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AFML-TR-69-144

MACHINABILITY PARAMETERS ON NEW AND SELECTIVE AEROSPACE MATERIALS

Norman Zlatin
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Metcut Research Associates Inc.

Technical Report AFML-TR-69-144

May 1969

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

MMP Project Nr. 708-8

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FOREWORD

This Final Technical Report covers work performed under Contract F33615-68-C-1148 from 1 December 1967 to 30 April 1969. The manuscript was released by the authors in April 1969 for publication.

This contract with Metcut Research Associates Inc., Cincinnati, Ohio, was initiated under Manufacturing Methods Project 703-8, "Machinability Parameters on New and Selective Aerospace Materials." It was accomplished under the technical direction of Mr. Max A. Guenther and Lt. Raymond Coe of the Fabrication Branch (MATF), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

Mr. Norman Zlatin, Director of Machinability Research at Metcut, was the engineer in charge. Others who cooperated in the preparation of this report were: Drs. Michael Field and F. E. Westermann and Messrs. John D. Christopher, L.R. Gatto, and John B. Kohls. This project has been given the Metcut Research Internal Number 960-11400.

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

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.

This technical report has been reviewed and is approved.

JACK R. MARSH
Chief, Fabrication Branch
Manufacturing Technology Division

ABSTRACT

Four groups of alloys of interest to the aerospace industry were selected for the machinability studies from a survey of the industry and a review of the literature. The four groups consisted of (1) high strength steels, (2) titanium alloys, (3) nickel base alloys and (4) stainless steel alloys. Both wrought and cast alloys were included in the first three groups.

Conventional tools were generally used in this program. However, during the span of this program, multiple-tooth carbide milling cutters (which provided a greater variety of tool geometries) were made available commercially. This development permitted a wider range of investigations with multiple-tooth cutters in face milling the variety of alloys included in this program. Also, end milling cutters utilizing "throwaway" inserts were made available which had a geometry more suitable for peripheral end milling the difficult-to-machine high nickel base alloys. Hence, these cutters were used in many of the tests. The cutting speeds with these carbide cutters were at least double those permitted with high speed steel end mills.

In general, the cast nickel base alloys required even lower cutting speeds than the wrought alloys in this category. Recommendations are listed in tables in the report for machining all of the alloys included in this program with commercially available tools. It should be noted, however, that in some instances small departures from the suggested cutting speeds, feeds, cutting fluids, tool geometries or tool materials could result in significant reductions in tool life.

The relationship between dimensional accuracy and length of end mill cutter was also determined. This investigation also included the effect of tool wear on cutter deflection.

A short study was also made of the machined surfaces obtained by face milling and grinding of two titanium alloys, a high strength steel, and a nickel base alloy.

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1. INTRODUCTION

New commercial alloys are continuing to be developed in order to meet the design requirements of advanced aerospace vehicles. Concurrently, it is necessary to develop machining know-how for these new alloys in order to meet the production requirements of the aerospace industry. It is imperative that the data be developed with enough lead-time to avoid duplication of effort on the part of prime contractors and their many subcontractors who are responsible for machining these new materials. Many of the newer alloys, including cast titanium and nickel base alloys, are becoming more and more difficult to machine. Consequently, every effort must be made to develop optimum conditions for commercial production conditions.

Reduction in machinability has a direct impact on the number of machine tools and general plant facilities required as well as labor requirements and costs. In view of the long machine tool delivery schedules as well as the general lack of machine tools, such as profilers, concerted effort must continually be made to isolate the best techniques for material removal.

The increasing application of N/C machine tools, including the potential of direct computer control of banks of N/C machines, dictates the need for readily available tool life data for the programmers. In addition, the time utilization of N/C machines which represents high capital investment could be increased.

In keeping pace with the aforementioned requirements, the Air Force Materials Laboratory at Wright-Patterson Air Force Base has sponsored this program. The MMP project covered by this report is concerned primarily with the conventional machining of these materials. Its purpose and objective has been to develop machining data and related information for direct utilization by the aerospace industry on selected new materials and machining processes for which data had not been available. Further, the data so developed had to be of such quality that the various contractors of the aerospace industry would not find it necessary to requalify nor duplicate the data realized from these machinability studies.

2. EQUIPMENT AND TESTING PROCEDURES USED

2.1 Turning

All of the turning tests described in this report were conducted on a LeBlond Heavy Duty Lathe, 16 in. by 54 in., equipped with a 30 hp. variable speed drive, illustrated in Figure 1, page 6. The spindle rpm could be varied to maintain the required cutting speed for any workpiece diameter. High speed steel and carbide tools were used in the turning tests. The turning test bars were 3 in. to 4 in. in diameter by 12 in. to 18 in. long. A skin cut of .050 to .100 in. depth was taken on each test bar prior to making a turning test to remove any surface effects. Tools with throwaway inserts were used.

The nomenclature for the single-point lathe tools is shown in Appendix I, page 289.

2.2 Face Milling

The face milling tests were performed on a Cincinnati No. 3 Horizontal Dial Type Milling Machine, a Cincinnati No. 2 Vertical Dial Type Milling Machine, and a Cincinnati Cinova 80 Vertical Milling Machine. These machines are shown in Figures 2, 3 and 4, pages 7, 8 and 9. Single and multiple-tooth high speed steel and carbide cutters were used in face milling. The setups used are shown in Figure 5, page 10.

The milling test bars were clamped in position on the milling machine using a specially-designed fixture to insure maximum rigidity. All test bars were 2 in. thick by 4 in. wide by 16 in. long. In most tests, the 2 in. side was milled; thus, the width of cut was 2 in. A clean-up machining cut of .050 to .100 in. depth was made on all sides to remove any surface effects on the test bar.

Tool geometry, tool material, cutting speed, and feed were evaluated using a 4 in. diameter single-tooth HSS or carbide cutter. The HSS multiple-tooth cutter was also 4 in. diameter with 14 teeth, while the carbide multiple-tooth cutter had six inserts.

The nomenclature for a typical face milling cutter is shown in Appendix II, page 290.

2.3 Peripheral End Milling and End Mill Slotting

The end milling tests were made on the Cincinnati No. 2 Dial Type Vertical Milling Machine and the Cincinnati Cinova 80 Vertical

2.3 Peripheral End Milling and End Mill Slotting (continued)

Milling Machine shown in Figures 3 and 4, pages 8 and 9. The test bar was clamped in an 8 in. heavy-duty vise attached to the milling machine table. Straight shank end mills were used and held in the machine with an adaptor.

The test bars were 2 in. by 4 in. by 1 in. long. All heat treated bars were first face milled to a depth of .050 to .100 in. to remove any surface effects on the bars.

Both end milling setups are shown in Figure 6, page 11. Tool life is expressed in inches work travel to obtain the specified wearland on the tool.

High speed steel and carbide end milling cutters were used in peripheral end milling. Only high speed steel cutters were used in slotting. The cutters were 1 in. for peripheral end milling and 3/4 in. diameter for slotting.

The nomenclature for end mills is illustrated in Appendix III, page 291.

2.4 Drilling

The drilling tests were performed on a Bickford 24 in. Heavy-Duty Box Column Drill Press and a Cincinnati 16 in. Sliding Head Box Column Drilling Machine. Both machines were equipped with continuously variable speed drives to produce any desired spindle speed in the speed range of 220 to 4500 rpm. An additional variable speed unit was used to drive the feed mechanism, making available feeds ranging from 0.0001 in./rev. to 0.015 in./rev. This equipment is illustrated in Figure 7, page 12. The drilling test samples were 1/2 in. thick plates cut from the 2 in. by 4 in. milling bar stock. A face milling cut of 0.060 in. was made on both faces of each plate to remove any surface effects and provide a smooth surface for drilling.

Most of the drilling tests were performed using 1/4 in. diameter high speed steel drills. Some tests were performed with smaller size drills. Drills made from several types of high speed steels were used.

The drill nomenclature for standard point and crankshaft point grind is illustrated in Appendix IV, page 292.

2.5 Reaming

The Cincinnati 16 in. Sliding Head Box Column Drilling Machine shown in Figure 7, page 12, was also used for the reaming tests. The reaming test samples were the 1/2 in. thick plates that had been used in the drilling tests.

Most of the reaming tests were conducted with letter I (.272 in. dia.) six-flute high speed steel reamers. Four-flute carbide reamers were used on several of the metals reamed. Reamer sizes were used to obtain 75 percent threads.

The nomenclature for the reamers is shown in Appendix V, page 233.

2.6 Tapping

The Bickford 24 in. Drill Press shown in Figure 7, page 12, was used for the tapping tests. The tapping test samples were 1/2 in. thick plates with the previously reamed holes. The tapping tests were run with 5/16-24 NF taps made from several high speed steels.

Tap nomenclature is indicated by Appendix VI, page 234.

2.7 Grinding

A Norton 8 in. by 24 in. Hydraulic Surface Grinder equipped with a 2 hp. variable speed spindle drive was used for the grinding tests. This grinder is shown in Figure 8, page 13, and the test setup is shown in Figure 9, page 14. A fixture was used to hold the test specimens which were 1 in. by 2 in. by 6 in. long. This fixture was slotted at both ends and in the center so that specimen thickness measurements could be made without removing the specimen or fixture from the machine. The effects of grinding conditions on grinding ratio (G ratio) were evaluated.

The grinding ratio (G ratio) is a measure of grinding wheel life, analogous to tool life in other machining operations, and is defined as:

$$G = \frac{\text{Volume Metal Removed}}{\text{Volume Wheel Removed}}$$

A wheel size of 10 in. by 1 in. by 3 in. was used for all tests.

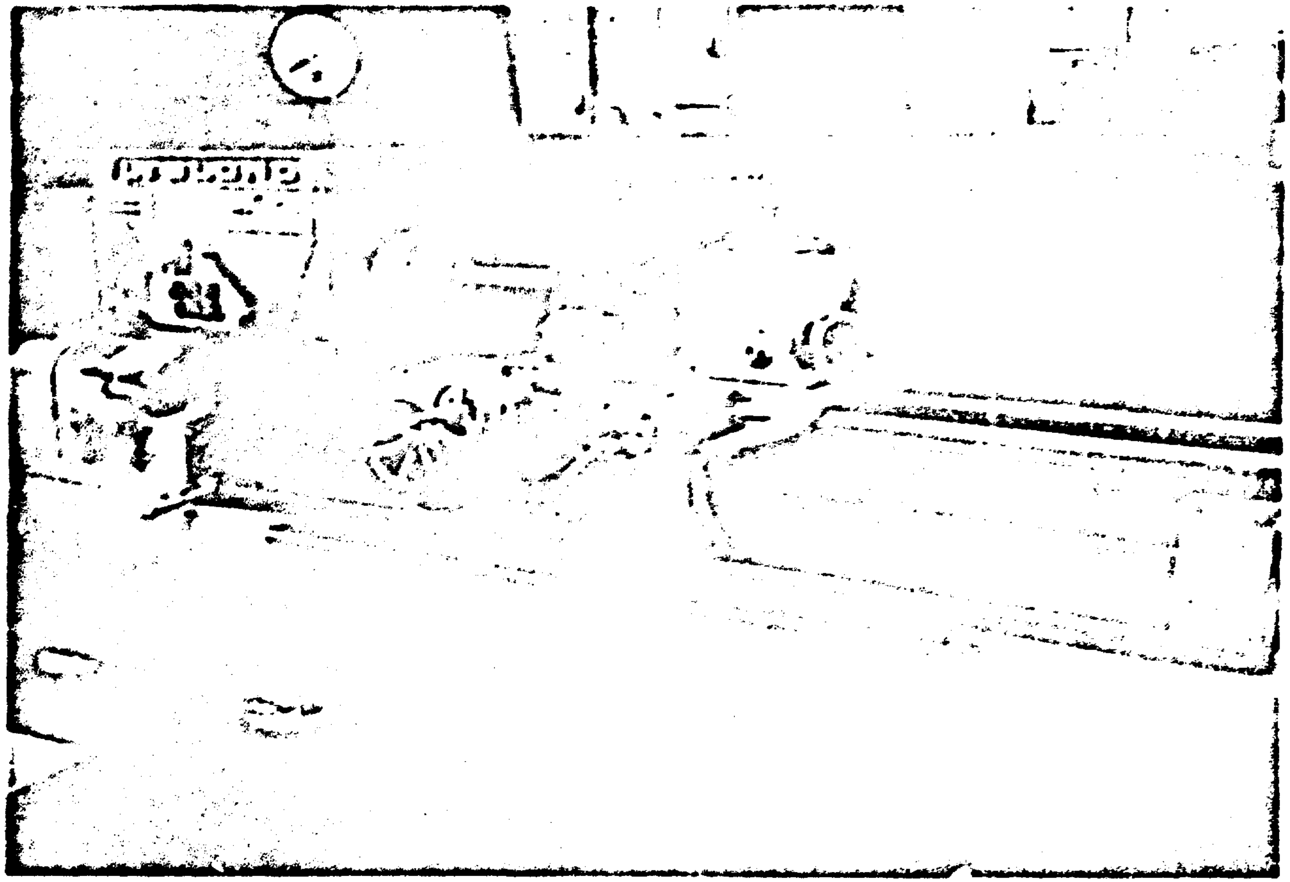
The following procedure was used for grinding tests. Before the grinding tests were started, a .030 in. deep by 1/2 in. wide step was dressed in the grinding wheel, see Figure 9, page 14. This step was

2.7 Grinding (Continued)

used as a reference in measuring wheel wear. A 0.0001 in. dial indicator mounted on a fixture attached to the wheel housing was brought in contact with this step and the indicator was set to read zero. The indicator was then moved to the upper step or grinding surface of the wheel and the initial reading was taken. Indicator readings were taken after 0.025 in. or after .050 in. depth metal removed. The difference between the initial indicator reading and successive readings was a measure of the radial wheel wear. The initial outside diameter of the wheel was accurately measured before each test with a vernier caliper. The volume of wheel removed was calculated from initial and final wheel diameters. Grinding ratios were calculated corresponding to a 0.3 cubic inch stock removal.

2.8 Cutting Tool Nomenclature

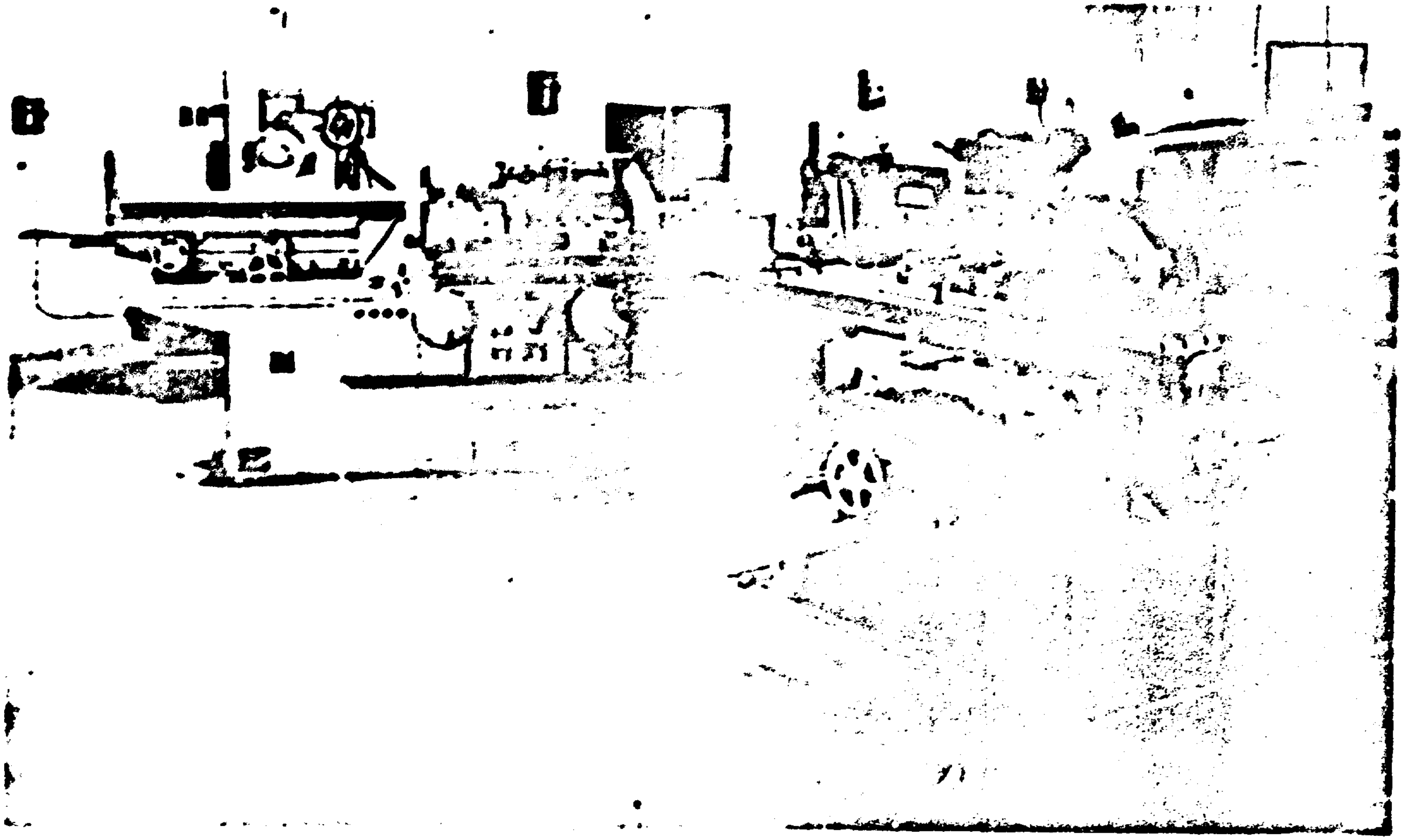
High speed steel and carbide cutting tools were used for this program. In general, the commercial designation for these materials is used throughout this report. An identification of these cutting tool materials is presented in Appendices VII and VIII, pages 295 and 296. A hardness conversion chart is shown in Appendix IX, page 297.



16" x 54" LeBlond Heavy Duty Lathe equipped with a 30 hp. continuously variable speed drive to provide exact cutting speed control for turning tests

Figure 1

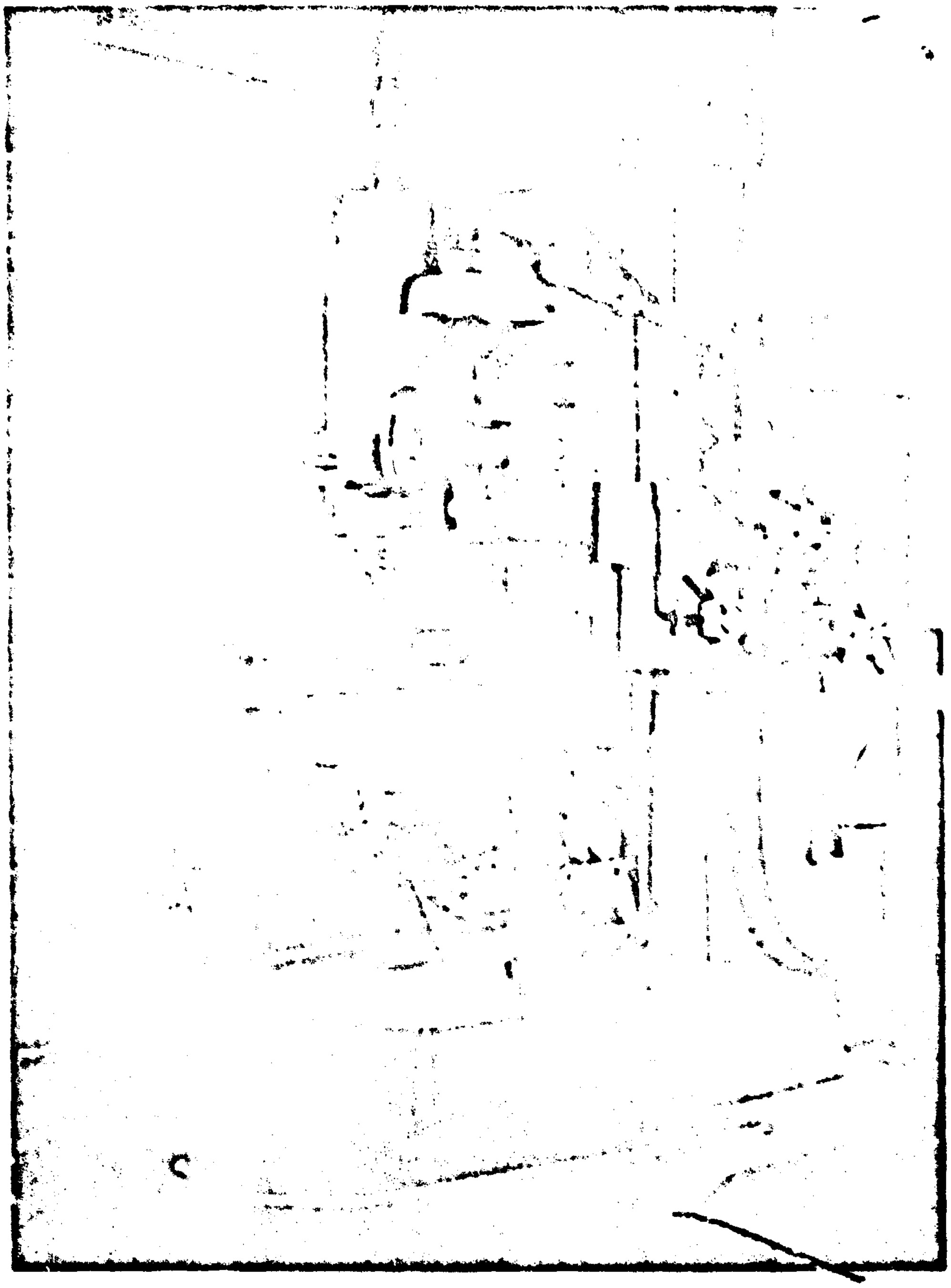
See text, page 2



Face milling tests were made on a Cincinnati No. 3 Horizontal High Speed Dial Type Milling Machine. Shown in the background is a Cincinnati 12" x 36" Hydraulic Universal Grinder and a Gallmeyer & Livingston No. 55 Hydraulic Feed Surface Grinder.

See Text, page 2

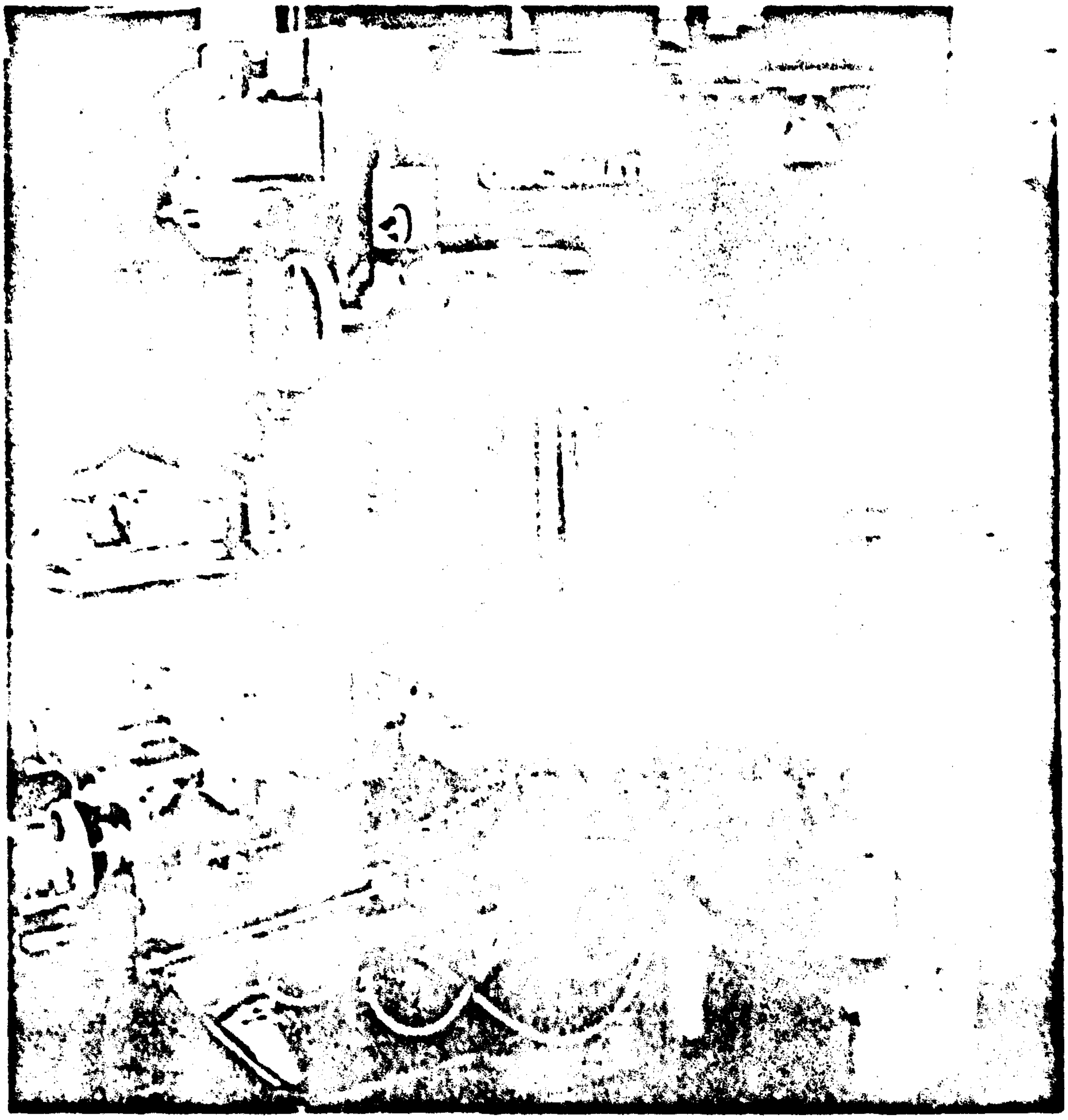
Figure 2



End milling tests were performed on a Cincinnati No. 2 Vertical Dial Type Milling Machine. A spray mist cutting fluid applicator is shown on the machine. A rotary seal is shown attached to the top of a hollow draw bar for applying spray mist or cutting fluid through a hole along the axis of the rotating cutter.

See Text, page 2

Figure 3



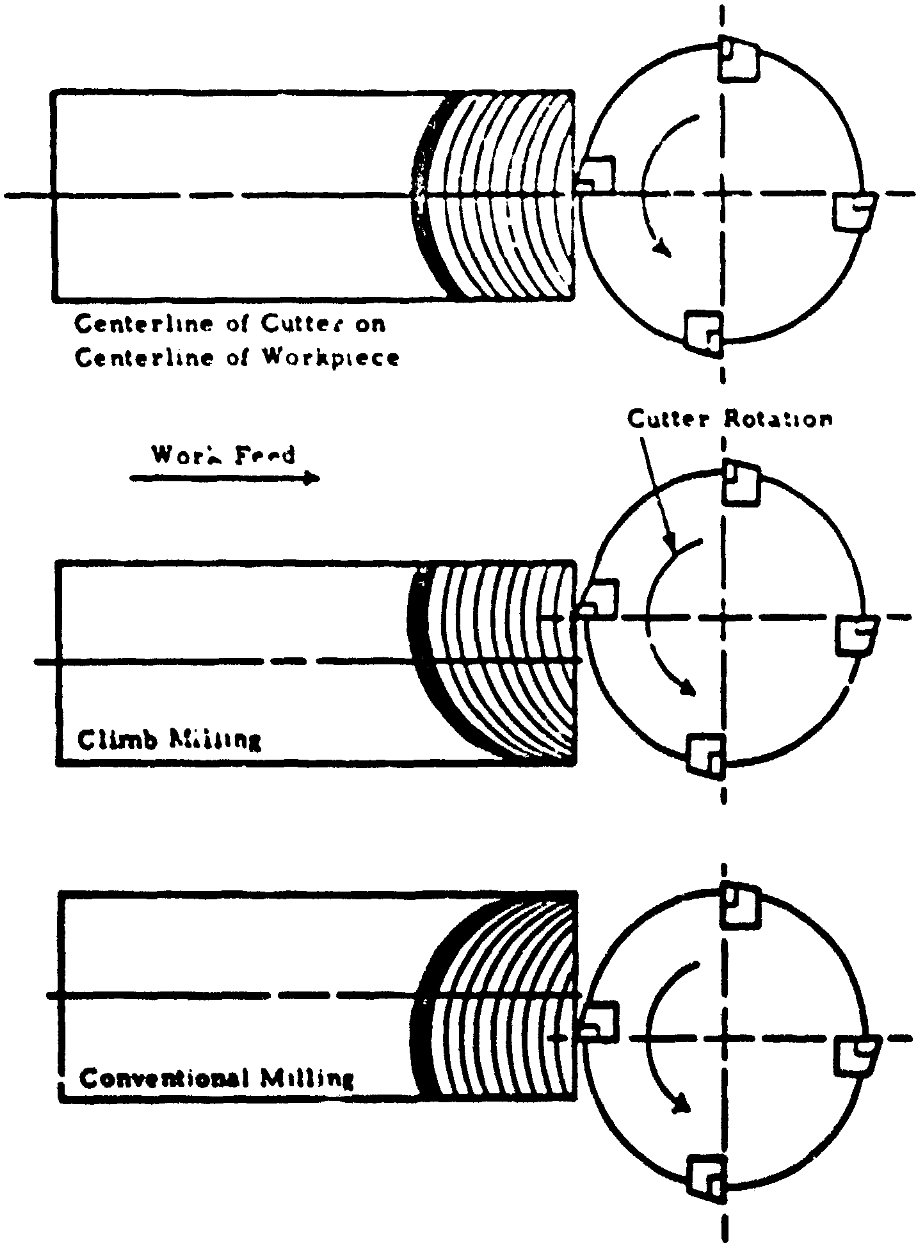
Face Milling and End Milling tests were performed on a Cincinnati Cinova 80 Vertical Milling Machine. This machine is equipped with a variable speed drive to provide exact cutting speeds.

See text, page 2

Figure 4

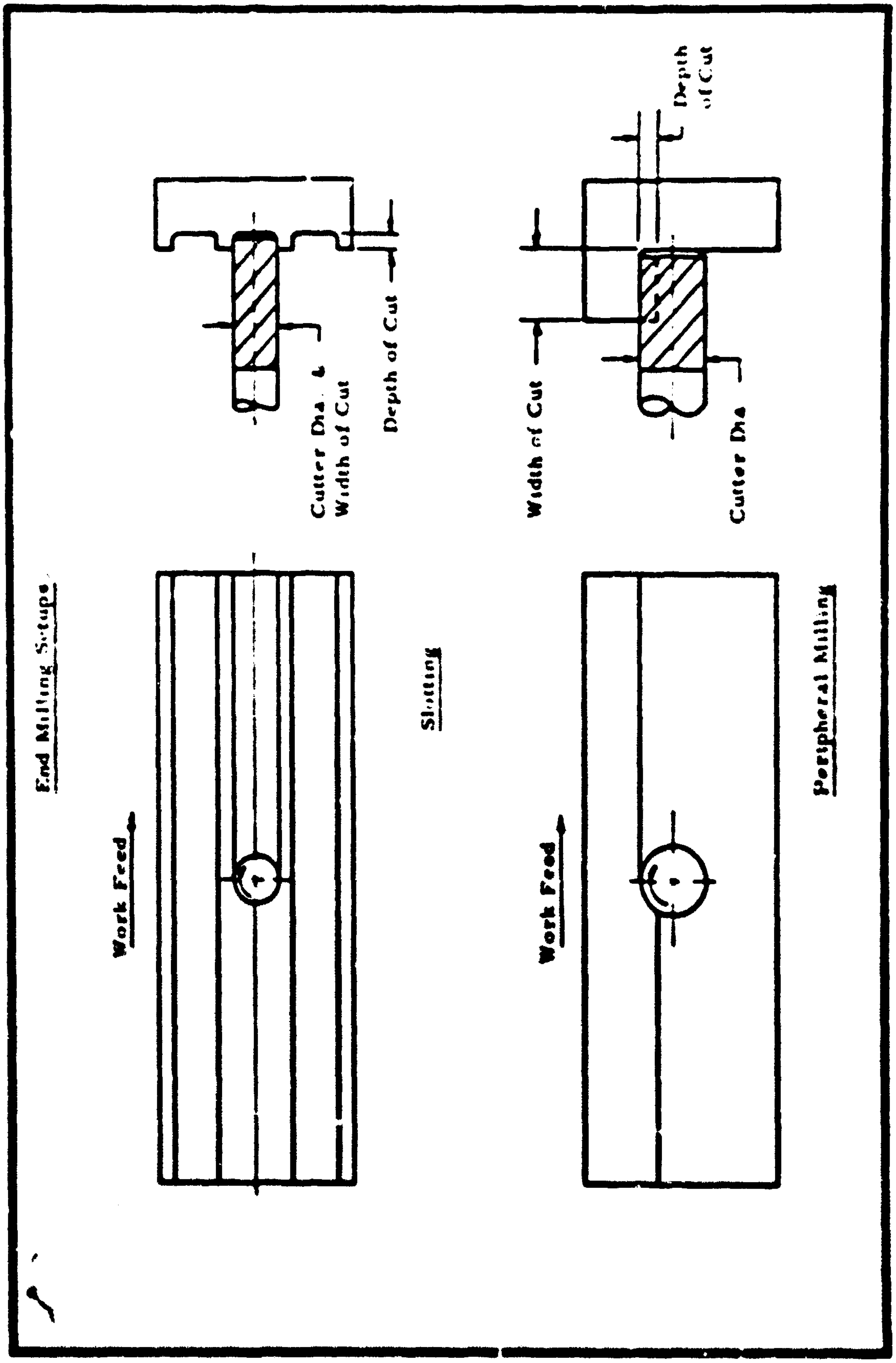
Face Milling Setups

Conventional and Climb Milling



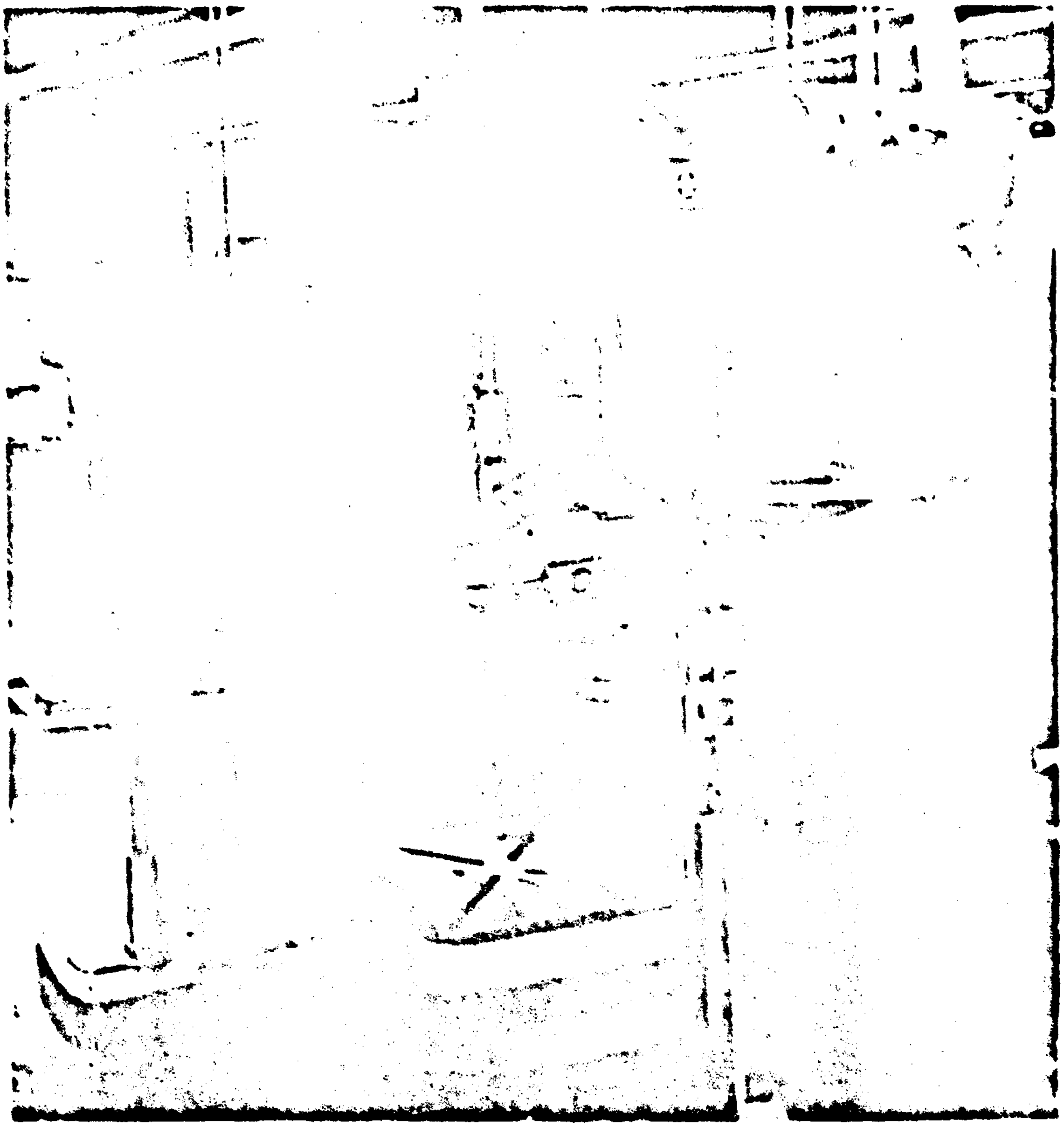
See text, page 2

Figure 5



See text, page 3

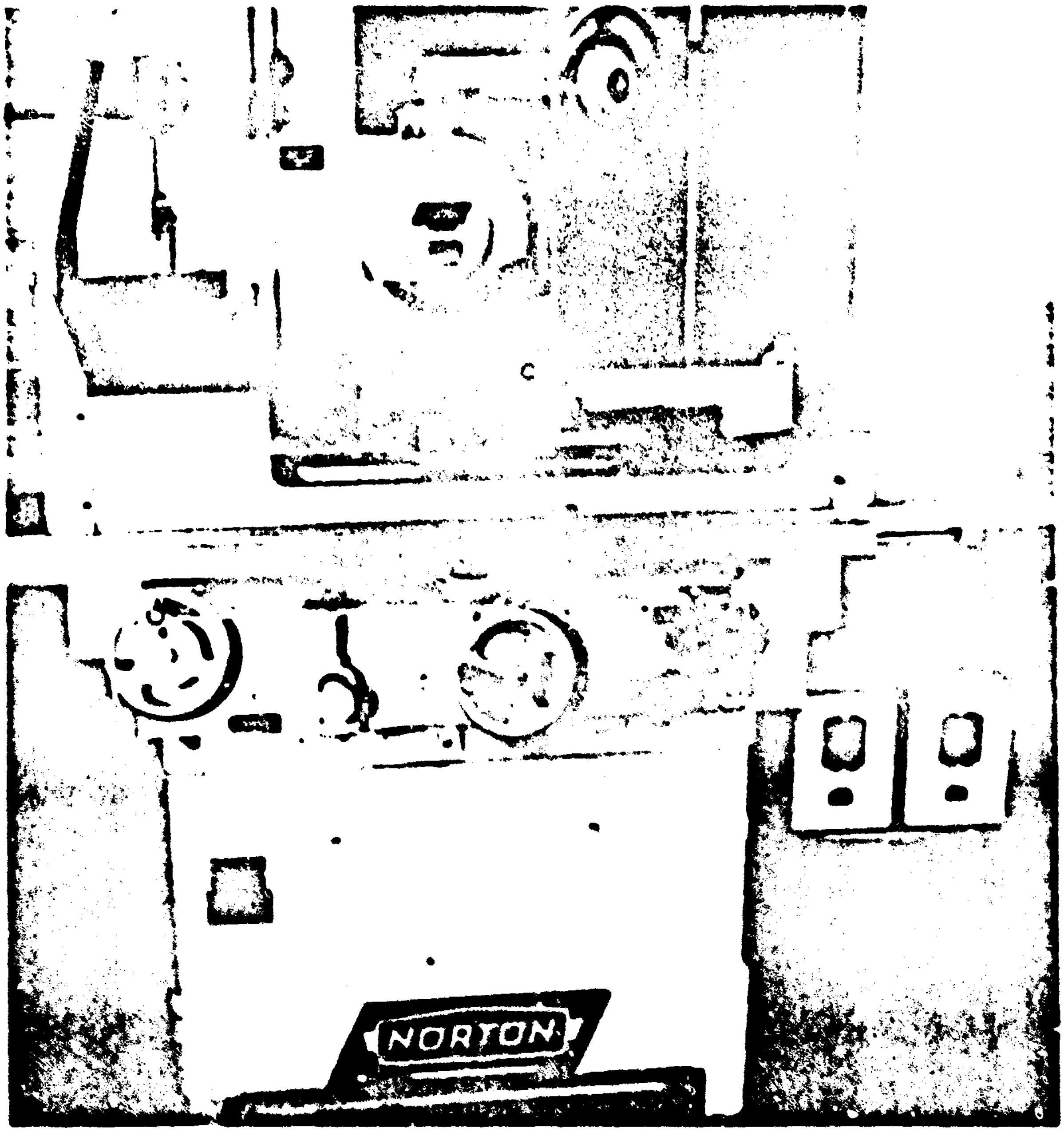
Figure 6



Drilling tests were performed on a Bickford 24" Heavy-Duty Box Column Drill Press (right) and a Cincinnati 16" Box Column Drilling Machine. Both machines are equipped with continuously variable speed drive units to provide exact cutting speeds.

See text, page 3

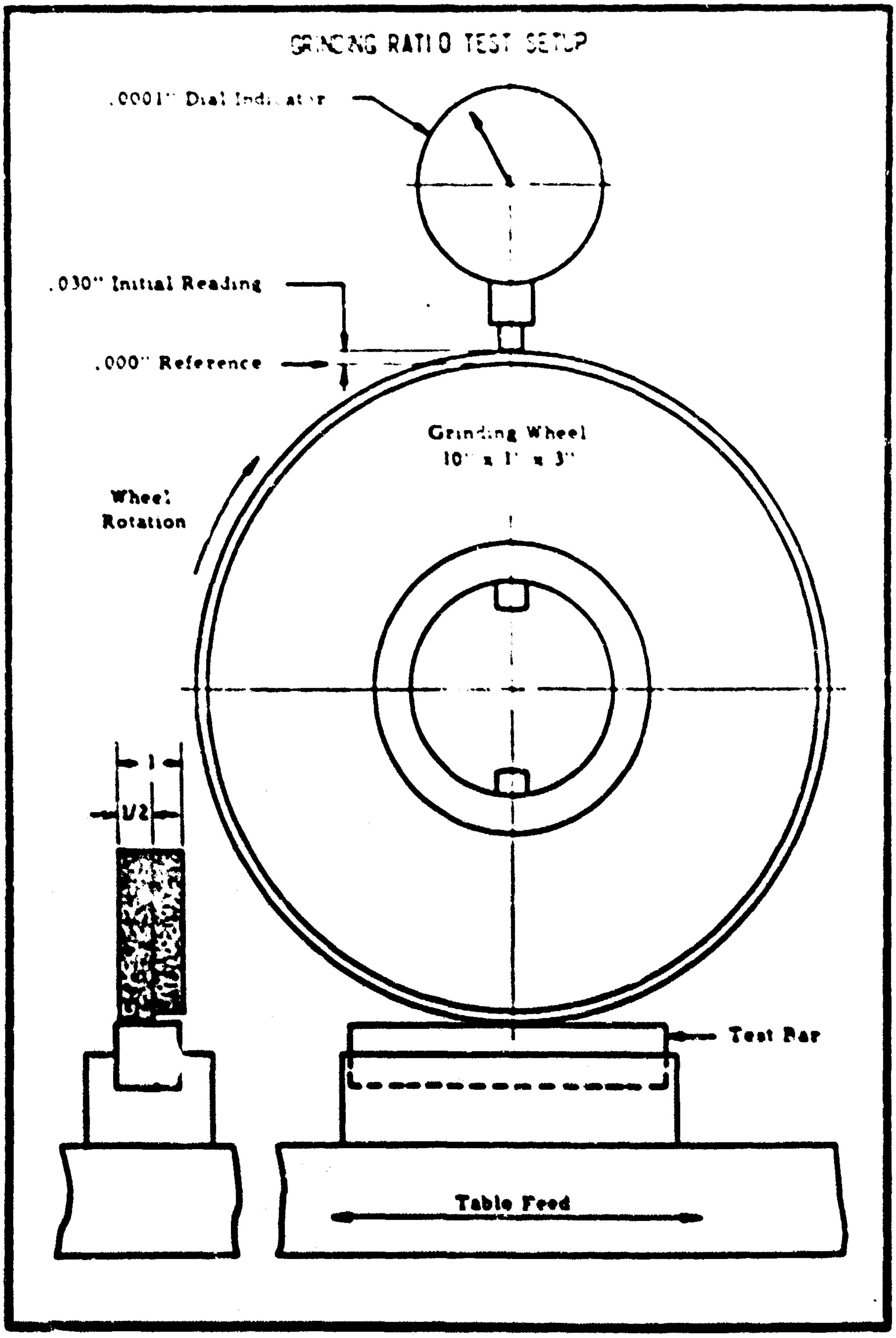
Figure 7



Surface Grinding tests were performed on a Norton 8" x 24" Hydraulic Surface Grinder equipped with a continuously variable speed drive. Grinding speeds ranging from 1000 to 7500 surface feet per minute can be obtained.

See text, page 4

Figure 8



GRINDING RATIO TEST SETUP

See text, page 4

Figure 3

3. MACHINING ULTRA HIGH STRENGTH STEELS

3.1 HP 9-4-45 Steel, Normalized

Alloy Identification

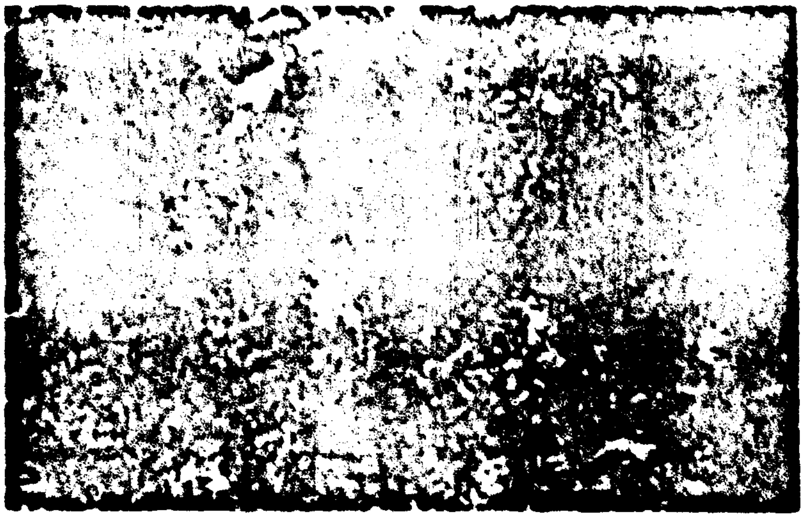
HP 9-4-45 is a nickel-cobalt, high strength, hardenable steel which is capable of yield strengths up to 250 ksi and exhibits good toughness characteristics. The nominal composition of this material is as follows:

Fe-9Ni-4Co-.45C-.3Cr-.3Mo

Forged, normalized 2 in. by 8 in. rectangular bars were procured for the milling tests. The normalizing treatment performed at the mill was as follows:

1625°F/2 hours/air cool

The as-received hardness of the material was 302-341 BHN. The normalizing treatment produced a microstructure which is essentially spheroidal. This condition is illustrated below.



HP 9-4-45, Normalized

Etchant: Kalling's Mag.: 1000X

[illegible] HP 9-4-45 Steel, Normalized (continued)

Turning (341 BHN)

The tool life results were similar with both the M2 and M42 HSS tools when turning the HP 9-4-45 steel in the normalized condition; see Figure 10, page 22. At a cutting speed of 70 feet/minute, the tool life with either of these two types of high speed steel was 48 minutes.

Tool life curves with three different grades of carbides are shown in Figure 11, page 22. There was a wide range of cutting speeds over which the three grades of carbides could be used. For example, at a tool life of 30 minutes, the C-6 grade of carbide would have to be used at a cutting speed of 350 feet/minute, while the titanium carbide could be used at a cutting speed of 650 feet/minute. The cutting speed with the C-2 grade, which performed the poorest, would be less than 200 feet/minute.

The surface found on the HP 9-4-45 steel as a result of normalizing was appreciably more difficult to machine than the base metal. Note in Figure 12, page 23, that at a cutting speed of 350 feet/minute the tool life under the skin with the C-6 grade of carbide was 40 minutes as compared to six minutes when machining the skin.

Face Milling (302 BHN)

Tool life curves with three different grades of high speed steel are shown in Figure 13, page 23. Note that in the lower cutting speed range the M2 HSS cutter performed the best. There was a tendency for the T15 and M42 HSS cutters to chip.

For a given cutter life, the cutting speed at a feed of .005 in./tooth was almost 25 percent faster than that at a feed of .010 in./tooth, see Figure 14, page 24. This is an important factor since with a multiple-tooth cutter generally the feed has to be reduced over that used with a single-tooth cutter. However, even at a feed of .005 in./tooth, the cutter life with a multiple-tooth cutter was very short over a range of cutting speeds; see Figure 15, page 24.

As shown in Figure 16, page 25, by further reducing the feed to .003 in./tooth, the life of the 14-tooth cutter increased from 20 to 72 inches of work travel per tooth. In other words, at a feed of .003 in./tooth and a cutting speed of 160 feet/minute, the total tool life of the 14-tooth cutter was slightly more than 1,000 inches of work travel.

3.3 HP 9-4-45 Steel, Normalized (continued)

Face Milling (302 BHN) (continued)

In several previous tests on high strength steels, the tool life in face milling with carbide was higher when machining dry than when machining with a cutting fluid. For example, as shown in Figure 17, page 25, the cutter life at 400 feet/minute with a single-tooth carbide cutter was 25 inches of work travel as compared to 72 inches of work travel when cutting dry. These results were obtained at a feed of .005 in./tooth. At feeds above .005 in./tooth, increasing the feed resulted in a decrease in tool life, see Figure 18, page 26. These results were with a single-tooth cutter.

However, as has been found before, the feed rate had to be reduced when a multiple-tooth cutter was used. Tool life curves are presented in Figure 19, page 26, for a single-tooth and a six-tooth cutter at a feed of .005 in./tooth. The cutter life per tooth was reduced from 90 to 75 inches of work travel in going from the single-tooth to the six-tooth cutter. However, the six-tooth cutter did provide a total tool life of 450 inches of work travel.

Peripheral End Milling (302 BHN)

Tool life curves over a range of cutting speeds are presented in Figure 20, page 27, for two different feed rates. Note that at a tool life of 125 inches of work travel, the cutting speed at the lighter feed was almost 20 percent greater than that at the feed of .004 in./tooth.

The effect of feed rate on cutter life is further demonstrated in Figure 21, page 27. At a cutting speed of 225 feet/minute, the tool life decreased from 210 to 127 inches of work travel when the feed rate was increased from .003 to .004 in./tooth.

End Mill Slotting (302 BHN)

The tool life curves shown in Figure 22, page 28, were obtained at two different feed rates. It is immediately apparent that the higher feed rate is much more desirable. Not only is the feed rate twice as great, but the cutting speeds are appreciably higher at the feed rate of .002 in./tooth.

The feed curve shown in Figure 23, page 28, indicates how critical the feed is when end mill slotting at a cutting speed of 150 feet/minute. For example, at a feed rate of .002 in./tooth, the tool life was 230 [illegible] Steel, Normalized (continued)

End Milling (302 BHN) (continued)

inches of work travel. Decreasing the feed rate 50 percent resulted in a 72 percent reduction in tool life. Also when the feed rate was increased 50 percent, the tool life was reduced 30 percent.

Drilling (302 BHN)

As shown in Figure 24, page 29, at a cutting speed of 70 feet/minute where the drill life was greater than 250 holes using a chemical emulsion cutting fluid, the drill lives with the M1 and M42 HSS drills were the same. As the cutting speed was increased, the drill life with the M1 HSS drills decreased much more rapidly than with the M42 HSS drills. However, when a chlorinated oil was used, the cutting speeds with both drills were appreciably less and the M1 HSS drills were superior to the M42 HSS drills, see Figure 25, page 29. For example at a cutting speed of 50 feet/minute the drill life with the M1 HSS drills was more than 250 holes as compared to less than 100 with the M42 HSS drills. At higher speeds above 65 feet/minute, the two different grades of HSS drills performed similarly.

It is interesting to note the effect of cutting fluid on tool life for both the M1 and the M42 HSS drills as shown in Figures 26 and 27, page 30. Using the M1 HSS drills, the cutting speed for a tool life of 250 holes was 40 percent faster when using the chemical emulsion as compared to using the chlorinated oil. When using the M42 HSS drills, the drill life was satisfactory with the chemical emulsion; however, the drill life dropped radically when a chlorinated oil was used. For example, over 250 holes were drilled at a cutting speed of 70 feet per minute with the chemical emulsion. Using the chlorinated oil, the drill life was only 80 holes.

Reaming (302 BHN)

A comparison of the tool life curves obtained with two different cutting fluids in reaming with an M2 HSS six-flute reamer is shown in Figure 28, page 31. Note that the chemical emulsion was much more effective than the chlorinated oil. For example, at a cutting speed of 125 feet per minute, the tool life with the chemical emulsion was 175 holes as compared to 35 holes with the chlorinated oil.

3.1 HP 9-4-45 Steel, Normalized (continued)

Tapping (302 BHN)

As shown in Figure 29, page 31, the three-flute tap provided considerably longer tap life than the two-flute tap. At a cutting speed of 200 feet/minute, the tap life was 35 holes with the two-flute tap and 215 holes with the three-flute tap. The cutting speed of 200 feet/minute was the maximum available on the machine.

The chlorinated oil was more effective than the chemical emulsion in tapping. Note in Figure 30, page 32, that at a cutting speed of 200 feet/minute, the tap life with the chemical emulsion was 50 holes as compared to 215 holes with the chlorinated oil.

TABLE I

RECOMMENDED CONDITIONS FOR MACHINING HP 9-4-45 STEEL, NORMALIZED 341 BHN

Nominal Chemical Composition, Percent

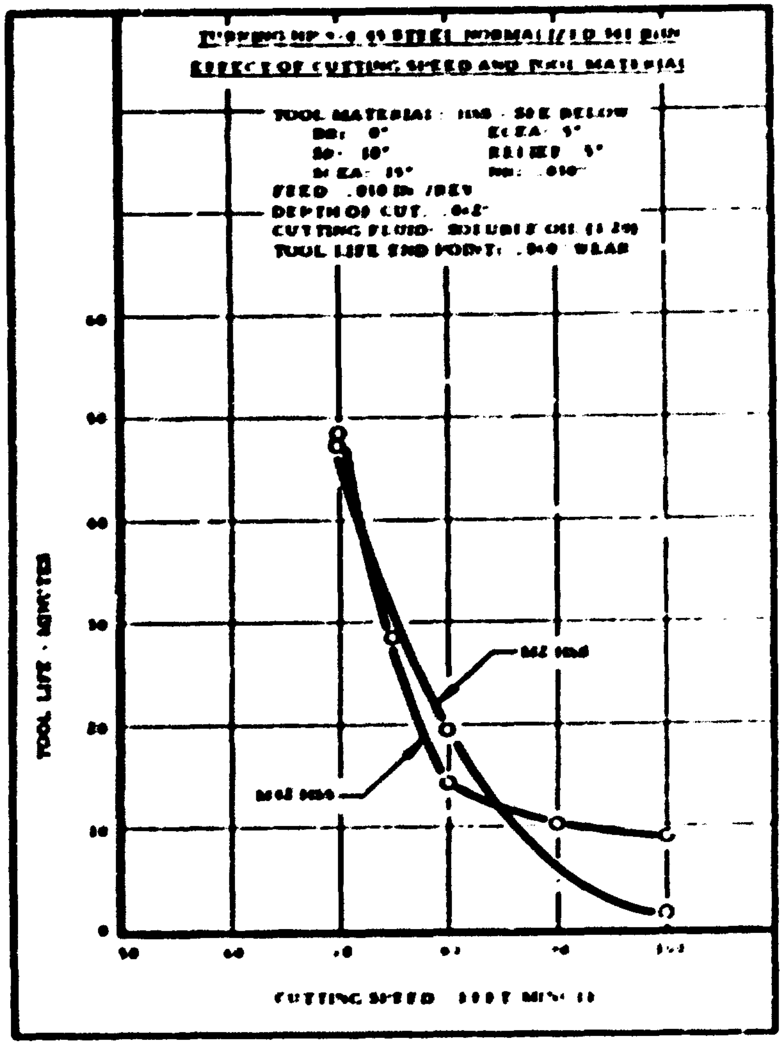
Fe	Ni	Co	C	Cr	Mo
Bal.	9	4	.45	1	1

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT INCHES	WIDTH OF CUT INCHES	FEED	CUTTING SPEED ft./min	TOOL LIFE	WEAR-LAND INCHES	CUTTING FLUID
Turning	M2 HSS	BR: 0° SCEA:15° SR:10° ECEA:5° Relief: 5° NR: .030"	5/8" Square Tool Bit	.062	-	.010 in/rev	70	48 min.	.060	Soluble Oil (1:20)
Turning	TiC Carbide	BR:-5° SCEA:15° SR:-5° ECEA:15° Relief: 5° NR: .030"	SNG 432 Insert	.062	-	.010 in/rev	650	30 min.	.006	Soluble Oil (1:20)
Face Milling	M2 HSS	AR:5° ECEA: 1° RR: 5° CA: 45° Clearance: 10°	4" Diameter 14 Tooth HSS Face Mill	.060	2	.003 in/tooth	160	1010" work travel	.060	Soluble Oil (1:20)
Face Milling	C-6 Carbide	AR:-5° ECEA:45° RR: -5° CA: 45° Clearance: 5°	4" Diameter 6 Tooth Face Mill	.060	2	.0[illegible] in/tooth	150	450" work travel	.015	Dry
Peripheral End Milling	M2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .050"	1" Diameter 4 Flute HSS End Mill	.250	.500	.003 in/tooth	225	205" work travel	.012	Soluble Oil (1:20)
End Mill Slotting	M2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" Diameter 4 Flute HSS End Mill	.250	.750	.002 in/tooth	150	225" work travel	.012	Soluble Oil (1:20)

TABLE I (continued)

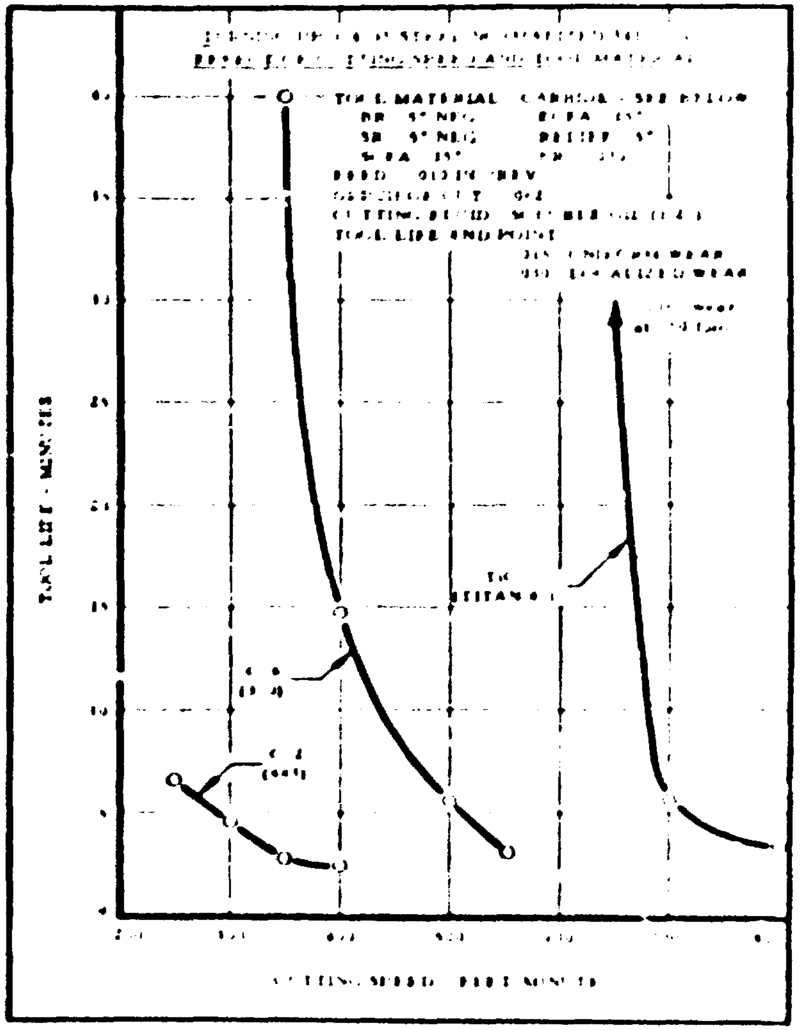
RECOMMENDED CONDITIONS FOR MACHINING
HP 9-4-45 STEEL, NORMALIZED 341 BHN

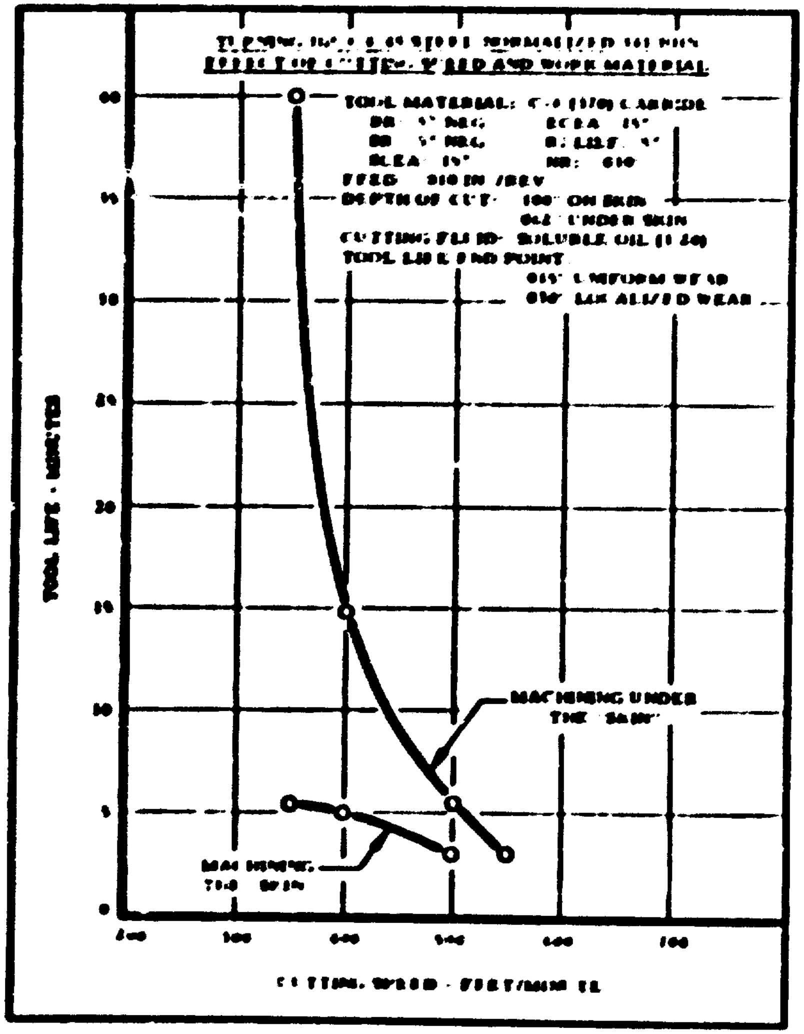
OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft/min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Drilling	M1 HSS	118° Crankshaft Point Helix Angle: 29° Clearance: 7°	1/4" Diameter HSS Drill 2-1/2" Long	.500 thru	--	.005 in/rev	70	250 holes	.012	Chemical Emulsion (1:20)
Reaming	M2 HSS	Helix Angle: 0° CA: 45° Clearance: 7°	.272" Diameter 6 Flute Chucking Reamer	.500 thru	--	.009 in/rev	125	175 holes	.006	Chemical Emulsion (1:20)
Tapping	M1 HSS	2 Flute Plug Spiral Point 75% Thread	5/16-24 NF Tap	.500 thru	--	--	200	220 holes	Under size Threa	Chlorinated Oil



See text page [illegible]

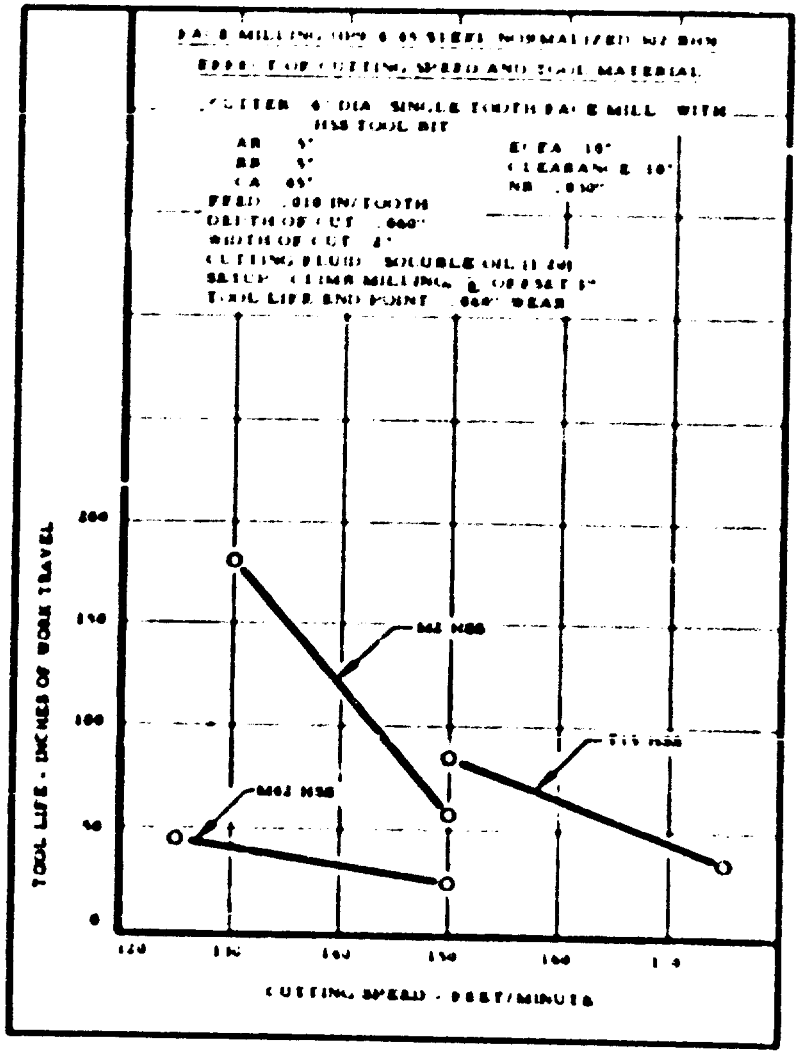
Figure [illegible]





