41	Rene 41	Rene 41
Type of Grind	Internal 3 Division	Internal 2 Division	Internal 1 Division	Internal Conventional	Internal Conventional	Internal 2 Division	Internal 1 Division	Internal 3 Division
Wheel Used	AA46-J8V40	AA46-J8V40	AA46-J8V40	AA60-J8V40	AA60-J8V40	AA60-J8V40	AA60-J8V40	AA46-J8V40
Traverse Speed in./min.	13.5	13.5	13.5	13.5	4	4	4	4
SFPM of Wheel	4625	4625	4625	4625	3960	3960	3960	3960
Spindle R.P.M.	2850	2850	2850	2850	2450	2450	2450	2450
SFPM of Specimen	150-160	150 - 160	150 - 160	150 - 160	50 - 55	50 - 55	50 - 55	50 - 55
Number of Passes	57	57	57	57	47	47		46
Depth of Cut	0.0005"	0.0005"	0.0005"	0.0005"	0.0006	0.0006"	0.0006"	0.0006"
Coolant Used	Sultran176M	Sultran176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M
Volume of Work Removed	0.294in.^{3}	0.305 in.^{3}	0.302 in.^{3}	0.276 in.^{3}	0.288 in.^{3}	0.284 in.^{3}	0.286 in.^{3}	0.311 in.^{3}
Relative Spindle Power	200	230	260	380	250	230	240	180
Grinding Ratio	60	66.4	46.2	117.3	13.0	25.5	16.4	15
Wheel diameter Before Grind	6.2484"	6.2240"	6.2153"	6.0235"	6.1289"	6.1625"	6.1810"	6.1119"
Wheel diameter After Grind	6.2474"	6.22322"	6.21396"	6.0230"	6.1243"	6.1602"	6.1774"i. d.	6.1076"
Part Dimensions	7.223"i.d.	7.323"i.d.	7.288"i.d.	7.3442"i. d.	7.1318"i.d.	7.0720"i.d.	7.1250"i.d.	7.1405"i.d.
Profilometer micro.in.(RMS)	36 - 38	35 - 37		27 - 28			30 - 32	
Wheel condition after grind	lt.prim.load clean,sh.ed	lt.prim.load very clean, sharp edges	sec.loading sharp edges	primary load. sharp edges	dirty	tertiary load. good cond. sharp edges	tertiary load good cond. sharp edges	lt.prim.load clean, sharp edges
Wheel dressing Used	2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"
Part condition after grind			very slight chatter and burn			slight chatter in center	slight chatter	light chatter no burn

Figure 395

RUN #	49	50	51	52	53	54	55	56
Material	Rene 41	Rene 41	Rene 41	Rene 41		H-11	H-11	H-11
Type of Grind	Internal 3 Division	Internal 2 Division	Internal 1 Division	Internal Conventional		Internal Conventional	Internal 2 Division	Internal 1 Division
Wheel Used	AA46-I8V40	AA46-I8V40	AA46-I8V40	AA46-I8V40		GA60-J8V40	GA60-J8V40	GA60-J8V40
Traverse Speed in./min.	4	4	4	4		13.5	13.5	13.5
SFPM of Wheel	3960	3960	3960	3960		4625	4625	4625
Spindle R.P.M.	2450	2450	2450	2450		2850	2850	2850
SFPM of Specimen	50 - 55	50 - 55	50 - 55	50 - 55		135 - 145	135 - 145	135 - 145
Number of Passes	46	47	57	50		57	100	100
Depth of Cut	0.0006"	0.0006"	0.0006"	0.0006"		0.0005"	0.0005"	0.0005"
Coolant Used	Sultran176M	Sultran176M	Sultran 176M	Sultran 176M		Sultran176M	Sultran 176M	Sultran 176M
Volume of Work Removed	0.280 in.^{3}	0.295 in.^{3}	0.377 in.^{3}	0.313 in.^{3}		0.318 in.^{3}	0.575 in.^{3}	0.583 in.^{3}
Relative Spindle Power	140	150	200	250		240	180	200
Grinding Ratio	9.9	10.9	13.3	11.2		92.8	209.7	597
Wheel diameter Before Grind	5.9710"	5.9455"	5.9300"	5.910"		6.2430"	6.2305"	6.2160"
Wheel diameter After Grind	5.965"	5.9397"	5.9239"	5.904"		6.2423"	6.22944"	6.2158"
Part Dimensions	7.1804" i.d	7.2070" i.d.	7.246" i. d.	7.215" i.d.		7.2946" i.d.	7.4180" i.d.	7.5250" i.d.
Profilometer micro. in. (RMS)	30		30	28		44		35
Wheel condition after grind	primary ld. sl. round ed dirty	tertiary load	sec. loading poor cond.	sec. loading metal bonded to wh. bd. cond		sharp edges, noloading good cond.	clean, sharp edges	clean, sharp edges
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"		2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind		very slight chatter		excessive chatter			finish fine free of burn	very slight chatter

RUN #	57	58	59	60	61			
Material	H - 11	15 - 7 MO	15 - 7 MO	15 - 7 MO	15 - 7 MO			
Type of Grind	Internal 3 Division	Internal Conventional	Internal 1 Division	Internal 2 Division	Internal 3 Division			
Wheel Used	GA60-J8V40	AA46-K8V40	AA46-K8V40	AA46-K8V40	AA46-K8V40			
Traverse Speed in./min.	13.5	13.5	13.5	13.5	13.5			
SFPM of Wheel	4540	4540	4540	4540	4540			
Spindle R.P.M.	2850	2850	2850	2850	2850			
SFPM of Specimen	135 - 145	150 - 160	150 - 160	150 - 160	150 - 160			
Number of Passes	202	57	57	57				
Depth of Cut	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"			
Coolant Used	Sultran176M	Sultran176M	Sultran 176M	Sultran 176M	Sultran 176 M			
Volume of Work Removed	1.1105in.^{3}	0.310 in.^{3}	0.298 in.^{3}	0.293 in.^{3}	0.328 in.^{3}			
Relative Spindle Power	250	310	290	260	250			
Grinding Ratio	285	67.1	67.5	55.9	79.9			
Wheel diameter Before Grind	6.2000"	6.1336"	6.1196"	6.1850"	6.094"			
Wheel diameter After Grind	6.1992"	6.13264"	6.11868"	6.18392"	6.09313"			
Part Dimensions	7.3550"id	7.4011"i.d	7.3338"i.d	7.4400"i.d	7.3945"i.d			
Profilometer micro.in.(RMS)	33	35	40	36-37	38-39			
Wheel condition after grind	clean, sharp edge	sharp edges, lt.prim.load.	slight primary sharp edges	light loading sharp edges	secondary loading			
Wheel dressing Used	2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"	2 - .002" 1 - .001"			
Part condition after grind		burned and chatter	very slight burn &chatter	light chatter	light chatter			

Figure 397

RUN #	62	63	64	65	66	67	68	69
Material	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
Type of Grind	Internal Conventional	Internal 1 Division	Internal 2 Division	Internal 3 Division	Internal 4 Division	Internal Conventional	Internal 1 Division	Internal 3 Division
Wheel Used	C60K4-VE	C60K4-VE	C60K4-VE	C60K4-VE	C60K4-VE	C60K4-VE	C60K4-VE	C60K4-VE
Traverse Speed in./min.	4	4	4	4	4	4	4	4
SFPM of Wheel	2870	2870	2870	2870	2870	2870	2870	2870
Spindle R.P.M.	1790	1790	1790	1790	1790	1790	1790	1790
SFPM of Specimen	38-40	38-40	38-40	38-40	38-40	38-40	38-40	38-40
Depth of Cut	0.001"	0.001"	0.001"	0.001"	0.001"	0.0005"	0.0005"	0.0005"
Number Passes	28		28	28	26	56	56	57
Coolant Used	Vantrol 5456M	Vantrol 5456M	Vantrol 5456 M	Vantrol 5456 M	Vantrol 5456 M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M
Volume of Work Removed	0.254in.^{3}	0.314in.^{3}	0.297 in.^{3}	0.293 in.^{3}	0.288 in.^{3}	0.278 in.^{3}	0.286 in.^{3}	0.308 in.^{3}
Relative Spindle Power	300	170	200	160	170	150	90	80
Grinding Ratio	5.95	32.5	56	55.4	35.3	32.3	300.4	327.
Wheel diameter Before Grind	6.1715"	6.1505"	6.1362"	6.1166"	6.0980"	6.0866"	6.0665"	6.0500"
Wheel diameter After Grind	6.1627"	6.1485"	6.1351"	6.1155"	6.0962"	6.0848"	6.0653"	6.0498"
Part Dimensions	7.0045"i.d.	6.990"i.d.	6.9843"i.d.	6.9840"i.d.	6.9835"i.d.	6.9885"i.d.	6.9825"i.d.	6.9850"i.d.
Profilometer micro. in. (RMS)	54	65	55	55	65	55	47	45
Wheel condition after grind	sharp edges primary load	sharp corner tert. loading	clean, sharp	sharp corners clean, no load	clear, clean, sharp	clean, slight load, rnd. cor.	no loading	round corners sec. loading
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	lt. burn, slt. chatter	lt. burning, slt. chatter	no chatter or burn		no chatter or burn	some chatter no burn	no burn or chatter, satin	no burn - satin finish

Figure 398

RUN #	70	71	72	73	74	75	76	77
Material	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
Type of Grind	Internal Conventional	Internal 3 Division	Internal Conventional	Internal 3 Division	Internal Conventional	Internal 3 Division	Internal Conventional	Internal 3 Division
Wheel Used	C60K4-VE	C60K4-VE	C60K4-VE	C60K4-VE	C60K4-VE	C60K4-VE	C60K4-VE	C60K4-VE
Traverse Speed in./min.	4	4	4	4	8	8	8	8
SFPM of Wheel	2870	2870	2870	2870	2870	2870	2870	2870
Spindle R.P.M.	1790	1790	1790	1790	1790	1790	1790	1790
SFPM of Specimen	38-40	38-40	38-40	38-40	38-40	38-40	38-40	38-40
Depth of Cut	0.0015"	0.0015"	0.002"	0.002"	0.0005"	0.0005"	0.001"	0.001"
Number Passes	19		14	16	56	57	57	57
Coolant Used	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456 M	Vantrol 5456 M	Vantrol 5456M
Volume of Work Removed	0.264in.^{3}	0.287 in.^{3}	0.238 in.^{3}	0.262 in.^{3}	0.278 in.^{3}	0.311 in.^{3}	0.224 in.^{3}	0.266 in.^{3}
Relative Spindle Power	400	200	460	340	300	150	400	200
Grinding Ratio	6.7	9.5	1.75	2.78	10.3	134.	3.6	7.23
Wheel diameter Before Grind	6.0400"	6.0220"	5.9948"	6.9379"	5.9198"	5.9010"	5.8910"	5.860"
Wheel diameter After Grind	6.0317"	6.0156"	5.9804"	6.9209"	5.9140"	5.9005"	5.8775"	5.852"
Part Dimensions	5.9930"i.d	7.0000"i.d.	6.9854" i.d.	7.0400"i.d.	7.045" i.d.	7.048" i.d.	7.0505"i.d	7.036"i.d.
Profilometer micro.in.(RMS)	80	90			70	45	100	80
Wheel condition after grind	round corn. sec.loading	sharp corners slt.loading	clean, primary loading	rounded, primary loading	secondary loading	sharp corners no loading	sec. loading broken corn.	tert. loading sharp corn.
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	slt.burn & chatter	very slt. burn & chatter	burned & chattered			burned & chattered	burn & chatter	slt. burn & chatter

Figure 399

RUN #	78	79	80	81	82	83	84	85
Material	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
Type of Grind	Internal Conventional	Internal 1 Division	Internal 2 Division	Internal 3 Division	Internal Conventional	Internal 1 Division	Internal 2 Division	Internal 3 Division
Wheel Used	AA46K8-V40	AA46K8-V40	AA46K8-V40	AA46K8-V40	AA46K8-V40	AA46K8-V40	AA46K8-V40	AA46K8-V40
Traverse Speed in./min.	4	4	4	4	4	4	4	4
SFPM of Wheel	2870	3870	2870	2870	2870	2870	2870	2870
Spindle R.P.M.	1790	1790	1790	1790	1790	1790	1790	1790
SFPM of Specimen	38-40	38-40	38-40	38-40	38-40	38-40	38-40	38-40
Depth of Cut	0.0005"	0.0005"	0.0005"	0.0005"	0.001"	0.001"	0.001"	0.001"
Number Passes	56	56	56	56	29	29	29	29
Coolant Used	Vantrol 5456M	Vantrol 5456 M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M
Volume of Work Removed	0.256 in.^{3}	0.265 in.^{3}	0.278 in.^{3}	0.272 in.^{3}	0.221 in.^{3}	0.221 in.^{3}	0.257 in.^{3}	0.274 in.^{3}
Relative Spindle Power	200	260	250	225	400	350	300	330
Grinding Ratio	3.4	7.07	11.47	13.3	3.18	5.0	7.67	9.6
Wheel diameter Before Grind	5.9947"	5.9678 "	5.9480"	5.933 "	5.9130"	5.8835"	5.8610"	5.8372 "
Wheel diameter After Grind	5.9787"	5.9597"	5.9427"	5.9286"	5.8980"	5.8739"	5.8537"	5.8310 "
Part Dimensions	7.0480"i.d	7.0370"i.d.	7.0400"i.d.	7.0460"i.d.	7.1960"i.d.	7.0360"i.d.	7.1075"i.d.	7.0830"i.d.
Profilometer micro.in.(RMS)	27	23	23	28	30	35	27	30
Wheel condition after grind	severe prim. load	prim. load. slight round.	sec. loading sharp corners	tertiary load. sharp corners	primary load. dull corners	sec. loading sharp corners	secondary loading	primary load round
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	burned & chattered	burned & chattered	chatter marks & burning	very little chatter	heavy chatter & burning	chattered & slt. burned	chattered & burned	burned & chattered

Figure 400

RUN #	86	87	88	89	90	91	90-A	94
Material	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
Type of Grind	Internal Conventional	Internal 3 Division	Internal 3 Division	Internal Conventional	Internal Conventional	Internal Conventional	Internal Conventional	Internal Conventional
Wheel Used	AA46K8-V40	AA46K8-V40	C60 K4-VE	C60K4-VE	C60K4-VE	C60K4-VE	C60K4-VE	C60P5-VE
Traverse Speed in./min.	1	1	1	1	2	3	4	2
SFPM of Wheel	2870	2870	2870	2870	2870	2870	2870	2870
Spindle R.P.M.	1790	1790	1790	1790	1790	1790	1790	1790
SFPM of Specimen	38-40	38-40	38-40	38-40	38-40	38-40	38-40	38-40
Depth of Cut	0.001"	0.001"	0.001"	0.001"	0.001"	0.001"	0.001"	0.001"
Number passes	28	28	28	28	28	28	28	28
Coolant Used	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M
Volume of Work Removed	$0.223 in.^3$	$0.269 in.^3$	$0.297 in.^3$	$0.315 in.^3$	$0.323 in.^3$	$0.305 in.^3$	$0.277 in.^3$	$0.279 in.^3$
Relative Spindle Power	175	125	80	100	80	240	450	280
Grinding Ratio	3.3	15.5	107.9	87.4	47.8	21.9	6.87	17.2
Wheel diameter Before Grind	5.8217"	5.7905"	5.8365"	5.7486"	5.7432"	5.7220 "	5.8238 "	6.2736 "
Wheel diameter After Grind	5.8068"	5.7866"	5.8359"	5.7478"	5.7417"	5.7189"	5.8150 "	6.2703 "
Part Dimensions	7.085"i.d.	7.1005"i.d.	7.0986"i.d.	7.1526"i.d.	7.1605"i.d.	7.1550"i.d.	7.162"i.d.	7.0200"i.d.
Profilometer micro.in.(RMS)	28	18	37	40	40	50	62	30
Wheel condition after grind	dirty, prim. load	tert. load. sharp corners	sharp corners clean	sharp corners no loading	minor primary loading	no loading	secondary load.sh.cor.	some primary load, rounded
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	terrible		no burn or chatter	no burn or chatter	no burn or chatter	no burn or chatter	burn & heavy scratching	burn & lt. chatter

Figure 401

RUN #	119	99	121	96	100	100-A	101	106
Material	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
Type of Grind	Internal 3 Division	Internal 3 Division	Internal 3 Division	Internal 3 Division	Internal 3 Division	Internal 3 Division	Internal 3 Division	Maximum Gen.Output
Wheel Used	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	A60R6-V10
Traverse Speed in./min.	2	3	3	4	4	4	3	4
SFPM of Wheel	2870	2870	2870	2870	2870	2870	2870	2870
Spindle R.P.M.	1790	1790	1790	1790	1790	1790	1790	1790
SFPM of Specimen	38-40	38-40	38-40	38-40	38-40	38-40	38-40	38-40
Depth of Cut	0.001"	0.001"	0.001"	0.001"	0.0015"	0.0015"	0.001"	0.001"
Number Passes	28	28	28	28	19	19	28	28
Coolant Used	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M
Volume of Work Removed	0.326in.	0.304 in.	0.319 in.	0.305 in.	0.276 in.	0.292 in.	0.313 in.	
Relative Spindle Power	100	160	141	320	470	400	140	310
Grinding Ratio	190.9	41.0	259.8	49.2	7.74	15.3	140.0	
Wheel diameter Before Grind	6.0420"	6.2245"	6.0115"	6.2536"	6.2108"	6.1699"	6.1498"	6.220"
Wheel diameter After Grind	6.04164"	6.22374"	6.01124"	6.25234"	6.20354"	6.15594"	6.14936"	
Part Dimensions	7.3060"i.d	7.1470"i.d.	7.2753"i.d.	7.1530"i.d.	7.2170"i.d.	7.1285"i.d.	7.2565"i.d.	7.2731"i.d
Profilometer micro.in.(RMS)	27	47	38	42		45	45	
Wheel condition after grind	no loading	no loading	no loading		rounded	very slight loading	no loading	
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	satin finish	satin finish	no burning satin finish	no burn or chatter	burned and chattered	burned	satin finish	

Figure 402

RUN #	104-A	104-B	102	123	122	125	126	127-B
Material	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
Type of Grind	Internal 3 Division	Internal 3 Division	Internal 3 Division	Internal 3 Division	Internal 3 Division	Internal 3 Division	Internal 3 Division	Internal 3 Division
Wheel Used	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE
Traverse Speed in./min.	3	3	3	3	3	3	3	3
SFPM of Wheel	2870	2870	2870	2870	2870	2870	2870	2870
Spindle R.P.M.	1790	1790	1790	1790	1790	1790	1790	1790
SFPM of Specimen	38-40	38-40	38-40	38-40	38-40	38-40	38-40	38-40
Depth of Cut	0.0015"	0.0015"	0.0015"	0.0015"	0.0015"	0.0015"	0.0015"	0.0015"
Number Passes				19	19	19	19	19
Coolant Used	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M
Volume of Work Removed	0.244 in.^{3}	0.319 in.^{3}	0.315 in.^{3}	0.294 in.^{3}	0.266 in.^{3}	0.340 in.^{3}	0.308 in.^{3}	0.291 in.^{3}
Relative Spindle Power	280	240	250	200	200	200	200	180
Grinding Ratio	29.9	74.1	217.6	22.9	10.4	61.7	110.1	24.9
Wheel diameter Before Grind	6.1055"	6.0830"	6.1408"	5.9726"	5.9999"	5.9602"	5.9408"	5.8981"
Wheel diameter After Grind	6.1038"	6.0821"	6.1405"	5.96986"	5.99446"	5.95902"	5.9402"	5.88558"
Part Dimensions	7.2619"i.d	7.2190"i.d.	7.2625"i.d.	7.3139"i.d.	7.313" i.d.	7.3240"i.d.	7.3239"i.d	7.3730"i.d.
Profilometer micro.in.(RMS)	40	45	52					
Wheel condition after grind			no loading	sharp no loading	rounded, no loading		no loading	rounded, no loading
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	burned & light chatt	slight burn	slight burn			satin finish	satin finish	

Figure 403

RUN #	107	108	109	110	111	112	113	115
Material	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4v
Type of Grind	Internal 3 Division	Internal 3 Division	Internal 3 Division	Internal 3 Division	Internal Conventional	Internal Conventional	Internal Conventional	Internal 3 Division
Wheel Used	A60J6-V10	A60J6-V10	A60J6-V10	A60J6-V10	A60J6-V10	A60J6-V10	A60J6-V10	C60P5-VE
Traverse Speed in./min.	4	1	2	3	1	2	3	4
SFPM of Wheel	2870	2870	2870	2870	2870	2870	2870	2870
Spindle R.P.M.	1790	1790	1790	1790	1790	1790	1790	1790
SFPM of Specimen	38-40	38-40	38-40	38-40	38-40	38-40	38-40	38-40
Depth of Cut	0.001"	0.001"	0.001"	0.001"	0.001"	0.001"	0.001"	0.001"
Number Passes	28	28	28	28	28		28	28
Coolant Used	Vantrol 5456 M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M
Volume of Work Removed		0.320in.^{3}	0.252in.^{3}	0.255 in.^{3}	0.227 in.^{3}	0.215 in.^{3}	0.220 in.^{3}	0.303 in.^{3}
Relative Spindle Power	310	100	290	300	200	250	270	200
Grinding Ratio	63	42	15.7	9.0	7.07	7.6	8.02	58.1
Wheel diameter Before Grind	6.2448"	6.2155"	6.2050"	6.1868"	6.1557"	6.1394"	6.1091"	6.0475"
Wheel diameter After Grind		6.21394"	6.2017"	6.1810"	6.14906"	6.1335"	6.10338"	6.0464"
Part Dimensions	7.2005"i.d	7.2568"i.d.	7.2060"i.d.	7.2116"i.d.	7.1975"i.d.	7.3081"i.d.	7.2748"i.d.	7.2615"i.d.
Profilometer micro.in.(RMS)		18	18	23		—		40
Wheel condition after grind	loaded	tertiary loading	secondary loading	primary loading	primary loading	square, severe primary load.		no loading
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	burn & chatter	light burn & chatter	chatter & burn	heavy burn & Chatter	heavy burn & chatter	burn & chatter	burn & chatter	very light burn

Figure 404

RUN #	120	132	131	92	95	97	118	98
Material	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
Type of Grind	Internal Conventional	Internal Conventional	Internal Conventional	Internal Conventional	Internal Conventional	Internal 3 Division	Internal 3 Division	Internal 3 Division
Wheel Used	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5 -VE	C60P5-VE	C60P5-VE
Traverse Speed in./min.	2	2	4	3	4	1	1	2
SFPM of Wheel	2870	2870	2870	2870	2870	2870	2870	2870
Spindle R.P.M.	1790	1790	1790	1790	1790	1790	1790	1790
SFPM of Specimen	38-40	38-40	38-40	38-40	38-40	38-40	38-40	38-40
Depth of Cut	0.001"	0.001"	0.001"	0.001"	0.001"	0.001"	0.001"	0.001"
Number Passes	28	28	28	28	28	28	28	28
Coolant Used	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M
Volume of Work Removed	0.297 $in.^3$	0.287 $in.^3$	0.240 $in.^3$	0.259 $in.^3$	0.268 $in.^3$	0.304 $in.^3$	0.316 $in.^3$	0.320 $in.^3$
Relative Spindle Power	264	240	300	240	460	280	50	140
Grinding Ratio	19.05	19.04	13.04	11.9	10.7	309.8	73.9	217.6
Wheel diameter Before Grind	6.0290"	5.8267"	5.8497"	6.29750"	6.2643"	6.2466"	6.0540"	6.2369"
Wheel diameter After Grind	6.0257"	5.8234"	5.8457"	6.2931"	6.2592"	6.2464"	6.0531"	6.2366"
Part Dimensions	7.2622"i.d	7.3842"i.d.	7.4177"i.d.	7.1500"i.d.	7.1480"i.d.	7.1410"i.d.	7.3163"i. d.	7.2164"i.d.
Profilometer micro. in. (RMS)	38	35	47	38	40	40	30	38
Wheel condition after grind	tertiary loading	secondary loading	primary loading	tertiary loading	primary loading	no loading		no loading
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	scratchy, light burn	burned & scratched	burned	slt. burning	some burn & chatter	no chatter or burn		satin finish

Figure 405

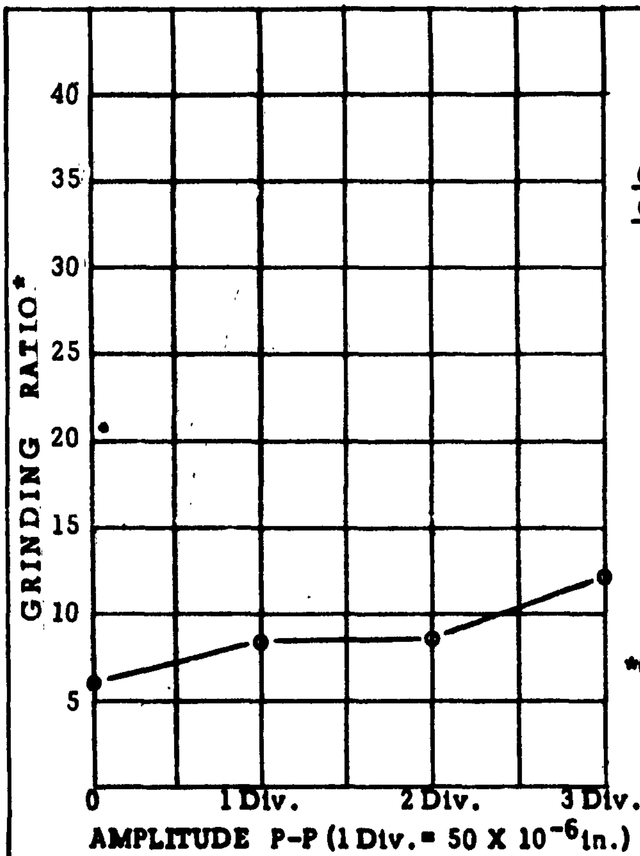
RUN #	127-A	93	103-A	103-B	114	117	130	116
Material	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
Type of Grind	Internal 3 Division	Internal Conventional	Internal Conventional	Internal Conventional	Internal Conventional	Internal Conventional	Internal Conventional	Internal 3 Division
Wheel Used	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE	C60P5-VE
Traverse Speed in./min.	3	3	1	1	1	1	1	3
SFPM of Wheel	2870	2870	2870	2870	2870	2870	2870	2870
Spindle R.P.M.	1790	1790	1790	1790	1790	1790	1790	1790
SFPM of Specimen	38-40	38-40	38-40	38-40	38-40	38-40	38-40	38-40
Depth of Cut	0.001"	0.001"	0.001"	0.001"	0.001"	0.001"	0.001"	0.001"
Number Passes	28	57	56	56	28	28	28	19
Coolant Used	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456 M
Volume of Work Removed	0.311 in.^{3}	0.299 in.^{3}	0.311 in.^{3}	0.304 in.^{3}	0.320 in.^{3}	0.312 in.^{3}	0.320 in.^{3}	0.318 in.^{3}
Relative Spindle Power	180	180	170	150	300	400	150	180
Grinding Ratio	74.2	23.3	43.0	48.7	33.6	36.8	68.1	40.5
Wheel diameter Before Grind	5.9270 "	6.2865"	6.1310"	6.1203 "	6.0604 "	6.0675"	5.8673"	6.0292"
Wheel diameter After Grind	5.9261 "	6.2839"	6.1285	6.1190 "	6.058"	6.06572"	5.86628"	6.0275"
Part Dimensions	7.3583"i.d	7.1475"i. d.	7.2153" i.d.	7.2051" i.d.	7.3200"i.d.	7.2430"i.d.	7.3802" i.d	7.2562"i.d.
Profilometer micro.in.(RMS)		25-30	28	28	48	37-38	32	60
Wheel condition after grind	no loading	Tert. loading	no load.sharp		tertiary loading	tertiary loading	very little loading	no loading
Wheel dressing Used	2 - .002" 2 - .001"	2 -.002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	satin finish	no burning or chatter			light burning	light burning	burned scratched	light burning

Figure 406

RUN #	129	133						
Material	Ti-6Al-4V	Ti-6Al-4V						
Type of Grind	Internal 3 Division	Internal 3 Division						
Wheel Used	C60P5-VE2	C60P5-VE3						
Traverse Speed in./min.	3	3						
SFPM of Wheel	2870	2870						
Spindle R.P.M.	1790	1790						
SFPM of Specimen	38-40	38-40						
Depth of Cut	0.0015"	0.0015"						
Number Passes	19	18						
Coolant Used	Vantrol 5456 M	Vantrol 5456 M						
Volume of Work Removed	0.312 in.^{3}	0.309 in.^{3}						
Relative Spindle Power	200	220						
Grinding Ratio	71.9	54.9						
Wheel diameter Before Grind	5.8811 "	6.2900"						
Wheel diameter After Grind	5.88016"	6.28886"						
Part Dimensions	7.3292"i.d.	7.3961"i.d.						
Profilometer micro.in. (RMS)		40						
Wheel condition after grind		no loading						
Wheel dressing Used	1 - .008" 2 - .002"	1 - .008" 2 - .002"						
Part condition after grind		light burn						

Figure 407

14.2 External Grinding Test Data



EXTERNAL GRINDING

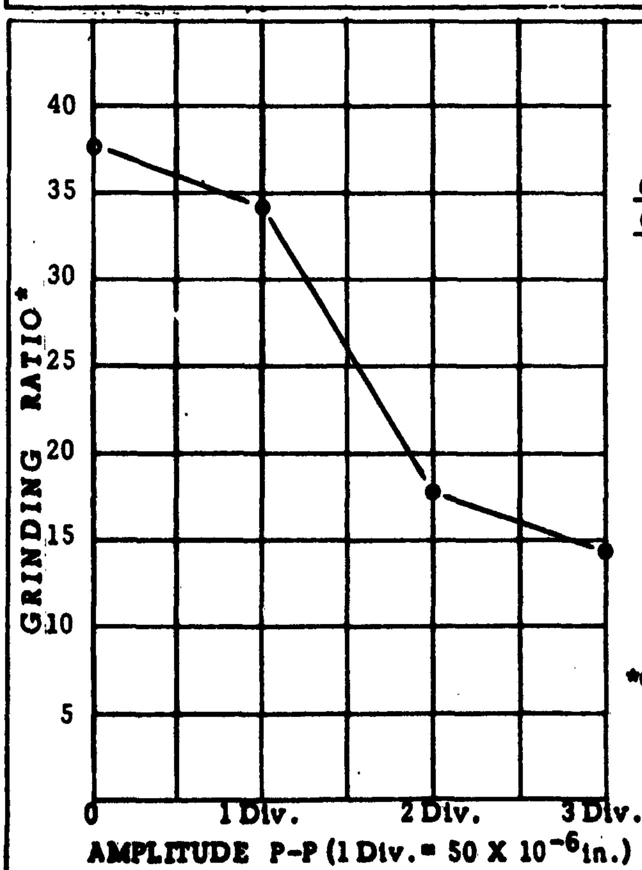
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	8 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 142, 143, 144, 145- III

Figure 408



EXTERNAL GRINDING

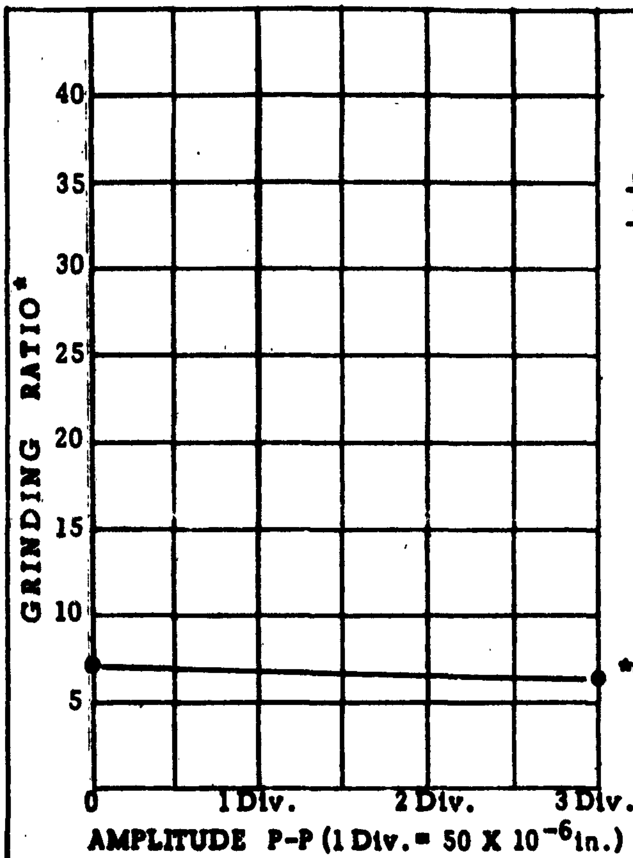
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	8 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 146, 147, 148, 149- III

Figure 409



EXTERNAL GRINDING

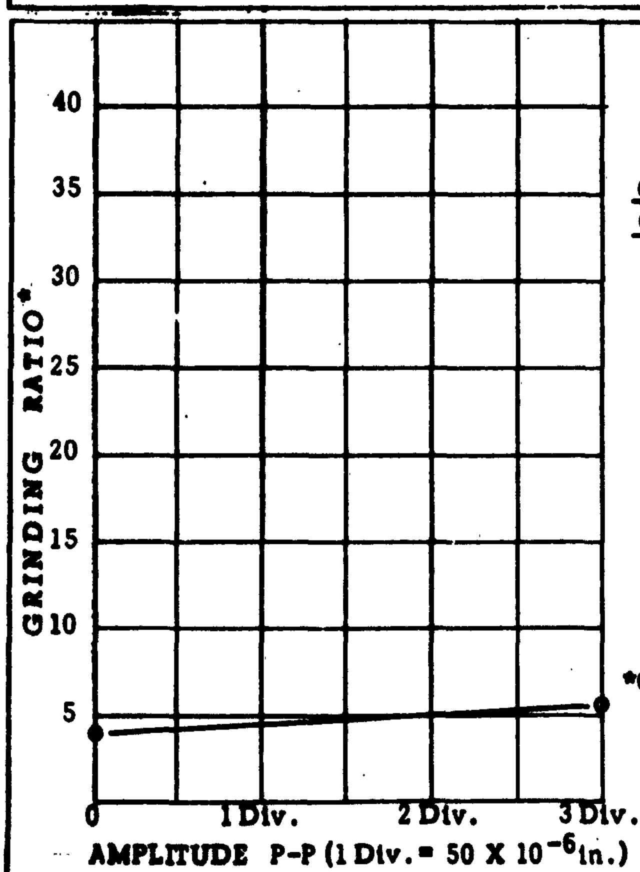
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	12 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.0005 in.
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 176, 177 - III

Figure 410



EXTERNAL GRINDING

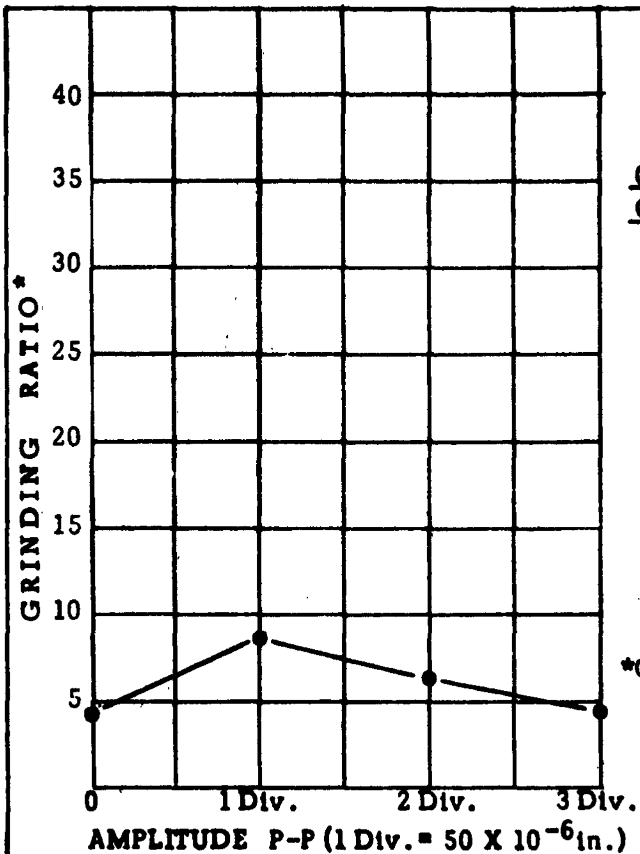
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	12 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 178, 179 - III

Figure 411



EXTERNAL GRINDING

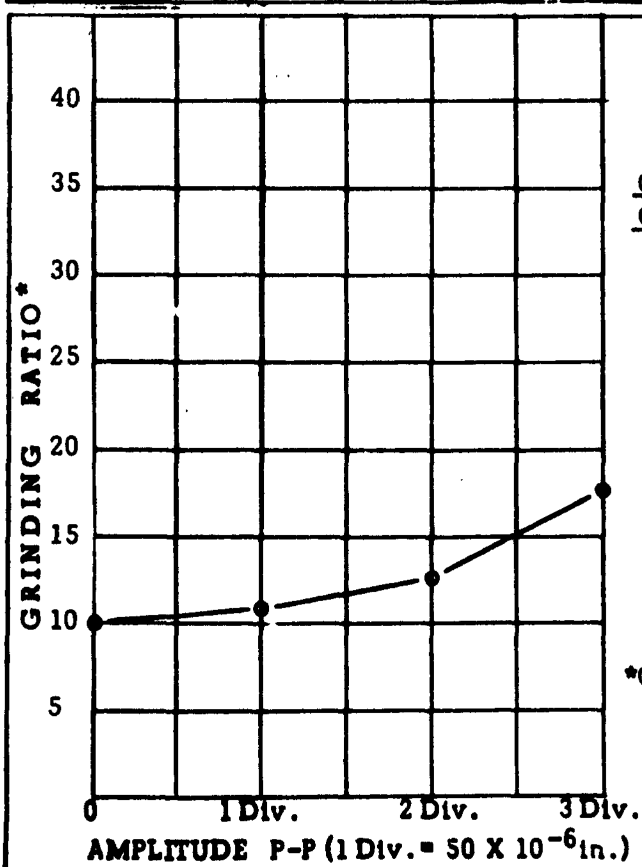
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	16 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 134, 135, 136, 137 - III

Figure 412



EXTERNAL GRINDING

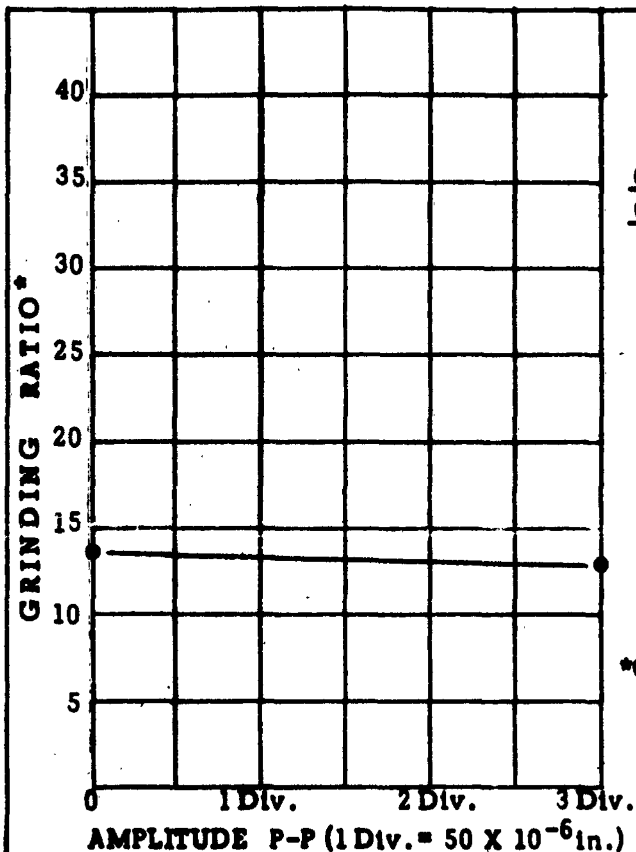
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	16 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 138, 139, 140, 141 - III

Figure 413



EXTERNAL GRINDING

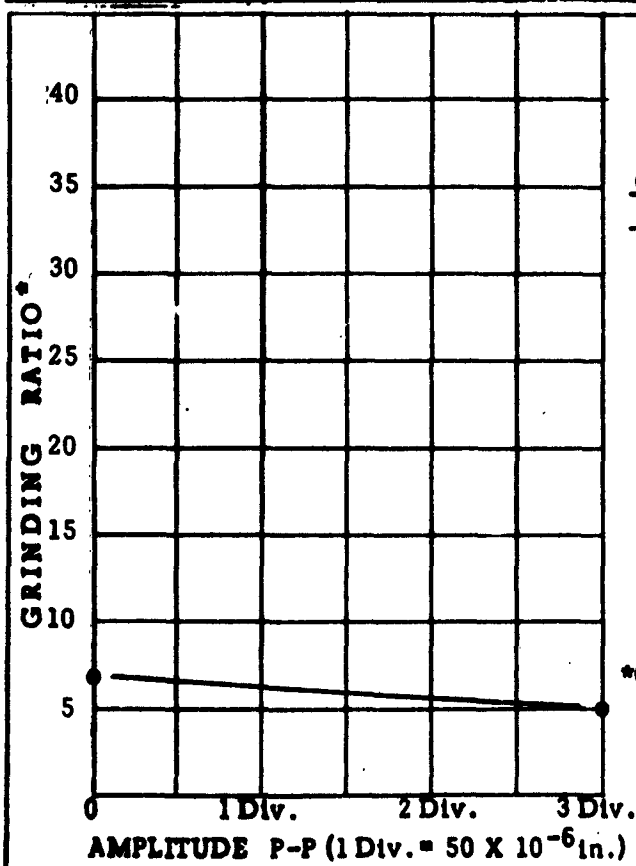
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60P6-V10
Wheel Speed	2060 - 2160
Traverse Feed	8 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 162, 163 - III

Figure 414



EXTERNAL GRINDING

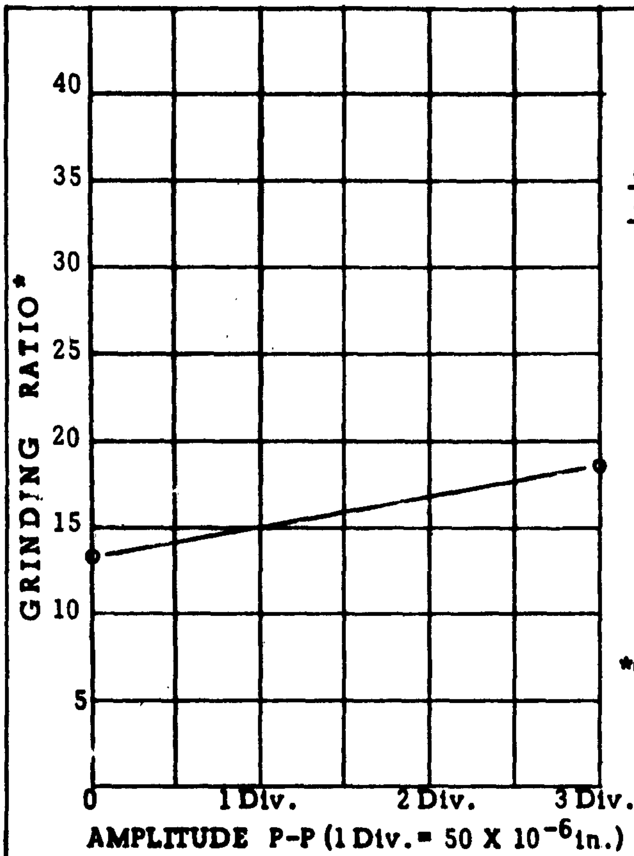
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60P6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	16 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 164, 165 - III

Figure 415



EXTERNAL GRINDING

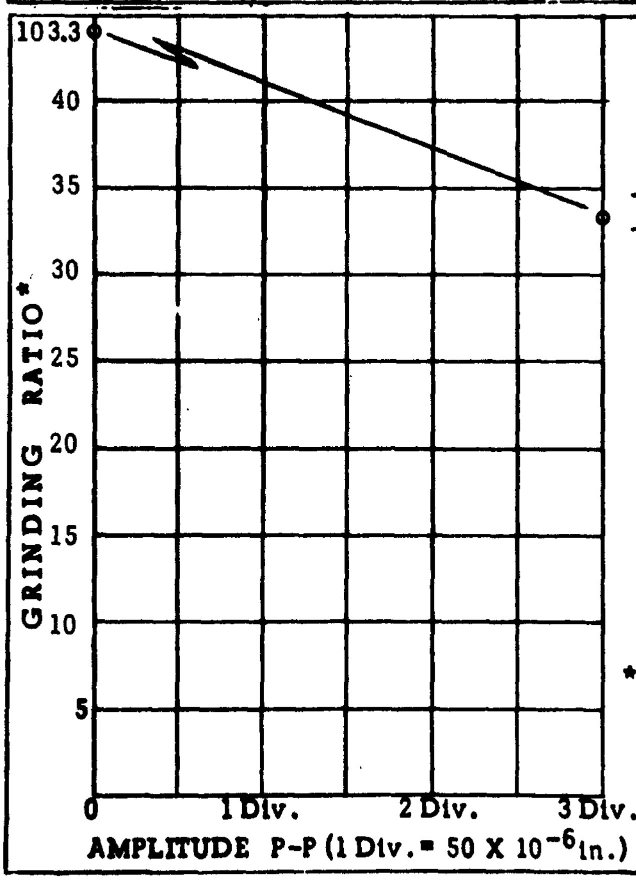
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	4 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 158, 159 - III

Figure 416



EXTERNAL GRINDING

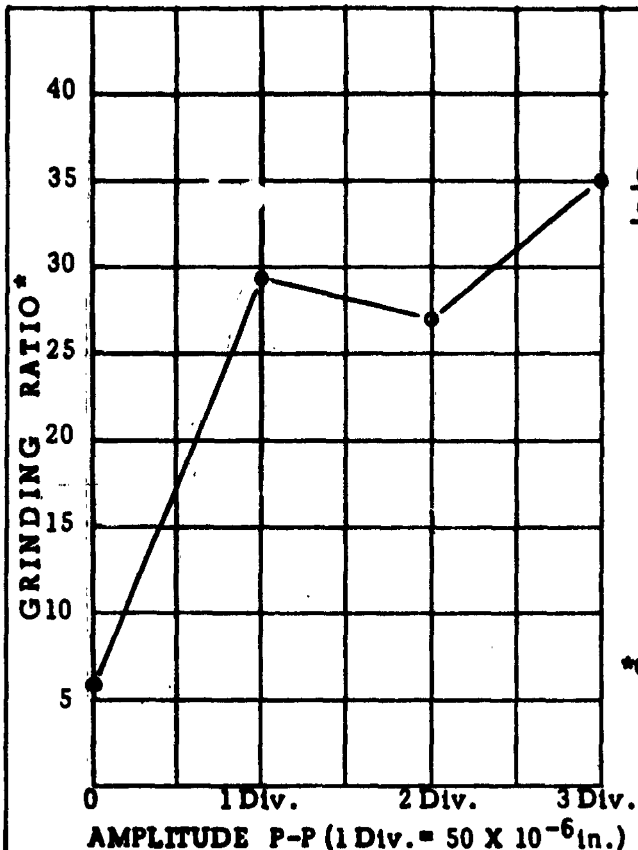
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed	2060 - 2160
Traverse Feed	4 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 160, 161 - III

Figure 417



EXTERNAL GRINDING

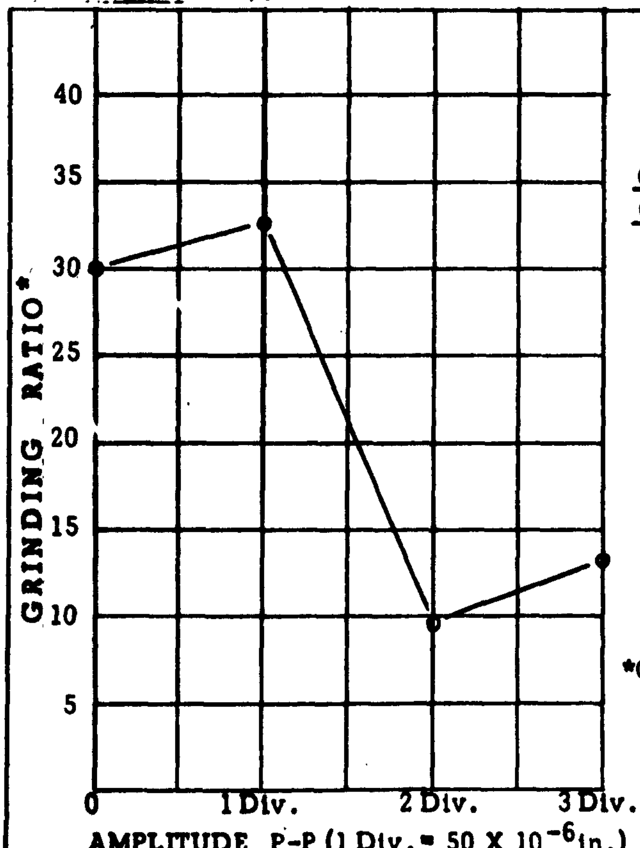
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed	2060 - 2160
Traverse Feed	8 in./min.
Workpiece SFPM	54 - 59
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 150, 153, 151, 152 - III

Figure 418



EXTERNAL GRINDING

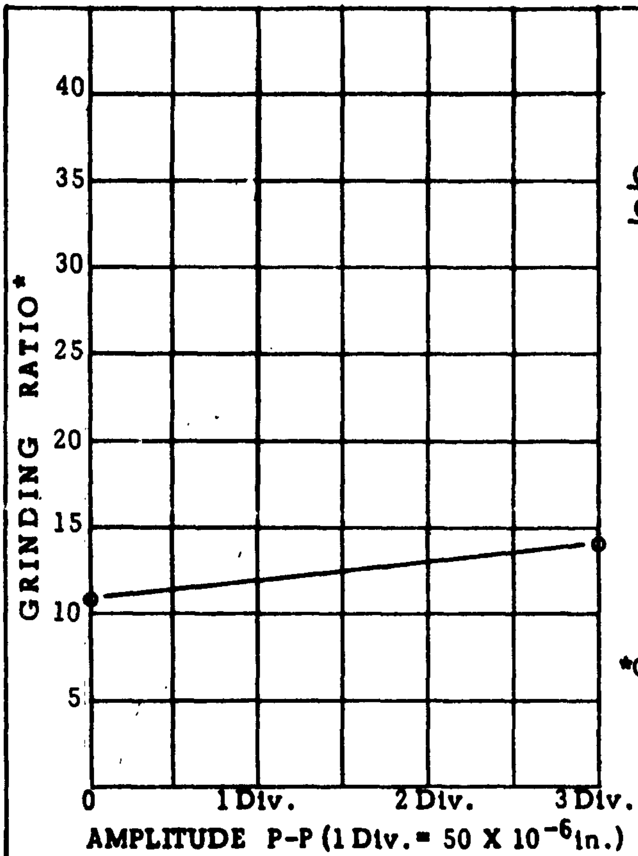
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	16 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 154, 155, 156, 157- III

Figure 419



EXTERNAL GRINDING

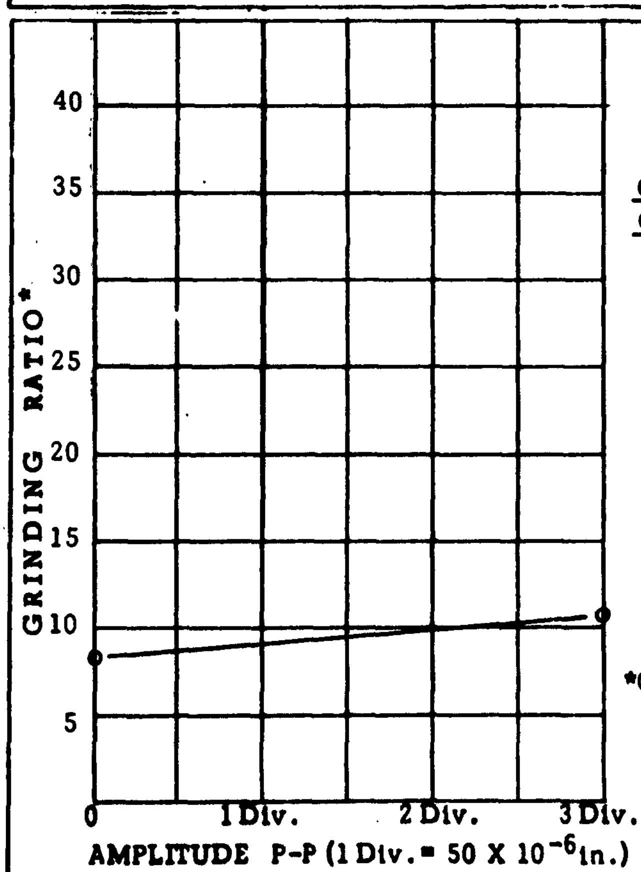
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	8 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.0005 in.
Coolant	Sultran 176M

$$*\text{GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 180, 181 - III

Figure 420



EXTERNAL GRINDING

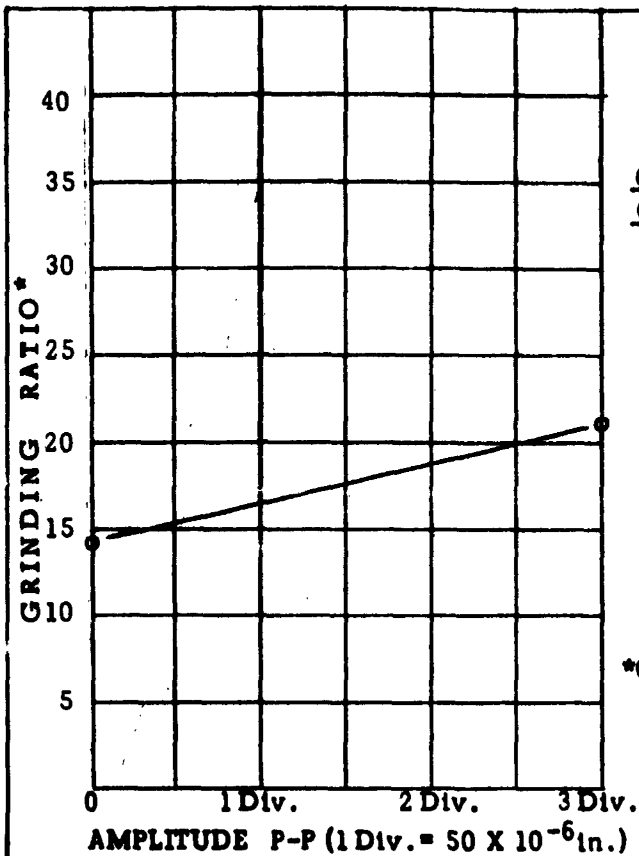
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	8 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

$$*\text{GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 182, 183 - III

Figure 421



EXTERNAL GRINDING

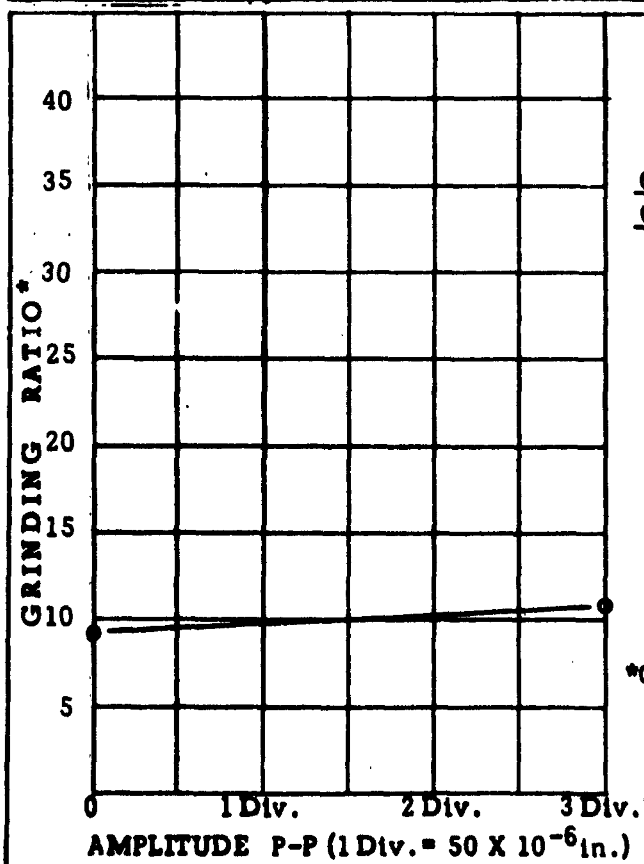
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	4 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.0005 in.
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 184, 185 - III

Figure 422



EXTERNAL GRINDING

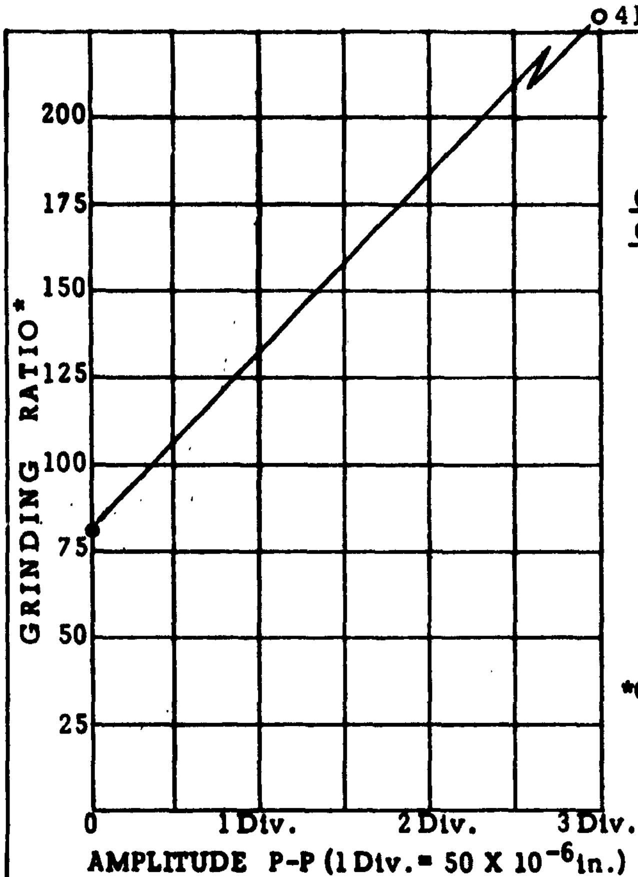
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	4 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 186, 187 - III

Figure 423



EXTERNAL GRINDING

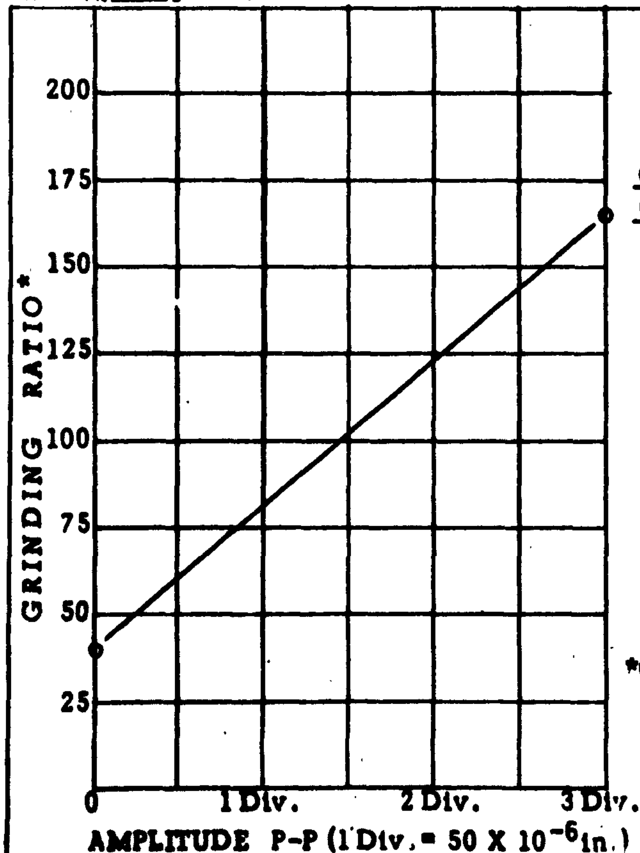
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60K6-V10
Wheel Speed SFPM	5362 to 5400
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: 188, 189 - III

Figure 424



EXTERNAL GRINDING

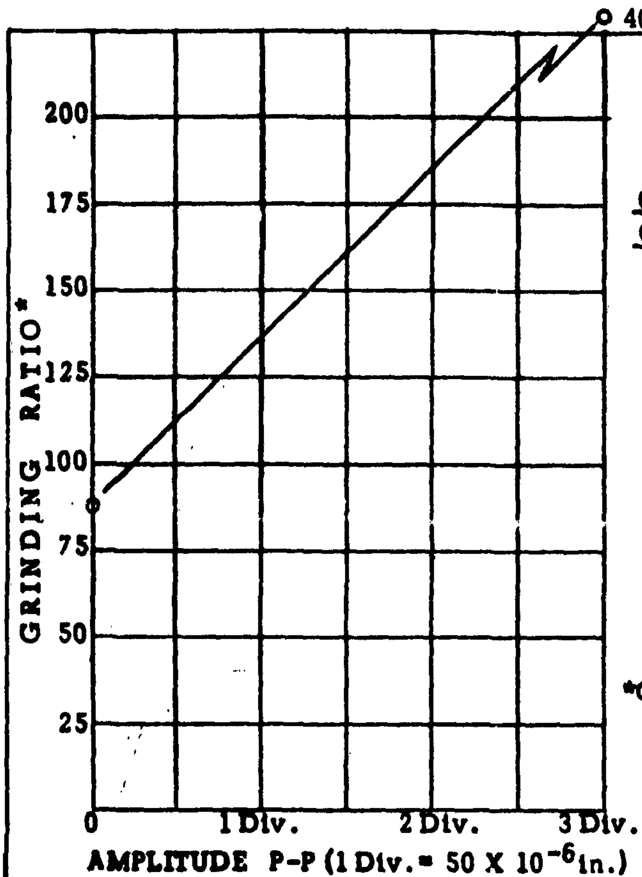
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60K6-V10
Wheel Speed SFPM	5362 to 5400
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: 190, 191 - III

Figure 425



EXTERNAL GRINDING

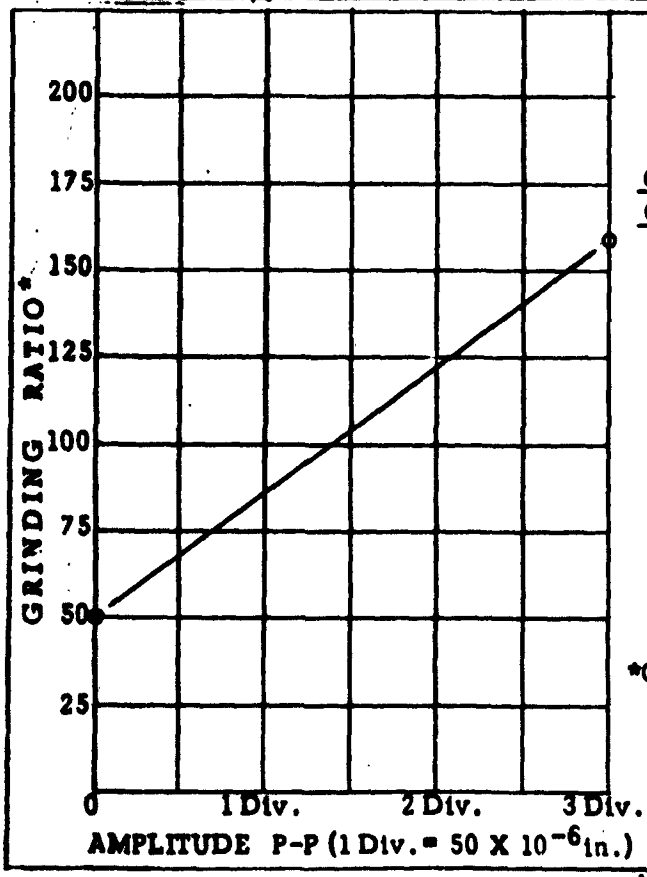
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60K6-V10
Wheel Speed SFPM	5362 to 5400
Traverse Feed	6 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 192, 193 - III

Figure 426



EXTERNAL GRINDING

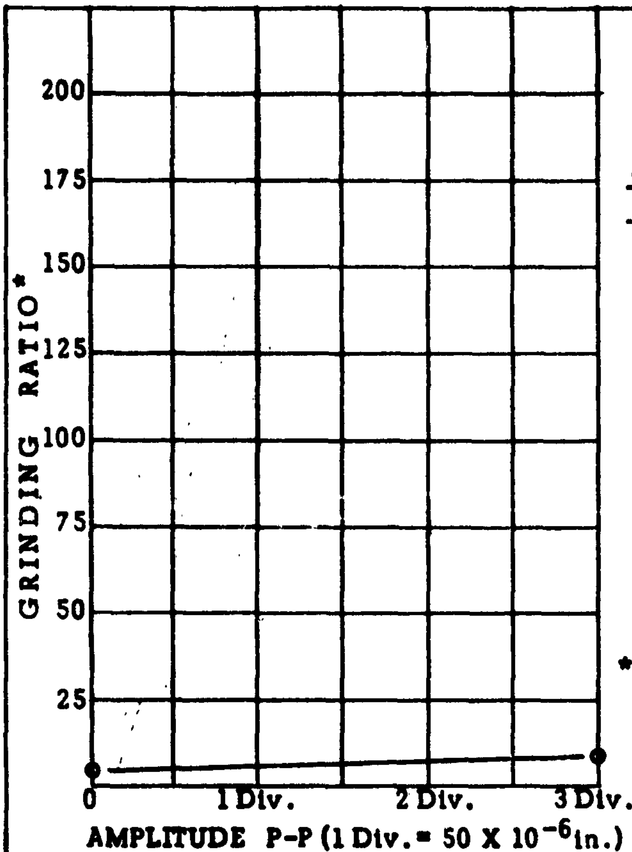
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	AA60I8-V40
Wheel Speed SFPM	5263 to 5346
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 195, 196 - III

Figure 427



EXTERNAL GRINDING

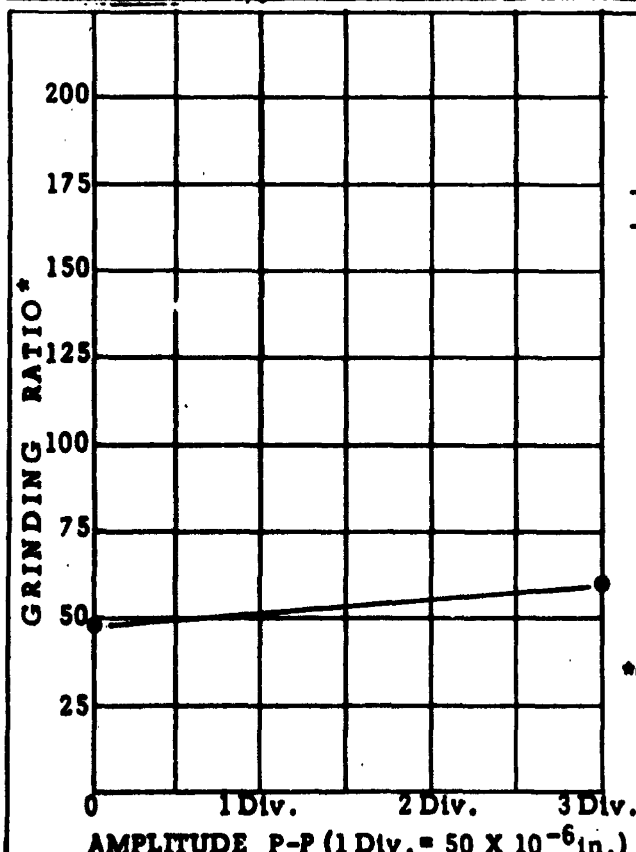
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	AA60I8-V40
Wheel Speed SFPM	5263 to 5346
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 197, 198 - III

Figure 428



EXTERNAL GRINDING

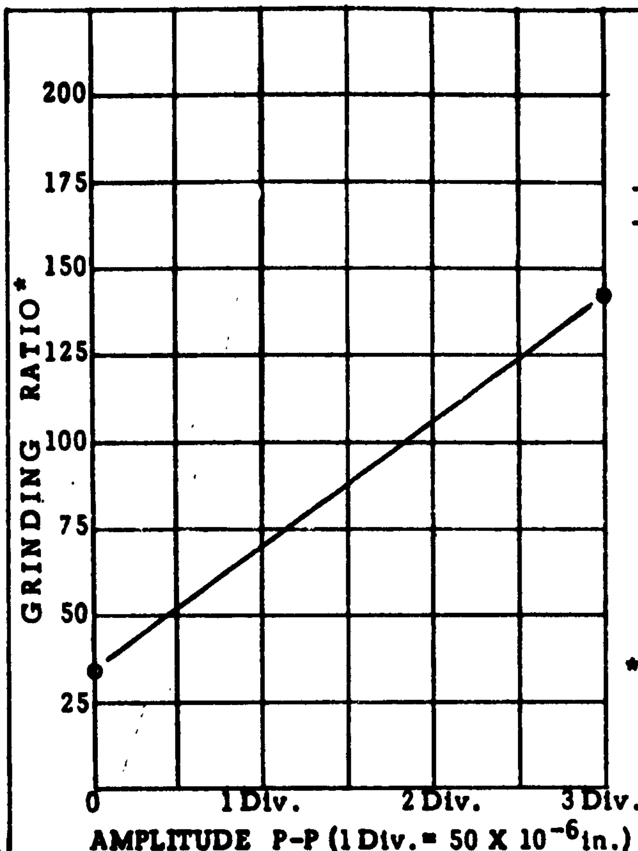
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	AA60I8-V40
Wheel Speed SFPM	5263 to 5346
Traverse Feed	6 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 199, 200 - III

Figure 429



EXTERNAL GRINDING

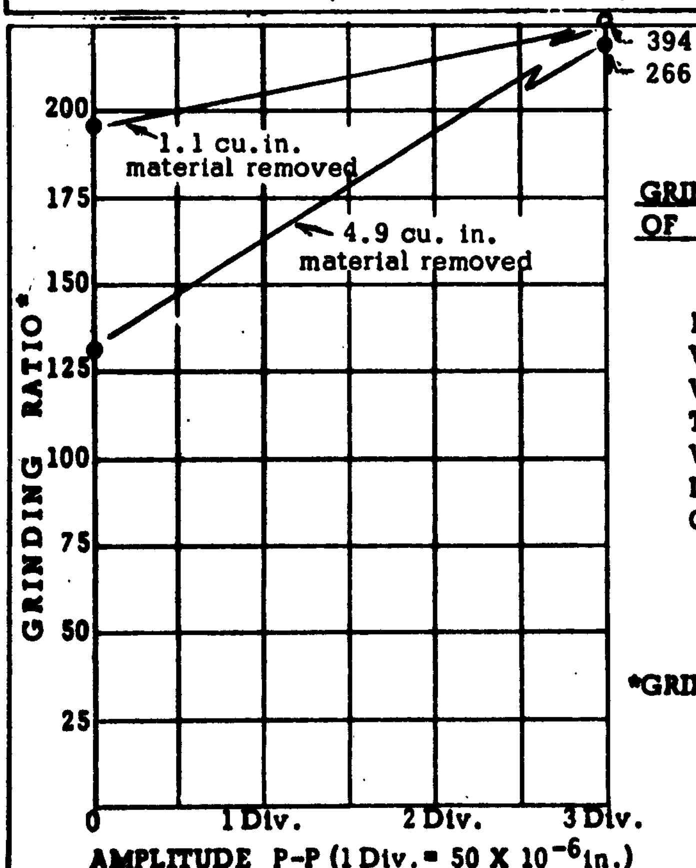
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	AA60I8-V40
Wheel Speed SFPM	5263 to 5346
Traverse Feed	4 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: III-201, 202

Figure 430



EXTERNAL GRINDING

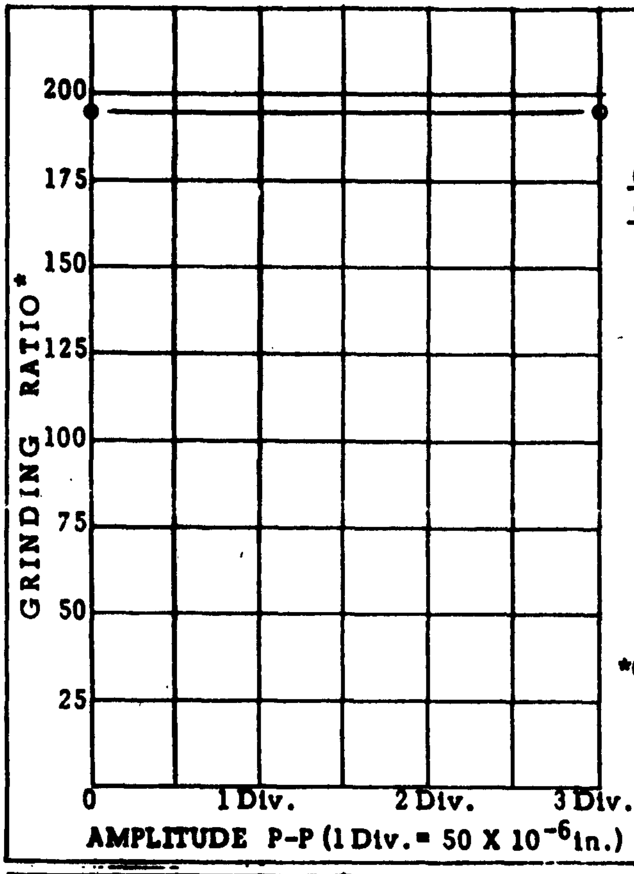
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60L6-V10
Wheel Speed SFPM	5332 to 5362
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

*GRINDING RATIO = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

Run Numbers: III-203, 204, 209, 210

Figure 431



EXTERNAL GRINDING

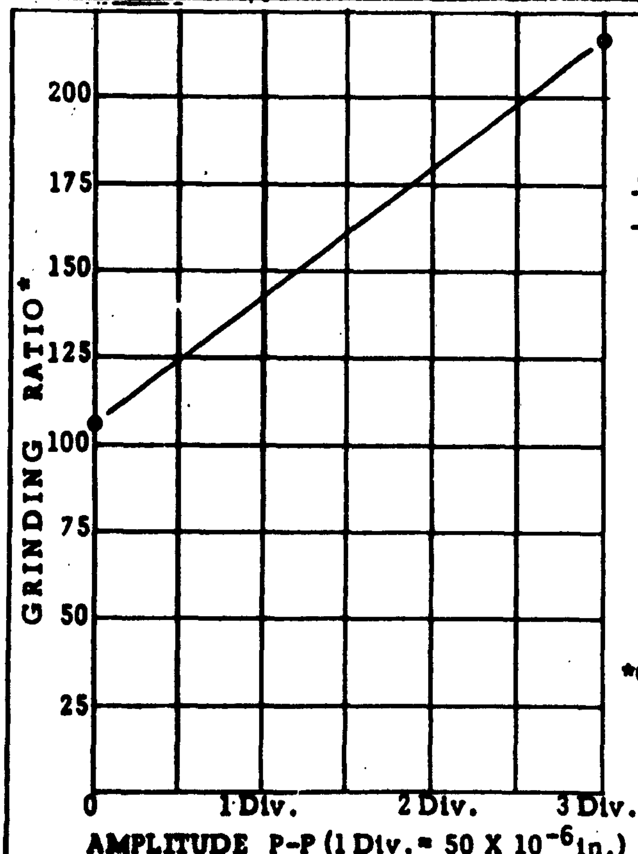
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60L6-V10
Wheel Speed	5332 to 5362
Traverse Feed	6 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: III - 205, 206