See text, page 16

Figure 12



See text, page 16

Figure 11

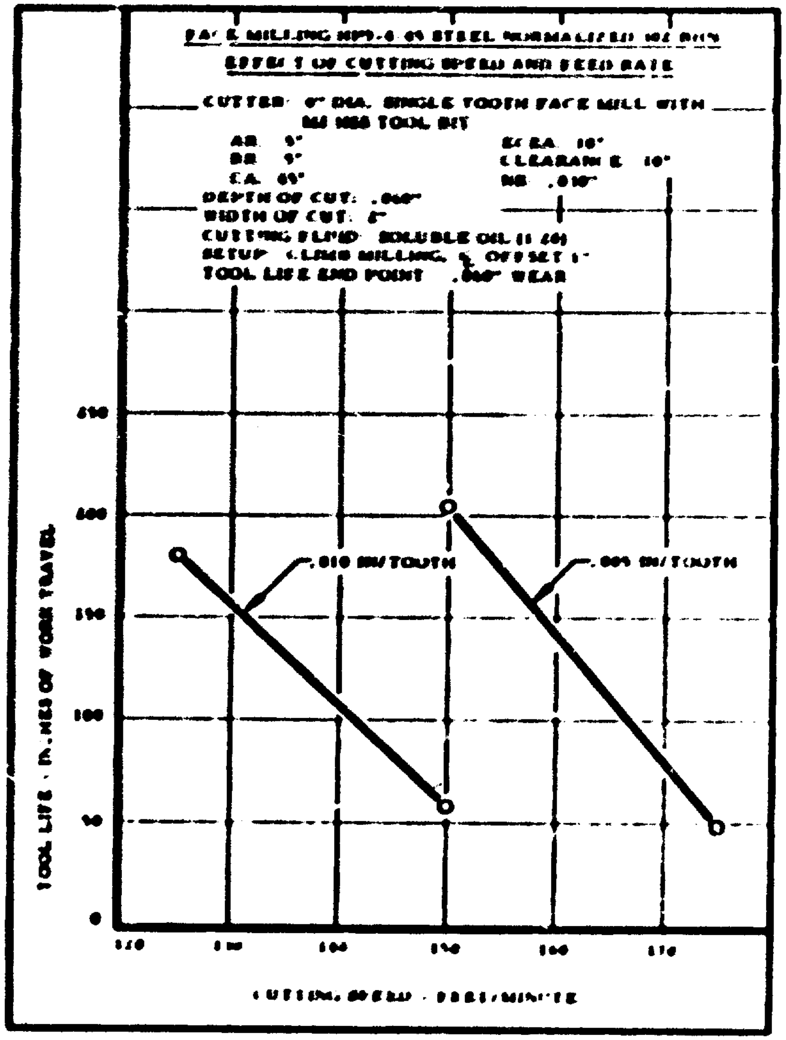


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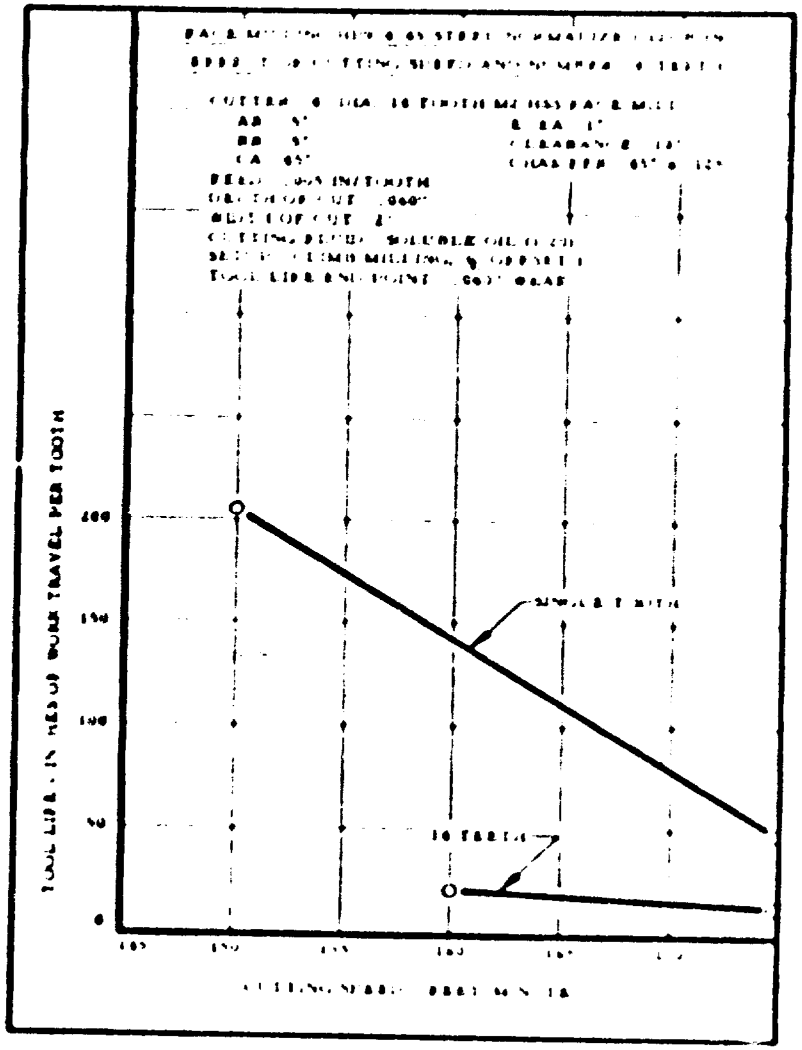
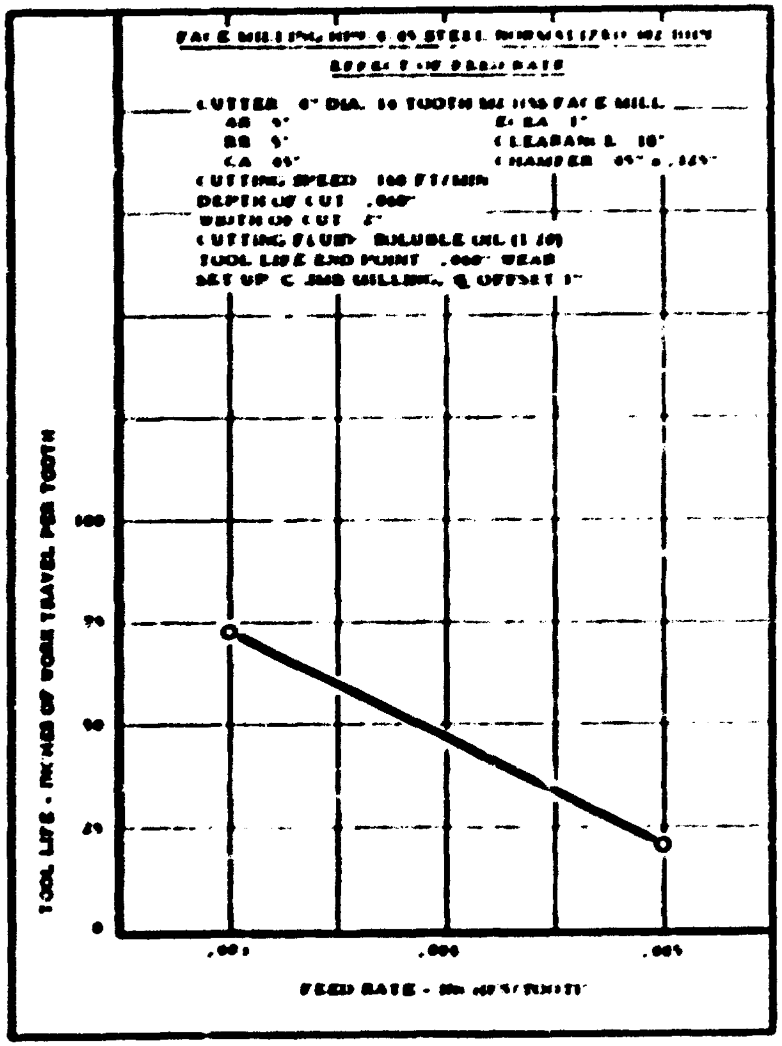
Figure 16



See text, page 17

Figure 17



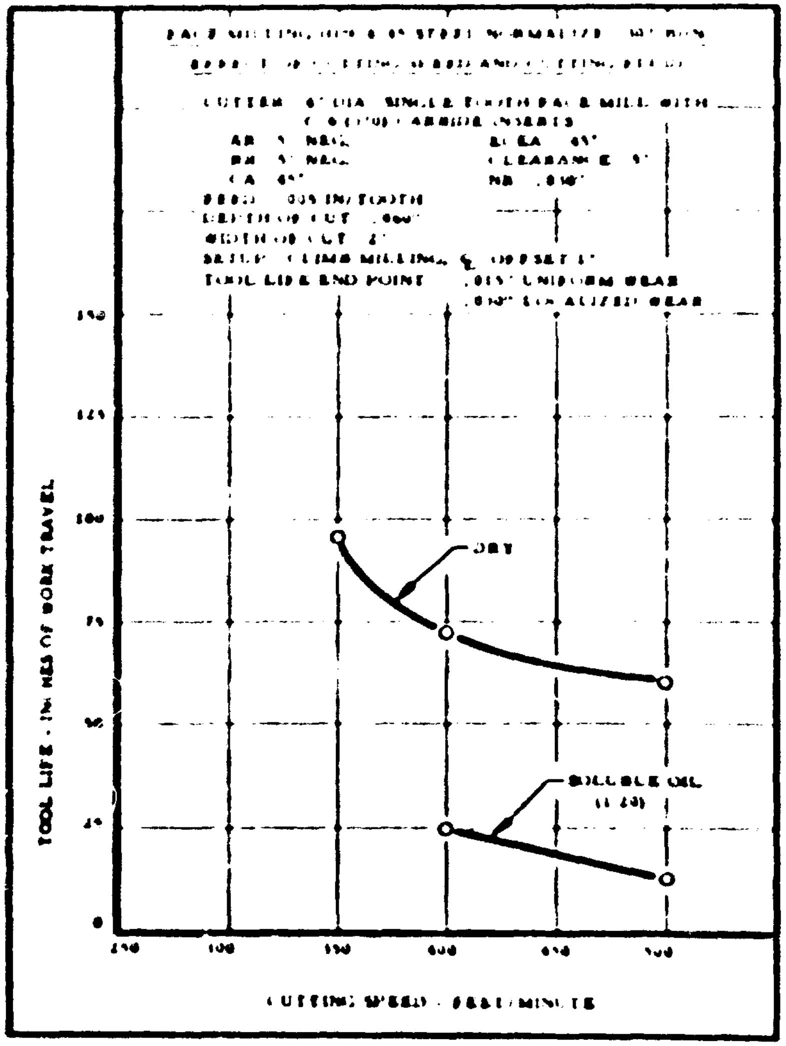
FACE MILLING, [illegible] STEEL NORMALIZED [illegible] BHN

EFFECT OF FEED RATE

CUTTER 6" DIA. 16 TOOTH [illegible] FACE MILL
AR 5° ECEA 1°
RR 5° CLEARANCE 10°
CA 45° CHAMFER 45° x .125"
CUTTING SPEED 100 FT/MIN
DEPTH OF CUT .060"
WIDTH OF CUT 2"
CUTTING FLUID SOLUBLE OIL (1:20)
TOOL LIFE END POINT .060" WEAR
SET UP CLIMB MILLING, ℄ OFFSET 1"

See text, page 16

Figure 16



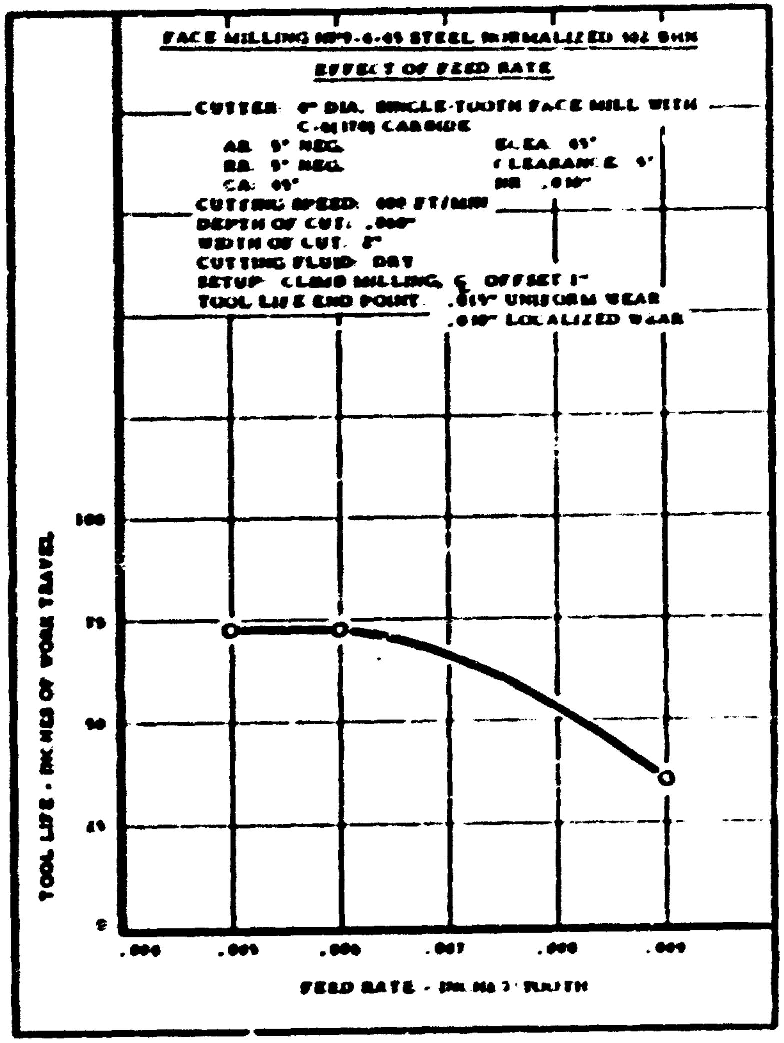
FACE MILLING, [illegible] STEEL NORMALIZED [illegible] BHN

EFFECT OF CUTTING SPEED AND CUTTING FLUID

CUTTER 6" DIA. SINGLE TOOTH FACE MILL WITH
CARBIDE INSERTS
AR 5° NEG. ECEA 45°
RR 5° NEG. CLEARANCE 5°
CA 45° NR .040"
FEED .005 IN/TOOTH
DEPTH OF CUT .060"
WIDTH OF CUT 2"
SETUP CLIMB MILLING, ℄ OFFSET 1"
TOOL LIFE END POINT .015" UNIFORM WEAR
.030" LOCALIZED WEAR

See text, page 17

Figure 17



See text, page 17

Figure 10

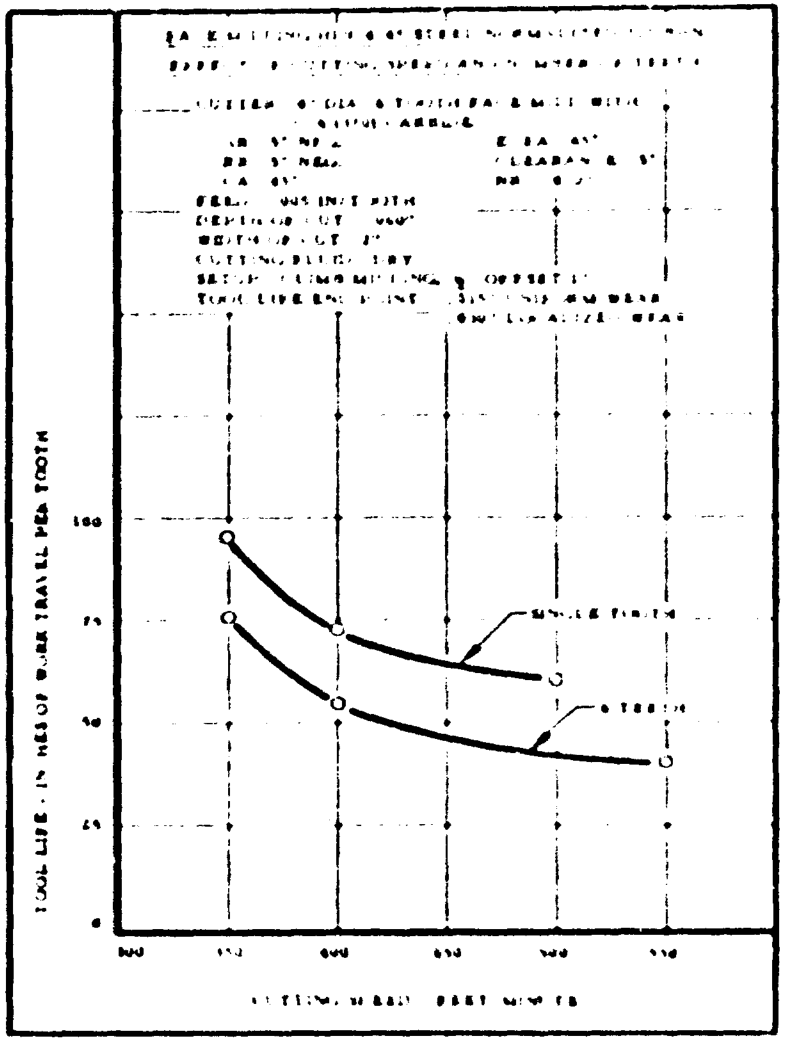


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Figure 11

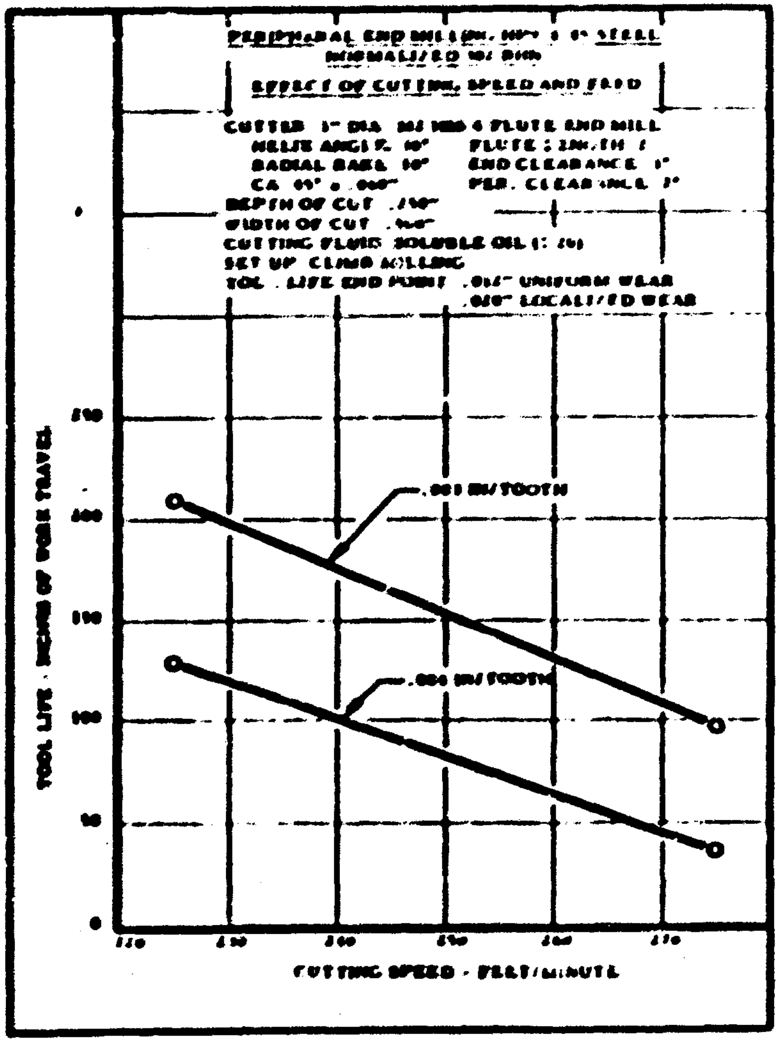

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Figure 20

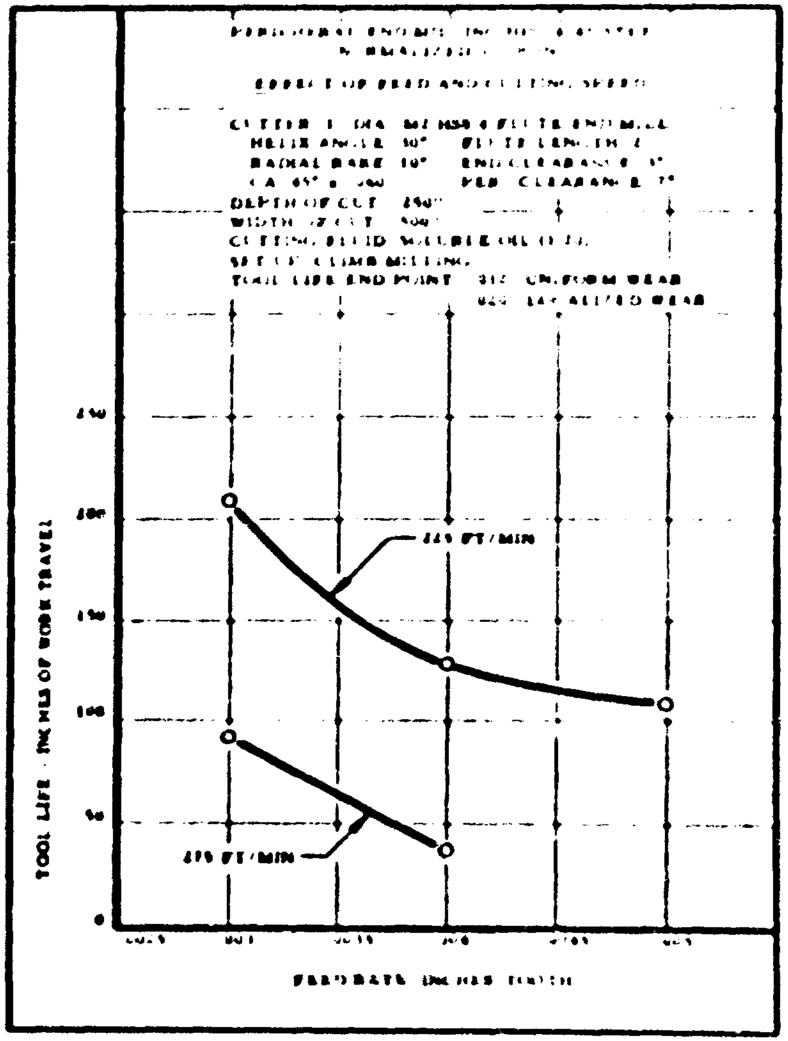

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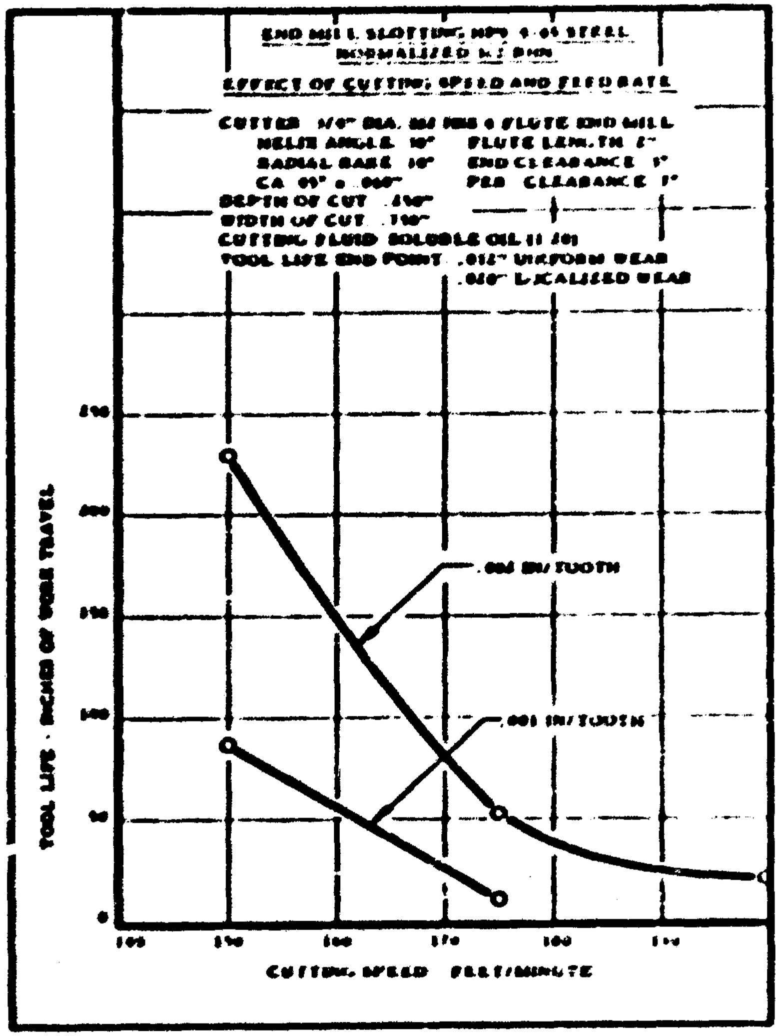
Figure 21



See text page 17

Figure 22

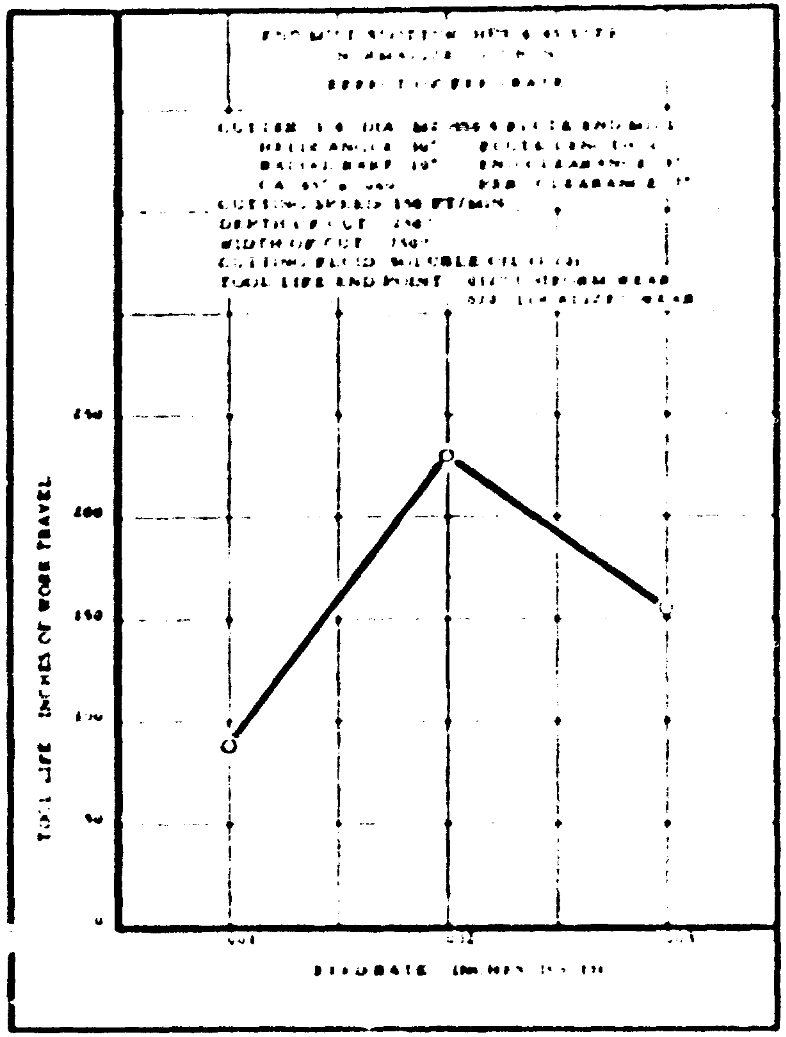


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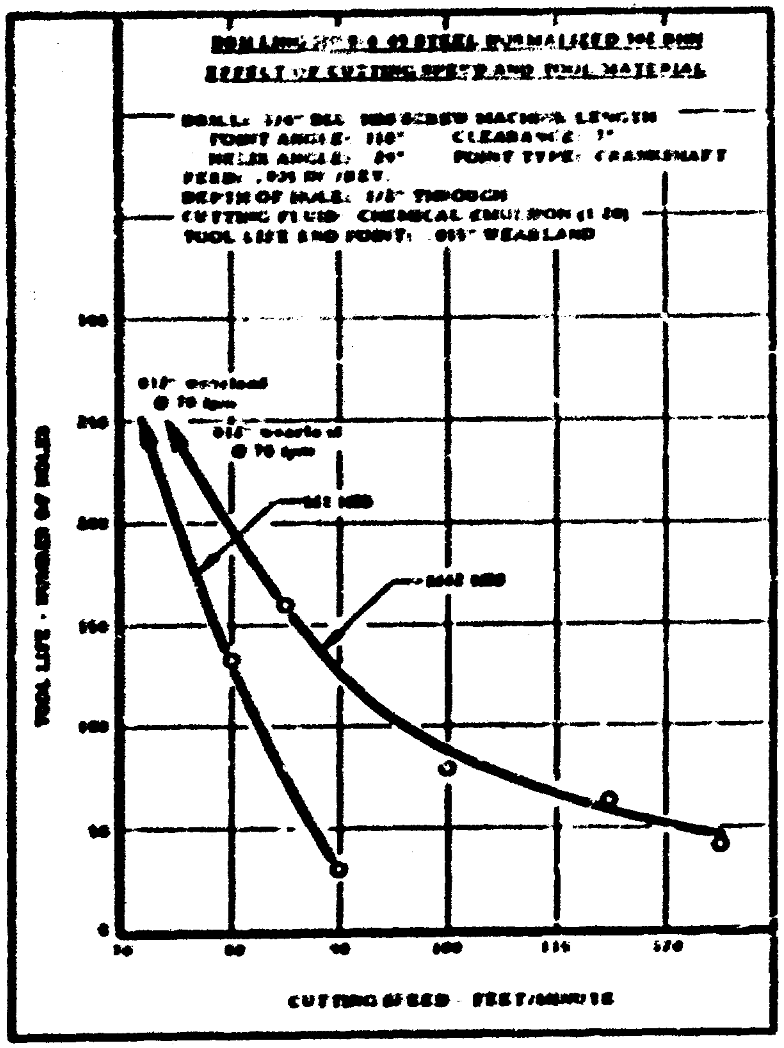
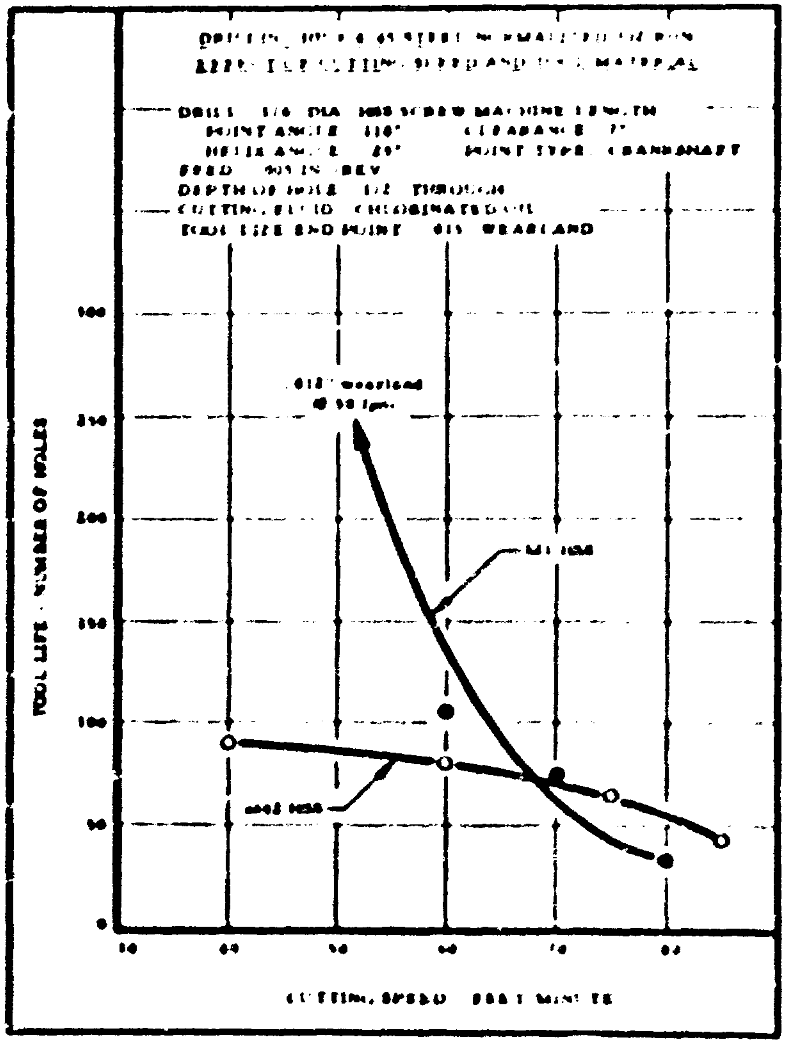
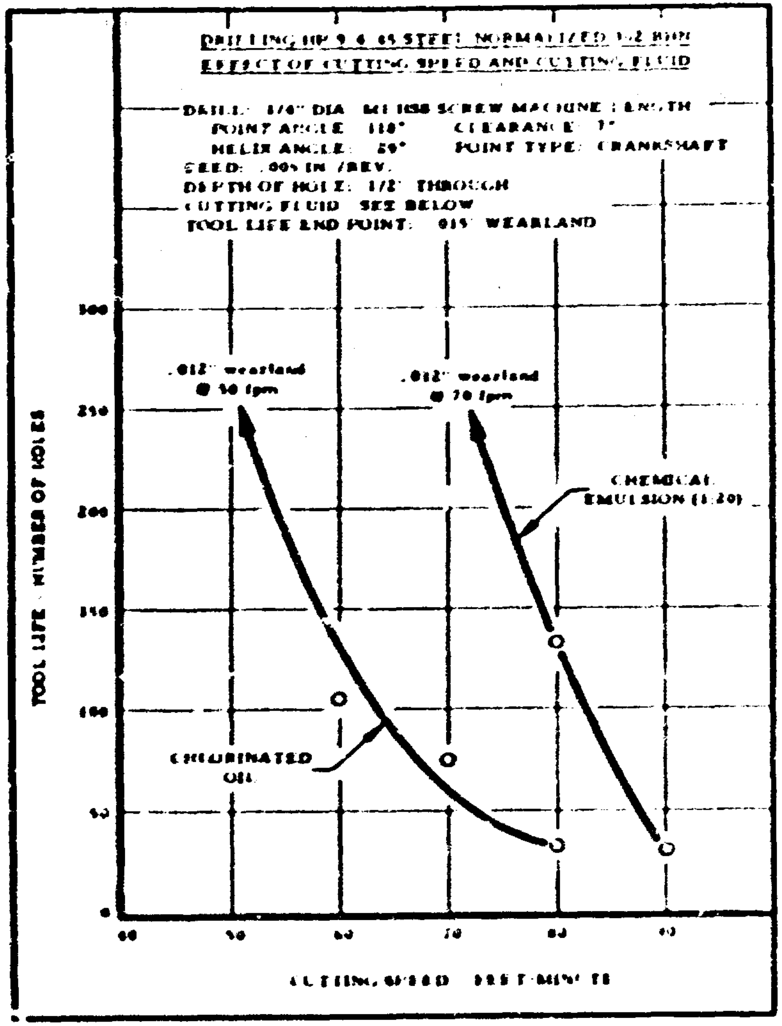
Figure [illegible]



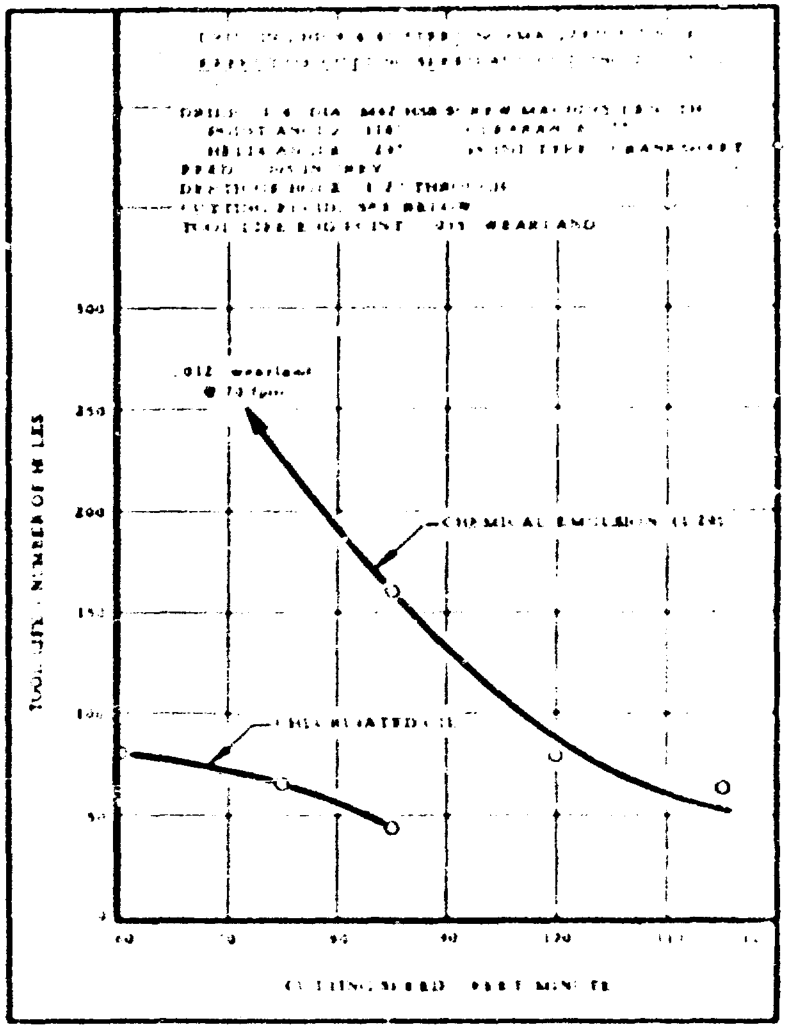
See text, page 10 Figure 26



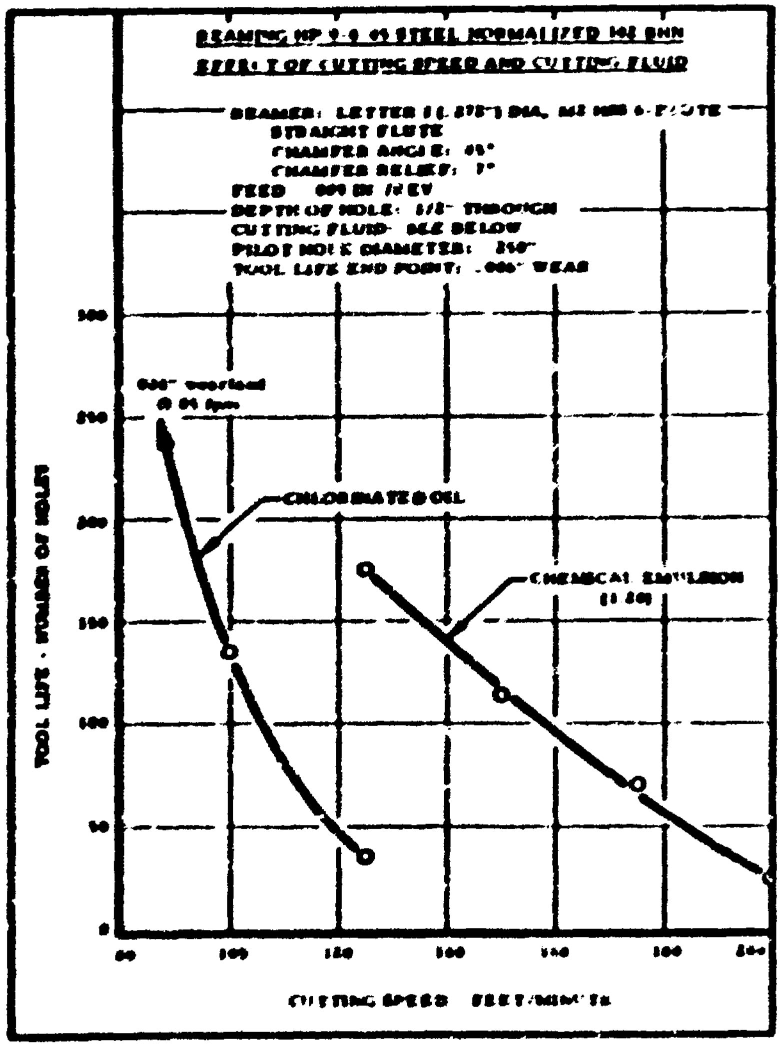
See text, page 10 Figure 25



See text page 18 Figure [illegible]



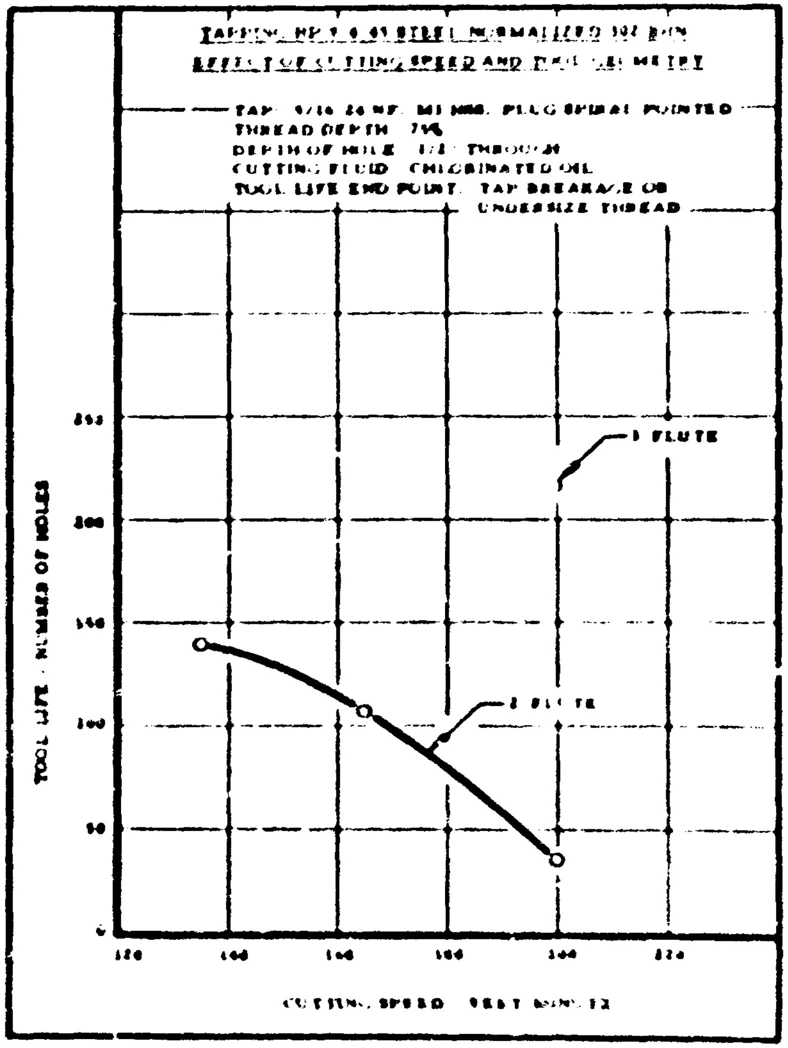
See text page 18 Figure [illegible]


REAMING HP 9-4-45 STEEL NORMALIZED 192 BHN
EFFECT OF CUTTING SPEED AND CUTTING FLUID

REAMER: LETTER I (.272") DIA, M2 HSS 6-FLUTE
STRAIGHT FLUTE
CHAMFER ANGLE: 45°
CHAMFER RELIEF: 7°
FEED .009 IN/REV
DEPTH OF HOLE: 1/2" THROUGH
CUTTING FLUID: SEE BELOW
PILOT HOLE DIAMETER: .250"
TOOL LIFE END POINT: .006" WEAR

See text, page 20

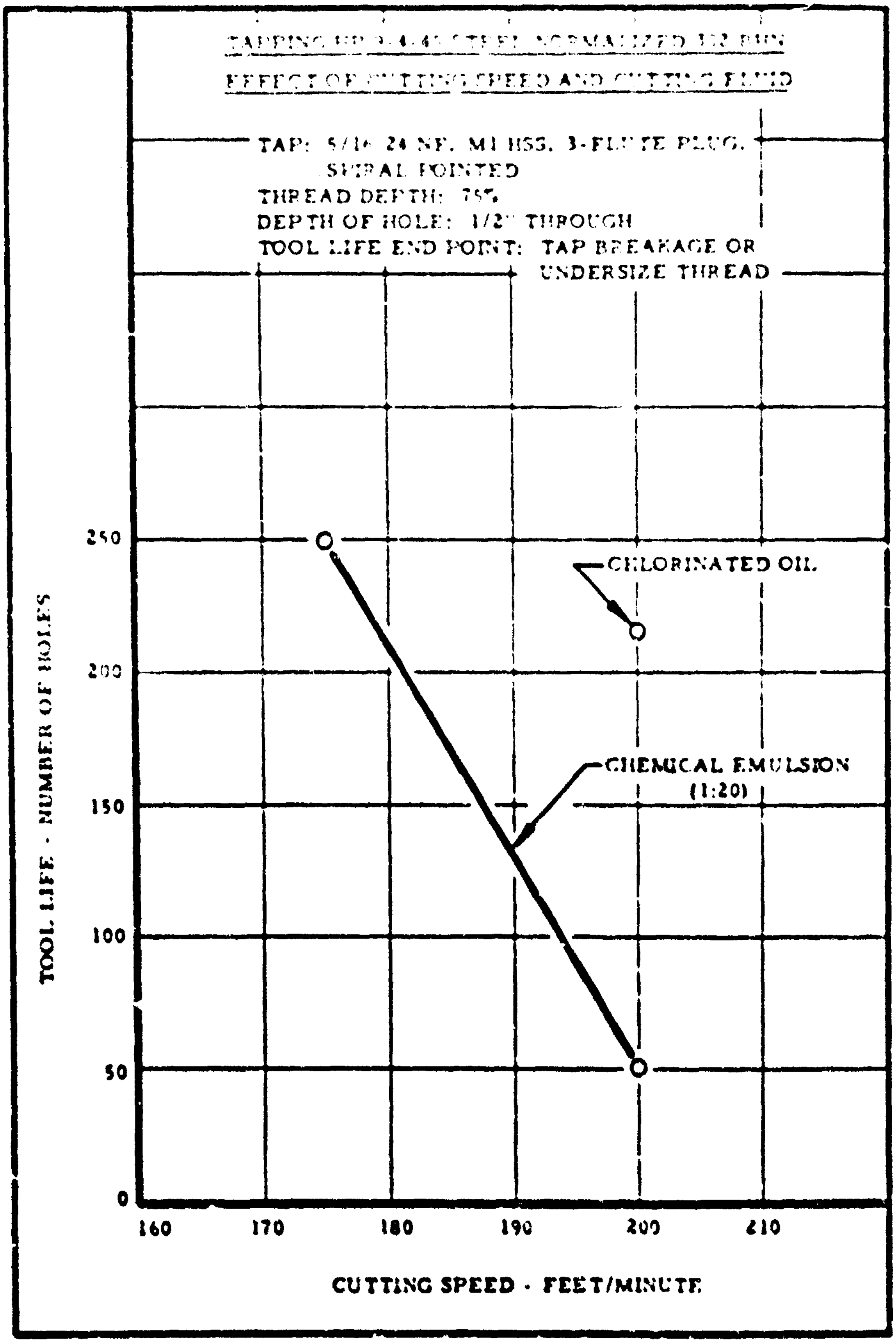
Figure 30


TAPPING HP 9-4-45 STEEL NORMALIZED 192 BHN
EFFECT OF CUTTING SPEED AND TAP GEOMETRY

TAP: 5/16-24 NF, M1 HSS, PLUG SPIRAL POINTED
THREAD DEPTH 75%
DEPTH OF HOLE 1/2" THROUGH
CUTTING FLUID CHLORINATED OIL
TOOL LIFE END POINT: TAP BREAKAGE OR UNDERSIZE THREAD

See text, page 19

Figure 29



See text, page 19

Figure 30

3.2 HP 9-4-45 Steel, Martempered

Alloy Identification

HP 9-4-45 is a nickel-cobalt, high strength, hardenable steel which is capable of yield strengths up to 250 ksi and exhibits good toughness characteristics. The nominal composition of this material is as follows:

FE-9Ni-4Co-.45C-.3Cr-.3Mo

The material for the turning tests was procured as forged, normalized 4 in. diameter bars. Forged rectangular bars 2 in. by 4 in., also in the normalized condition, were procured for the grinding tests. All of the material was then subjected to the following hardening heat treatment:

Austenitize: 1475°F/1 hour
Isothermal Temper: Transfer to furnace at 475°F/7 hours/
air cool

The resulting hardness was 51 R_c. This treatment produced a microstructure, shown below, which consists of bainite and martensite.

HP 9-4-45, Martempered

Etchant: Kalling's Mag.: 1000X

3.2 HP 9-4-45 Steel, Martempered (Continued)

Turning (51 R_c)

A comparison of tool life curves obtained with two grades of high speed steel is shown in Figure 31, page 37. At cutting speeds above 62 feet/minute, there was very little difference between the performances of the M2 and M42 HSS tools. However, at a cutting speed of 60 feet per minute, the tool life with the M2 HSS tool was 49 minutes as compared to 84 minutes plus with the M42 HSS tool.

As shown in Figure 32, page 37, the harder C-8 grade of carbide was appreciably better than the C-6 grade. For example, for a tool life of 20 minutes, the cutting speed with the C-6 grade was 200 feet/minute as compared to 305 feet/minute with the C-8 grade of carbide. Note that the feed was .007 in./rev. However, as shown in Figure 33, page 38, increasing the feed from .007 to .010 in./rev. with the C-8 grade of carbide resulted in decreasing the tool life from 24 minutes to 9 minutes. However, the same tool life (24 minutes) can be obtained at the higher feed if the cutting speed is reduced about 16 percent. In other words, when turning the HP 9-4-45 steel, quenched and tempered to a hardness of 51 R_c, a heavier feed of .010 in./rev. will provide the same tool life as a feed of .007 in./rev. if the cutting speed is reduced about 15 to 20 percent. Thus, a higher rate of metal removal can be obtained by using the heavier feed rate and slightly lower cutting speed.

Surface Grinding (51 R_c)

The effect of wheel speed on grinding ratio (G ratio) is shown in Figure 34, page 38. Note that the grinding ratio increased from 5 to 36 as the wheel speed was increased from 2000 to 6000 feet/minute.

As shown in Figure 35, page 39, increasing the cross feed resulted in a decrease in the G ratio. At a cross feed of .050 in./pass, the grinding ratio was 9.6 as compared to 4.8 at a cross feed of .100 in./pass.

Increasing the table speed also resulted in a marked decrease in the G ratio, see Figure 36, page 39. For example, as the table speed was increased from 40 to 60 feet/minute, the grinding ratio decreased from 36 to 9.

The grinding ratio decreased markedly when the down feed was increased as shown in Figure 37, page 40. Doubling the down feed

3.2 HP 9-4-45 Steel, Martempered (continued)

Surface Grinding (51 R_C) (continued)

(.001 to .002 in./pass) resulted in decreasing the G ratio from 45 to 36. Doubling the down feed again to .004 in./pass further decreased the G ratio to 9.

TABLE II

RECOMMENDED CONDITIONS FOR MACHINING
HP 9-4-45 STEEL, MARTEMPERED 51 R_c

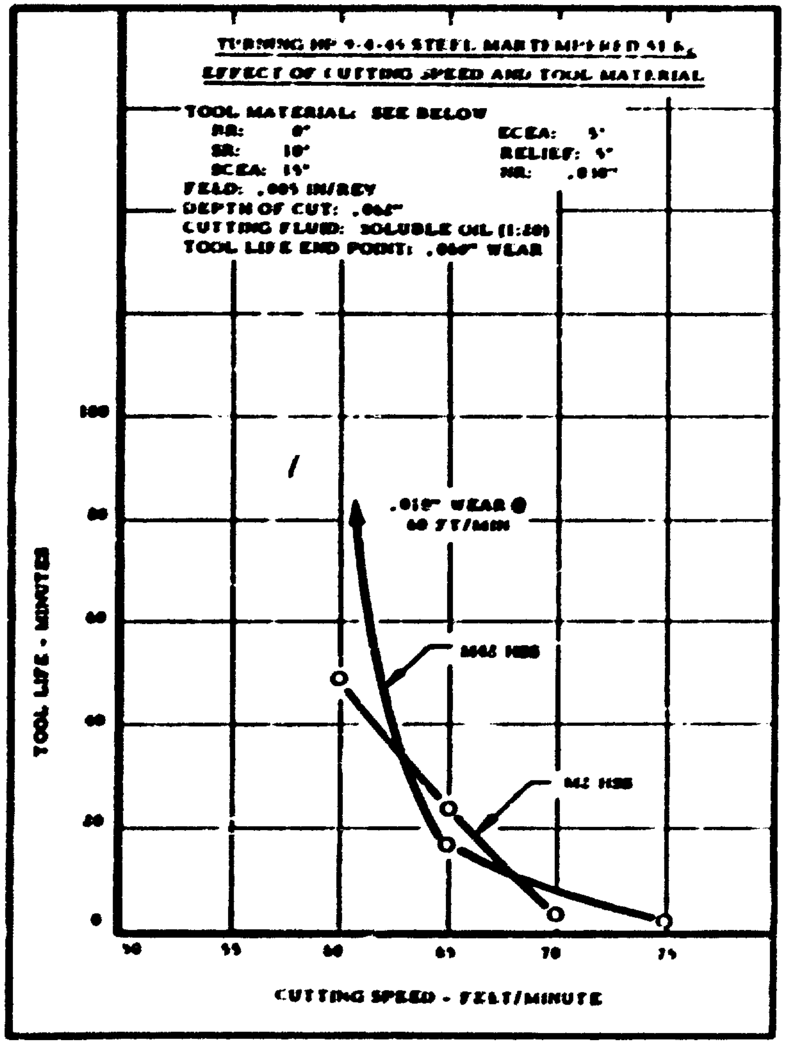
Nominal Chemical Composition, Percent

Fe	Ni	Co	C	Cr	Mo
Bal.	9	4	.45	3	3

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Turning	M42 HSS	BR: 0° SCEA: 15° SR: 10° ECEA: 15° Relief: 5° NR: .030"	5/8" Square Tool Bit	.062	--	.005 in/rev	60	85 min.	.018	Soluble Oil (1:20)
Turning	C-8 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	SNG-432 Insert	.062	--	.007 in/rev	300	24 min.	.015	Soluble Oil (1:20)

SURFACE GRINDING

Wheel Grade	Grinding Fluid	Wheel Speed ft./min.	Table Speed ft./min.	Down Feed in./pass	Cross Feed in./pass	G Ratio
32A46K8VBE	Soluble Oil (1:20)	6000	40	.001	.050	45



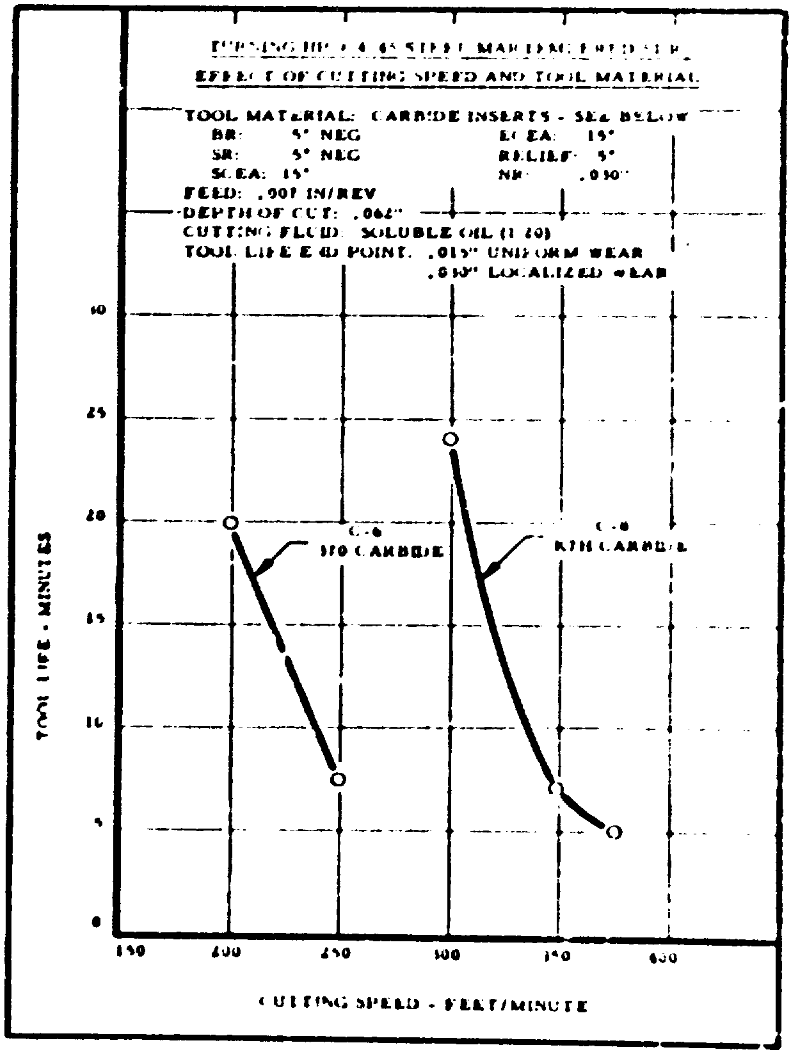
TURNING HP 9-4-45 STEEL MARTEMPERED 41 R_C

EFFECT OF CUTTING SPEED AND TOOL MATERIAL

TOOL MATERIAL: SEE BELOW
BR: 0°
SR: 10°
SCEA: 15°
ECEA: 5°
RELIEF: 5°
NR: .010"
FEED: .005 IN/REV
DEPTH OF CUT: .062"
CUTTING FLUID: SOLUBLE OIL (1:20)
TOOL LIFE END POINT: .060" WEAR

See text, page 34

Figure 11



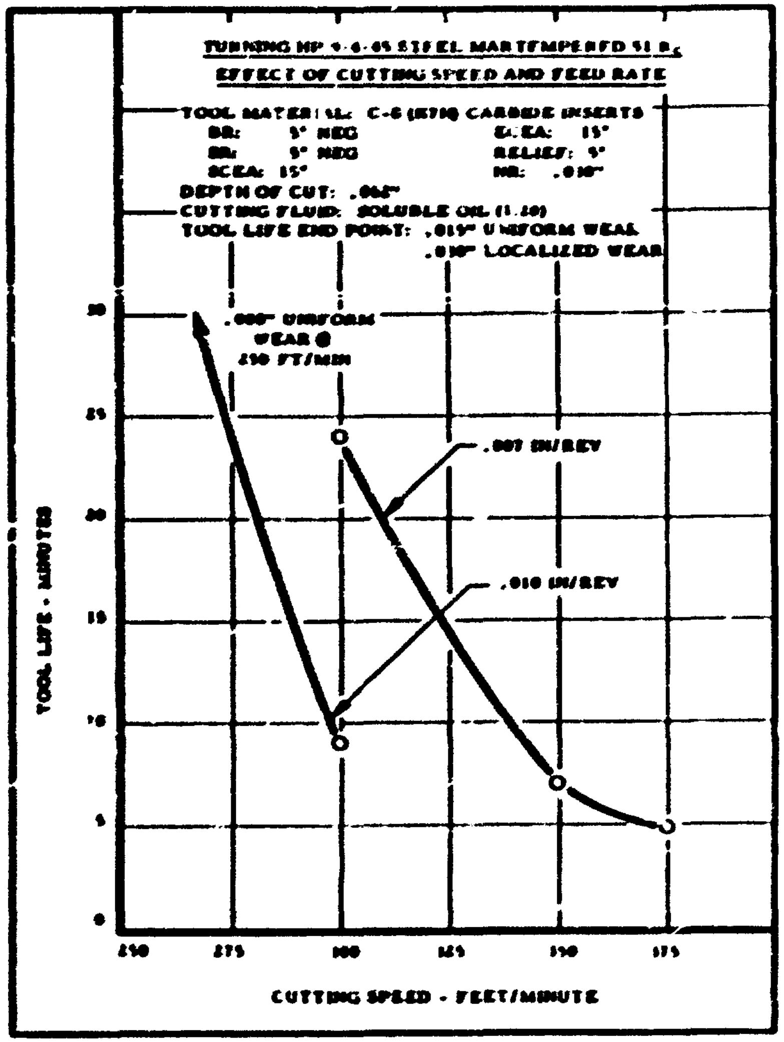
TURNING HP 9-4-45 STEEL MARTEMPERED [illegible]

EFFECT OF CUTTING SPEED AND TOOL MATERIAL

TOOL MATERIAL: CARBIDE INSERTS - SEE BELOW
BR: 5° NEG
SR: 5° NEG
SCEA: 15°
ECEA: 15°
RELIEF: 5°
NR: .030"
FEED: .007 IN/REV
DEPTH OF CUT: .062"
CUTTING FLUID: SOLUBLE OIL (1:20)
TOOL LIFE END POINT: .015" UNIFORM WEAR
.030" LOCALIZED WEAR

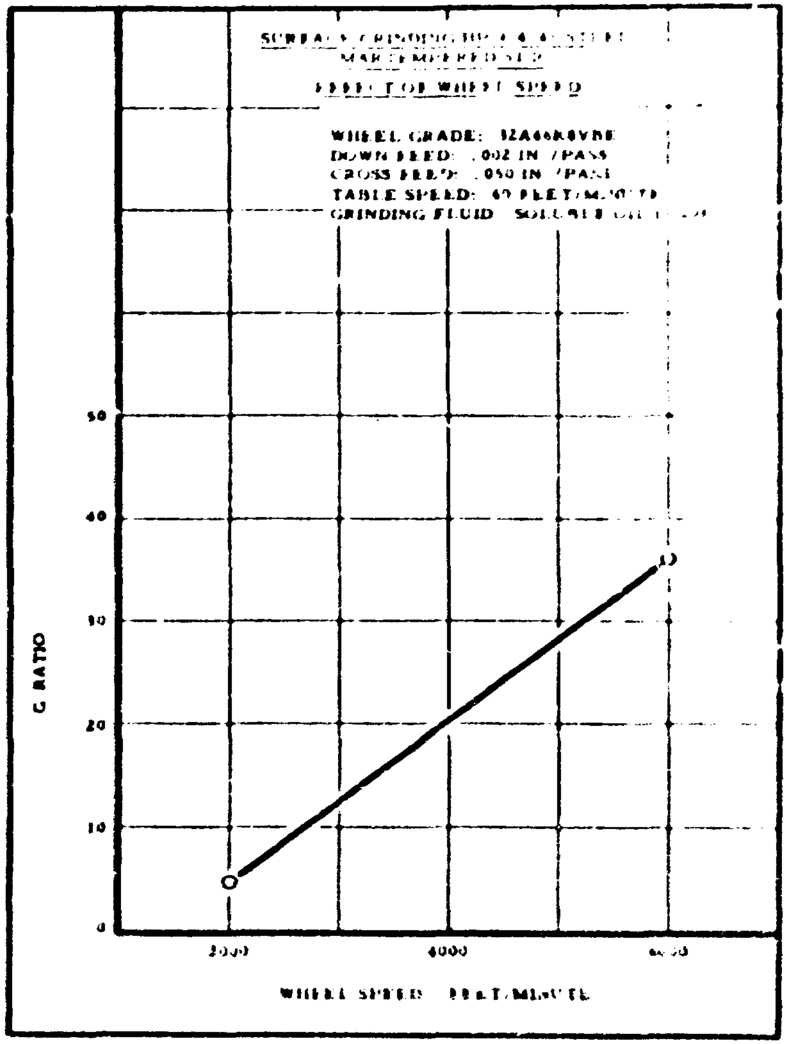
See text, page 34

Figure 12



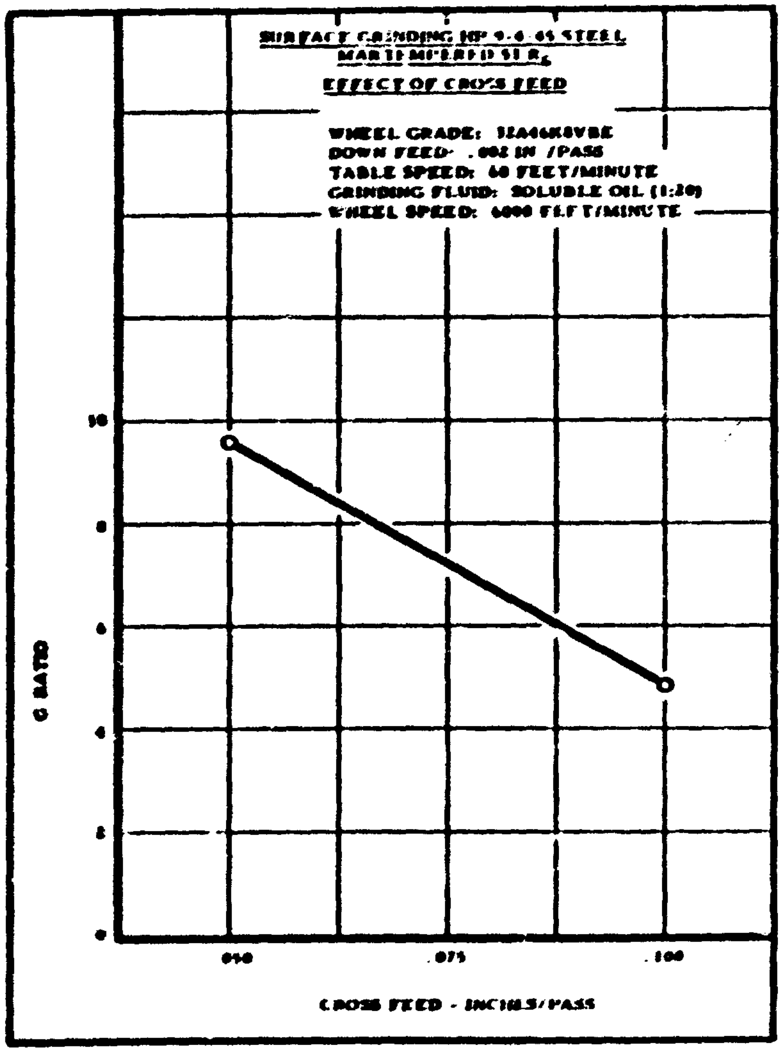
See text, page 30

Figure 33



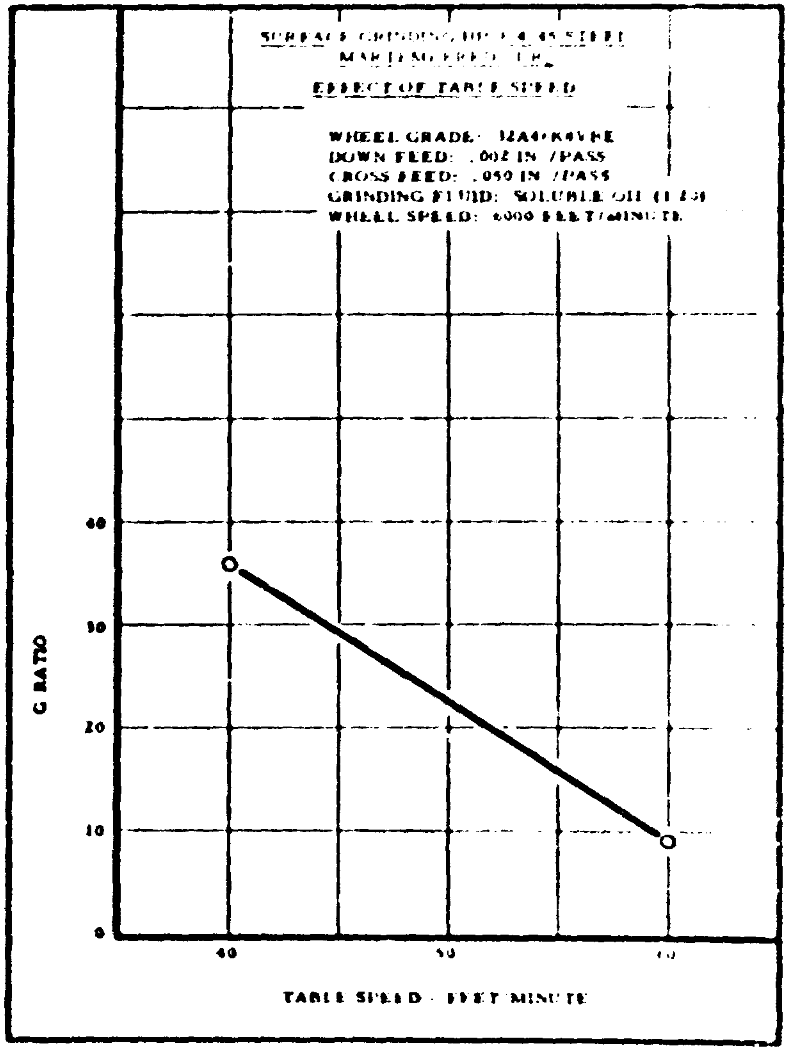
See text, page 34

Figure 34



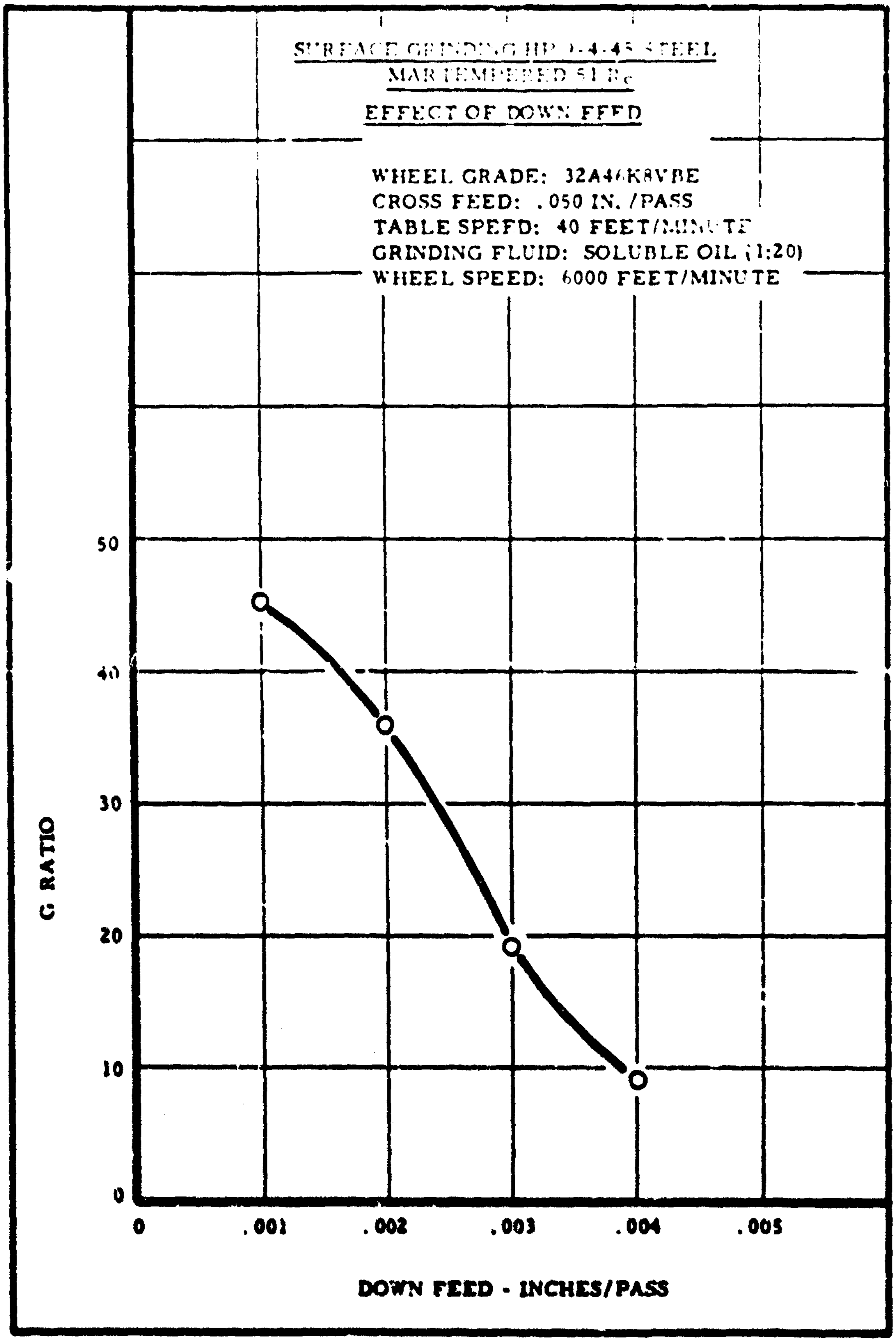
See text, page 34

Figure 15



See text, page 34

Figure 16



See text, page 34

Figure 37

3.3 Cast 18% Nickel Maraging Steel, Solution Treated

Alloy Identification

18% nickel maraging steel can be categorized as an ultra high strength steel which can develop yield strengths of 200 to 340 ksi. This is accomplished by an aging treatment which strengthens the prior annealed martensitic structure.

The nominal composition of the cast alloy is as follows:

Fe-18Ni-10Co-4.6Mo-.3Ti-.01C

The material for the turning tests was procured as cast logs, approximately 4 in. in diameter. Cast bars 2 in. by 4 in. were procured for the milling tests. The material for the drilling tests was obtained by sectioning 1/2 in. thick plates from the 2" by 4" cast bars. All of the material had been given the following solution annealing treatment at the mill:

1650°F/1 hour/air cool
1450°F/1 hour/air cool

The hardness of this as-received material was 331 BHN. In the solution annealed condition, the microstructure evidenced below consists of coarse equiaxed martensite.