Figure 432



EXTERNAL GRINDING

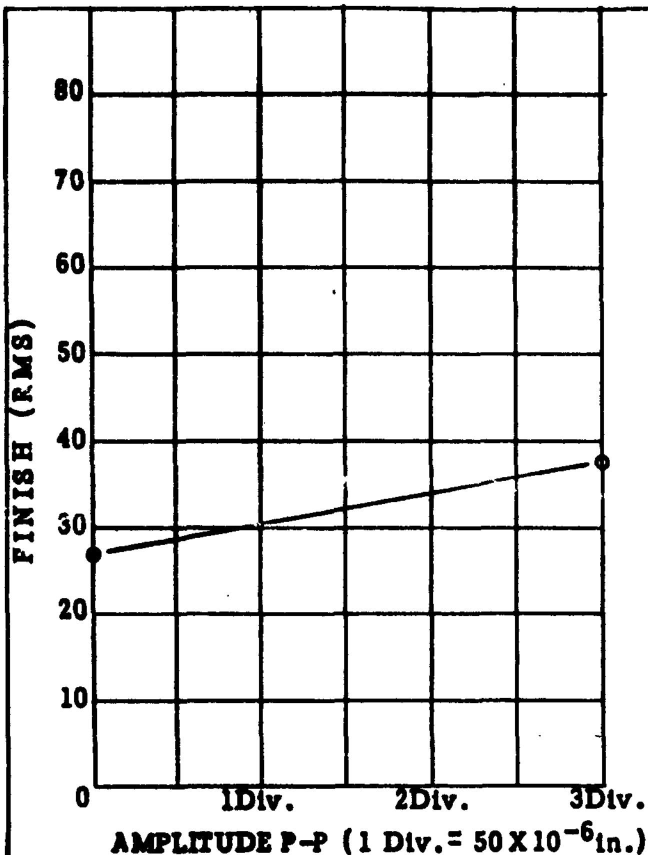
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60L6-V10
Wheel Speed SFPM	5332 to 5362
Traverse Feed	4 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 207, 208 - III

Figure 433



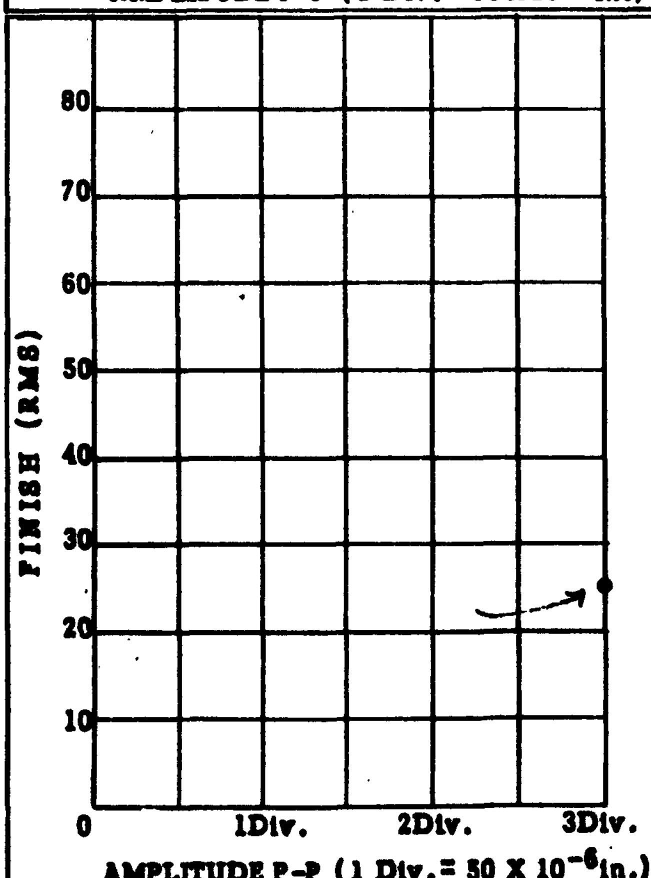
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	4 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

Run Numbers: 158, 159 - III

Figure 434



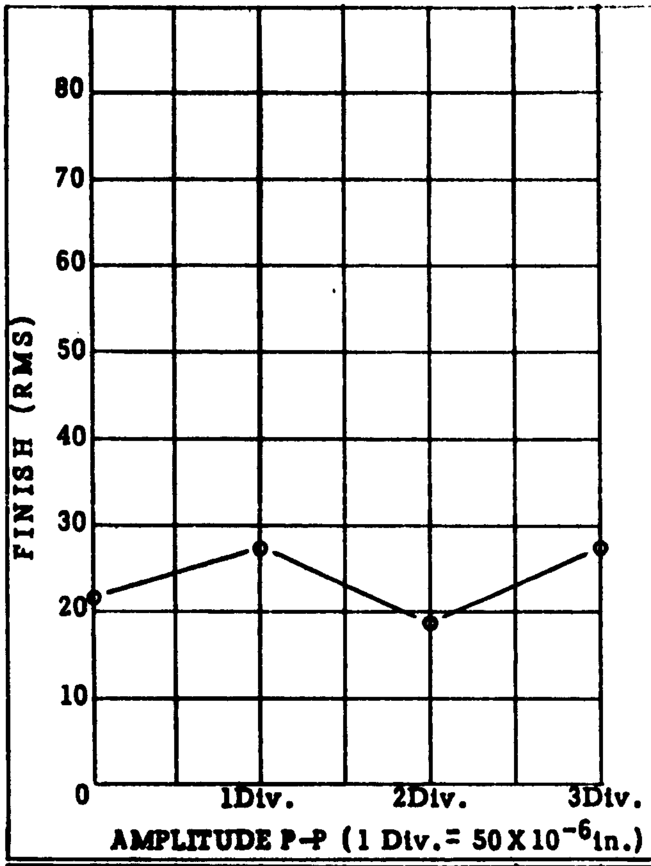
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	4 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

Run Number: 161 - III

Figure 435



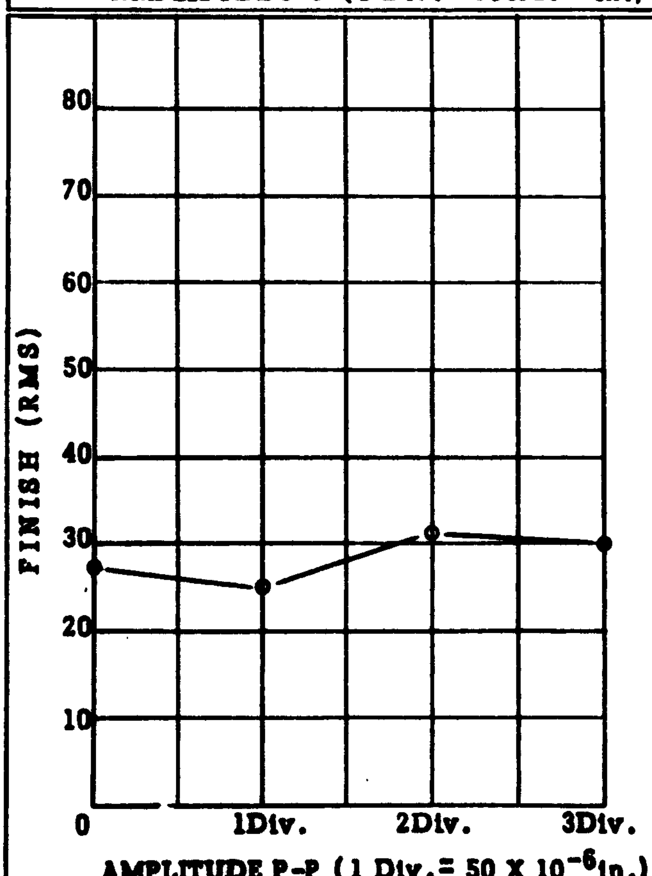
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	8 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

Run Numbers: 150, 153, 151, 152 - III

Figure 436



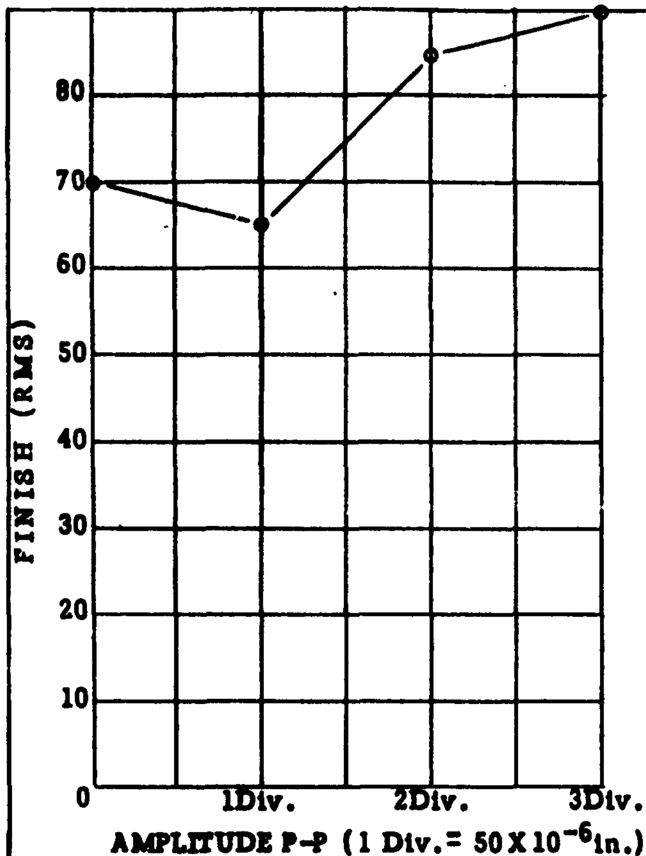
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	16 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

Run Numbers: 154, 155, 156, 157-III

Figure 437



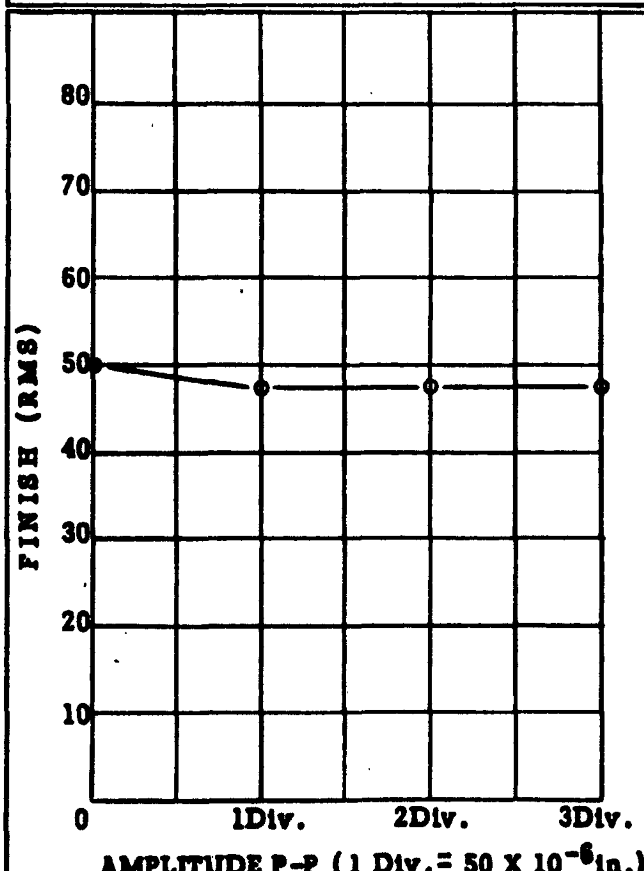
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	T16Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	16 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

Run Numbers: 134, 135, 136, 137 -III

Figure 438



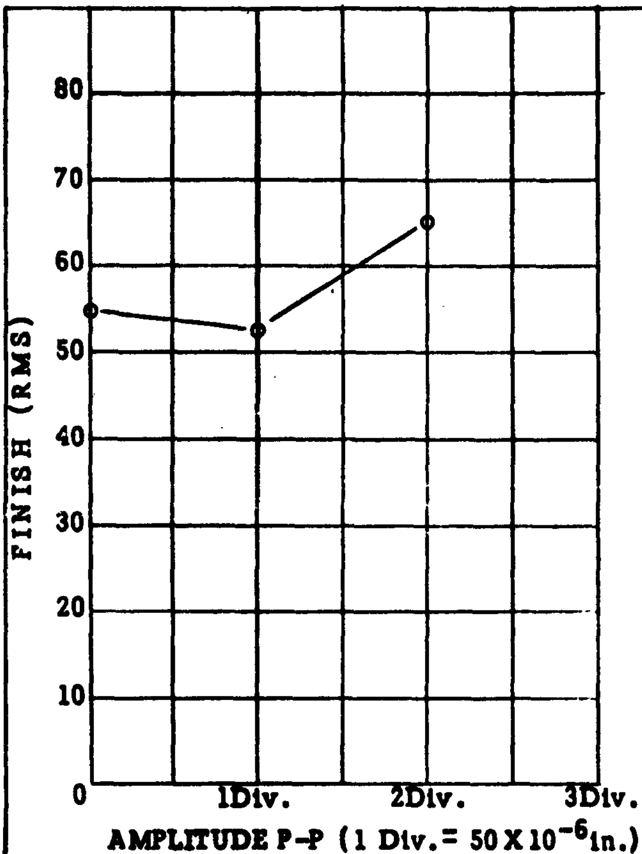
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	T16Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	16 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 138, 139, 140, 141-III

Figure 439



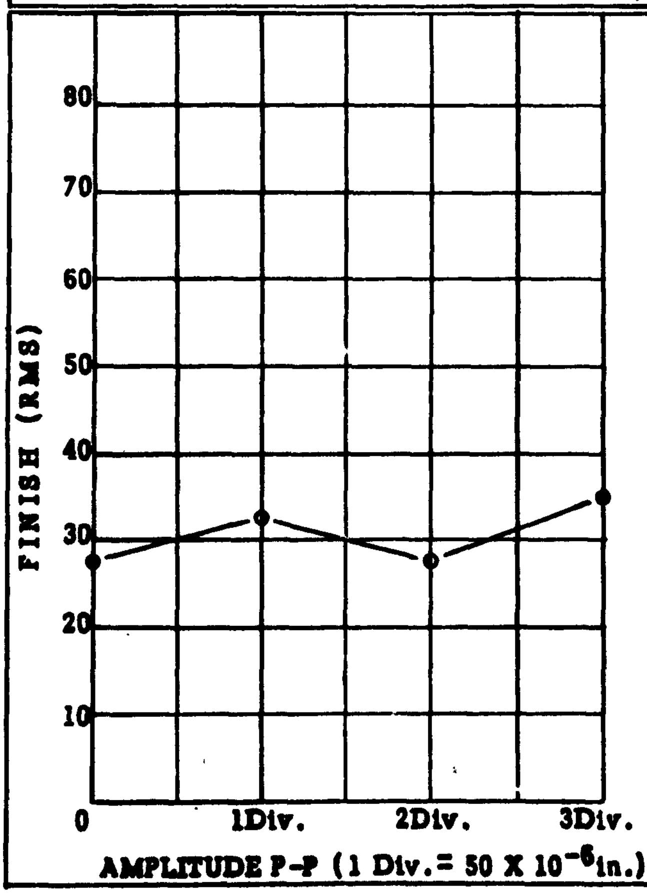
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	8 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

Run Numbers: 142, 143, 144 - III

Figure 440



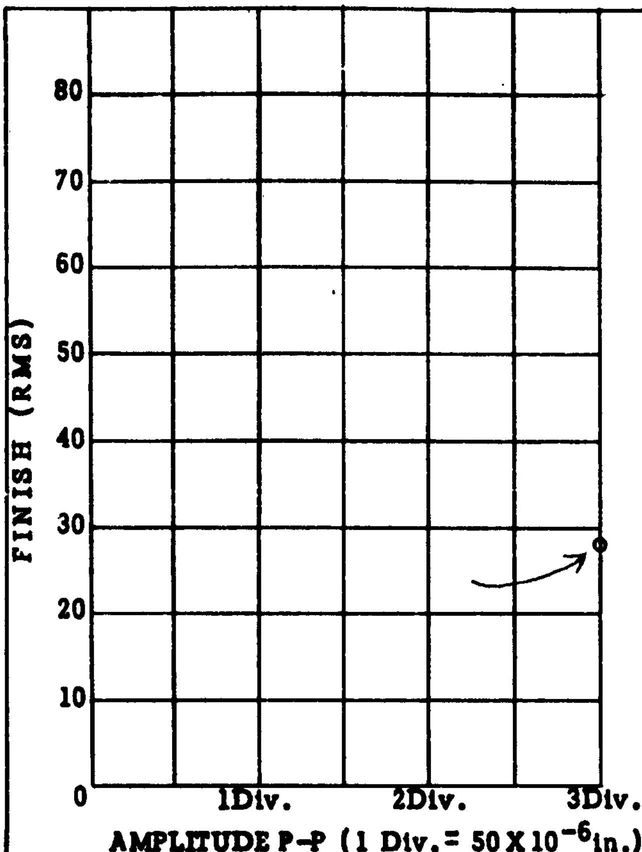
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	8 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 146, 147, 148, 149 - III

Figure 441



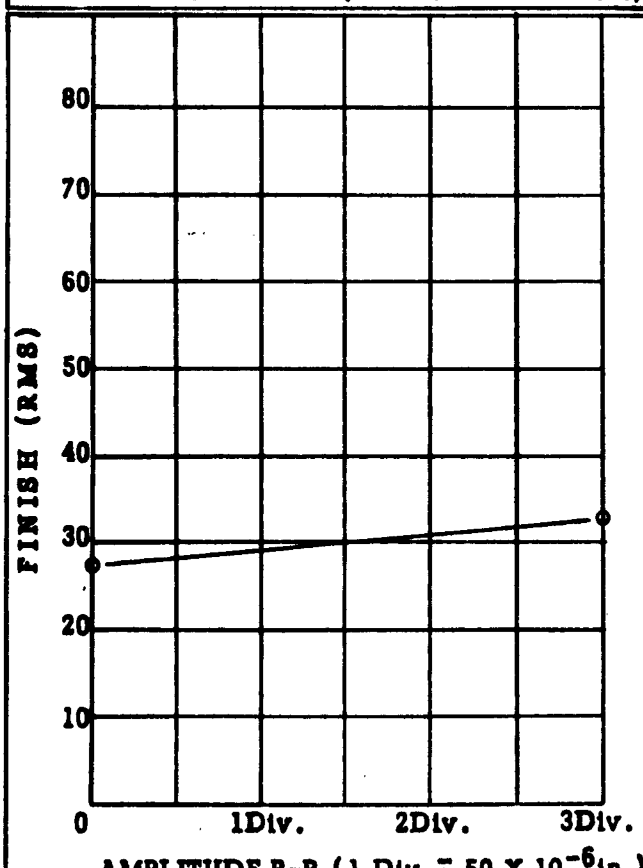
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	A60K6-V10
Wheel Speed SFPM	4558 - 4680
Traverse Feed	16 in./min.
Workpiece SFPM	74 to 81
Depth of Cut	0.0005 in.
Coolant	Sultran 176M

Run Number: 173 - III

Figure 442



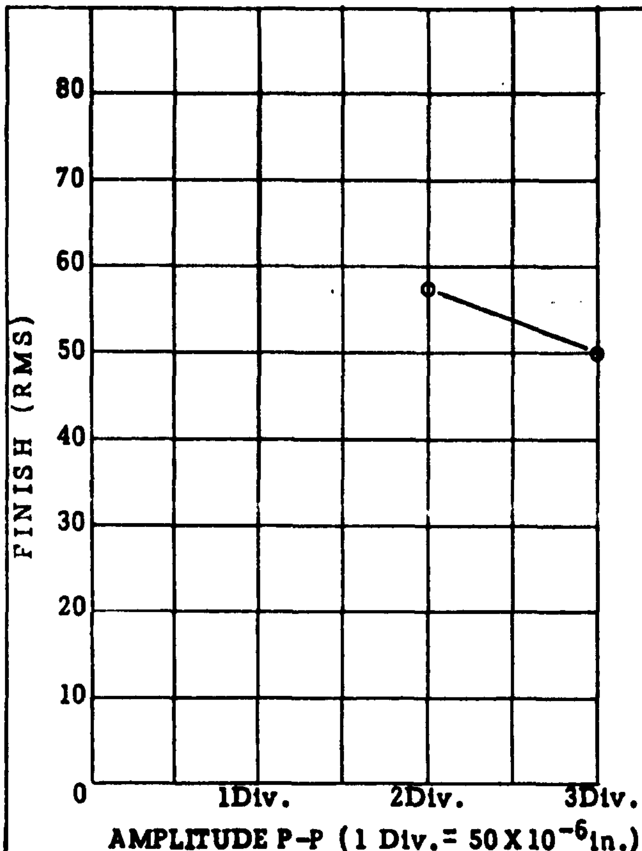
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	A60K6-V10
Wheel Speed SFPM	4558 - 4680
Traverse Feed	8 in./min.
Workpiece SFPM	74 to 81
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 174, 175 - III

Figure 443



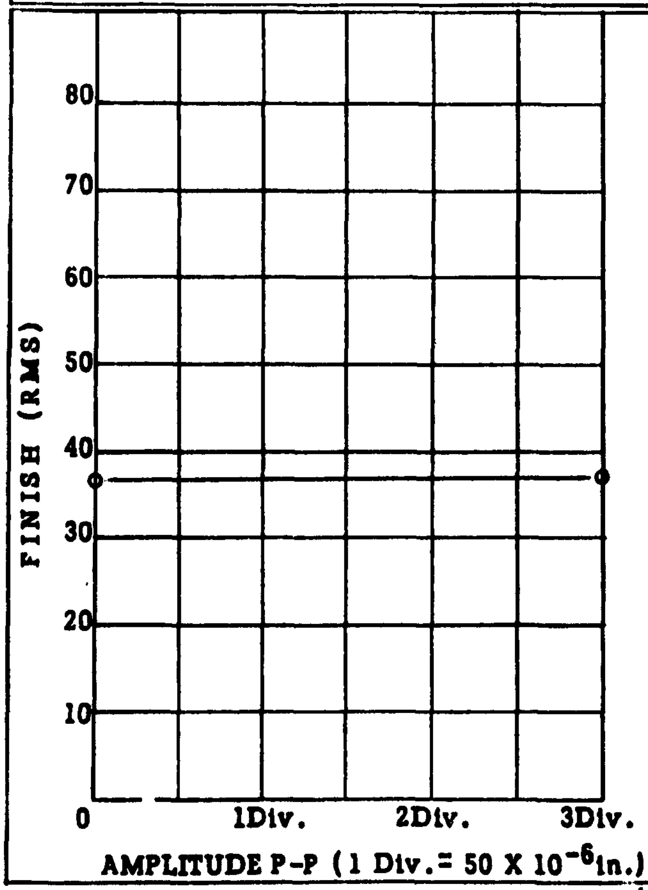
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	A60K6-V10
Wheel Speed SFPM	4558 - 4580
Traverse Feed	16 in./min.
Workpiece SFPM	74 to 81
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 168, 169, 169A - III

Figure 444



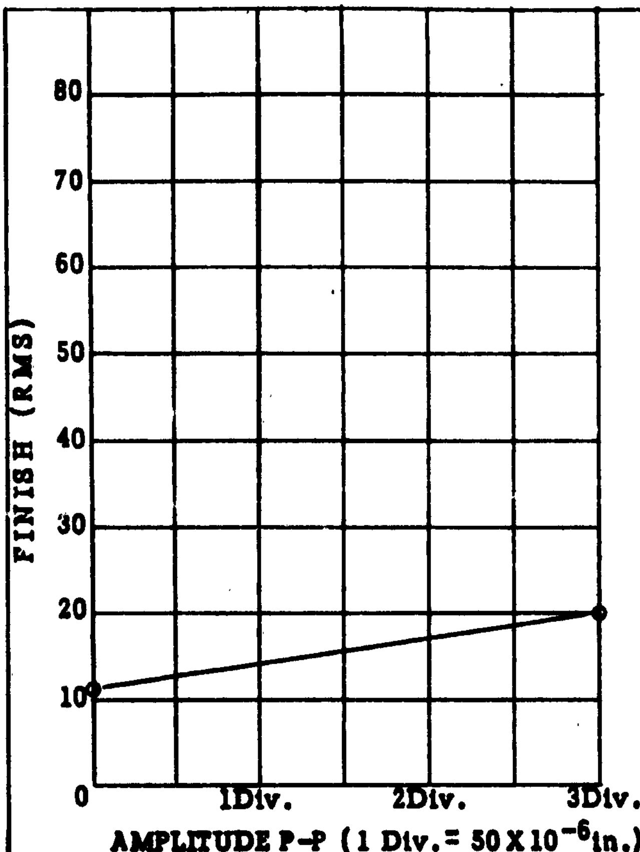
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	15-7 MO
Wheel	A60K6-V10
Wheel Speed SFPM	4558 - 4680
Traverse Feed	16 in./min.
Workpiece SFPM	74 to 81
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 170, 171 - III

Figure 445



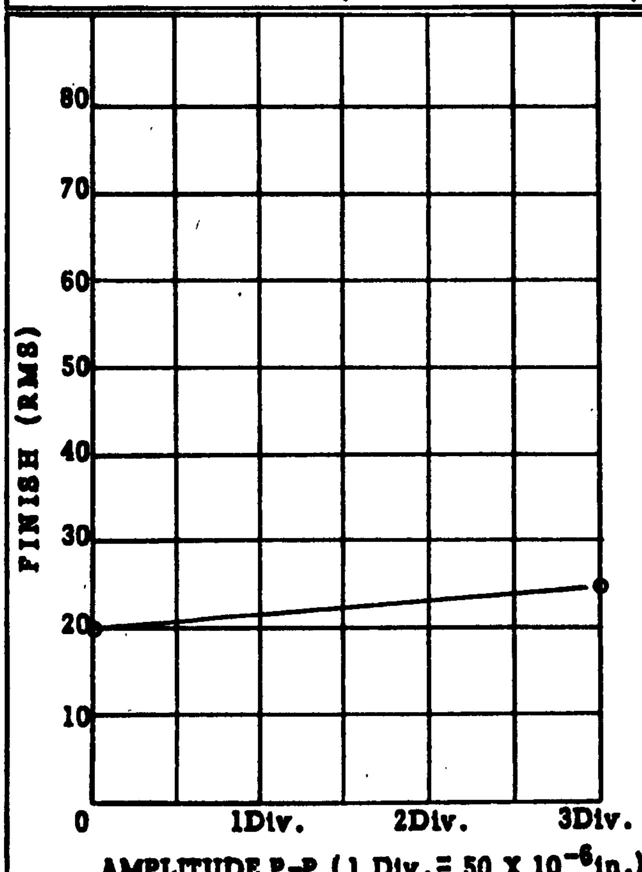
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	4 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.0005 in.
Coolant	Sultran 176M

Run Numbers: 184, 185 - III

Figure 446



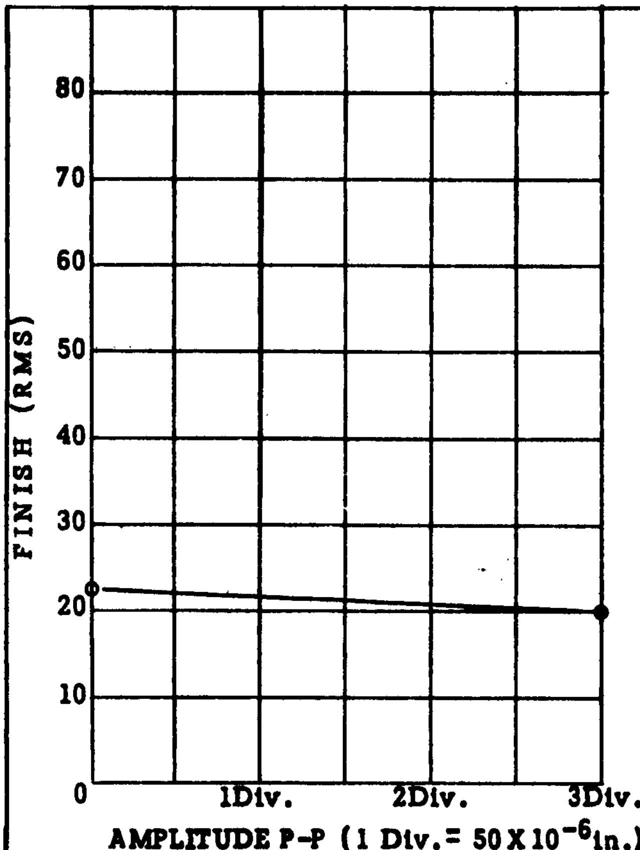
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	4 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 186, 187 - III

Figure 447



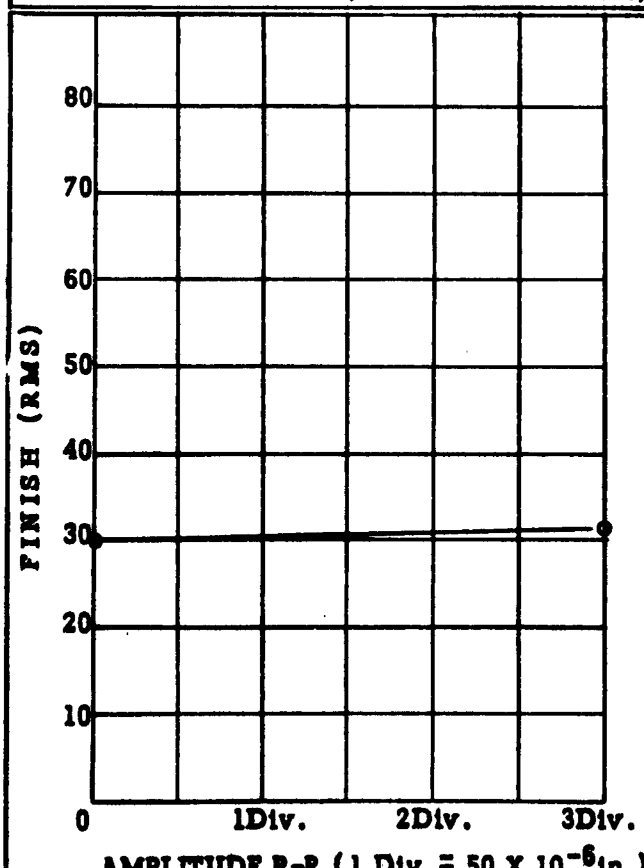
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	8 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.0005 in.
Coolant	Sultran 176M

Run Numbers: 180, 181 - III

Figure 448



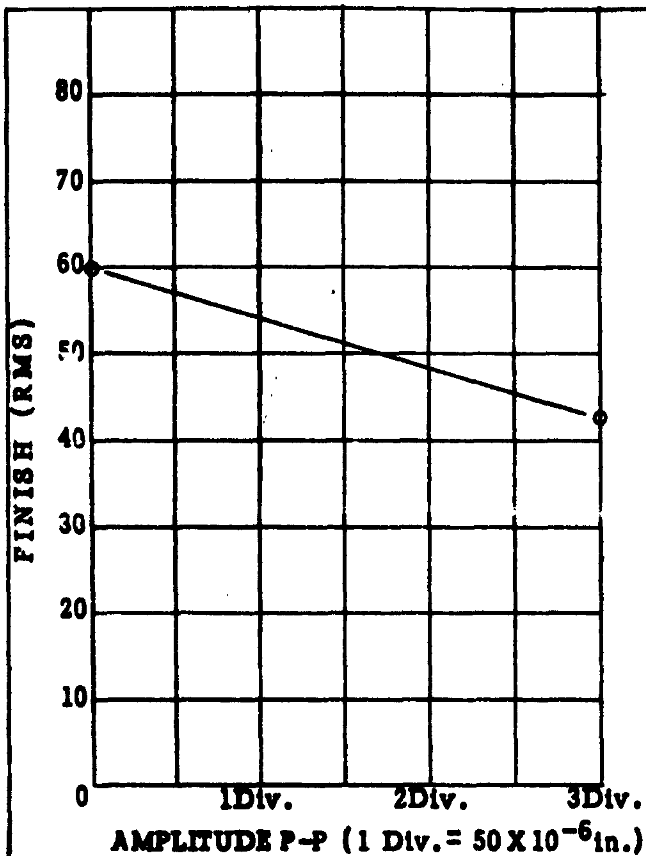
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	8 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 182, 183 - III

Figure 449



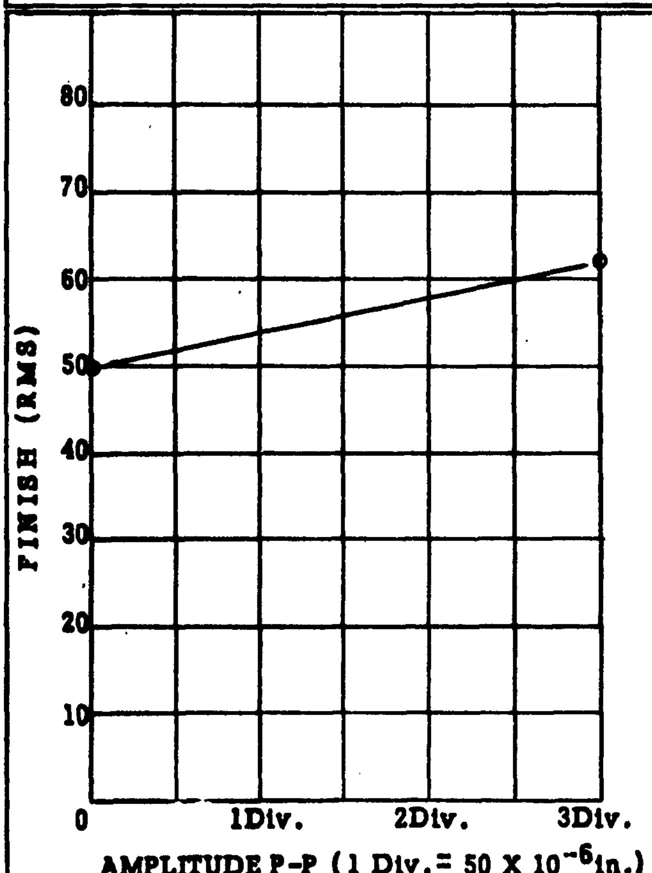
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	12 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.0005 in.
Coolant	Sultran 176M

Run Numbers: 176, 177 - III

Figure 450



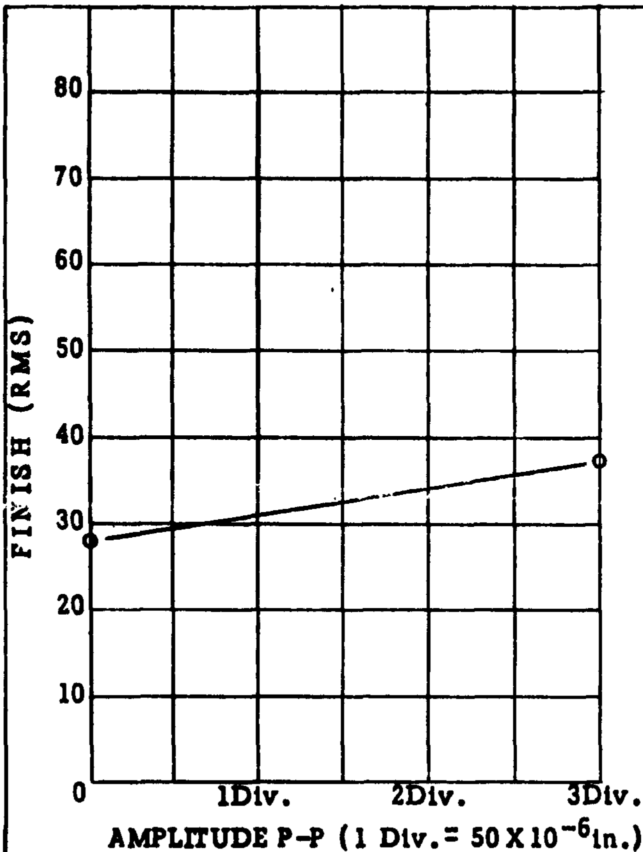
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	12 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 178, 179 - III

Figure 451



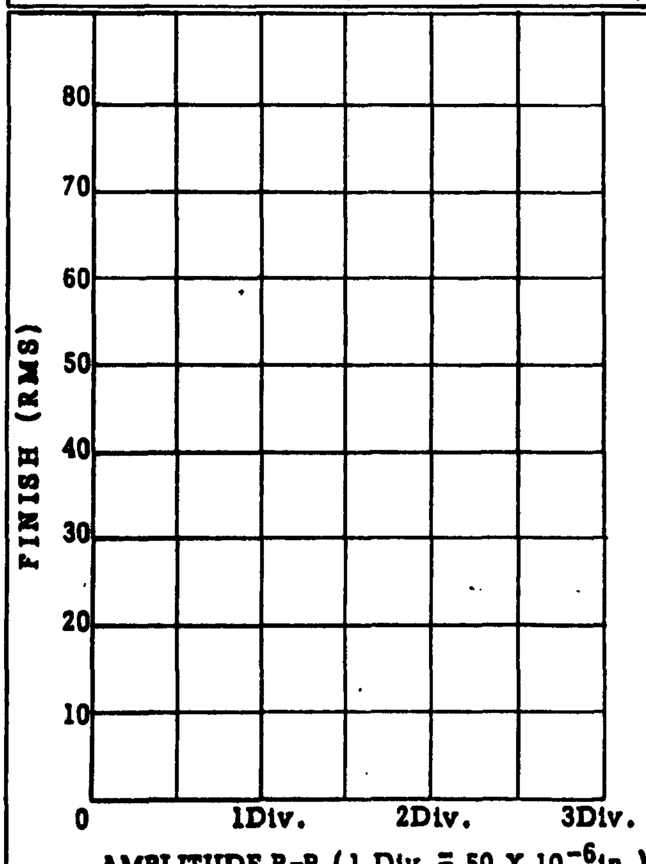
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	A60P6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	8 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Number: 162, 163 - III

Figure 452



EXTERNAL GRINDING

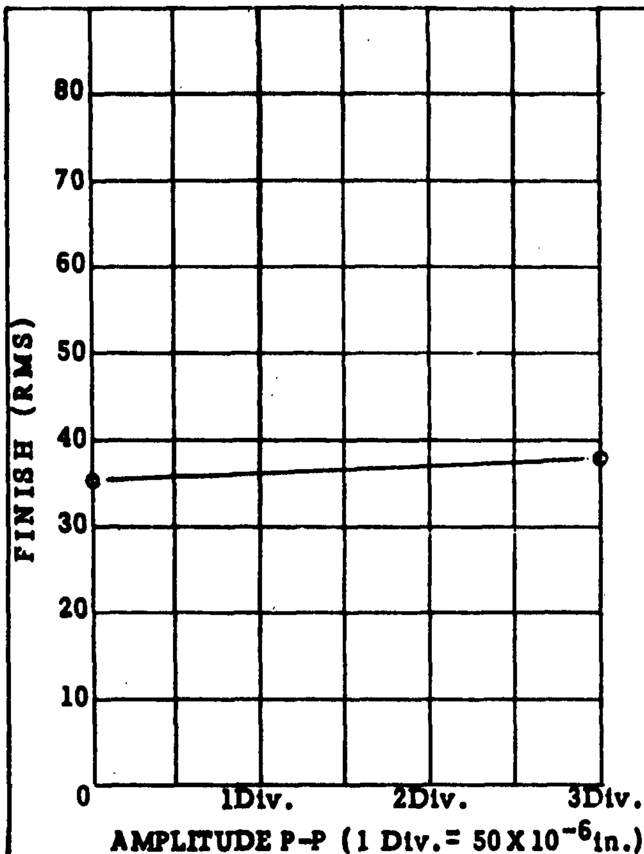
FINISH AS A FUNCTION OF AMPLITUDE

Material	Ti6Al-4V
Wheel	A60P6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	16 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

(extreme burn and chatter with conventional and 3 division.)