Cast 18% Nickel Maraging Steel, Solution Treated

Etchant: $FeCl_3$ **Mag.: 500X**

3.3 Cast 18% Nickel Maraging Steel, Solution Treated (continued)

Turning (331 BHN)

A comparison of the tool life curves obtained with an M42 and an M2 HSS tool is shown in Figure 38, page 46. Note that for a given tool life, the M42 HSS tool permitted a 10 percent increase in cutting speed over the M2 HSS tool. It is also interesting to note that at a cutting speed of 85 feet/minute the tool life with the M2 HSS tool was 30 minutes, while the M42 tool was still cutting after 70 minutes. The wearland at this point was only .010 in. on the M42 tool.

Of the three grades of carbide used, the C-3 grade proved to be superior to the other two; see Figure 39, page 46. For example, at a cutting speed of 420 feet/minute, the tool life with the C-6 tool was 5 minutes; with the C-2, 9-1/2 minutes; and with the C-3 grade, 36 minutes.

Face Milling (311 BHN)

As shown in Figure 40, page 47, the T15 HSS tool proved to be slightly better than the M2 tool in face milling. The tool life with the M42 tool was, however, somewhat less than either of the other two tools. At a cutting speed of 210 feet/minute, the tool life values obtained with the three tools were as follows: M42, 95; M2, 120; and T15, 145 inches of work travel.

The effect of feed rate on tool life with both the M2 and the T15 HSS cutters appeared to be relatively low over the range of feed rates of .003 to .006 in./tooth. For as shown in Figure 41, page 47, the T15 HSS cutter provided the same tool life at .005 in./tooth feed rate as it did at a feed of .006 in./tooth. With the M2 HSS tool, the cutter life dropped from 145 inches of work travel at a feed rate of .003 in./tooth to 122 inches of work travel at a feed rate of .005 in./tooth.

As shown in Figure 42, page 48, the cutter life obtained with the chlorinated oil was almost the same as that with the soluble oil. Hence, a soluble oil was used in the tests with the multiple-tooth cutter. A comparison of the single-tooth with the multiple-tooth cutter, shown in Figure 43, page 48, indicates that at a cutting speed of 225 feet per minute the tool life <u>per tooth</u> with the single-tooth cutter was almost double that obtained with the multiple-tooth cutter. However, the total tool life with the 14-tooth cutter was 560 inches of work travel as compared to 78 inches of work travel with the single-tooth cutter.

3.3 Cast 18% Nickel Maraging Steel, Solution Treated (continued)

Face Milling (311 BHN) (continued)

In face milling with carbide tools, the cutter life decreased rapidly with increased feed rate. Note in Figure 44, page 49, that the cutter life decreased from 194 at a feed rate of .005 in./tooth to 65 inches of work travel at a feed of .007 in./tooth.

As shown in Figure 45, page 49, a cutter having negative rake angles provided slightly longer tool life than a cutter having positive rake angles at a cutting speed of 500 feet/minute. Note in Figure 46, page 50, the C-2 grade of carbide provided appreciably longer tool life than the C-6 grade. For example, at a cutting speed of 500 feet/minute, the cutter life with the C-2 grade was 194 as compared to 120 inches of work travel with the C-6 grade of carbide.

Cutter life was appreciably less in terms of inches of work travel per tooth with the multiple-tooth cutter as compared with a single-tooth cutter in face milling the cast 18% nickel maraging steel. As shown in Figure 47, page 50, the C-2 grade provided somewhat better tool life, at least at the higher cutting speeds, than the C-6 grades. However, as shown in Figure 48, page 51, the cutter life in terms of inches of work travel per tooth was considerably less for the six-tooth cutter than for a single-tooth cutter at the same cutting speed. Using a cutting fluid such as soluble oil resulted in improving the tool life of the multiple-tooth cutter; however, the cutter life was still considerably less with the multiple-tooth cutter, see Figure 49, page 51. Note also in Figure 49 that at a cutting speed of 500 feet/minute the cutter life with the six-tooth cutter was 30 inches of work travel per tooth, or a total metal removal of 180 inches of work travel. This compares to 194 inches of work travel for the single-tooth cutter see Figure 48. The only advantage then in using the multiple-tooth cutter is the fact that the metal is being removed six times faster than with a single-tooth cutter.

Peripheral End Milling (311 BHN)

The relationship between cutting speed and tool life with a 1 in. dia., four-flute, M2 HSS end mill is shown in Figure 50, page 52. Note that at a cutting speed of 275 feet/minute, a tool life of 145 inches of work travel was obtained.

The feed rate is very critical when peripheral end milling the cast 18% nickel maraging steel. Note in Figure 51, page 52, how rapidly the tool life decreased when the feed rate was either increased or

3.3 Cast 18% Nickel Maraging Steel, Solution Treated (continued)

Peripheral End Milling (311 BHN) (continued)

decreased from a feed rate of .005 in./tooth. The tool life decreased from 96 at a feed rate of .005 in./tooth to 20 inches of work travel at a feed rate of .0035 in./tooth and to 52 inches of work travel at a feed rate of .007 in./tooth.

Drilling (311 BHN)

The 18% nickel maraging steel in the solution treated condition can be drilled without difficulty. Note in Figure 52, page 53, that when the drilling test was stopped after drilling 250 holes at a cutting speed of 1[illegible]0 feet/minute, the wearland on the drill was only .012 in.

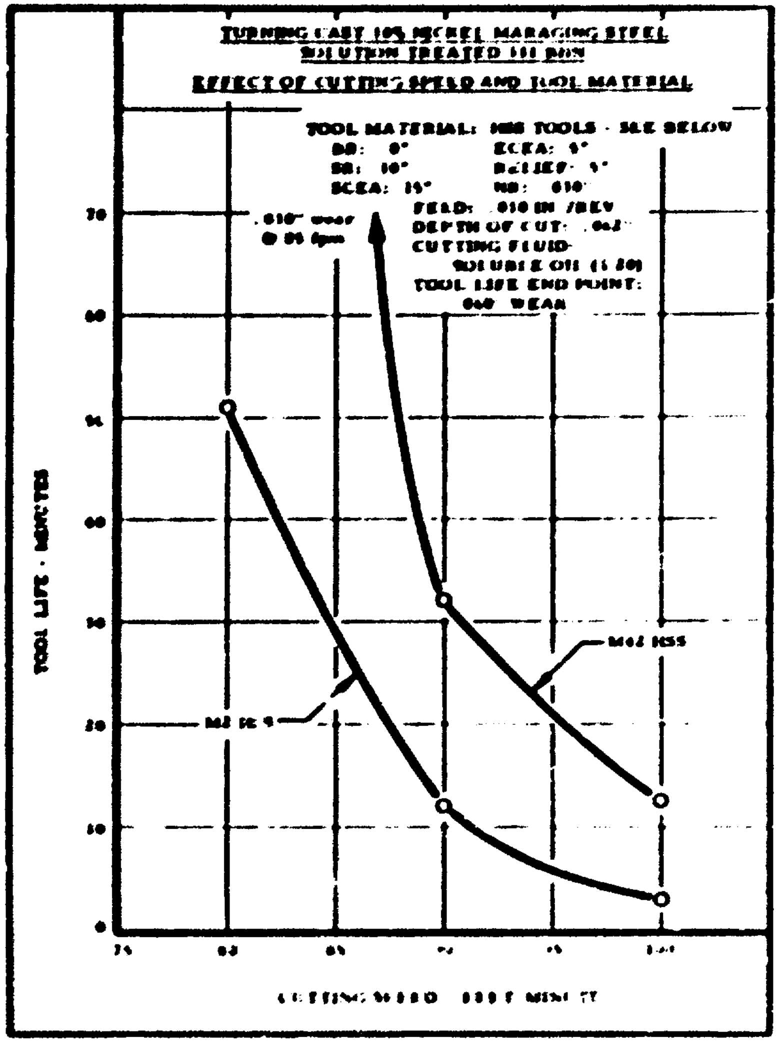
TABLE III

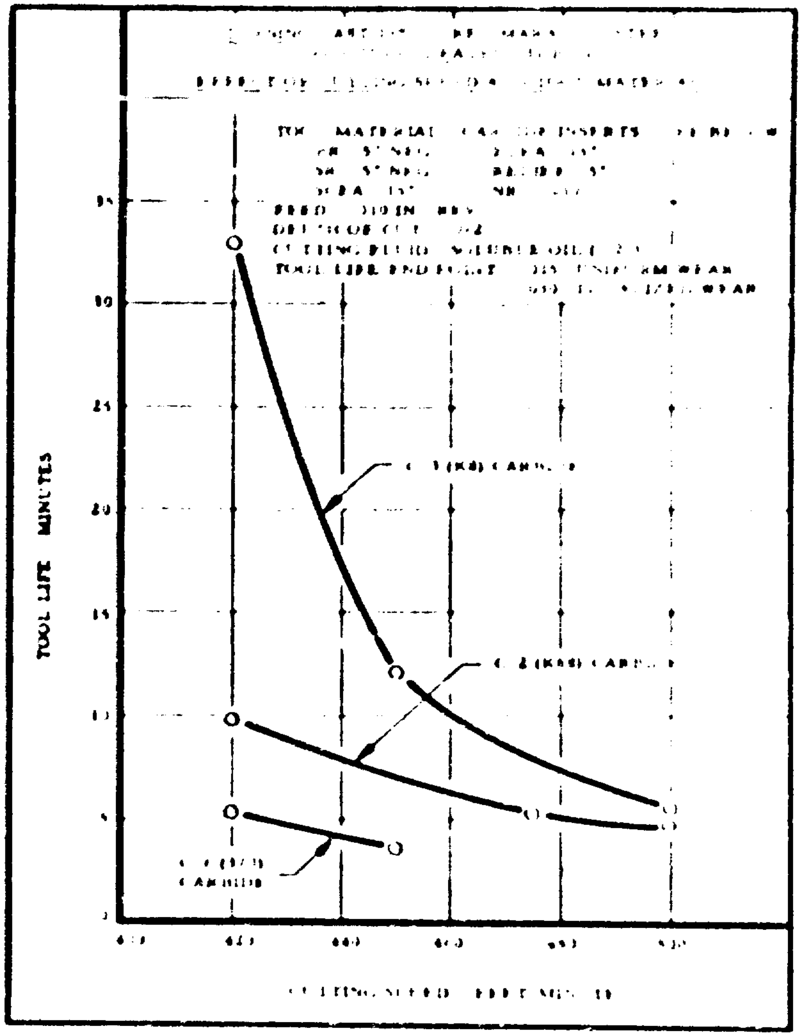
RECOMMENDED CONDITIONS FOR MACHINING
CAST 18% NICKEL MARAGING STEEL, SOLUTION TREATED 331 BHN

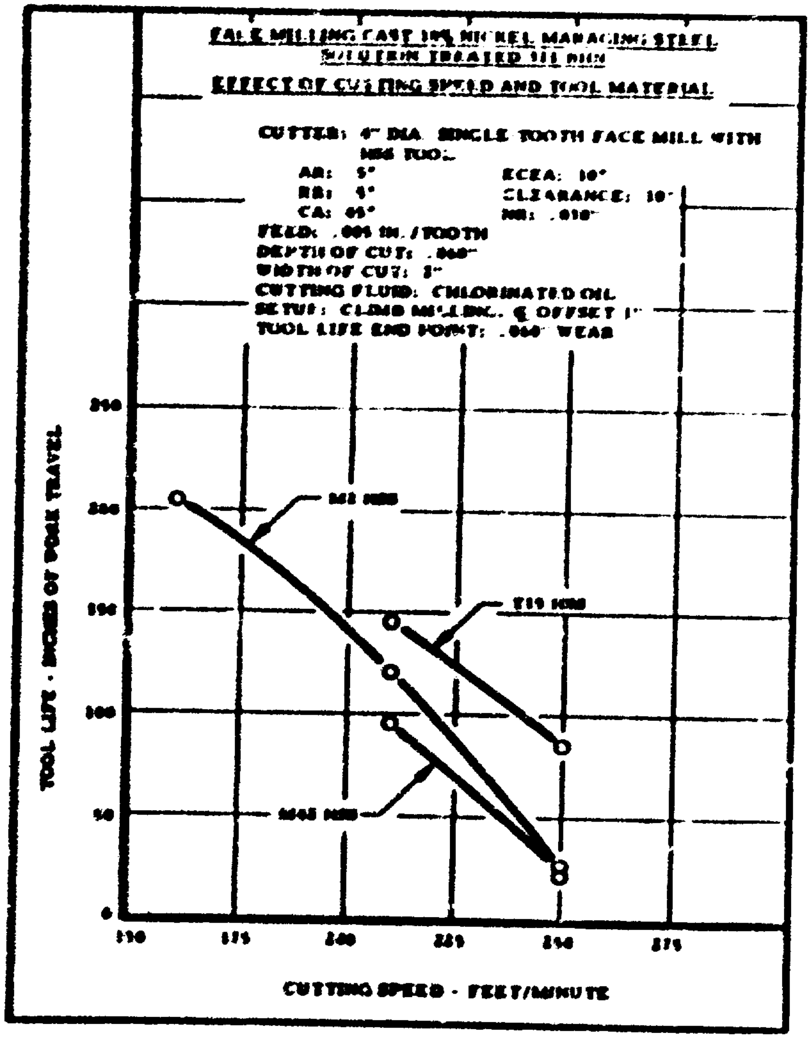
Nominal Chemical Composition, Percent

Fe	Ni	Co	Mo	Ti	C
Bal.	18	10	4.6	.3	.01

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft. min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Turning	M42 HSS	BR: 0° SCEA:15° SR: 10° ECEA, 5° Relief: 5° NR: .030"	5/8" Square Tool Bit	.062	--	.010 in/rev	85	70 min.	.016	Soluble Oil (1:20)
Turning	C-3 Carbide	BR:-5° SCEA:15° SR:-5° ECEA:15° Relief: 5° NR: .030"	SNG-432 Insert	.062	--	.010 in/rev	420	33 min.	.015	Soluble Oil (1:20)
Face Milling	M2 HSS	AR: 5° ECEA: 1° RR: 5° CA: 45° Clearance: 10°	4" Diameter 14 Tooth Face Mill	.060	2	.005 in/tooth	225	532" work travel	.010	Soluble Oil (1:20)
Face Milling	C-2 Carbide	AR:-5° ECEA:45° RR:-5° NR:.030" CA: 45° Clearance: 5°	4" Diameter Single Tooth Face Mill	.060	2	.005 in/tooth	500	110" work travel	.015	Dry
Peripheral End Milling	M2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	1" Diameter 4 Flute HSS End Mill	.250	.500	.005 in/tooth	275	140" work travel	.012	Soluble Oil (1:20)
Drilling	M1 HSS	118° Crankshaft Point Helix Angle: 29° Clearance: 7°	1/4" Diameter HSS Drill 2-1/2" Long	.500 thru	--	.005 in/rev	100	250 holes	.012	Chlorinated Oil

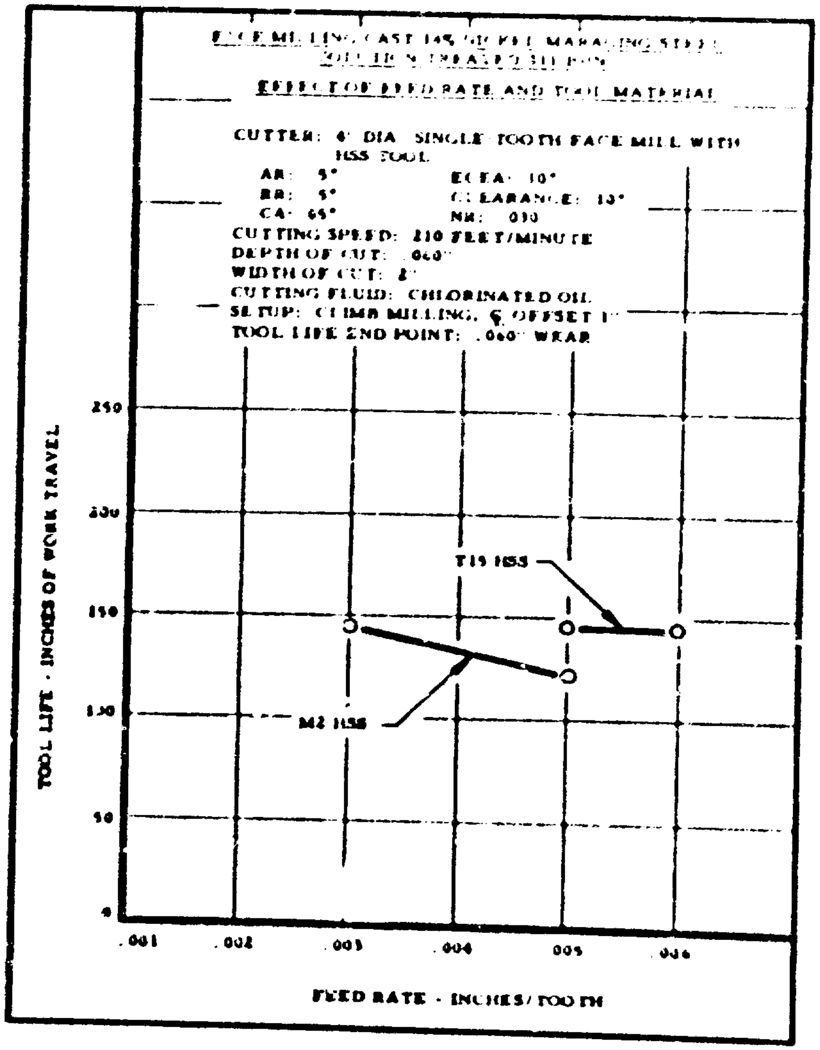

TURNING CAST 18% NICKEL MARAGING STEEL
SOLUTION TREATED 311 BHN
EFFECT OF CUTTING SPEED AND TOOL MATERIAL
TOOL MATERIAL: HSS TOOLS - SEE BELOW
BR: 0°
SR: 10°
SCEA: 15°
ECEA: 5°
RELIEF: 5°
NR: .010"
FEED: .010 IN./REV
DEPTH OF CUT: .062"
CUTTING FLUID-
SOLUBLE OIL (1:20)
TOOL LIFE END POINT:
.060" WEAR
.010" wear @ 95 fpm
M42 HSS
M2 HSS
TOOL LIFE - MINUTES
0
10
20
30
40
50
60
70
75
80
85
90
95
100
CUTTING SPEED - FEET/MINUTE


TOOL MATERIAL CARBIDE INSERTS
FEED .010 IN./REV
CUTTING FLUID SOLUBLE OIL
TOOL LIFE END POINT .015" UNIFORM WEAR
C-7 (K68) CARBIDE
C-2 (K68) CARBIDE
CARBIDE
TOOL LIFE MINUTES
5
10
15
20
25
30
35
CUTTING SPEED - FEET/MINUTE



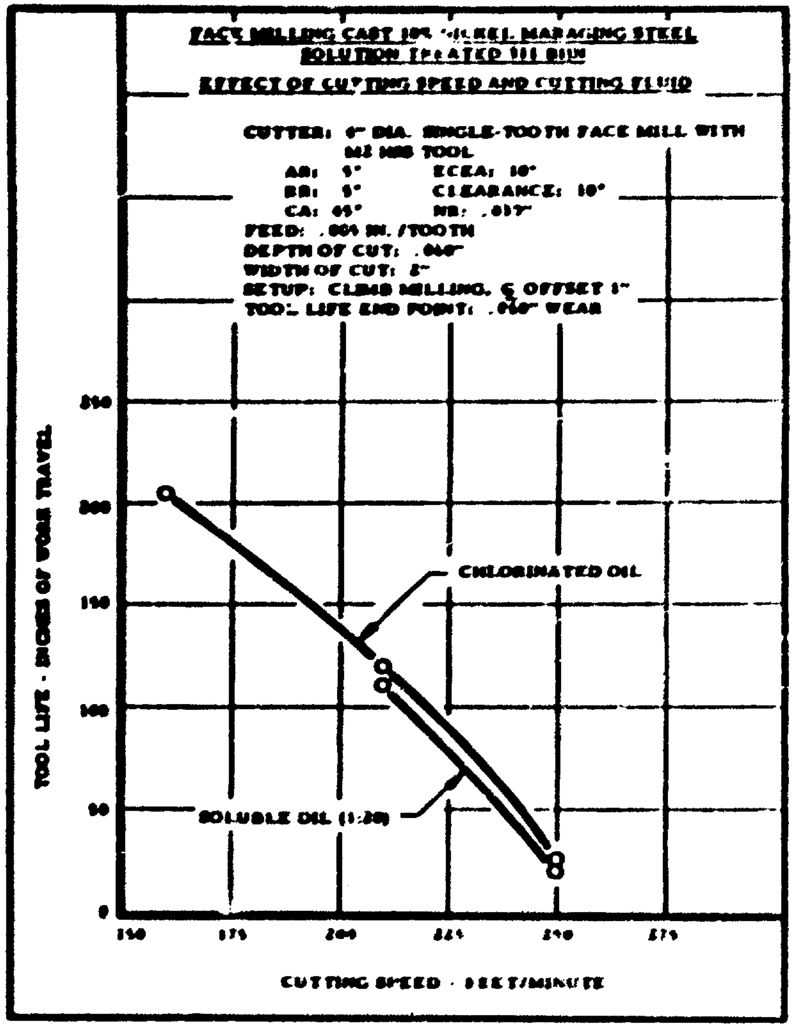
See text, page 62

Figure 40



See text, page 62

Figure 41



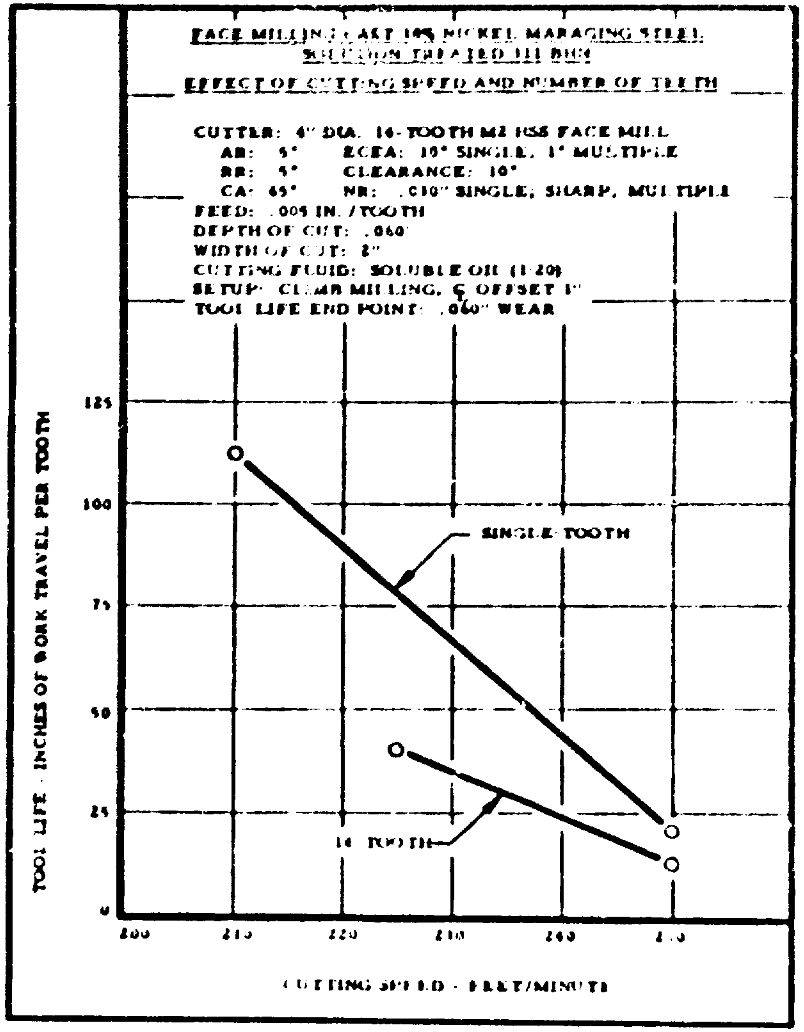
FACE MILLING CAST 18% NICKEL MARAGING STEEL
SOLUTION TREATED 311 BHN

EFFECT OF CUTTING SPEED AND CUTTING FLUID

CUTTER: 6" DIA. SINGLE-TOOTH FACE MILL WITH M2 HSS TOOL
AR: 5° ECEA: 10°
RR: 5° CLEARANCE: 10°
CA: 45° NR: .037"
FEED: .004 IN./TOOTH
DEPTH OF CUT: .060"
WIDTH OF CUT: 2"
SETUP: CLIMB MILLING, ℄ OFFSET 1"
TOOL LIFE END POINT: .060" WEAR

See text, page 42

Figure 42



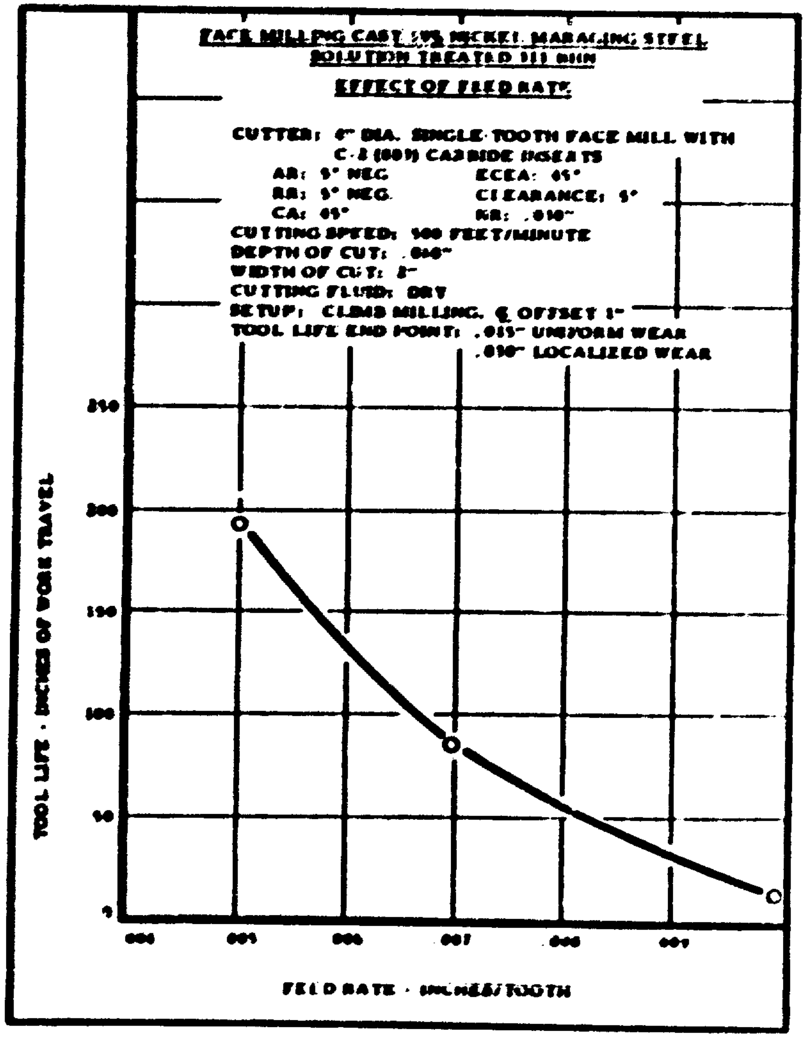
FACE MILLING CAST 18% NICKEL MARAGING STEEL
SOLUTION TREATED 311 BHN

EFFECT OF CUTTING SPEED AND NUMBER OF TEETH

CUTTER: 4" DIA. 14-TOOTH M2 HSS FACE MILL
AR: 5° ECEA: 10° SINGLE, 1° MULTIPLE
RR: 5° CLEARANCE: 10°
CA: 45° NR: .010" SINGLE; SHARP, MULTIPLE
FEED: .005 IN./TOOTH
DEPTH OF CUT: .060"
WIDTH OF CUT: 2"
CUTTING FLUID: SOLUBLE OIL (1:20)
SETUP: CLIMB MILLING, ℄ OFFSET 1"
TOOL LIFE END POINT: .060" WEAR

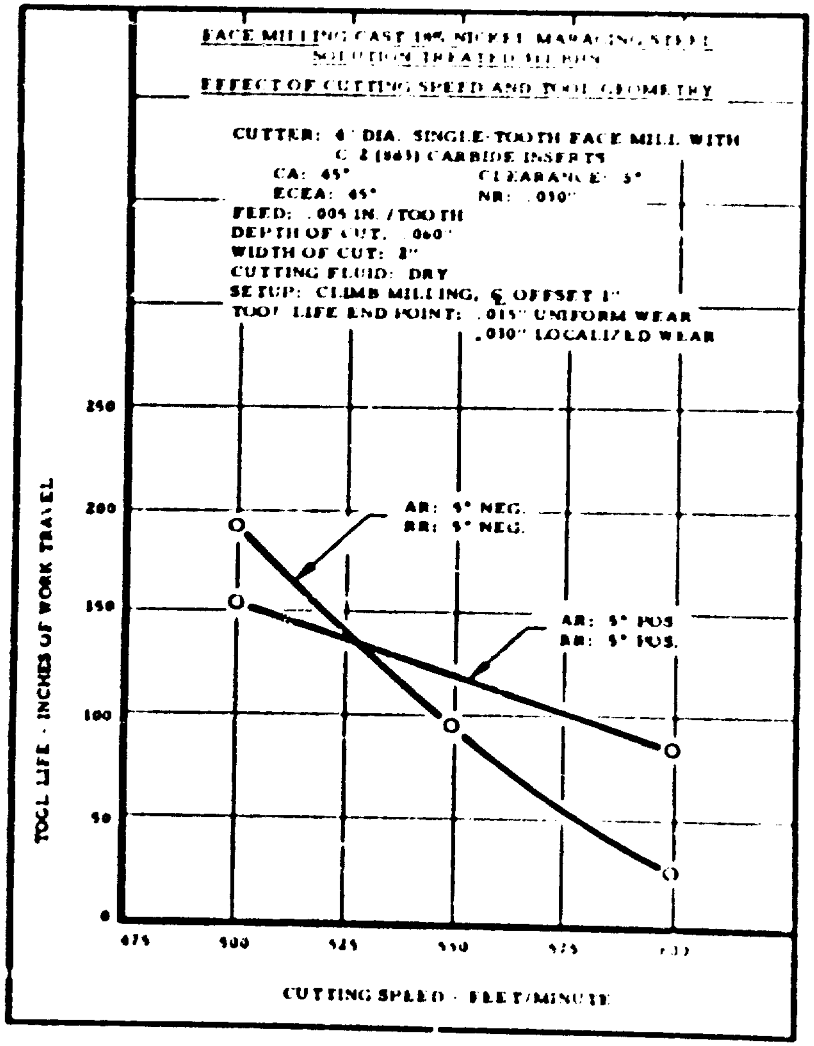
See text, page 42

Figure 43



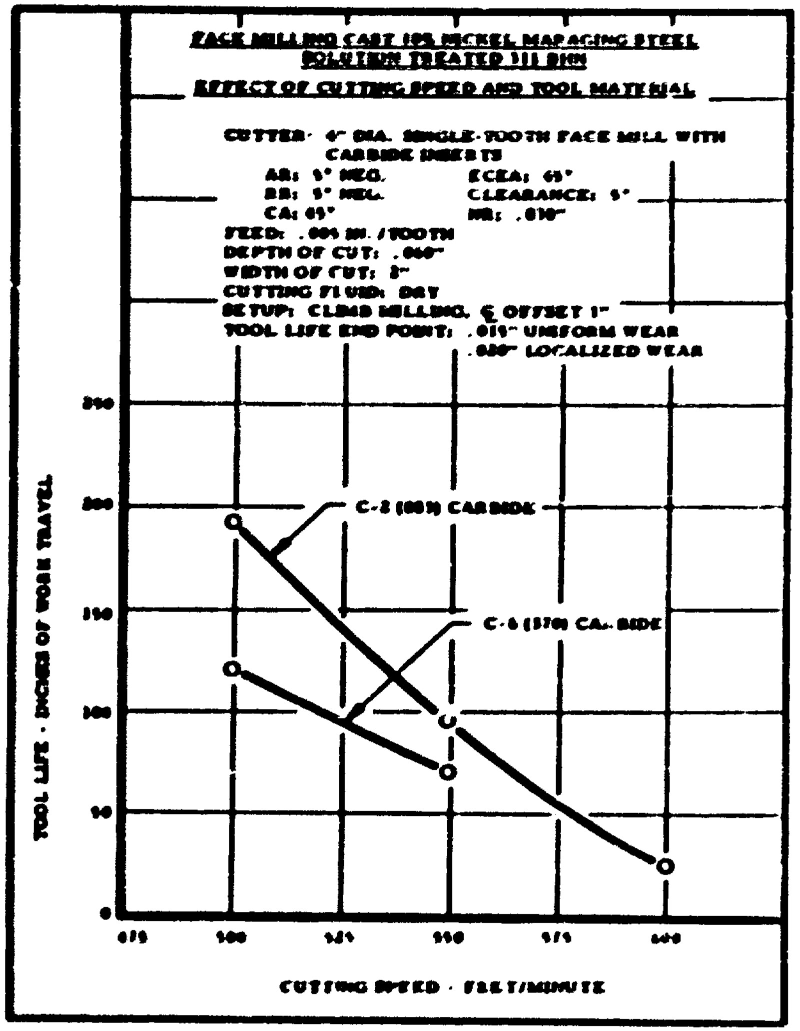
See text, page 63

Figure 44



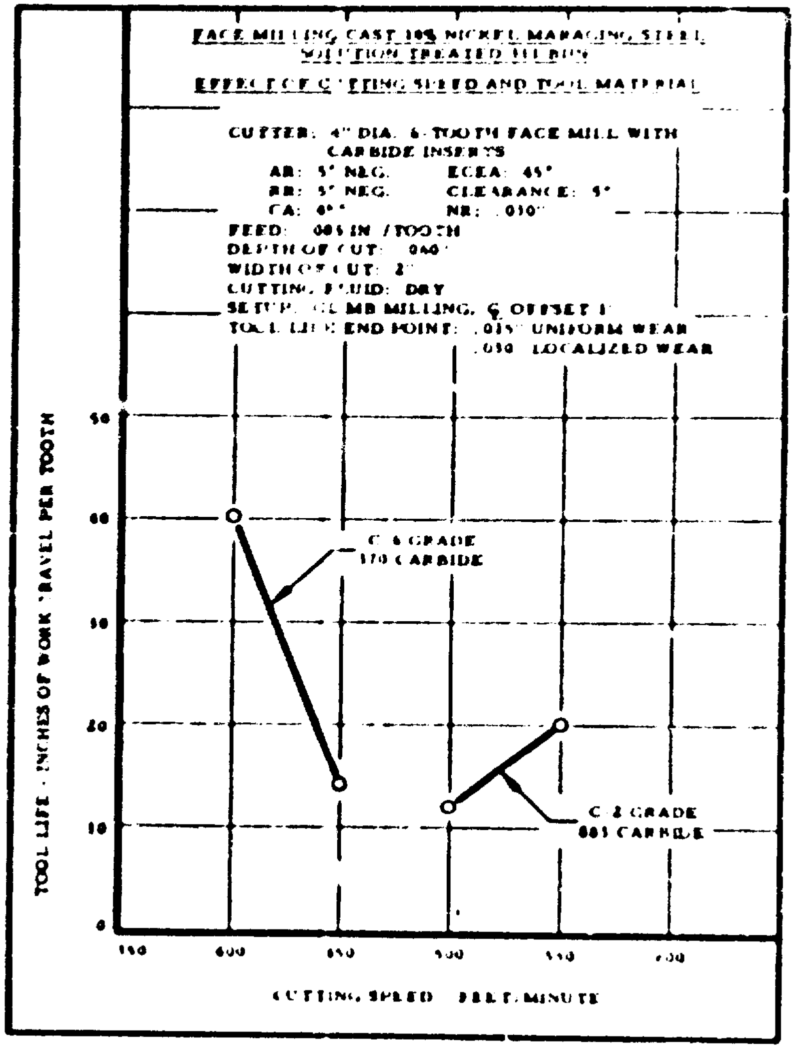
See text, page 63

Figure 45



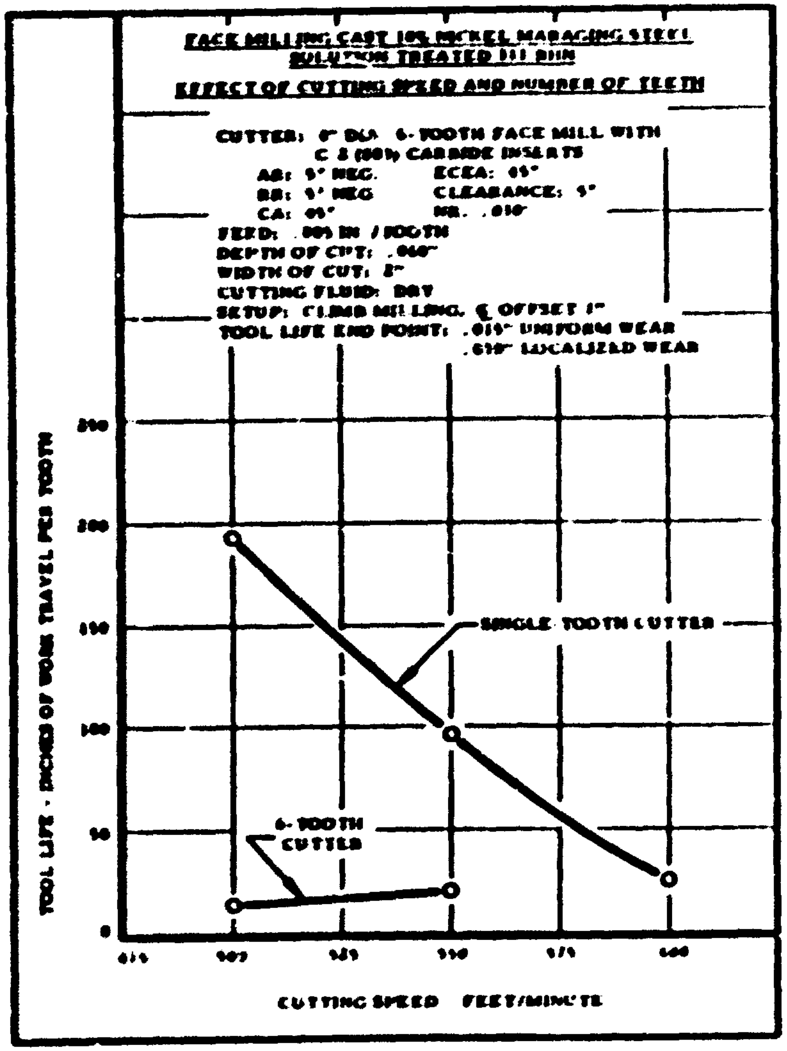
See text, page 43

Figure 46



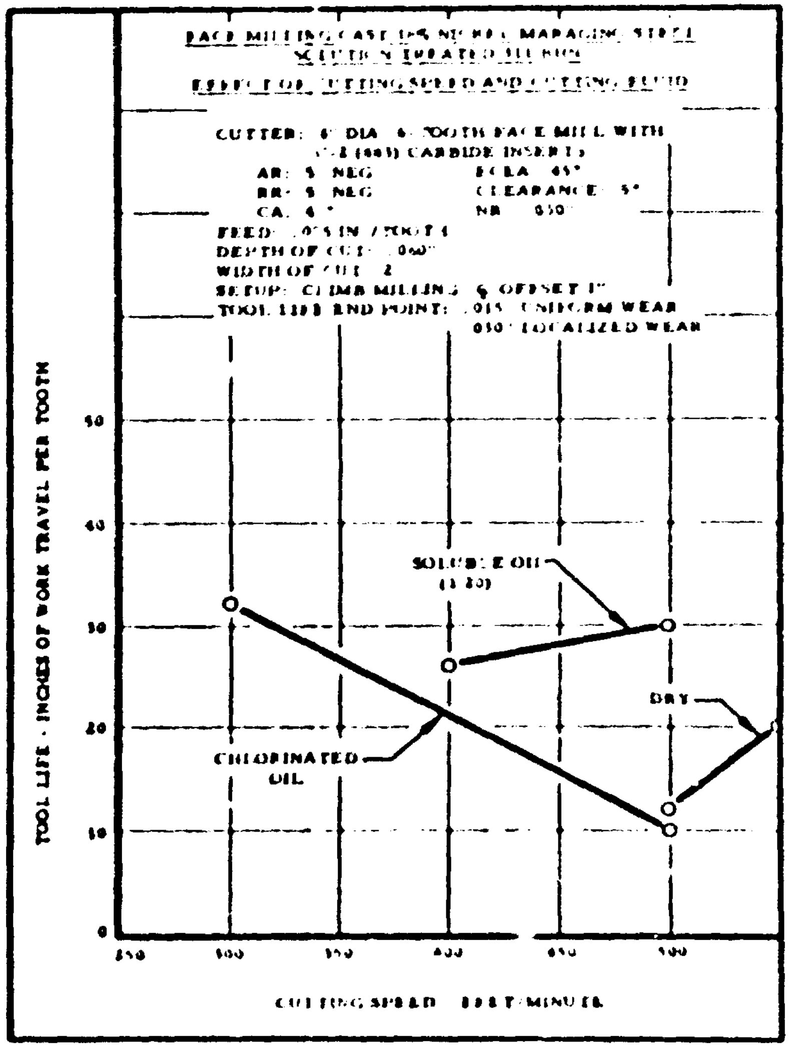
See text, page 43

Figure 47



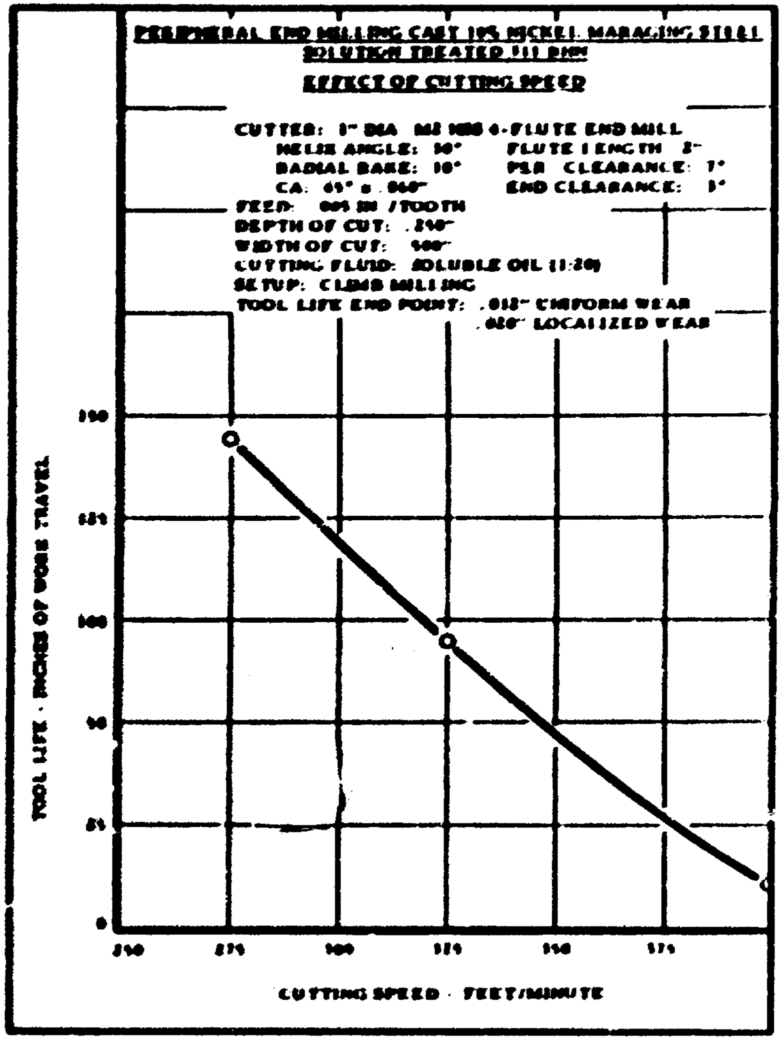
See text, page 43

Figure 48



See text, page 43

Figure 49



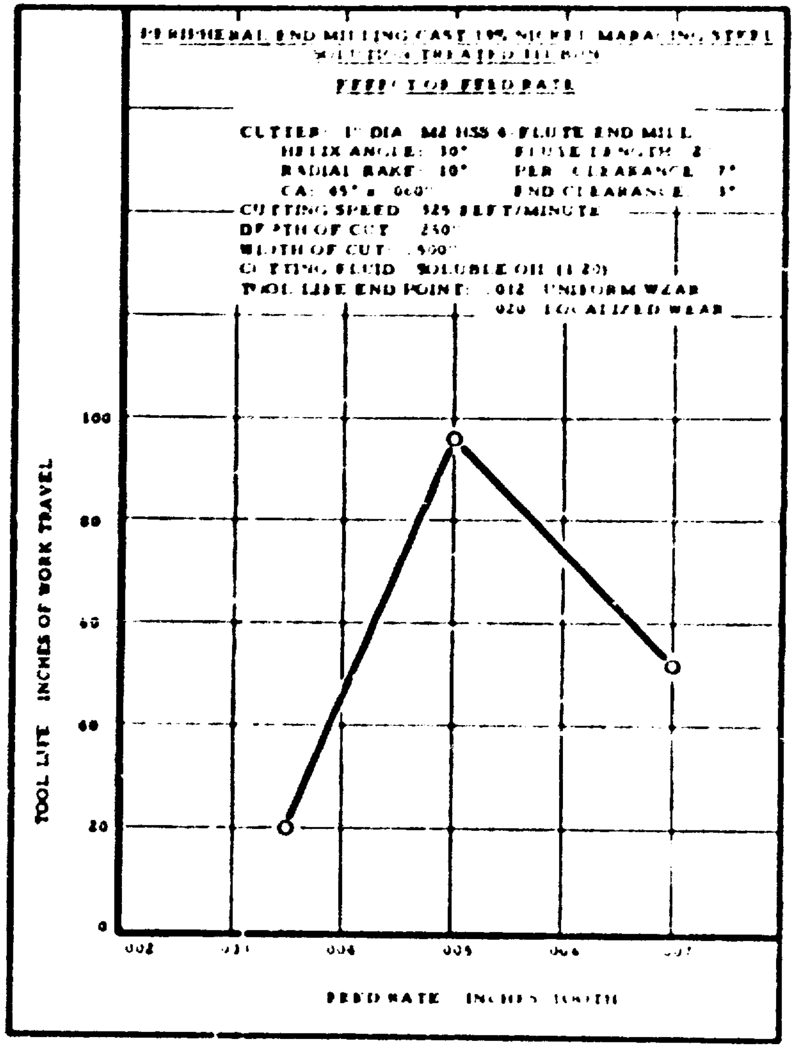
PERIPHERAL END MILLING CAST 19% NICKEL MARAGING STEEL
SOLUTION TREATED 311 BHN

EFFECT OF CUTTING SPEED

CUTTER: 1" DIA M2 HSS 4-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2"
RADIAL RAKE: 10° PER CLEARANCE: 7°
CA: 45° x .060" END CLEARANCE: 3°
FEED: .005 IN./TOOTH
DEPTH OF CUT: .250"
WIDTH OF CUT: .900"
CUTTING FLUID: SOLUBLE OIL (1:20)
SETUP: CLIMB MILLING
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 61

Figure 50



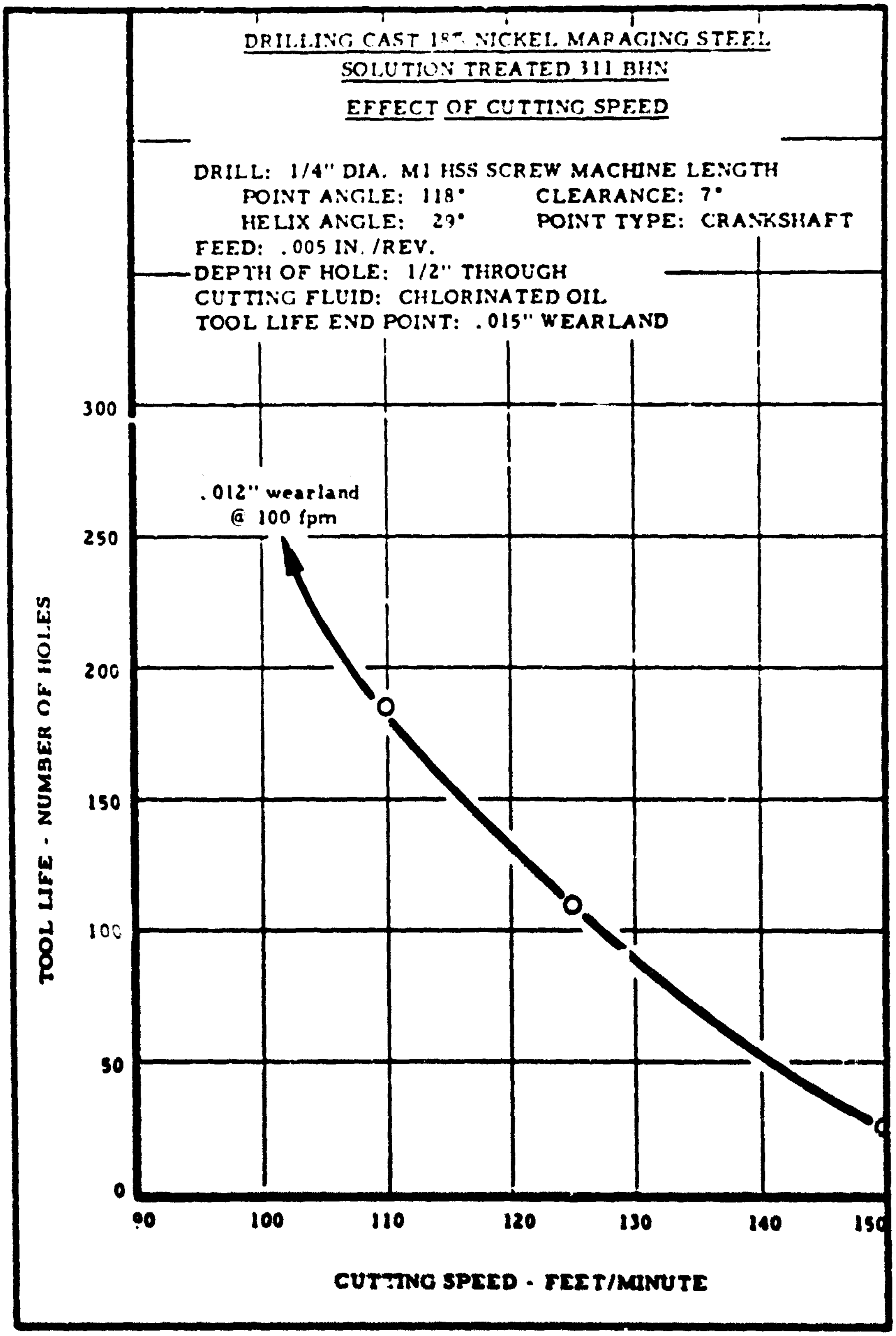
PERIPHERAL END MILLING CAST 19% NICKEL MARAGING STEEL
SOLUTION TREATED 311 BHN

EFFECT OF FEED RATE

CUTTER: 1" DIA M2 HSS 4-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2"
RADIAL RAKE: 10° PER CLEARANCE: 7°
CA: 45° x .060" END CLEARANCE: 3°
CUTTING SPEED: 325 FEET/MINUTE
DEPTH OF CUT: .250"
WIDTH OF CUT: .900"
CUTTING FLUID: SOLUBLE OIL (1:20)
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 61

Figure 51



DRILLING CAST 18% NICKEL MARAGING STEEL
SOLUTION TREATED 311 BHN
EFFECT OF CUTTING SPEED

DRILL: 1/4" DIA. M1 HSS SCREW MACHINE LENGTH
POINT ANGLE: 118° CLEARANCE: 7°
HELIX ANGLE: 29° POINT TYPE: CRANKSHAFT
FEED: .005 IN./REV.
DEPTH OF HOLE: 1/2" THROUGH
CUTTING FLUID: CHLORINATED OIL
TOOL LIFE END POINT: .015" WEARLAND

See text, page 43

Figure 52

3.4 Cast 18% Nickel Maraging Steel, Aged

Alloy Identification

The turning tests were performed only on material which had been maraged after the solution anneal treatment. The maraging treatment was as follows:

850°F/9 hours/air cool

It resulted in a hardness of 49 R_c.

The microstructure of the aged grade, which is illustrated below, consists of coarse platelets of martensite strengthened by the formation of intermetallics of Ni, Mo and Fe in various stoichiometric forms.

Cast 18% Nickel Maraging Steel, Aged

Etchant: $FeCl_3$ **Mag.: 500X**

3.4 Cast 18% Nickel Maraging Steel, Aged

Turning (49 R_c)

The performance of the M42 HSS tool was considerably better than that of the M2 HSS tool. Note in Figure 53, page 57, that for a 50-minute tool life, the cutting speed with the M42 HSS tool was about 20 percent faster than that with the M2 HSS tool.

Figures 54 and 55, page 57 and 58, show a comparison of the tool life curves obtained on the steel in two heat treated conditions with an M42 HSS tool and carbide tools. With the HSS tools, the steel in the solution treated condition (331 BHN) could be machined about 16 percent faster than the same steel in the aged 49 R_c condition, while with carbide tools the cutting speed was 100 percent faster. Note also that a tool life of 35 minutes was obtained at a cutting speed of 200 feet/minute.

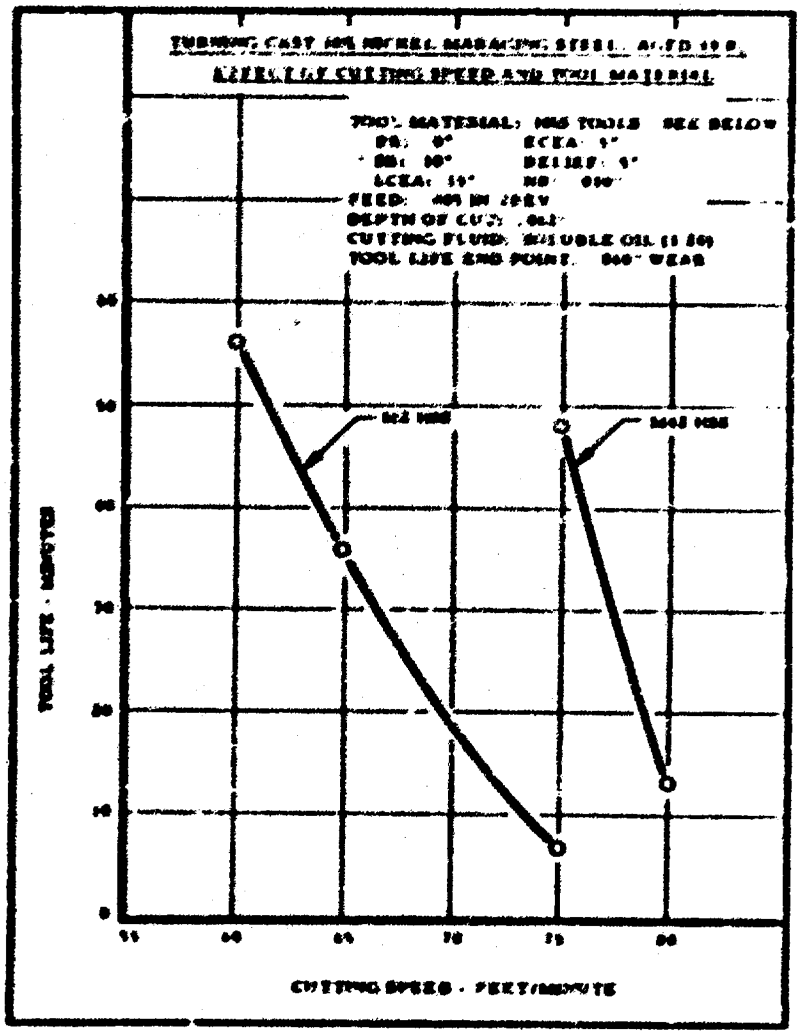
TABLE IV

RECOMMENDED CONDITIONS FOR MACHINING
CAST 18% NICKEL MARAGING STEEL, AGED 49 R_c

Nominal Chemical Composition, Percent

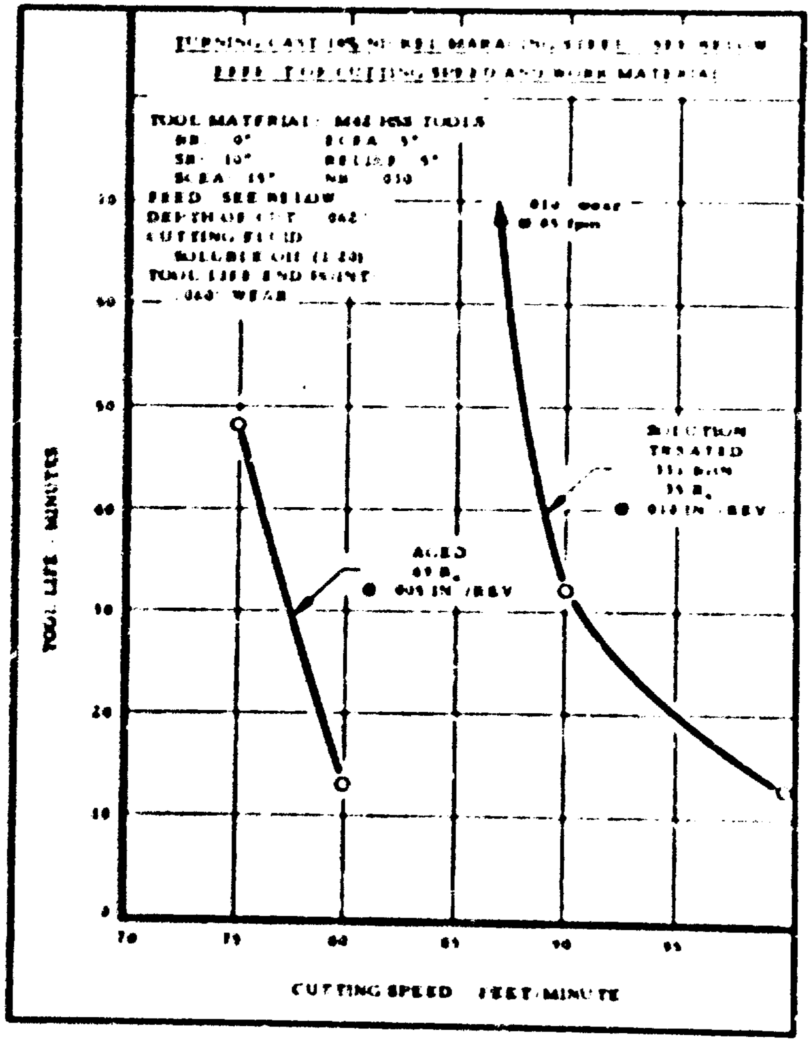
Fe	Ni	Co	Mo	Ti	C
Bal.	18	10	4.6	1	.01

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Turning	M42 HSS	BR: 0° SCEA: 15° SR: 10° ECEA: 5° Relief: 5° NR: .030"	5/8" Square Tool Bit	.062	--	.005 in/rev	75	49 min.	.060	Soluble Oil (1:20)
Turning	C-3 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	SNG-432 Insert	.062	--	.010 in/rev	200	35 min.	.015	Soluble Oil (1:20)



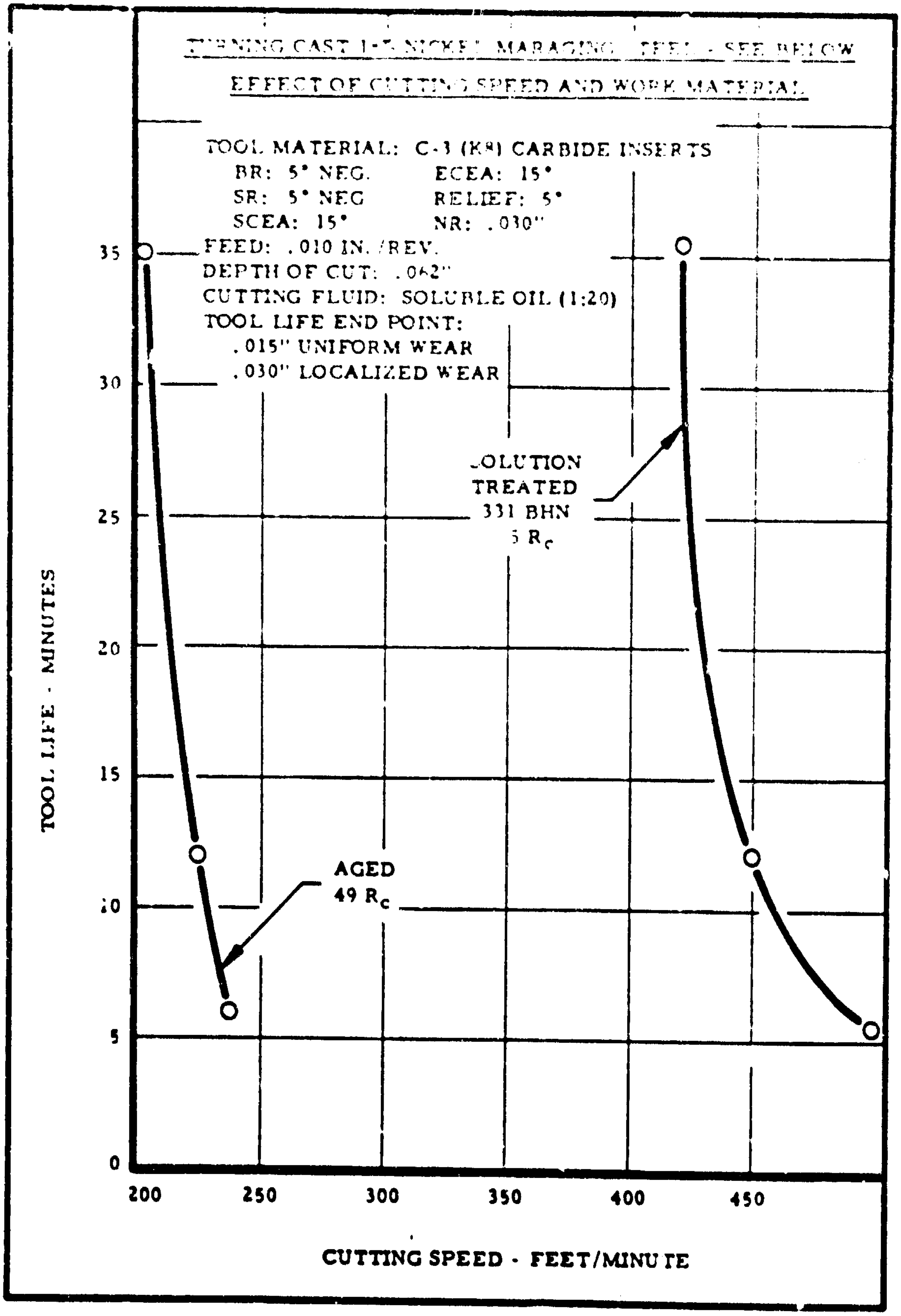
See text, page 55

Figure 52



See text, page 55

Figure 51



See text, page 55

Figure 55

3.5 Cast 17-4 PH Stainless Steel, Solution Treated and Aged

Alloy Identification

17-4 PH is a precipitation-hardening martensitic stainless steel which has been attracted to the casting industry because of its desirable castability characteristics. The alloy which has high strength and good corrosion resistance has found application in the aircraft industry. The nominal composition of this material is as follows:

Fe-16.0Cr-4.0Ni-3.0Cu-.75Si-.35Mn-.3Cb+Ta-.03C

The material for the milling tests was procured as 2 in. by 4 in. rectangular bars in the solution treated and aged condition. The heat treatment performed at the mill was as follows:

2100°F/90 min./air cool; 1450°F/4 hours/air cool;
1950°F/90 min./oil quench; 930°F/90 min./air cool

The material exhibited a hardness of 415 BHN in this condition. The microstructure evidenced below consists of coarse, equiaxed martensite and islands of delta ferrite. The matrix is strengthened by the precipitation of a copper-rich phase.

Cast 17-4 PH, Solution Treated and Aged

Etchant: $FeCl_3$ **Mag.: 500X**

3.5 Cast 17-4 PH Stainless Steel, Solution Treated and Aged (Continued)

Face Milling (415 BHN)

Tool life curves for two different grades of HSS milling cutters are shown in Figure 56, page 65. Note that the M42 HSS cutter provided only a slightly longer tool life than the M2 HSS cutter over the range of speeds used. Both were single-tooth cutters

The effect of feed on cutter life is shown in Figure 57, page 65. Note that even though the cutter life at the heavier feed was somewhat lower, the production rate was higher at the heavier feed rate For example, at a tool life of 90 inches of work travel, the cutting speed at a feed of .005 in./tooth was 100 feet minute. By reducing the cutting speed 10 percent, an equivalent tool life was obtained at twice the feed or .010 in./tooth. However, it should also be pointed out that when using multiple-tooth cutters it is usually necessary to use lower feeds than those found with single-tooth cutters.

In Figure 58, page 66, a comparison is made between a single-tooth and a multiple-tooth cutter having 14 teeth at a feed of .005 in./tooth. Note that even at this lower feed the cutter life per tooth at a cutting speed of 100 feet/minute decreased from 92 with a single-tooth cutter to 60 inches of work travel with the multiple-tooth cutter. However, at this tool life of 60 inches of work travel per tooth, the 14-tooth cutter cut a total of 840 inches of work travel.

The effect of carbide grade on tool life in face milling the cast 17-4 PH alloy is shown in Figure 59, page 66. The C-2 grade proved to be far superior to the C-6 grade. For example, at a cutting speed of 200 feet/minute with a single-tooth cutter, the tool life with the C-2 grade was 240 inches as compared to 25 inches with the C-6 grade.

The results shown in Figure 60, page 67, indicate that when face milling the cast 17-4 PH alloy in the solution treated and aged condition with carbide cutters, it is best to cut dry. Also, as shown in Figure 61, page 67, the carbide cutter should have negative rake angles. The cutter with the negative axial and radial rake angles provided much longer tool life than the cutter with the positive axial and radial rake angles.

Note in Figure 62, page 68, the comparison between a single-tooth and a multiple-tooth cutter based on tool life in terms of work travel per tooth. As the feed rate was increased, the difference between the single-tooth and the multiple-tooth cutter increased appreciably. A comparison is shown in Figure 63, page 68, between a single-tooth

3.5 Cast 17-4 PH, Solution Treated and Aged (continued)

Face Milling (415 BHN) (continued)

cutter at a feed of .010 in./tooth and a multiple-tooth (six-tooth) cutter at a feed of .007 in./tooth. The cutter life in inches of work travel per tooth at 300 feet/minute with the multiple-tooth cutter was somewhat less, even though the feed was lower than with the single-tooth cutter. Nevertheless, at this cutting speed, the multiple-tooth cutter cut a total of 480 inches of work travel.

Peripheral End Milling (415 BHN)

Tool life curves for both the M2 and the M42 HSS end mills are shown in Figure 64, page 69. Note that for a tool life of 125 inches of work travel, the cutting speed with the M42 HSS cutter was slightly more than 25 percent faster than with the M2 HSS cutter.

As shown in Figure 65, page 69 the magnitude of the feed rate was not very critical. For example, at a cutting speed of 150 feet/minute, the cutter life decreased from 85 at a feed of .002 in./tooth to 60 inches of work travel at a feed of .004 in./tooth. Nevertheless, a feed of .003 in./tooth was used in subsequent tests, since it was felt that a feed of .004 in./tooth would result in excessive deflection of the cutter.

An oil base cutting fluid at the cutting speeds used in peripheral end milling the cast 17-4 PH alloy resulted in the generation of excessive smoke at the cutter. Hence, a chlorinated soluble oil was used at a dilution of 1:20. The curves in Figure 66, page 70, show the improvement gained by using this chlorinated soluble oil. For example, at a tool life of 175 inches of work travel, the chlorinated soluble oil permitted a 20 percent increase in cutting speed over that used with the plain soluble oil.

As shown in Figure 67, page 70, at a cutting speed of 150 feet/minute doubling the depth of cut resulted in a decrease in tool life from 180 to 120 inches of work travel. However, it should be noted that by decreasing the cutting speed from 160 to 150 feet/minute, it was possible to increase the depth of cut from .125 to .250 in. without any change in tool life. In other words, the metal removal rate was considerably higher at the depth of cut of .250 in. and a cutting speed of 150 feet/minute without any sacrifice in tool life.

3.5 Cast 17-4 PH, Solution Treated and Aged (continued)

End Mill Slotting (415 BHN)

The chlorinated soluble oil also proved to be beneficial in end mill slotting the cast 17-4 PH alloy. For as shown in Figure 68, page 71, the cutting speed was approximately 10 percent greater with the chlorinated soluble oil as compared to the plain soluble oil.

A comparison of two grades of HSS cutters is shown in Figure 69, page 71. At a tool life of 120 inches of work travel, the M42 HSS tool provided a 15 percent higher cutting speed than the M2 HSS cutter.

As shown in Figure 70, page 72, the cutter life did not change appreciably as the feed rate was increased from .002 to .004 in./tooth. The variation was from 50 to 70 inches of work travel. The tool life of 70 inches was obtained at a feed of .003 in./tooth and a cutting speed of 120 feet/minute. The tool curves in Figure 71, page 72, show that the cutter life was longer with the feed of .003 in./tooth, even at lower cutting speeds. While the increase in tool life was about 20 percent, the production rate at this higher feed was also 50 percent higher. Hence, a feed of .003 in./tooth will be recommended.

Drilling (415 BHN)

Tool life curves for both M42 and M2 HSS tools are presented in Figure 72, page 73. Note the vast difference in the performances of these two types of HSS drills. For a drill life of 250 holes, the cutting speed with the M42 HSS drills was 50 feet/minute, while with the M2 HSS drills it was only 10 feet/minute.

Reaming (415 BHN)

As shown in Figure 73, page 73, the chemical emulsion proved to be even slightly better than a chlorinated oil. A reamer life of more than 250 holes resulted at a cutting speed of 40 feet/minute and a feed of .009 in./rev.

Tapping (415 BHN)

The chlorinated oil was far more effective than the chemical emulsion in tapping; see Figure 74, page 74. Over 250 holes can be tapped at a cutting speed of 90 feet/minute with the chlorinated oil. Using the chemical emulsion, the tap life was 68 holes at a cutting speed of 25 feet/minute.

TABLE V

RECOMMENDED CONDITIONS FOR MACHINING
17-4 PH CAST, SOLUTION TREATED AND AGED 415 BHN

Nominal Chemical Composition, Percent

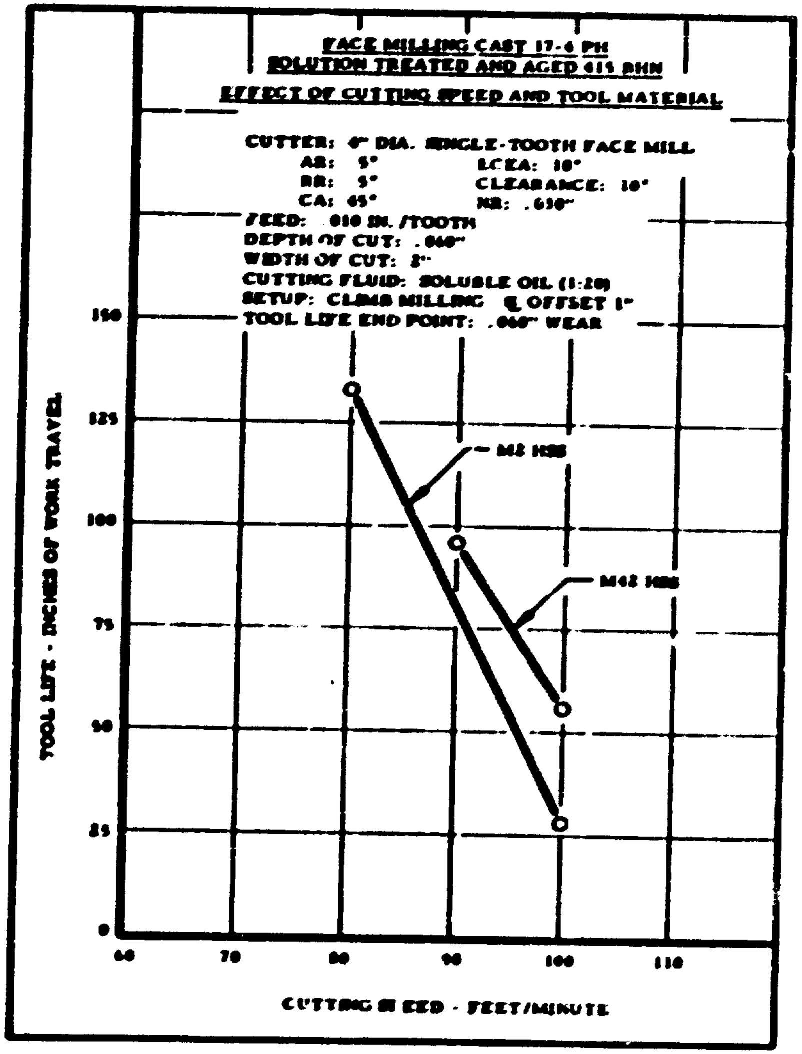
Fe	Cr	Ni	Cu	Si	Mn	Cb+Ta	C
Bal.	16.0	4.0	3.0	.75	.35	.3	.03

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Face Milling	M42 HSS	AR: 5° ECEA: 1° RR: 5° CA: 45° Clearance: 10°	4" Diameter 14 Tooth Face Mill	.060	2	.005 in/tooth	100	840" work travel	.060	Soluble Oil (1:20)
Face Milling	C-2 Carbide	AR: -5° ECEA: 45 RR: -5° CA: 45° Clearance: 5°	4" Diameter 6 Tooth Face Mill	.060	2	.007 in/tooth	300	480" work travel	.015	Dry
Peripheral End Milling	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	1" Diameter 4 Flute End Mill	.125	.500	.003 in/tooth	173	220" work travel	.012	Chlorinated Oil
End Mill Slotting	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" Diameter 4 Flute End Mill	.250	.750	.003 in/tooth	110	120" work travel	.012	Chlorinated Soluble Oil (1:20)
Drilling	M42 HSS	118° Crankshaft Point Helix Angle: 29° Clearance: 7°	1/4" Diameter HSS Drill 2-3/4" Long	.500 thru	--	.005 in/rev	50	250+ holes	.013	Chemical Emulsion (1:20)
Reaming	M2 HSS	Helix Angle: 0° CA: 45° Clearance: 7°	.272" Diameter 6 Flute Chucking Reamer	.500 thru	--	.009 in/rev	40	250+ holes	.004	Chemical Emulsion (1:20)

TABLE V (continued)

RECOMMENDED CONDITIONS FOR MACHINING
17-4 PH CAST, SOLUTION TREATED AND AGED 415 BHN

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min.	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Tapping	M1 HSS	3 Flute Plug Spiral Point 75% Thread	5/16-24 NF Tap	.500 thru	--	--	85	250+ holes	Under-size Thread	Chlorinated Oil



See text, page 63

Figure 56

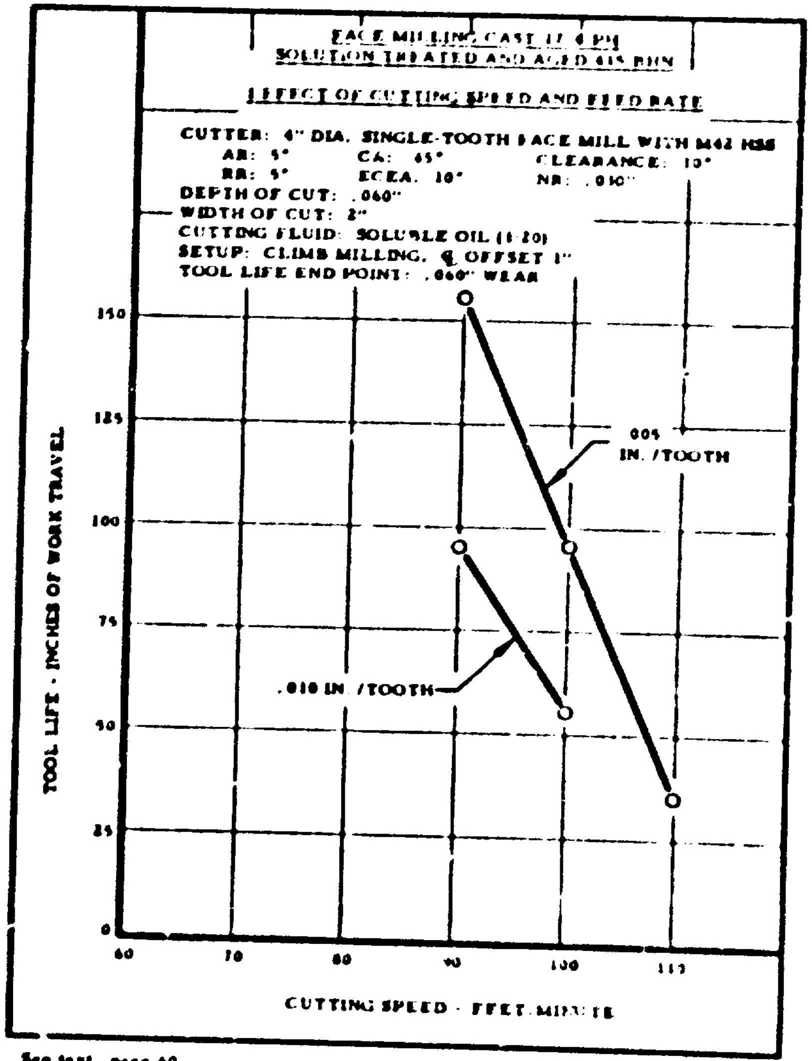


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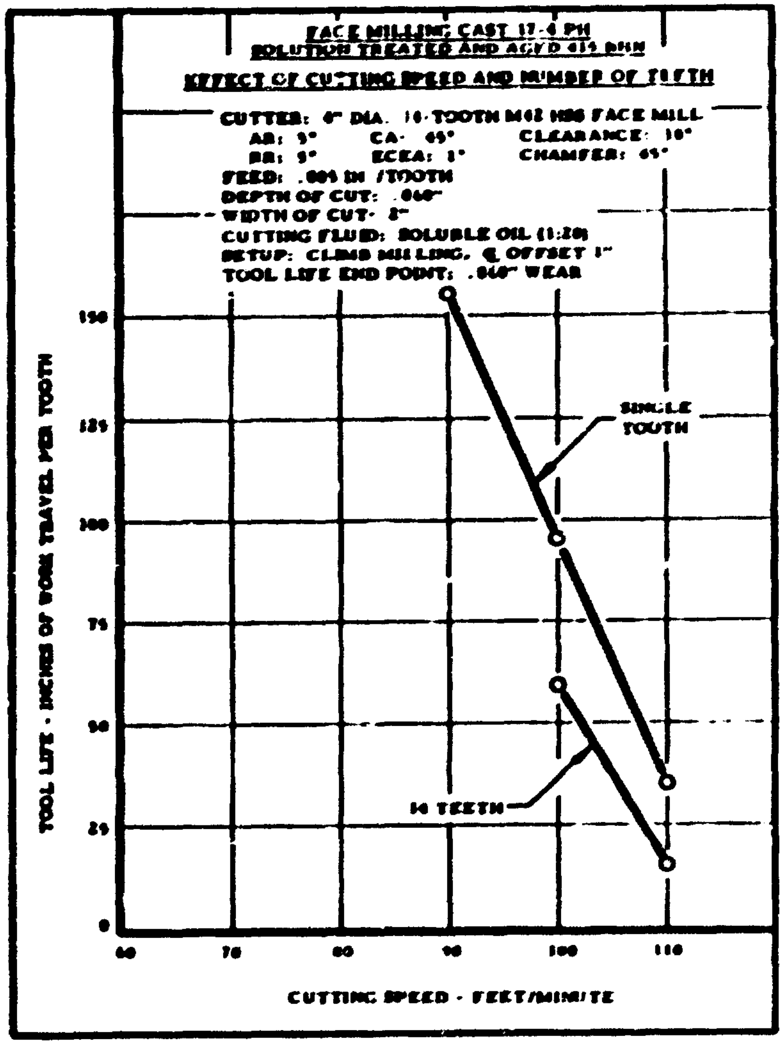
Figure 57



See text, page 68

Figure 58

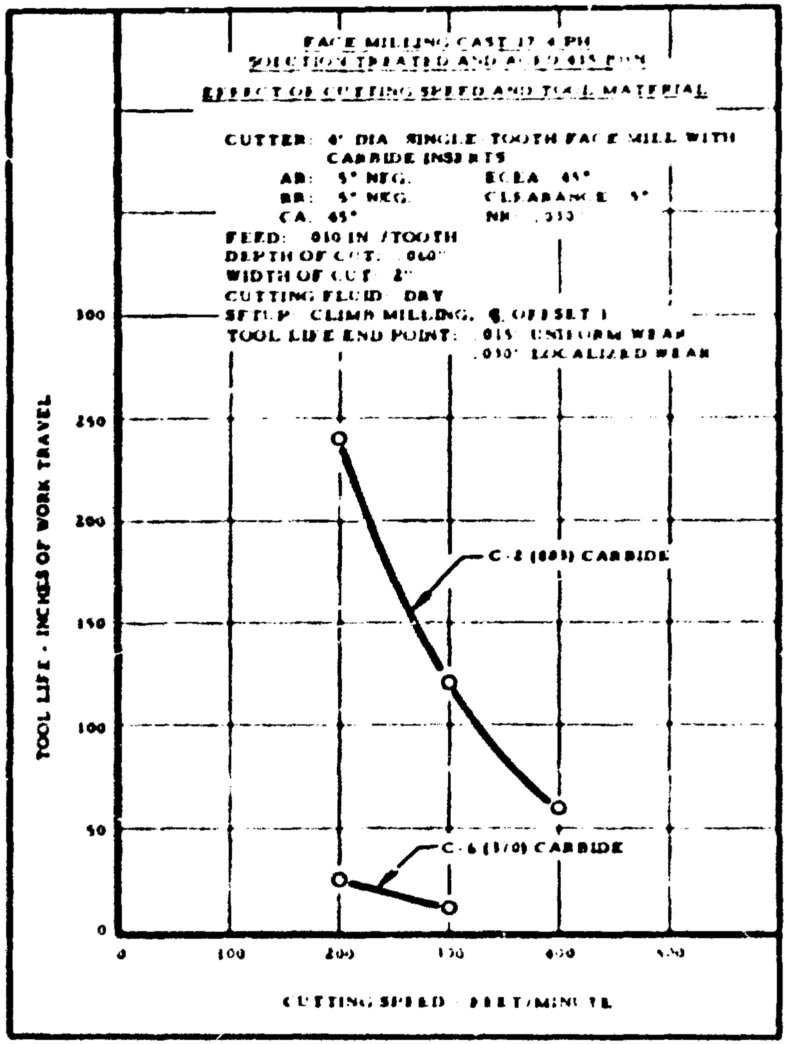


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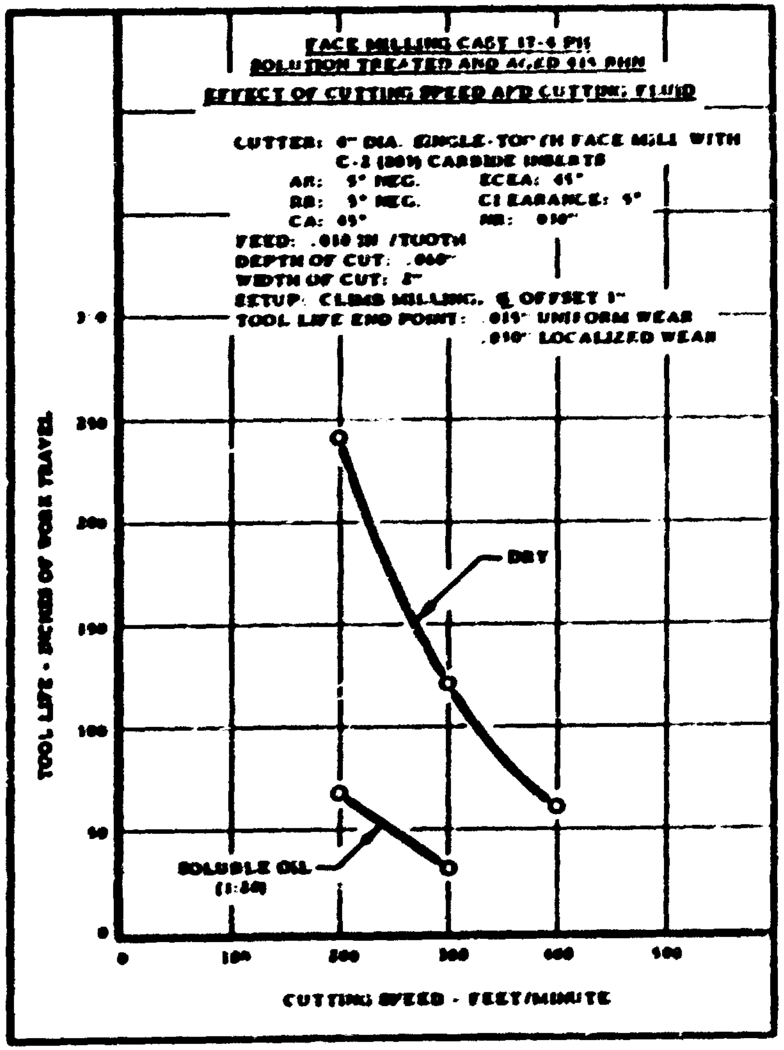
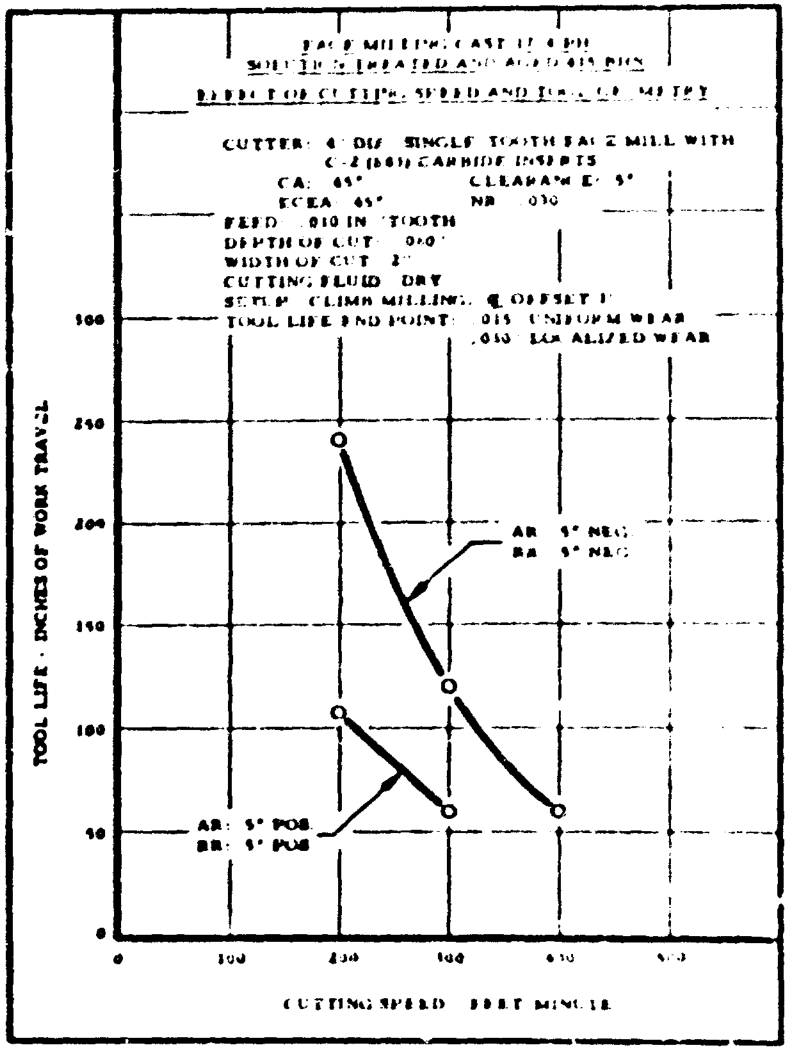
Figure 59



See text, page 60

Figure 60



See text, page 60

Figure 61

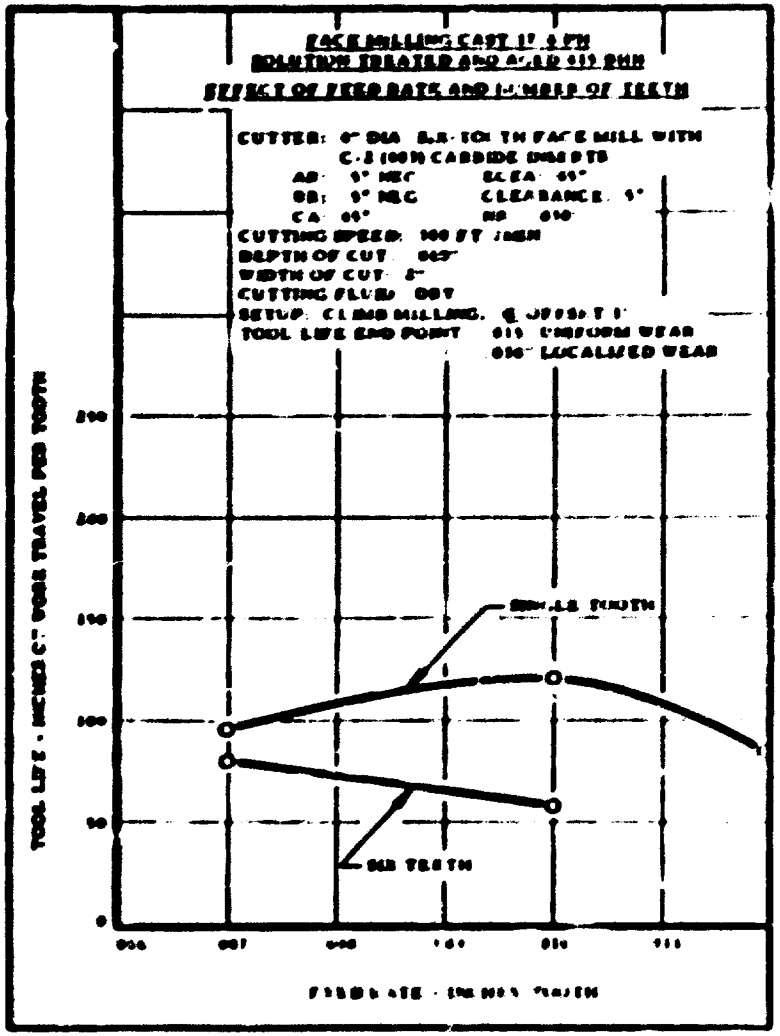


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Figure [illegible]

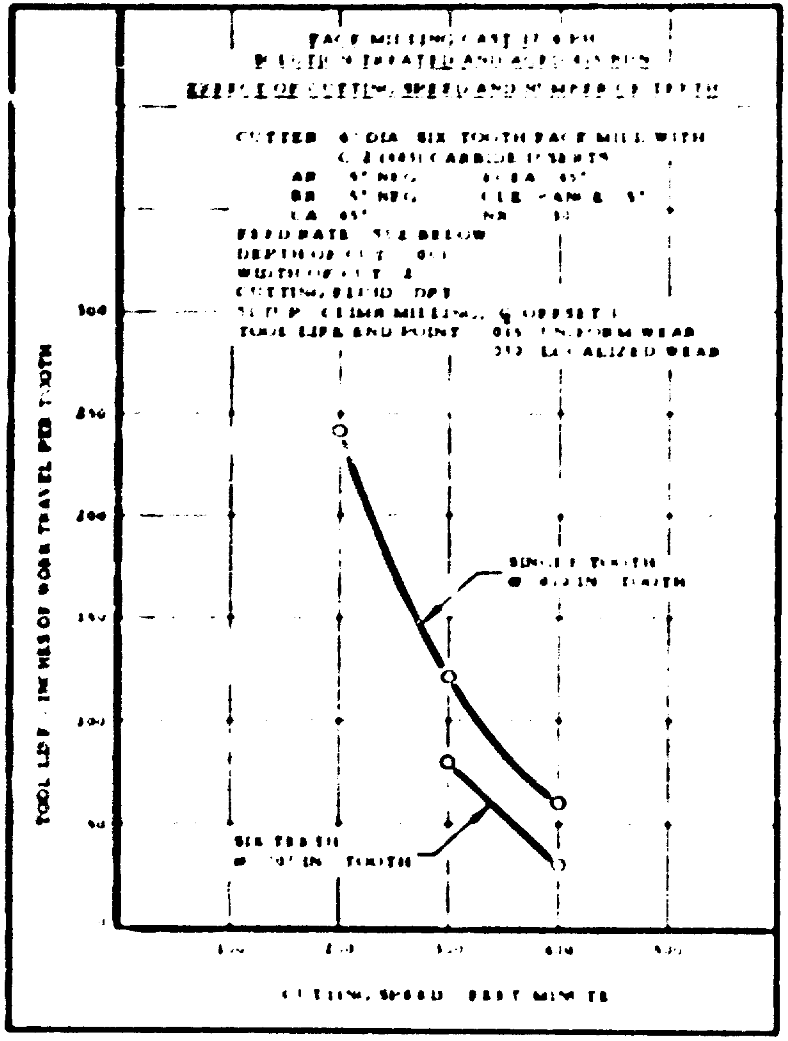

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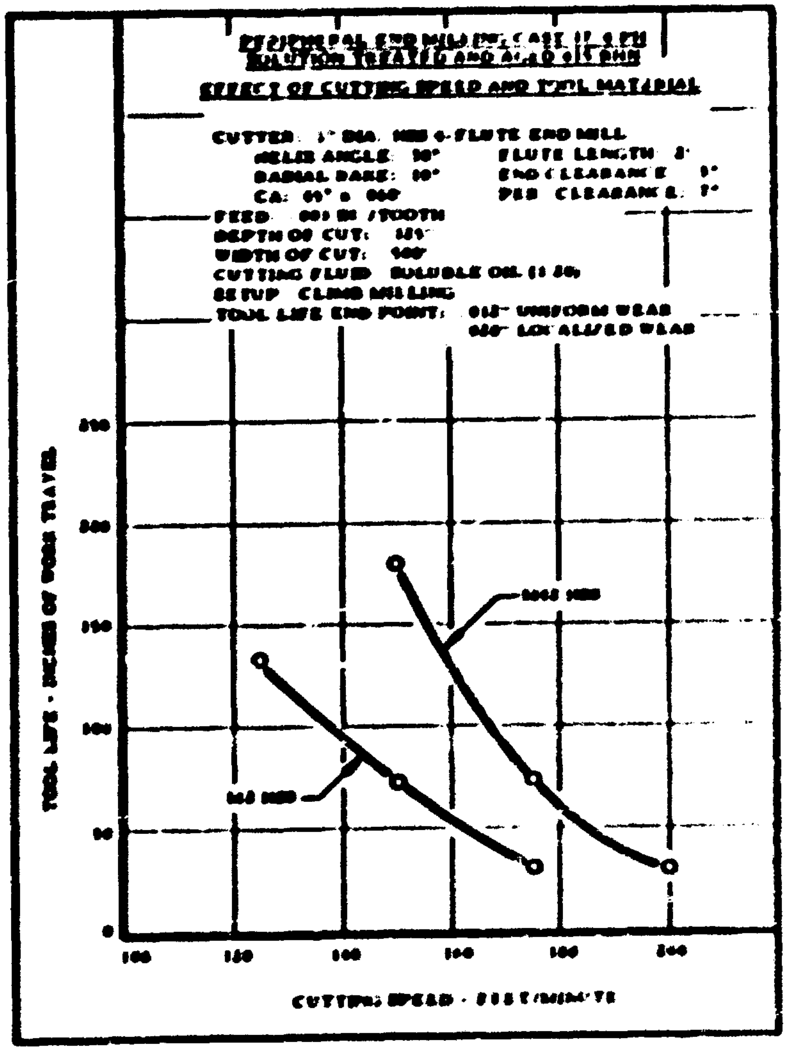
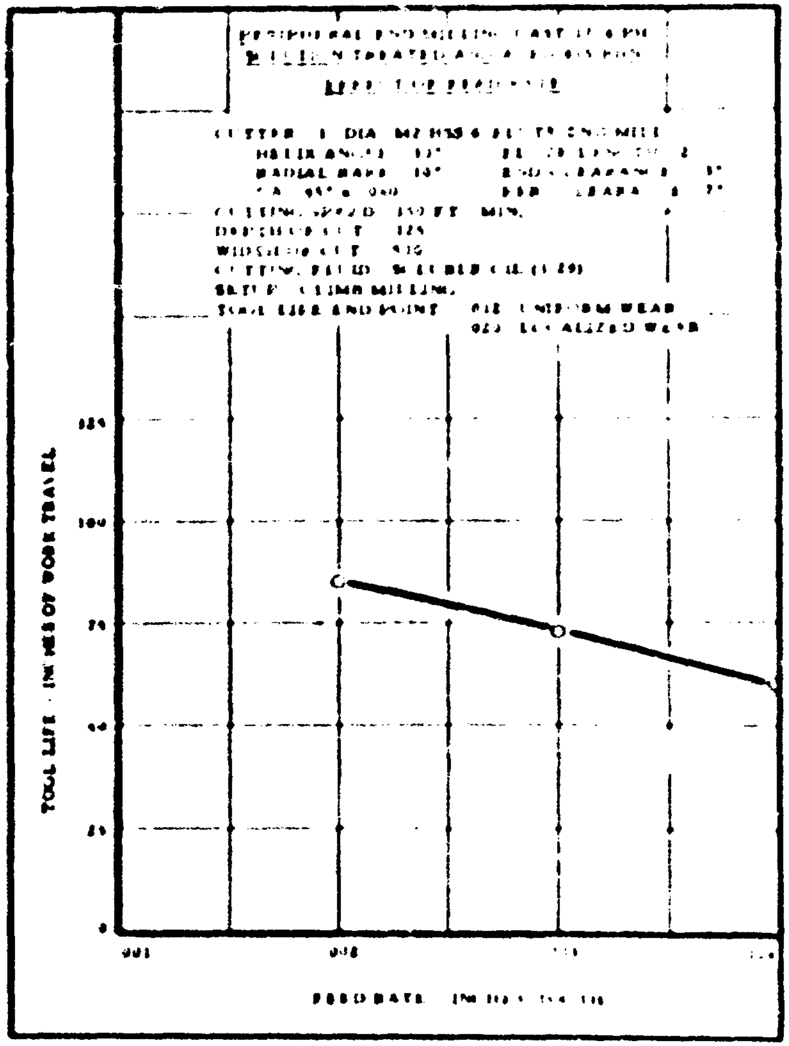
Figure [illegible]



See text, page 61

Figure 54



See text, page 61

Figure 55

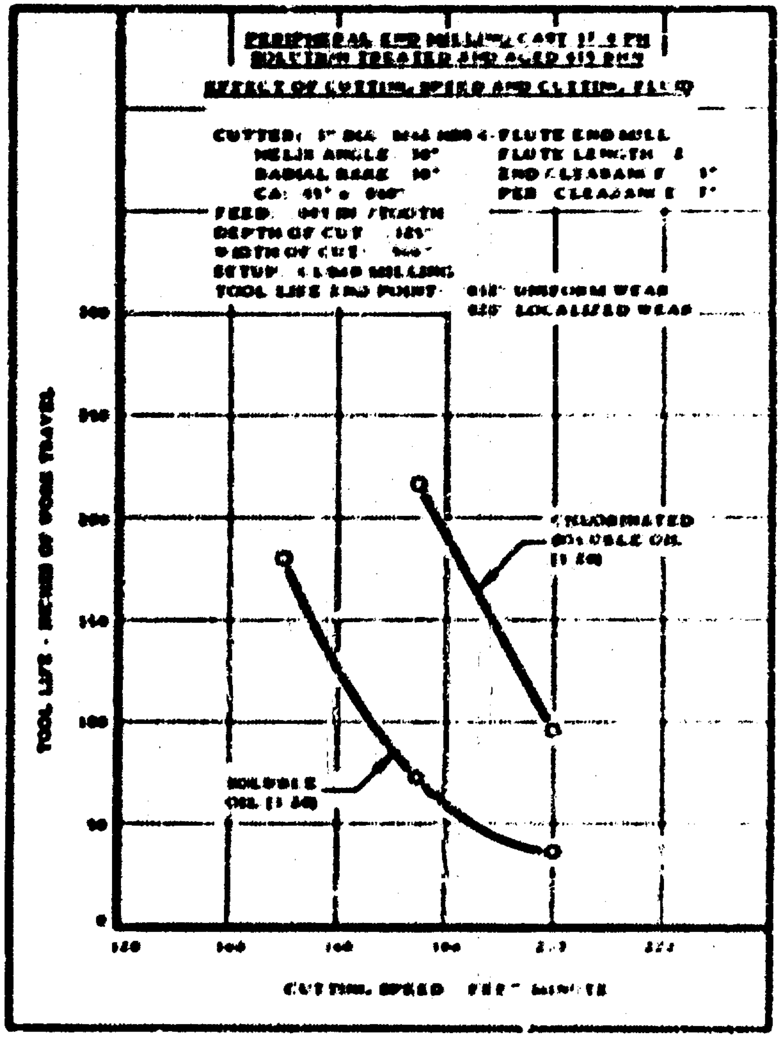


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Figure [illegible]

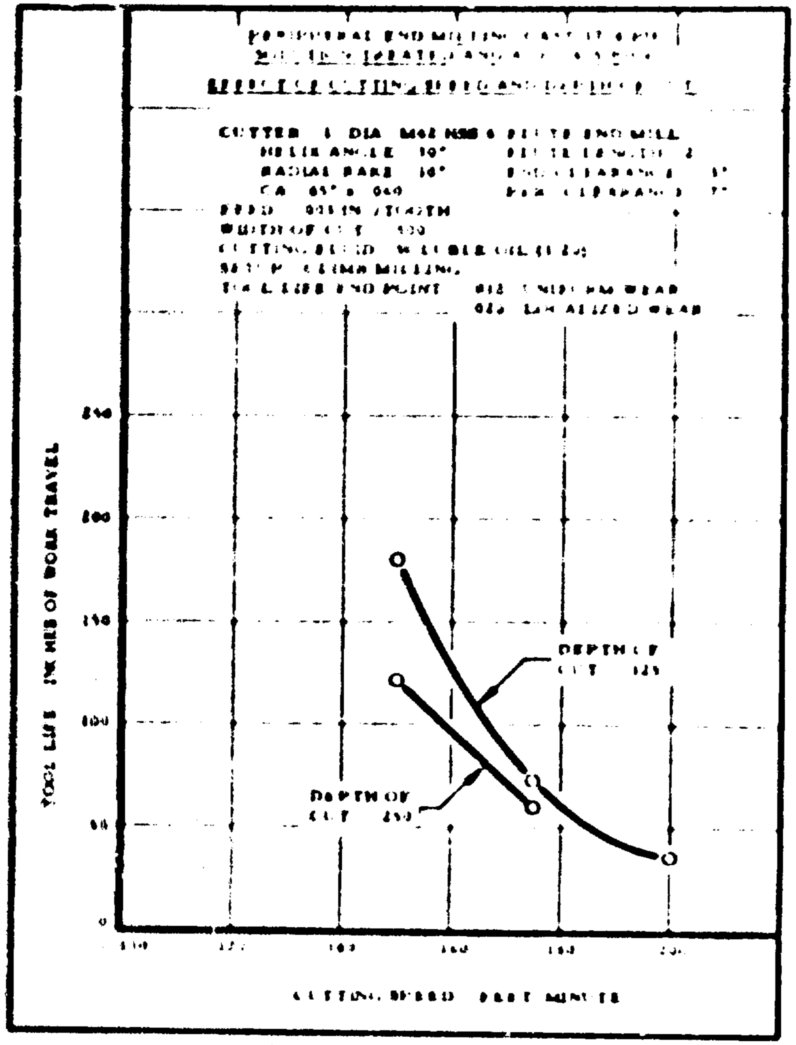

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Figure [illegible]

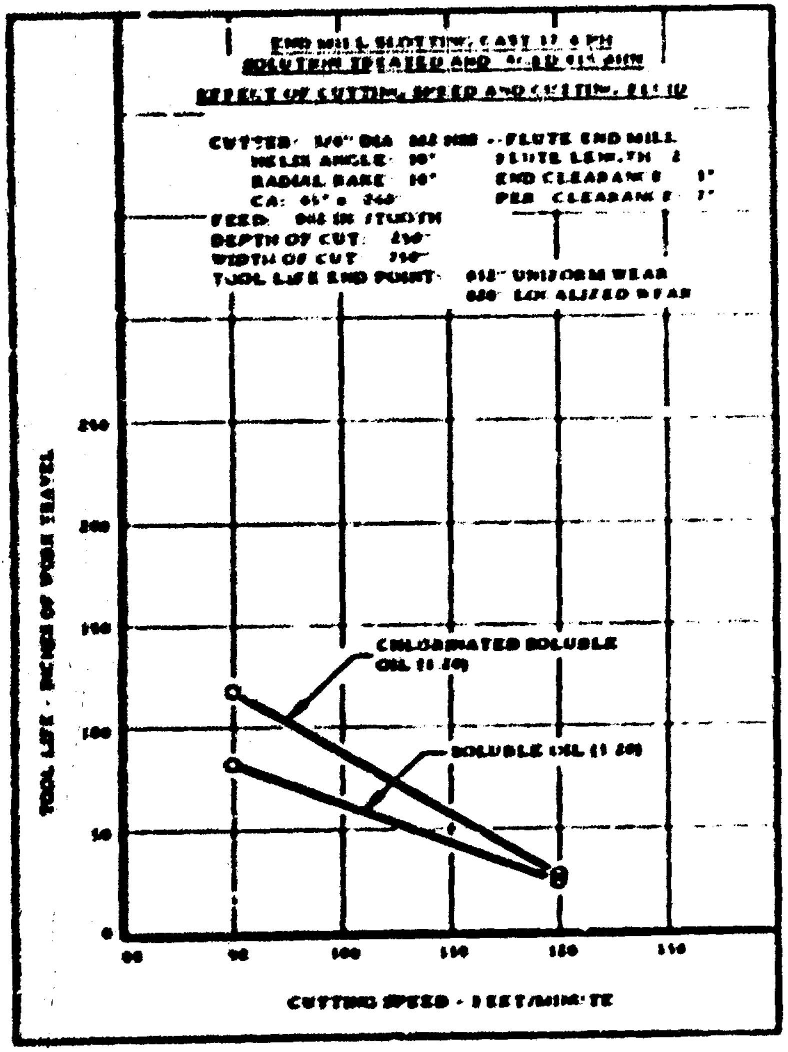

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Figure 48

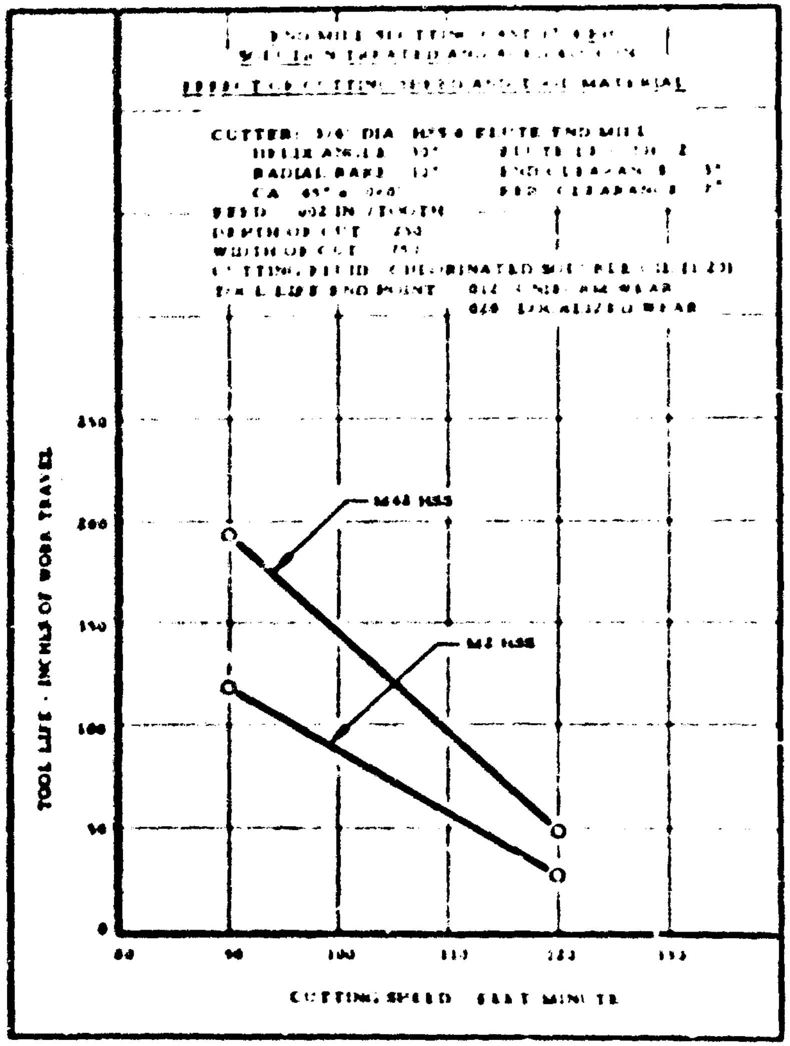

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Figure [illegible]

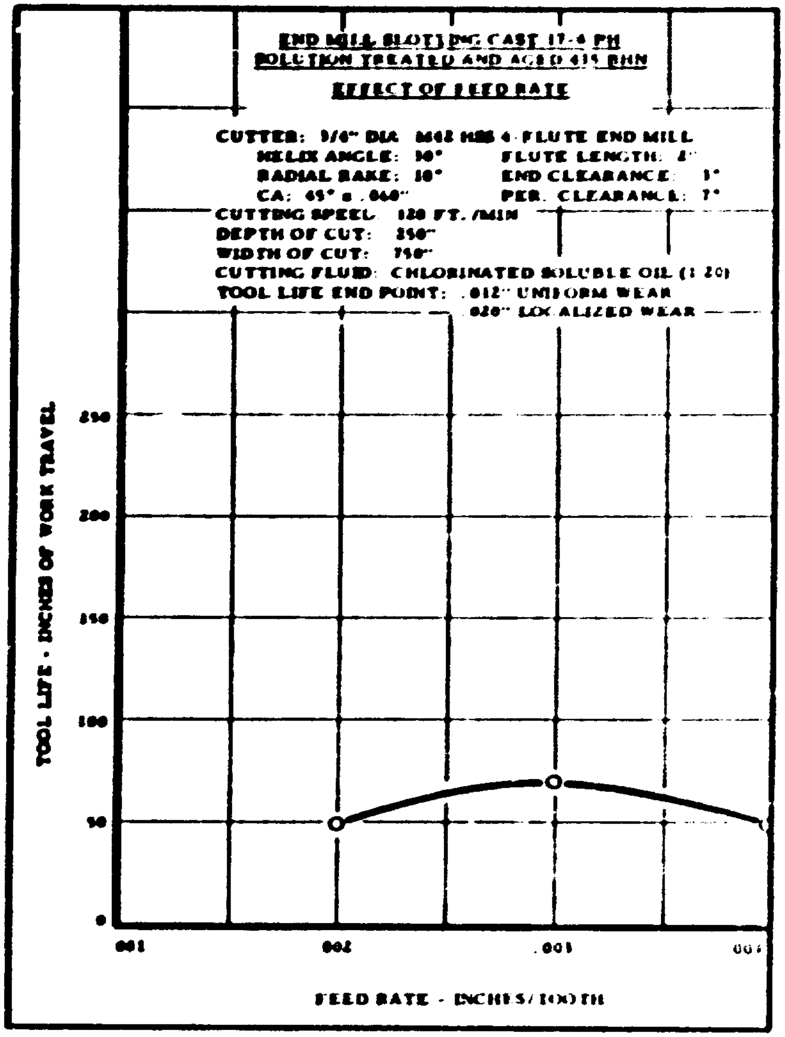

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Figure 70

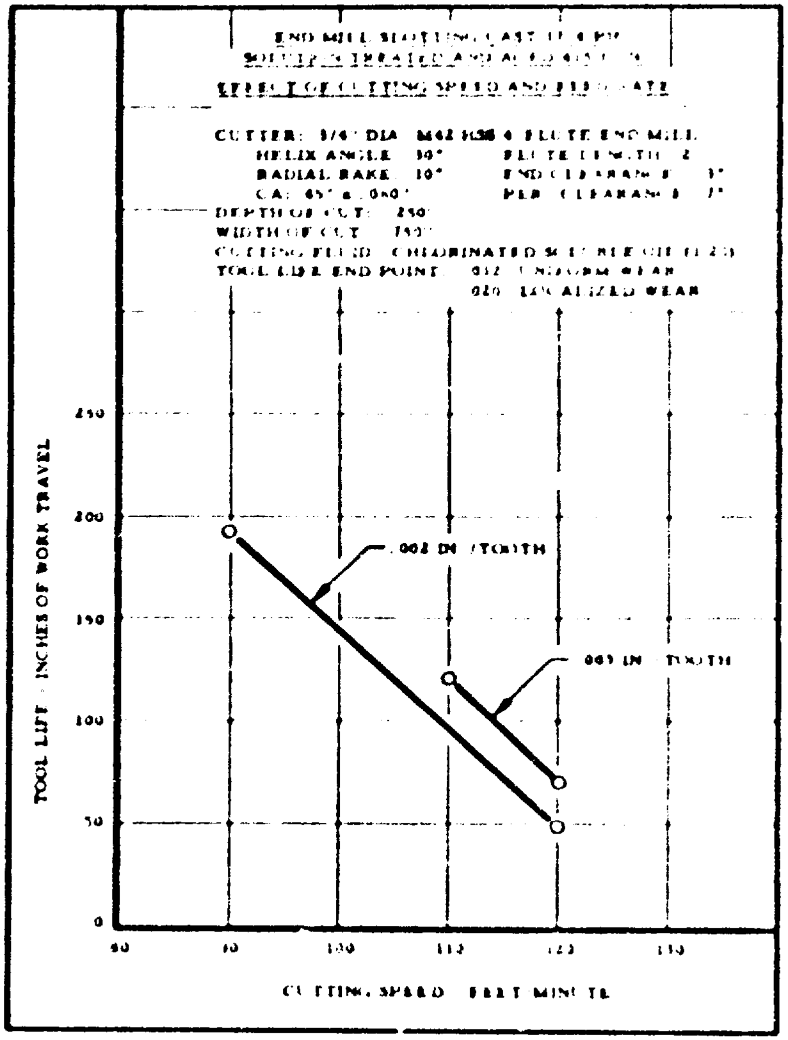

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Figure 71

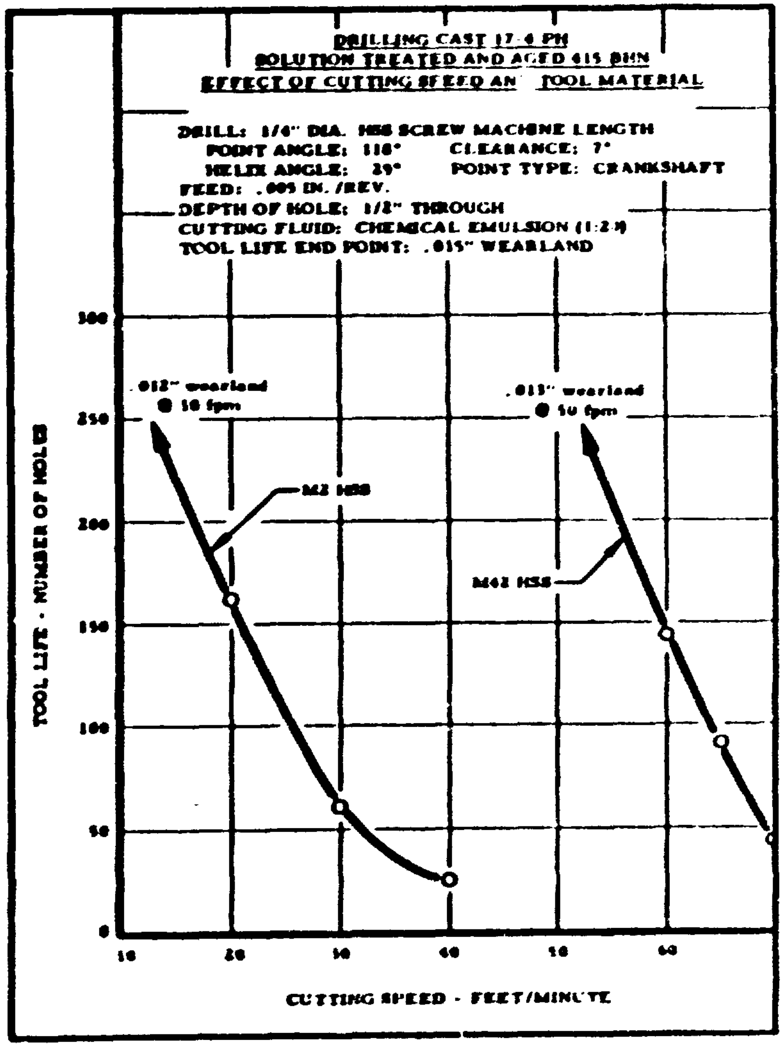

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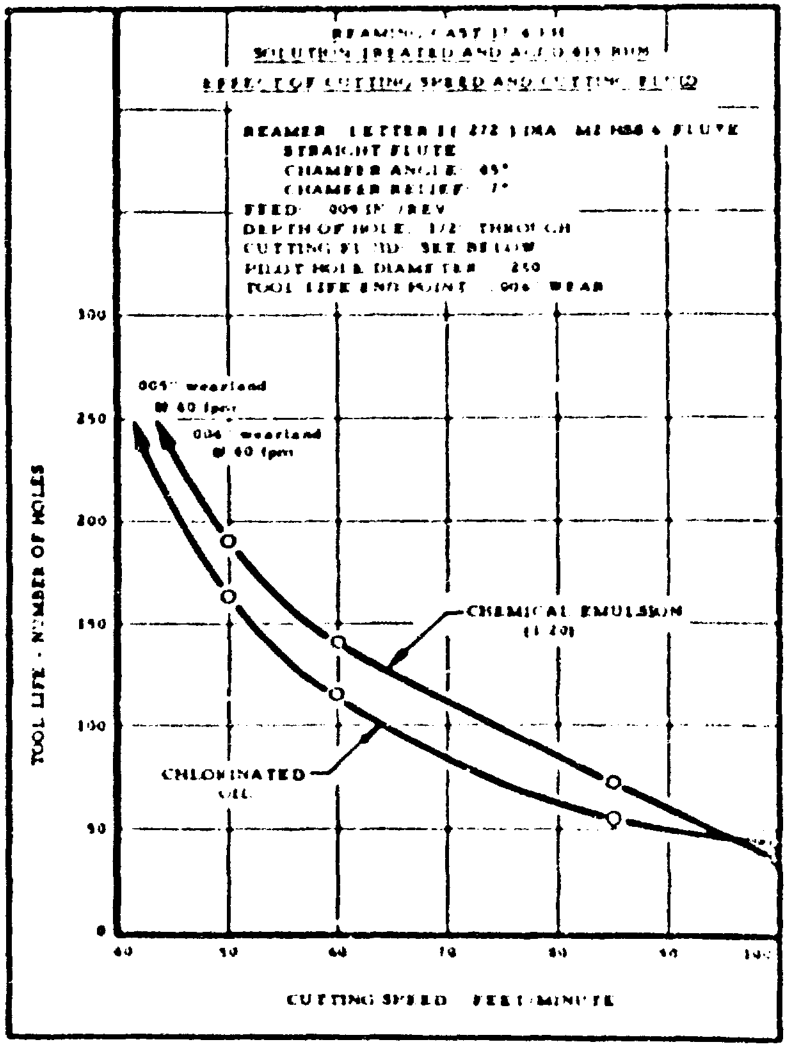
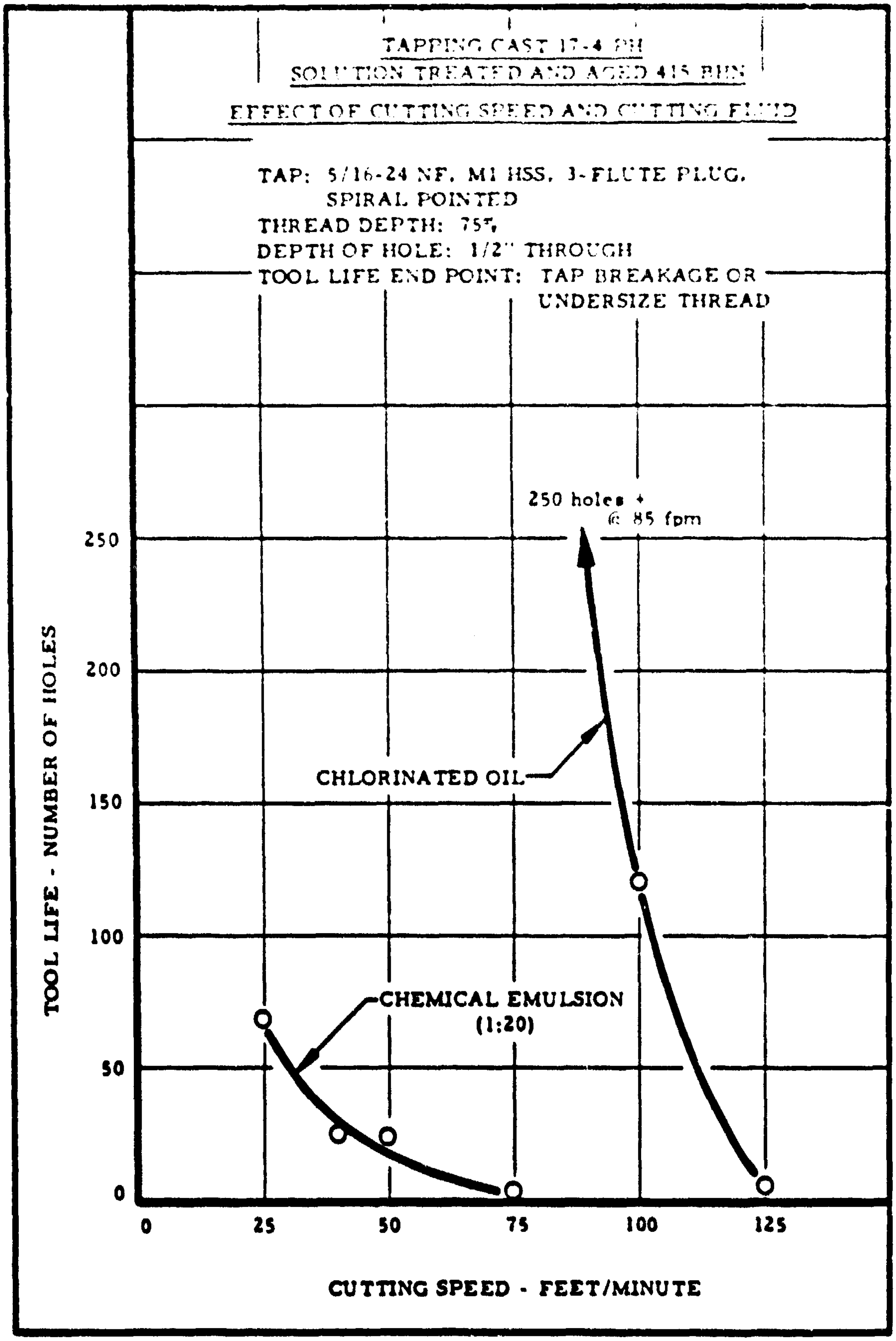
Figure 72



See text, page 62

Figure 73



See text, page 62

Figure 74

3.6 Almar 362, Annealed

Alloy Identification

Almar 362 can be defined as a stainless maraging steel which contains an addition of chromium that renders the alloy good corrosive and oxidation resistance properties. The nominal composition of this alloy is as follows:

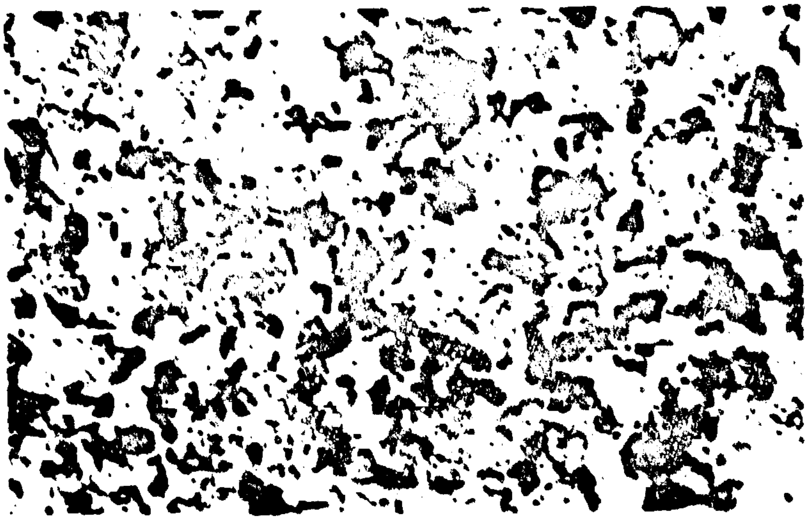
Fe-14.5Cr-6.5Ni-.8Ti-.3Mn-.2Si-.03C

The material for the peripheral end milling tests was procured as forged, mill annealed, 2 in. by 4 in. rectangular bars. The material for the drilling tests was obtained by sectioning 1/2 in. thick plates from the 2 in. by 4 in. bar stock. The annealing treatment at the mill was as follows:

1500°F/1 hour per inch of thickness/air cool

The resulting hardness was 248 BHN.

The microstructure, illustrated below, consists of soft, ductile martensite.



Almar 362, Annealed

Etchant: $FeCl_3$ **Mag.:** 500X

3.6 Almar 362, Annealed (continued)

Peripheral End Milling (248 BHN)

Tool life curves are shown in Figure 75, page 78, for peripheral end milling Almar 362 in the annealed condition using conventional milling and climb milling. A 30 percent increase in tool life was obtained by climb milling compared to conventional milling.

A comparison of two cutting fluids, a soluble oil and a chlorinated oil, is shown in Figure 76, page 78. Note that the soluble oil was slightly better than the chlorinated oil.

The relationship between feed rate and tool life is presented in Figure 77, page 79. The difference in the tool life was not as great as one might expect when the feed rate was increased from .003 to .005 in./tooth. At the higher feed of .005, however, there is always the problem of tool deflection. Hence, a feed of .003 or .004 is recommended, depending on the depth and width of cut.

In a case where heavier depths of cut were used, the feed was set at .003 in./tooth as shown in Figure 78, page 79. Note that for a given tool life the cutting speed had to be reduced about 10 percent when the depth of cut was increased from .125 to .250 inches.

A comparison of two different high speed steels, M2 and M42, is presented in Figure 79, page 80. The M42 tool permitted a 20 percent increase in cutting speed as compared to the M2 tool.

Drilling (255 BHN)

Tool life curves with two different types of HSS tools are shown in Figure 80, page 80. The tool life was appreciably better with the M42 HSS drills as compared to the M1 HSS drill, for the drilling speed with the M42 HSS drills for a given tool life was about 20 percent higher than with the M1 HSS drills.

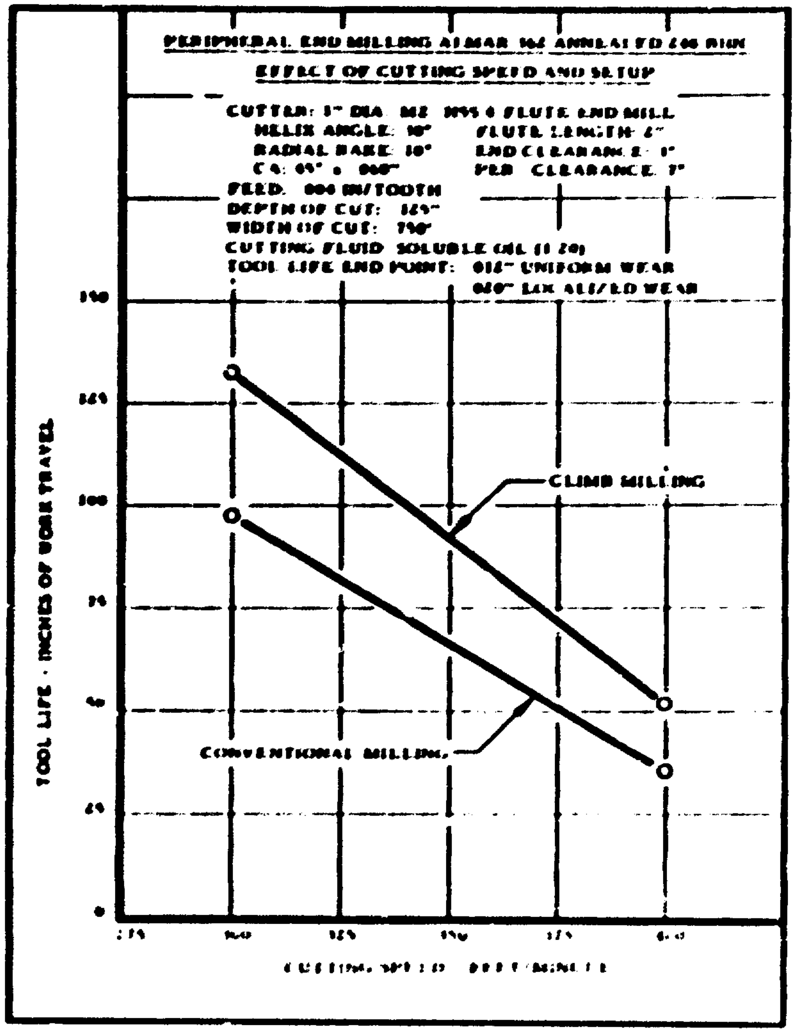
TABLE VI

RECOMMENDED CONDITIONS FOR MACHINING
ALMAR 362, ANNEALED 248 BHN

Nominal Chemical Composition, Percent

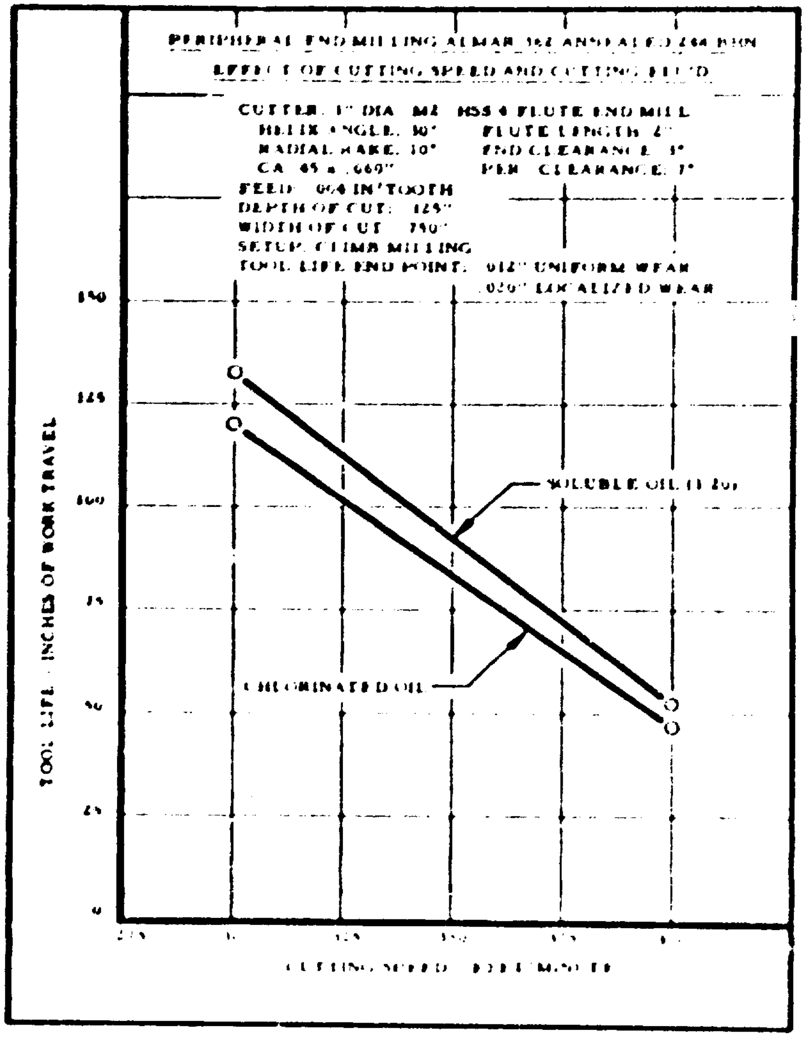
Fe	Cr	Ni	Ti	Mn	Si	C
Bal.	14.5	6.5	.8	3	2	.03

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Peripheral End Milling	M42 HSS	Point Angle: 118° RR: 10° Clearance: 7° CA: 45° x .060"	1" Diameter 4 Flute HSS End Mill	.125	.750	.004 in/tooth	250	260" work travel	.012	Soluble Oil (1:20)
Drilling	M42 HSS	Point Angle: 118° Helix Angle: 29° Clearance Angle: 7°	1/4" Diameter HSS Drill 2-1/2" long	.500 thru	-	.005 in/rev	85	160 holes	.015	Soluble Oil (1:20)



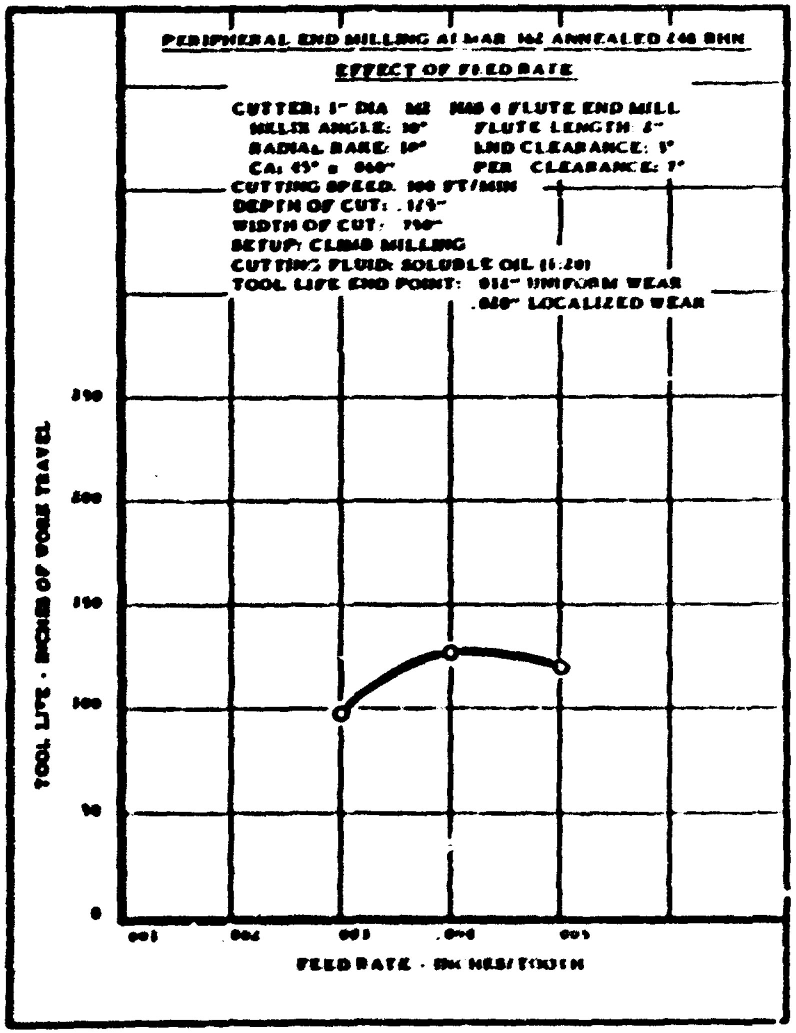
See text, page [illegible]

Figure [illegible]



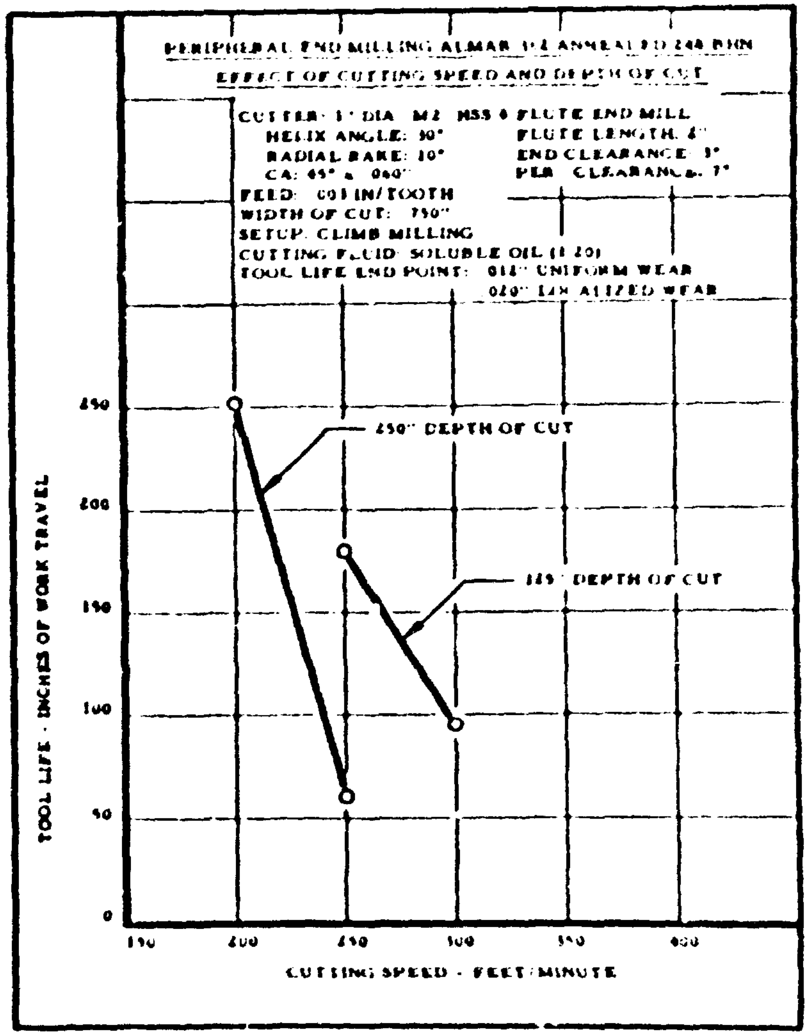
See text, page [illegible]

Figure [illegible]



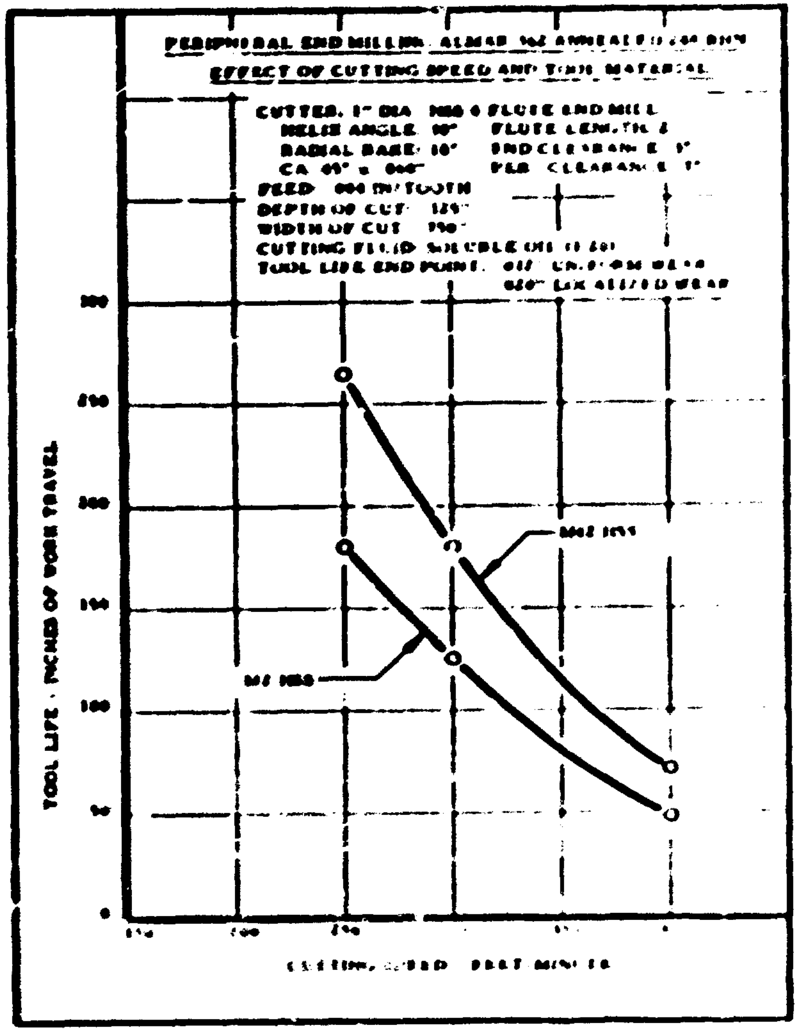
See text, page 76

Figure 77

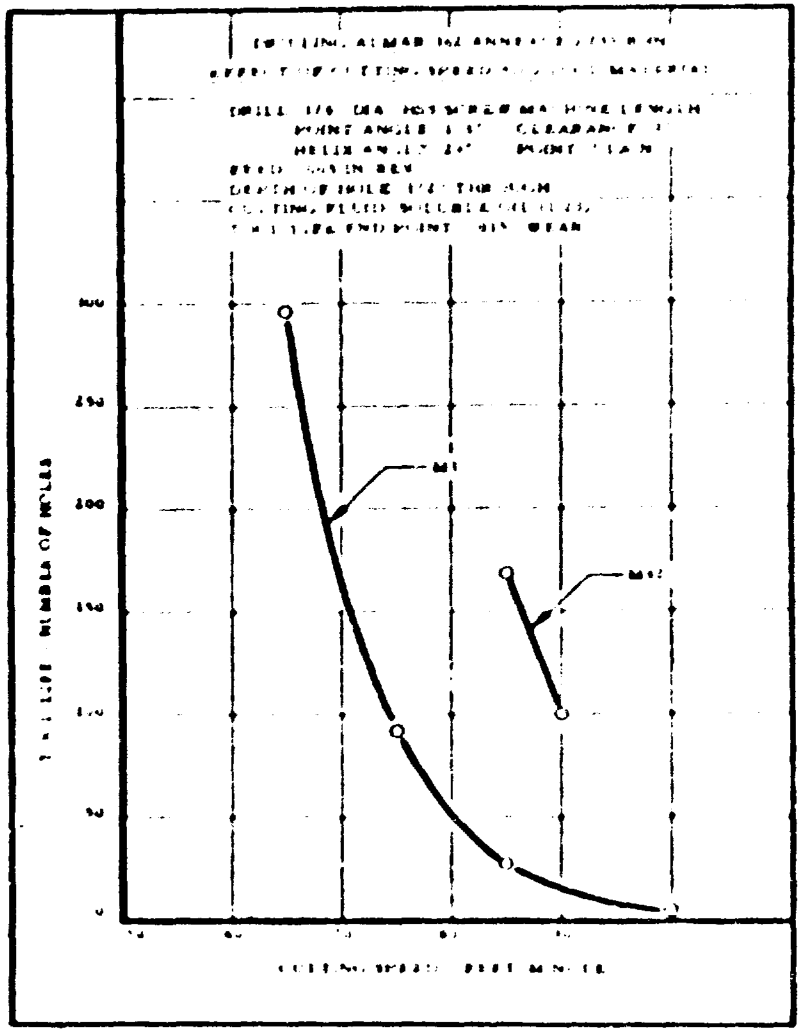


See text, page 76

Figure 78



See text, page 76 Figure [illegible]



See text, page [illegible] Figure [illegible]

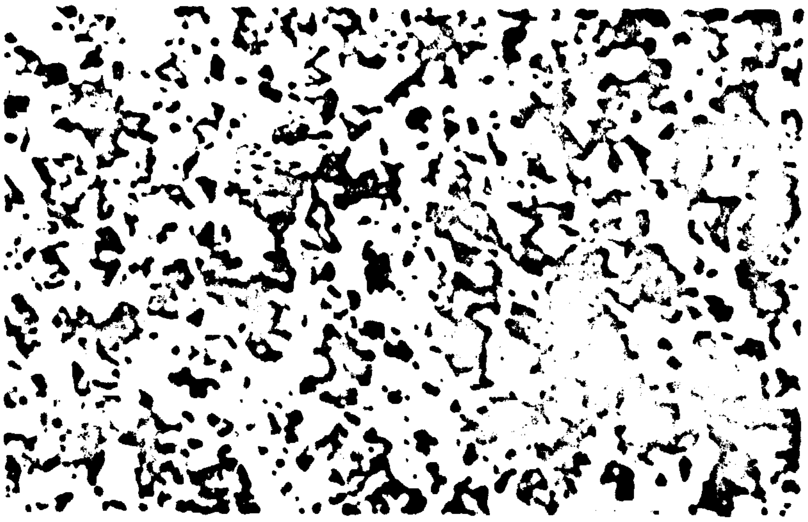
3.7 Almar 362, Aged

Alloy Identification

In order to compare the aged to the mill annealed condition, a portion of the material was heat treated as follows:

900°F/2 hours/air cool

The treatment resulted in a hardness of 375-388 BHN. The microstructure of the aged grade, which is evidenced below, consists of a martensite matrix strengthened by precipitates.