Run Number: 164, 165 - III

Figure 453



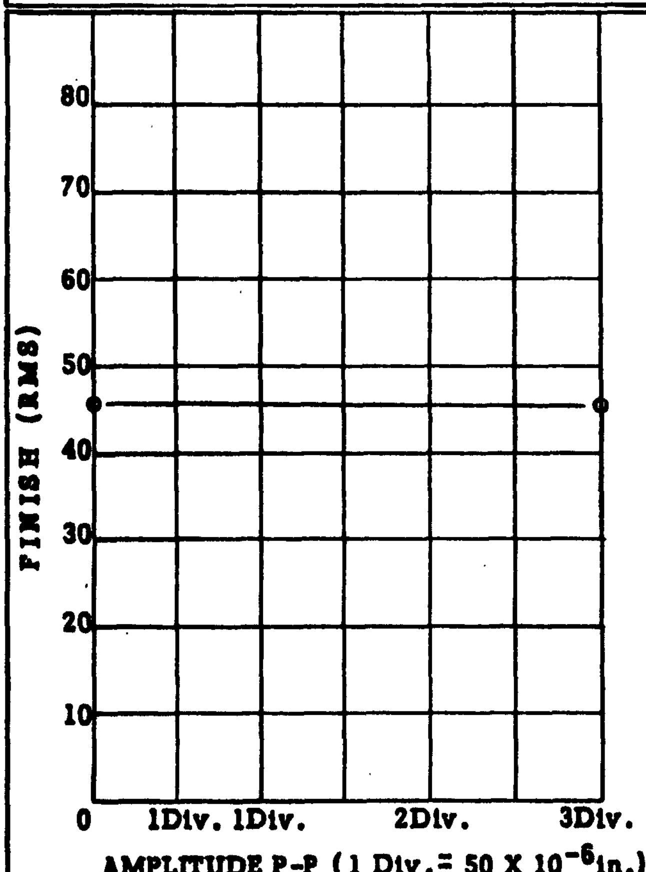
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H-11
Wheel	AA60I8-V40
Wheel Speed SFPM	5263 to 5346
Traverse Feed	4 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 201, 202 - III

Figure 454



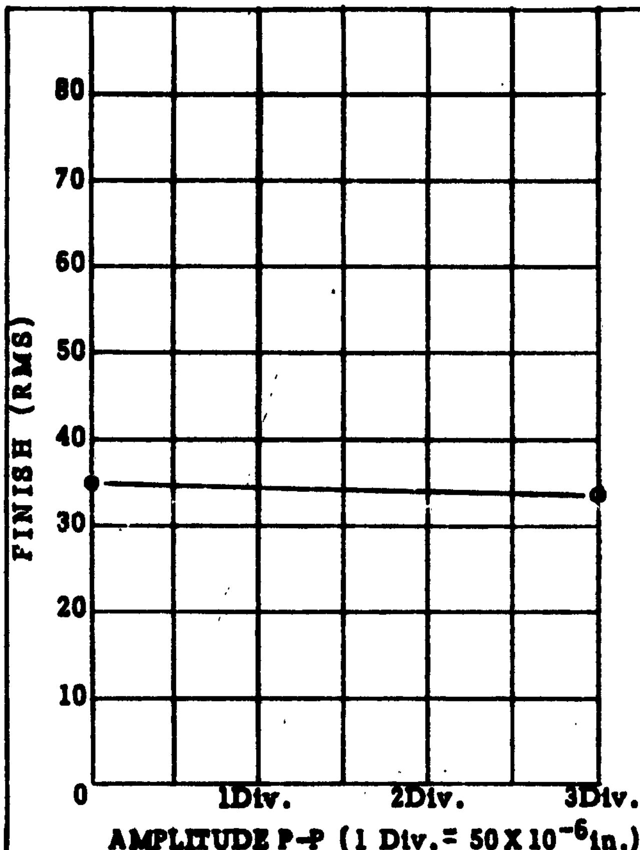
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H-11
Wheel	A60L6-V10
Wheel Speed SFPM	5332 to 5362
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 203, 204 - III

Figure 455



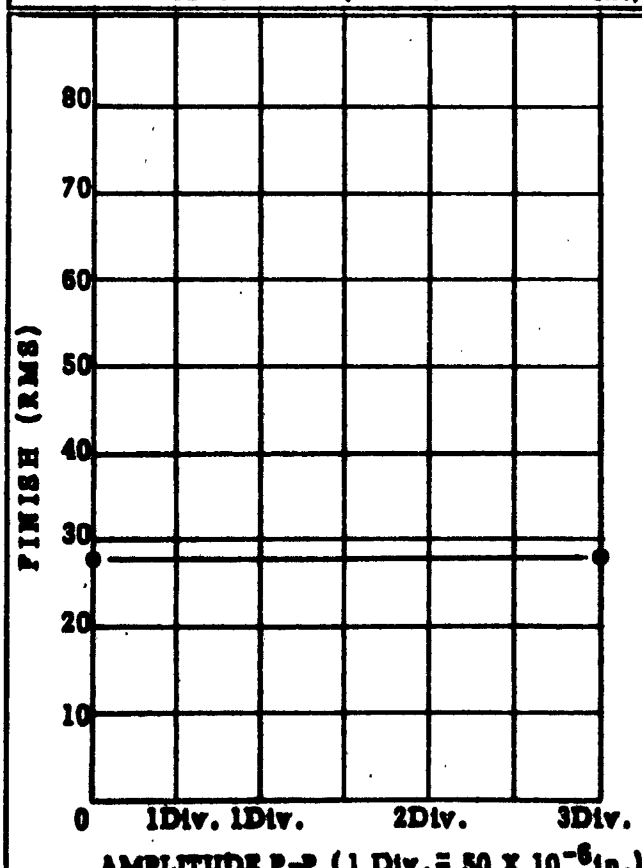
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H-11
Wheel	A60L6-V10
Wheel Speed SFPM	5332 to 5362
Traverse Feed	6 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 205, 206 - III

Figure 456



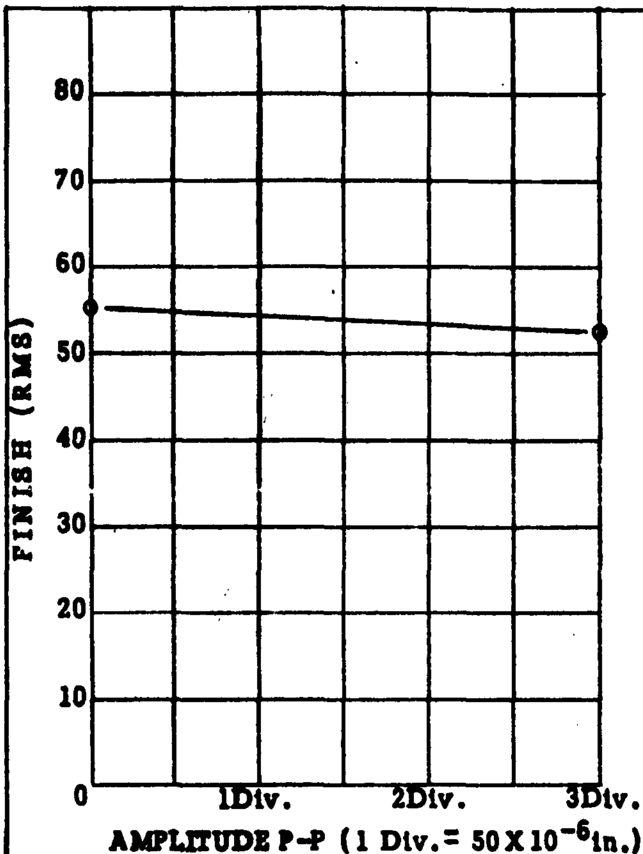
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H-11
Wheel	A60L6-V10
Wheel Speed SFPM	5332 to 5362
Traverse Feed	4 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 207, 208 - III

Figure 457



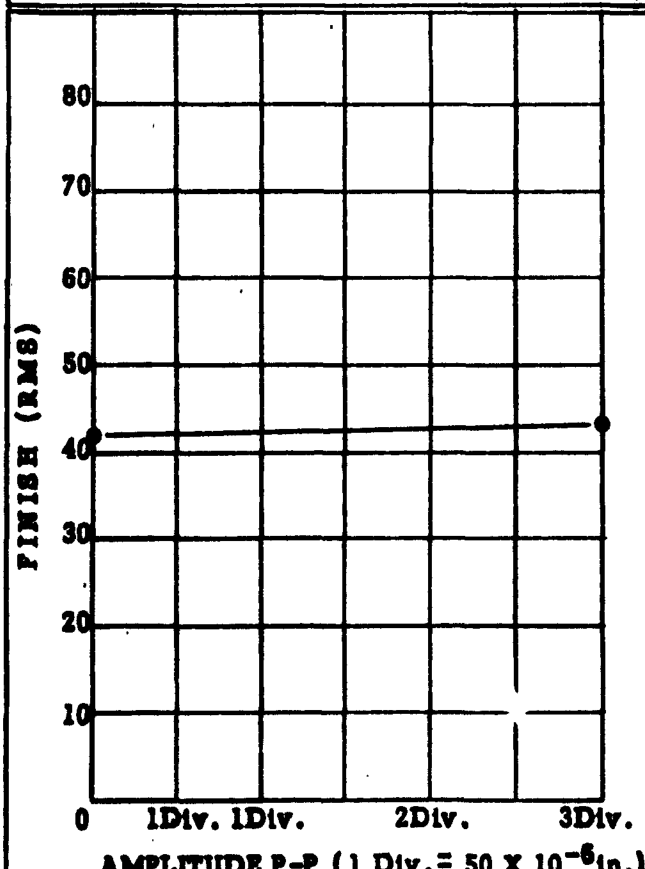
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H-11
Wheel	A60K6-V10
Wheel Speed SFPM	5362 to 5400
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 188, 189 - III

Figure 458



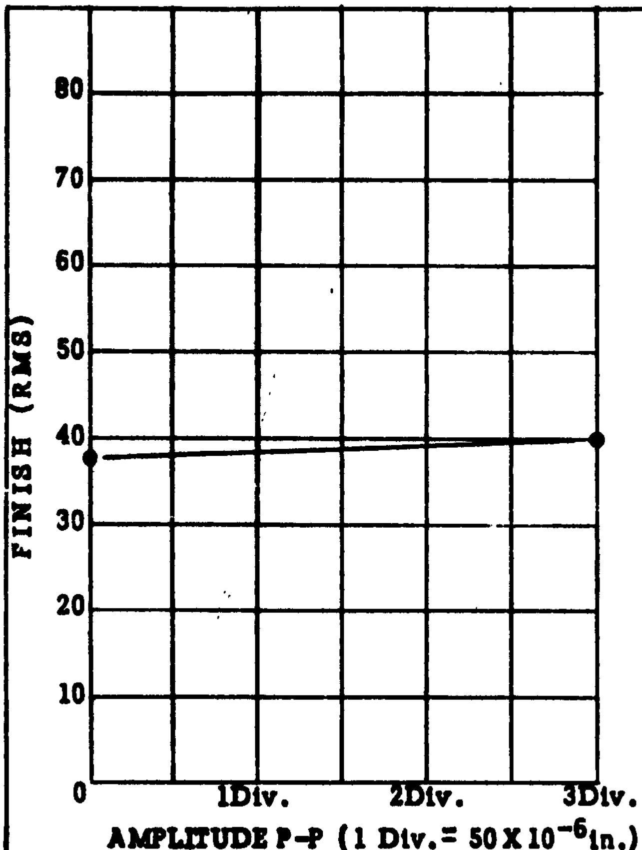
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H-11
Wheel	A60K6-V10
Wheel Speed SFPM	5362 to 5400
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 190, 191 - III

Figure 459



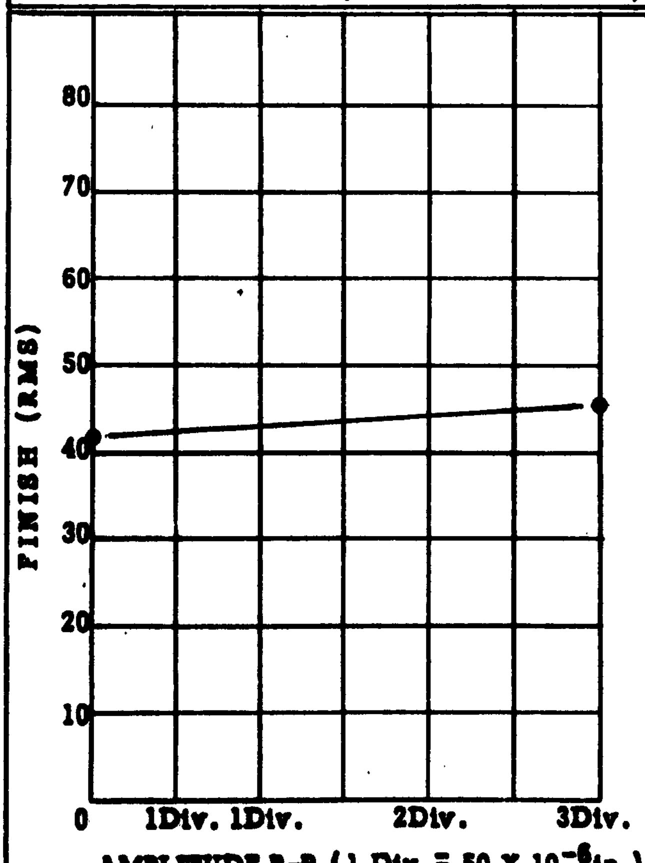
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H-11
Wheel	A60K6-V10
Wheel Speed SFPM	5362 to 5400
Traverse Feed	6 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 192, 193 - III

Figure 460



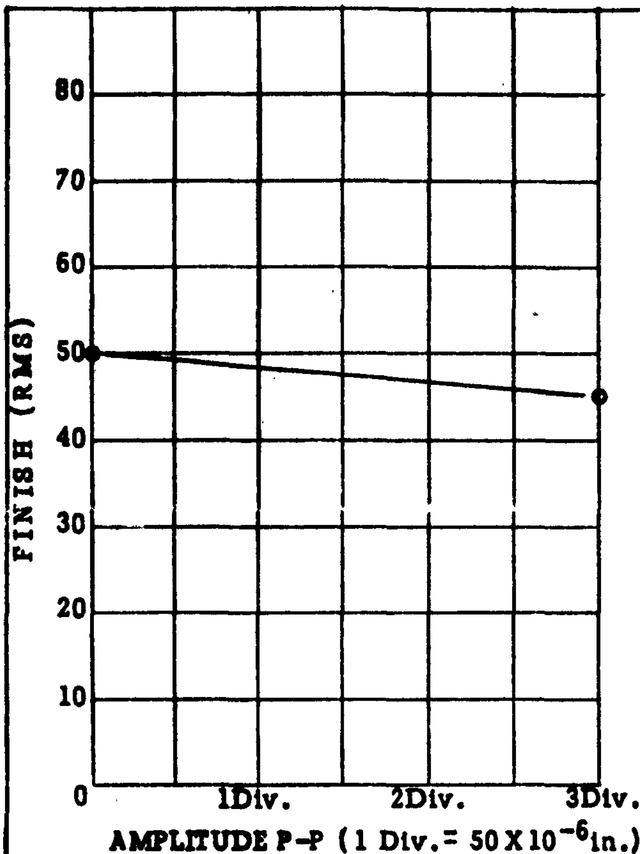
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H-11
Wheel	AA60I8-V40
Wheel Speed SFPM	5263 to 5346
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 195, 196 - III

Figure 461



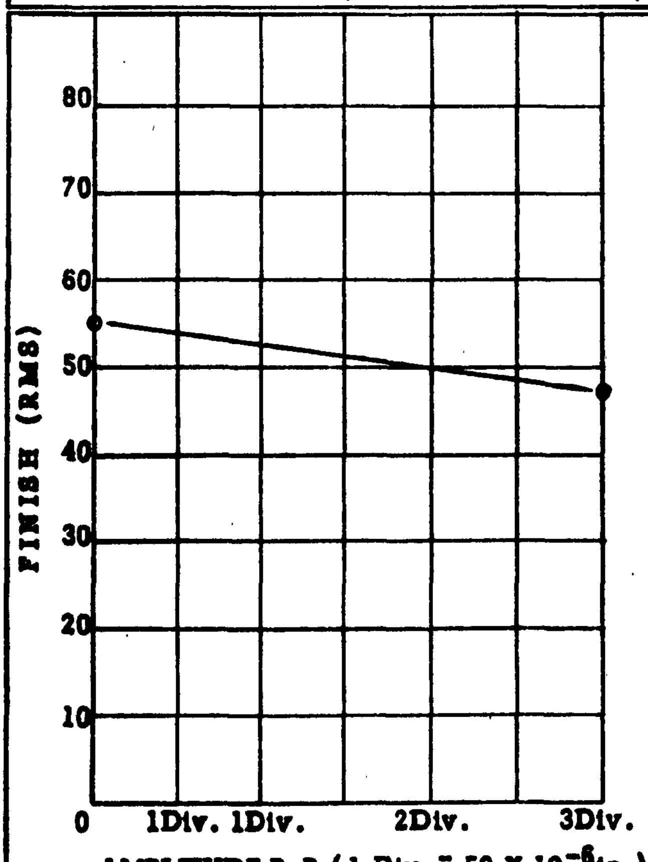
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H-11
Wheel	AA60I8-V40
Wheel Speed SFPM	5263 to 5346
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 197, 198 - III

Figure 462



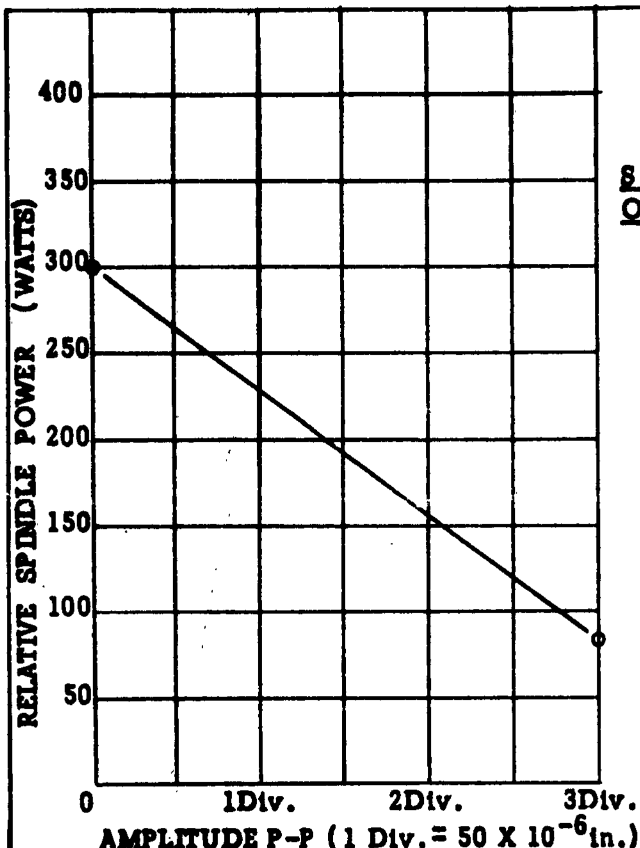
EXTERNAL GRINDING

FINISH AS A FUNCTION OF AMPLITUDE

Material	H-11
Wheel	AA60I8-V40
Wheel Speed SFPM	5263 to 5346
Traverse Feed	6 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 199, 200 - III

Figure 463



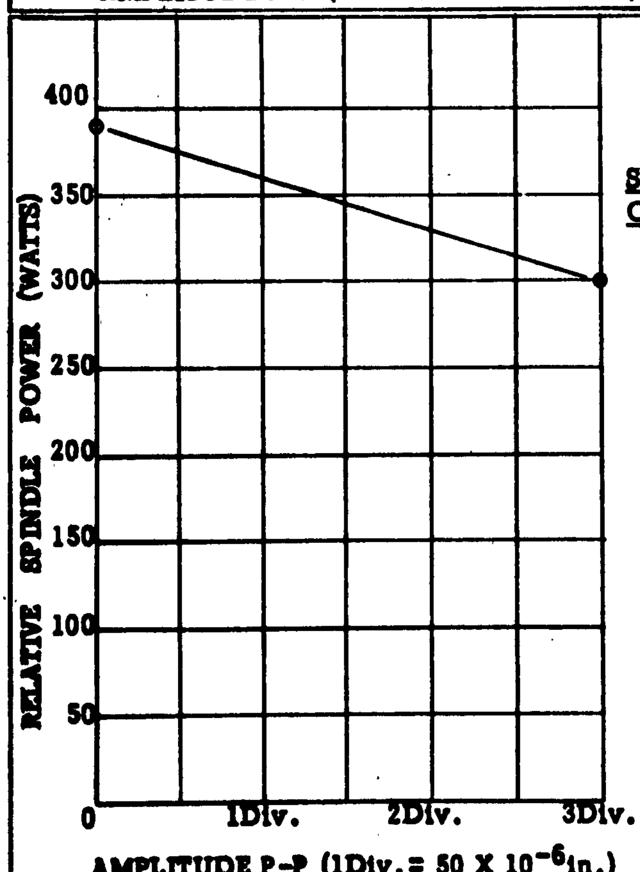
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	12 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.0005 in.
Coolant	Sultran 176M

Run Numbers: 176, 177 - III

Figure 464



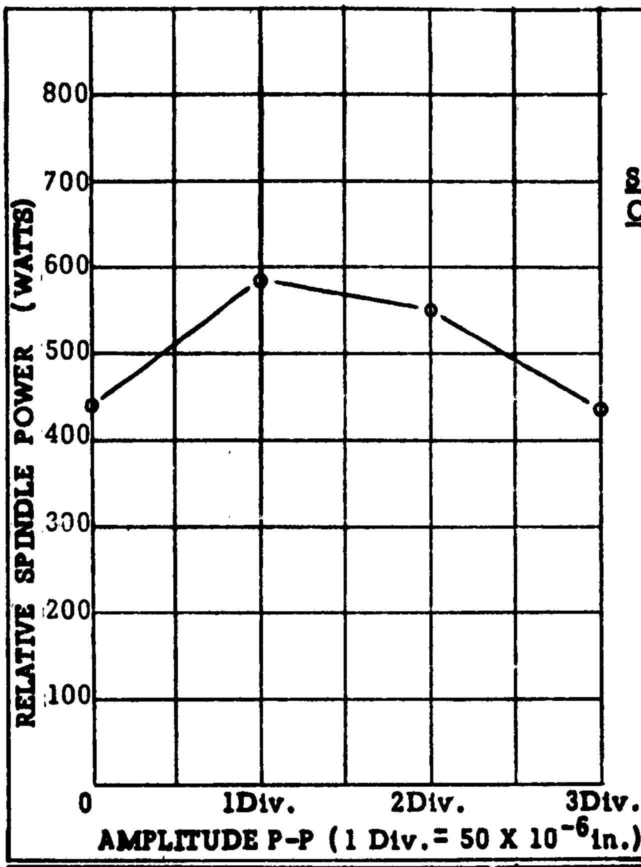
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	12 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 178, 179 - III

Figure 465



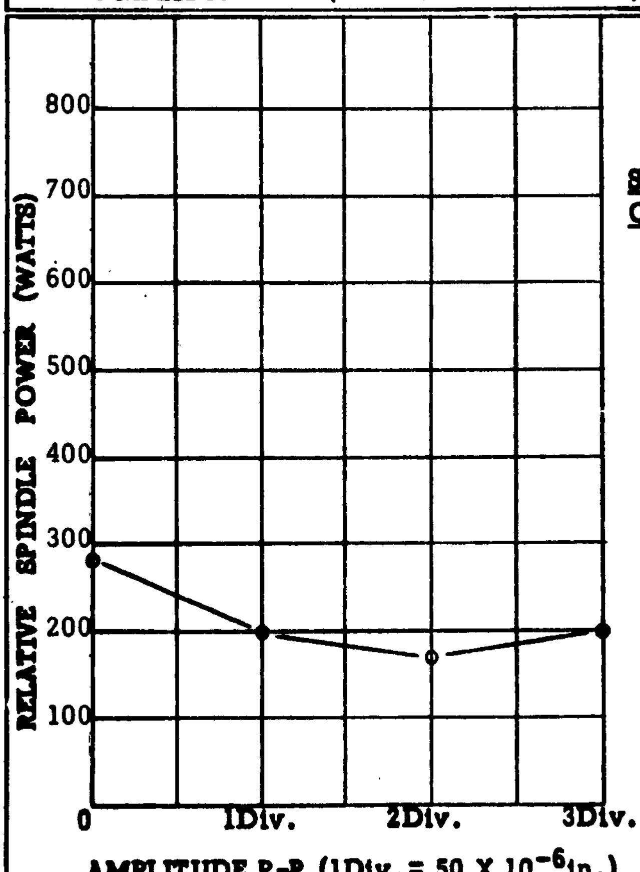
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	8 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

Run Numbers: 142, 143, 144, 145- III

Figure 466



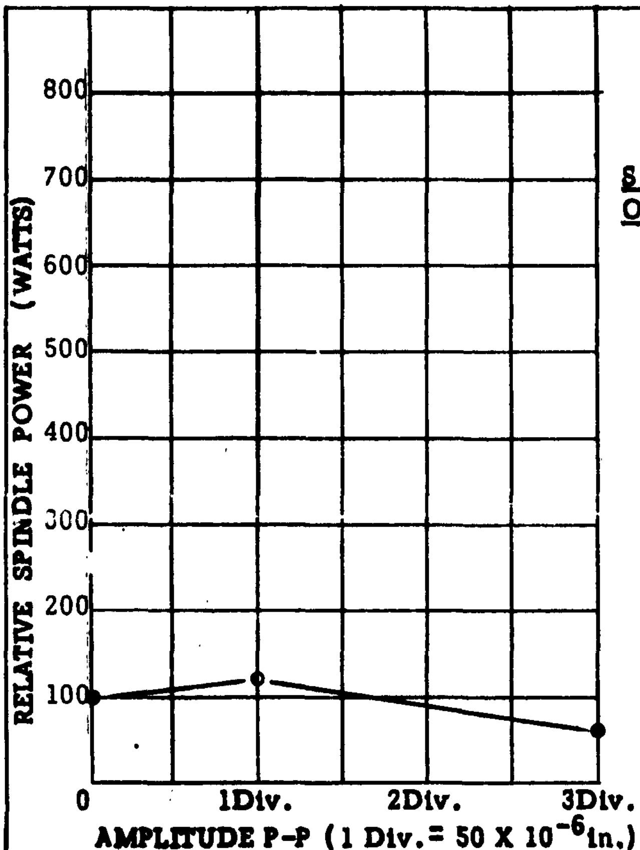
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	8 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

Run Numbers: 146, 147, 148, 144-III

Figure 467



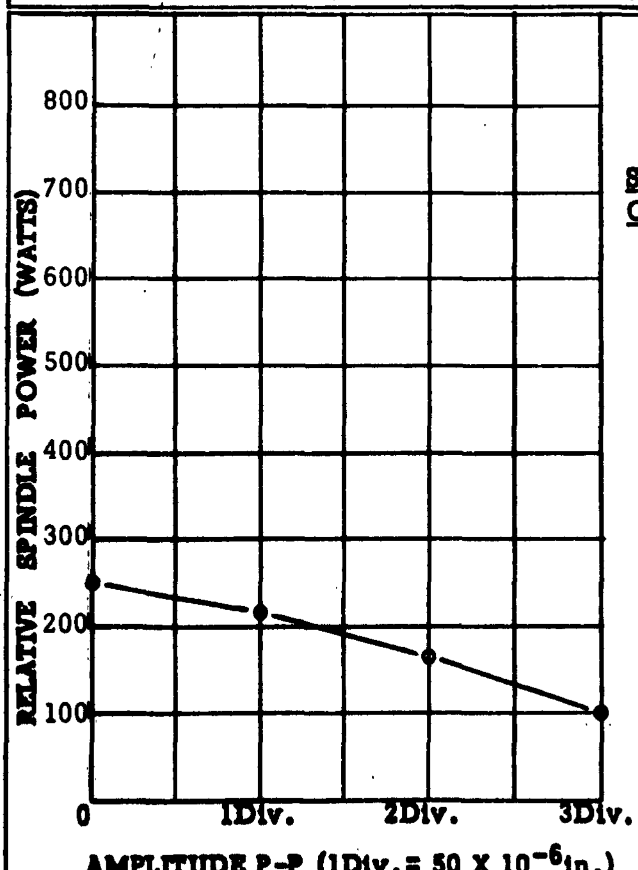
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	8 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

Run Numbers: 150, 153, 152 - III

Figure 468



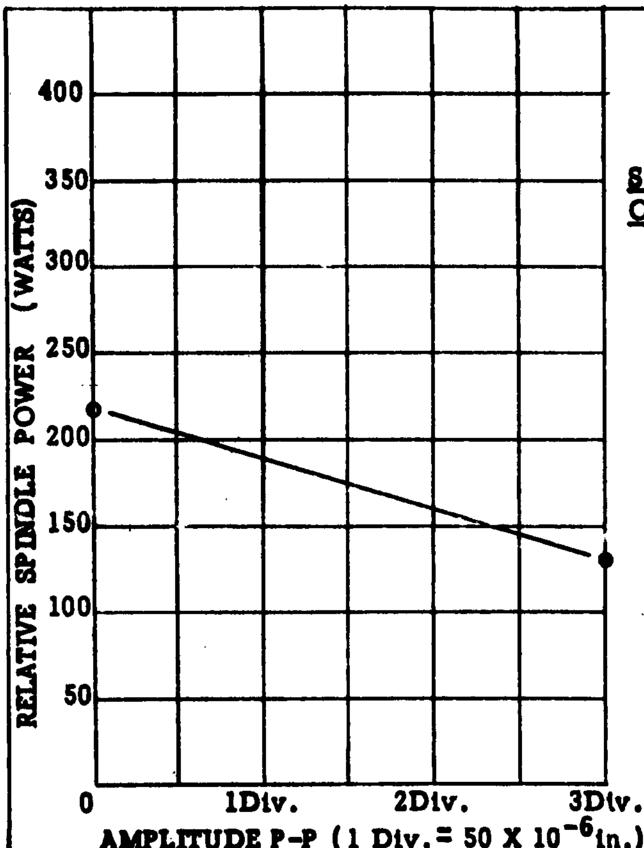
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	16 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

Run Numbers: III-154, 155, 156, 157

Figure 469



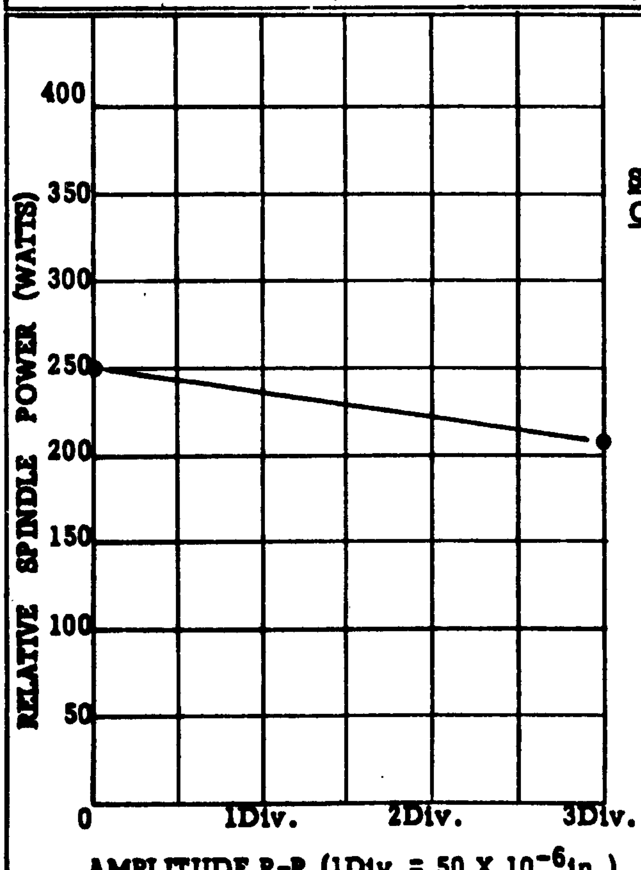
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	8 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.0005 in.
Coolant	Sultran 176M

Run Numbers: 180, 181-III

Figure 470



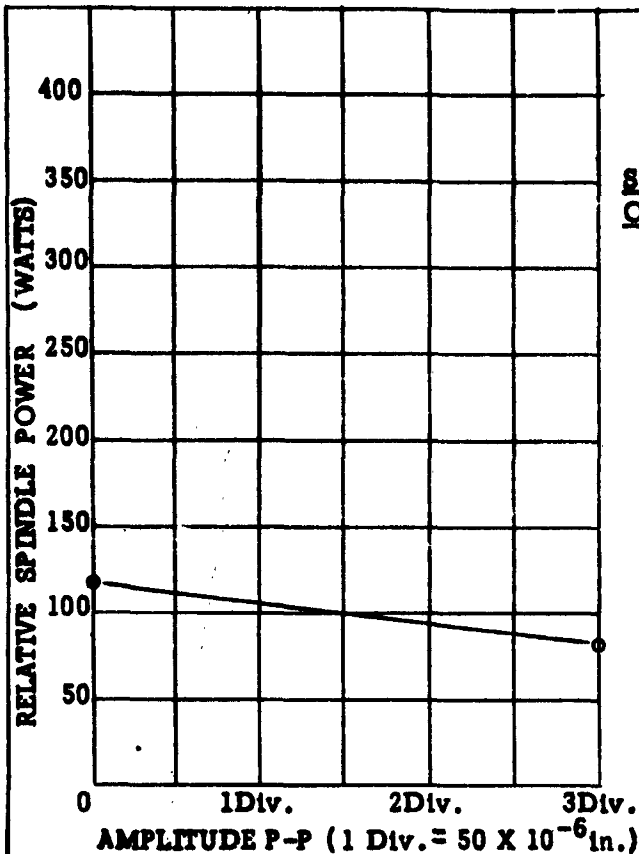
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	8 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 182, 183- III

Figure 471



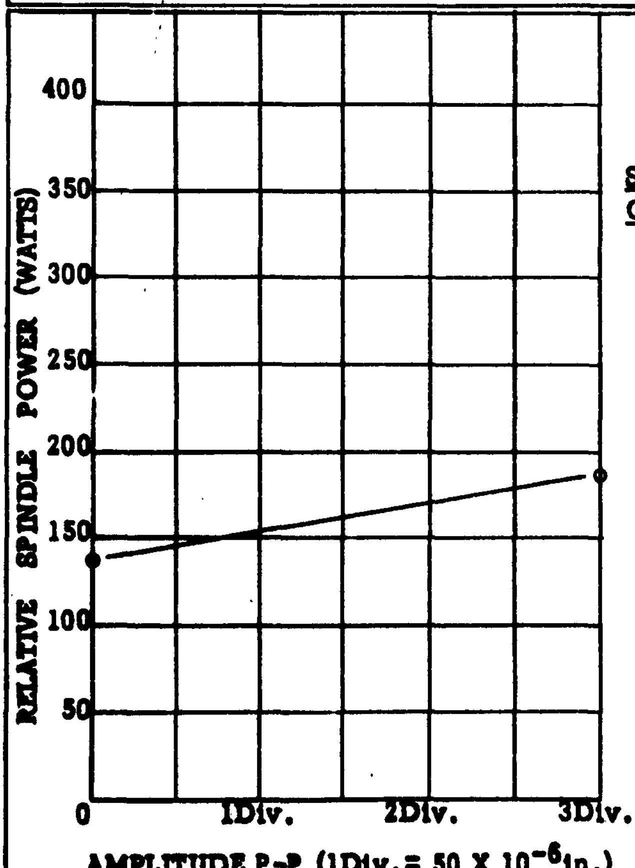
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	4 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.0005 in.
Coolant	Sultran 176M