Almar 362, Aged

Etchant: $FeCl_3$ **Mag.:** 500X

Almar 362, Aged (continued)

Peripheral End Milling (382 BHN)

Tool life curves using three different types of HSS tools are presented in Figure 81, page 84. The M42 HSS tool provided the longest tool life. Of the three tools used, the tool life with the T15 HSS tool was poorest. The cutting speeds for a tool life of 100 inches of work travel with the T15, M2 and M42 HSS tools were 100, 145 and 162 feet/minute, respectively.

As shown in Figure 82, page 84, a feed of .003 in./tooth provided the best tool life. Increasing the feed to .004 in./tooth resulted in a 25 percent decrease in tool life at a cutting speed of 150 feet/minute.

A comparison of tool life curves for peripheral end milling the Almar 362 alloy in the annealed condition and the aged condition is shown in Figure 83, page 85. Note that the alloy in the annealed condition can be machined about three times faster than the same alloy in the aged condition.

Drilling (388 BHN)

Tool life curves at two different feeds are shown in Figure 84, page 85, for drilling Almar 362, aged to 388 BHN. Note that for a tool life of 200 holes the cutting speed with the .004 in./rev. was 30 percent higher than that which was used at a speed of .005 in./rev. The relationships between feed and tool life are shown at several different cutting speeds in Figure 85, page 86.

A comparison of tool life curves in drilling the Almar 362 alloy in two different heat treated conditions is shown in Figure 86, page 86. For a tool life of 170 holes, the alloy in the annealed condition (255 BHN) can be machined at twice the drilling speed that would be required for the alloy in the aged condition (388 BHN).

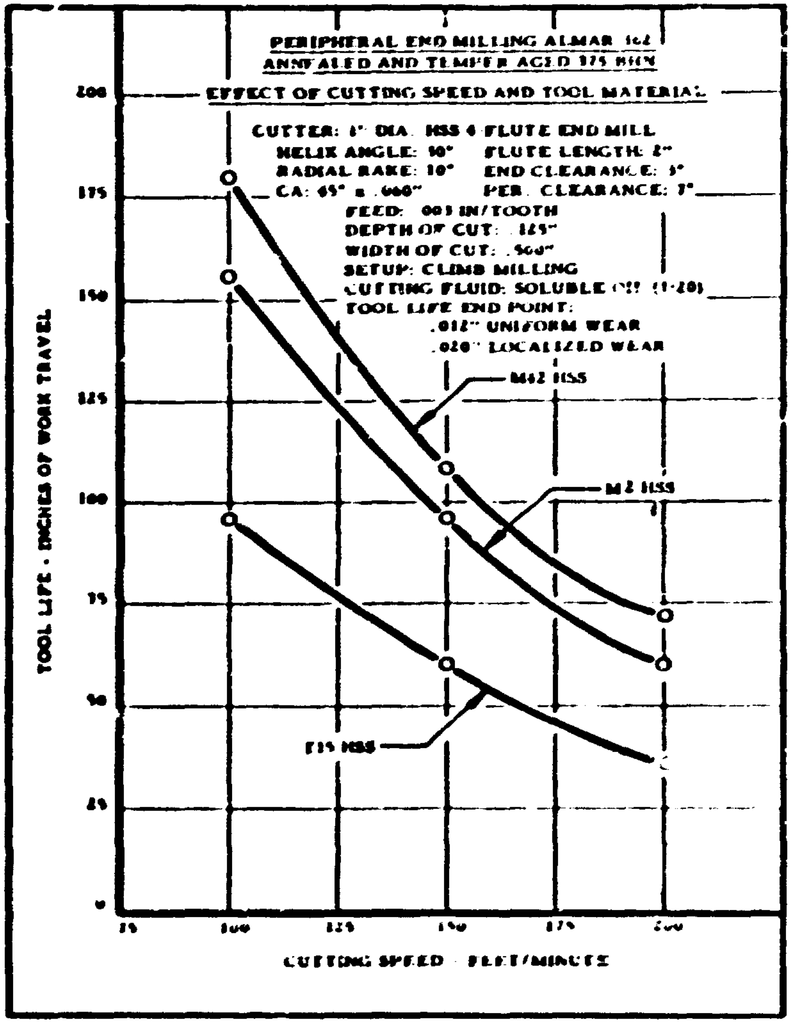
TABLE VII

RECOMMENDED CONDITIONS FOR MACHINING
ALMAR 362, ANNEALED AND TEMPERED AGED 375 BHN

Nominal Chemical Composition, Percent

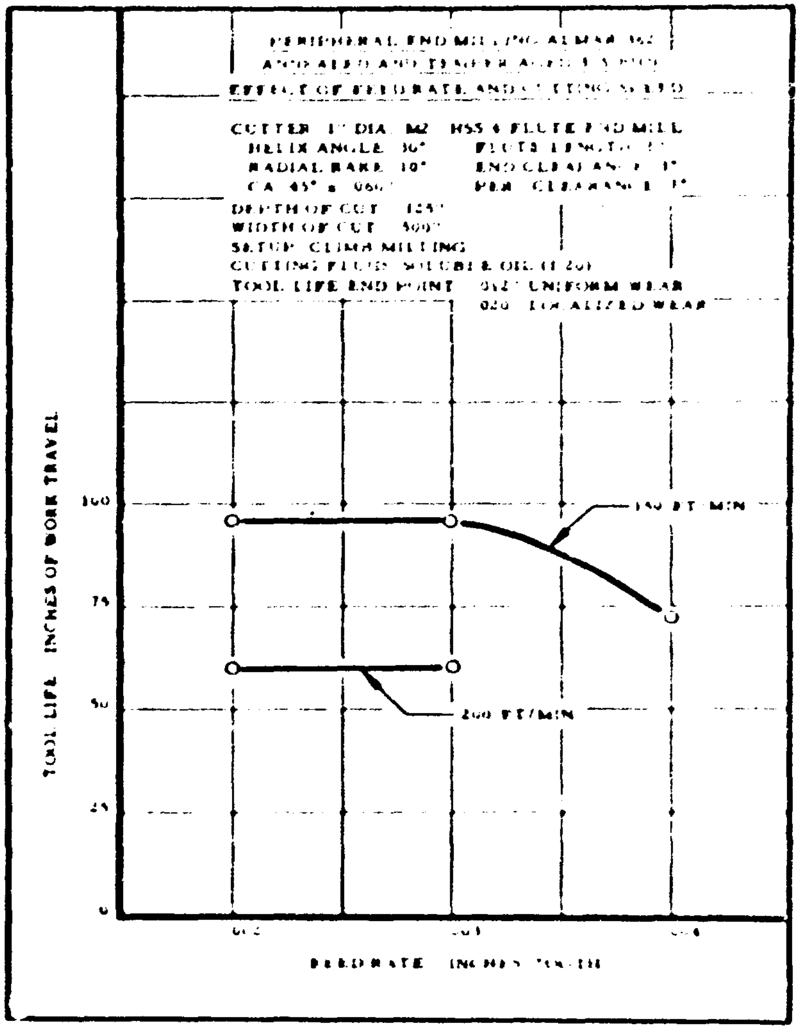
Fe	Cr	Ni	Ti	Mn	Si	C
Bal.	14.5	6.5	.8	3	2	.03

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft/min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Peripheral End Milling	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	1" Diameter 4 Flute HSS End Mill	.125	.500	.003 in/tooth	100	180" work travel	.012	Soluble Oil (1:20)
Drilling	M42 HSS	Point Angle: 118° Helix Angle: 29° Clearance Angle: 7°	1/4" Diameter HSS Drill 2-1/2" long	.500 thru	-	.004 in/rev	50	225 holes	.015	Soluble Oil (1:20)



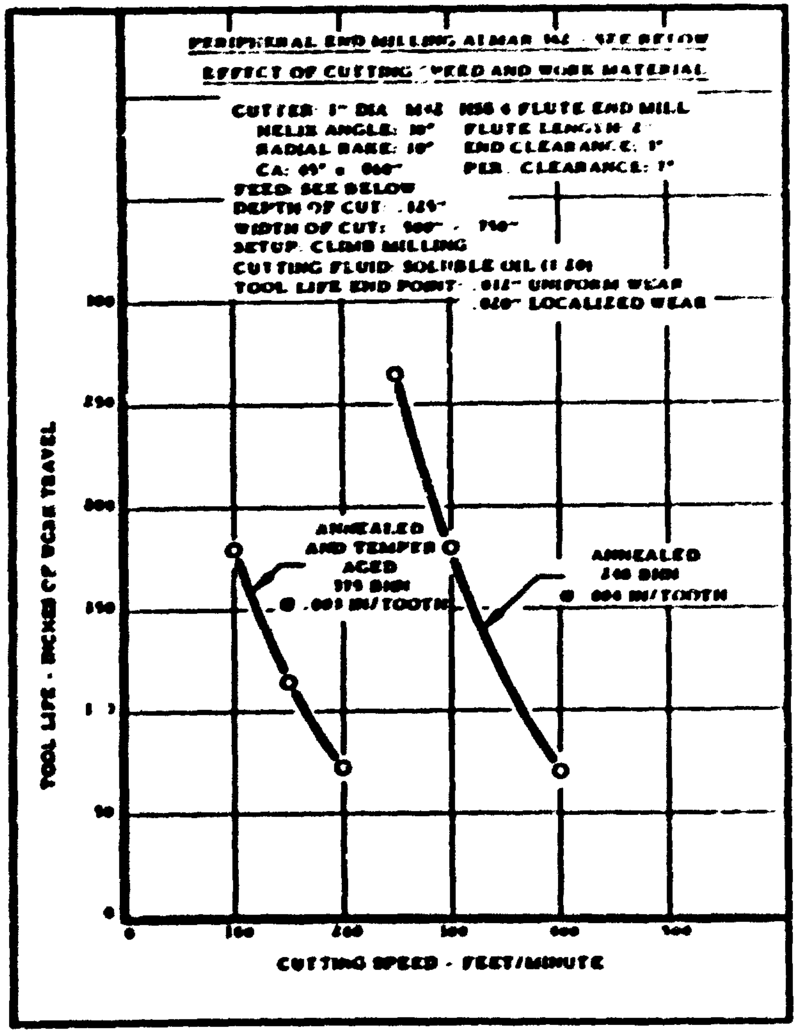
See text, page 42

Figure 51

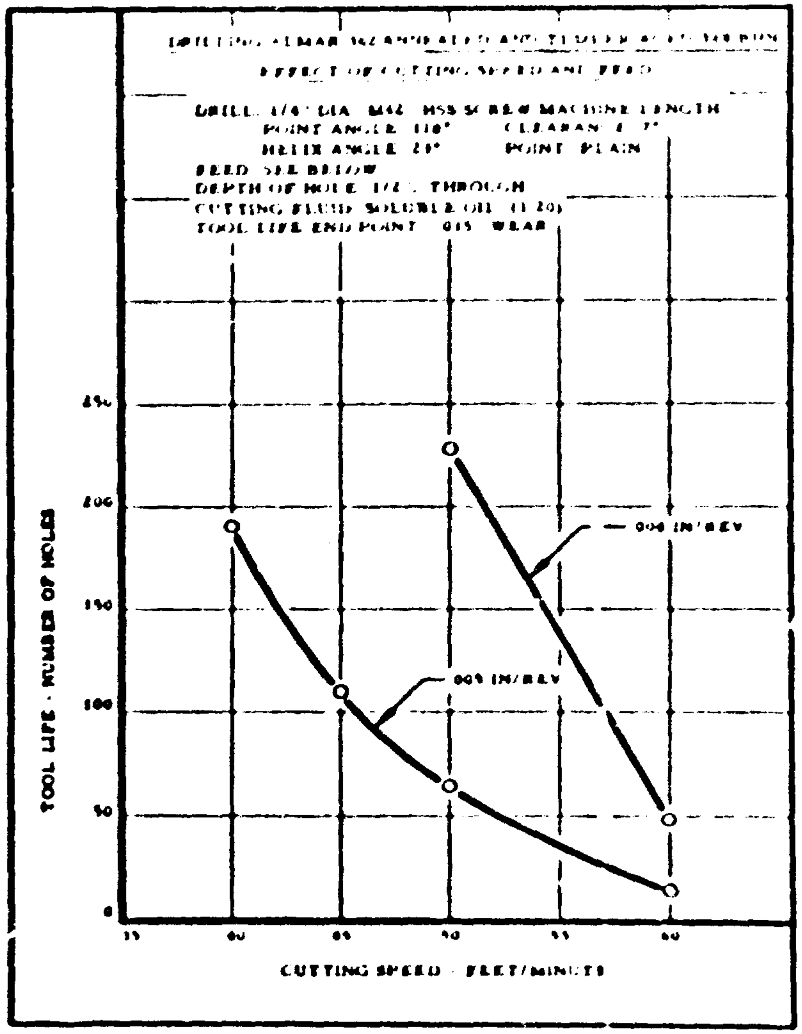


See text, page 42

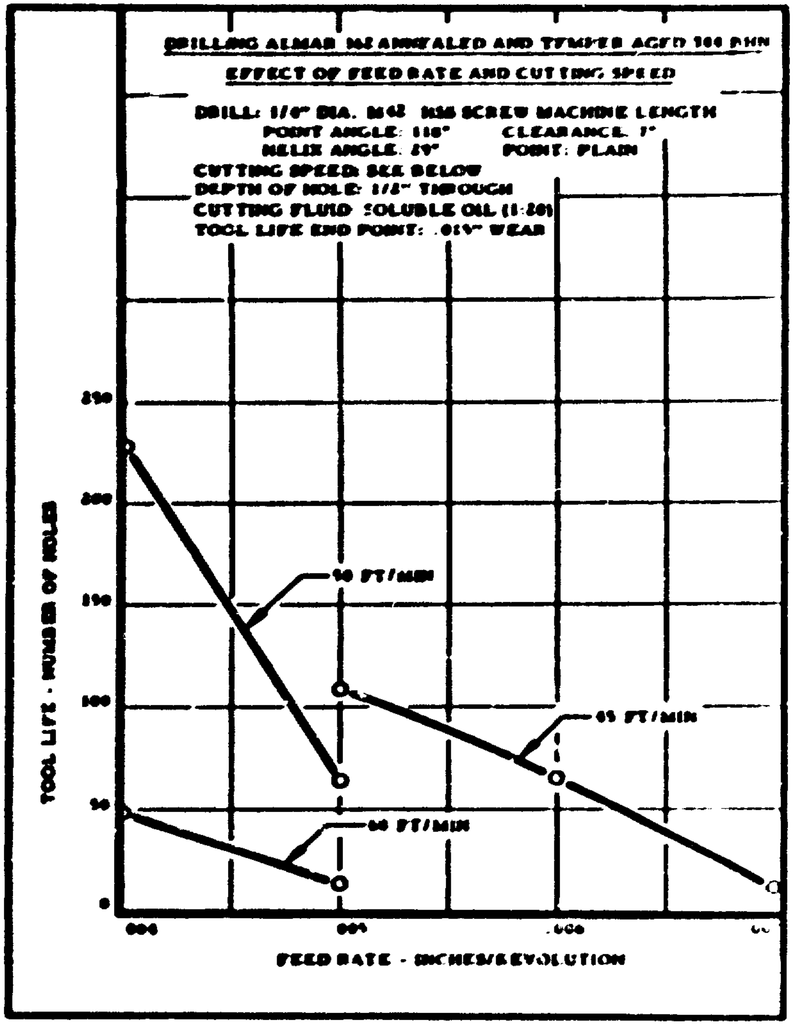
Figure 52



See text, page 62 Figure 65



See text, page 64 Figure 66



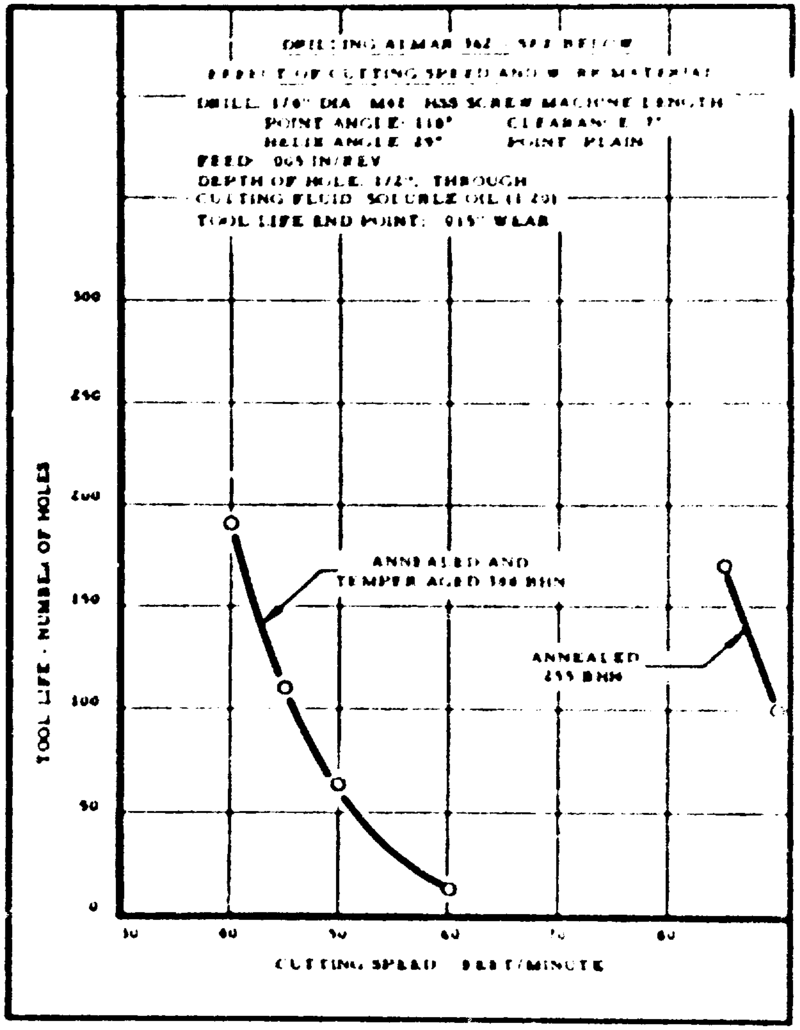
DRILLING ALMAR 362 ANNEALED AND TEMPER AGED 388 BHN

EFFECT OF FEED RATE AND CUTTING SPEED

DRILL: 1/8" DIA. M42 HSS SCREW MACHINE LENGTH
POINT ANGLE: 118° CLEARANCE: 7°
HELIX ANGLE: 29° POINT: PLAIN
CUTTING SPEED: SEE BELOW
DEPTH OF HOLE: 1/2" THROUGH
CUTTING FLUID: SOLUBLE OIL (1:20)
TOOL LIFE END POINT: .015" WEAR

See text, page 82

Figure 85



DRILLING ALMAR 362 – SEE BELOW

EFFECT OF CUTTING SPEED AND WORK MATERIAL

DRILL: 1/8" DIA. M42 HSS SCREW MACHINE LENGTH
POINT ANGLE: 118° CLEARANCE: 7°
HELIX ANGLE: 29° POINT: PLAIN
FEED: .005 IN/REV
DEPTH OF HOLE: 1/2" THROUGH
CUTTING FLUID: SOLUBLE OIL (1:20)
TOOL LIFE END POINT: .015" WEAR

See text, page 82

Figure 86

4. MACHINING TITANIUM ALLOYS

4.1 Titanium 6Al-4V, Beta Forged

Alloy Identification

Ti-6Al-4V is a high-alpha, lean-beta titanium alloy which exhibits excellent elevated temperature strength and stability as well as a wide range of hot workability. One of the most recent developments has been centered on forging the alloy above the alpha plus beta/beta transus. This practice has not shown any significant effect in reduction of mechanical properties, but rather has improved creep strength and fracture toughness. The alloy has the following nominal composition:

Ti-6.0Al-4.0V-.05C

The material for turning tests was procured as 3 in. diameter bars in the beta forged condition. It was reportedly forged at 1950°F and air cooled to room temperature. The hardness of the bars was 331 BHN.

The resulting microstructure, which is illustrated below, consists principally of acicular alpha.

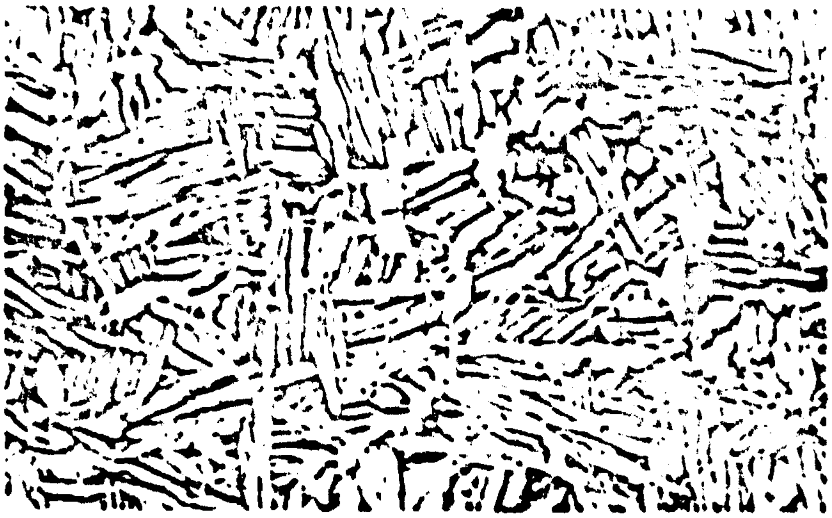
Titanium 6Al-4V, Beta Forged

Etchant: HF, HNO_3, H_2O Mag.: 500X

4.1 Titanium 6Al-4V, Beta Forged (continued)

The 1/2 in. thick sections for the milling tests were machined from 2 in. by 4 in. rectangular bars in the beta forged condition. Beta forged slabs 1/2 in. by 4 in. were procured for the drilling tests. The material was reportedly forged at 1950°F and air cooled to room temperature. The resulting hardness on all the material was 331 BHN.

The microstructure of the 2 in. by 4 in. bars, shown below, consists of alpha platelets. This coarser structure in contrast to that of the 1/2 in. by 4 in. slabs is indicative of a slower cooling rate.

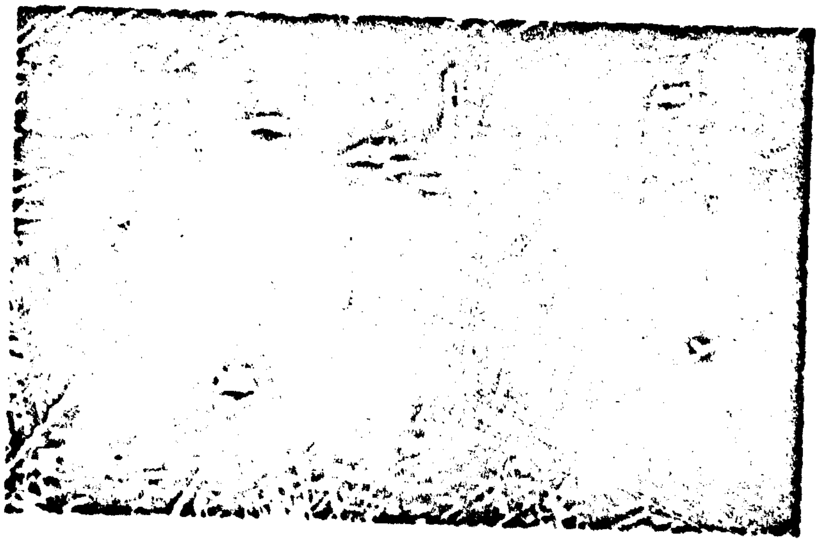


Titanium 6Al-4V, Beta Forged

Etchant: HF, HNO_3, H_2O **Mag.: 500X**

4.1 Titanium 6Al-4V, Beta Forged (continued)

The microstructure of the 1/2 in. by 4 in. material is evidenced below. It consists principally of acicular alpha.



Titanium 6Al-4V, Beta Forged

Etchant: HF, HNO_3, H_2O **Mag.:** 500X

4.1 Titanium 6Al-4V Beta Forged (continued)

Turning (341 BHN)

Tool life curves with three different types of HSS tools are shown in Figure 87, page 100 for turning Titanium 6Al-4V beta forged, 341 BHN. Note that for a 60-minute tool life, the cutting speeds were 46 feet/minute for the M2, 52 feet/minute for the T15 and 56 feet per minute for the M42 HSS tools.

The type M42 HSS tool was even more superior at the heavier feeds. For example, as shown in Figure 88, page 100, the cutting speeds at a feed of .015 in./rev. were about 40 percent faster than at a feed of .010 in./rev. and 70 percent faster than at a feed of .005 in./rev.

In general, the cutting speeds used in machining the surfaces of the forged bars of the titanium alloy were appreciably less than those used for machining under the skin. Note in Figure 89, page 101, that the cutting speeds in turning the skin of these forged bars were less than 50 percent of those used under the skin. The difference in the depths of cut for the two different curves is not believed to be an important factor in the comparison.

Tool life curves with carbide tools are shown in Figure 90, page 101, for the two tool geometries: (1) 5° negative back rake and 5° negative side rake and (2) 0° back rake and 5° positive side rake. Note that the tool with the negative rake angles provided slightly higher tool life than those tools having the positive side rake.

The C-2 grade of carbide again provided the longest tool life. Note in Figure 91, page 102, that both the titanium carbide and the C-7 grade performed poorly compared to the C-2 grade of carbide. Also the advantage of using a cutting oil was not very significant when compared to cutting dry, see Figure 92, page 102. At a 30 minute tool life, the cutting speed with the oil was less than 10 percent faster than cutting dry. However, it is to be expected that the tool life values would be more consistent when using a cutting oil since there would be less of a tendency for the chip to weld to the cutting edge.

It is interesting to note in Figure 92, page 103 that at a cutting speed of 175 feet/minute with carbide, the tool life dropped 50 percent when the feed was increased from .010 to .015 in./rev. When cutting with high speed steel tools, as shown earlier, the tool life increased when the feed was increased to .015 in./rev.

4.1 Titanium 6Al-4V, Beta Forged (continued)

Face Milling (331 BHN)

Tool life curves with M2 and M42 HSS single-tooth cutters are shown in Figure 94, page 103. At a cutting speed of 80 feet/minute, the tool life with the M42 HSS cutter was 160 inches of work travel while with the M2 HSS cutter the tool life was 90 inches of work travel.

Figure 95, page 104, presents tool life curves at two different feeds over a range of cutting speeds with an M42 HSS single-tooth cutter. These two curves reveal that with the single-tooth cutter, the higher production rate is at the feed of .005 in./tooth. However, it has been found in the past that when using a multiple-tooth cutter the feed generally has to be reduced somewhat in order to maintain a reasonable tool life. Hence, a comparison of the performance of a single-tooth cutter with a 14-tooth cutter is made in Figure 96, page 104, at a feed of .003 in./tooth. Note that at a cutting speed of 90 feet/minute the cutter life in terms of inches of work travel per tooth dropped from 90 with a single-tooth cutter to 40 with the 14-tooth cutter. However, even with the lower tool life per tooth using the multiple-tooth cutter, the total length of workpiece cut was 14 times 40, or 560 inches of work travel.

A comparison of the tool life values obtained with a variety of grades of carbide is presented in Figure 97, page 105. Note that no cutting fluid was used with a single-tooth cutter having 5° positive rake angles. Also, the feed was .005 in./tooth. Under these conditions, the C-2 grade 883 was superior to all of the other grades tested.

As shown in Figure 98, page 105, a cutter with 5° negative axial and radial rake angles provided longer tool life than a cutter with 5° positive axial and radial rake angles at a cutting speed of 100 feet/minute. At this speed, the tool life was 290 inches of work travel with the cutter having the negative rake angles, while with the cutter having the positive rake angles the tool life was 215 inches of work travel.

Another comparison of the cutters having negative and positive rake angles is presented in Figure 99, page 106, at a cutting speed of 150 feet/minute. Except at a feed of .007 in./tooth, the difference in the two cutters is insignificant.

Cutter life was increased appreciably by using a phosphated oil instead of cutting dry; see Figure 100, page 106. For example, at a tool life of 130 inches of work travel, the cutting speed with the oil

Face Milling (331 BHN) (Continued)

was 220 feet/minute as compared to 150 feet/minute cutting dry. The soluble oil provided even less tool life than cutting dry.

Using a phosphated oil, the single-tooth cutter with the 5° negative axial and radial rake angles was appreciably better than a cutter having the 5° positive axial and radial rake angles. For example, as shown in Figure 101, page 107, at a cutting speed of 2[illegible] feet/minute the tool life with the cutter having the positive rake angles was [illegible] inches of work travel as compared to 205 inches with the cutter having the negative rake angles.

It is interesting to note in Figure 102, page 107, that at a cutting speed of 220 feet/minute the cutter life per tooth with the six-tooth cutter was only 125 inches as compared to 180 inches with the single-tooth cutter. However, it should be pointed out that at this speed the six-tooth cutter cut a total of 750 inches of work travel, while the single-tooth cutter only cut 180 inches total.

Peripheral End Milling (331 BHN)

A comparison is shown in Figure 103, page 108, of the tool life curves obtained with a soluble oil and a phosphated oil. At the cutting speeds at which these curves were obtained, the soluble oil outperformed the phosphated oil.

As shown in Figure 104, page 108, at a tool life of 2[illegible] inches of work the cutting speed with an M42 HSS end mill was 20 percent greater than that with the M2 HSS cutter. Note that the depth of cut was .250 inches. At a depth of cut of .125 in., the cutting speeds were 40 percent higher than at a depth of cut of .250 in. (see Figure 105, page 109). It should be pointed out, however, that at the depth of cut of .250 in. (which is twice as great) only a 40 percent decrease in cutting speed was required to obtain the equivalent tool life. Hence the metal removal rate was appreciably greater in the case of the higher depth of cut.

The curve shown in Figure 106, page 109, represents the relationship between tool life and feed at a cutting speed of 150 feet/minute. Note that the cutter life actually increased from 207 to 325 inches of work travel by increasing the feed from .002 to .004 in./tooth.

4. Titanium 6Al-4V, Beta Forged (continued)

Peripheral End Milling (331 BHN) (continued)

A comparison of tool life curves obtained with two different grades of HSS end mills having 4 in. flute lengths is shown in Figure 107, page 110. The M42 HSS tools were far superior to the M2 HSS tools. For example, at a cutting speed of 150 feet/minute and a feed of .002 in./tooth, the tool life with the M42 HSS tools was 304 inches of work travel as compared to 32 inches of work travel with the M2 HSS tools.

Note in Figure 108, page 110, the effect of depth of cut on tool life with the 4 in. flute length end mills. At a cutting speed of 150 feet/minute, the tool life decreased from 304 to 132 inches of work travel when the depth of cut was increased from .060 to .125 in.

Using longer end mills, 6 in. flute length, cutter life decreased even more rapidly with the increased depth of cut. As a matter of fact, as shown in Figure 109, page 111, the cutter life with the 6 in. flute length cutter was only 15 inches of work travel, even at speeds as low as 100 feet/minute. However, decreasing the depth of cut to .030 in. resulted in a tool life of 128 inches at a cutting speed of 150 feet/minute.

In order to increase the tool life even more with the 6 in. flute length cutter, it was necessary to also decrease the width of cut to .250 in. Note in Figure 110, page 111, that at a cutting speed of 100 feet/minute the tool life increased from 127 inches of work travel at a width of cut of .500 in. to 240 inches of work travel at a width of cut of .250 in.

A very interesting comparison is made in Figure 111, page 112, of the tool life curves for end mills with three different flute lengths. At a cutting speed of 200 feet/minute the cutter with the 2 in. flute length produced a tool life of 310 inches of work travel, while the tool life with the cutter having a flute length of 4 in. was only 115 inches of work travel. In order to produce a tool life of even 50 inches of work travel with the 6 in. flute length cutter, the depth of cut had to be reduced from .125 in. to .030 in.

As shown in the previous paragraphs tool life decreases appreciably as the length of the flute of the end mill is increased. Also, cutter deflection is a more serious problem with the longer end mills. As a result, dimensional accuracy suffers. Note in Figure 112, page 112, how the deflection of the cutter having a 4 in. flute length increased as

Peripheral End Milling (331 BHN) (Continued)

tool wear developed. The tool deflection increased to .0[illegible] in. when the tool wear was .020 in.

The curves shown in Figure 113, page 113, relate the cutter deflection for tool wear at a width of cut of .250 in. for a cutter having a flute length of 6 in. Note in this case that at a tool wear of .020 the deflection was .030 in. for both depths of cut, .030 and .060 in. It should be noted that with this cutter the width of cut was only .250 in.

The results shown in Figure 114, page 113, indicate that the deflection of the 6 in. flute length cutter was appreciably less at a width of cut of .500 in. as compared to a width of cut of .250 in. Note that at a tool wear of .020 in., the deflection was .059 in., while at a width of cut of .500 in. the deflection was only .014 in. It appeared that at the lighter width of cut the cutter tended to bend more than with the heavier width of cut.

The relationships between cutter deflection and tool wear are shown in Figure 115, page 114, for three different cutting speeds. Note that the deflection was least for the highest speed. However, the tool life was also less and the cutter wear pattern was different for each of the three different cutting speeds.

End Mill Slotting (331 BHN)

As shown in Figure 116, page 114, the M42 HSS end mill performed appreciably better than the M2 HSS end mill in slotting the titanium alloy. The cutting speeds were about 18 percent greater with the M42 HSS cutter. Also, decreasing the depth of cut to .125 in. permitted an increase in cutting speed of slightly less than 15 percent see Figure 117, page 115. These results indicate, however, that a higher rate of metal removal is obtained by using a depth of cut of .250 in. at the lower cutting speed instead of using the lighter depth of cut at the higher cutting speed.

It was found in the case of end mill slotting that the lighter feeds provide appreciably longer tool life than the heavier feeds. For example, as shown in Figure 118, page 115, the cutter life was 150 inches of work travel at a feed of .002 in./tooth as compared to 2[illegible]5 at a feed of .001 in./tooth at a cutting speed of 115 feet/minute

4.1 Titanium 6Al-4V, Beta Forged (continued)

Drilling (331 BHN)

A comparison is shown in Figure 119, page 116, of three different grades of HSS tools in drilling Titanium 6Al-4V, beta forged, at 331 BHN. Note that for a tool life of 250 holes the cutting speeds for the various HSS tools were as follows:

M1:	31 feet/minute
M42:	40 feet/minute
T15:	46 feet/minute

Thus, the T15 HSS tool permitted a 50 percent higher cutting speed over that used with the M1 HSS tool and a 15 percent higher cutting speed than that with the M42 HSS tool.

The beta forged blocks used for the initial drilling tests were 4 in. by 6 in. by 1/2 in. thick. It has been the custom in these drilling tests to also use the 1/2 in. thick plates remaining from the milling tests for drill blocks. (The milling blocks, as beta forged, were 2 in. by 4 in. by 12 in. long.) When this is done, several tests are rerun on the mill blocks to make sure that they have the same machining characteristics as the drill blocks. As shown in Figure 120, page 116, the drill life on the mill blocks was much greater than on the drill blocks. At a tool life of 250 holes, the cutting speed on the drilling blocks was 40 feet/minute as compared to 46 feet/minute on the mill block. The difference is even more pronounced when a comparison is made on the tool life values obtained at a given cutting speed. For example, at a cutting speed of 45 feet/minute, the tool life on the drill blocks was 15 holes as compared to more than 250 holes on the mill blocks.

An examination of the photomicrographs of the drill and mill blocks shown in Figure 121, page 117, reveals a considerable difference in their microstructures. Hence, the machining characteristics of the two sets of blocks were different. The drill blocks, having been beta forged to a 1/2 in. thick section, had a much finer acicular structure than the mill blocks, which were machined from a 2 in. thick section.

Further tests on the mill blocks revealed that a phosphated oil was appreciably more effective in increasing tool life than a chemical emulsion. Note in Figure 122, page 118, that for a tool life of 250 holes the cutting speed with the chemical emulsion was 42-1/2 feet per minute as compared to 48 feet/minute with the phosphated oil. These results were obtained at a feed of .005 in./rev.

Drilling (331 BHN) (Continued)

At a lighter feed of .003 in./rev., the cutting speeds were somewhat higher. Under these conditions, the chemical emulsion provided the longer tool life. For example, as shown in Figure 123, page 118 at a tool life of 200 holes the cutting speed with the phosphated oil was 52-1/2 feet/minute and 60 feet/minute with the chemical emulsion.

Rigidity in machining of any titanium alloy is of utmost importance. This was again shown in drilling the beta forged Titanium 6Al-4V, see Figure 124, page 119. Here a comparison was made between jobbers length and screw machine length drills. Note that for a drill life of 175 holes the cutting speed with the jobbers length drill was 50 feet per minute as compared to 60 feet/minute (20 percent faster) with the screw machine length. The feed was .003 in./rev. If the feed had been higher, it is quite possible that the difference would have been even greater. The length of the drill is of particular importance in drilling titanium since the chisel edge tends to wear rapidly and, as a result, the thrust force increases considerably. The longer the drill, the greater the deflection of the drill. When the drill deflects, the titanium tends to smear over the margin of the drill resulting in oversize holes, poor finish and accelerated tool failure.

Reaming (331 BHN)

Results shown in Figure 125, page 119, were obtained with two different cutting fluids on the blocks that had been forged to a 1/2 in thickness (drill blocks). Note that the phosphated oil provided considerably longer reamer life than the chemical emulsion. The feed was .009 in./rev.

Note in Figure 126, page 120, that in the reaming operation the blocks forged to a thin section (1/2 in. thick) provided longer reamer life than the 1/2 in. thick sections machined from blocks forged to a 2 in. thickness. At a reamer life of 250 holes the cutting speed on the blocks forged to a 2 in. thickness was 65 feet/minute as compared to 77 feet/minute on the blocks forged to a 1/2 in. thickness. This was the reverse of that obtained in the drilling tests.

The feed is very critical when reaming the beta forged Titanium 6Al-4V. Note in Figure 127, page 120, that at a feed of .009 in./rev. the reamer life was 110 holes and that when the feed was increased to .015 in./rev., the reamer life decreased to five holes. Also on the mill blocks, by using a cutting oil containing sulfur instead of a

4.1 Titanium 6Al-4V, Beta Forged (continued)

Reaming (331 BHN) (continued)

phosphated oil, the reamer life increased from 110 holes to 230 holes at a cutting speed of 70 feet/minute, see Figure 128, page 121.

As shown in Figure 129, page 121, the cutter life with the four-fluted carbide-tipped reamer was not satisfactory. The M33 HSS reamer performed much better than the carbide-tipped reamer. Chipping occurred on the carbide reamers even though the feed was reduced to .005 in./rev.

An M2 HSS reamer provided longer tool life than the M33 HSS reamer. For example, in Figure 130, page 122, at a cutting speed of 80 feet per minute, the reamer life was 150 holes with the M2 HSS reamer as compared to 60 holes with the M33 HSS reamer.

Tapping (331 BHN)

A comparison with several types of cutting fluids is presented in Figure 131, page 122, using a two-flute spiral point tap. The chlorinated oil was used for comparison purposes only since it is not permitted to be used in machining titanium alloys. The oil containing a phosphate and the one containing sulfur performed similarly, but appreciably poorer than the chlorinated oil. Using a three-flute tap, the oil containing sulfur was far more effective, see Figure 132, page 123.

A comparison of various types of taps is presented in Figures 133, 134 and 135, pages 123 and 124. The three-flute taps were always the best of the group. Also chrome-cladding the three-flute taps resulted in increasing tap life from 58 to 250 holes at a cutting speed of 15 feet/minute, see Figure 135, page 124.

TABLE VIII

RECOMMENDED CONDITIONS FOR MACHINING TITANIUM 6Al-4V BETA FORGED 331 BHN

Nominal Chemical Composition, Percent

Ti	Al	V	C
Bal.	6.0	4.0	.05

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Turning	M42 HSS	BR: 0° SCEA:15° SR:10° ECEA:5° Relief: 5° NR: .030"	5/8" Square Tool Bit	.062	-	.010 in/rev	55	72 min.	.060	Phosphated Oil
Turning	C-2 Carbide	BR:-5° SCEA:15° SR:-5° ECEA:15° Relief: 5° NR: .030"	SNG 432 Insert	.062	-	.010 in/rev	150	43 min.	.015	Phosphated Oil
Face Milling	M42 HSS	AR: 5° ECEA:1° RR: 5° CA: 45° Clearance: 10°	4" Diameter 14 Tooth Face Mill	.060	2	.003 in/tooth	70	1260" work travel	.060	Soluble Oil (1:20)
Face Milling	C-2 Carbide	AR:-5° ECEA:45° RR:-5° CA:45° Clearance: 5°	4" Diameter 6 Tooth Face Mill	.060	2	.005 in/tooth	220	625" work travel	.060	Phosphated Oil (1:20)
Peripheral End Milling	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45°x.060"	1" Diameter 4 Flute HSS End Mill	.250	.500	.004 in/tooth	150	120" work travel	.012	Soluble Oil (1:20)
End Mill Slotting	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45°x.060"	3/4" Diameter 4 Flute HSS End Mill	.125	.750	.002 in/tooth	115	240" work travel	.012	Soluble Oil (1:20)

TABLE VIII (continued)

RECOMMENDED CONDITIONS FOR MACHINING TITANIUM 6Al-4V BETA FORGED 331 BHN

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min.	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Drilling	T15 HSS	118° Crankshaft Point Helix Angle: 29° Clearance: 7°	1/4" Diameter HSS Drill 2-1/2" Long	.500 thru	--	.005 in/rev	45	300 holes	.008	Phosphated Oil
Reaming	M33 HSS	Helix Angle: 0° CA: 45° Clearance: 7°	.272" Diameter 6 Flute Chucking Reamer	.500 thru	--	.009 in/rev	75	300 holes	.005	Phosphated Oil
Tapping	M1 HSS Chrome Plated	3 Flute Plug Spiral Point 75% Thread	5/16-24 NF Tap	.500 thru	--	--	15	250 holes	Under Size Thread	Sulfurized Oil

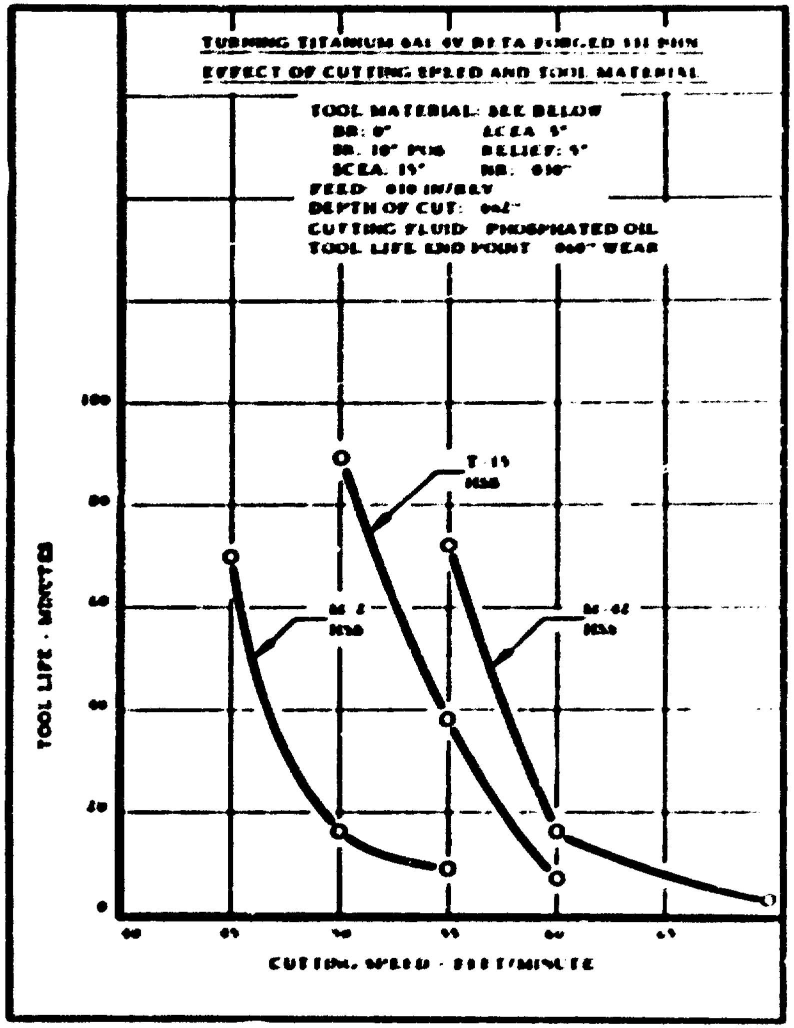


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Figure [illegible]

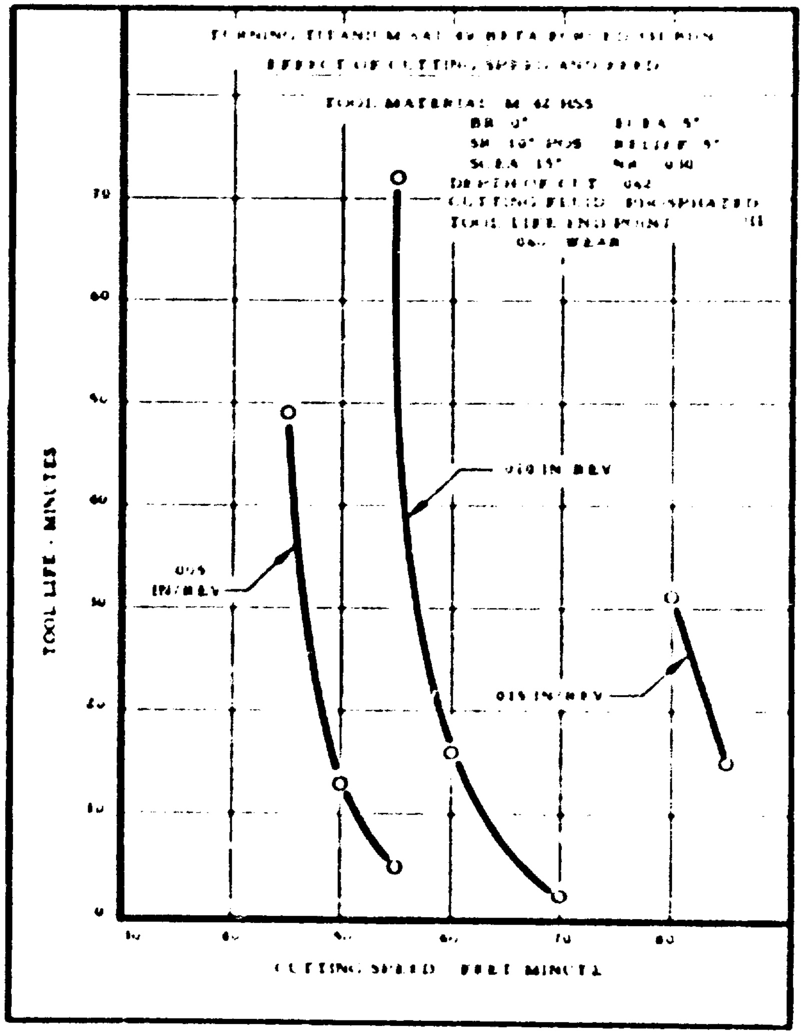

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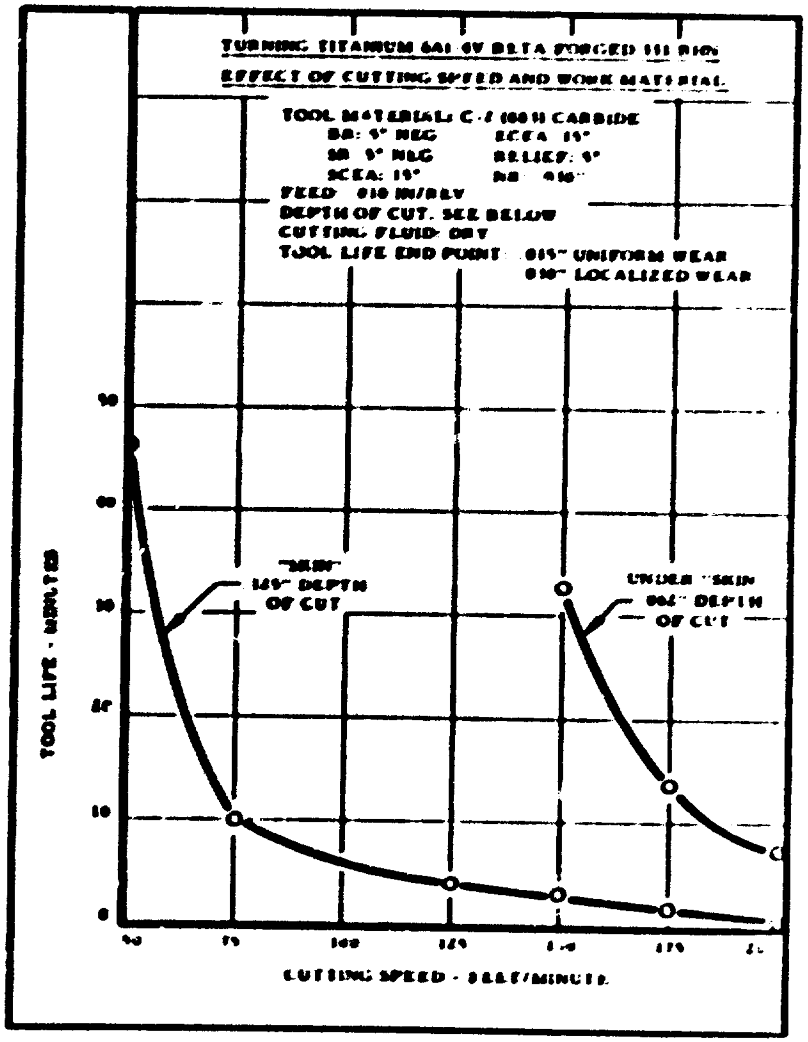
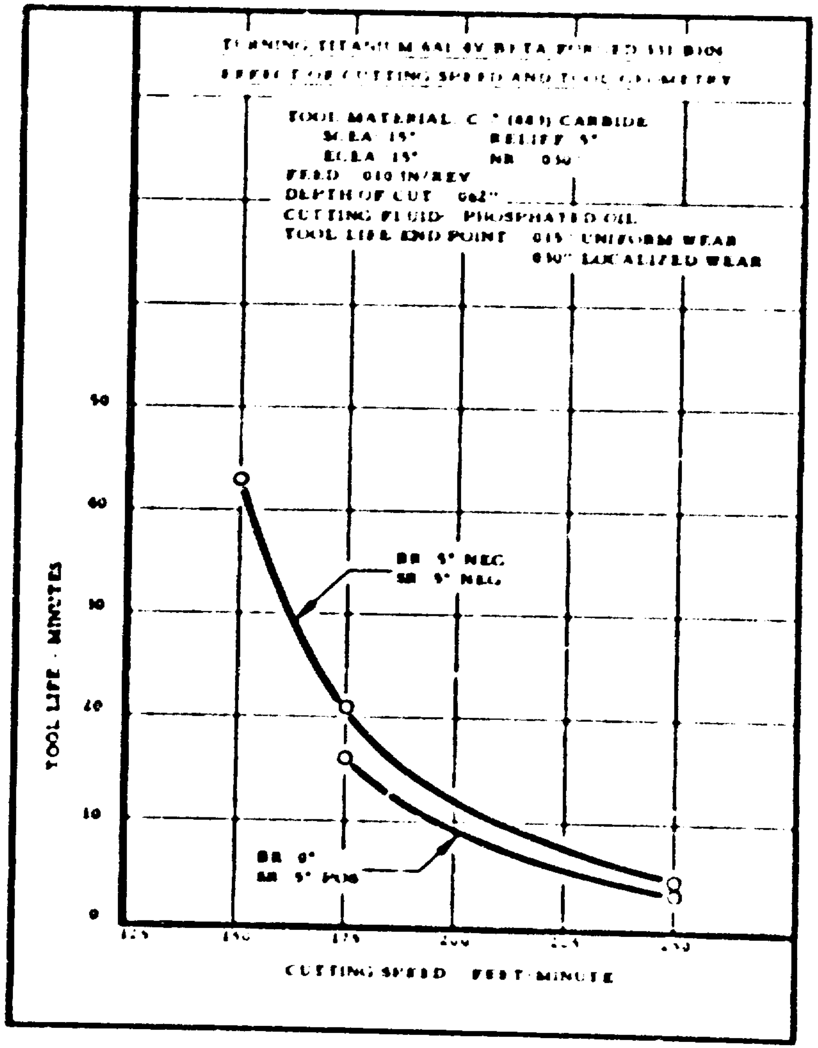
Figure [illegible]


TURNING TITANIUM 6AL-4V BETA FORGED 331 BHN

EFFECT OF CUTTING SPEED AND WORK MATERIAL

See text, page 90

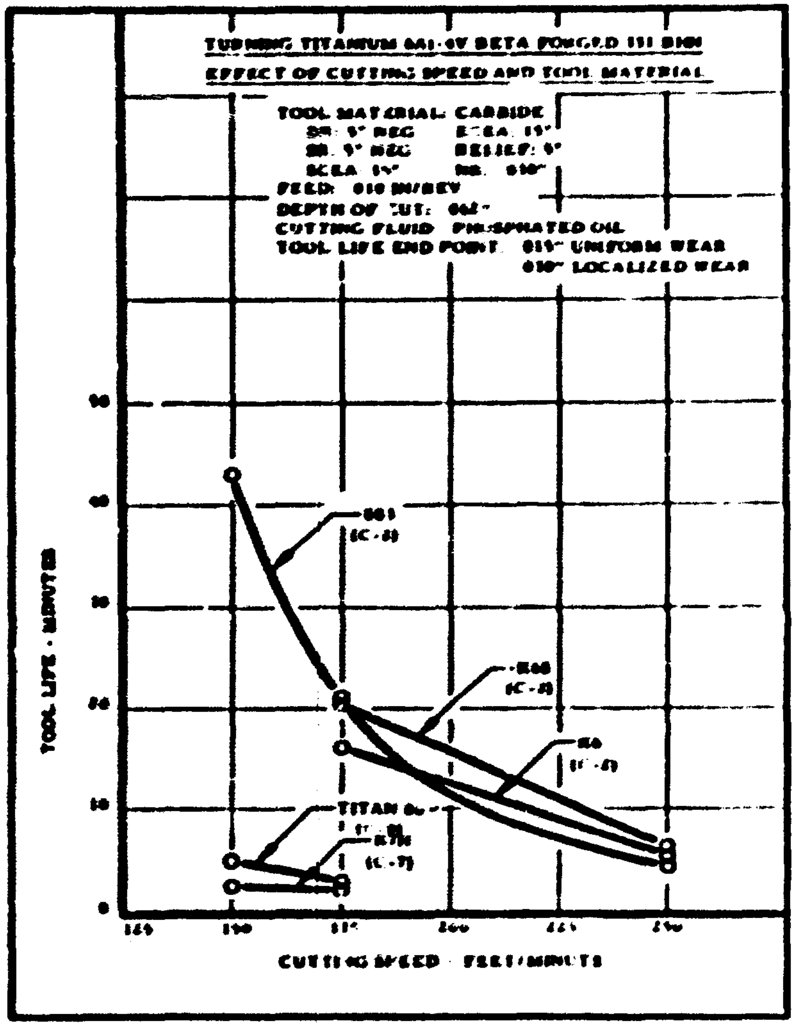
Figure [illegible]


TURNING TITANIUM 6AL-4V BETA FORGED 331 BHN

EFFECT OF CUTTING SPEED AND TOOL GEOMETRY

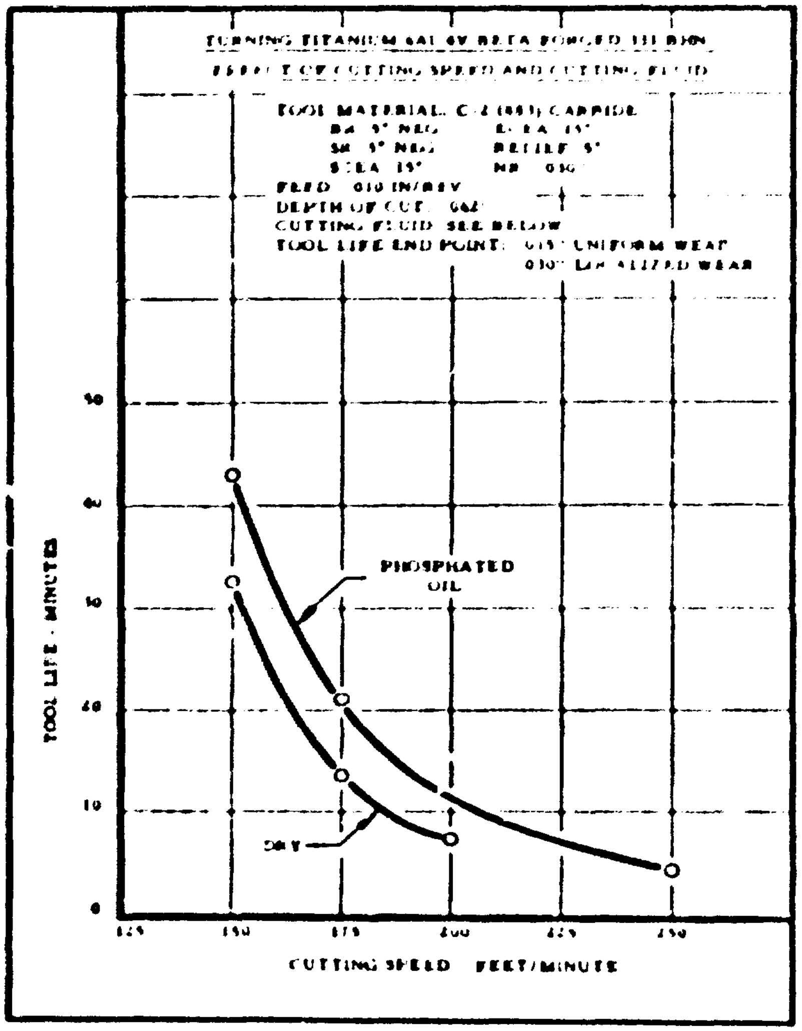
See text, page 90

Figure [illegible]



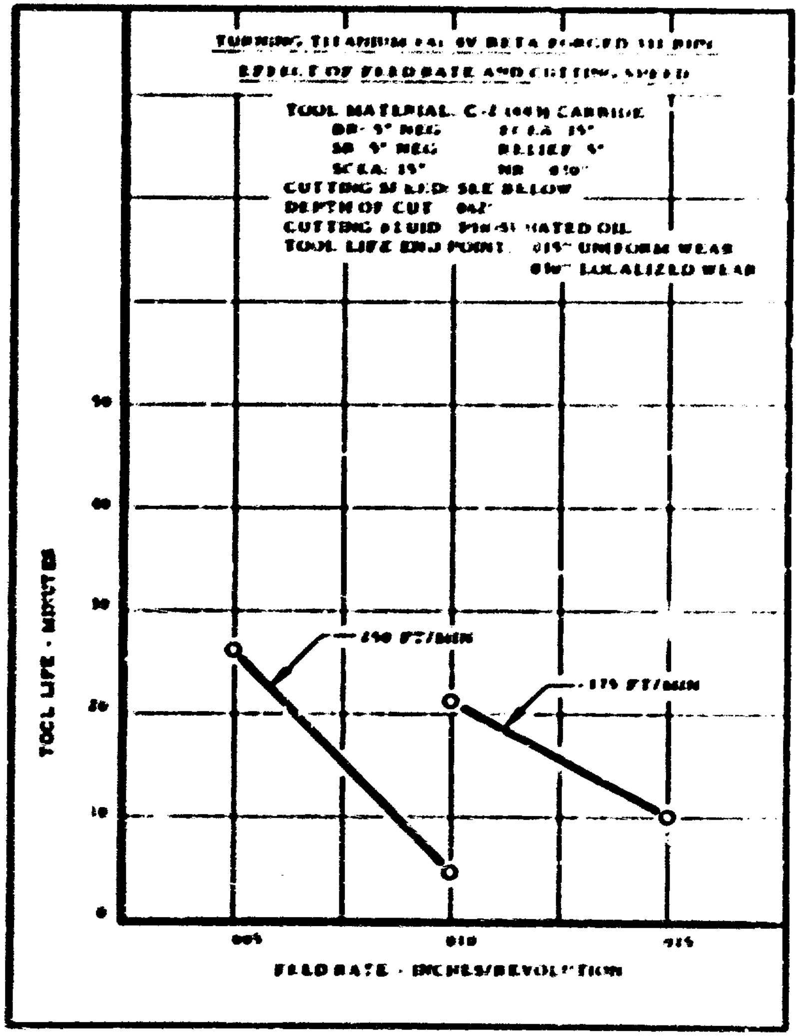
See text, page 40

Figure 41



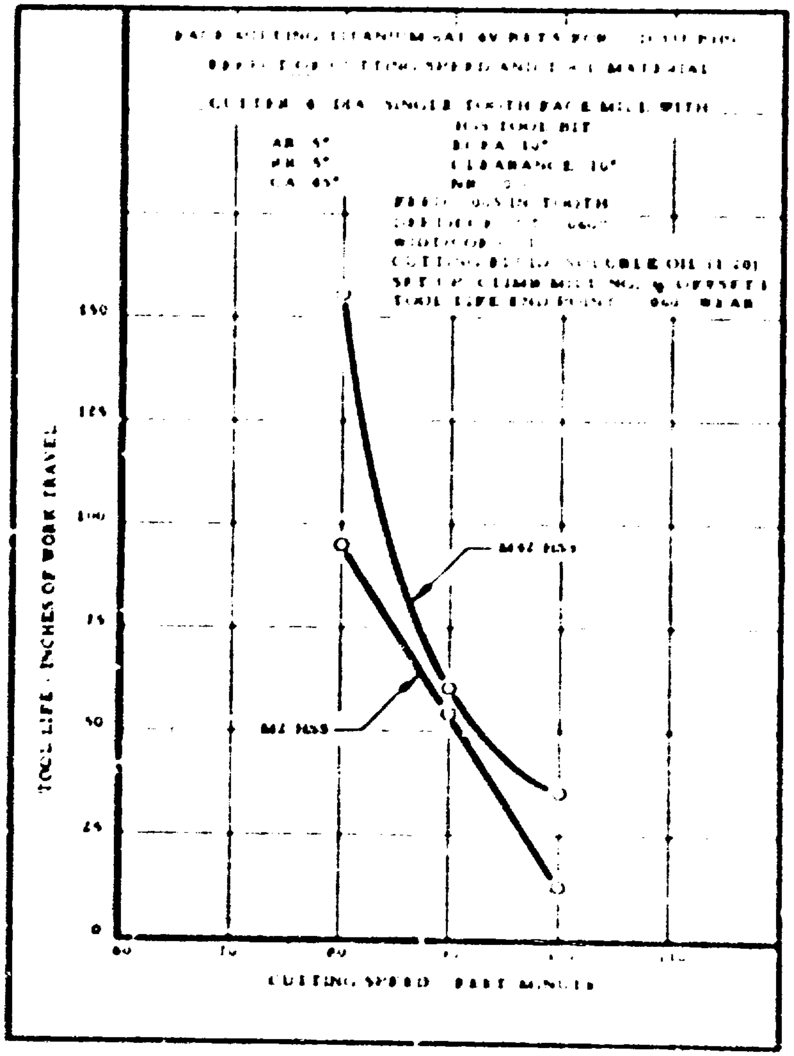
See text, page 41

Figure 42



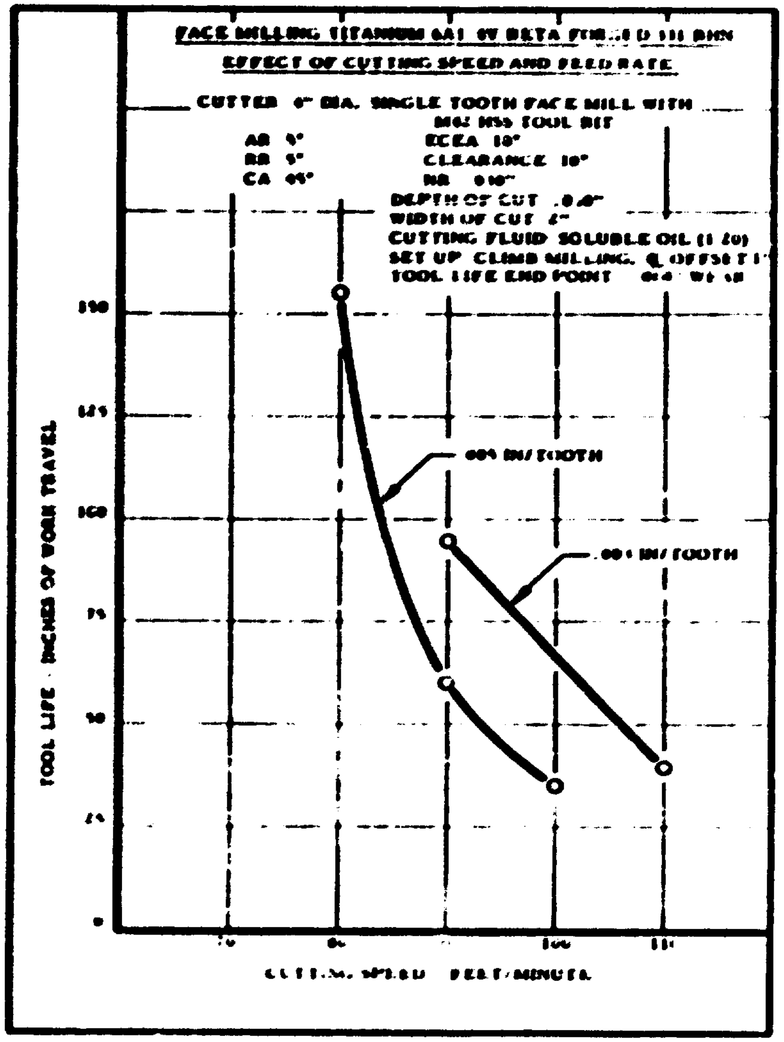
See text, page 40

Figure 41



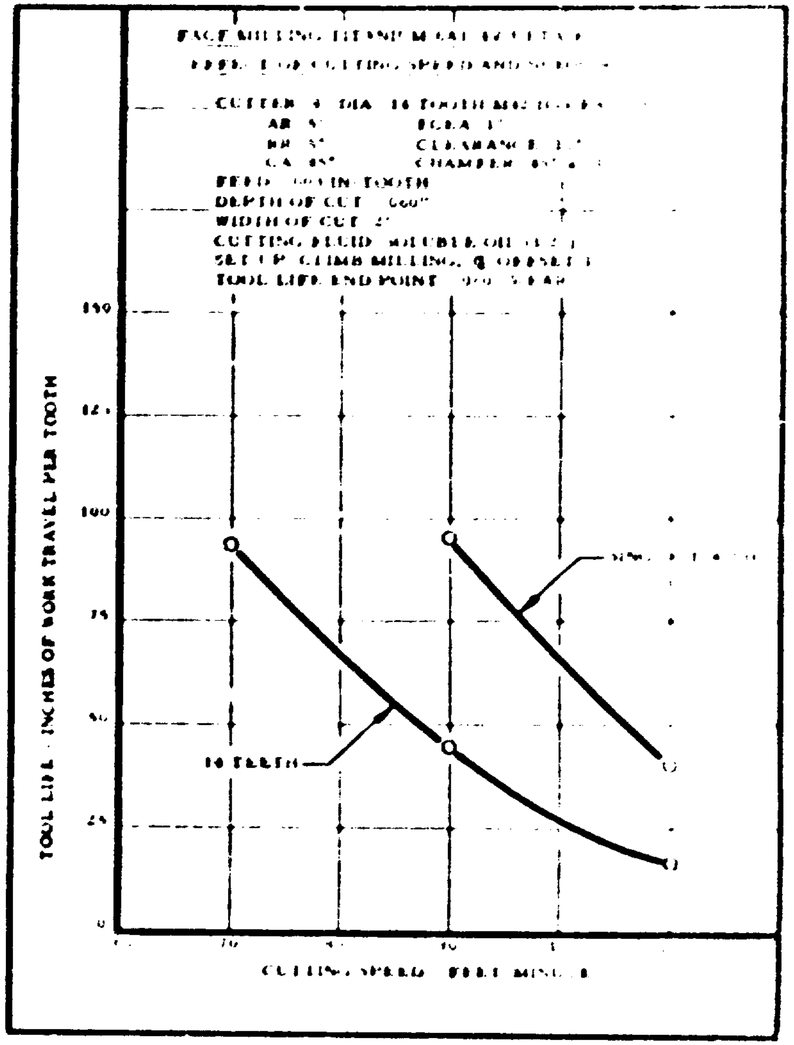
See text, page 41

Figure 42



See text, page 41

Figure 49



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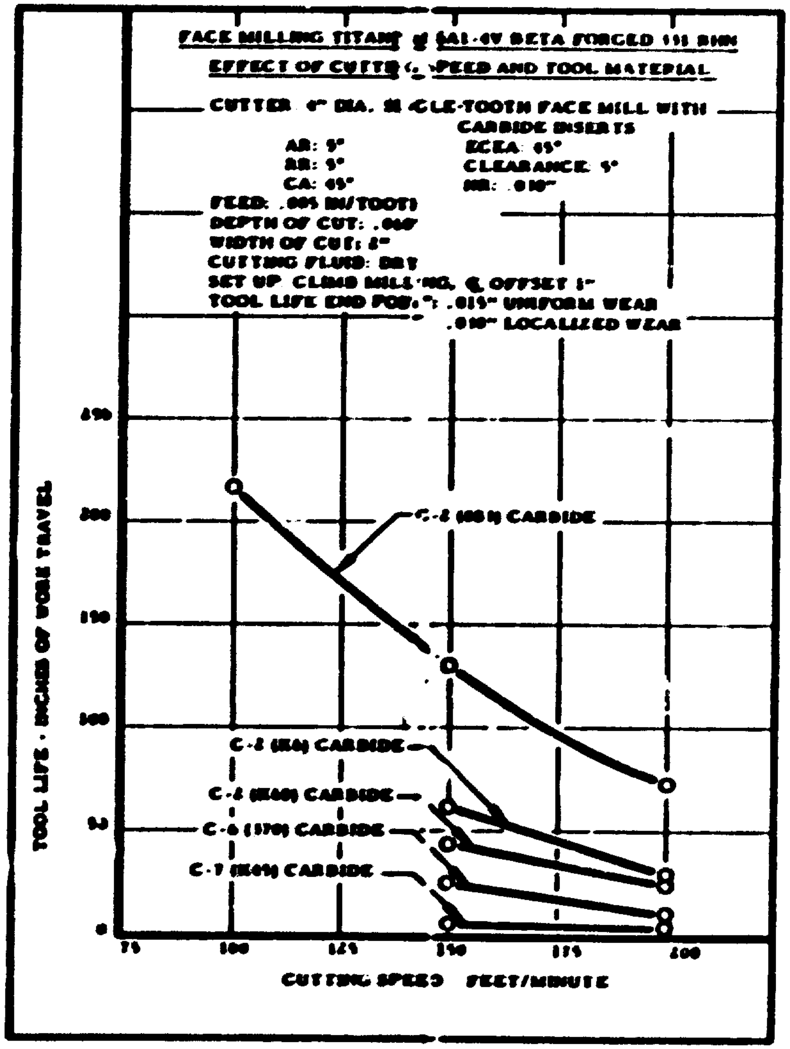
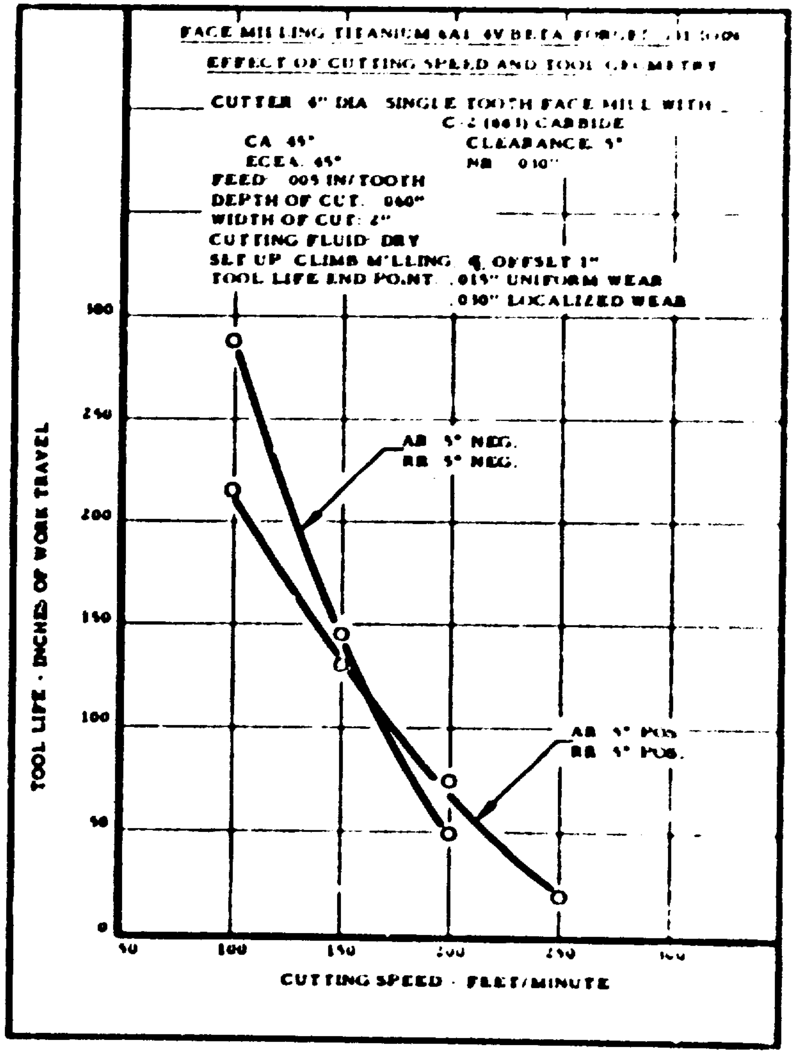


See text, page 91

Figure 47



See text, page 91

Figure 48

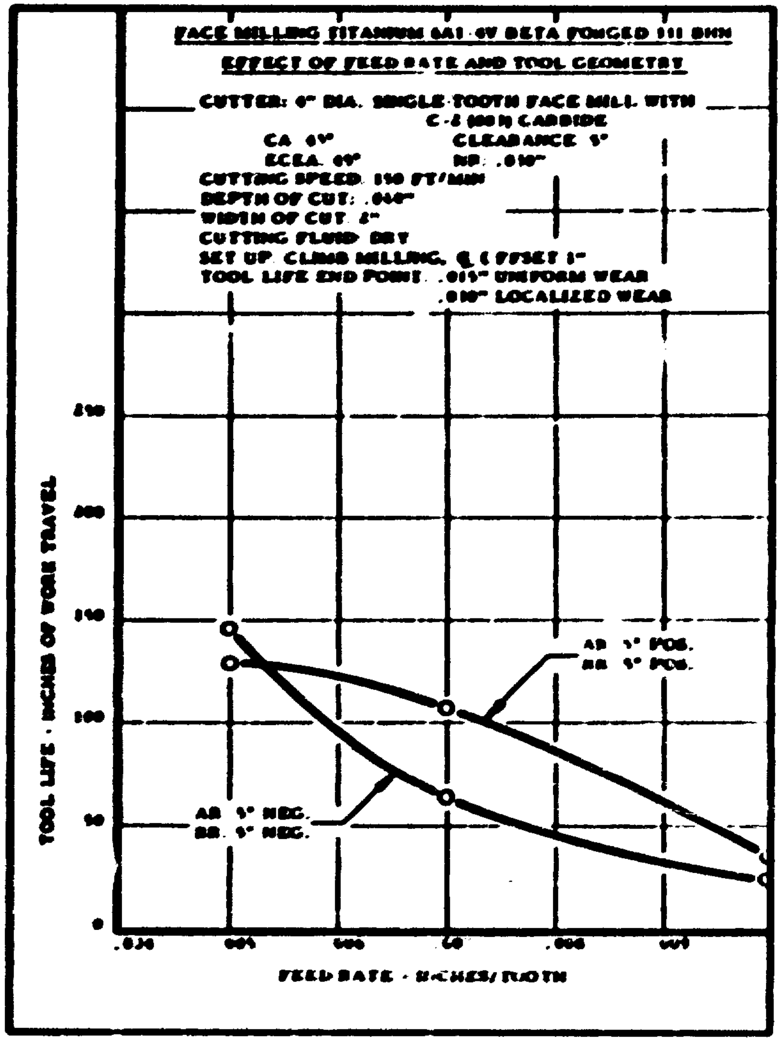


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Figure 44

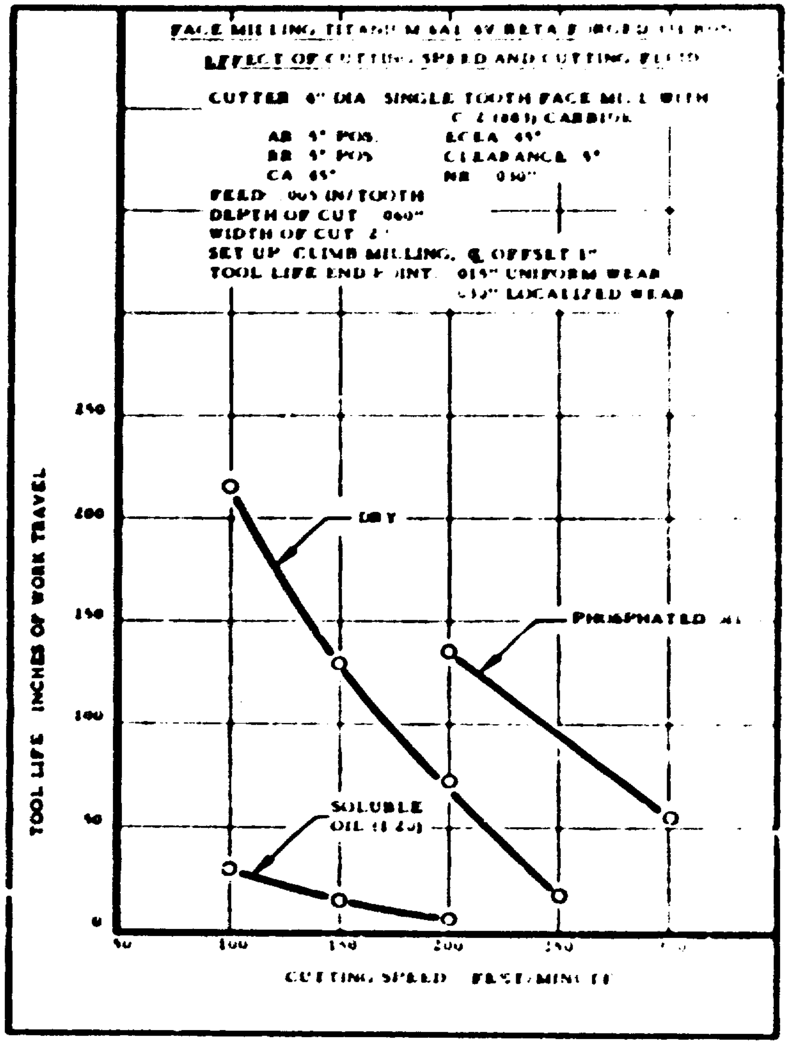

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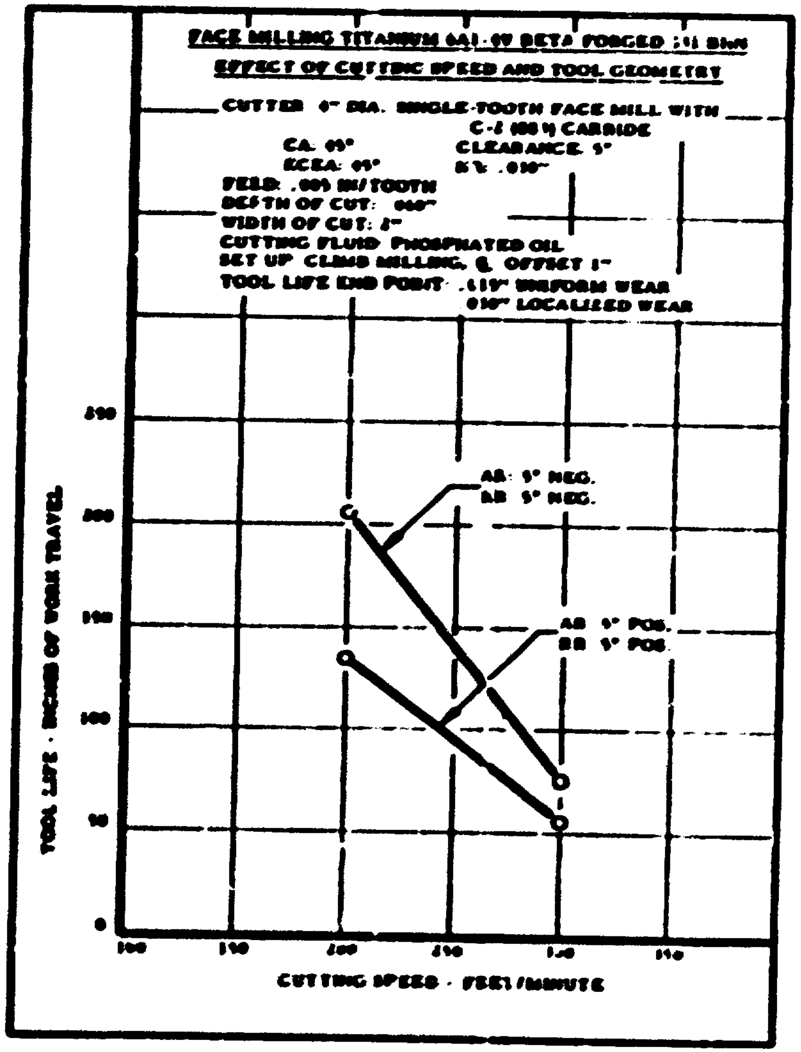
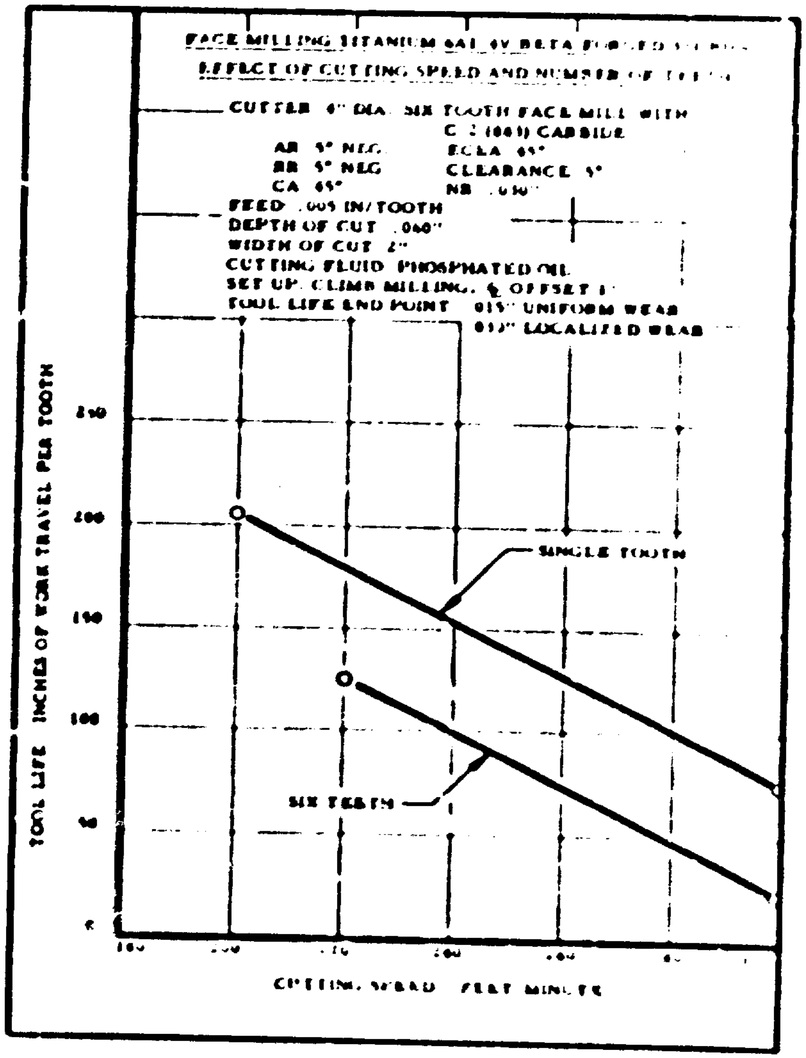
Figure [illegible]



See text, page 92

Figure 111



See text, page 92

Figure 112

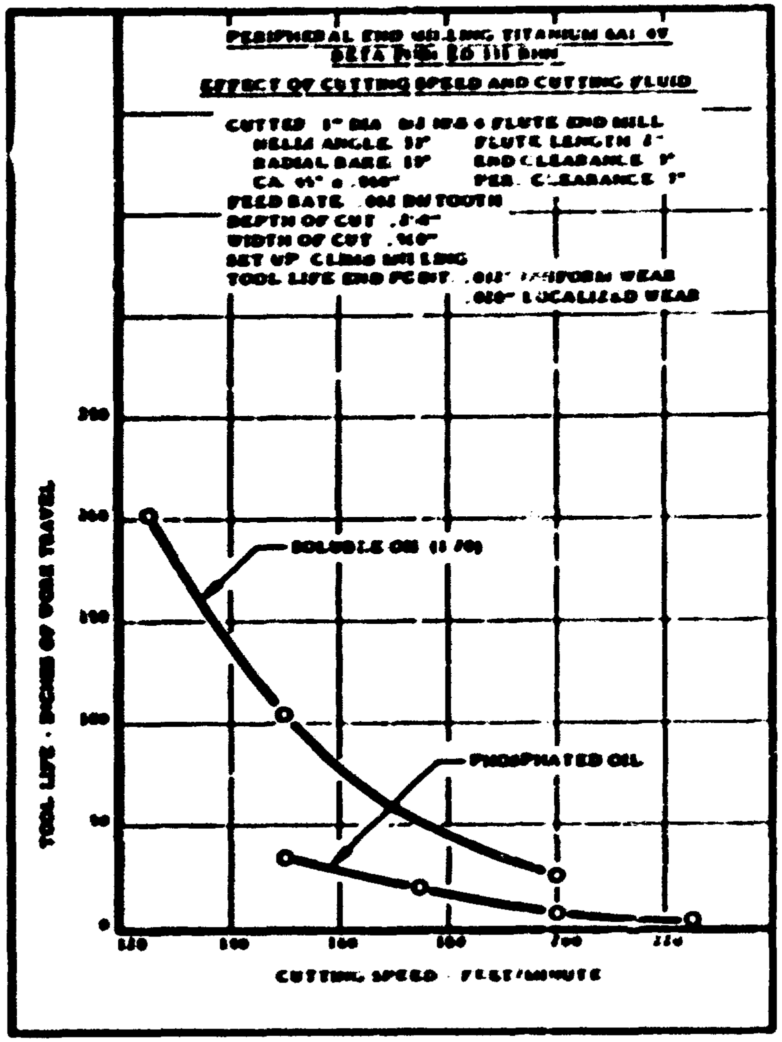


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Figure [illegible]

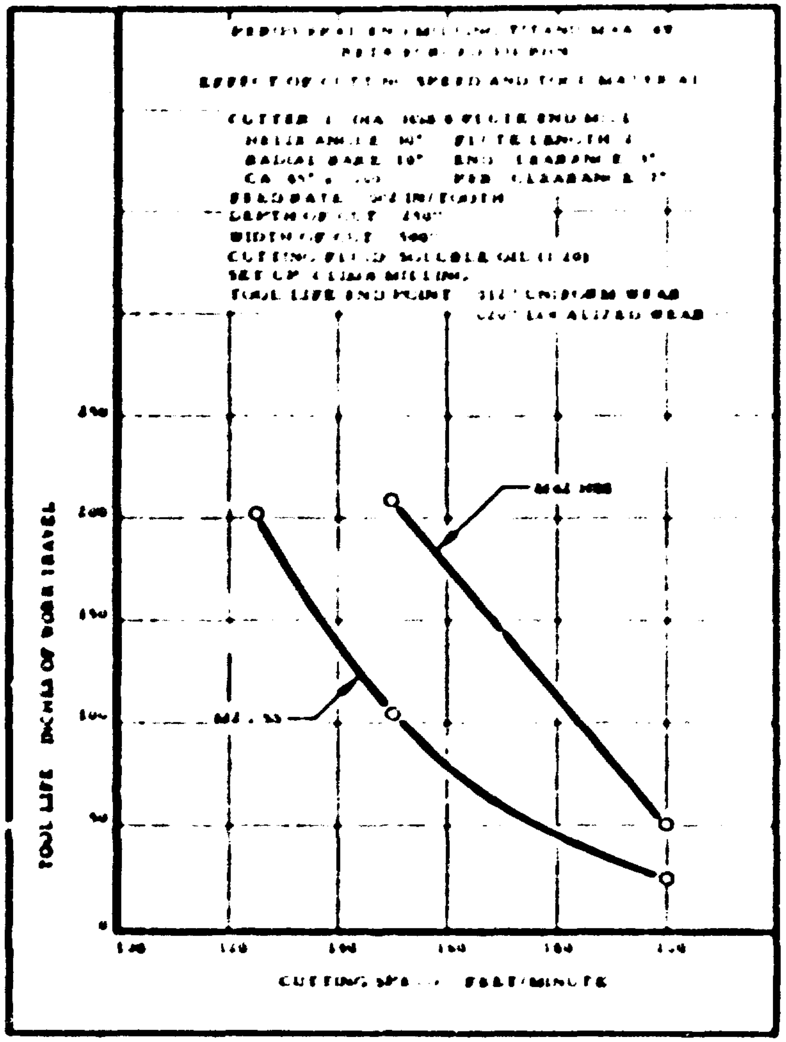

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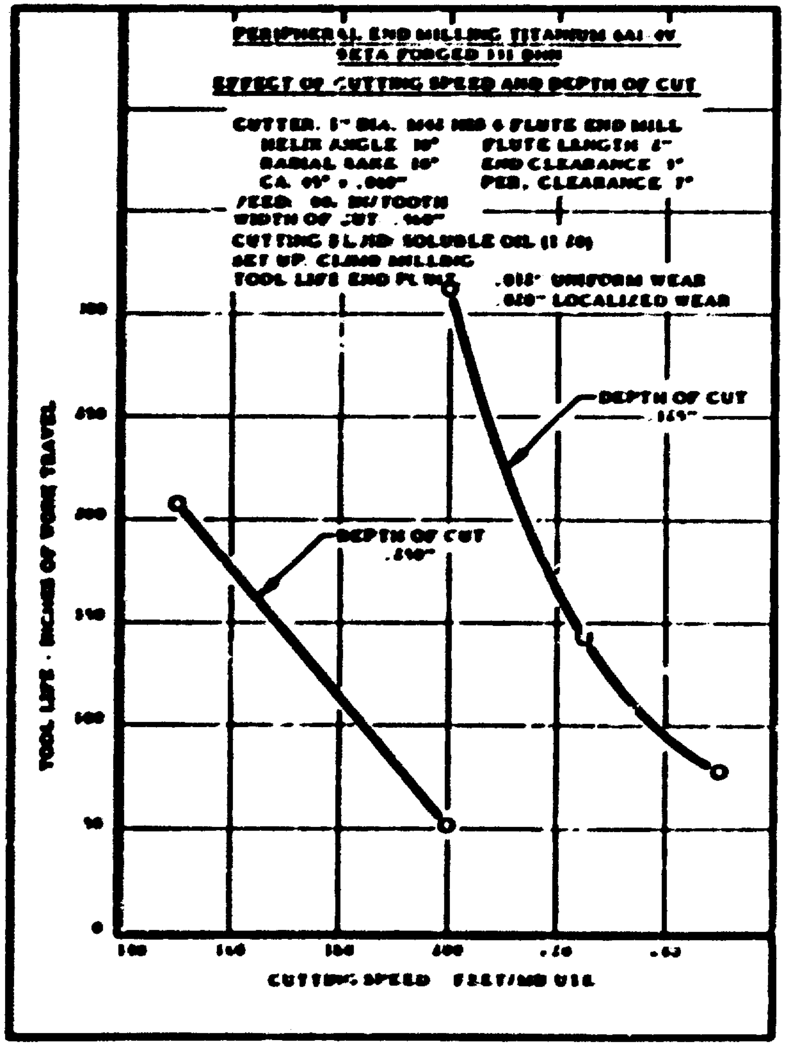
Figure [illegible]



See text, page 42

Figure 105

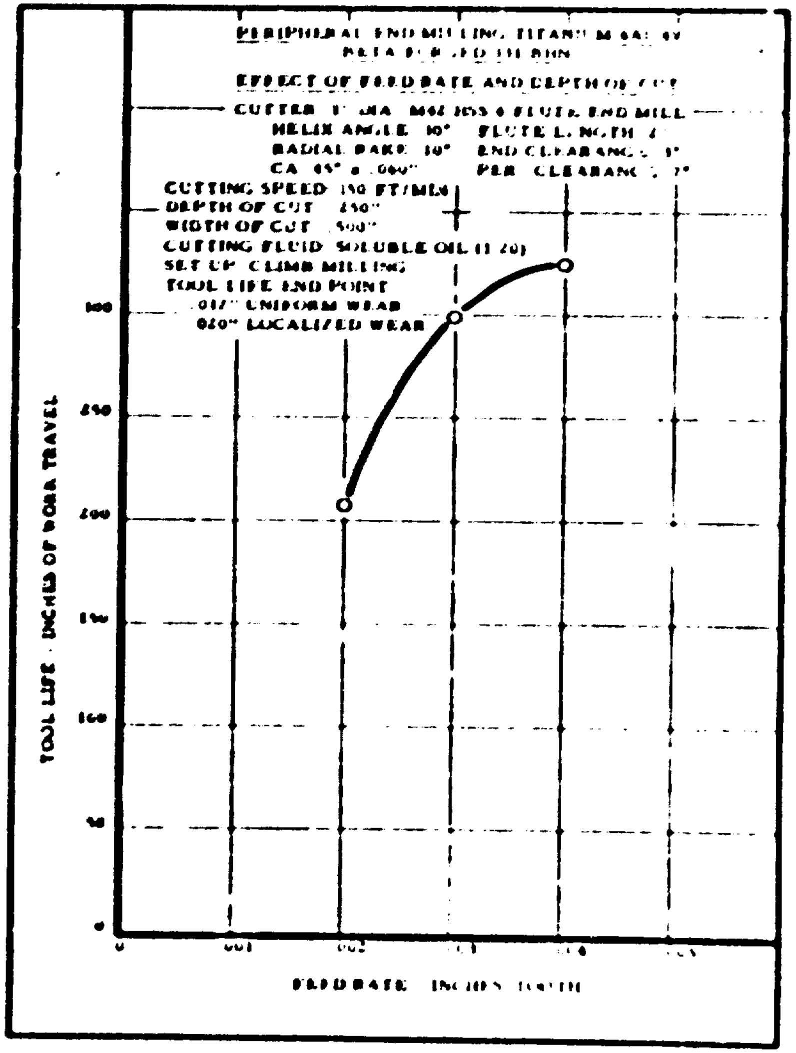


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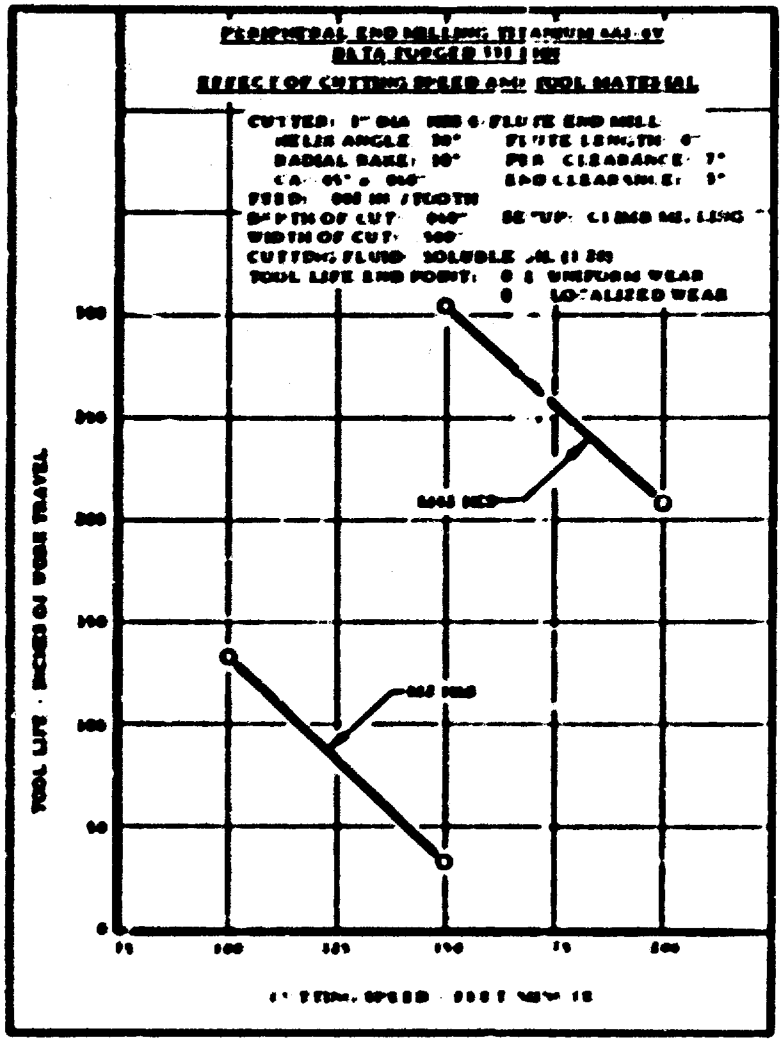
Figure [illegible]



See text, page 41

Figure 137

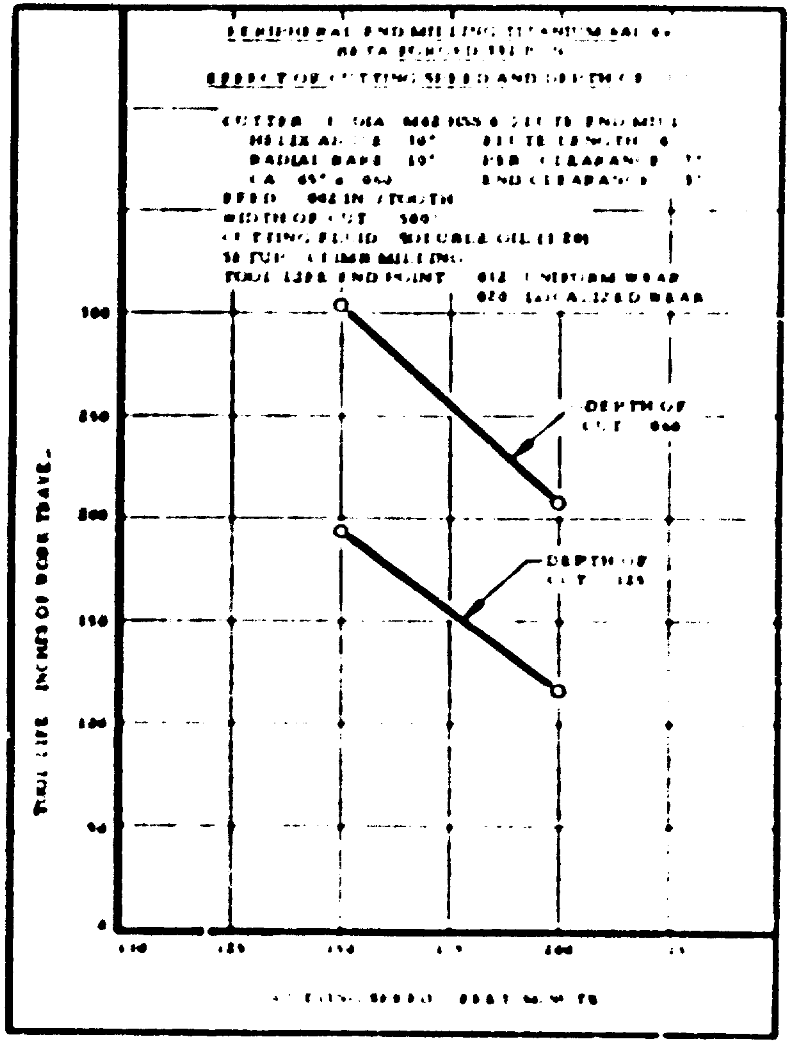


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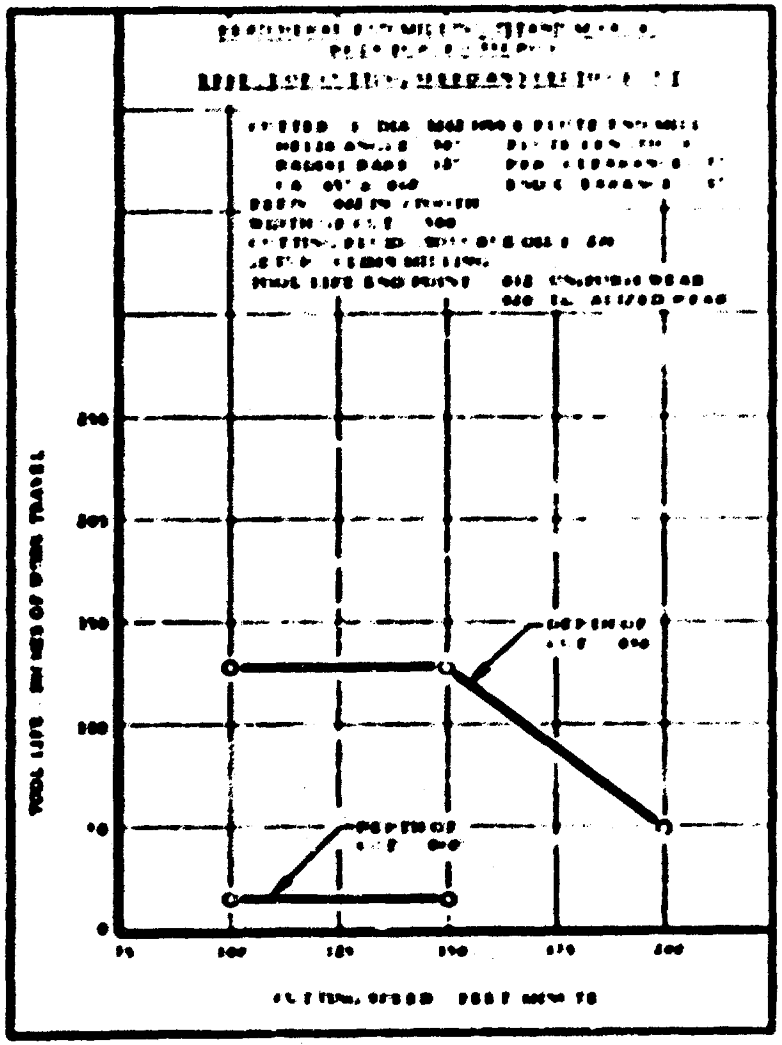
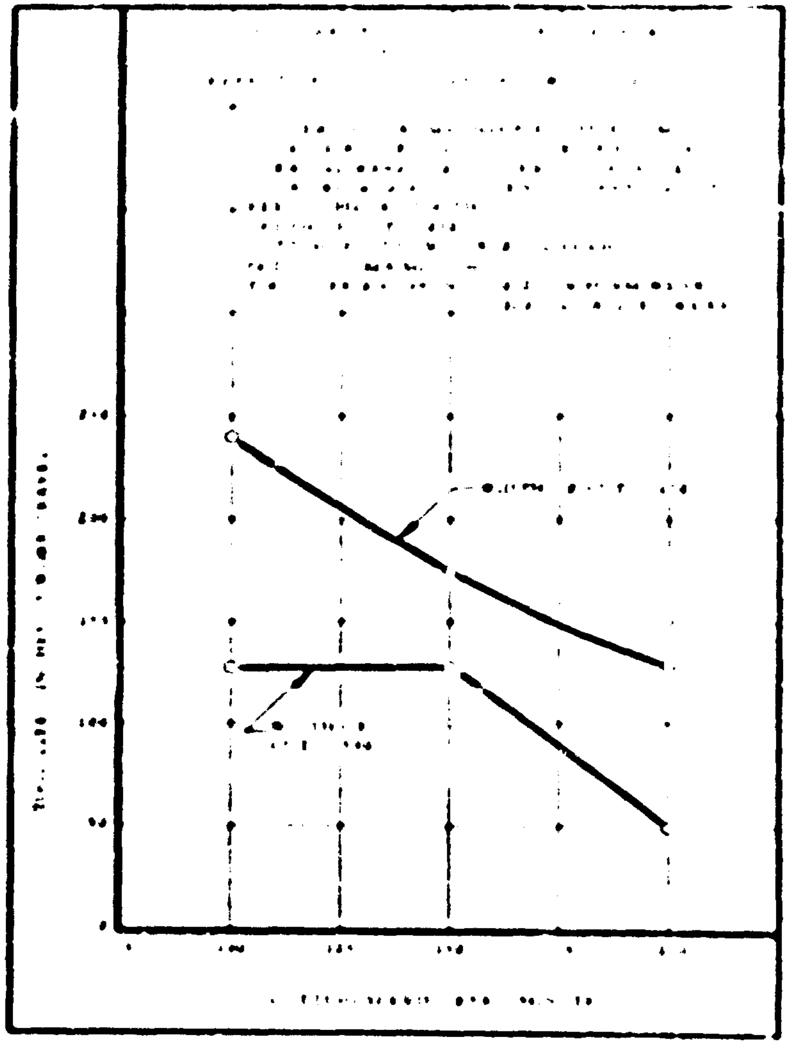
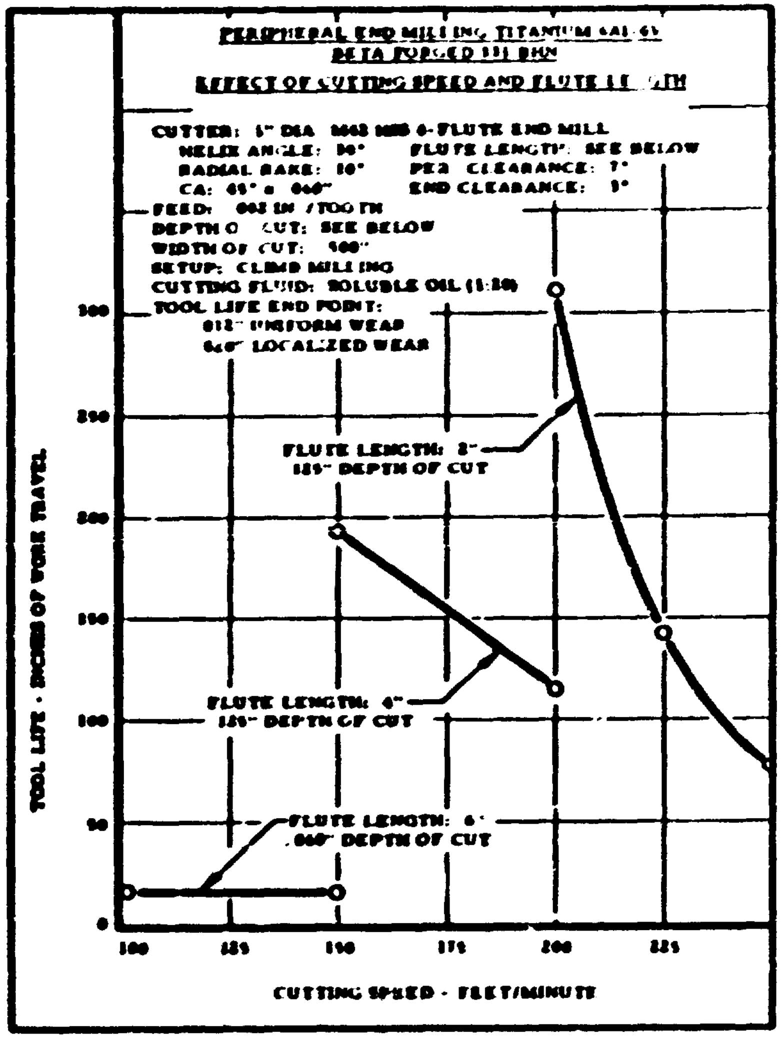
Figure [illegible]

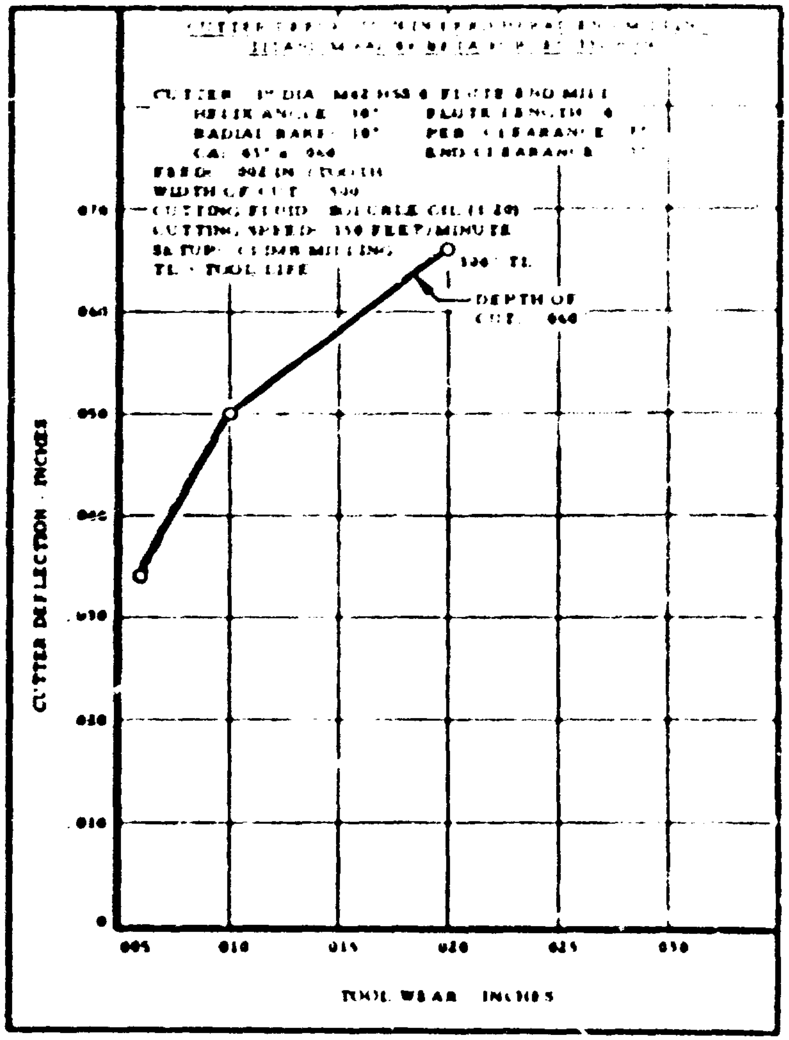

TOOL LIFE - INCHES OF WORK TRAVEL
0
50
100
150
200
250
75
100
125
150
175
200
CUTTING SPEED - FEET/MINUTE





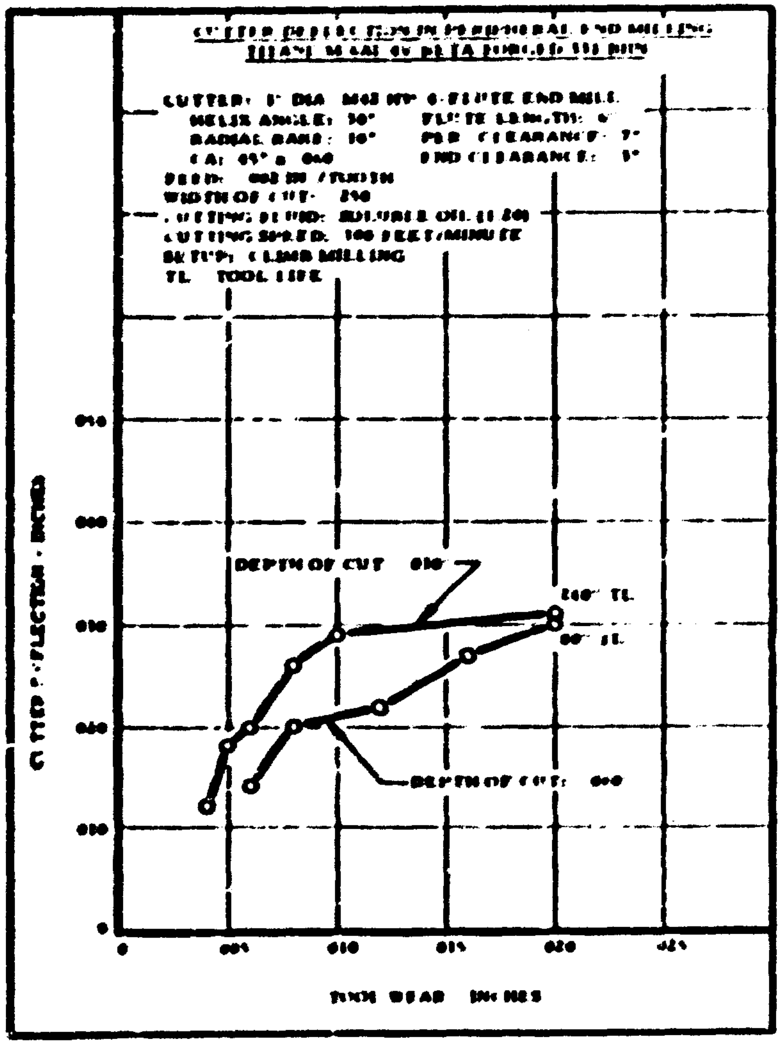
See text, page 41

Figure 111



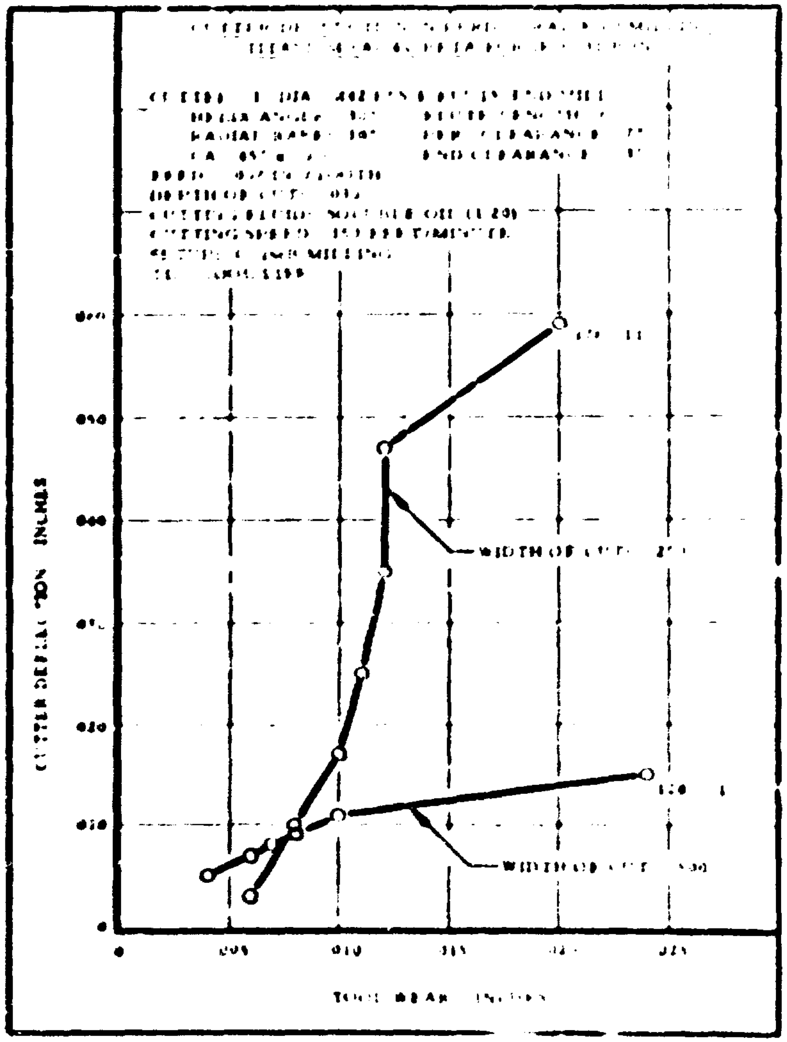
See text, page 41

Figure 112



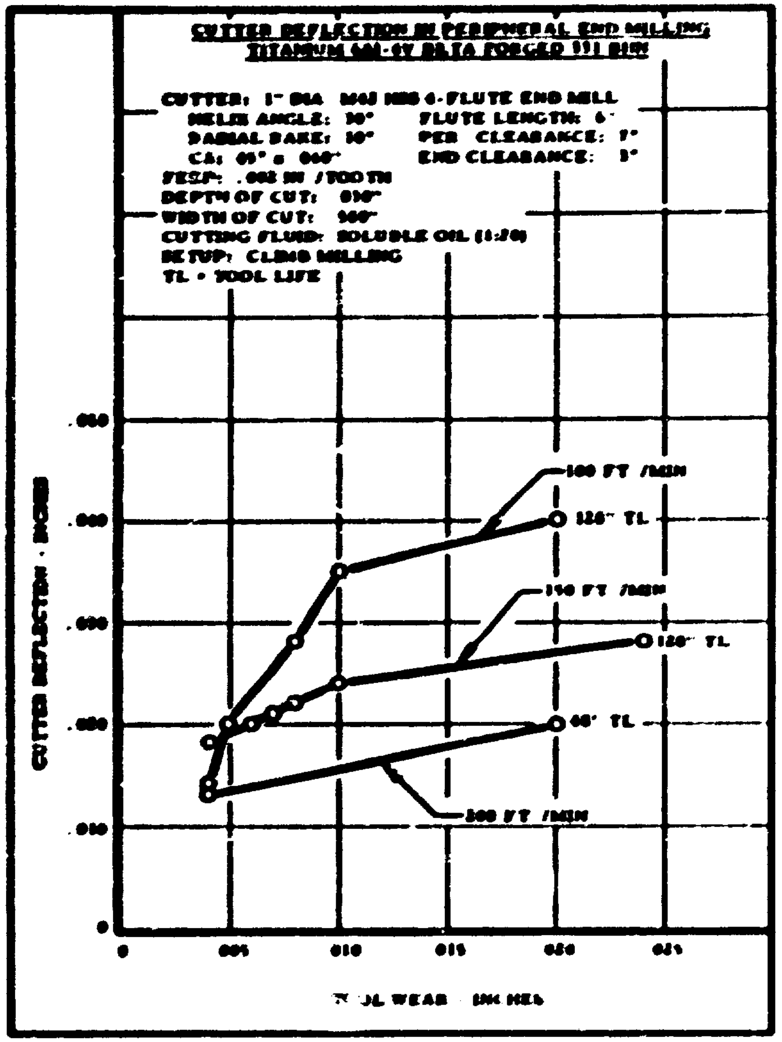
See text, page 74

Figure 111



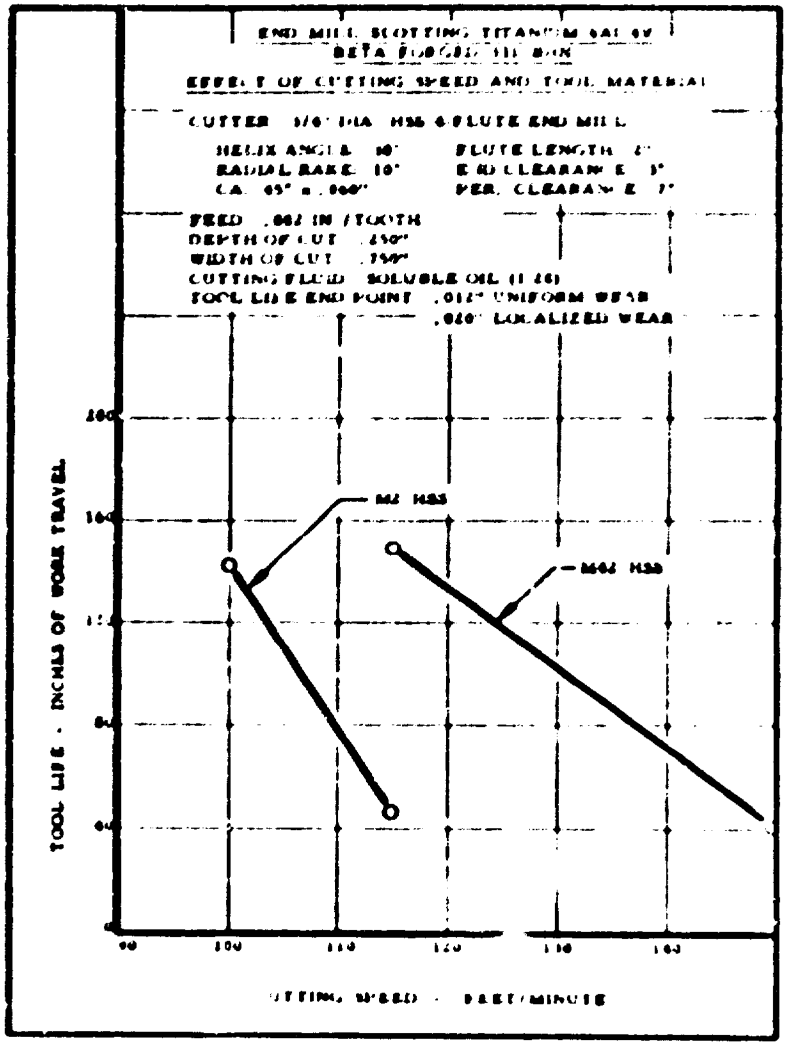
See text, page 74

Figure [illegible]



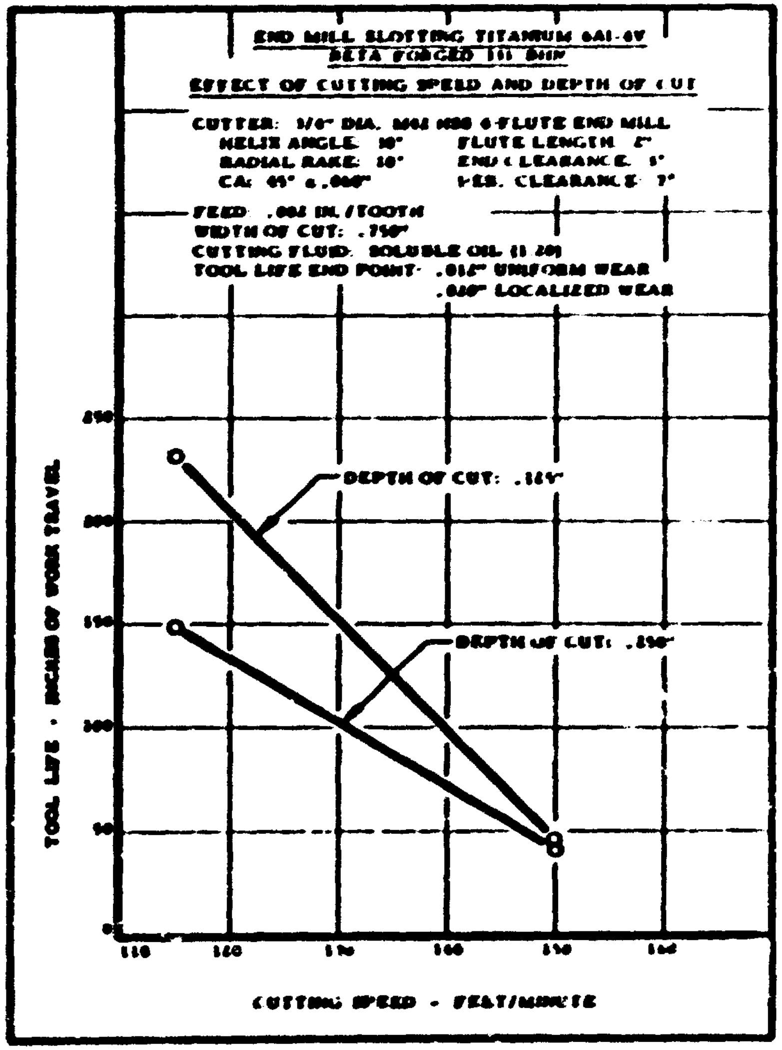
See text, page 96

Figure 114



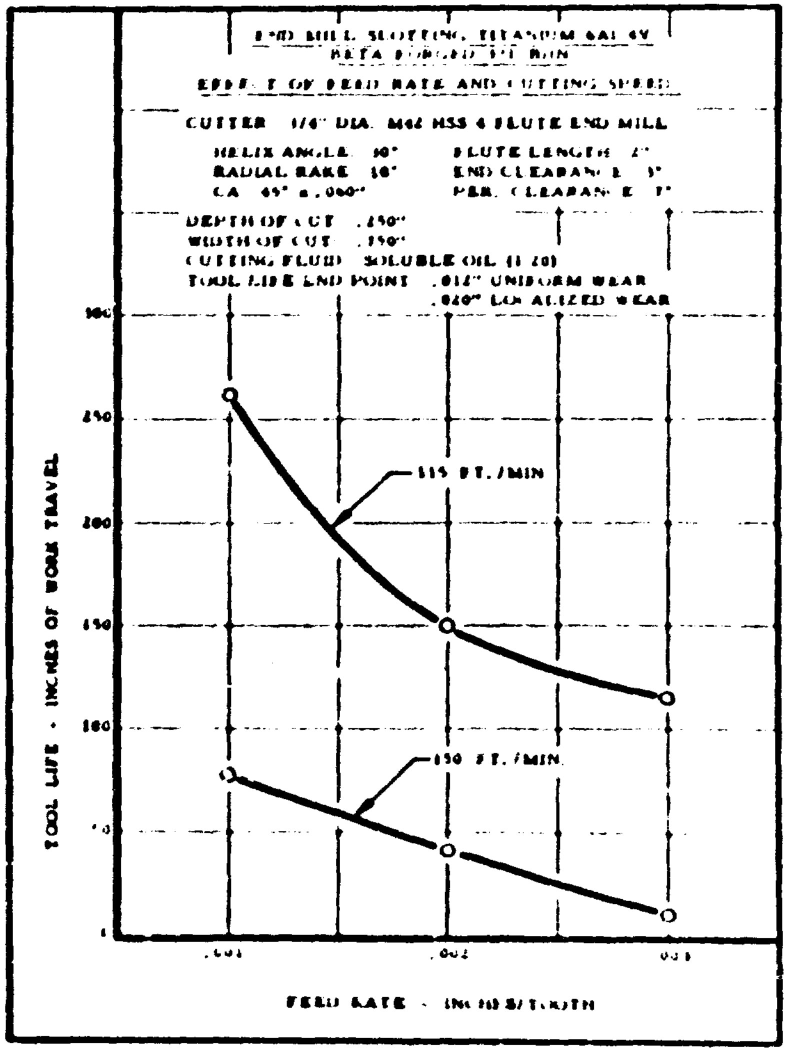
See text, page 96

Figure 115



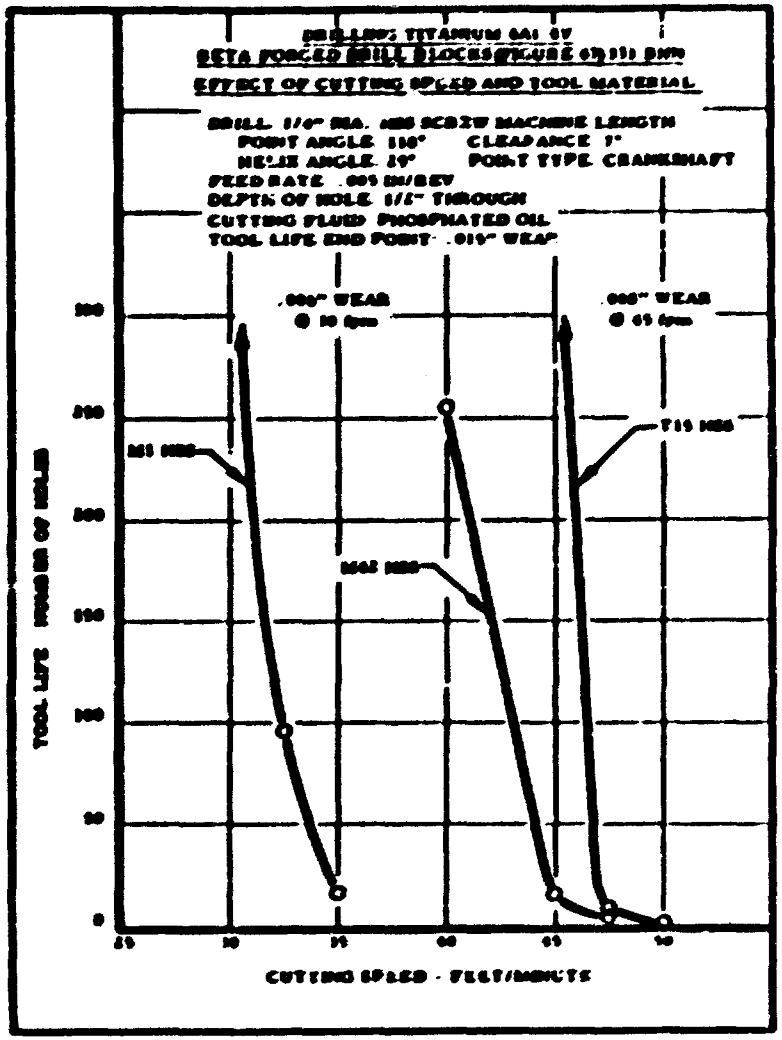
See text, page 96

Figure 117



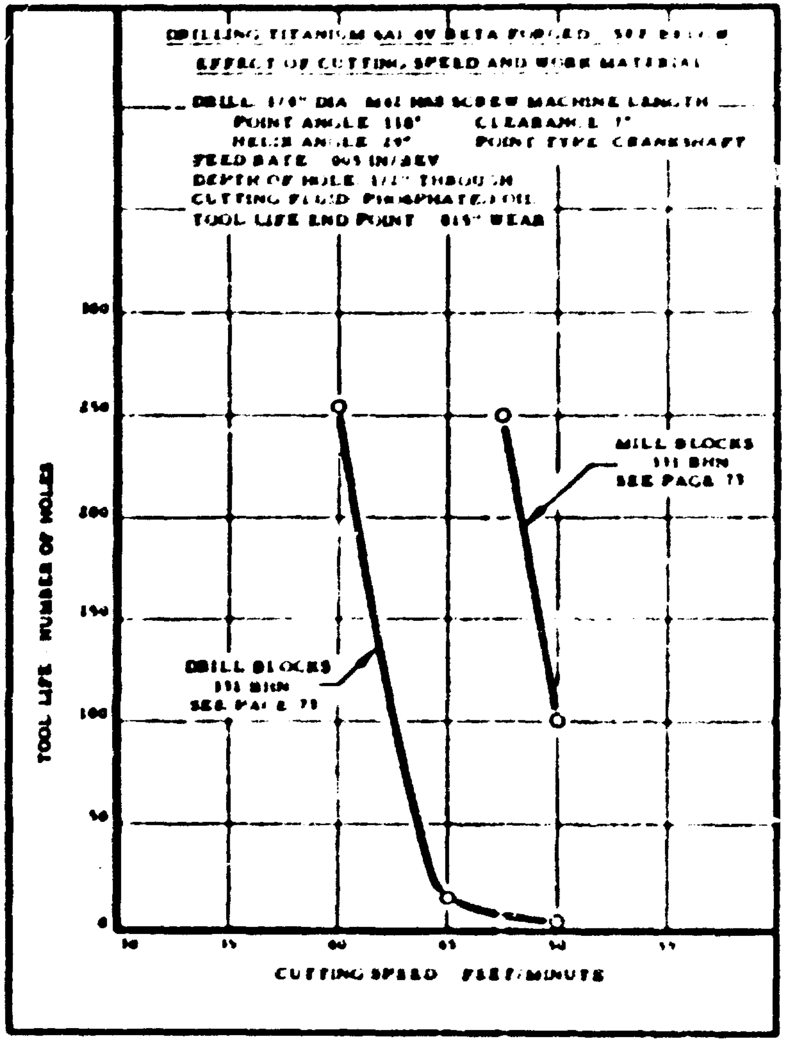
See text, page 96

Figure 118



See text, page 99

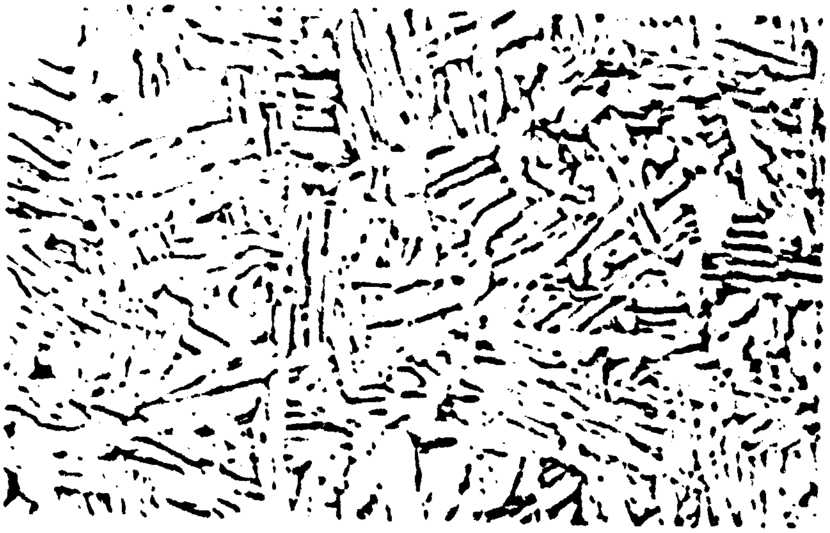
Figure 111



See text page 99

Figure 110

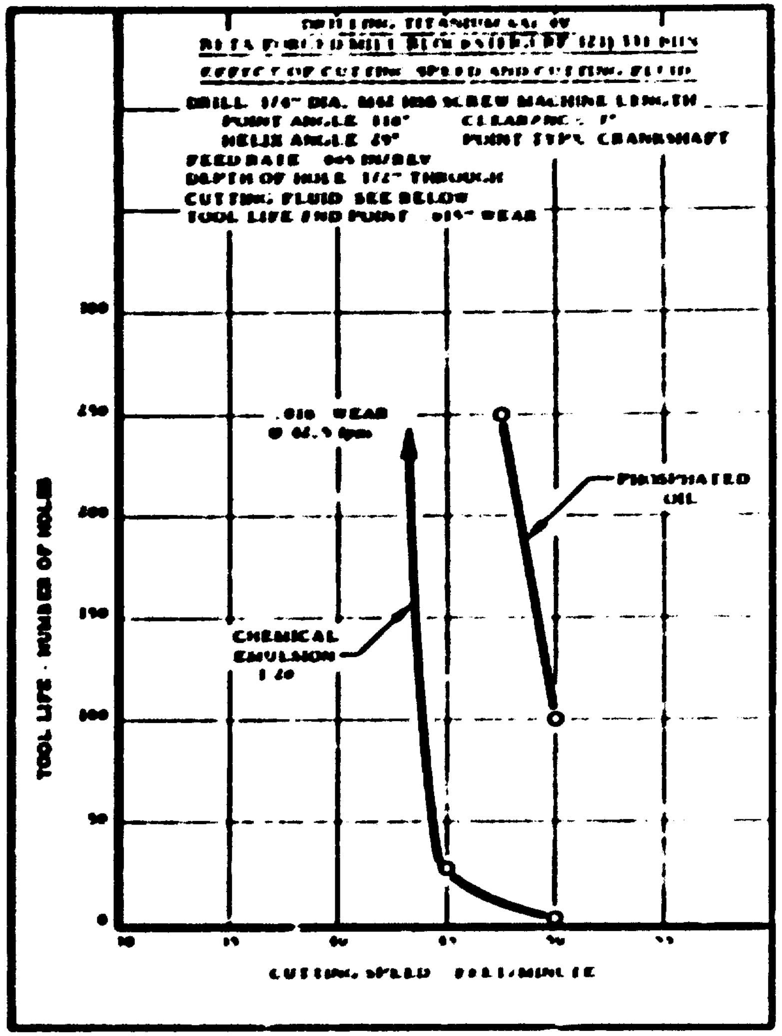
Titanium 6Al-4V Beta Forged



Mill Blocks, Beta Forged, 2" x 4"