Run Numbers: 184, 185 - III

Figure 472



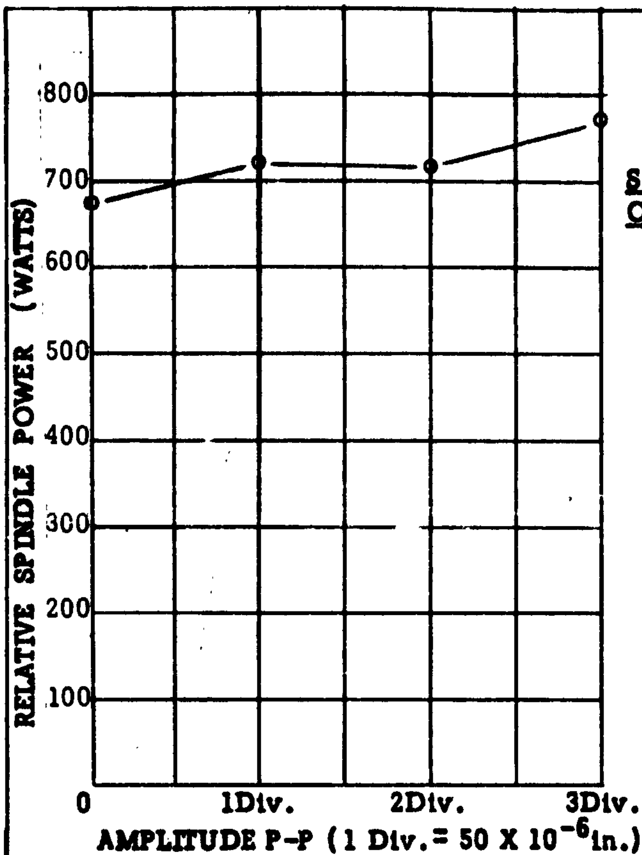
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	A60K6-V10
Wheel Speed SFPM	3275 - 3330
Traverse Feed	4 in./min.
Workpiece SFPM	48 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 186, 187 - III

Figure 473



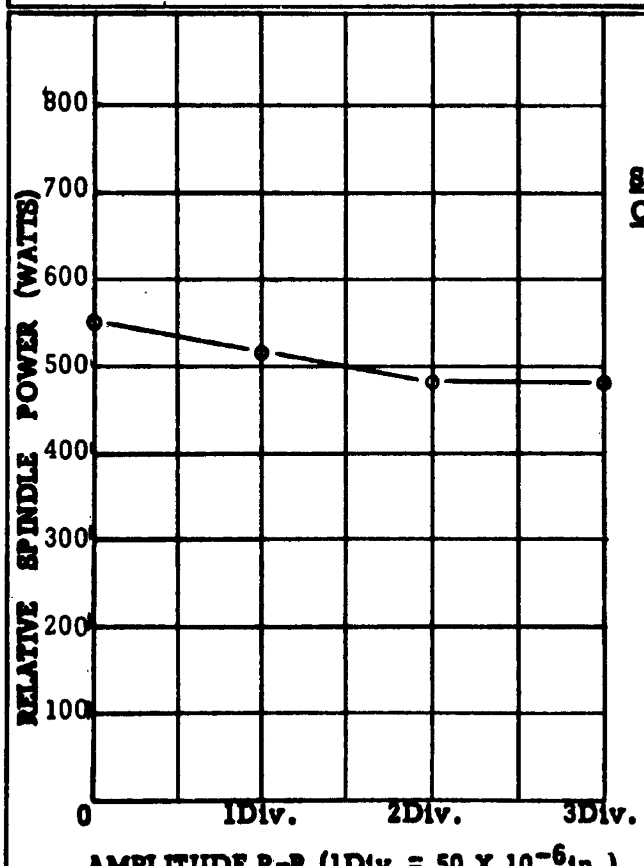
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	16 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

Run Numbers: 134, 135, 136, 137-III

Figure 474



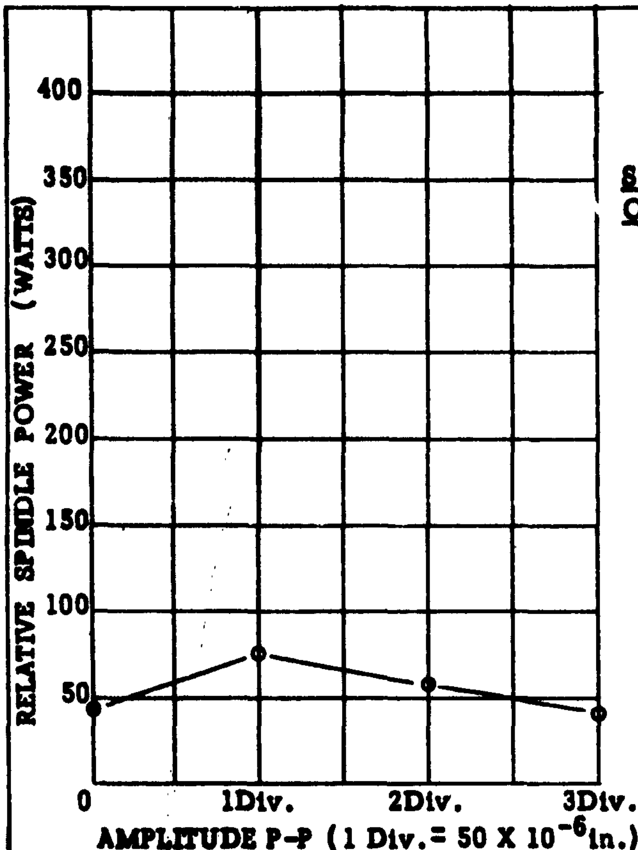
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	16 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.001 in.
Coolant	Vantrol 5456M

Run Numbers: 138, 139, 140, 141-III

Figure 475



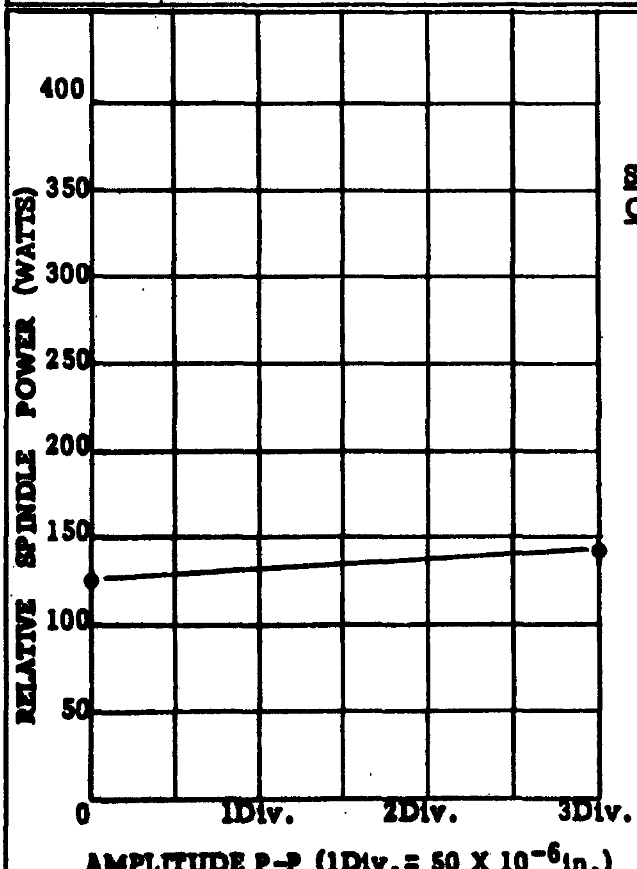
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material		15-7 MO
Wheel		A60K6-V10
Wheel Speed	SFPM	4558 - 4680
Traverse Feed		16 in./min.
Workpiece SFPM		74 to 81
Depth of Cut		0.002 in.
Coolant		Sultran 176M

Run Numbers: 166, 167, 168, 169, 169A - III

Figure 476



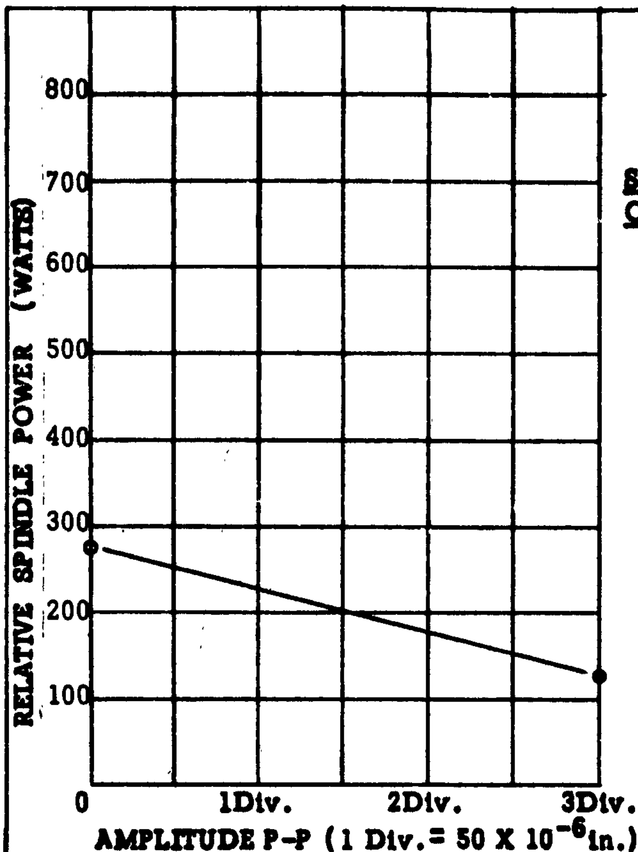
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material		15-7 MO
Wheel		A60K6-V10
Wheel Speed	SFPM	4558 - 4680
Traverse Feed		16 in./min.
Workpiece SFPM		74 to 81
Depth of Cut		0.001 in.
Coolant		Sultran 176M

Run Numbers: 170, 171 - III

Figure 477



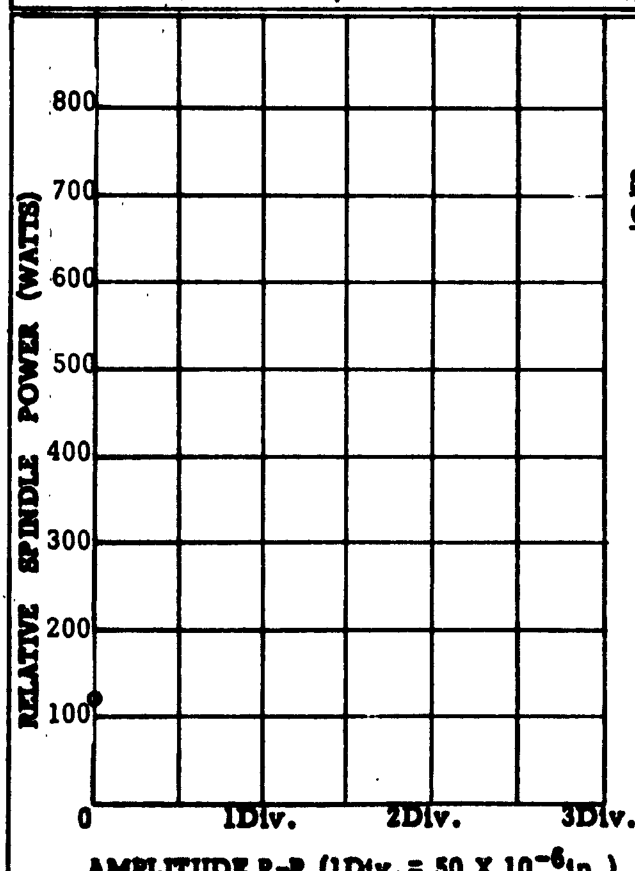
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti 6Al-4V
Wheel	A60-K6-V10
Wheel Speed SFPM	2060 - 2160
Traverse Feed	4 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.002 in.
Coolant	Vantrol 5456M

Run Numbers: 158, 159 - III

Figure 478



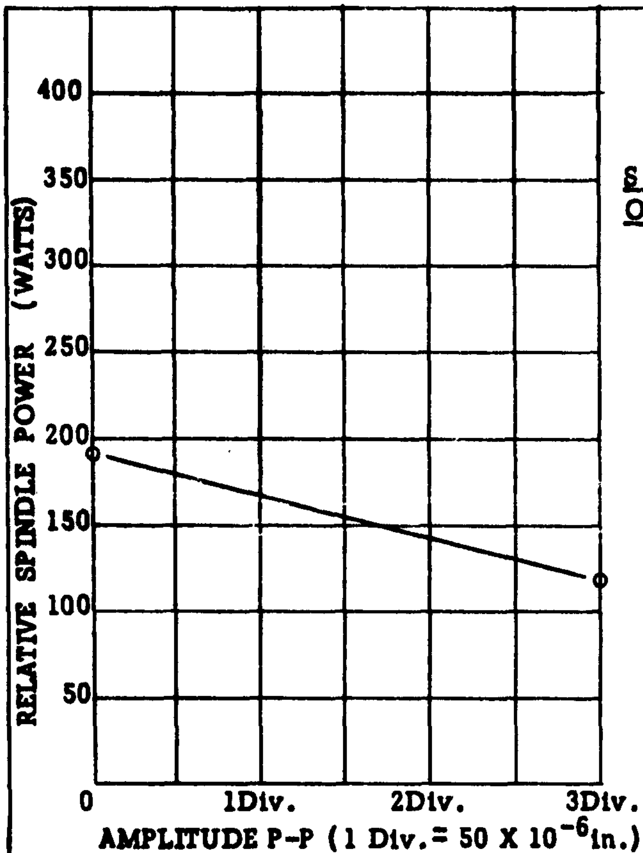
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60K6-V10
Wheel Speed	2060 - 2160
Traverse Feed	4 in./min.
Workpiece SFPM	54 to 59
Depth of Cut	0.0005 in.
Coolant	Vantrol 5456M

Run Number: 160 - III

Figure 479



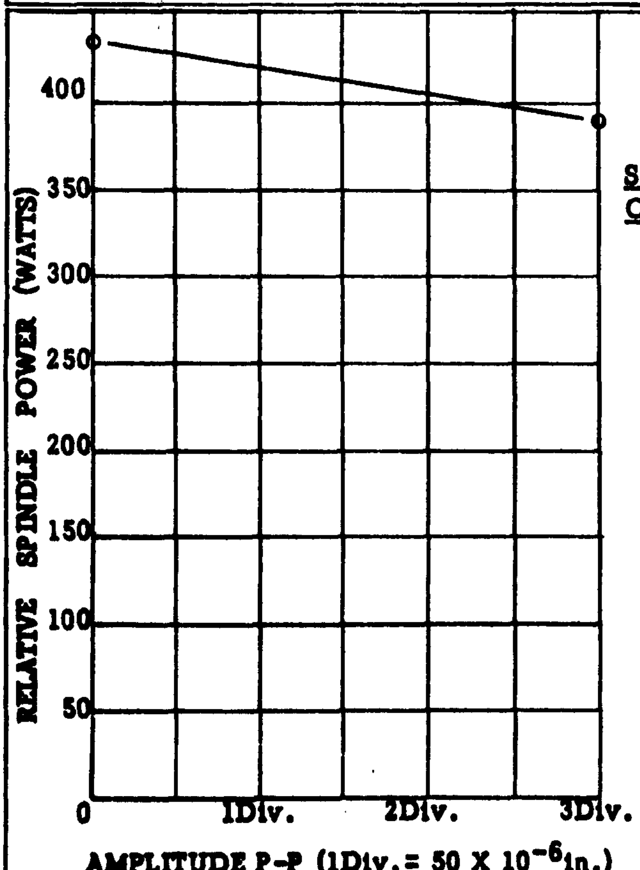
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	AA60I8-V40
Wheel Speed SFPM	5263 to 5346
Traverse Feed	4 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 201, 202 - III

Figure 480



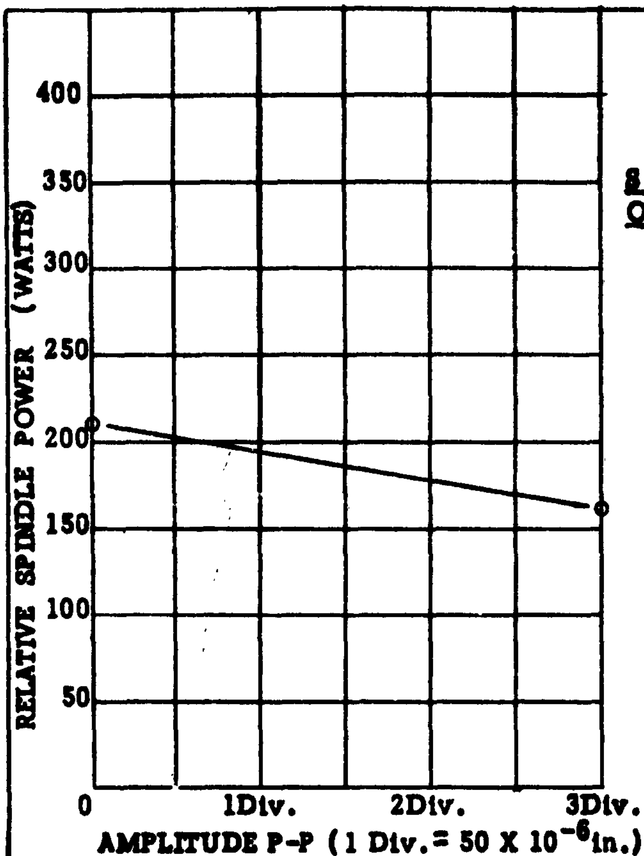
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60L6-V10
Wheel Speed SFPM	5332 to 5362
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 203, 204 - III

Figure 481



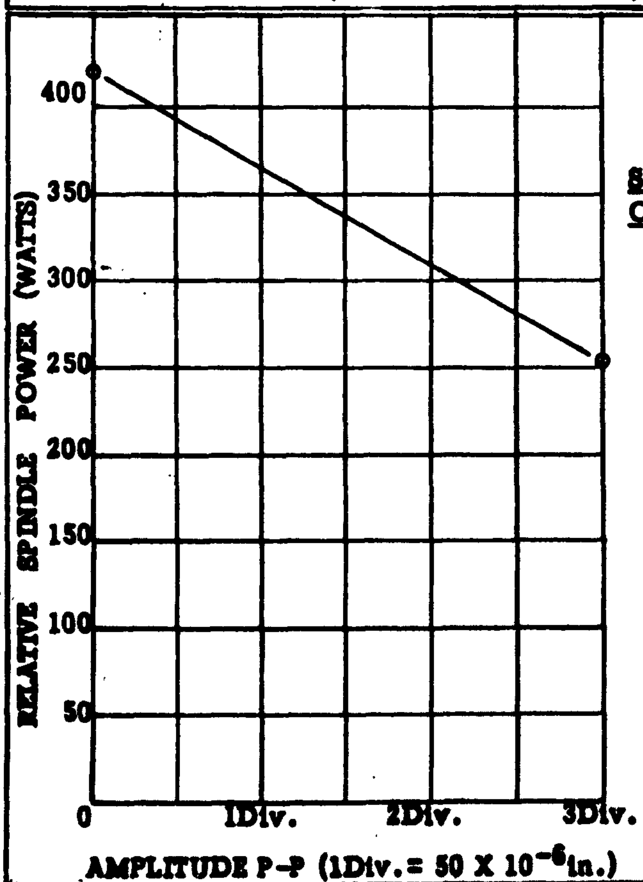
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60K6-V10
Wheel Speed SFPM	5362 - 5400
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 188, 189 - III

Figure 482



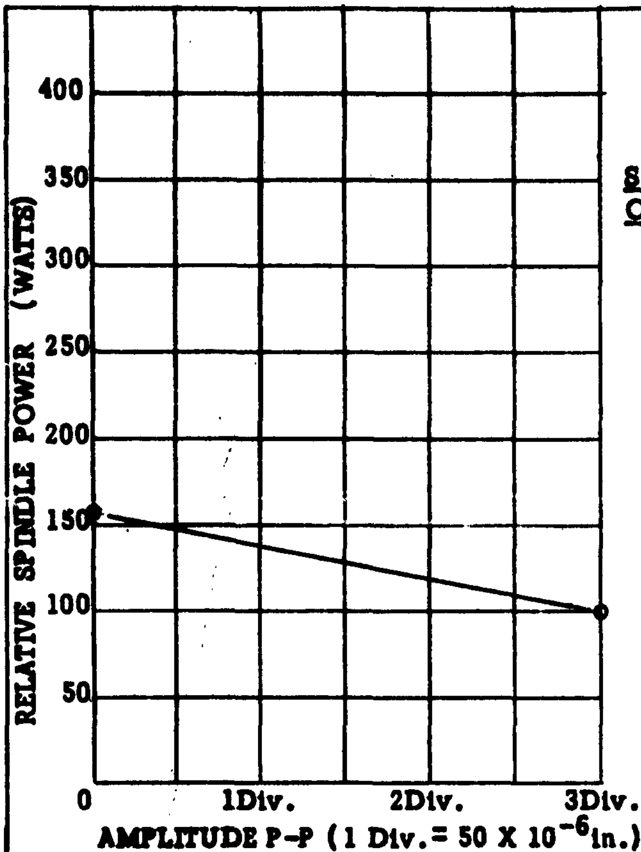
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60K6-V10
Wheel Speed SFPM	5362 - 5400
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 190, 191 - III

Figure 483



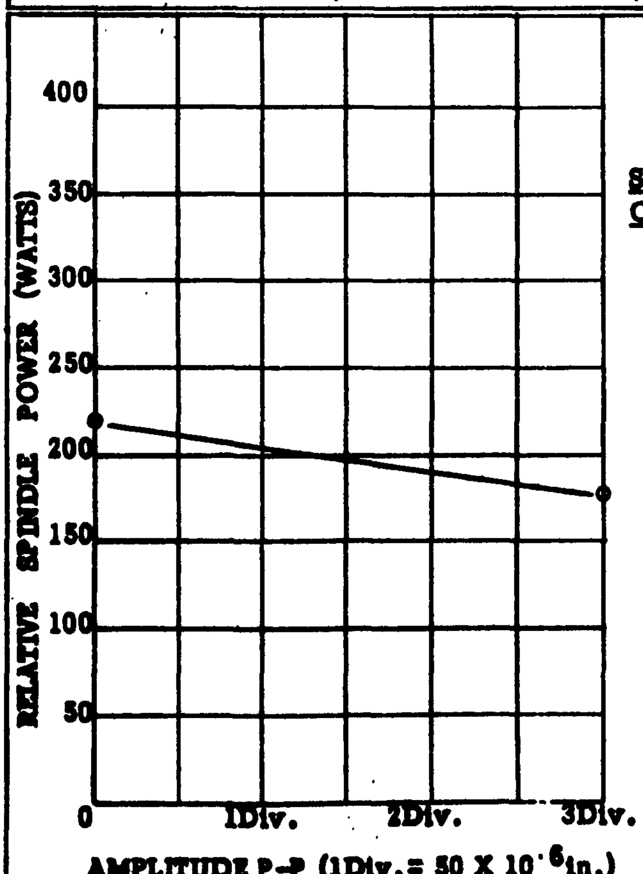
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60K6-V10
Wheel Speed SFPM	5362 to 5400
Traverse Feed	6 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 192, 193 - III

Figure 484



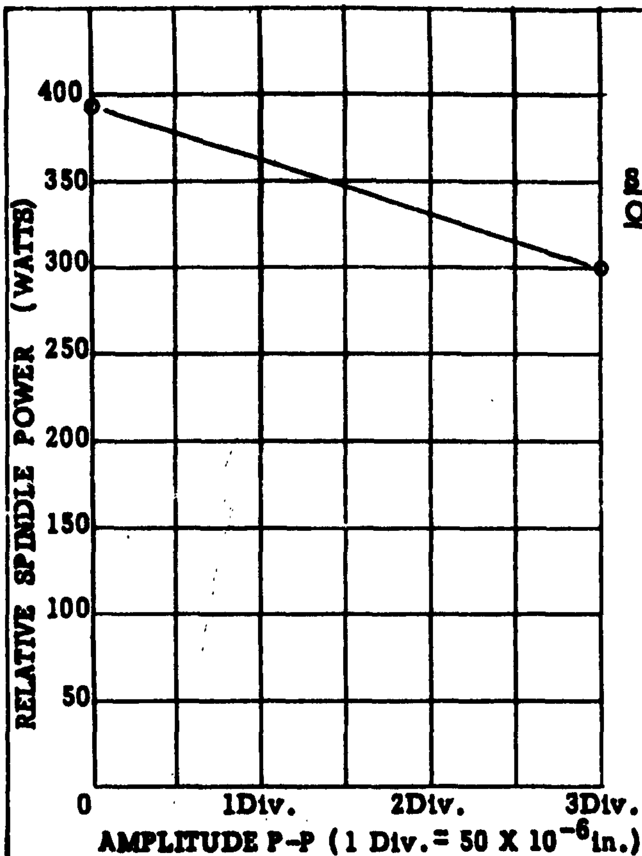
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	AA60-I8-V40
Wheel Speed SFPM	5263 to 5346
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.001 in.
Coolant	Sultran 176M

Run Numbers: 195, 196 - III

Figure 485



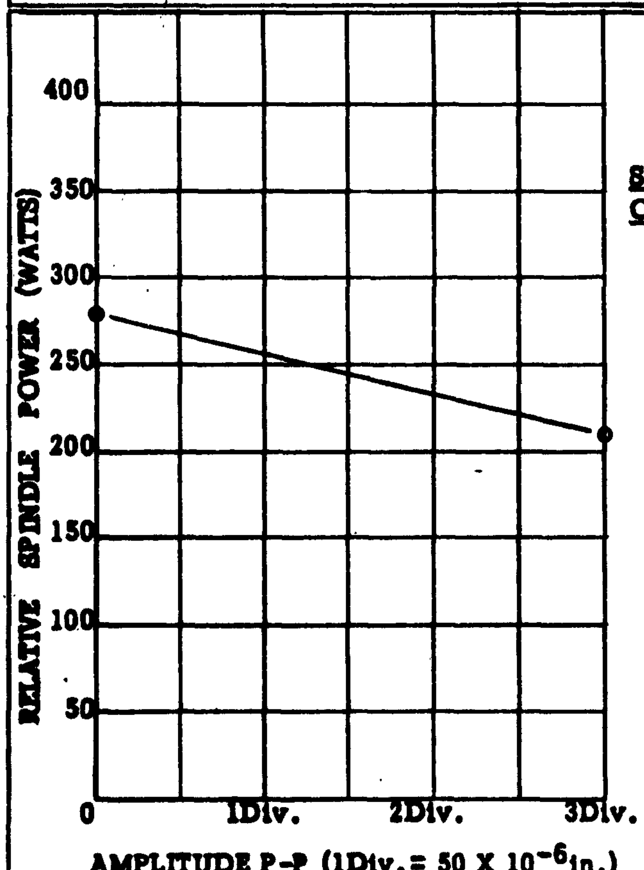
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	AA60I8-V40
Wheel Speed SFPM	5263 to 5346
Traverse Feed	10 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 197, 198 - III

Figure 486



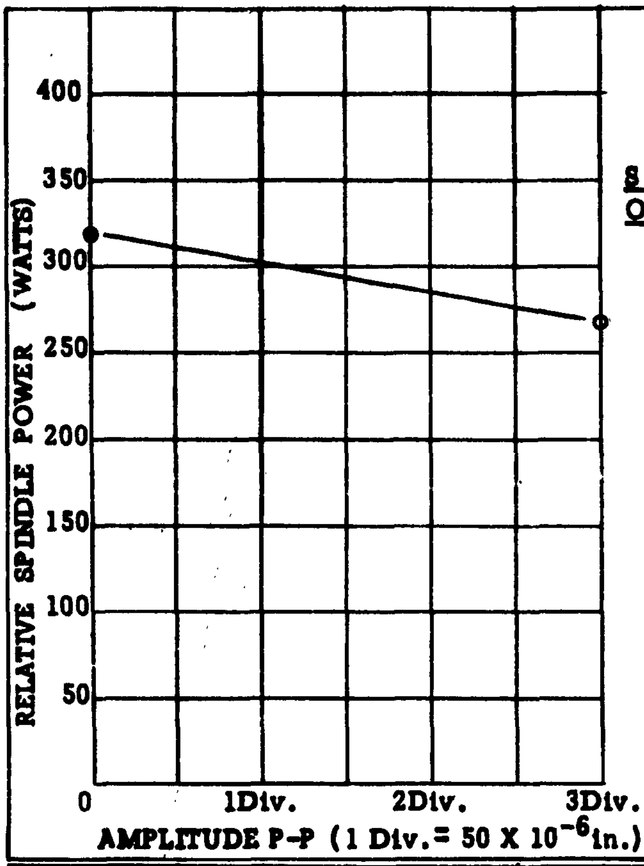
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	AA60I8-V40
Wheel Speed SFPM	5263 to 5346
Traverse Feed	6 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 199, 200 - III

Figure 487



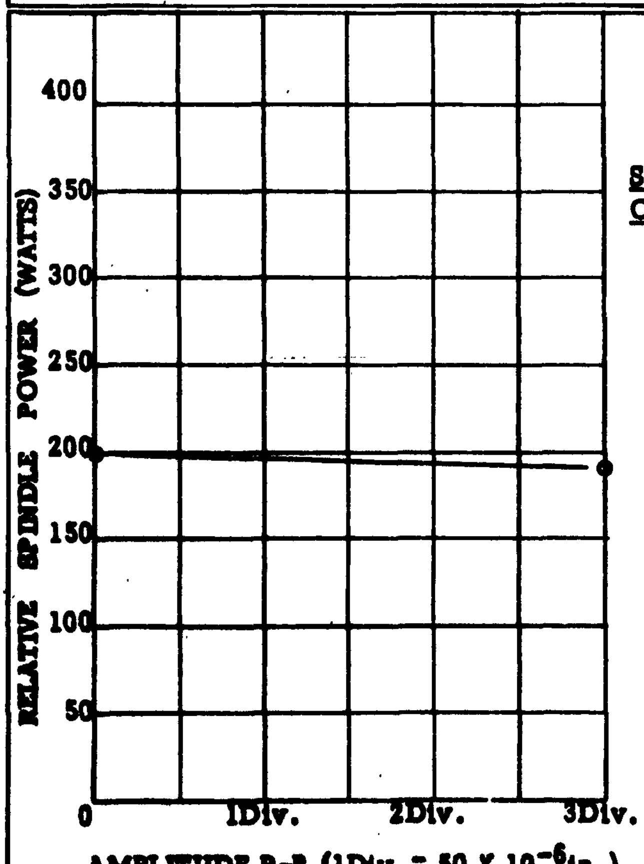
EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60L6-V10
Wheel Speed SFPM	5332 to 5362
Traverse Feed	6 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 205, 206 - III

Figure 488



EXTERNAL GRINDING

SPINDLE POWER AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60L6-V10
Wheel Speed SFPM	5332 to 5362
Traverse Feed	4 in./min.
Workpiece SFPM	45 to 50
Depth of Cut	0.002 in.
Coolant	Sultran 176M

Run Numbers: 207, 208 - III

Figure 489

RUN #	181	182	183	184	185	186	187	188
Material	Rene 41	Rene 41	Rene 41	Rene 41	Rene 41	Rene 41	Rene 41	H-11
Type of Grind	External 3 Division	External conventional	External 3 Division	External conventional	External 3 Division	External conventional	External 3 Division	External conventional
Wheel Used	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10
Traverse Speed in./min.	8	8	8	4	4	4	4	10
SFPM of Wheel	3275-3330	3275 - 3330	3275 - 3330	3275 - 3330	3275 - 3330	3275 - 3330	3275 - 3330	5362-5400
Spindle R.P.M.	1370	1370	1370	1370	1370	1370	1370	2260
SFPM of Specimen	48 to 50	48 to 50	48 to 50	48 to 50	48 to 50	48 to 50	48 to 50	45 to 50
Depth of Cut	0.0005"	0.001"	0.001"	0.0005"	0.0005"	0.001"	0.001"	0.001"
Number Passes	16	8	8	16	16	8	8	30
Coolant Used	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M
Volume of Work Removed	0.303 $in.^3$	0.292 $in.^3$	0.305 $in.^3$	0.289 $in.^3$	0.305 $in.^3$	0.268 $in.^3$	0.288 $in.^3$	1.159 $in.^3$
Relative Spindle Power	130	248	212	124	80	140	188	210
Grinding Ratio	14	8	11	14	21	9	11	80.9
Wheel diameter Before Grind	9.2055"	9.1925"	9.1815"	9.1690"	9.1560"	9.1455"	9.1335"	9.1225"
Wheel diameter After Grind	9.2040"	9.190"	9.1795"	9.1676"	9.1550"	9.1435"	9.1316"	9.1215"
Part Dimensions	2.500"o.d.	2.484"o.d.	2.475"o.d.	2.4675"o.d.	2.481"o.d.	2.4485"o.d.	2.453"o.d.	2.490"o.d.
Profilometer micro. in. (RMS)	20	30	30-32	10 - 13	18-22	18-22	22 - 28	50 - 60
Wheel condition after grind	very slight load	primary load glazed			no load no glaze	clean, no load no glaze	slight load	no loading
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind					no chatter	no chatter	slight chatter	

Figure 490

RUN #	189	190	191	192	193	194	195	196
Material	H - 11	H-11	H - 11	H - 11	H - 11		H - 11	H - 11
Type of Grind	External 3 Division	External conventional	External 3 Division	External conventional	External 3 Division	External	External conventional	External 3 Division
Wheel Used	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10		AA60I8-V40	AA60I8-V40
Traverse Speed in./min.	10	10	10	6	6		10	10
SFPM of Wheel	5362-5400	5362 - 5400	5362 - 5400	5362 - 5400	5362 -5400		5362 - 5400	5362 - 5400
Spindle R P M	2260	2260	2260	2260	2260		2260	2260
SFPM of Specimen	45 - 50	45 - 50	45 - 50	45 to 50	45 to 50		45 to 50	45 to 50
Depth of Cut	0.001"	0.002"	0.002"	0.001"	0.001"		0.001"	0.001"
Number Passes	30	15	15	30	30		30	30
Coolant Used	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M		Sultran 176M	Sultran 176M
Volume of Work Removed	1.166in.^{3}	1.196 in.^{3}	1.164 in.^{3}	1.11 in.^{3}	1.162 in.^{3}		1.126 in.^{3}	1.133 in.^{3}
Relative Spindle Power	160	430	354	157	100		220	175
Grinding Ratio	412	38	163	87	409		50	160
Wheel diameter Before Grind	9.0125"	9.0925"	9.0830"	9.0725"	9.0642"		9.0380"	9.0250"
Wheel diameter After Grind	9.0123"	9.0903"	9.0825"	9.0716"	9.0640"		9.0364"	9.0245"
Part Dimensions	2.505"o.d.	2.508"o.d.	2.501" o.d.	2.511" o.d.	2.493" o.d.		2.4400"o.d.	2.434"o.d.
Profilometer micro. in. (RMS)	45 - 60	38 - 45	40 - 45	35 - 40	35 - 45		38 - 45	40 - 52
Wheel condition after grind	very clean	slight loading	no loading	very slight loading	cracked		slight load	no load
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"		2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind		slight chatter		slight chatter			no chatter	

Figure 491

RUN #	197	198	199	200	201	202	203	204
Material	H-11	H - 11	H - 11	H - 11	H - 11	H - 11	H - 11	H - 11
Type of Grind	External convention	External 3 Division	External conventional	External 3 Division	External conventional	External 3 Division	External conventional	External 3 Division
Wheel Used	AA60I8-V40	AA60I8-V40	AA60I8-V40	AA60I8-V40	AA60I8-V40	AA60I8-V40	A60L6-V10	A60L6-V10
Traverse Speed in./min.	10	10	6	6	4	4	10	10
SFPM of Wheel	5362-5400	5362 - 5400	5362-5400	5362 - 5400	5362 - 5400	5362 - 5400	5362 - 5400	5362 - 5400
Spindle R.P.M.	2260	2260	2260	2260	2260	2260	2260	2260
SFPM of Specimen	45 to 50	45 to 50	45 to 50	45 to 50	45 to 50	45 to 50	45 to 50	45 to 50
Depth of Cut	0.002"	0.002"	0.002"	0.002"	0.002"	0.002"	0.002"	0.002"
Number Passes	15	15	15	15	15	15	15	15
Coolant Used	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M
Volume of Work Removed	1.015 in.^{3}	1.045 in.^{3}	1.092 in.^{3}	1.154 in.^{3}	1.075 in.^{3}	1.167 in.^{3}	1.114 in.^{3}	1.111 in.^{3}
Relative Spindle Power	386	298	280	220	192	120	430	394
Grinding Ratio	5	9	49	59	32	139	197	394
Wheel diameter Before Grind	9.0000"	8.980"	8.9610"	8.9450"	8.9135"	8.8970"	8.992"	8.9850"
Wheel diameter After Grind	8.9852"	8.972"	8.9594"	8.94355"	8.9111"	8.8964"	8.9916"	8.9848"
Part Dimensions	2.4440"o.d	2.492"o.d.	2.4900"o.d.	2.439"o.d.	2.431"o.d.	2.428" o.d.	2.4335"o.d.	2.3680"od.
Profilometer micro.in.(RMS)	42 - 58	42 - 50	50 - 60	45 - 52	30 - 42	35 - 42	40 - 52	40 - 52
Wheel condition after grind	heavy load	slight load	partial load	partial load	partial load	very slight load	no load	very slight load
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind			no chatter	slight chatter	slight chatter	slight chatter		

Figure 492

RUN #	205	206	207	208	209	210		
Material	H - 11	H - 11	H - 11	H - 11	H-11	H - 11		
Type of Grind	External convention	External 3 Division	External conventional	External 3 Division	External conventional	External 3 Division		
Wheel Used	A60L6-V10	A60L6-V10	A60L6-V10	A60L6-V10	A60L6-V10	A60L6-V10		
Traverse Speed in./min.	6	6	4	4	10	10		
SFPM of Wheel	5362-5400	5362 - 5400	5362 - 5400	5362 - 5400	5332 - 5362	5332 - 5362		
Spindle R.P.M.	2260	2260	2260	2260	2260	2260		
SFPM of specimen	45 to 50	45 to 50	45 to 50	45 to 50	45 to 50	45 to 50		
Depth of Cut	0.002"	0.002"	0.002"	0.002"	0.002 "	0.002"		
Number Passes	30	30	30	30	68	76		
Coolant Used	Sultran 176 M	Sultran 176 M	Sultran 176 M	Sultran 176 M	Sultran 176 M	Sultran 176 M		
Volume of Work Removed	2.180in.^{3}	2.158 in.^{3}	2.114 in.^{3}	2.158 in.^{3}	5.000in.^{3}	4.87 in.^{3}		
Relative Spindle Power	320	272	200	188	208	187		
Grinding Ratio	192	190	110	218	131	266		
Wheel diameter Before Grind	9.0460"	9.0360"	9.0280"	9.0125"	9.008"	8.9775"		
Wheel diameter After Grind	9.0452"	9.0352"	9.02664"	9.0118"	9.00535"	8.9762"		
Part Dimensions	2.431"o.d	2.369"o.d.	2.379"o.d.	2.369"o.d.	2.4925"o.d.	2.2180"od.		
Profilometer micro. in. (RMS)	30 - 40	30 - 38	25 - 32	22 - 35	2.2295"o.d.	1.918"o.d.		
Wheel condition after grind	very slight load	very slight load		no load	slight loading	very clean		
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002 " 2 - .001 "	2 - .002" 2 - .001"		
Part condition after grind					slight burn & chatter	no burn or chatter		