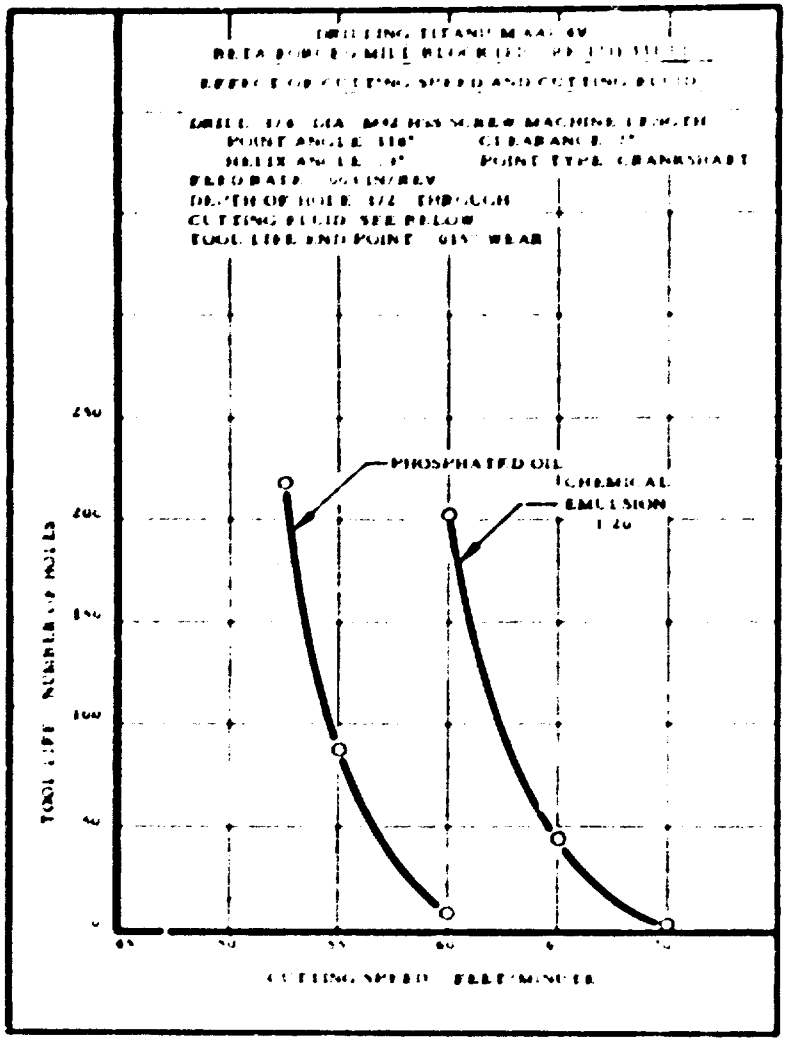
Drill Blocks, Beta Forged, 1/2" x 4"

Figure 121



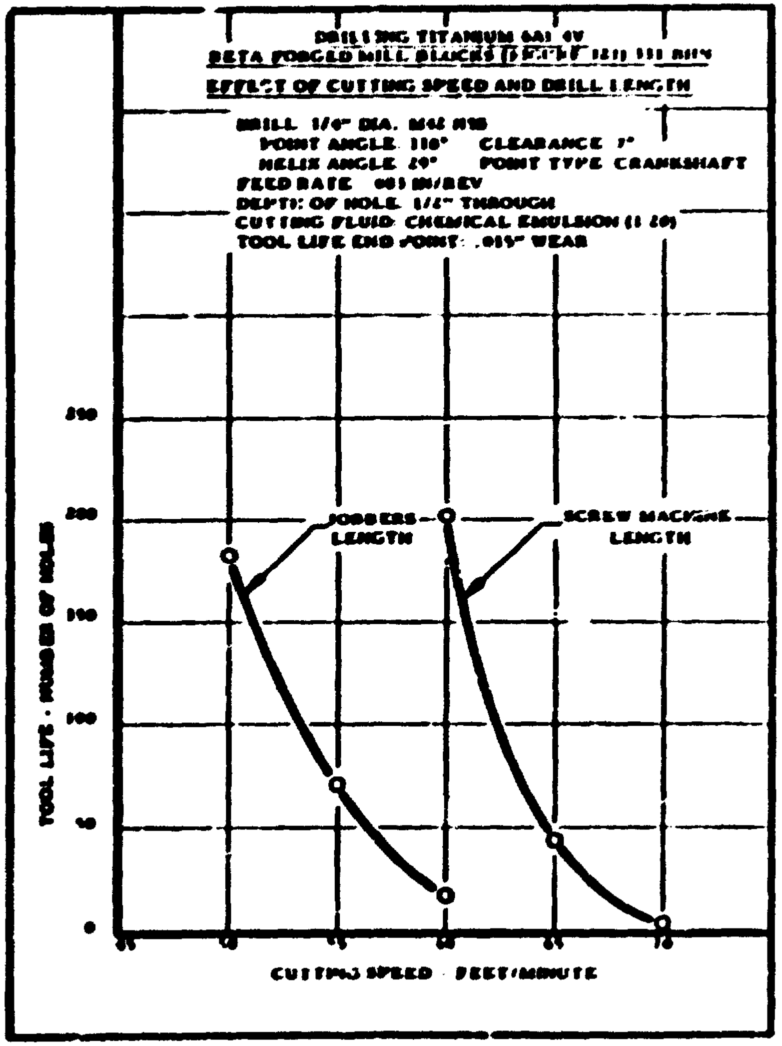
See text page 96

Figure 122



See text page 96

Figure 121



See text, page 96

Figure 124

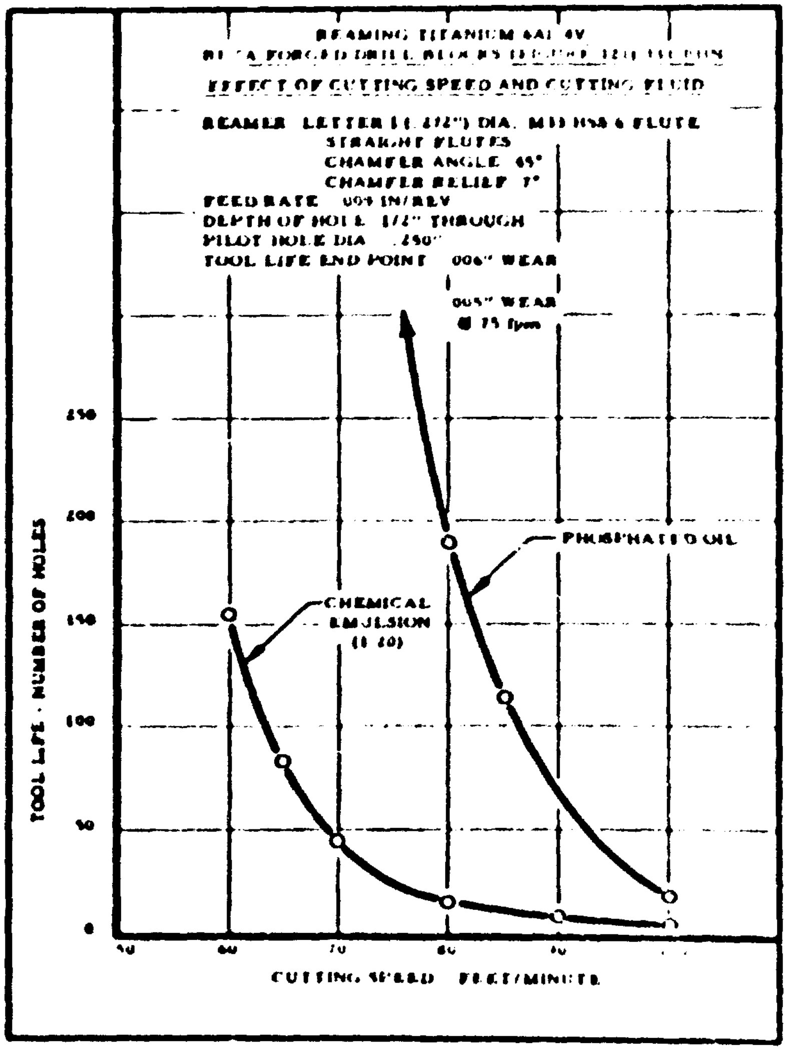


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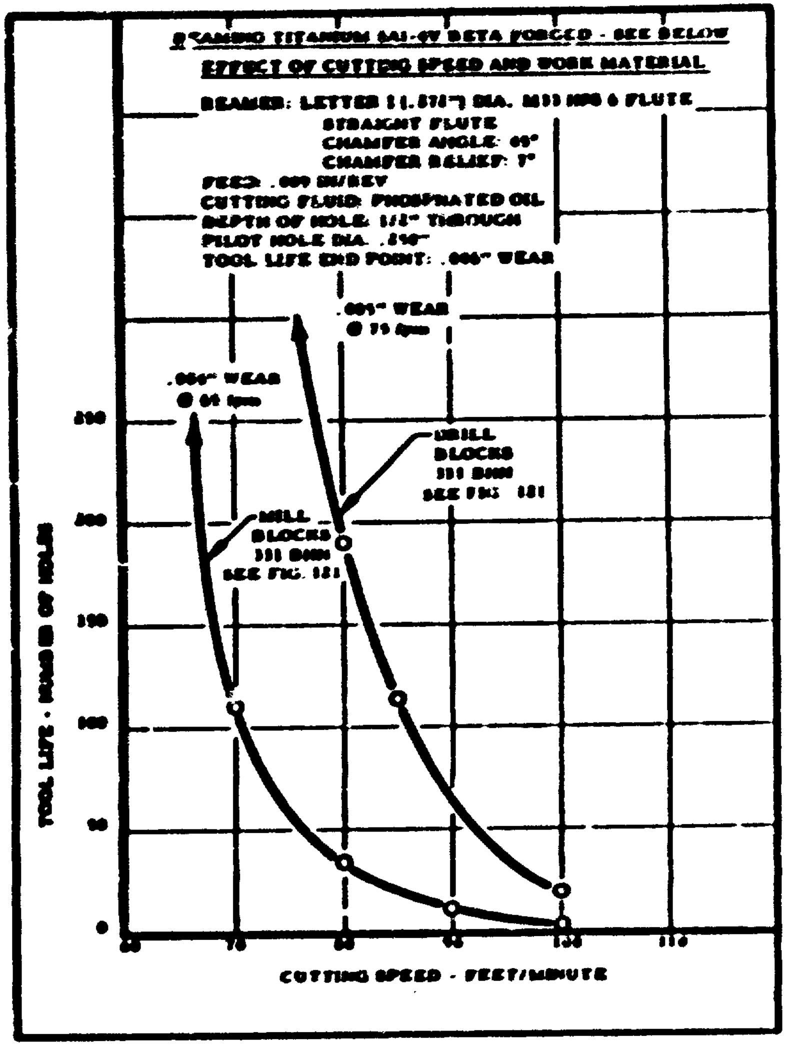
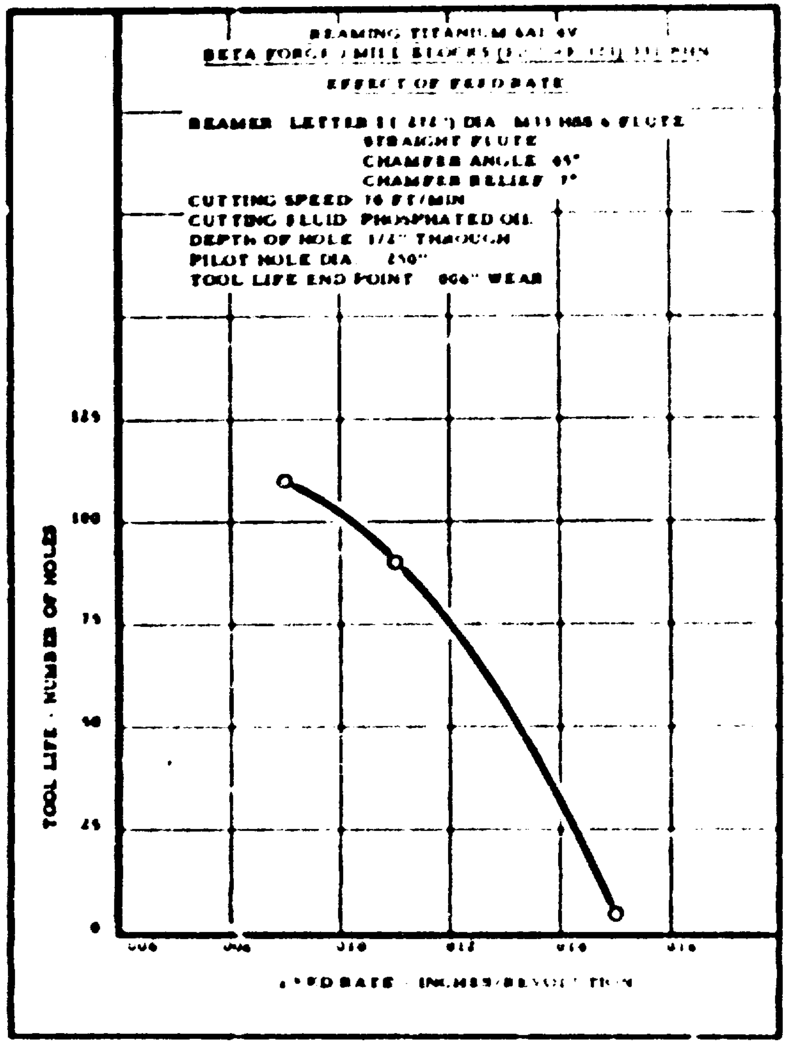
Figure 125



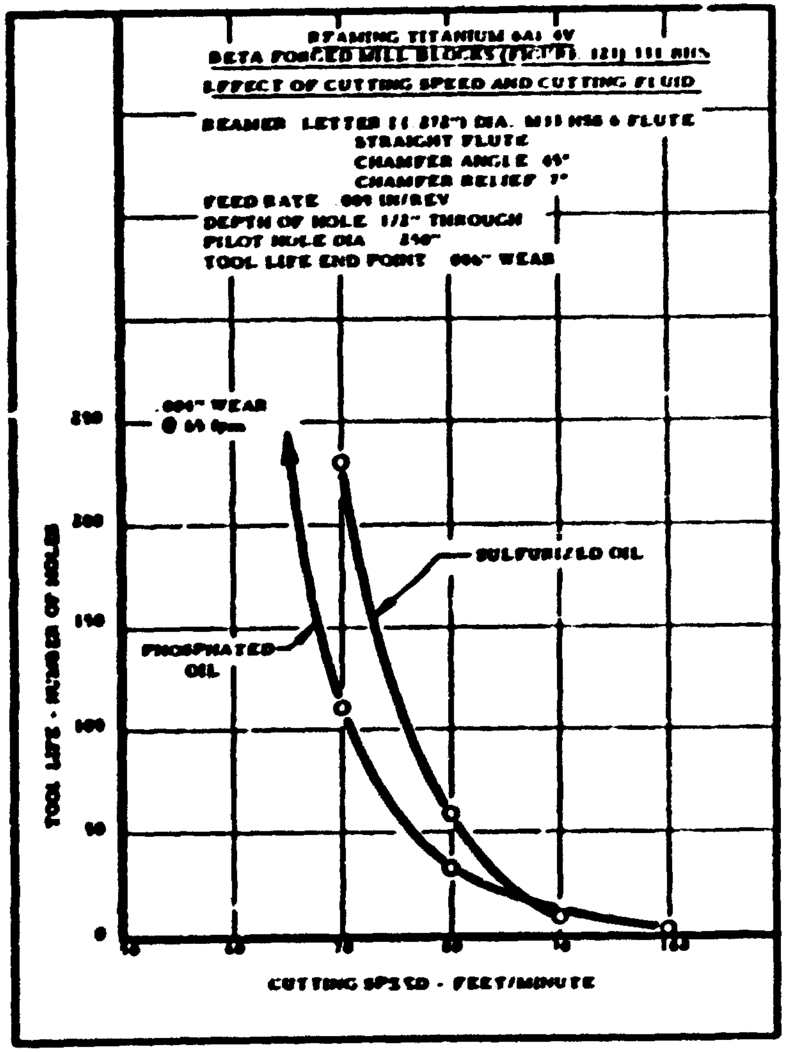
See text, page 96

Figure 116



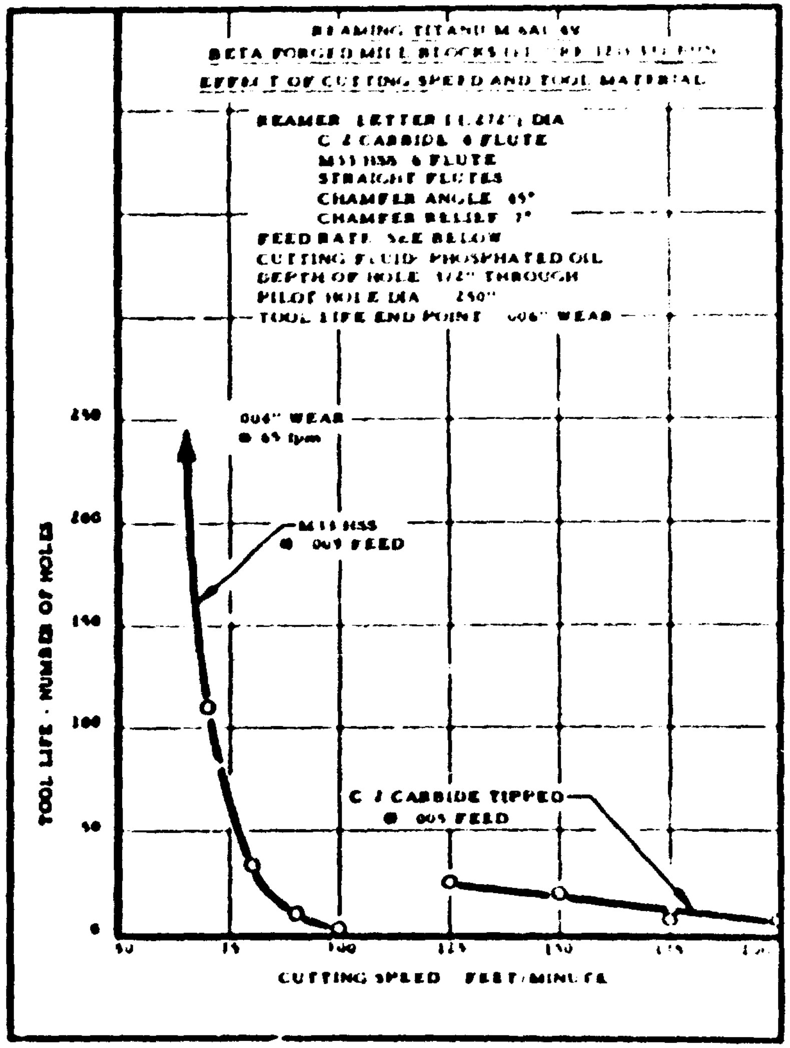
See text, pag. 96

Figure 117



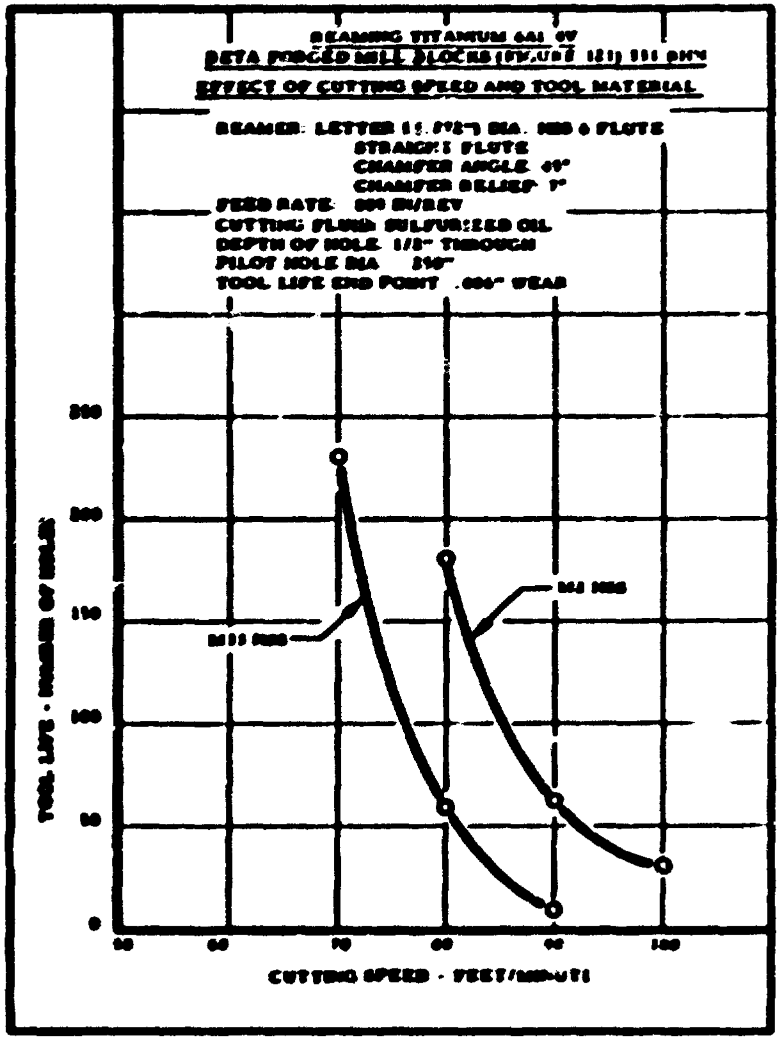
See text, page 97

Figure 120



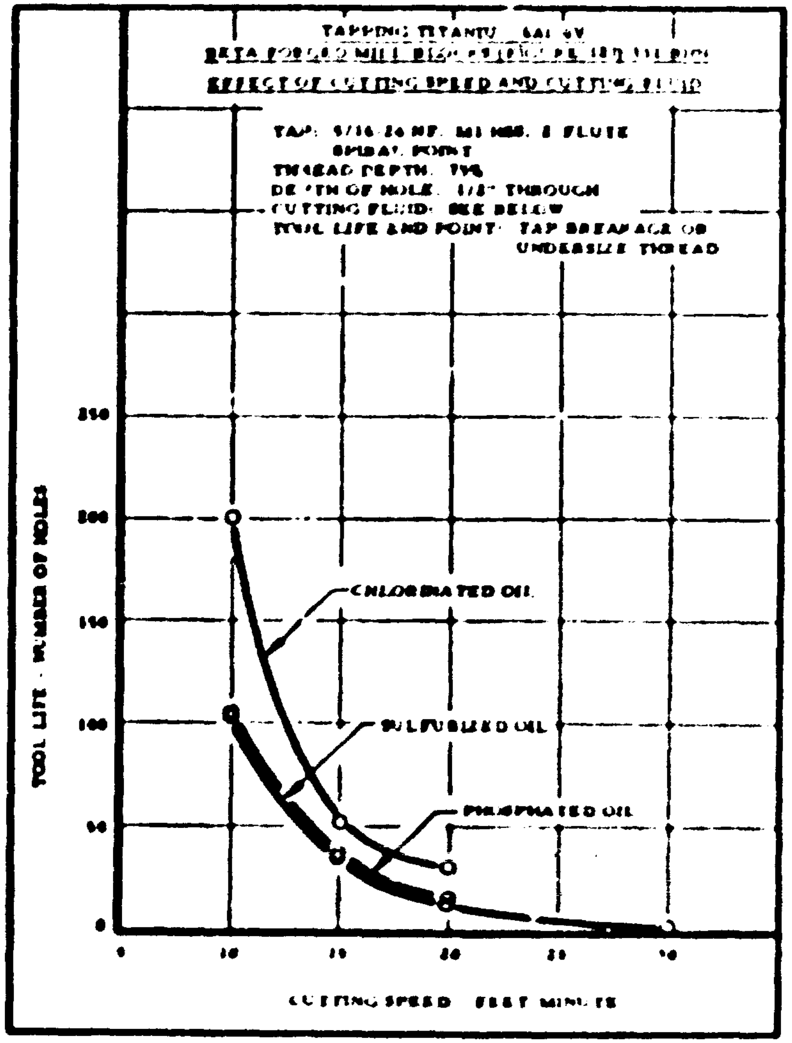
See text, page 97

Figure 121



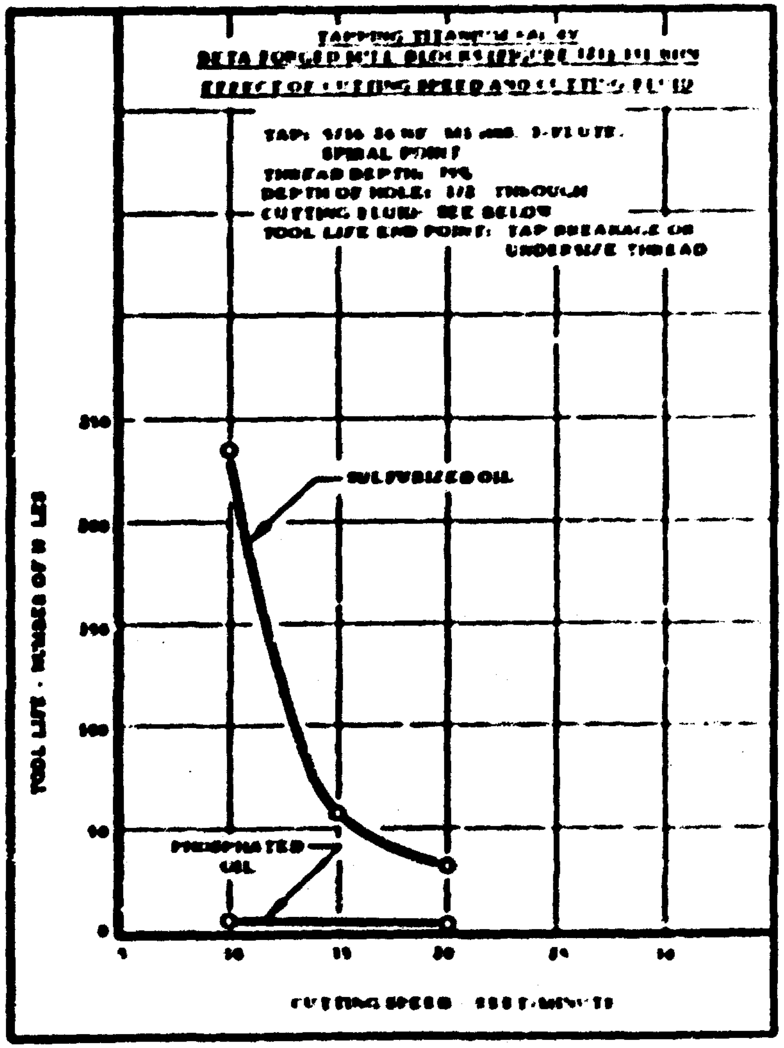
See text, page 97

Figure 110



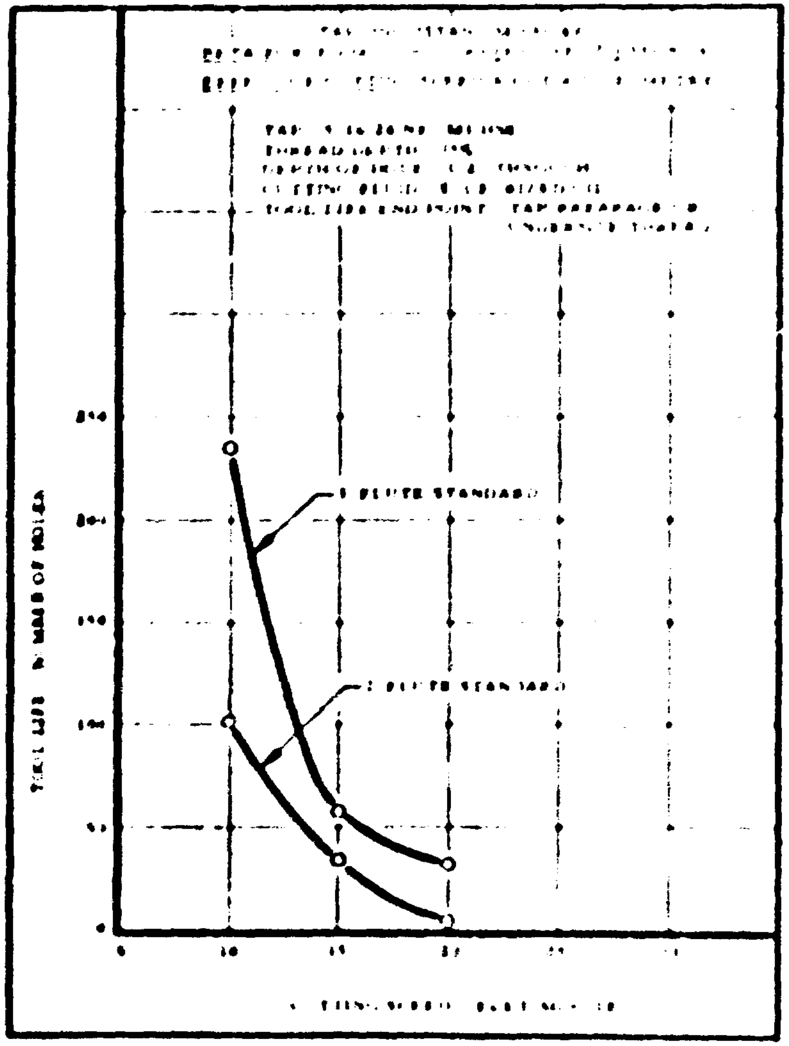
See text, page 97

Figure 111



See text, page 97

Figure 118



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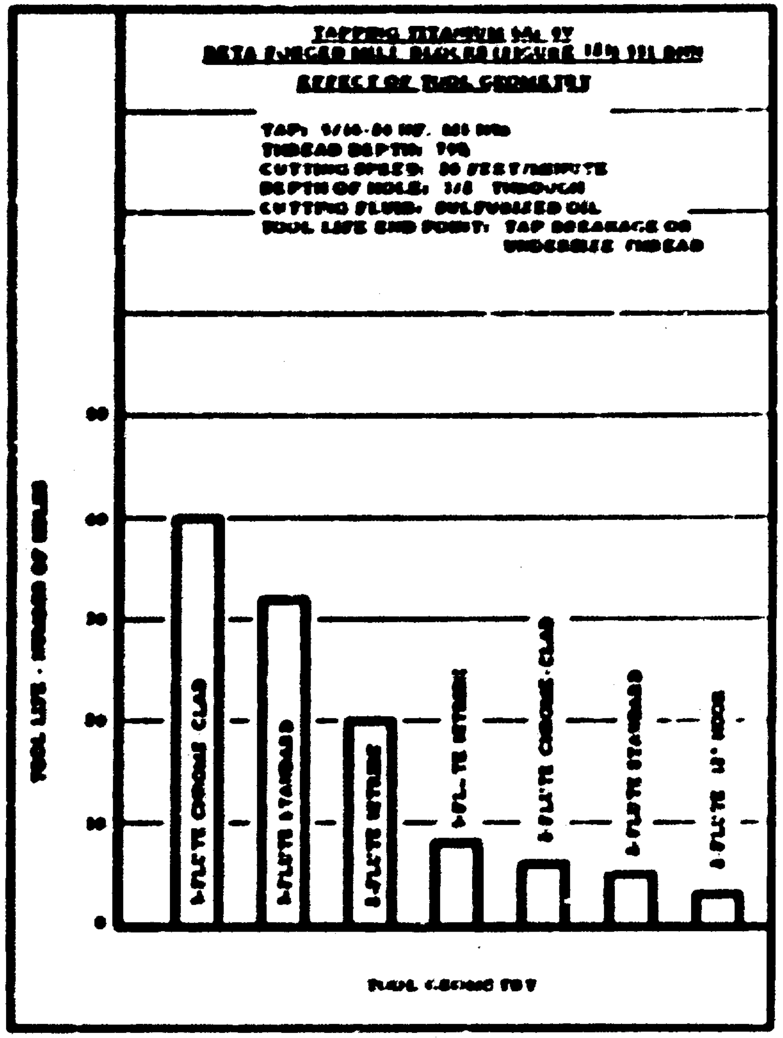
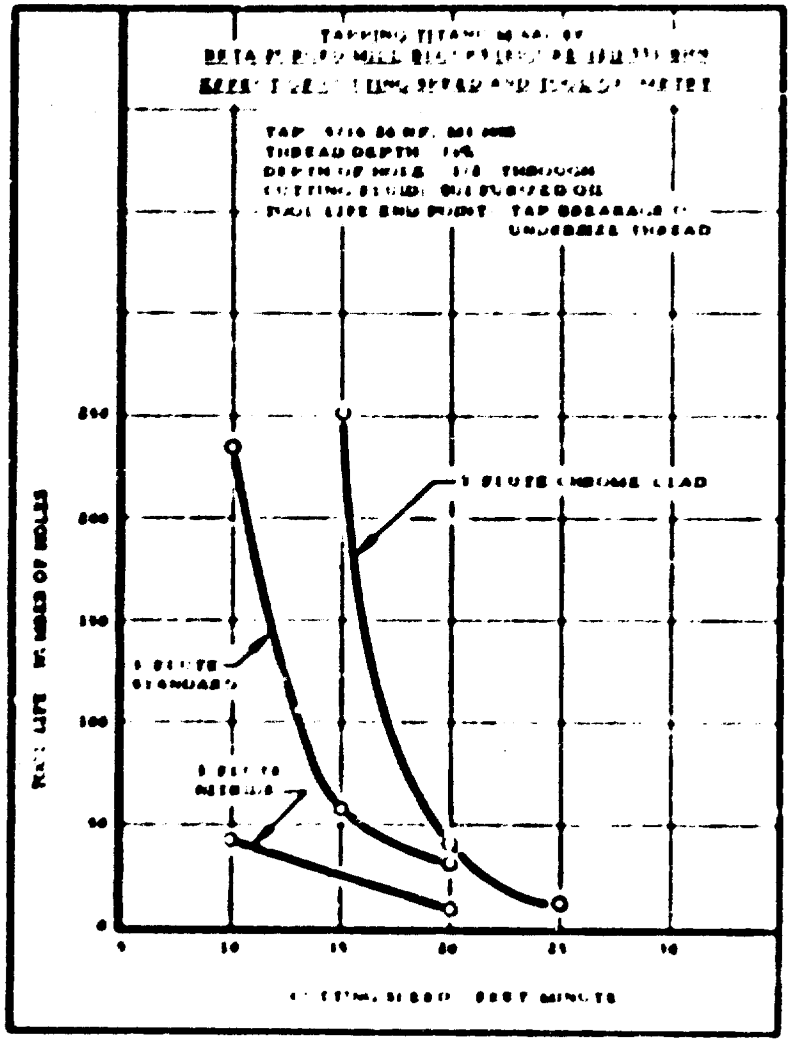


See text, page 97 Figure 110



See text, page 97 Figure 109

4.2 Cast Titanium 6Al-4V, As Cast

Alloy Identification

Titanium 6Al-4V is a high-alpha, lean-beta titanium alloy which exhibits excellent elevated temperature strength and stability.

This alloy in the cast form has shown equivalent corrosion resistance and mechanical properties as compared to its wrought counterpart. Castings have been used in airframe structural applications where complex design-shaped hardware was needed. The nominal composition of this alloy is as follows:

Ti-6.0Al-4.0V-.05C

The material for the milling tests was procured as 2 in. by 4 in. cast bars. The material for the drilling tests was obtained by sectioning 1/2 in. thick plates from these bars. Tests were performed on this material in the as cast condition. The hardness of this material was 341 BHN.

The microstructure, illustrated below, consists of Widmanstatten (basket weave) alpha.

Titanium 6Al-4V, As Cast

Etchant: HF, HNO_3, H_2O **Mag.: 500X**

4.2 Cast Titanium 6Al-4V, As Cast (continued)

Face Milling (341 BHN)

Tool life curves with two different grades of HSS tools are shown in Figure 136, page 129. Note that at a cutting speed of 80 feet/minute and a feed of .005 in./tooth, the tool life with the M42 HSS single-tooth cutter was 124 inches of work travel and 55 inches of work travel with the M2 HSS cutter.

As has been found in previous tests, the cutter life per tooth is usually less with the multiple-tooth cutter as compared to a single-tooth cutter. The cutter life, as shown in Figure 137, page 129, was 124 inches with the single-tooth cutter as compared to 37 inches of work travel per tooth with the 14-tooth cutter at a cutting speed of 80 feet/minute. However, it should be pointed out that the 14-tooth cutter actually milled a total of 518 inches of work travel and that the rate of metal removal was 14 times faster with the multiple-tooth cutter than with the single-tooth cutter.

The M42 HSS multiple-tooth cutter was only slightly better than the M2 HSS multiple-tooth cutter see Figure 138, page 130.

A comparison of various cutting fluids with cutting dry in face milling with a single-tooth carbide cutter is shown in Figure 139, page 130. Note that face milling dry provided appreciably longer tool life than when using the cutting fluids shown in the chart.

It has been found in the past that tool life in machining titanium alloys usually decreases with increased feed. The results shown in Figure 140, page 131, confirm these findings. At a cutting speed of 240 feet/minute, the cutter life decreased about 30 percent when the feed rate was increased from .003 to .005 in./tooth. However, this higher feed rate provided approximately the same tool life as the lower feed rate when the cutting speed was decreased from 240 to 197 feet/minute.

As shown in Figure 141, page 131, the cutter life in terms of inches of work travel per tooth was also considerably less with the carbide multiple-tooth cutter. However, by decreasing the cutting speed, it was possible to increase the tool life appreciably. For example, at a cutting speed of 150 feet/minute, the tool life with the six-tooth cutter was the same as that with the single-tooth cutter, cutting at a speed of 275 feet/minute. Hence with the multiple-tooth cutter, the rate of metal removal was still three times faster than with the single-tooth cutter, even though the cutting speed was reduced.

4.2 Cast Titanium (Al-4V, As Cast (continued)

Peripheral End Milling (311 BHN)

The M42 HSS end mills permitted a 16 percent increase in cutting speed over the M2 HSS cutters, see Figure 142, page 132. The relationship between tool life and feed rate with the M42 HSS cutter is shown in Figure 143, page 132. Note again how critical the feed rate is in end milling titanium alloys. In this case, the cutter life at a feed rate of .002 in./tooth was 185 inches of work travel. Increasing the feed rate to .0025 resulted in decreasing the tool life to 50 inches of work travel.

End Mill Slotting (311 BHN)

The M42 HSS cutters also provided an increase in cutting speed over that with the M2 HSS cutters in slotting. As shown in Figure 144, page 133, the increase in cutting speed was 10 percent.

The results shown in Figure 145, page 133, clearly indicate the need for using a lighter feed in end mill slotting the titanium alloy. Increasing the feed from .002 in./tooth to .003 in./tooth resulted in a considerable decrease in tool life.

Drilling (311 BHN)

A comparison of M42 HSS drills with M1 HSS drills is shown in Figure 146, page 134. The cutting speed with the M42 HSS drills was 20 percent higher for a given tool life than with the M1 HSS drills.

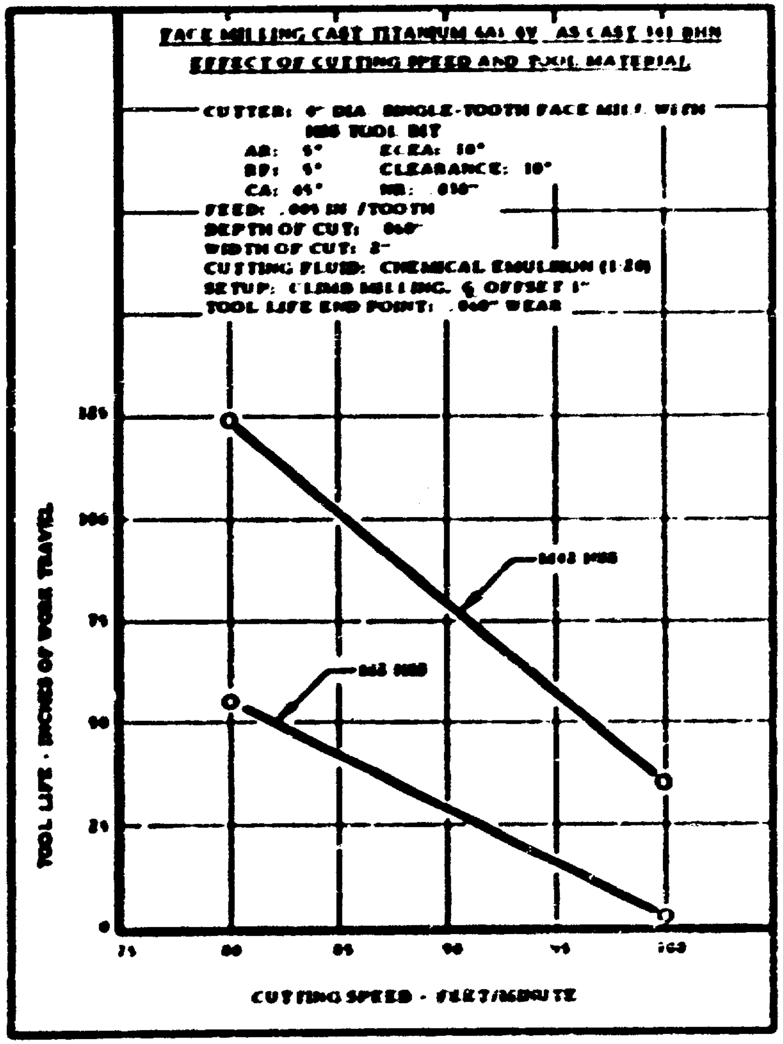
TABLE IX

RECOMMENDED CONDITIONS FOR MACHINING CAST TITANIUM 6Al-4V, AS CAST 341BHN

Nominal Chemical Composition, Percent

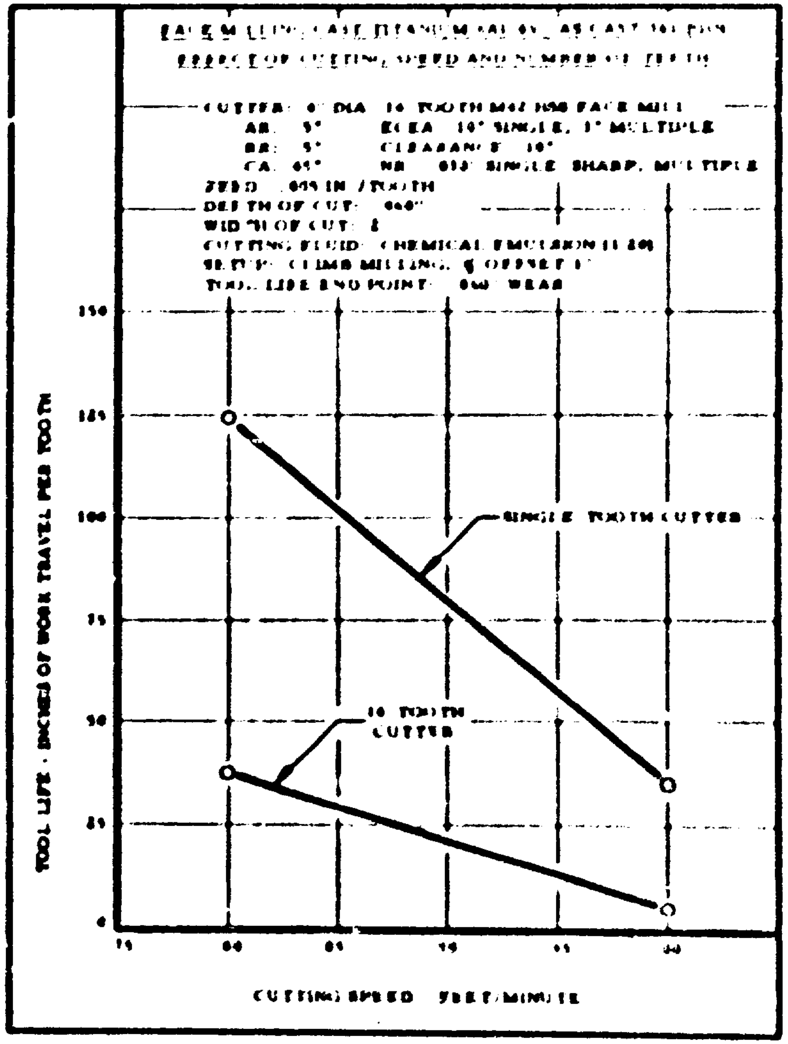
Ti	Al	V	C
Bal.	6.0	4.0	.05

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Face Milling	M2 HSS	AR: 5° ECEA:1° RR: 5° CA: 45° Clearance: 10°	4" Diameter 14 Tooth HSS Face Mill	.060	2	.005 in/tooth	80	465" work travel	.060	Chemical Emulsion (1:20)
Face Milling	C-2 Carbide	AR:-5° ECEA45° RR: -5° CA: 45° Clearance: 5°	4" Diameter 6 Tooth Face Mill	.060	2	.003 in/tooth	160	660" work travel	.015	Dry
Peripheral End Milling	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	1" Diameter 4 Flute HSS End Mill	.250	.500	.002 in/tooth	165	180" work travel	.012	Chemical Emulsion (1:20)
End Mill Slotting	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" Diameter 4 Flute HSS End Mill	.250	.750	.002 in/tooth	100	135" work travel	.012	Chemical Emulsion (1:20)
Drilling	M42 HSS	Point Angle: 118° Helix Angle: 29° Clearance Angle: 7°	1/4" Diameter HSS Drill 2-1/2" long	.500 thru	-	.005 in/rev	30	250 holes	.012	Chemical Emulsion (1:20)



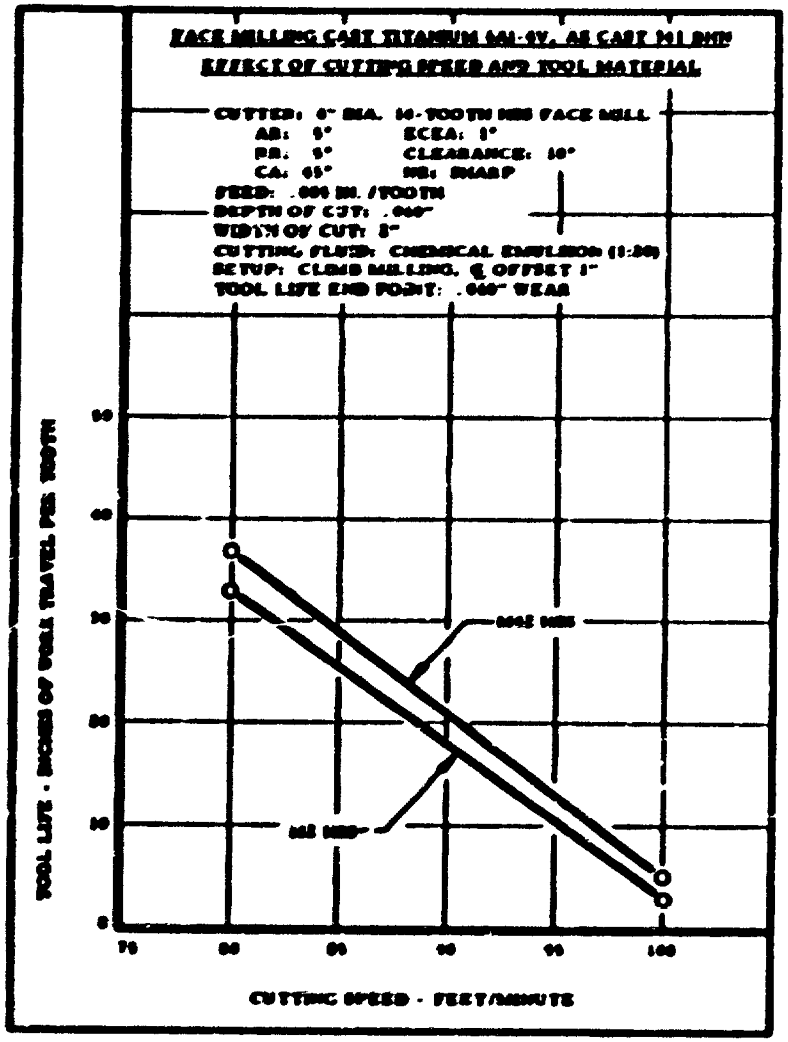
See text, page 126

Figure 156



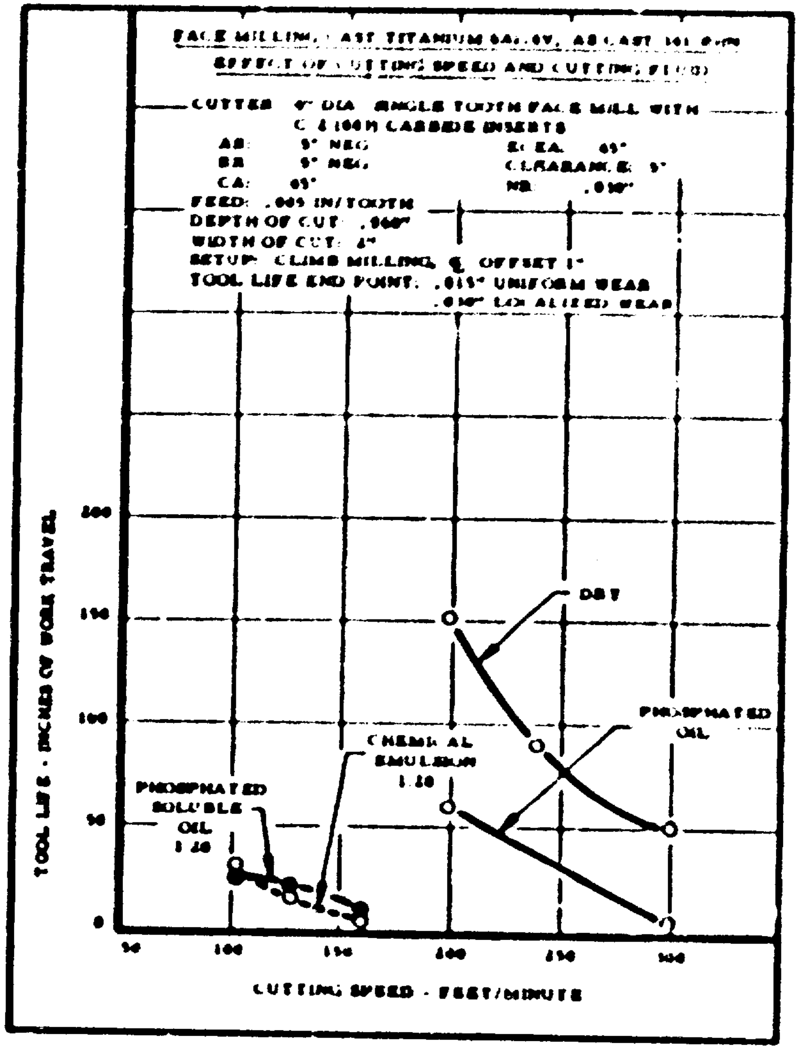
See text, page 126

Figure 157



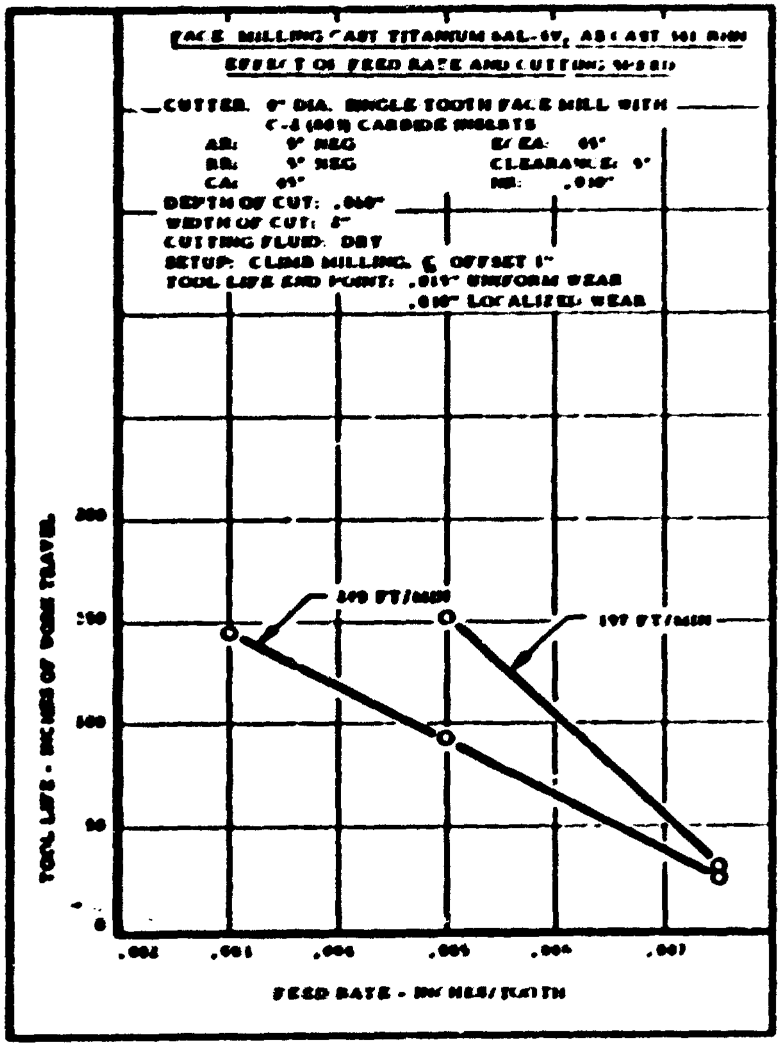
See text, page 126

Figure 118



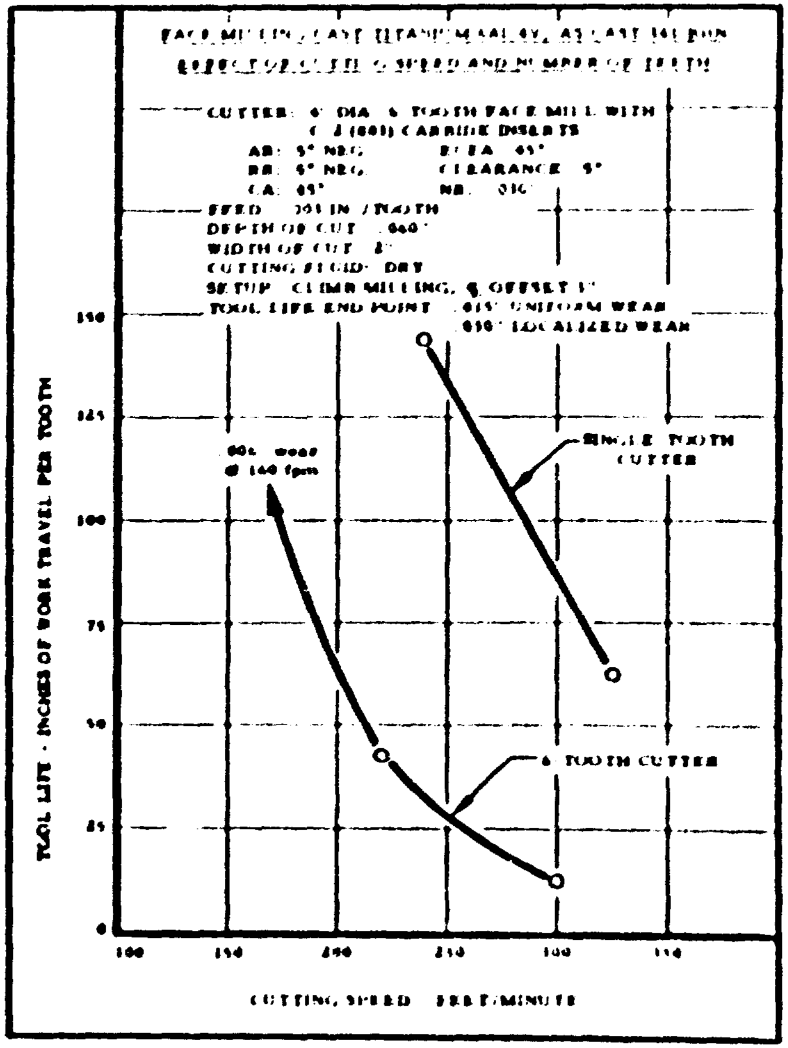
See text, page 126

Figure 119



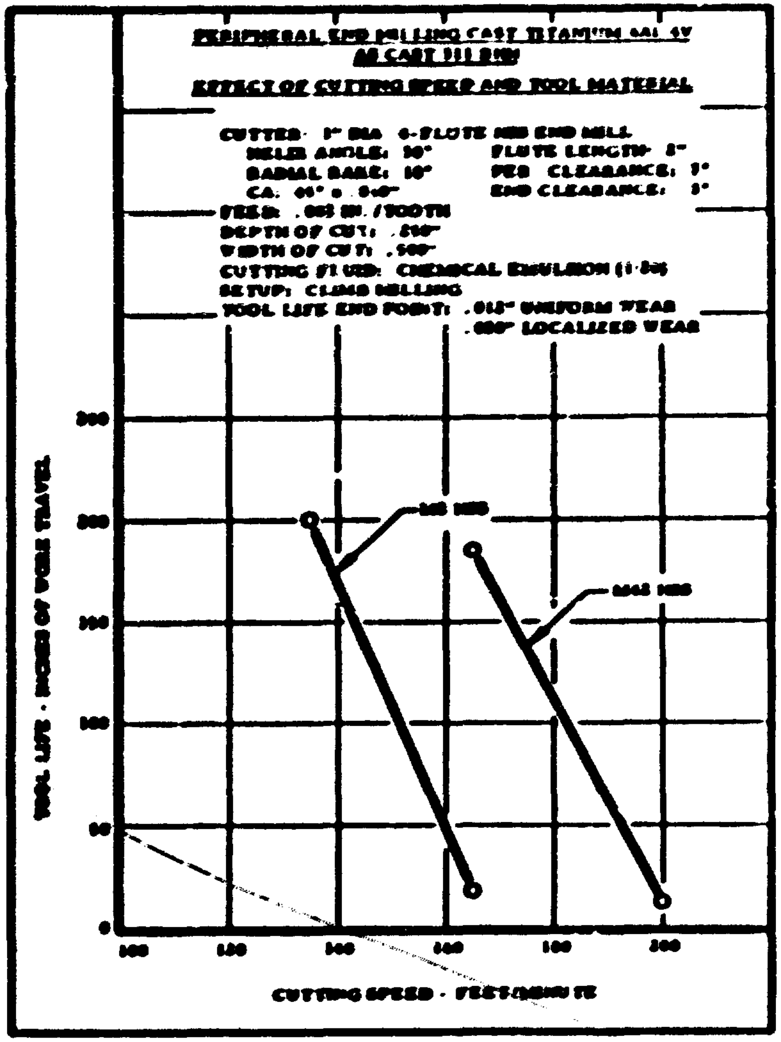
See text, page 126

Figure 160



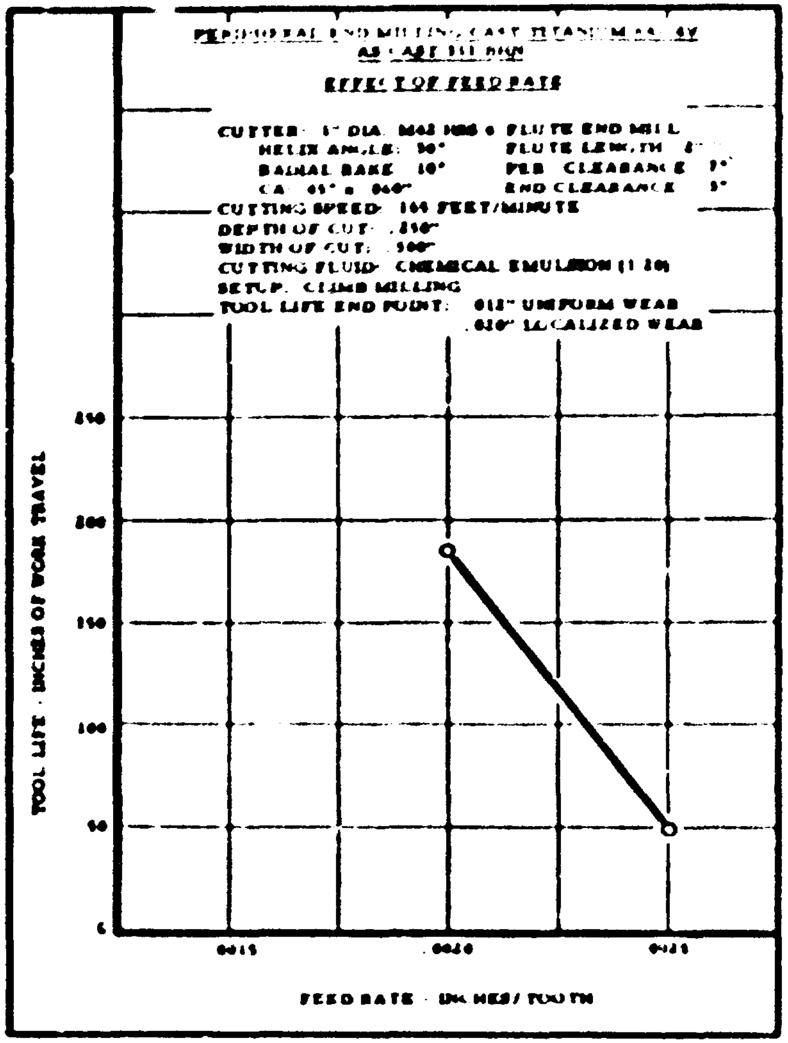
See text, page 126

Figure 161



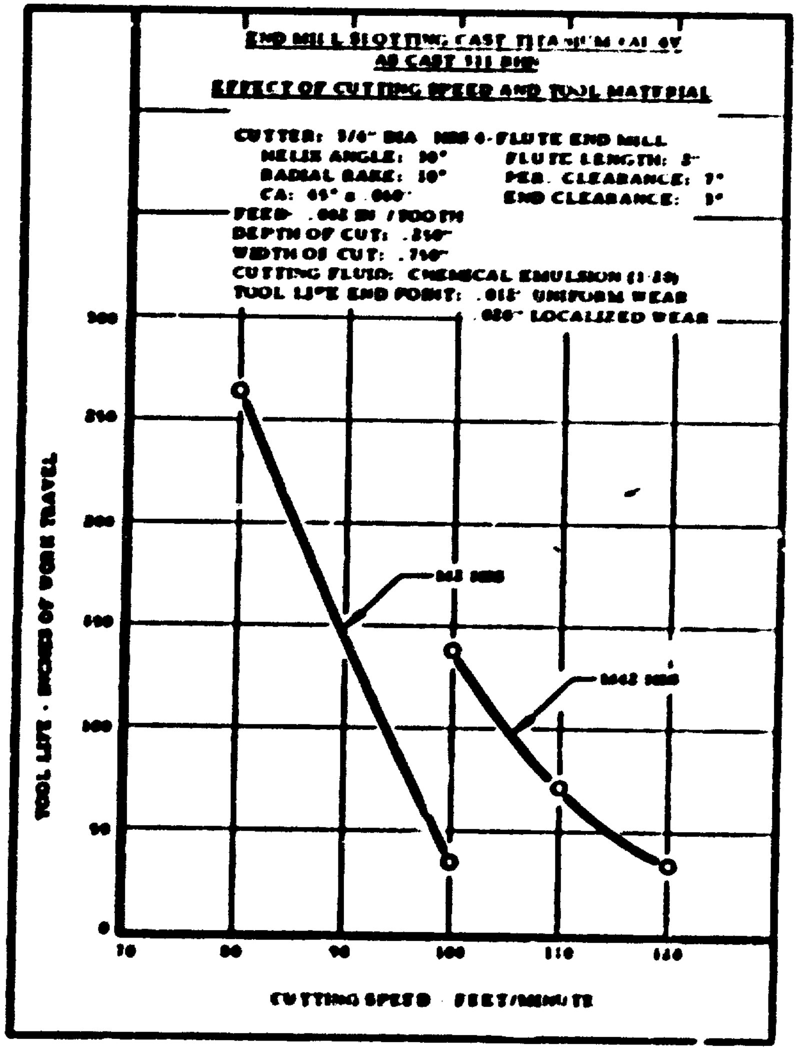
See text, page 157

Figure 112



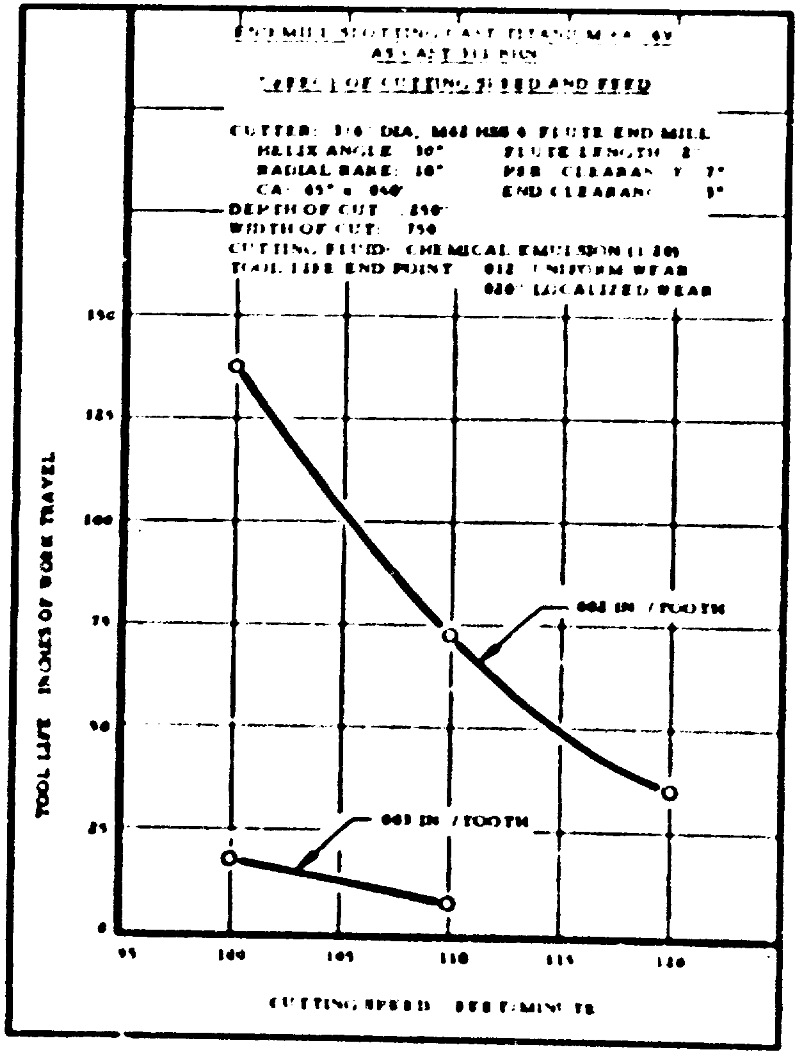
See text, page 157

Figure 113



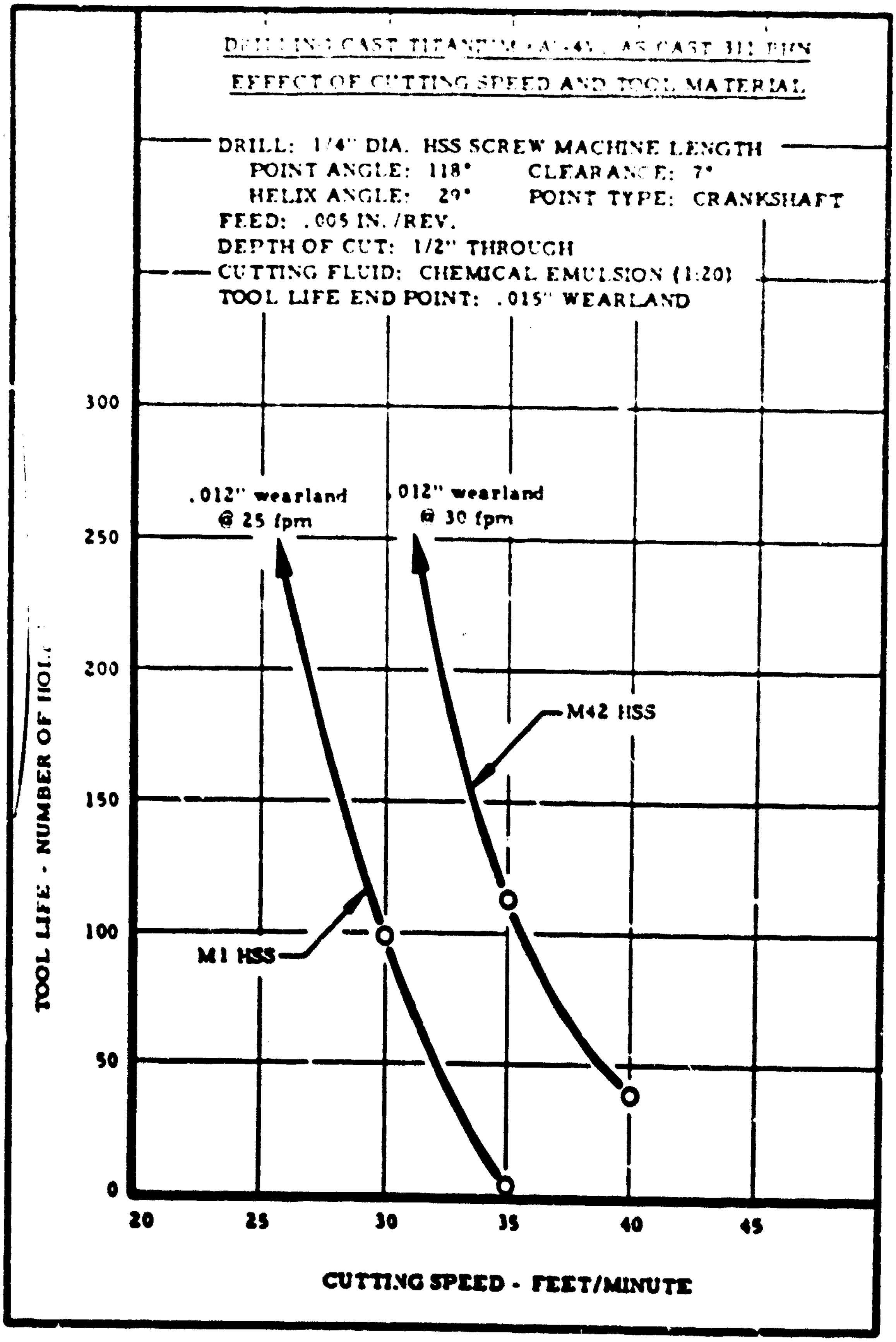
See text, page 127

Figure 164



See text, page 127

Figure 165



See text, page 127

Figure 146

4.3 Titanium 6Al-2Sn-4Zr-2Mo, Solution Treated and Aged

Alloy Identification

Ti-6Al-2Sn-4Zr-2Mo is a super-alpha titanium alloy which combines low density, high strength, plus excellent creep resistance and stability at elevated temperature. The nominal composition of this alloy is as follows:

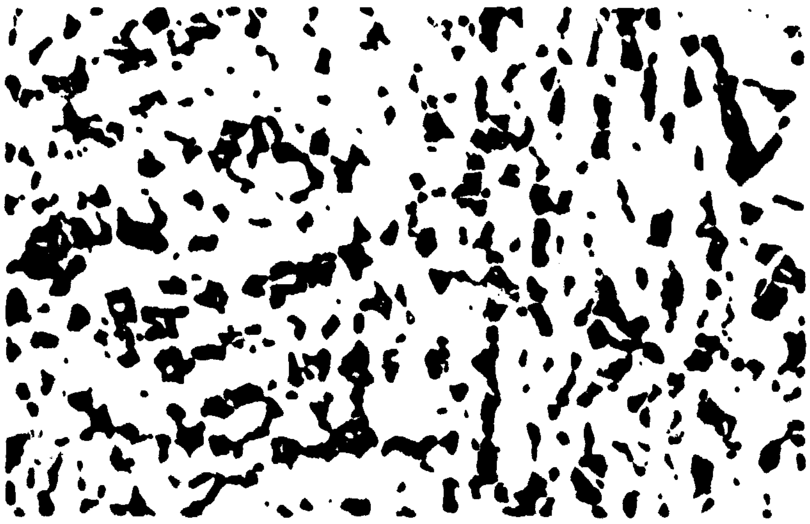
Ti-6.0Al-2.0Sn-4.0Zr-2.0Mo-.03C

The material for the milling tests was procured as 2 in. by 4 in. rectangular bars in the as-forged condition. The material for the drilling, reaming, and tapping tests was procured as 1/2 in. by 4 in. plates, also in the as-forged condition.