Figure 493

RUN #	134	135	136	137	138	139	140	141
Material	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V
Type of Grind	External Conventional	External 1 Division	External 2 Division	External 3 Division	External Conventional	External 1 Division	External 2 Division	External 3 Division
Wheel Used	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10
Traverse Speed in./min.	16	16	16	16	16	16	16	16
SFPM of Wheel	2060-2160	2060-2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160
Spindle R.P.M.	825	825	825	825	825	825	825	825
SFPM of Specimen	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59
Depth of Cut	0.002"	0.002"	0.002"	0.002"	0.001"	0.001"	0.001"	0.001"
Number Passes	8	4	4	4	8	8	8	
Coolant Used	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M
Volume of Work Removed	0.452in.^{3}	0.292 in.^{3}	0.243 in.^{3}	0.226 in.^{3}	0.305 in.^{3}	0.273 in.^{3}	0.305 in.^{3}	0.267 in.^{3}
Relative Spindle Power	680	620	620	760	570	520	480	480
Grinding Ratio	4.72	8.79	6.16	4.91	10.0	11.24	12.64	17.56
Wheel diameter Before Grind	10.009"	9.9902"	9.9804"	9.9624"	9.9191"	9.9039"	9.9929"	9.8752"
Wheel diameter After Grind	10.0029"	9.98808"	9.97788"	9.95946"	9.91714"	9.90234"	9.99136"	9.87422"
Part Dimensions	2.4308"dia.	2.4875"dia.	2.4765"dia.	2.402"dia.	2.4687"dia.	2.3852"dia.	2.4492"dia	2.4602"dia.
Profilometer micro.in.(RMS)	70	65	80 - 90	90 - 100	50	45 - 50	45 - 50	45 - 50
Wheel condition after grind	Primary loading			primary loading	primary loading			
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	burned & Scratchy	burned	burned & scratched	chatter & burn	some burn & chatter	moderate burn	moderate burn	light threaded burn

Figure 494

RUN #	142	143	144	145	146	147	148	149
Material	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V
Type of Grind	External conventional	External 1 Division	External 2 Division	External 3 Division	External conventional	External 1 division	External 2 Division	External 3 Division
Wheel Used	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10
Traverse Speed in./min.	8	8	8	8	8	8	8	8
SFPM of Wheel	2060 - 2160	2060 -2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160
Spindle R.P.M.	825	825	825	825	825	825	825	825
SFPM of Specimen	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59
Depth of Cut	0.002"	0.002"	0.002"	0.002"	0.001"	0.001"	0.001"	0.001"
Number Passes	4	4	4	4	8	8	8	8
Coolant Used	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M
Volume of Work Removed	0.227 $in.^3$	0.282 $in.^3$	0.276 $in.^3$	0.261 $in.^3$	0.288 $in.^3$	0.369 $in.^3$	0.261 $in.^3$	0.326 $in.^3$
Relative Spindle Power	440	590	550	440	280	200	160	204
Grinding Ratio	5.92	8.3	8.61	12.12	37.42	34.33	17.76	14.64
Wheel diameter Before Grind	9.6062"	9.8417"	9.8193"	9.8055"	9.7895"	9.7707"	9.7392"	9.7253"
Wheel diameter After Grind	9.60366"	9.8395"	9.81722"	9.8041"	9.789"	9.77"	9.7383"	9.72384"
Part Dimensions	2.3360"dia	2.4255"dia.	2.4412"dia.	2.3419"dia.	2.4092"dia.	2.4230"dia.	2.3113"dia	2.390"dia.
Profilometer micro.in.(RMS)	50-60	50-55	60-70		25-30	32	25-30	35
Wheel condition after grind		primary loading	primary loading	primary loading			slight prim. loading	slight prim. loading
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind		little chatter	no chatter or burn	moderate burning	very light burn	very light burn	very nice finish	nice finish

Figure 495

RUN #	150	151	152	153	154	155	156	157
Material	Ti6Al-4V	Ti6Al-4V	Ti6Al-4V	Ti6Al-4V	Ti6Al-4V	Ti6Al-4V	Ti6Al-4V	Ti6Al-4V
Type of Grind	External conventional	External 2 Division	External 3 Division	External 1 Division	External conventional	External 1 Division	External 2 Division	External 3 Division
Wheel Used	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10
Traverse Speed in./min.	8	8	8	8	16	16	16	16
SFPM of Wheel	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160
Spindle R.P.M.	825	825	825	825	825	825	825	825
SFPM of Specimen	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59
Depth of Cut	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"	0.0005"
Number Passes	16	16	16	16	16	16	16	16
Coolant Used	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M
Volume of Work Removed	0.291 $in.^3$	0.294 $in.^3$	0.323 $in.^3$	0.293 $in.^3$	0.338 $in.^3$	0.317 $in.^3$	0.319 $in.^3$	0.292 $in.^3$
Relative Spindle Power	204	100		60	120	250	220	160
Grinding Ratio	14.64	6.32	27.58	35.41	29.24	29.87	32.71	9.51
Wheel diameter Before Grind	9.7253"	9.7038"	9.6871"	9.6739"	9.6603"	9.65000"	9.6415"	9.6316"
Wheel diameter After Grind	9.72384"	9.70078"	9.6864"	9.6733"	9.65964"	9.64916"	9.64086"	9.62938"
Part Dimensions	2.390"dia.	2.394"dia.	2.2942"dia.	2.3763"dia.	2.367"dia.	2.3482"dia.	2.3546"dia	2.2736"dia.
Profilometer micro.in.(RMS)	20 - 23	18 - 20	25 - 28	25 - 28	25 - 30	22 - 28	30 - 32	28 - 32
Wheel condition after grind	minor prim. load	secondary loading	secondary loading	minor primary loading	minor primary loading	minor primary loading		
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	excellent	satin finish	satin finish	good	fairly good	fairly good	satin finish	satin finish

Figure 496

RUN #	158	159	160	161	162	163	164	165
Material	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V	T16Al-4V
Type of Grind	External conventional	External 3 Division	External conventional	External 3 Division	External conventional	External 3 Division	External conventional	External 3 Division
Wheel Used	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60P6-V10	A60P6-V10	A60P6-V10	A60P6-V10
Traverse Speed in./min.	4	4	4	4	8	8	16	16
SFPM of Wheel	2060-2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160	2060 - 2160
Spindle R.P.M.	825	825	825	825	825	825	825	825
SFPM of Specimen	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59	54 - 59
Depth of Cut	0.002"	0.002"	0.0005"	0.0005"	0.001"	0.001"	0.002"	0.002"
Number Passes	4	4	16	16	8	8	4	4
Coolant Used	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M	Vantrol 5456M
Volume of Work Removed	$0.298 in.^3$	$0.294 in.^3$	$0.248 in.^3$	$0.350 in.^3$	$0.232 in.^3$	$0.286 in.^3$	$0.252 in.^3$	$0.261 in.^3$
Relative Spindle Power	270	130	120		320	240	910	780
Grinding Ratio	13.35	18.79	103.3	33.32	13.56	12.54	7.18	4.99
Wheel diameter Before Grind	9.5895"	9.5787"	9.5677"	9.5477"	10.0900"	10.0854"	10.1670"	10.1074"
Wheel diameter After Grind	9.58802"	9.57766"	9.56754"	9.547"	10.08892"	10.08396"	10.1648"	10.1041"
Part Dimensions	2.2488"dia.	2.304" dia.	2.3150"dia.	2.2260"dia.	2.2882"dia.	2.2989"dia.	2.2673"dia.	2.2790"dia
Profilometer micro.in.(RMS)	22-30	35-40		22-25	25 - 32	35 - 38		
Wheel condition after grind	primary loading	primary loading	secondary loading	secondary loading	primary loading	primary loading	severe prim. loading	primary loading
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	fair finish	good finish	satin finish	satin finish	light burn	light burn & chatter	burn & chatter	light burn

Figure 497

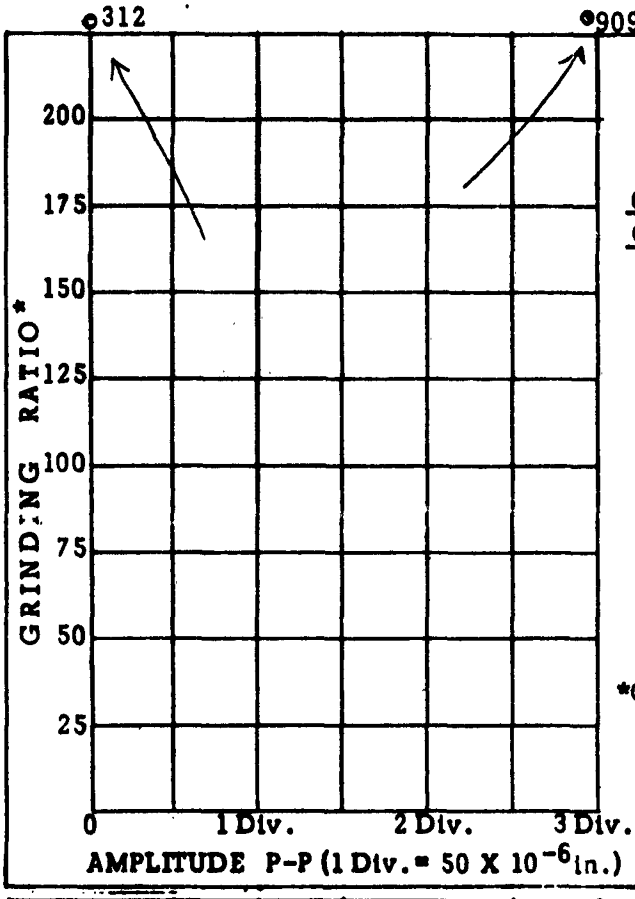
RUN #	166	167	168	169	169-A	170	171	172
Material	15 - 7MO	15-7 MO	15-7 MO	15-7 MO	15-7 MO	15-7 MO	15-7 MO	15-7 MO
Type of Grind	External conventional	External 1 Division	External 2 Division	External 3 Division	External 3 Division	External conventional	External 3 Division	External conventional
Wheel Used	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10
Traverse Speed in./min.	16	16	16	16	16	16	16	16
SFPM of Wheel	4558-4680	4558 - 4680	4558 - 4680	4558 - 4680	4558 - 4680	4558 - 4680	4558 - 4680	4558 - 4680
Spindle R.P.M.	1882	1882	1882	1882	1882	1882	1882	1882
SFPM of Specimen	74 to 81	74 to 81	74 to 81	74 to 81	74 to 81	74 to 81	74 to 81	74 to 81
Depth of Cut	0.002"	0.002"	0.002"	0.002"	0.002"	0.001"	0.001"	0.0005"
Number Passes	4	6	6	6	6	12	24	48
Coolant Used	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M
Volume of Work Removed	0.193in.^{3}	0.439 in.^{3}	0.498 in.^{3}	0.484 in.^{3}	0.483 in.^{3}	0.477 in.^{3}	0.923 in.^{3}	0.867 in.^{3}
Relative Spindle Power	1320	1000	960	1080	970	760	520	390
Grinding Ratio	47	74	58	63	29	124	142	140
Wheel diameter Before Grind	9.4968"	9.4865"	9.4716"	9.4485"	9.4290"	9.4090"	9.3904"	9.3691"
Wheel diameter After Grind	9.49652"	9.4861"	9.47102"	9.44798"	9.42788"	9.40874"	9.38996"	9.36868"
Part Dimensions	2.5057"o.d.	2.5032"o.d.	2.4995"o.d.	2.4839"o.d.	2.4753"o.d.	2.4727"o.d.	2.4546"o.d	2.4460"o.d.
Profilometer micro.in.(RMS)			55 - 60	50 - 55	45 - 50	35 - 38	35 - 38	
Wheel condition after grind	primary loading		primary loading		severe primary load on edges	minor primary loading	minor primary loading	minor primary loading
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	moderate burn	light burn	light burn at one end		good finish	little burn	good finish	burn & chatter

Figure 498

RUN #	173	174	175	176	177	178	179	180
Material	15-7 MO	15-7 MO	15-7 MO	Rene 41	Rene 41	Rene 41	Rene 41	Rene 41
Type of Grind	External 3 Division	External conventional	External 3 Division	External conventional	External 3 Division	External conventional	External 3 Division	External conventional
Wheel Used	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10	A60K6-V10
Traverse Speed in./min.	16	8	8	12	12	12	12	8
SFPM of Wheel	4558 -4680	4558 - 4680	4558 - 4680	3275 - 3330	3275 - 3330	3275 - 3330	3275 - 3330	3275 - 3330
Spindle R.P.M.	1882	1882	1882	1370	1370	1370	1370	1370
SFPM of Specimen	74 to 81	74 to 81	74 to 81	48 to 50	48 to 50	48 to 50	48 to 50	48 to 50
Depth of Cut	0.0005"	0.001"	0.001"	0.0005"	0.0005"	0.001"	0.001"	0.0005"
Number Passes	48	50	50	16	16	8	8	16
Coolant Used	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176M	Sultran 176 M	Sultran 176M	Sultran 176M
Volume of Work Removed	0.923 in.^{3}	1.794 in.^{3}	1.804 in.^{3}	0.296 in.^{3}	0.295 in.^{3}	0.237 in.^{3}	0.294 in.^{3}	0.293 in.^{3}
Relative Spindle Power	380	490	440	300	80	386	300	220
Grinding Ratio	393	471	154	7	7	4	5	11
Wheel diameter Before Grind	9.3567"	9.324"	9.3014"	9.2835"	9.2670"	9.2495"	9.2350"	9.2195"
Wheel diameter After Grind	9.35654"	9.32374"	9.3006"	9.2807"	9.2640"	9.2454"	9.23124"	9.21768"
Part Dimensions	2.3923" o.d	2.402" o.d.	2.3993" o.d.	2.521" o.d.	2.508" o.d.	2.515" o.d.	2.503" o.d	2.493" o.d.
Profilometer micro.in.(RMS)	25 - 32	25 - 32	30 - 35	55 - 65	40 - 45	45 - 55	60 - 65	25 - 30
Wheel condition after grind	very minor prim. load	light primary loading	minor primary loading	primary load sharp corners	slight loading sharp corners	slight load sharp corners	slight load sharp corner	glazed primary load
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind	excellent		excellent	chatter	slight chatter	chatter	chatter	chatter

Figure 499

14.3 Surface Grinding Test Data



SURFACE GRINDING

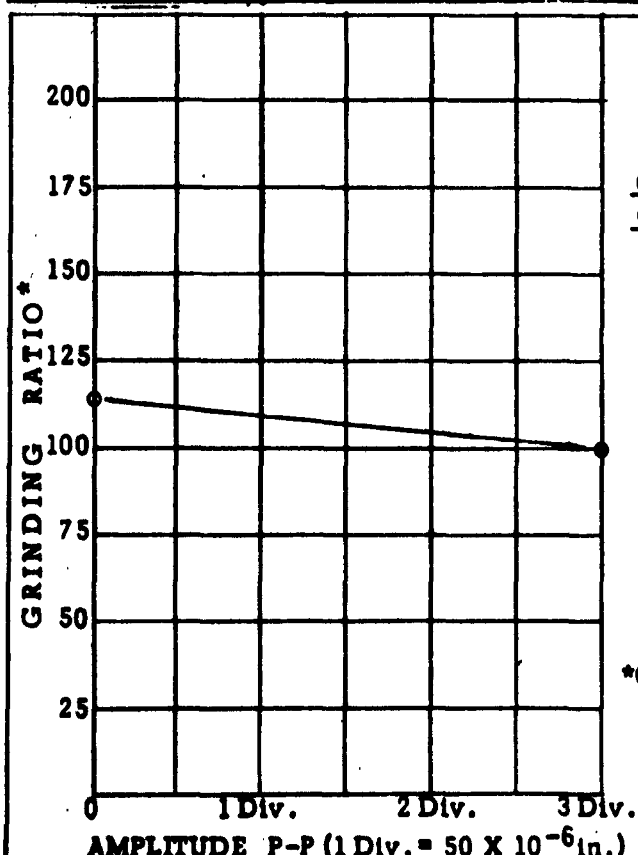
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	15-7 MO
Wheel	AA60-I8-V40
Wheel Speed	5775 SFPM
Traverse Feed	35 FPM
Infeed	0.050 inch
Depth of Cut	0.001 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers; 218, 219 - III

Figure 500



SURFACE GRINDING

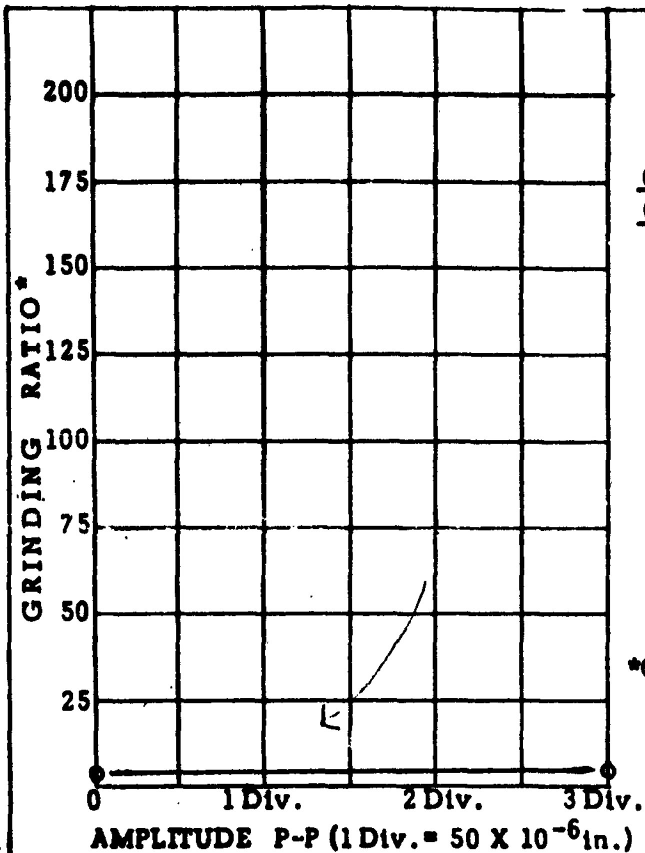
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	15-7 MO
Wheel	AA60-F8-V40
Wheel Speed	5775 SFPM
Traverse Feed	35 FPM
Infeed	0.050 inch
Depth of Cut	0.001 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 220, 221 - III

Figure 501



SURFACE GRINDING

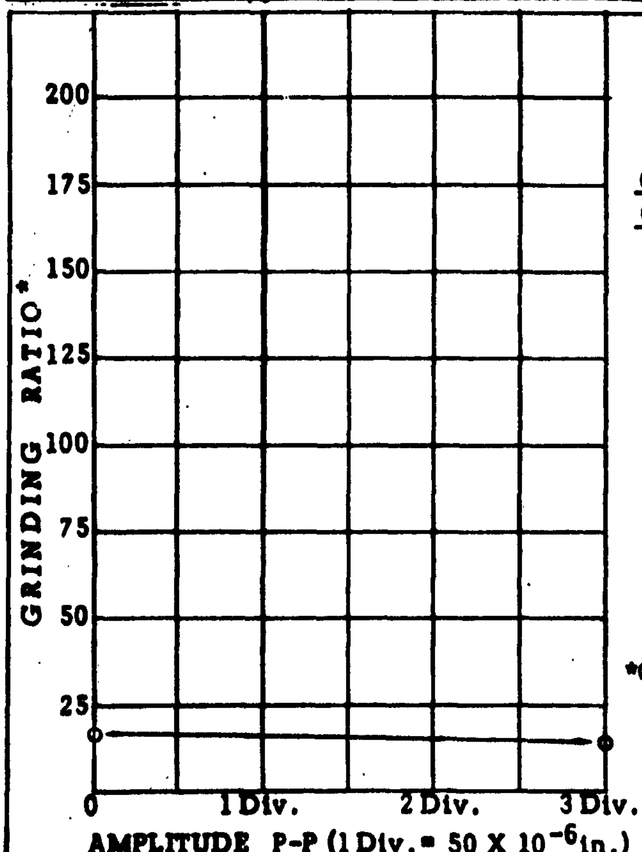
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	T16Al-4V
Wheel	A60-L8-V40
Wheel Speed	1885-1858 SFPM
Traverse Feed	35 FPM
Infeed	0.050 inch
Depth of Cut	0.001 inch
Coolant	Vantrol 5456M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 214, 215 - III

Figure 502



SURFACE GRINDING

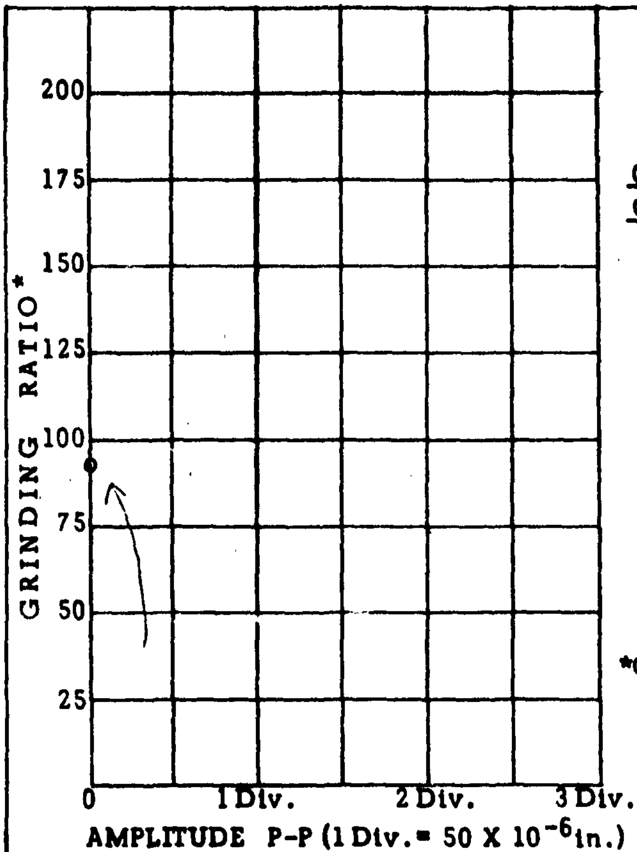
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	AA60-I8-V40
Wheel Speed	2305-2290 SFPM
Traverse Feed	35 FPM
Infeed	0.050 inch
Depth of Cut	0.001 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 216, 217 - III

Figure 503



SURFACE GRINDING

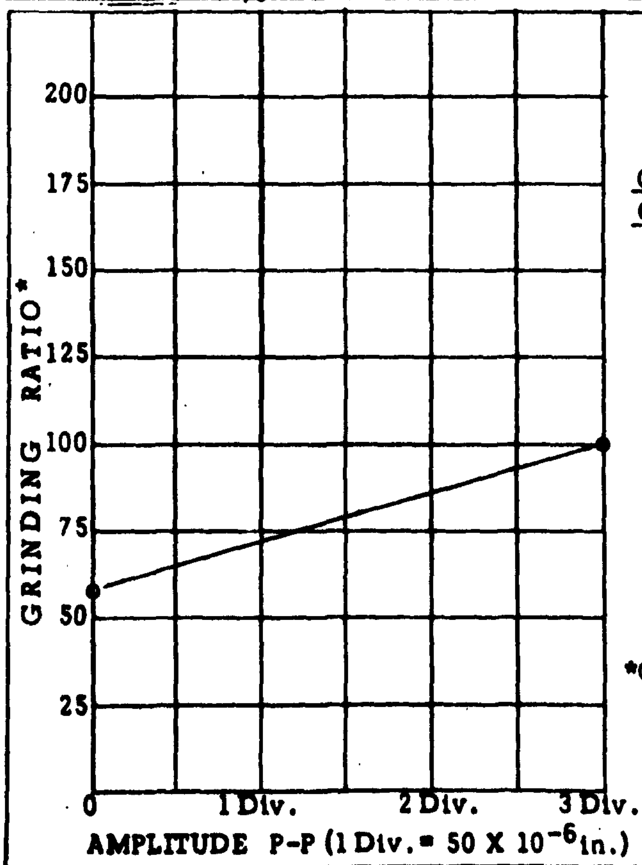
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60-R8-V10
Wheel Speed	4900 SFPM
Traverse Feed	35 FPM
Infeed	0.050 inch
Depth of Cut	0.001 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Number: 211 - III

Figure 504



SURFACE GRINDING

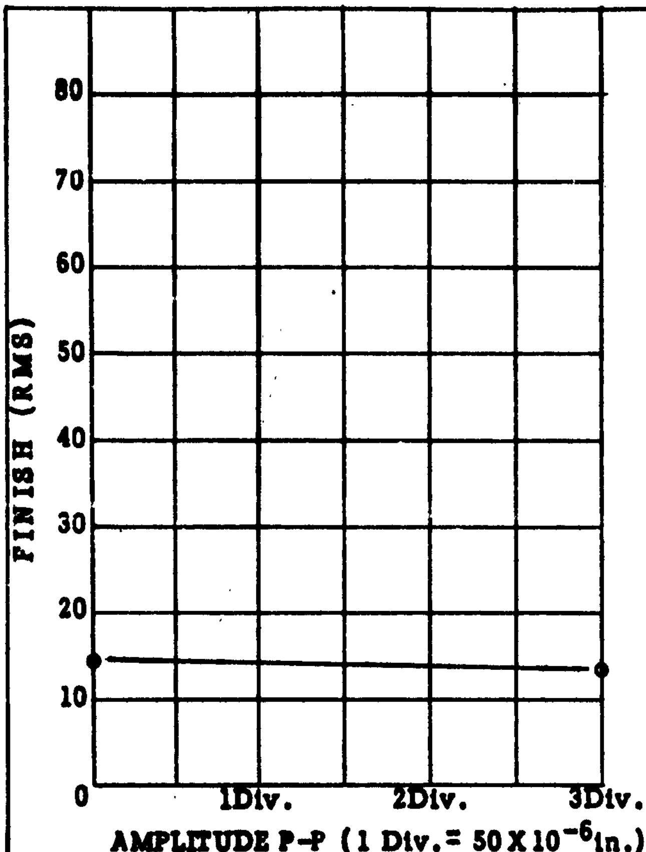
GRINDING RATIOS AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	AA60-I8-V40
Wheel Speed	4870-4860 SFPM
Traverse Feed	35 FPM
Infeed	0.050 inch
Depth of Cut	0.001 inch
Coolant	Sultran 176M

$$\text{*GRINDING RATIO} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Run Numbers: 212, 213 - III

Figure 505



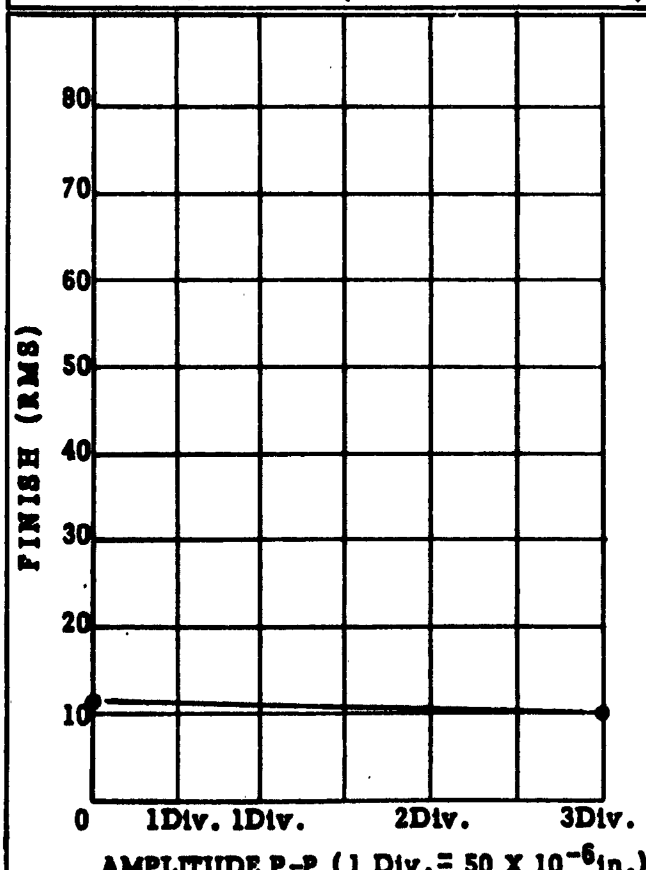
SURFACE GRINDING

FINISH AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	15-7 MO
Wheel	AA60-I8-V40
Wheel Speed	5775 SFPM
Traverse Feed	35 FPM
Infeed	0.050 inch
Depth of Cut	0.001 inch
Coolant	Sultran 176M

Run Numbers: 218, 219 - III

Figure 506



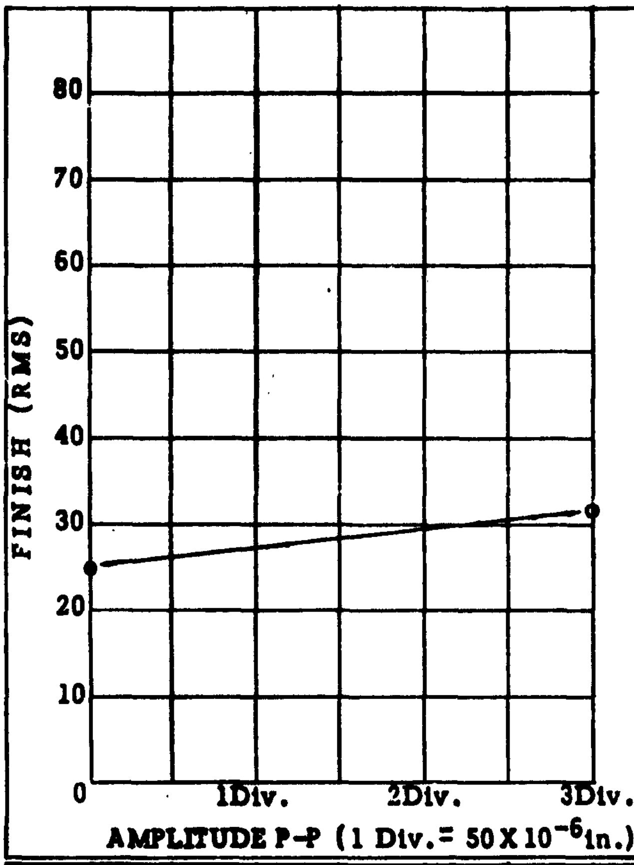
SURFACE GRINDING

FINISH AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	15-7 MO
Wheel	AA60-F8-V40
Wheel Speed	5775 SFPM
Traverse Feed	35 FPM
Infeed	0.050 inch
Depth of Cut	0.001 inch
Coolant	Sultran 176M

Run Numbers: 220, 221 - III

Figure 507



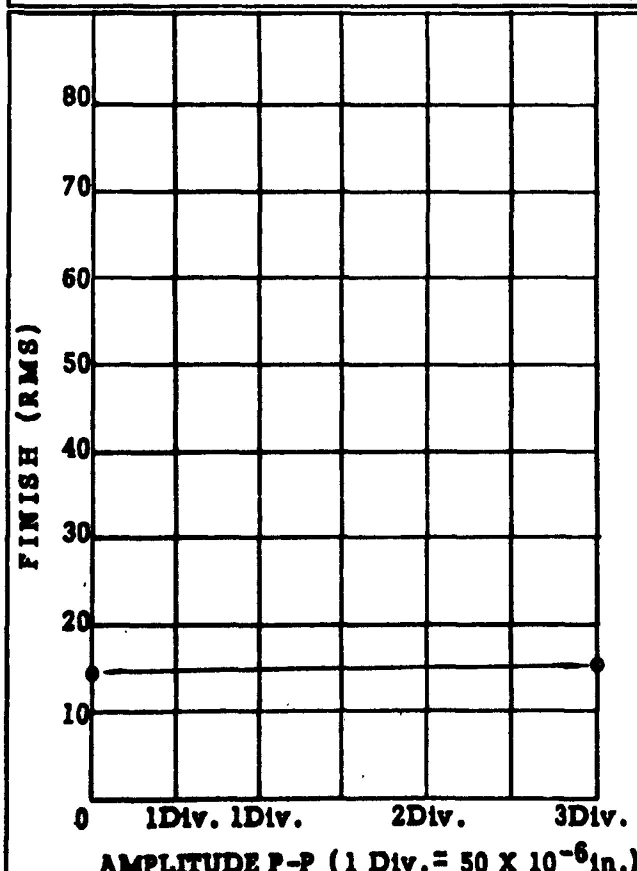
SURFACE GRINDING

FINISH AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Ti6Al-4V
Wheel	A60-L8-V40
Wheel Speed	1885-1858 SFPM
Traverse Feed	35 FPM
Infeed	0.050 inch
Depth of Cut	0.001 inch
Coolant	Vantrol 5456M

Run Numbers: 214, 215 - III

Figure 508



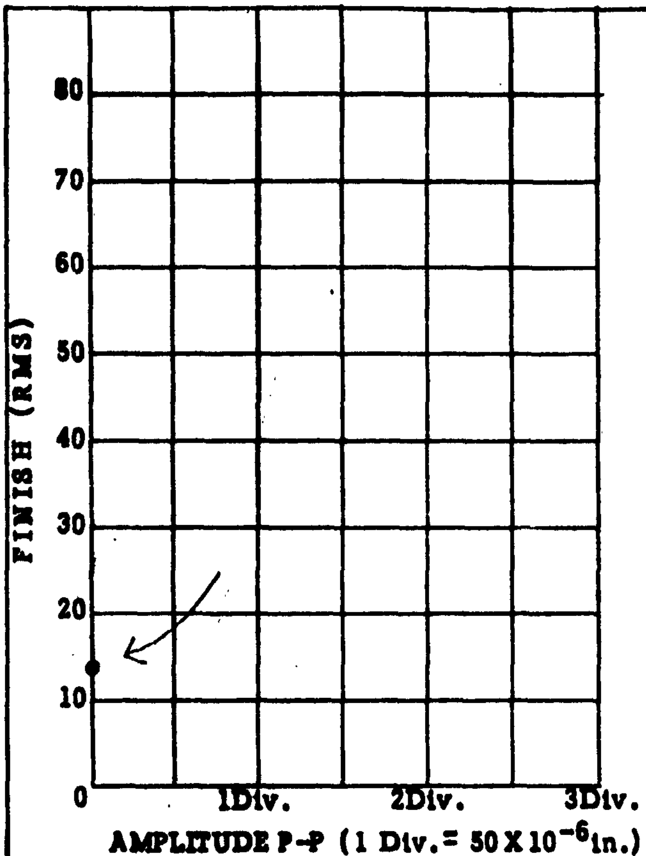
SURFACE GRINDING

FINISH AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	Rene 41
Wheel	AA60-I8-V40
Wheel Speed	2305-2290 SFPM
Traverse Feed	35 FPM
Infeed	0.050 inch
Depth of Cut	0.001 inch
Coolant	Sultran 176M

Run Numbers: 216, 217 - III

Figure 509



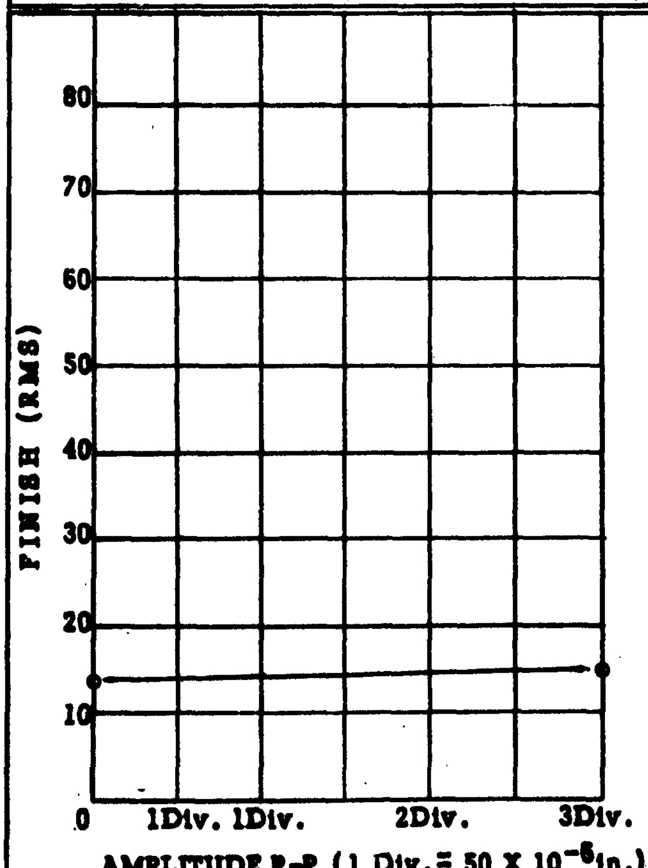
SURFACE GRINDING

FINISH AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	A60-R8-V10
Wheel Speed	4900 SFPM
Traverse Feed	35 FPM
Infeed	0.050 inch
Depth of Cut	0.001 inch
Coolant	Sultran 176M

Run Numbers: 211 - III

Figure 510



SURFACE GRINDING

FINISH AS A FUNCTION OF AMPLITUDE OF VIBRATION

Material	H-11
Wheel	AA60-I8-V40
Wheel Speed	4870-4860 SFPM
Traverse Feed	35 FPM
Infeed	0.050 inch
Depth of Cut	0.001 inch
Coolant	Sultran 176M

Run Numbers: 212, 213 - III

Figure 511

RUN #	219	220	221					
Material	15-7 MO	15 - 7 MO	15 - 7 MO					
Type of Grind	Surface 3 Division	Surface conventional	Surface 3 Division					
Wheel Used	AA60I8-V40	AA60F8-V40	AA60F8-V40					
Traverse Speed ft./min.	35	35	35					
SFPM of Wheel	5770	5775	5775					
Spindle R.P.M.	2500	2500	2500					
Infeed/pass	0.050"	0.050"	0.050"					
Depth of Cut	0.001"	0.001"	0.001"					
Number Passes	80		80					
Coolant Used	Sultran 176M	Sultran 176M	Sultran 176 M					
Volume of Work Removed	0.619in.^{3}	0.636in.^{3}	0.64in.^{3}					
Relative Spindle Power								
Grinding Ratio	909	114	103					
Wheel diameter Before Grind	8.6690"	8.8800"	8.8200"					
Wheel diameter After Grind	8.6689"	8.8792"	8.8191"					
Part Dimensions								
Profilometer micro.in.(RMS)	13	13	11					
Wheel condition after grind	primary load	primary loading	primary loading					
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"					
Part condition after grind		slight burn	no burning					

Figure 512

RUN #	211	212	213	214	215	216	217	218
Material	H -11	H - 11	H - 11	T16Al-4V	T16Al-4V	Rene 41	Rene 41	15-7 MO
Type of Grind	Surface convention	Surface conventional	Surface 3 Division	Surface conventional	Surface 3 Division	Surface conventional	Surface 3 Division	Surface conventional
Wheel Used	A60R8-V10	AA60I8-V40	AA60I8-V40	A60L8-V40	A60L8-V40	AA60I8-V40	AA60I8-V40	AA60I8-V40
Traverse Speed ft./min.	35	35	35	35	35	35	35	35
SFPM of Wheel	4900	4870	4860	1885	1858	2305	2290	5775
Spindle R.P.M.	2100	2100	2100	810	810	1000	1000	2500
Infeed/pass	0.050"	0.050"	0.050"	0.050"	0.050"	0.050"	0.050"	0.050"
Depth of Cut	.001"	.001"	.001"	.001"	.001"	.001"	.001"	.001"
Number Passes	80	80		40	40		40	80
Coolant Used	Sultran 176M	Sultran 176M	Sultran 176M	Vantrol 5456M	Vantrol 5456M	Sultran 5456M	Sultran 5456 M	Sultran 5456M
Volume of Work Removed	0.632 in.^{3}	0.616 in.^{3}	0.632 in.^{3}	0.28 in.^{3}	0.312 in.^{3}	0.254 in.^{3}	0.608 in.^{3}	0.64 in.^{3}
Relative Spindle Power	120		40					
Grinding Ratio	90	58	101	4	6	16	15	312
Wheel diameter Before Grind	8.9220"	8.8630"	8.845"	8.8900"	8.765"	8.804"	8.753"	8.714"
Wheel diameter After Grind	8.9210"	8.8615"	8.8441"	8.8788"	8.757"	8.8017"	8.750"	8.7137"
Part Dimensions								
Profilometer micro.in.(RMS)	13	13	15	25	32	15	16	14
Wheel condition after grind	heavy load	secondary loading		primary load	slightly loaded	primary load	very slight loading	primary loaded
Wheel dressing Used	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2-.002" 2-.001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"	2 - .002" 2 - .001"
Part condition after grind		burned			no burning slt. chatter			

Figure 513

14.4 **Simulated Production Runs Selected and Made from Grinding Tests Performed (Sections 14.1 - 14.3)**

Run	Type Grind	Depth of Cut	Traverse Feed (Inches/min.)	Grinding Ratio	Volume of work removed	Total Time	Volume of work removed/hour	Finish R.M.S.	surface cracking	Burns	Spindle Power
P-1	ult. 3div.	0.0015"	3	31	0.322cu.in.	16.7min.	1.157 cu.in.	60	none	none	200
P-2	ult. 3div.	0.0015"	3	55	0.328cu.in.	16.7min	1.178 cu. in.	59	none	none	180
P-3	ult. 3div.	0.0015"	3	120	0.331cu.in.	16.7min	1.189 cu. in.	50	none	none	220
P-4	ult. 3div.	0.0015"	3	70	0.345cu.in.	16.7min	1.240 cu. in.	50	none	none	210
P-5	ult. 3div.	0.0015"	3	48	0.332cu.in.	16.7min	1.193 cu. in.	58	none	none	215
P-6	conv.	0.001"	1	43	0.341cu.in.	75 min.	0.273 cu. in.	26	none	none	180
P-7	conv.	0.001"	[illegible]	49	0.369cu.in.	75 min.	0.295 cu. in.	26	none	none	170
P-8	conv.	0.001"	1	64	0.344cu.in.	75 min.	0.275 cu. in.	25	none	none	150
P-9	conv.	0.001"	1	34	0.348cu.in.	75 min.	0.278 cu. in.	30	none	none	200
P-10	conv.	0.001"	1	37	0.352cu.in.	75 min.	0.282 cu. in.	32	none	none	180
P-11	ult. 3div.	0.001"	2	282	0.342cu.in.	37.5min	0.547 cu. in.	28	none	none	140
P-12	ult. 3div.	0.001"	2	249	0.343cu.in.	37.5min	0.549 cu. in.	34	none	none	100
P-13	ult. 3div.	0.001"	2	265	0.341cu.in.	37.5min	0.546 cu. in.	30	none	none	120
P-14	ult. 3div.	0.001"	2	207	0.336cu.in.	37.5min	0.538 cu. in.	30	none	none	130
P-15	ult. 3div.	0.001"	2	104	0.337cu.in.	37.5min	0.539 cu. in.	34	none	none	130

1 div. = 50×10^{-6} P-P Amplitude of Vibration

Grinding Ratio = $\frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$

INTERNAL SIMULATED PRODUCTION GRINDS

Material - Ti6Al-4V
Workhead SFPM - 38 to 40

Wheel - C60P5-VE
Wheel Speed - 2850 to 2900 SFPM

Figure 514

Run	Type Grind	Depth of Cut	Traverse Feed (inches/min.)	Grinding Ratio	Volume of work Removed	Total Time	Volume of work removed / hour	Finish R.M.S.	Surface cracking	burns	Spindle Power
P-16	conv.	0.002"	10	150	1.046 $in.^3$	15 min.	4.164 $in.^3$	50	none	none	404
P-17	conv.	0.002"	10	156	1.10 $in.^3$	15 min.	4.40 $in.^3$	45	none	none	400
P-18	conv.	0.002"	10	149	1.05 $in.^3$	15 min.	4.20 $in.^3$	50	none	none	402
P-19	conv.	0.002"	10	156	1.05 $in.^3$	15 min.	4.20 $in.^3$	55	none	none	420
P-20	conv.	0.002"	10	157	1.1 $in.^3$	15 min.	4.40 $in.^3$	45	none	none	444
P-21	3 Div Ult.	0.002"	10	394	1.05 $in.^3$	15 min.	4.20 $in.^3$	47	none	none	370
P-22	3 Div. Ult.	0.002"	10	390	1.06 $in.^3$	15 min.	4.24 $in.^3$	47	none	none	360
P-23	3 Div. Ult.	0.002"	10	394	1.07 $in.^3$	15 min.	4.28 $in.^3$	47	none	none	376
P-24	3 Div. Ult.	0.002"	10	391	1.06 $in.^3$	15 min.	4.24 $in.^3$	47	none	none	358
P-25	3 Div. Ult.	0.002"	10	403	1.08 $in.^3$	15 min.	4.32 $in.^3$	45	none	none	374

1 div. = 50×10^{-6} P-P Amplitude of Vibration

$$\text{Grinding Ratio} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

EXTERNAL SIMULATED PRODUCTION GRINDS

Material - H-11
Workhead SFPM - 47

Wheel - A60-L6V10
Wheel Speed - 2260 SFPM

Figure 515

Run	Type Grind	Depth of Cut	Infeed/ Pass	Grinding Ratio	Volume of work Removed	TOTAL TIME	Volume of work removed/hour	Finish R.M.S.	surface cracking	Burns	spindle power
P-26	conv.	0.001"	0.050"		0.632 cu. in.	4hrs. 40 min.	0.136 cu. in.	12	none	none	100
P-27	conv.	0.001"	0.050"		0.634 cu. in.	5hrs. 10 min.***	0.122 cu. in.	13	none	none	200
P-28	conv.	0.001"	0.050"		0.638 cu. in.	4hrs. 40 min.	0.137 cu. in.	10	none	none	160
P-29	conv.	0.001"	0.050"		0.642 cu. in.	5hrs. 10 min.***	0.124 cu. in.	13	none	none	240
P-30	conv.	0.001"	0.050"	116*	0.647 cu. in.	4hrs. 40 min.	0.139 cu. in.	11	none	none	200
P-31	3div. Ult.	0.001"	0.050"		0.624 cu. in.	4hrs. 40 min.	0.134 cu. in.	14	none	none	100
P-32	3 div. Ult.	0.001"	0.050"		0.659 cu. in.	4hrs. 40 min.	0.141 cu. in.	14	none	none	150
P-33	3 div. Ult.	0.001"	0.050"		0.627 cu. in.	4hrs. 40 min.	0.135 cu. in.	13	none	none	100
P-34	3 div. Ult.	0.001"	0.050"		0.632 cu. in.	4hrs. 40 min.	0.136 cu. in.	15	none	none	100
P-35	3 div. Ult.	0.001"	0.050"	197**	0.656 cu. in.	4 hrs. 40 min.	0.140 cu. in.	15	none	none	100

*Grinding Ratio for the Conventional Group **Grinding Ratio for the Ultrasonic Group

Wheel Dressed After
Run 27 &
Run 29 due to burn

SURFACE SIMULATED PRODUCTION GRINDS

1 div. = 50×10^{-6} P-P Amplitude of Vibration

Material 15-7 MO

Wheel was not Dressed after beginning of the ultrasonic grind - Run # 31

$$\text{Grinding Ratio} = \frac{\text{Vol. Material Removed}}{\text{Vol. Wheel Loss}}$$

Wheel:
Conventional AA60F8V40
Ultrasonic AA60I8V40

*** includes time to dress and measure wheel to determine wheel wear

Wheel Speed 2500 SFPM Traverse Speed 35 FPM

Figure 516

15. Determinations from Tests and Simulated Production Runs

15.1 Operational Feasibility

15.2 Adaptability to Specific Grinding Operations Performed

15.3 Design Variations for Effectiveness on Different Grinders

15.4 Design Portrayals of Adaptations or Modifications of Existing Grinder Types

15.5 Substantiations of Phase II Findings

15.6 Procurement Specifications

PHASE III

15.1 Operational Feasibility

After careful study and evaluation of production tests and previous information, the determination of operational feasibility of inducing vibrations to the grinding wheel has been established. Set forth below is a detailed account:

A. Wheel and Bond Life

1. Endurance of grinding wheel: - through previous ultrasonic grinding tests and operations, a maximum amplitude of vibration of 150 X 10^{-6}in. peak to peak amplitude has been established. This stroke is sufficiently under an amplitude of vibration that would cause the wheel to fracture. (approximately 350 X 10^{-6}in. peak to peak)

2. Endurance of Bond: - a maximum amplitude of 150 X 10^{-6} in. peak to peak vibration also has been determined as being a safe level for the A-4 type epoxy bond. Therefore (outside of any external stresses) the bond life should be indefinite.

3. Wear life of Grinding Wheel: - the ultrasonic grinding tests definitely proved, in most cases their superiority of the grinding ratios over that of conventional grinding, which in turn improves the wear life of the grinding wheels.

B. Transducer and Hub Life

1. Transducer. Previous experience under more severe operating conditions; the transducer is of the same design and material as the transducers used on Sheffield's 1000 Watt Cavitron machine Tool. The later machines, through many varied machine applications, have had their respective transducers subjected to four times the stress levels that will ever be experienced by the ultrasonic grinding transducer.

2. Project Experience: approximately 1000 hours of ultrasonic excitation has been applied to the ultrasonic transducer without any indication of fatigue or failure.

3. Transducer Designed More Robust than Power Required to Put Forth: Since the Transducer had been a stock item, it was well suited for the design requirements of the 1000 Watt ultrasonic spindle. The only disadvantage was its large overall rectangular dimension.

4. Extra Care in Winding and Insulating Transducer: the transducer was wound very carefully with tight turns of special Kel-F coated wire whose ends were secured to prevent chafing and shorting of the wires. A .010" mylar insulation sheet was placed between the coils to prevent chafing, for added coil life.

5. Exact Mounting of Transducer to Connecting Body: the rectangular cross section of the transducer stack was symetrically located around the center line of the connecting body and induction silver soldered to the rear face of the connecting body. Then, the whole unit was normalized (*) to relieve stress and insure longer connecting body life. *600°F for 1 hour. furnace cool with reducing atmosphere.

6. Robust Connecting Body: - the existing connecting body was designed to cover all grinding, and ultrasonic stresses encountered during internal, surface and external grinding, plus having additional rigidity to minimize wheel chatter to piece part.

7. Robust Connecting Stud: - the stud is so designed as to assure a rigid connection between hub and connecting body. The stud thread is undercut and stress relived at the parting surface junction to guarantee 100% stud thread contact when properly tightened.

8. Effective Mounting of Transducer to Minimize Transmission of Vibration to other Components: a mounting flange was designed at the nodal plane of the connecting body and dowel pinned to a matching surface of the transducer enclosure. The above parting surfaces were coupled by evenly torqued cap screws. Vibration transmission through these interfaces was minimized by virtue of the poor ultrasonic coupling this shear junction offers.

Hubs

1. Resonant body with proper flange (dimensions) and cross sectional the hub flange was designed to accommodate the varied wheel thicknesses used. The flange periphery was knurled to increase the bonding surface area. The cross section was of suitable area to drive (ultrasonically resonant) the largest wheel of 9" diameter.

2. Endurance: - the hub, (made of K Monel) upon completion of fabrication was stress relieved and all of the surface areas surrounding the nodal plane were vapor honed to stress relieve the surface, assuring longer hub life.

3. Attachment Provision: - a counterbored recess (a round threaded hole) was machined on one end of the hub to receive the male end of the connecting body. This was to alleviate shear stresses to the connecting stud and to maintain concentric alignment of hub and connecting body.

4. Minimum Wear Characteristics: - stress relieved hub provides longer hub resonant life. Molybdenum coating to female thread and counter bore reduces wear on removal and installation performances.

C. Bearings

1. Availability: - Bearings selected are standard tapered roller bearings which are easily purchased.

2. Load Characteristics: - Bearings are arranged, in the spindle, with a slight preload, to maintain good coupling of the bearing rollers between their respective races. This damping effect, reduces any possible roller chatter which would occur when the ultrasonic spindle was energized. Without this preload, the bearings would wear.

3. Wear Life: - over 1000 running hours have been logged against the existing prototype spindle bearings, without any signs of wear.

4. Physical size: - the minimum diameter of the bearings were dictated by the outside dimension of the connecting body flange. Therefore bearing selection became selective.

5. Surface Feet Per Minute Range: - the maximum RPM experienced by the spindle (during internal grinding) was 3500 RPM. The latter fell 10% short of the maximum operating safe limits of the bearings. With proper lubrication, bearing life should be indefinite.

6. Temperature: - One of the advantages that the ultrasonic spindle has over conventional spindles is, bearing temperature control. Normal bearing operating temperatures (130°F to 160°F) can be controlled by the coolant water flow through the transducer housing.

D. Brushes

1. Availability: - the brushes are standard slip ring type brushes and are readily available.

2. Load characteristics: - the cross sectional area of the brushes are 4 times the area required to carry the maximum current supplied by the polarizing current

3. Wear Life: - as previously stated, there is sufficient cross section area to the brushes to insure longer wear life.

4. S.F.M. - the brushes contact the slip ring on a small diameter to reduce wear caused by higher S.F.M.

E. Generator

1. Availability: - generators are commercially available to suit power and frequency requirements.

2. Power Regulators and Control: - the power can be manually operated by turning power control knob on generator panel.

3. Frequency Stability: - the operating frequency of 19 to 20 kc in the 1000 Watt generator is stable to within ± 100 cycles of any setting.

4. Breakdown and Maintenance: - this particular model generator (1000 Watt, 20 kc) has been in service, supply power to Sheffield Cavitron machine tools for several years with a good service record.

F. Corrosion

1. Corrosion Resistance of Components: - all parts in the spindle coming into contact with the water coolant are fabricated of corrosion resistant materials such as 303 stainless, K Monel, and heat treated 420 stainless.

2. Sound Insulation of Components from Cavitation Erosion: - all internal surfaces housing the nickel transducer stack have been coated with a thin layer of silicone cured rubber as well as the surface of the free end of the nickel stack.

3. Proper Coolant Supply Passages: - all conduit supplying coolant water have sufficient capacity to allow moderate flow at low pressures (operating flow varies 1 quart to 1 gallon/minute).

G. Coolants

1. Proper Coolant: - Water free of harmful mineral deposits should be used.

2. Flow Control: - Spindle should be equipped with reducing pressure regulator and flow control valve.

3. Rotary Seals: - two neoprene lip seals are used on the small diameter spindle shaft. This shaft offers low S.F.M. to the seal lips insuring a longer seal life. These seals can withstand 20 times the maximum water pressure they will ever experience under normal coolant requirements.

4. Static Seals: - there are two types of static seals used:

   a. neoprene gasket seal
   b. "O" rings (Buna Rubber)

   Both are sufficient for the static sealing requirements of the spindle.

15.2 Adaptability to Specific Grinding Operations Performed: - after development and testing in Phase III of the selected vibration mechanism (internal, external and surface grinding), the adaptability to each grinding operation has been determined with each grinder type becoming an ultrasonic grinder by attaching an ultrasonic spindle.

Surface Grinding

External Grinding

Internal Grinding

a. Spindle dimensions - *limited by ultrasonic requirements and machine capacity.

b. wheel sizes and types - *limited by ultrasonic requirements and machine capacity.

c. spindle horsepower - *limited by ultrasonic requirements and machine capacity.

d. speed range of spindle - *limited by S.F.M of bearings and the state of balance of ultrasonic transducer in spindle.

e. part size range - *limited by ultrasonic requirements and machine capacity.

*see precurement specifications, Section 4, part 7.

15.3 Design Variations for Effectiveness on Different Grinders

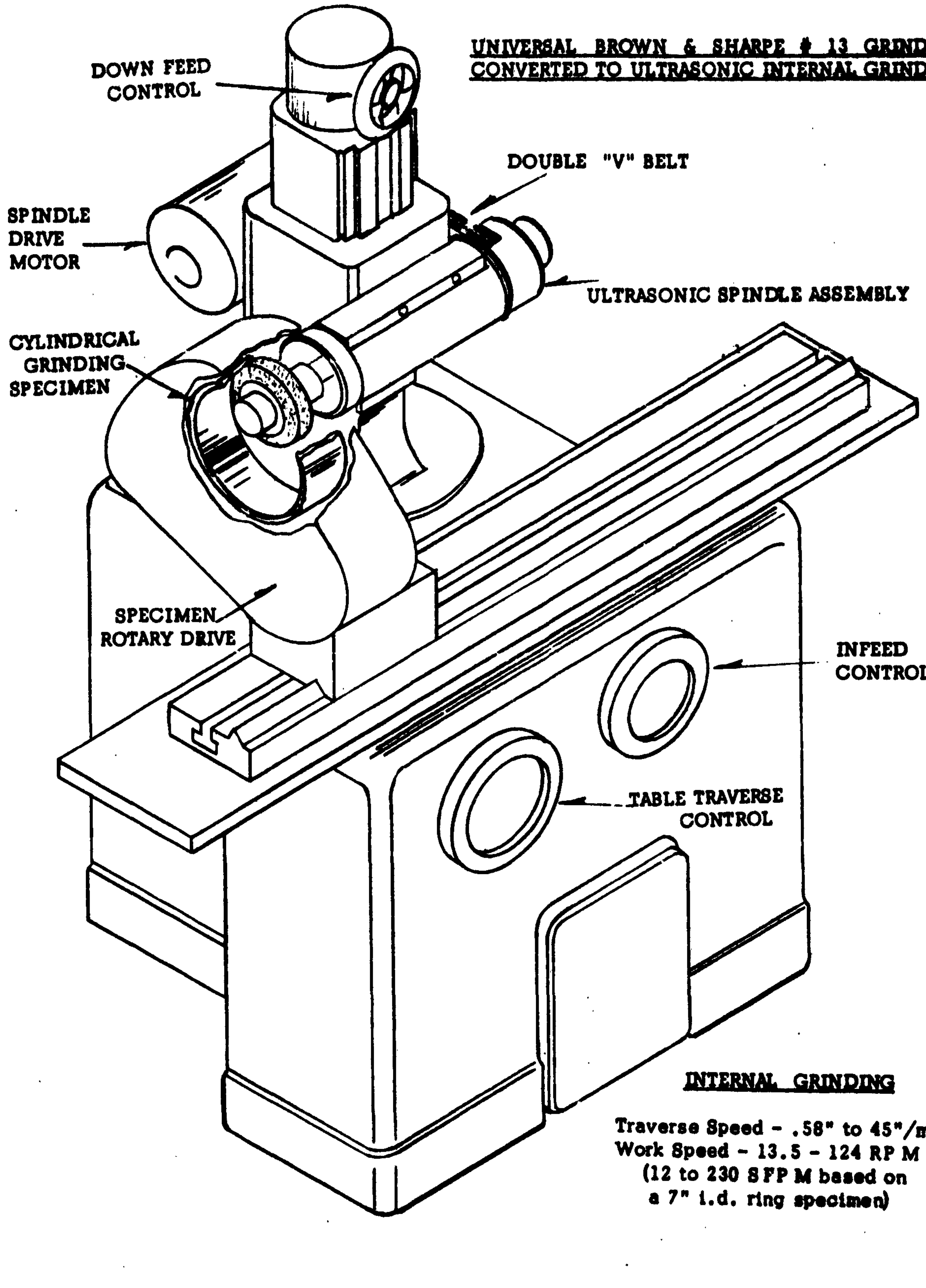
15.3 Design Variations for Effectiveness on Different Grinders

Figures (517, 518 & 519) show the physical arrangements for internal, external and surface grinding that were used to perform the various grinding tests in Phase III. Please note that safety features and coolant supply details are omitted for clarity.

In each grinder, an ultrasonic spindle is used having features permitting its use on the three grinders with only position changes being made.

An ultrasonic grinder, consisting of an ultrasonic vibrated spindle and wheel assembly will modify existing grinder types primarily to the extent of replacing the existing spindle and wheel assembly by the ultrasonic spindle and wheel assembly.

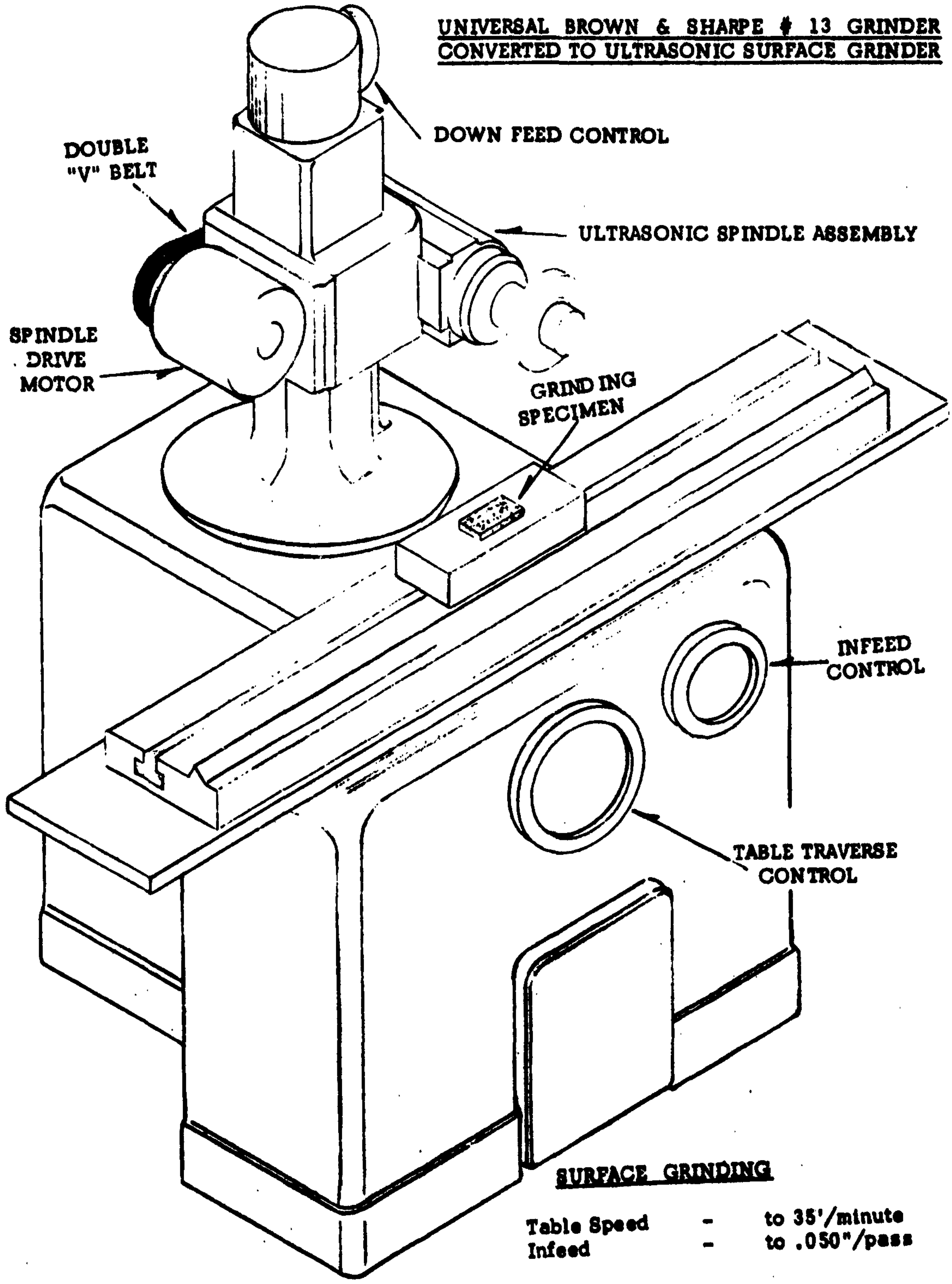
UNIVERSAL BROWN & SHARPE # 13 GRINDER
CONVERTED TO ULTRASONIC INTERNAL GRINDER



INTERNAL GRINDING

Traverse Speed - .58" to 45"/minute
Work Speed - 13.5 - 124 RPM
(12 to 230 SFPM based on
a 7" i.d. ring specimen)

UNIVERSAL BROWN & SHARPE # 13 GRINDER
CONVERTED TO ULTRASONIC SURFACE GRINDER

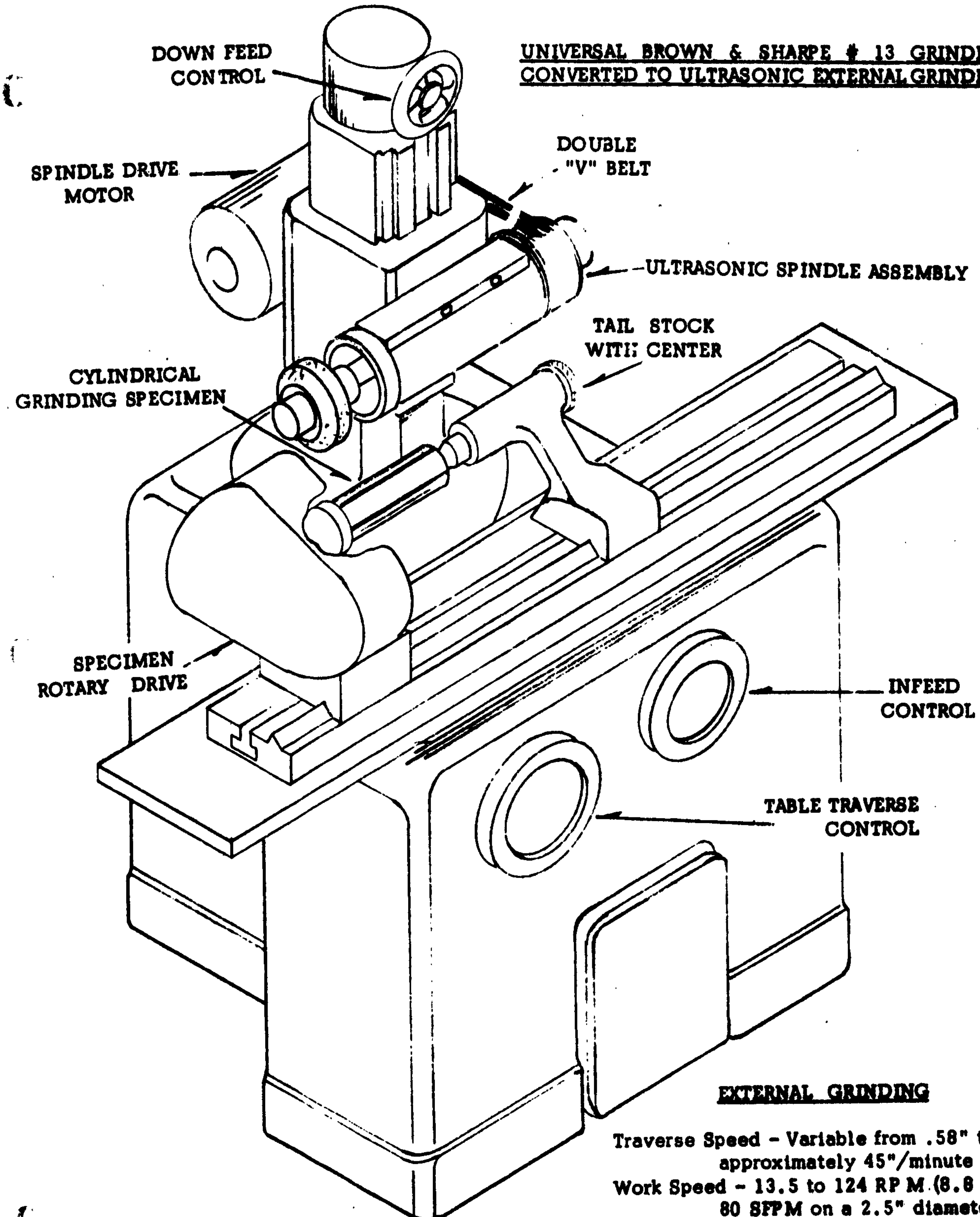


SURFACE GRINDING

Table Speed	-	to 35'/minute
Infeed	-	to .050"/pass

Figure 518

UNIVERSAL BROWN & SHARPE # 13 GRINDER CONVERTED TO ULTRASONIC EXTERNAL GRINDER



EXTERNAL GRINDING

Traverse Speed - Variable from .58" to approximately 45"/minute
Work Speed - 13.5 to 124 RP M (8.8 to 80 SFPM on a 2.5" diameter test specimen

Figure 519

15.4 Design Portrayals of Adaptations or Modifications of Existing Grinder Types

EXTERNAL GRINDER

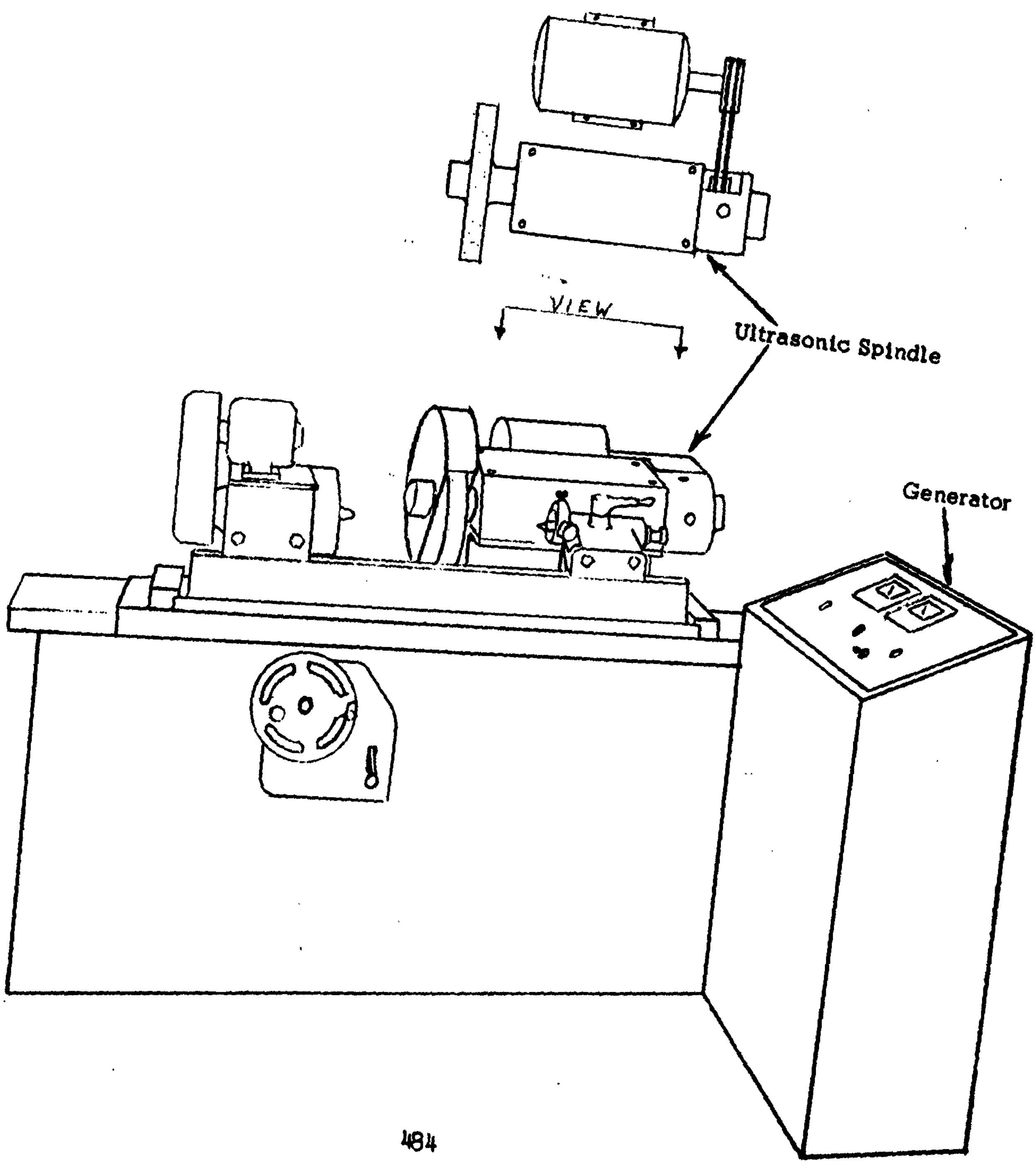


Figure 520

EXTERNAL GRINDER

Capacity	10" diameter X 28" long.
Grinding Wheel	14" diameter X 3" width(epoxy mounted on ultrasonic hub)
Spindle Speed	1500 RPM
Spindle Motor	5 h.p. 1750 RPM

Spindle Transducer 1000 Watt - 20 kc

Ultrasonic Generator 1000 Watt - 20 kc

Spindle output diameter 1-5/8"

Spindle output stud size 7/8 - 20 UNEF - left hand thread

SURFACE GRINDER

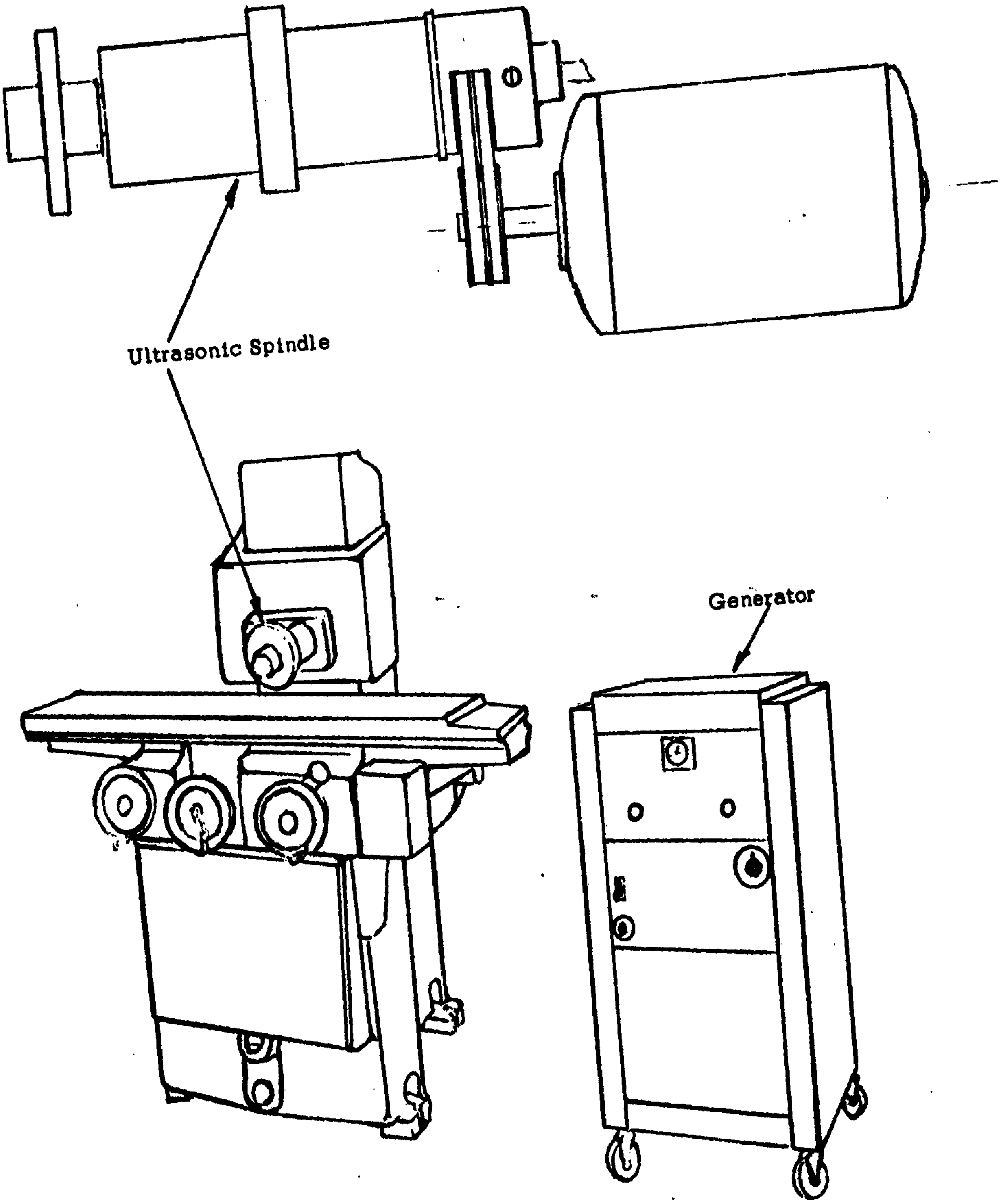


Figure 521

SURFACE GRINDER

Capacity	6" X 18"
Grinding Wheel	9" X 1/2" (epoxy mounted on ultrasonic hub)
Spindle Speed	2400 RPM
Spindle Motor	1½ h.p. 3450 RPM
Spindle Transducer	1000 Watt - 20 kc
Ultrasonic Generator	1000Watt - 20 kc
Spindle Output	1" diameter
spindle output stud size	1/2 - 28 UNEF - right hand thread

SURFACE GRINDER

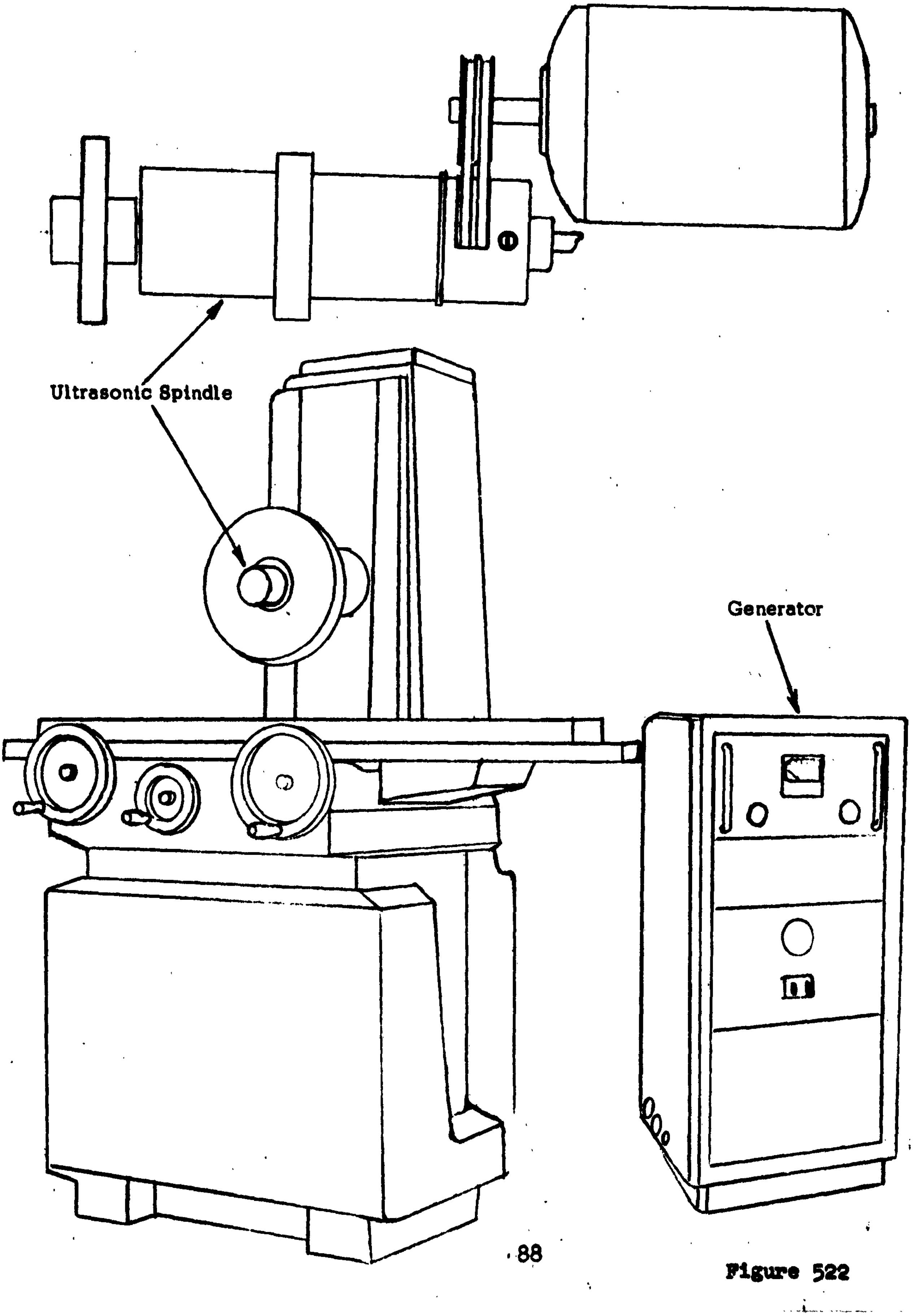


Figure 522

SURFACE GRINDER

Capacity	12" X 30" X 12"
Grinding Wheel	14" X 2" (epoxy mounted on ultrasonic hub)
Spindle Speed	1500 RPM
Spindle Motor	5 h.p. 1725 RPM
Spindle Transducer	1000 Watt 20 kc
Ultrasonic Generator	1000 Watt 20 kc
Spindle output diameter	1-5/8"
Spindle output stud size	7/8 - 20 UNEF

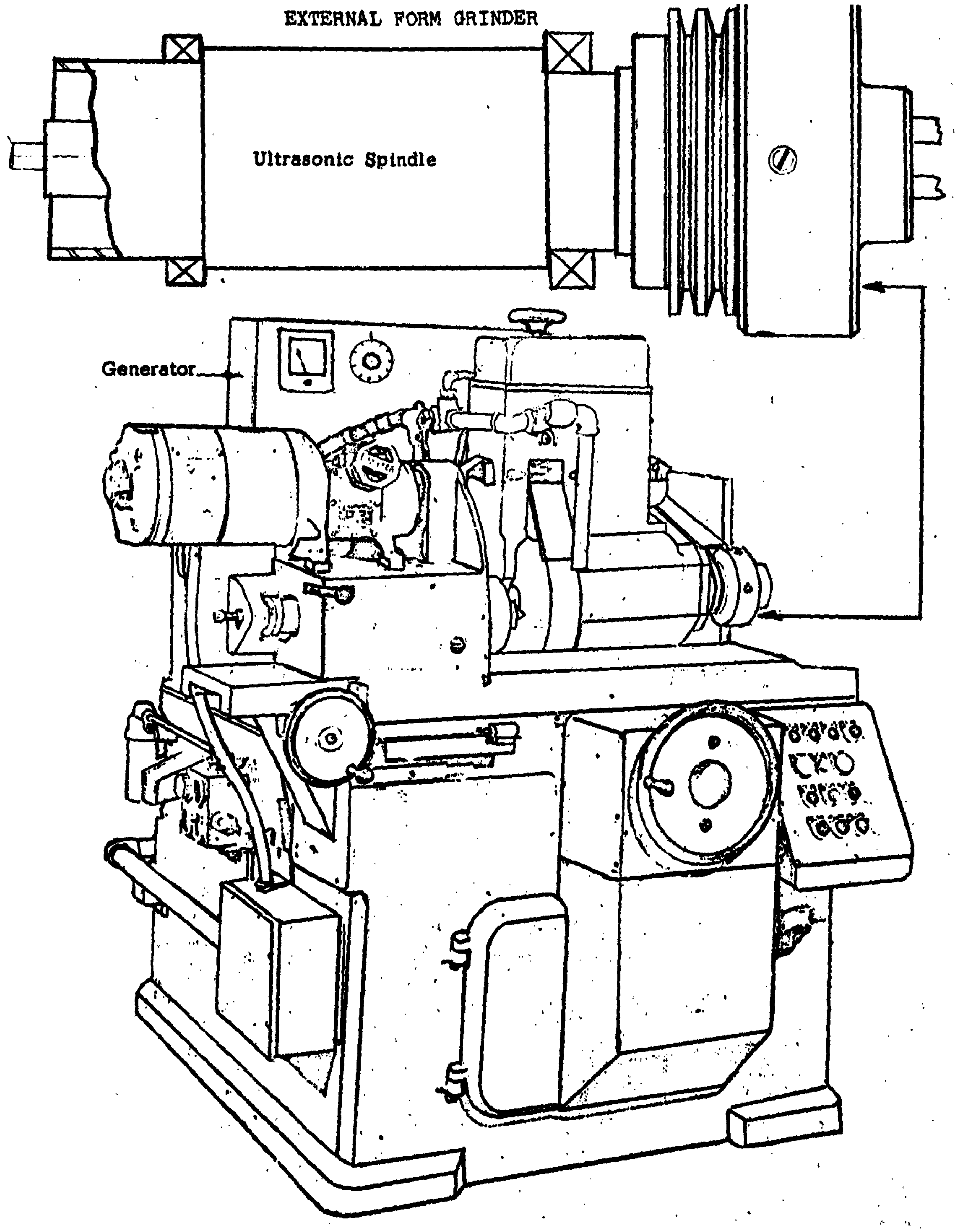


Figure 523

EXTERNAL FORM GRINDER

Capacity	6" X 12" long center to center
Grinding Wheel	14" X 3" (epoxy mounted on ultra-sonic hub)
Spindle Speed	1500 RPM
Spindle Motor	5 h.p. 1750 RPM
Spindle Transducer	1000 Watt 20 kc
Ultrasonic Generator	1000 Watt 20 kc
Spindle output diameter	1-5/8"
Spindle output stud size	7/8 - 20 UNEF (left hand thread)

EXTERNAL GRINDER

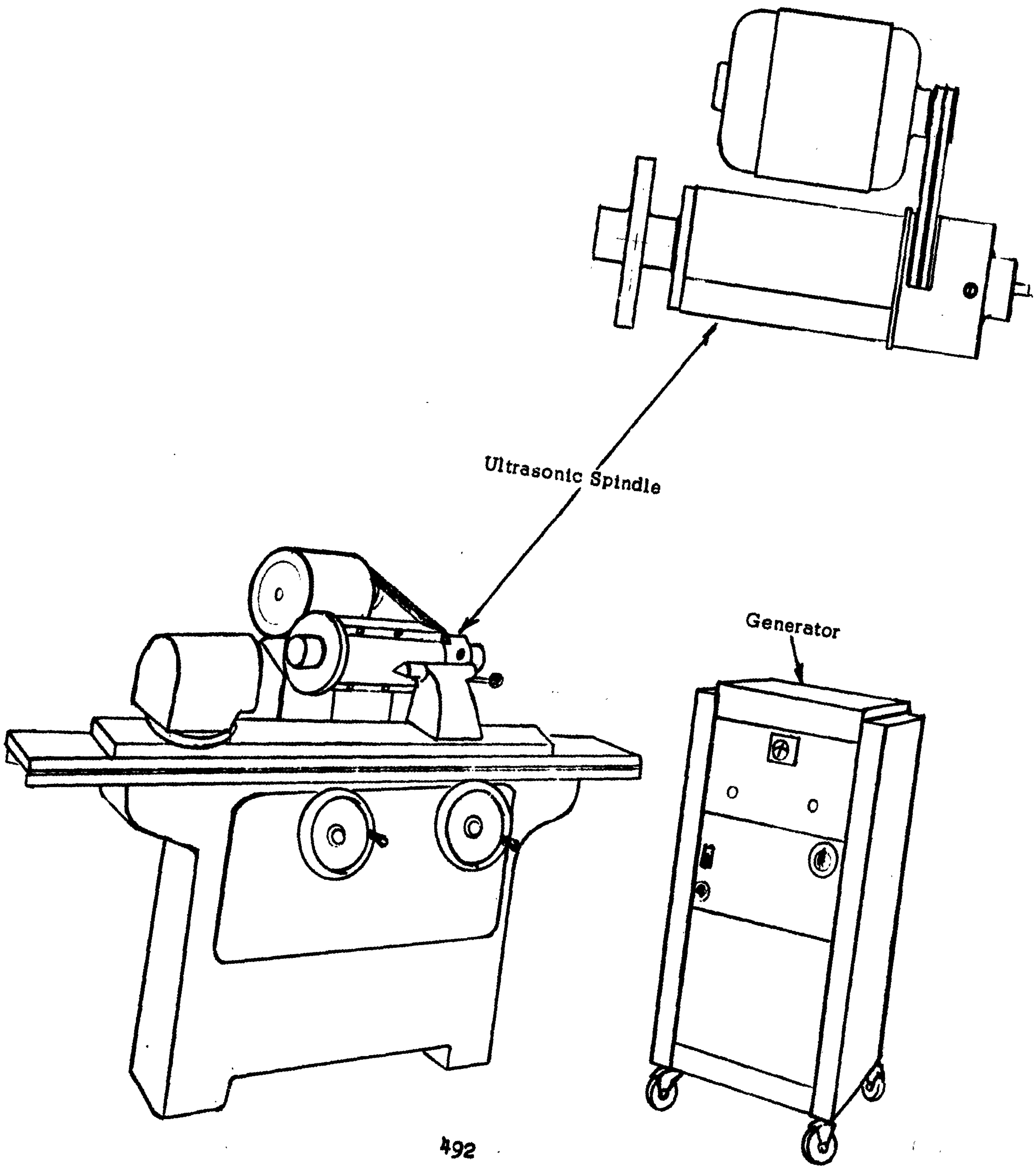


Figure 524

EXTERNAL GRINDER

Capacity	12-3/8" X 28"
Grinding Wheel	9" X 1/2" (epoxy mounted on ultrasonic hub)
Spindle Speed	2400 RPM
Spindle Motor	$1\frac{1}{2}$ h.p. 3450 RPM
Spindle Transducer	1000 Watt - 20 kc
Ultrasonic Generator	1000 Watt - 20 kc
Spindle output diameter	1"
Spindle output stud size	1/2 - 28 UNEF - left hand thread

INTERNAL GRINDER

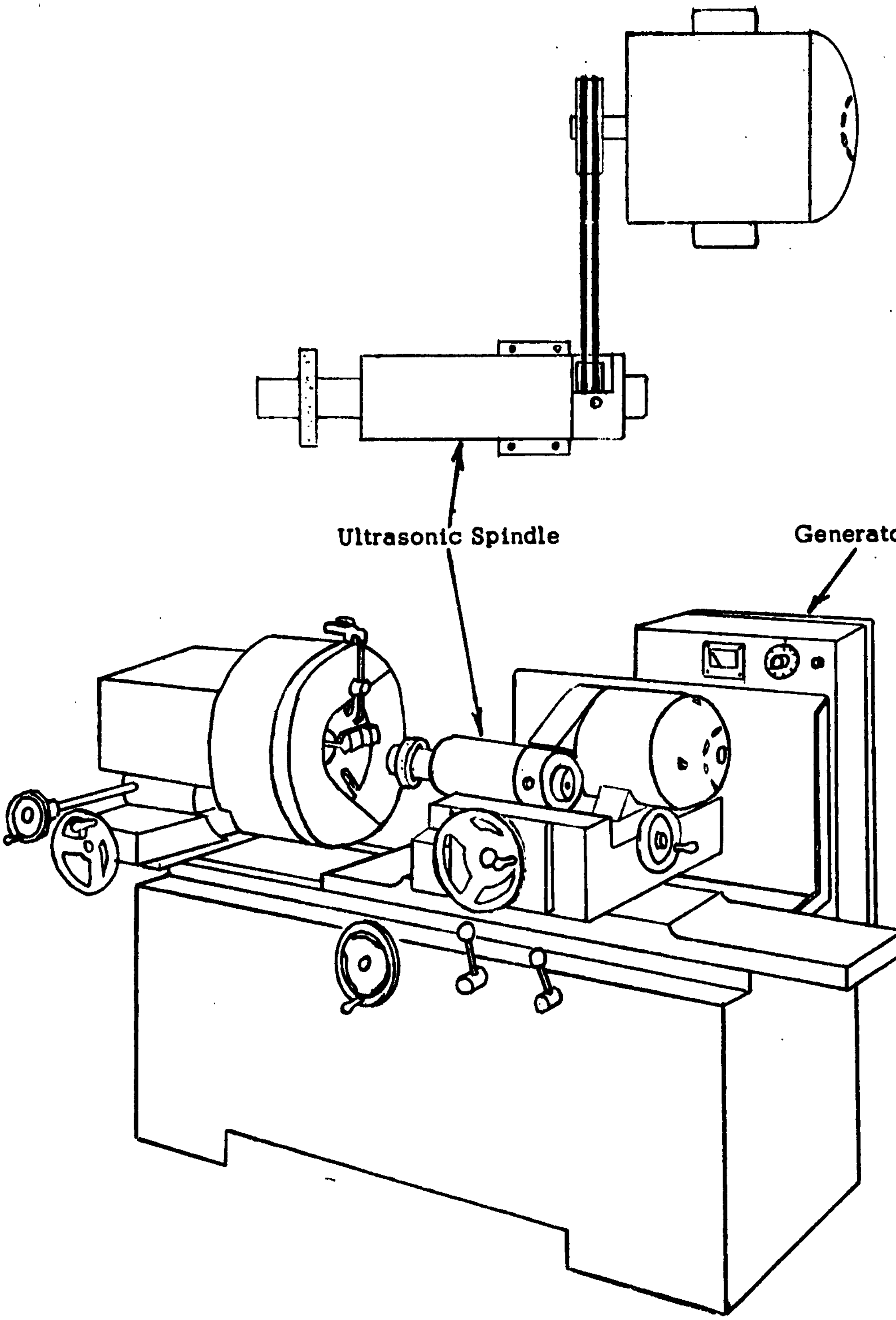


Figure 525

INTERNAL GRINDER

Capacity	30" diameter X 12" long
Grinding Wheel	6" X 1" (epoxy mounted on ultrasonic hub)
Spindle Speed	3500 RPM
Spindle Motor	5 h.p. 3450 RPM
Spindle Transducer	1000 Watt 20 kc
Ultrasonic Generator	1000 Watt 20 kc
Spindle output diameter	1-5/8"
Spindle output stud size	7/8 - 20 UNEF

15.5 Substantiations of Phase II Findings

15.5 Substantiation of Phase II Findings from Phase III Grinding Tests and Simulated Production Runs (advantages of ultrasonic vs. conventional)

Phase II Findings

In Phase II, certain advantages were established in ultrasonic grinding using an ultrasonic spindle which vibrated the grinding wheel. This Phase II spindle left certain undesirable features such as, poor bearings, balance and stiffness. Nevertheless, the comparison tests between ultrasonic and conventional grinding with this spindle indicated the following advantages:

1. Increased grinding ratios

2. Significant decrease in grinding temperatures by direct measurement as well as evidenced by the

3. Decrease in spindle power to grind

4. Elimination of surface burn with grinding ratios of 3 or 4 times the rate which might otherwise burn under conventional conditions.

5. Decreased wheel loading

6. No impairment in surface finish

7. Greater stock removal rate for the same grinding ratio.

Phase III Test Criteria Correlation with Phase II*

In Phase III, a new spindle of improved design eliminated the disadvantages of the spindle mentioned above. Numerous preliminary grinding tests, selected from and varying slightly from recommended practice, were made on internal, external and surface grinders with this spindle. This was done to select the test conditions under which the three simulated production runs would be made. (pages 327 - 329)

The results of the grinding tests made to establish the criteria for production run conditions, are in excellent agreement with the findings of Phase II described above. (ref. pages 327- 329) This applies to internal and external grinding as well.

Simulated Production Runs

The grinding conditions for the simulated production runs were selected with maximum production rate as a guide governed by the limitations imposed throughout the grinding cycle by:

*see page 327 for test criteria

1. excessive burn
2. low grinding ratios
3. bad finish
4. checks or cracks
5. excessive part bowing
6. excessive power to grind
7. excessive chatter
8. froquent redressing

Pages 468-470 depict the results of the simulated production runs in table form. Conventional runs made were the greatest stock removal rate conditions found commensurate with the above limitations as a guide.

The ultrasonic runs were made at stock removal rates equal to or greater than the conventional runs. The following is a cost comparison of these runs.

COST COMPARISONS - SIMULATED PRODUCTION RUNS

Ti6Al-4V, H-11, 15-7MO	Conventional	Ultrasonic
Assumed Grinder Depreciation/hour	$ .50	$ 1.00
Assumed Labor/hour	3.00	3.00
Total Assumed cost/hour	$ 3.50	$ 4.00

METAL	RUNS	TYPE OF RUN	METAL REMOVED/ HOUR	COST/ PART	COST TO REMOVE 1 in.^{3} OF METAL
Ti6Al-4V	P-1-5	Internal Grind Ultrasonic	1.191	$1.11	$ 3.36
Ti6Al-4V	P-11-15	Internal Grind Ultrasonic	0.544	$2.43	$ 7.35
Ti6Al-4V	P-6-10	Internal Grind Conventional	0.281	$4.37	$12.45
H - 11	P-21-25	External Grind Ultrasonic	4.250	$1.00	$ 0.94
H - 11	P-16-20	External Grind Conventional	4.273	$0.88	$ 0.82
15-7 MO	P-31-35	Surface Grind Ultrasonic	0.137	$18.68	$29.20
15-7 MO	P-26-30	urface Grind Conventional	0.132	$16.92	$26.51

Although significant cost reductions are apparent in Titanium only, the less frequent wheel dressing, its consequent reduction in dressing time results in potential cost reductions in all cases.

Further, surface finish measurements made on the conventional and ultrasonic specimens after grinding and after polishing an area on the specimens with 400 grit paper indicate that ultrasonic ground specimens could be finished by honing or lapping in less time. This could result therefore in over all part cost reductions using ultrasonics grinding when better finishes are indicated.

15.6 Procurement Specifications

The following procurement specifications prepared for industrial machines to cover surface grinders, internal grinders and external grinders (including centerless).

In accordance with contractual requirements these specifications have been sent by the Sheffield Corporation to Mr. Ludlow King, Executive Vice President of National Machine Tool Builders Association for coordination and comment.

Unfortunately this Association as a mater of policy does not review such specifications for the purpose of making comments or recommendations.

The specifications have been placed in the permanent file of the National Machine Tool Builders Associations Library.

PROCUREMENT SPECIFICATIONS

Procurement specifications on industrial ultrasonic grinding machines: surface grinders, internal grinders, and external grinders (including centerless) - will be basically in the form of supplements to existing specifications as to type and capacity of base machines.

BASE MACHINES

Reference is made to ASA Standards B5.32-1953 and B5.33-1953 covering designation and working ranges of surface grinding machines of the horizontal reciprocating table type and plain cylindrical grinding machines respectively.

Existing specifications as to capacities and types of base machines in general include the following criteria:

I. Horizontal surface grinders
   a. work table dimensional capacity
   b. work table load supporting capacity
   c. table traverse
   d. saddle movement
   e. feed types and speeds
   f. vertical capacity under wheel
   g. spindle drive power and speeds
   h. floor space
   i. machine weight
   j. electrics
   k. accessories (dressing, etc.)

II. Cylindrical Grinders

   A. Center Type - External
      a. nominal swing
      b. length between centers
      c. wheel size
      d. work speed
      e. feed types and speeds
      f. traverse speed
      g. work drive
      h. wheel drive
      i. work weight
      j. table swivel
      k. floor space
      l. machine weight
      m. electrics
      n. accessories (dressing, etc.)

   B. Chucking - Internal
      a. chucking type
      b. internal diameter range,
      c. maximum outside diameter
      d. depth range

e. feeds and speeds
f. quill style and drive
g. workhead speed and power
h. work weight
i. floor space
j. machine weight
k. electrics
l. accessories (dressing, etc.)

C. Centerless (Internal and External)
a. type of feed (through or infeed)
b. work support
c. work outside diameter range
d. maximum hole depth
e. hole diameter range
f. taper precision
g. feeds and speeds
h. wheel diameter and width
i. regulating wheel diameter and width
j. regulating wheel speeds
k. grinding wheel power
l. work weight
m. dressing
n. floor space
o. electrics
p. accessories

SUPPLEMENTAL SPECIFICATIONS FOR ULTRASONIC APPLICATIONS

Machine to be equipped to reliably obtain, under production grinding conditions, radial expansions and contractions of the grinding wheel periphery at ultrasonic frequencies - superimposed on and simultaneous with normal wheel rotation. The grinding wheel is to be ultrasonically coupled at a nodal point along and radial to the longitudinal axis of a resonant system driven at ultrasonic frequencies while under grinding rotation.

The periphery of the grinding wheel under grinding conditions is to radially expand and contract under positive amplitude control through a range of amplitudes.

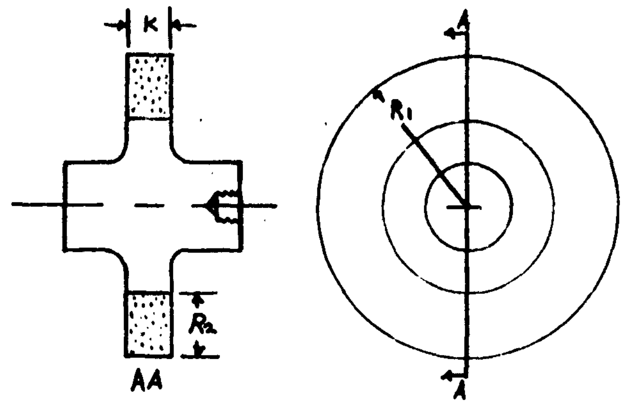
The full ultrasonic wheel, wheel mounting, and driving assembly is to include the following major components incorporated as an operating assembly in the specified machine:

a. wheel
b. wheel hub
c. ultrasonic transducer
d. spindle
e. ultrasonic generator

Preferred specifications for these major components are set forth below for supplemental application to the type and capacity specifications of the base machine.

a. wheel

Maximum diameter	- 20" subject to limitation by grinder capacity
Minimum diameter	- 5"
Wheel face width	- Wheel face width (K) should be at least ¼ of that part of the wheel radius dimension (R_2) that projects from the grinding wheel hub flange. Maximum face width no greater than 3".



b. wheel hubs

material	- "K" or "M" monel, annealed and stress relieved after machining, (in accordance with International Nickel Company Technical Bulletin Specifications). For optimum performance, all hubs should be tuned to design frequency (20kc $\pm$100 cycles) and be free of cracks, flaws, and be of smooth finish (40uin.RMS or better) and be free from tool marks. Ultrasonic inspection of raw material before machining is desirable.

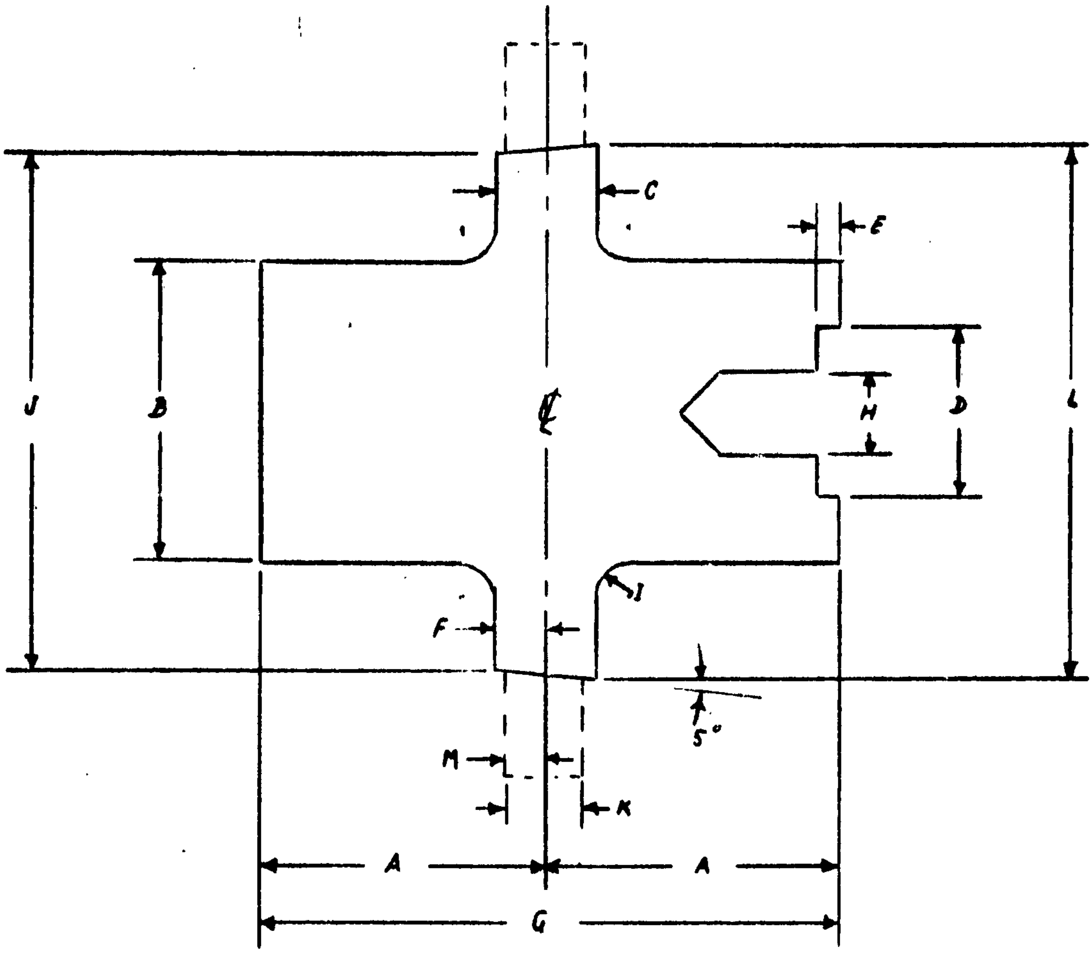
See following page for legend.

Hub Geometry - Hubs shall conform to the following specifications:

(K)	1/2"	1"	1-1/2 "	2"	2-1/2 "	3"
A	2.166	2.166	2.166	2.166	2.166	2.166
B	3.5"	3.5"	3.5"	3.5"	3.5"	3.5"
C	5/8"	1-5/8"	1-5/8"	2-1/8"	2-5/8"	3-1/8"
D	*	*	*	*	*	*
E	0.130"	0.130"	0.130"	0.130"	0.130"	0.130"
F	5/16"	9/16"	13/16"	1-1/16"	1-5/16"	1-9/16"
G	4.332	4.332	4.332	4.332	4.332	4.332
	(Tolerance +.000 -.004)					
H	**	**	**	**	**	**
I	3/8R	3/8R	3/8R	3/8 R	3/8R	3/8R
J	4.278	4.233	4.190	4.146	4.102	4.058
	(Tolerance +.000 -.004)					
L	4.387	4.430	4.474	4.518	4.562	4.605
	(Tolerance +.000 -.004)					
M	1/4"	1/2"	3/4"	1"	1-1/4"	1-1/2"

Epoxy bonding of wheel to hub is made in final assembly.

* See section c Output Diameter
** See Section c Stud Size



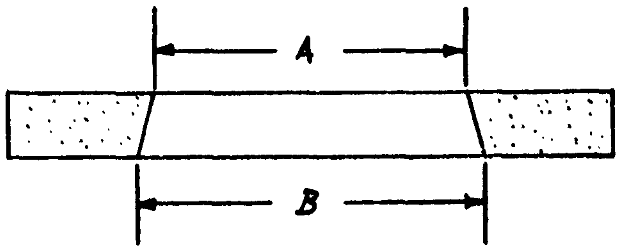
Equations for determining hub diameters (J & L) and flange widths (C) for wheel face widths not listed in table.

$$J = 4.332 - .08749\ C$$
$$L = 4.332 + .08749\ C$$
$$K = C - 1/8$$

where: J = Small diameter (tolerance +.000" - .004")
L = Large diameter (tolerance +.000" - .004")
K = Wheel width
C = Flange width

Wheel hole dimensions

wheel face	1/2"	1"	1-1/2"	2"	2-1/2"	3"
Dimension A + .000" - .004"	4.277"	4.234"	4.190 "	4.146"	4.102"	4.059"
Dimension B + .000" - .004"	4.387"	4.430"	4.474"	4.518"	4.562"	4.605"



Wheel type - Standard - Vitrified bond

c. Ultrasonic transducer

Power Rating - Controllable to a maximum of 1000 Watts.

Frequency Range - Controllable from 18 to 21 kc.

Output Diameter (diameter to which wheel hub is attached) - For wheels up to 8" in diameter and not exceeding 2 shaft horse power on spindle 1" output diameter. For wheels from 8" to 20" in diameter and not exceeding 5 shaft horse power on spindle 1-58" output diameter.

Stud Size - 1/2 - 28 UNEF (left or righthand thread depending on spindle rotation) for up to 8" wheels not exceeding 2 shaft horse power.

7/8 - 20 UNEF (left or righthand thread depending on spindle rotation) for wheels from 8" to 20" in diameter.

Cooling - Continuous water cooling 1 quart/minute capability.

c. Ultrasonic transducer (continued)

Amplitude (Peak to Peak)	-	Controllable to 0.001"P-P at 20 kc
Type	-	Magnetostrictive - Nickel window type
Input Impedance	-	8 - 16 ohms

d. Spindle

bearings	-	Anti-friction bearings, front bearing double row tapered rollers;rear bearings in radial thrust and float-axially. Front bearings must be in the nodal location of the connecting body of the transducer.
lubrication	-	oil mist
R.P.M.	-	not to exceed 3800
drive	-	belt - single or multi"V" type
slip rings	-	copper slip rings - carbon brushes

e. Generator

power output	-	controllable to 1000 Watts
frequency range	-	controllable from 18 - 20 kc
tuning	-	manual. Frequency drift of oscillator not exceeding ± 100 cps after initial 30 minute warmup.
input	-	preferred 60 cycles - 220 V, 3 phase, 2.4 KVA
output impedance	-	8 - 16 ohms

SUGGESTIONS FOR ALTERATION OF ASA STANDARDS-B5.32-3-1953

An ultrasonic grinder, consisting of an ultrasonic vibrated spindle and wheel assembly will modify existing grinder types primarily to the extent of replacing the existing spindle and wheel assembly by a new spindle and wheel assembly. This applies to:

1. Horizontal Reciprocating Surface Grinders(ASA-B5.32-1953)
2. Plain Cylindrical Grinding Machines(ASA-B5.33-1953)
3. Centerless Grinders
4. Internal Grinders

However, the ultrasonic grinder, utilizing a vibrating spindle and wheel, assembly, requires certain conditions for basic performance that are not entirely compatible with certain sections of ASA-B5.32-1953 and ASA-B5.33-1955.

For instance, to vibrate a grinding wheel in radial resonance at ultrasonic frequencies, a grinding wheel hub of such a flange diameter is required, that when a grinding wheel is firmly attached to it, (as by epoxy resin bonded to level of vibration. Therefore, the design of the hub, such as its diameter, length, flange diameter and width are closely governed by the desired frequency and the physical properties of the material of which the hub is made, and must not be chosen arbitrarily.

1. Therefore, for horizontal reciprocating surface grinders, page 5 of ASA-B5.32-1953 under "Wheel sleeve diameters" should be deleted for ultrasonic grinders of the horizontal reciprocating type. This would allow existing specifications 5.32-1953 to apply in the case of ultrasonic grinders of the type herein described by using a footnote in said specification applicable to ultrasonic grinders.

2. Similarly for ASA-5.33-1953 page 7 under "wheel hole sizes" certain standard hole sizes are indicated. In as much as a wheel for ultrasonic grinding must attach to the ultrasonic hub, the flange diameter of which is closely determined by its acoustical properties, it is also suggested that this be deleted for ultrasonic grinders and replaced in the existing specification 5.33-1953 by a footnote indicating said circumstances as relates to ultrasonic grinders.

3. & 4. It is further suggested, that when ASA specifications may be planned in the future for internal and centerless type grinders that consideration be given to the wheel-hub exemptions previously noted for surface and plain cylindrical types.

16. Conclusions and Recommendations

16. Conclusions and Recommendations

Conclusions

In Phase I, strong indications of the benefits in ultrasonic grinding were shown. The most versatile method of introducing ultrasonic vibrations was by vibration of the grinding wheel through the use of an ultrasonic spindle.

Phase II effort provided confirmation of the previously indicated advantages of ultrasonic grinding as applied to surface grinding. Performance of the ultrasonic spindle was hampered by poor bearings, lack of spindle rigidity and proper balance.

In Phase III, an improved spindle was designed, built and tested on three grinder types - external, internal and surface. Previously established benefits such as lower power and temperatures to grind, greater grinding ratios, decreased burn indications, no impairment of surface finish, and decreased wheel loading and chatter were maintained. Simulated production runs were made on each grinder type disclosing consistency of previously established advantages of ultrasonic grinding as well as operational feasibility and adaptability.

Procurement specifications were than drafted for a center-less type grinder as well as the previously mentioned surface, external and internal types.

Recommendations

It is recommended that consideration be given to additional programs in the following areas in order to speed up in - dustrial applications:

1. to find means of ultrasonically vibrating hard wheels at greater amplitudes, perhaps to .001" peak to peak.
2. determine performance of ultrasonic grinding using other wheel types such as bonded Boron Carbide, Carbide, diamond and resonoid bonded wheels.
3. Improve wheel to hub mounting techniques
4. more fully explore the fatigue properties of various materials ultrasnically ground vs. conventionallly ground.

Consultants:

Phase I	-	Professor L. V. Colwell University of Michigan Ann Arbor, Michigan
Phase I & II	-	Paul F. Maker, Staff Engineer Mechanical Development Bendix Research Division Detroit, Michigan

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