The machining tests were performed on this material in the solution treated and aged condition. The heat treatment to which the material was subjected was as follows:

1775°F/1 hour/air cool
1100°F/8 hours/air cool

Resulting hardness of all the material was 321 BHN. The microstructure of the 2 in. by 4 in. bars (shown below) consists of alpha platelets, beta, and small quantities of alpha prime.



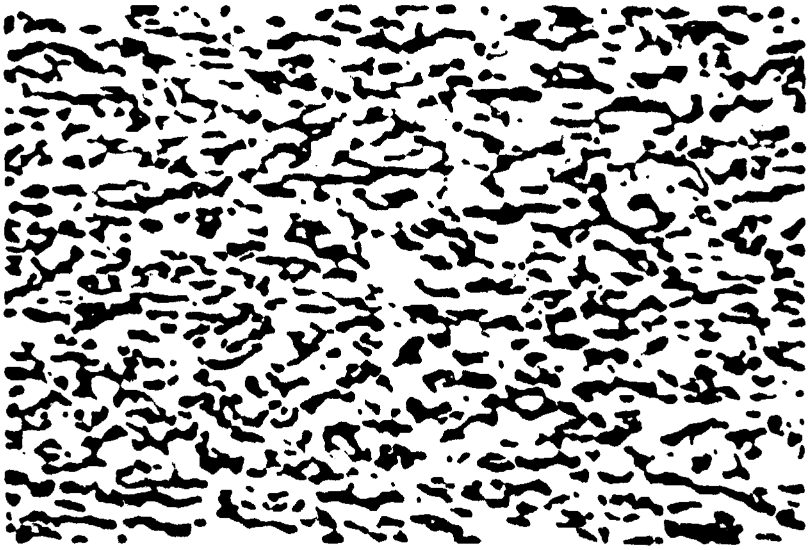
Ti-6Al-2Sn-4Zr-2Mo, Solution Treated and Aged

Etchant: HF, HNO_3, Glycerol **Mag.: 500X**

4.3 Titanium 6Al-2Sn-4Zr-2Mo, Solution Treated and Aged (continued)

Alloy Identification (continued)

The microstructure of the 1/2 in. by 4 in. material is illustrated below. It consists of a slightly elongation alpha-beta structure.



Ti-6Al-2Sn-4Zr-2Mo, Solution Treated and Aged

Etchant: HF, HNO_3, Glycerol Mag.: 500X

4.9 Titanium (Al-2Sn-4Zr-2Mo, Solution Treated and Aged (continued)

End Mill Slotting (321 BHN)

Of the cutting fluids used, see Figure 147, page 140, the water-base fluids performed much better than the phosphated oil. There was very little difference in the performances of the three water-base fluids however, the soluble oil appeared to be slightly better than either the chemical emulsion or the phosphated soluble oil.

As shown in Figure 148, page 140, the M42 HSS cutter performed appreciably better than the M2 HSS cutter. For example, at a tool life of 150 inches of work travel, the cutting speed with the M42 HSS cutter was slightly more than 10 percent higher than that with the M2 HSS cutter.

From the results shown in Figure 149, page 141, it would appear that a feed of .0015 in./tooth is the best feed to use in end mill slotting this titanium alloy. The cutting speed at this feed for a tool life of 150 inches of work travel was almost 20 percent higher than that with a feed of .002 in./tooth. In addition, the results were more consistent with the lighter feed.

Drilling (321 BHN)

It is very interesting to examine Figures 150 and 151, page 142. Note that in Figure 150 using a phosphated oil the M1 HSS drill provided appreciably longer tool life than the M42. However, as shown in Figure 151 using a chemical emulsion the M42 HSS drill was considerably better than the M1 HSS drill. As a matter of fact, using the chemical emulsion and the M42 HSS drill, a cutting speed of 40 feet/minute was used to obtain more than 250 holes. Under any of the other conditions cited, the cutting speed was 25 feet/minute or less for the same number of holes.

Further comparisons of the two cutting fluids for each of the two HSS drills are presented in Figures 152 and 153, page 143. Note that with the M1 HSS drill the phosphated oil and the chemical emulsion performed similarly at a cutting speed of 25 feet/minute. The drill life was slightly more than 250 holes. However, as shown in Figure 153, the chemical emulsion performed appreciably better than the phosphated oil when using an M42 HSS drill. Note that at a cutting speed of 40 feet/minute with the phosphated oil the drill life was 15 holes, while with the chemical emulsion a drill life of over 250 holes was obtained.

4.3 Titanium 6Al-2Sn-4Zr-2Mo, Solution Treated and Aged (continued)

Reaming (321 BHN)

The relationship between tool life and cutting speed in reaming the titanium alloy is shown in Figure 154, page 144. Note that with an M2 HSS six-flute reamer more than 250 holes were reamed at a cutting speed of 105 feet/minute. The feed was .009 in./rev

Tapping (321 BHN)

As shown in Figure 155, page 144, both the chemical emulsion and phosphated oil provided about the same tool life in tapping. A tap life of slightly over 250 holes was obtained with both cutting fluids at a cutting speed of 20 feet/minute.

The tool life curves in Figure 156, page 145, indicate the advantage of chrome plating a tap. Both of the taps used in these tests were three-fluted, spiral-pointed taps. However, with the plain tap the maximum tap life was 30 holes at a cutting speed of 20 feet/minute as compared to 250 plus holes with the chrome-plated tap at the same cutting speed.

A comparison of a two-fluted and a three-fluted tap, both chrome-plated, is shown in Figure 157, page 145. Note the great difference in the performances of these two types of taps. The tap life with the two-fluted tap was very poor compared to that with the three-fluted tap.

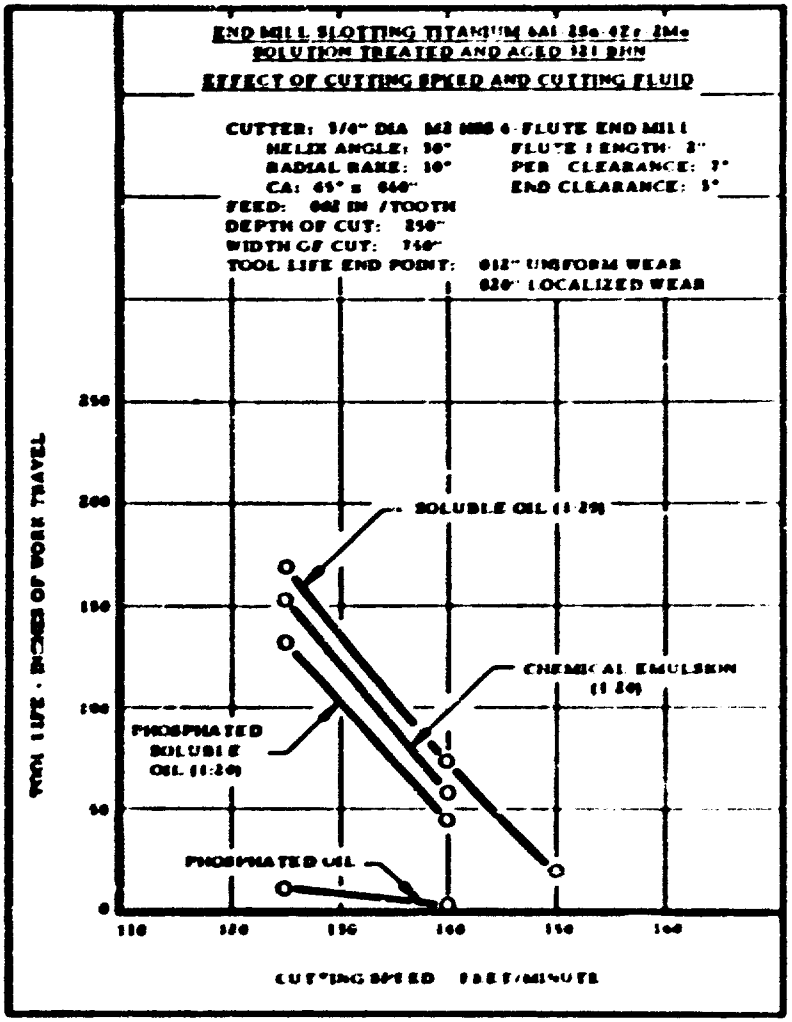
TABLE X

RECOMMENDED CONDITIONS FOR MACHINING
TITANIUM 6Al-2Sn-4Zr-2Mo, SOLUTION TREATED AND AGED 321 BHN

Nominal Chemical Composition, Percent

Ti	Al	Sn	Zr	Mo	C
Bal.	6.0	2.0	4.0	2.0	.03

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
End Mill Slotting	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" Diameter 4 Flute HSS End Mill	.250	.750	.0015 in/tooth	150	340" work travel	.012	Soluble Oil (1:20)
Drilling	M42 HSS	Point Angle: 118° Helix Angle: 29° Clearance Angle: 7°	1/4" Diameter HSS Drill 2-1/2" long	.500 thru	-	.005 in/rev	40	250 holes	.013	Chemical Emulsion (1:20)
Reaming	M2 HSS	Helix Angle: 0° CA: 45° Clearance: 7°	.272" Diameter 6 Flute Chucking Reamer	.500 thru	-	.009 in/rev	105	250 holes	.003	Phosphated Oil
Tapping	M1 HSS	3 Flute Plug Spiral Point 75% Thread	5/16-24 NF Chrome Plated Tap	.500 thru	-	-	60	250 holes	-	Chemical Emulsion (1:20)



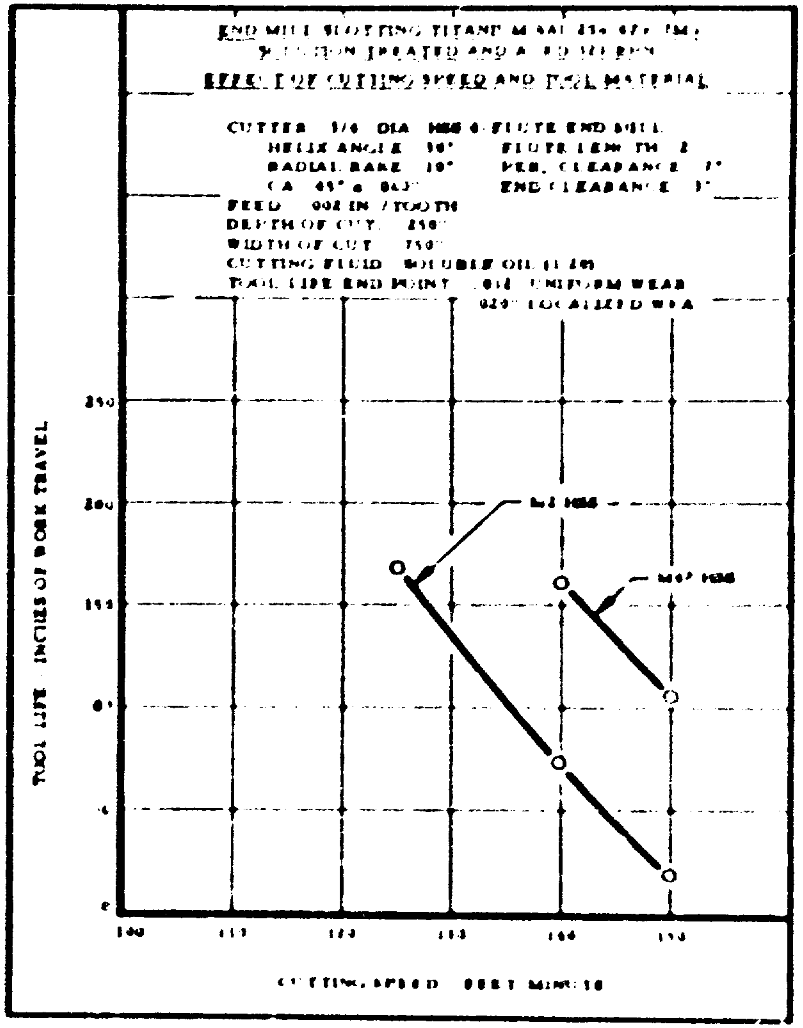
END MILL SLOTTING TITANIUM 6Al-2Sn-4Zr-2Mo
SOLUTION TREATED AND AGED 321 BHN

EFFECT OF CUTTING SPEED AND CUTTING FLUID

CUTTER: 3/4" DIA M2 HSS 4-FLUTE END MILL
HELIX ANGLE: 30°
FLUTE LENGTH: 2"
RADIAL RAKE: 10°
PER. CLEARANCE: 7°
CA: 45° x .060"
END CLEARANCE: 3°
FEED: .002 IN./TOOTH
DEPTH OF CUT: .250"
WIDTH OF CUT: .750"
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 157

Figure 107



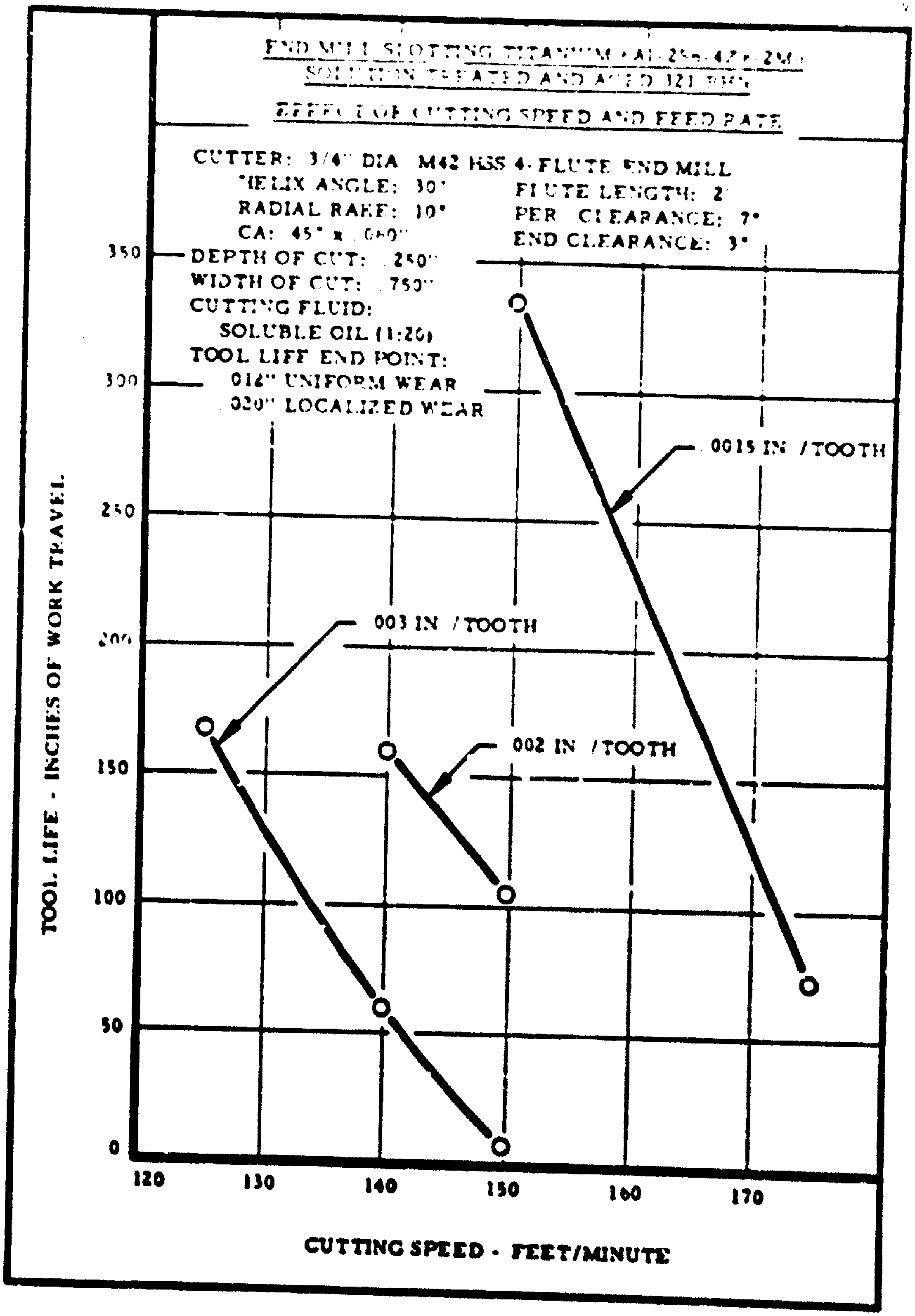
END MILL SLOTTING TITANIUM 6Al-2Sn-4Zr-2Mo
SOLUTION TREATED AND AGED 321 BHN

EFFECT OF CUTTING SPEED AND TOOL MATERIAL

CUTTER: 3/4" DIA HSS 4-FLUTE END MILL
HELIX ANGLE: 30°
FLUTE LENGTH: 2"
RADIAL RAKE: 10°
PER. CLEARANCE: 7°
CA: 45° x .060"
END CLEARANCE: 3°
FEED: .002 IN./TOOTH
DEPTH OF CUT: .250"
WIDTH OF CUT: .750"
CUTTING FLUID: SOLUBLE OIL (1:20)
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 157

Figure 108

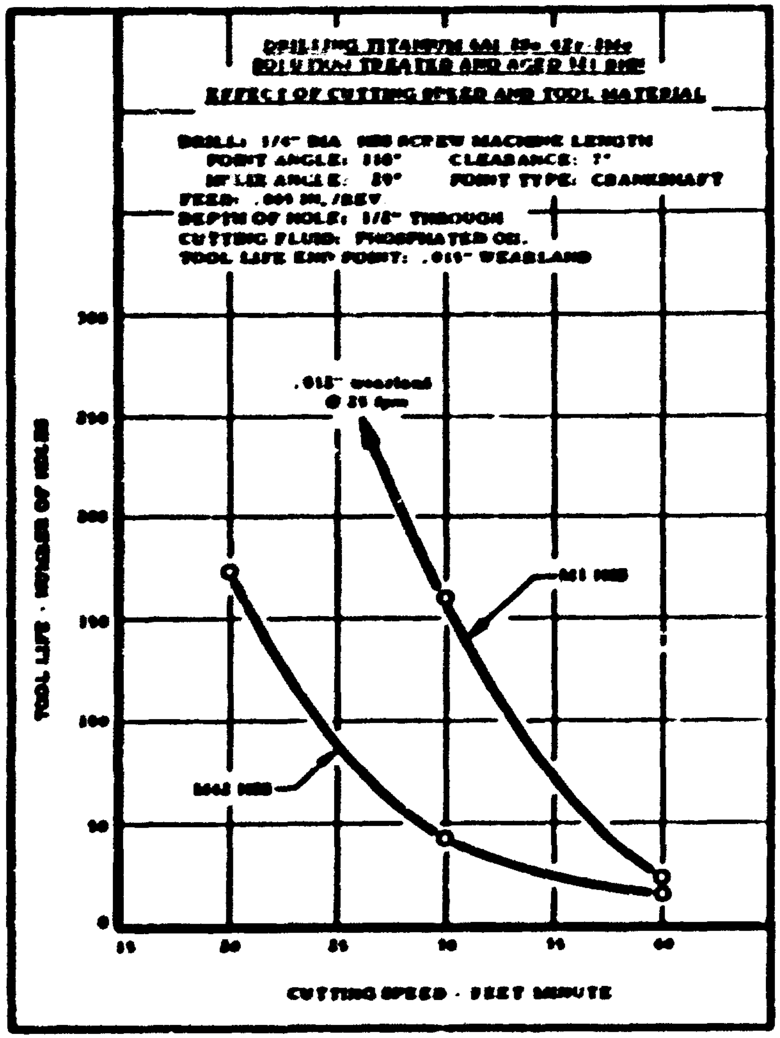


See text, page 137

Figure 149

DRILLING TITANIUM 6Al-2Sn-4Zr-2Mo
SOLUTION TREATED AND AGED 341 BHN
EFFECT OF CUTTING SPEED AND TOOL MATERIAL

DRILL: 1/4" DIA HSS SCREW MACHINE LENGTH
POINT ANGLE: 118° CLEARANCE: 7°
HELIX ANGLE: 29° POINT TYPE: CRANKSHAFT
FEED: .004 IN./REV
DEPTH OF HOLE: 1/2" THROUGH
CUTTING FLUID: PHOSPHATED OIL
TOOL LIFE END POINT: .015" WEARLAND

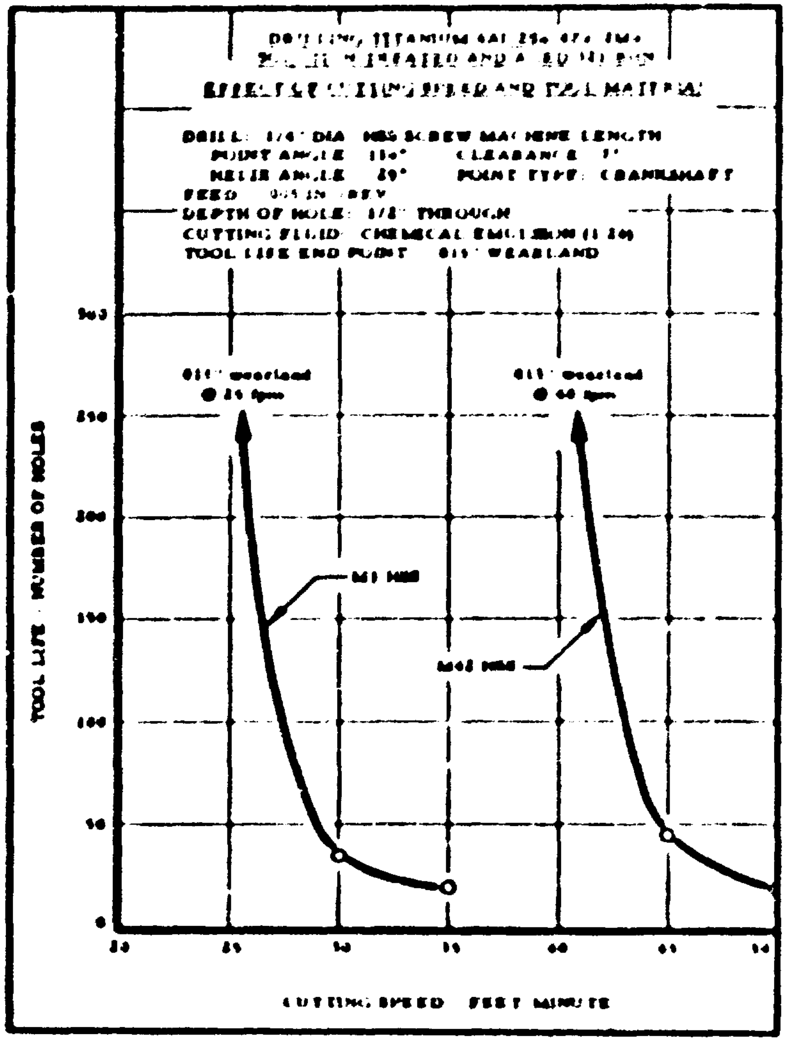


See text, page 117

Figure 150

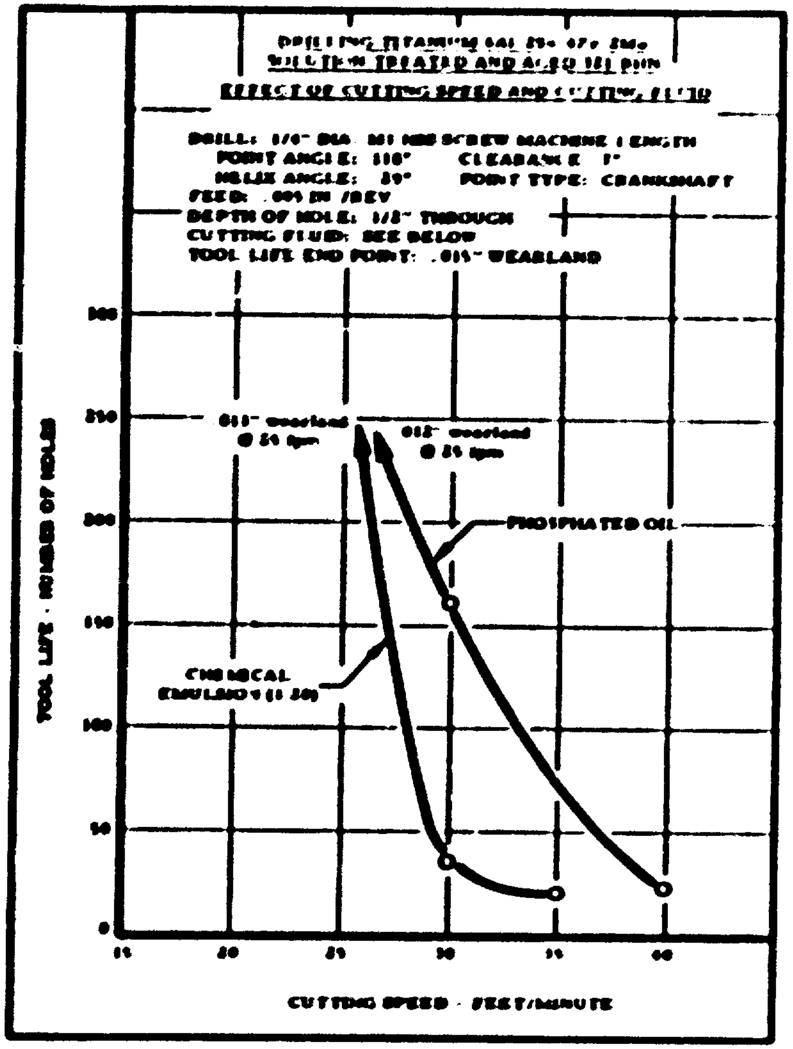
DRILLING TITANIUM 6Al-2Sn-4Zr-2Mo
SOLUTION TREATED AND AGED 341 BHN
EFFECT OF CUTTING SPEED AND TOOL MATERIAL

DRILL: 1/4" DIA HSS SCREW MACHINE LENGTH
POINT ANGLE: 118° CLEARANCE: 7°
HELIX ANGLE: 29° POINT TYPE: CRANKSHAFT
FEED: .005 IN./REV
DEPTH OF HOLE: 1/2" THROUGH
CUTTING FLUID: CHEMICAL EMULSION (1:20)
TOOL LIFE END POINT: .015" WEARLAND



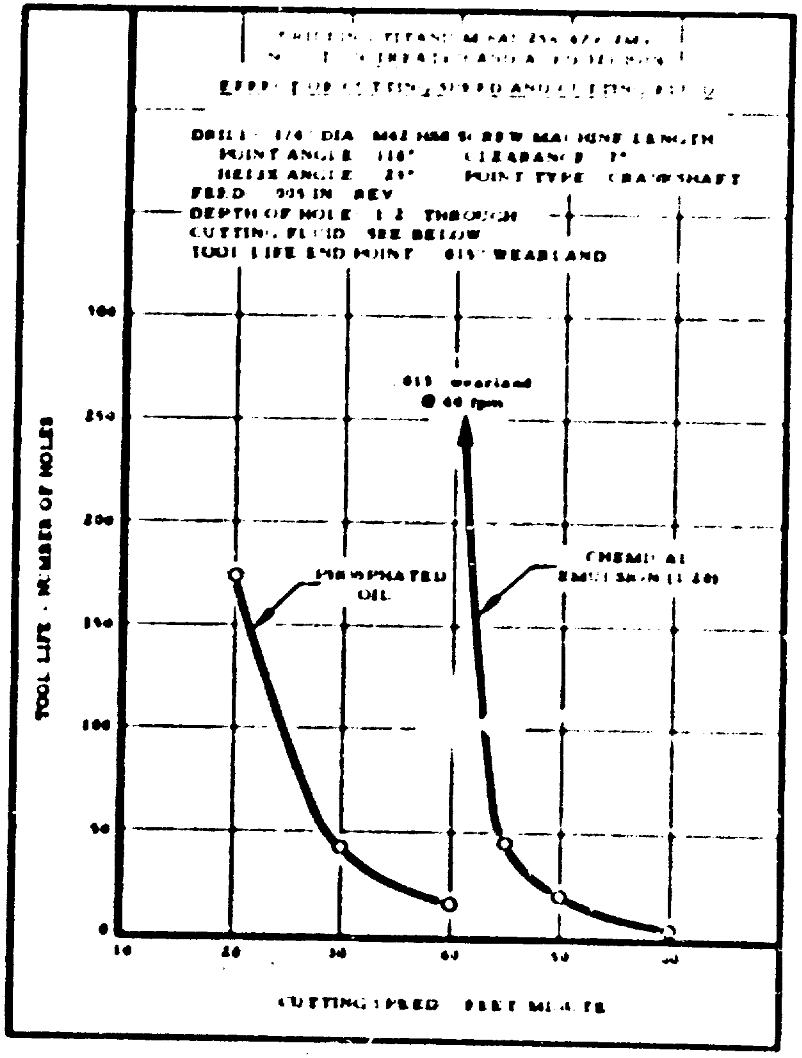
See text, page 117

Figure 151



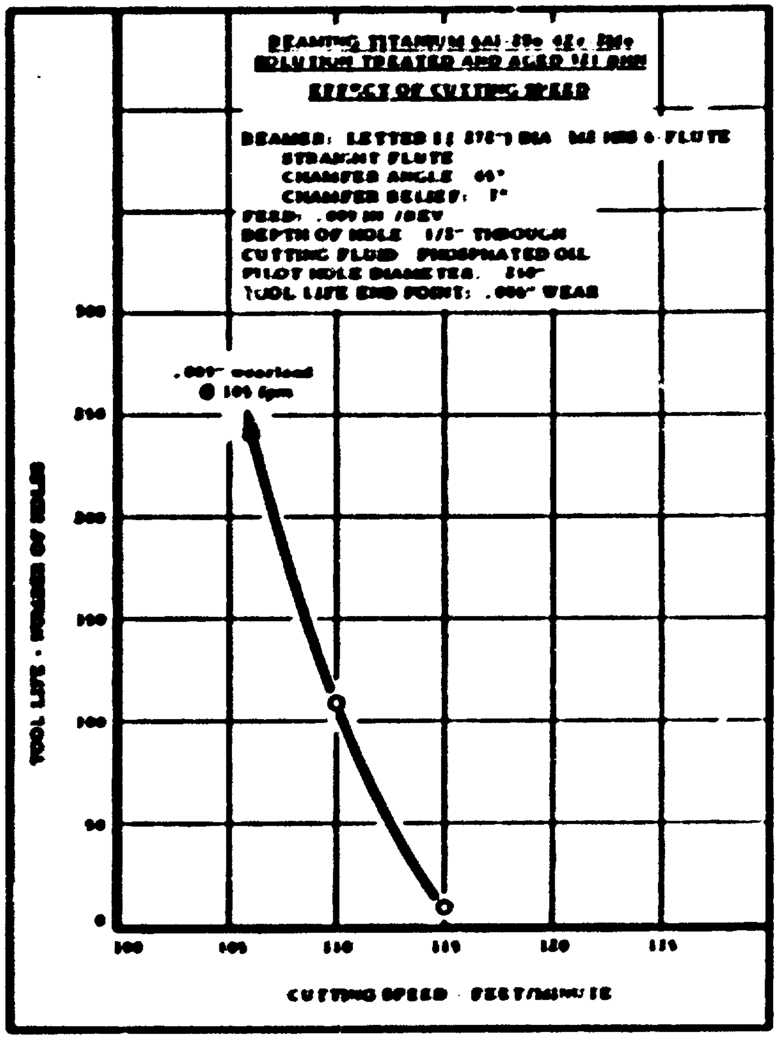
See text, page 117

Figure 112



See text, page 117

Figure 113

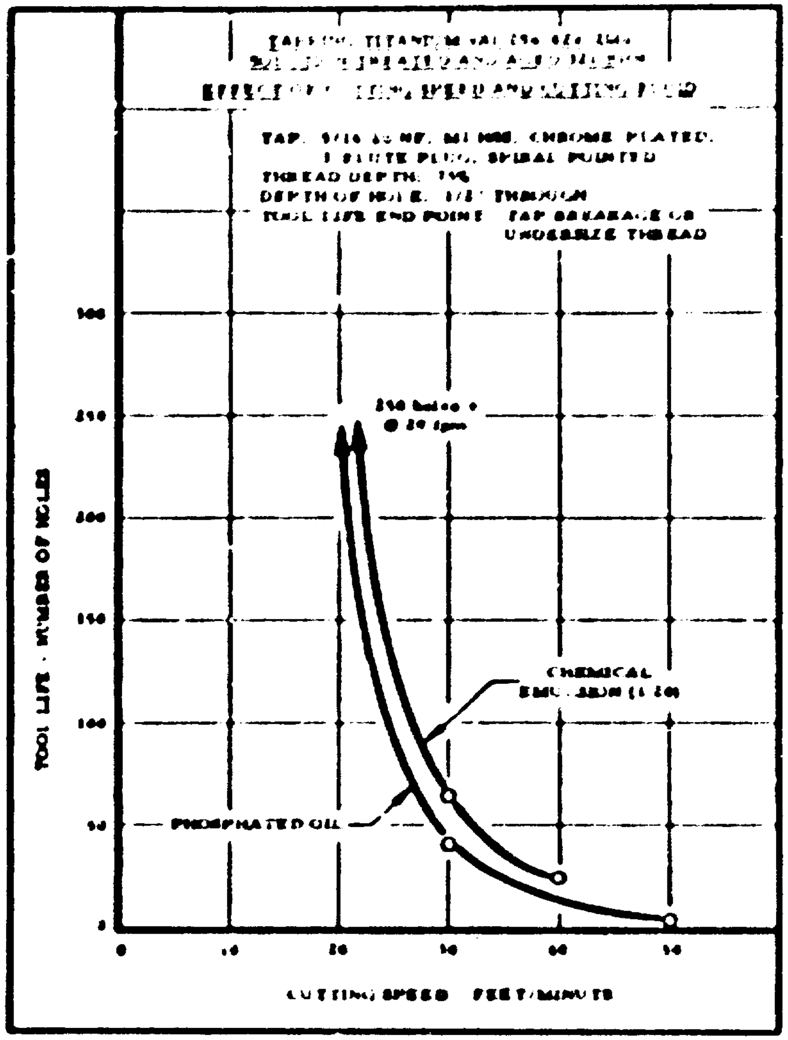


REAMING TITANIUM 6Al-2Sn-4Zr-2Mo
SOLUTION TREATED AND AGED 341 BHN
EFFECT OF CUTTING SPEED

REAMER: LETTER [illegible] DIA M2 HSS 6-FLUTE
STRAIGHT FLUTE
CHAMFER ANGLE 45°
CHAMFER RELIEF: 7°
FEED: .009 IN /REV
DEPTH OF HOLE 1/2" THROUGH
CUTTING FLUID PHOSPHATED OIL
PILOT HOLE DIAMETER .340"
TOOL LIFE END POINT: .006" WEAR

See text, page 110

Figure 116

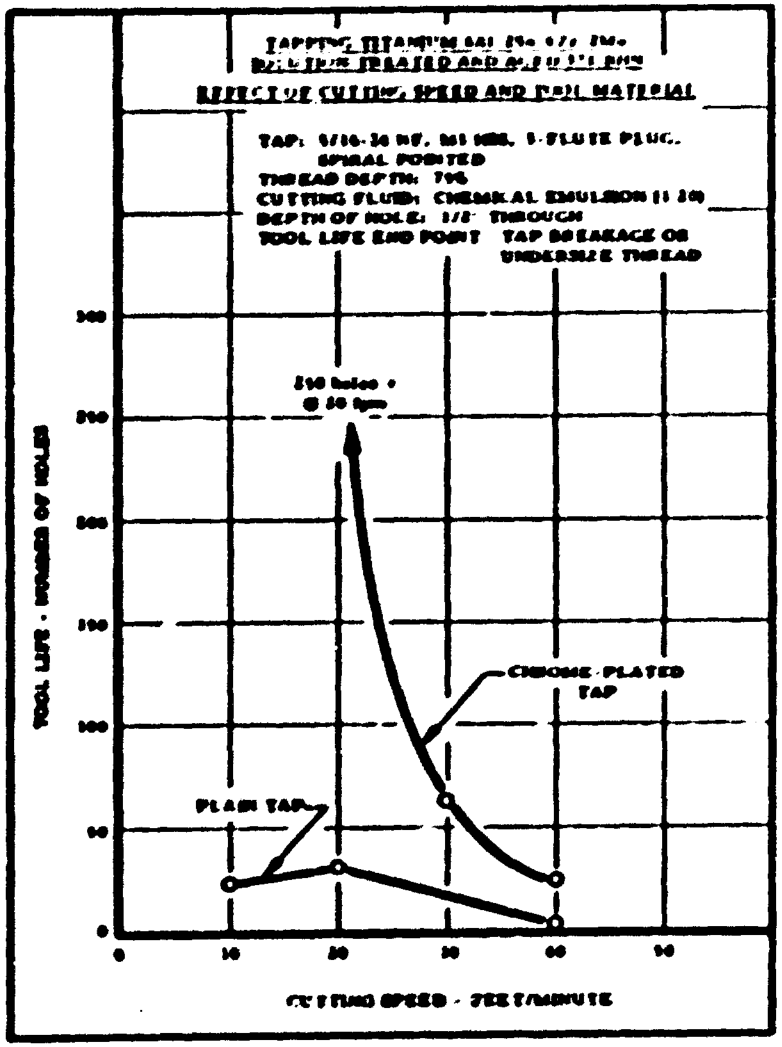


TAPPING TITANIUM 6Al-2Sn-4Zr-2Mo
SOLUTION TREATED AND AGED 341 BHN
EFFECT OF CUTTING SPEED AND CUTTING FLUID

TAP: 5/16-24 NF, M1 HSS, CHROME PLATED,
3 FLUTE PLUG, SPIRAL POINTED
THREAD DEPTH: 75%
DEPTH OF HOLE: 1/2" THROUGH
TOOL LIFE END POINT: TAP BREAKAGE OR
UNDERSIZE THREAD

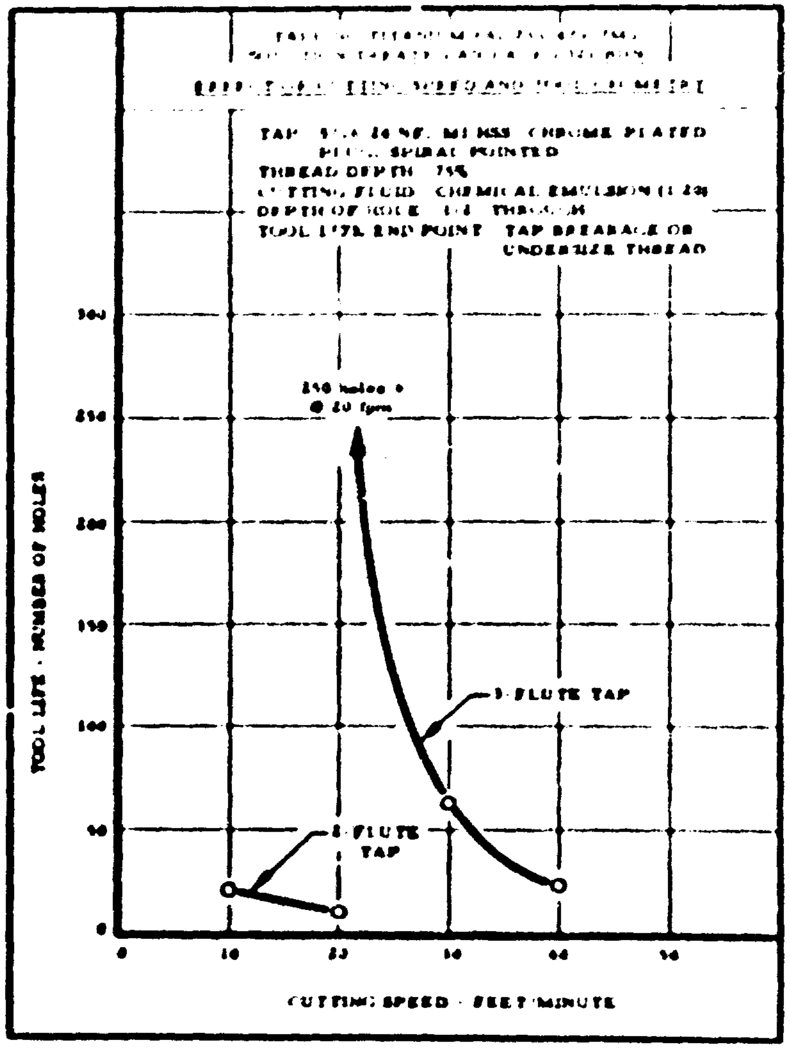
See text, page 110

Figure 117



See text, page 116

Figure 156



See text, page 116

Figure 157

4.4 Titanium 679, Solution Treated and Aged

Alloy Identification

Titanium 679 is a complex alpha-beta titanium alloy designed for elevated temperature application up to 900°F. The nominal composition of this alloy is as follows:

Ti-11.0Sn-5.0Zr-1.0Mo-2.3Al-.2Si-.02C

The material for turning tests was procured as 3 in. diameter bars in the solution treated and aged condition. Rectangular bar stock 2 in. by 4 in. for the milling tests was also procured in the solution treated and aged condition.

The heat treatment performed on this material at the mill was as follows:

Solution Treatment:	1650°F/1 hour/air cool
Age:	930°F/24 hours/air cool

The resulting hardness was 352 BHN. The microstructure, illustrated below, consists of equiaxed alpha plus grain boundary beta and compound phases.

Titanium 679, Solution Treated and Aged

Etchant: HF, HNO_3, H_2 **Mag.: 500X**

4.4 Titanium 679, Solution Treated and Aged (Continued)

Turning (352 BHN)

Figure 158, page 150, presents the tool life curves for both M2 and M42 HSS tools. For a given cutter life, the M42 HSS tool permitted a 12 percent higher cutting speed than the M2 HSS tool.

As shown in Figure 159, page 150, the C-2 grade of carbide again proved to be superior to the C-6 grade in turning a titanium alloy. For example, at a cutting speed of 175 feet/minute, the cutter life with the C-2 grade was 20 minutes as compared to 9 minutes with the C-6 grade.

The use of a soluble oil permitted an increase in cutting speed of about 10 percent over cutting dry when using carbide tools in turning Titanium 679, see Figure 160, page 151. At a cutting speed of 150 feet/minute, the tool life cutting dry was 24 minutes as compared to 41 minutes when using a soluble oil.

The results shown in Figure 161, page 151, indicate that there is a slight advantage in tool life in using tools having negative rake angles over the positive rake angle tools. For example, the turning tool with the 5° negative back rake and side rake angles provided a slightly longer tool life than the cutter having a 0° back rake and a 5° positive side rake angle. In addition, the negative rake angle tool geometry provides more cutting edges per insert and hence is more economical.

Peripheral End Milling (352 BHN)

The tool life curves in Figure 162, page 152, show the effect of various types of cutting fluids on tool life. Note that the chemical emulsion (1:10) was considerably more effective than either the sulfurized oil or the phosphated soluble oil. For example, at a cutting speed of 175 feet/minute, the tool life values were 12 inches of work travel for the phosphated soluble oil, 60 inches for the sulfurized oil, and 215 inches for the chemical emulsion.

As has been found in the past, the selection of the feed rate in peripheral end milling titanium alloys is somewhat critical. Note that in Figure 163, page 152, at a cutting speed of 165 feet/minute the cutter life dropped from 200 to 120 inches of work travel when the feed was increased from .002 to .0025 in./tooth.

Peripheral End Milling (352 BHN) (continued)

As shown in Figure 164, page 153, the M42 HSS end mills provided appreciably longer tool life than the M2 HSS cutters. At a cutting speed of 230 feet/minute, the cutter life increased from 80 to 335 inches of work travel when an M42 HSS tool was substituted for the M2 HSS tool. From a production standpoint, at a tool life of 200 inches of work travel, the M42 HSS tool permitted a cutting speed of 215 feet/minute as compared to 178 feet/minute for the M2 HSS tool, an increase of 20 percent.

Very often, in order to increase the tool life when machining a more difficult alloy, there is a tendency to increase the richness of the water soluble fluid. As shown in Figure 165, page 153, this is not always advantageous. For example, the chemical emulsion that was used performs slightly better when diluted 1:20 as compared to a 1:10 dilution.

It is particularly important when machining titanium alloys to use a rigid setup. This fact is again demonstrated in Figure 166, page 154. Note that when the depth of cut was doubled, that is increased from .125 to .250 in., an appreciable decrease in cutter life occurred. The feed was .002 in./tooth. At a tool life of 150 inches of work travel, the cutting speed at a depth of cut of .125 in. was 227 feet per minute, while at a depth of cut of .250 in. the cutting speed has to be reduced to 180 feet/minute.

Drilling (352 BHN)

The drilling speeds with the M42 HSS tools were over 100 percent faster than the speeds with the M1 HSS tools; see Figure 167, page 154. At a tool life of over 250 holes, the drilling speed with the M1 HSS drills was 15 feet/minute as compared to 40 feet/minute with the M42 HSS drill.

A comparison of two cutting fluids in drilling is presented in Figure 168, page 155. The drilling speeds with the chemical emulsion were four times faster with the phosphated oil.

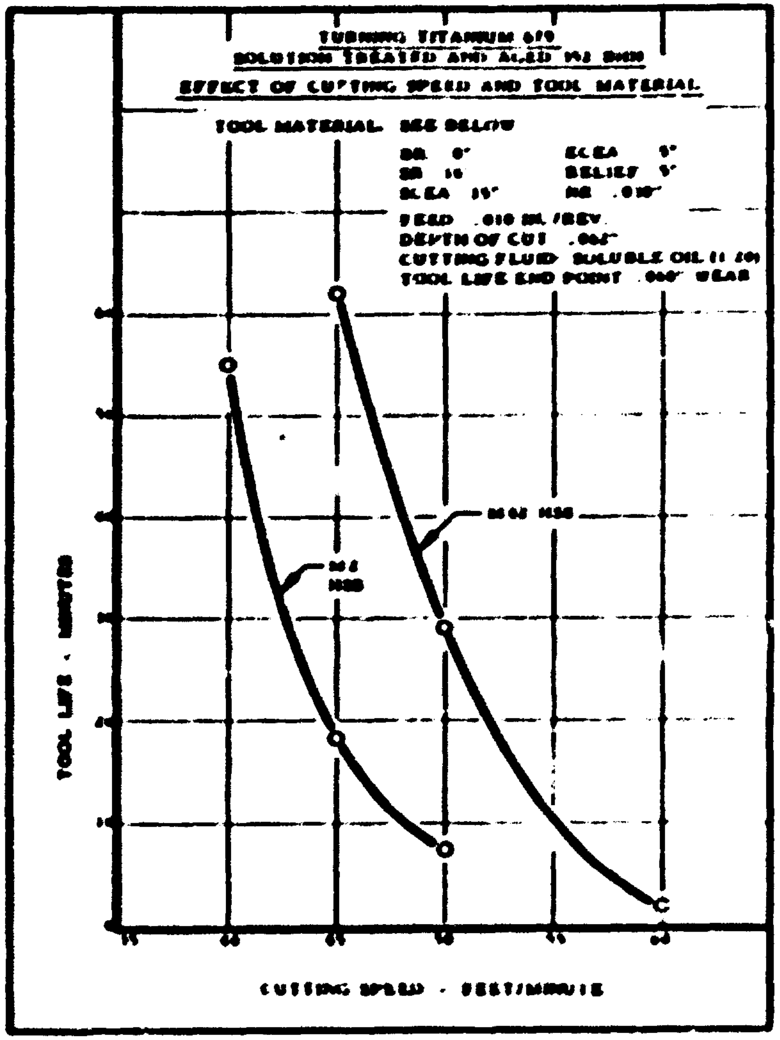
TABLE XI

RECOMMENDED CONDITIONS FOR MACHINING TITANIUM 679, SOLUTION TREATED AND AGED 352 BHN

Nominal Chemical Composition, Percent

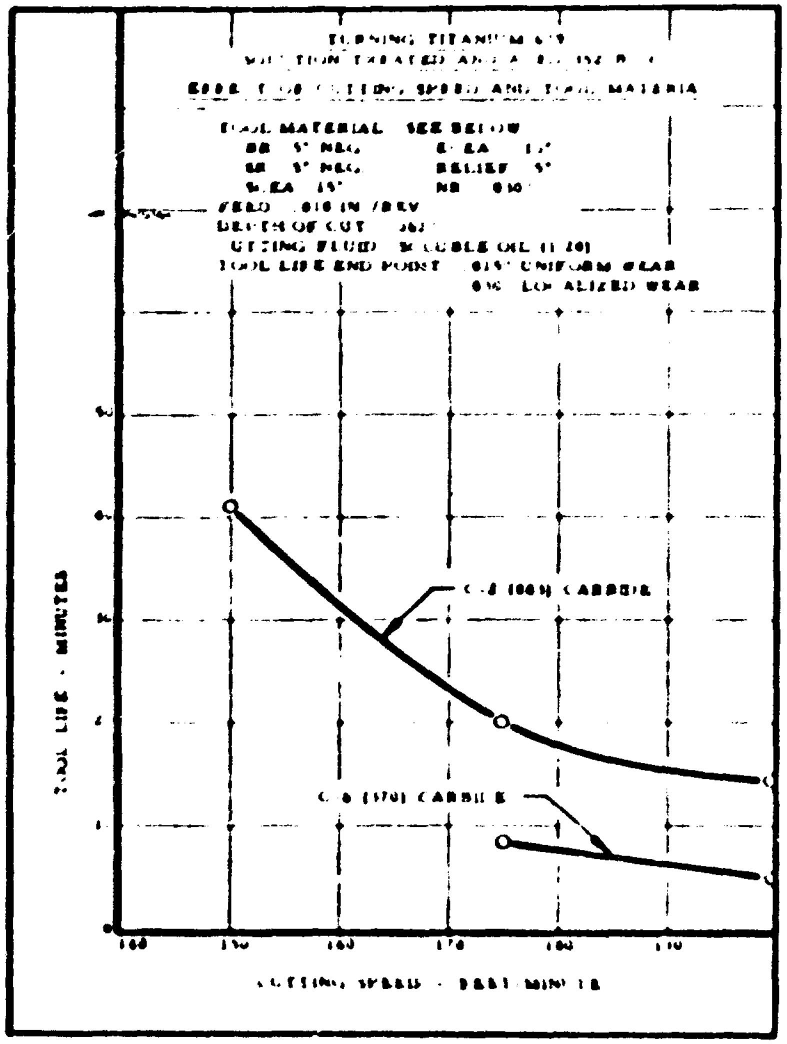
Ti	Sn	Zr	Mo	Al	Si	C
Bal.	11.0	5.0	1.0	2.3	.2	.02

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Turning	M42 HSS	BR: 0° SCEA:15° SR:10° ECEA:5° Relief: 5° NR: .030"	5/8" square tool bit	.062	-	.010 in/rev	45	62 min.	.060	Soluble Oil (1:20)
Turning	C-2 Carbide	BR:-5° SCEA:15° SR: -5° ECEA:15° Relief: 5° NR: .030"	SNG 432 Insert	.062	-	.010 in/rev	150	41 min.	.015	Soluble Oil (1:20)
Peripheral End Milling	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA:45° x .060"	1" diameter 4 Flute HSS End Mill	.125	.500	.002 in/tooth	225	160" work travel	.012	Chemical Emulsion (1:20)
Drilling	M42 HSS	Point Angle:118° Helix Angle: 29° Clearance Angle: 7°	1/4" dia. HSS Drill 2-1/2" long	.500 thru	-	.005 in/rev	40	250 holes	.015	Chemical Emulsion (1:20)



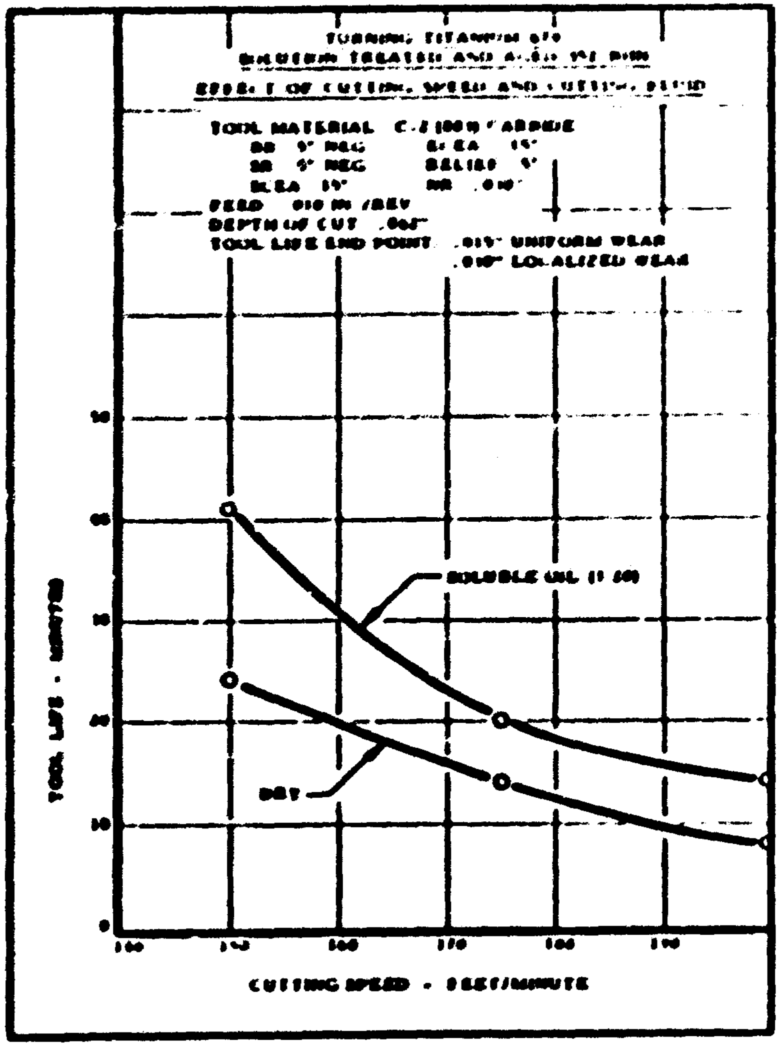
See text, page 167

Figure 110



See text, page 167

Figure 111



See text, page 167

Figure 140

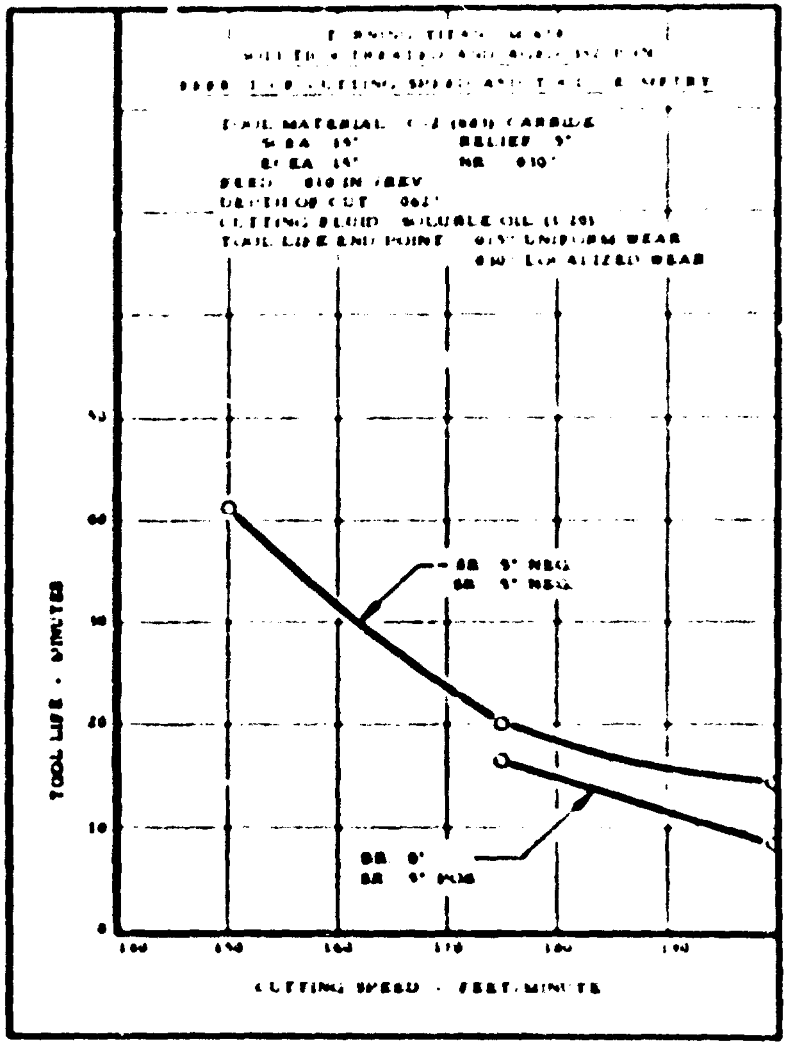


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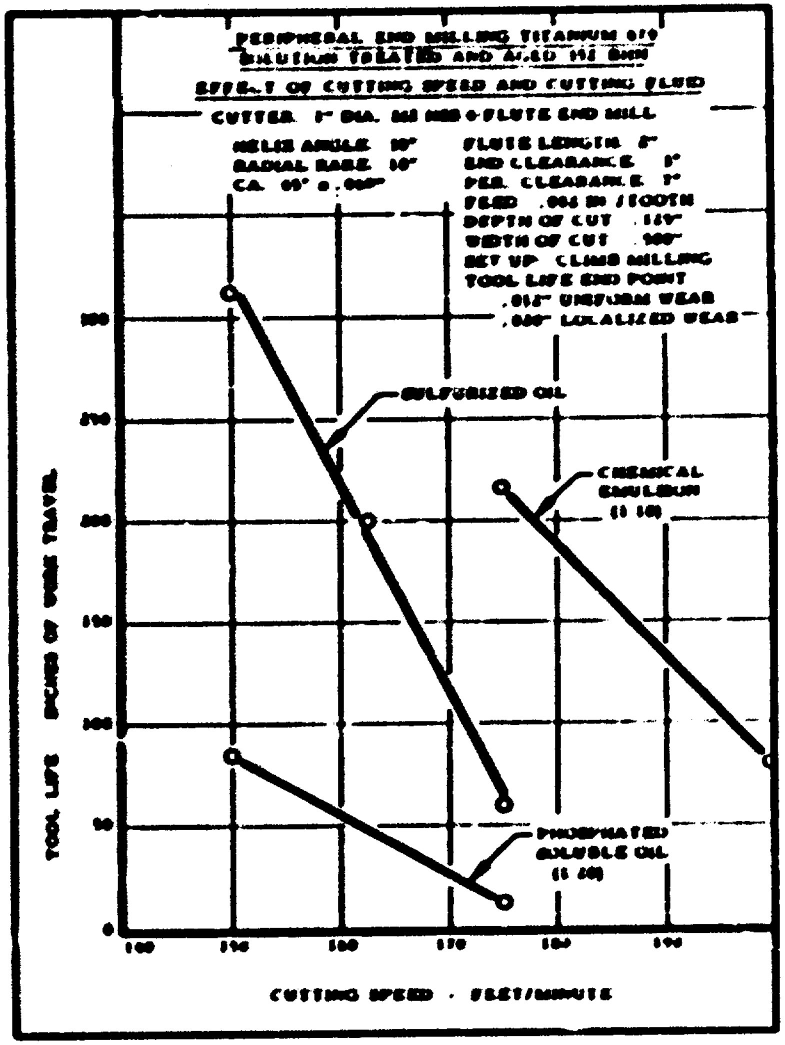
Figure 141



See text, page 167

Figure 1-2

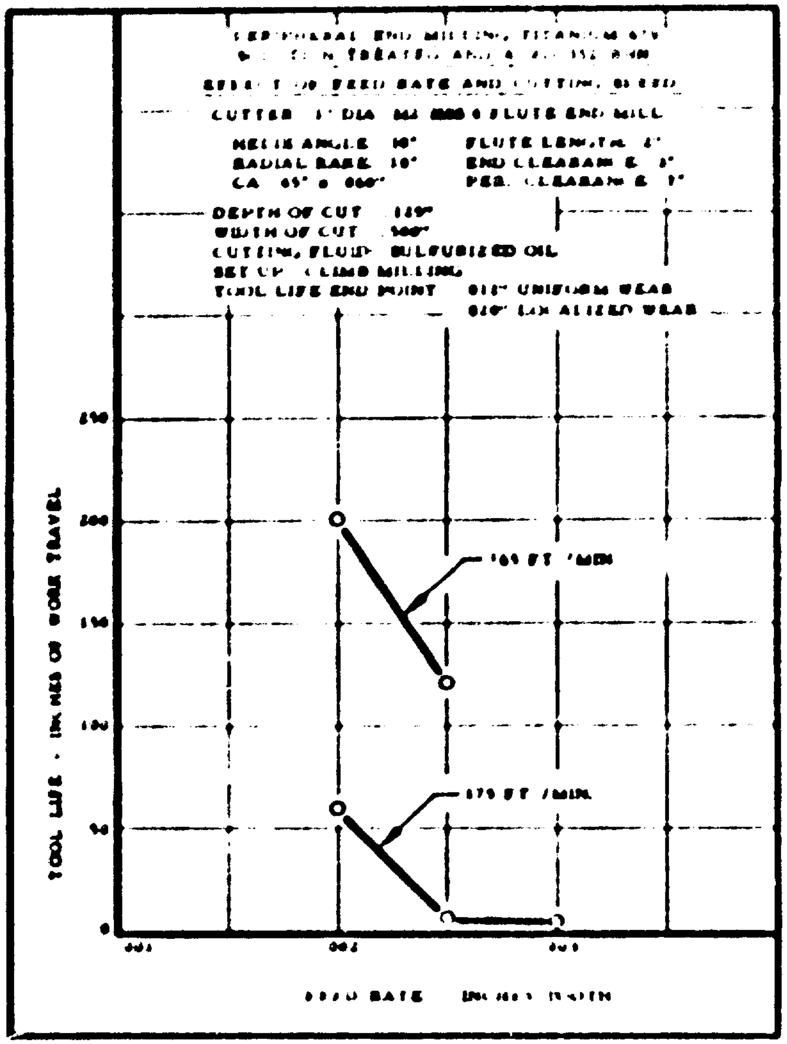


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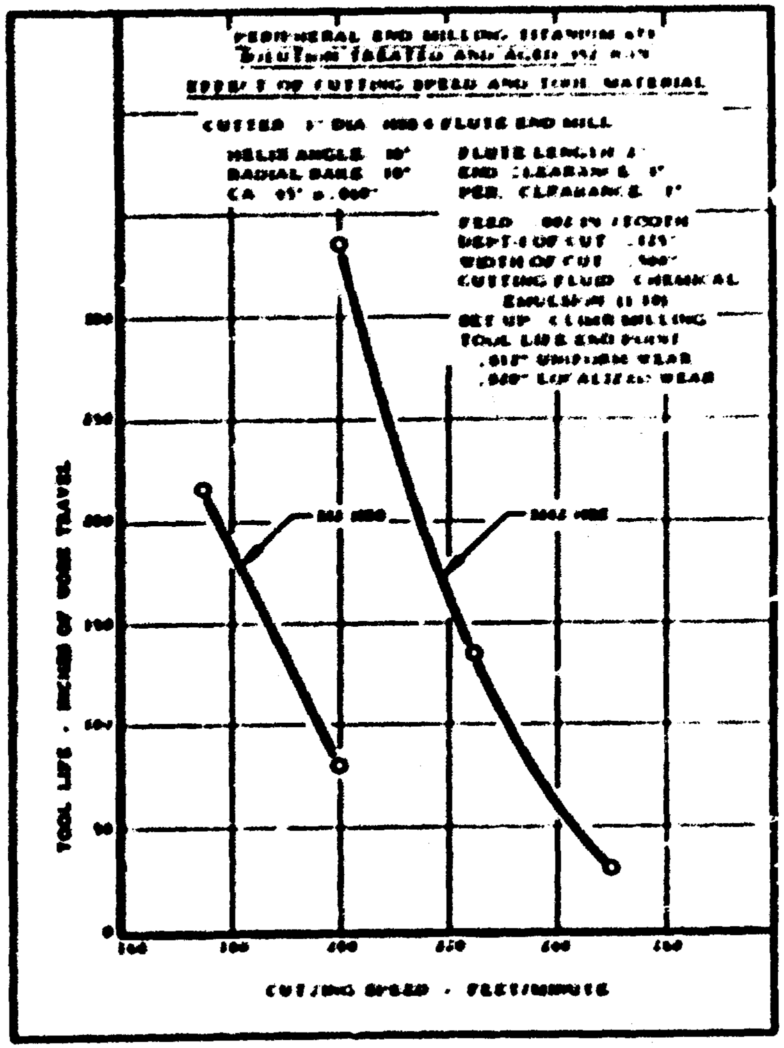
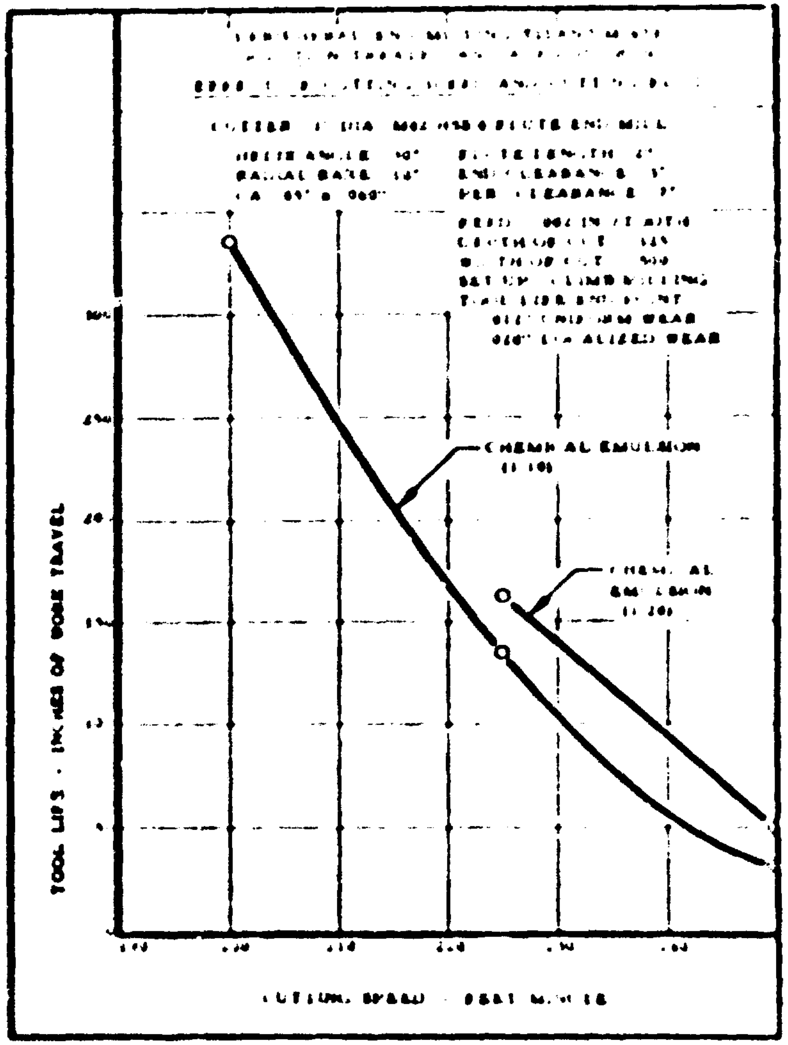
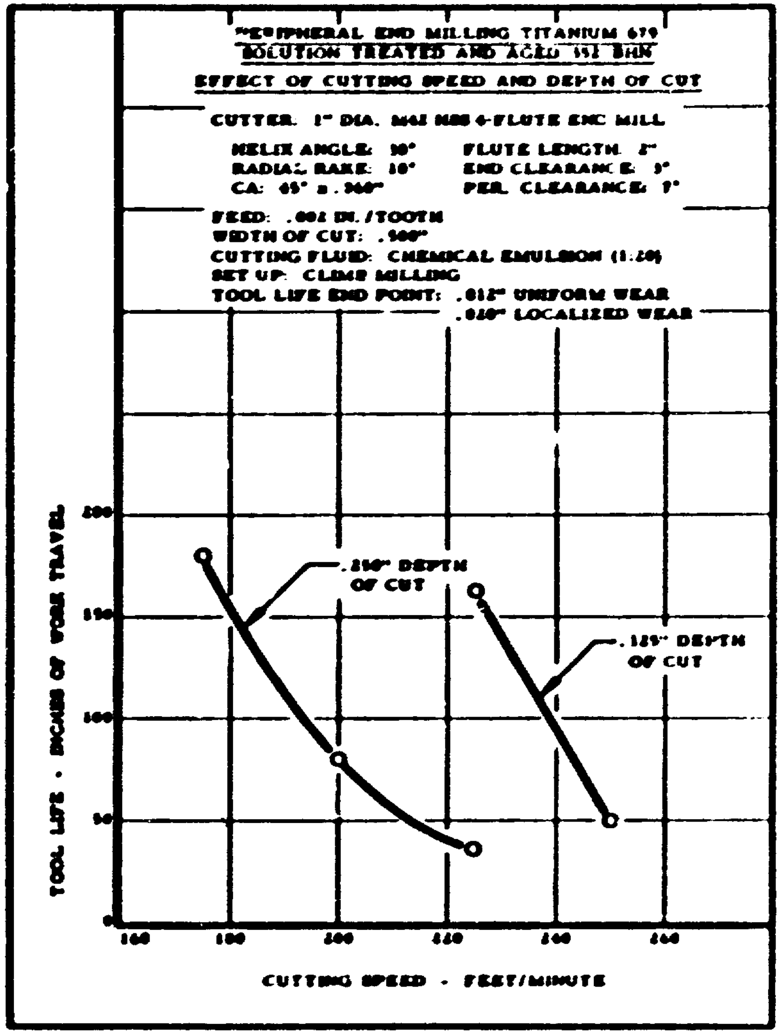
Figure 1-1



See text, page 160 Figure 166



See text page 160 Figure 165



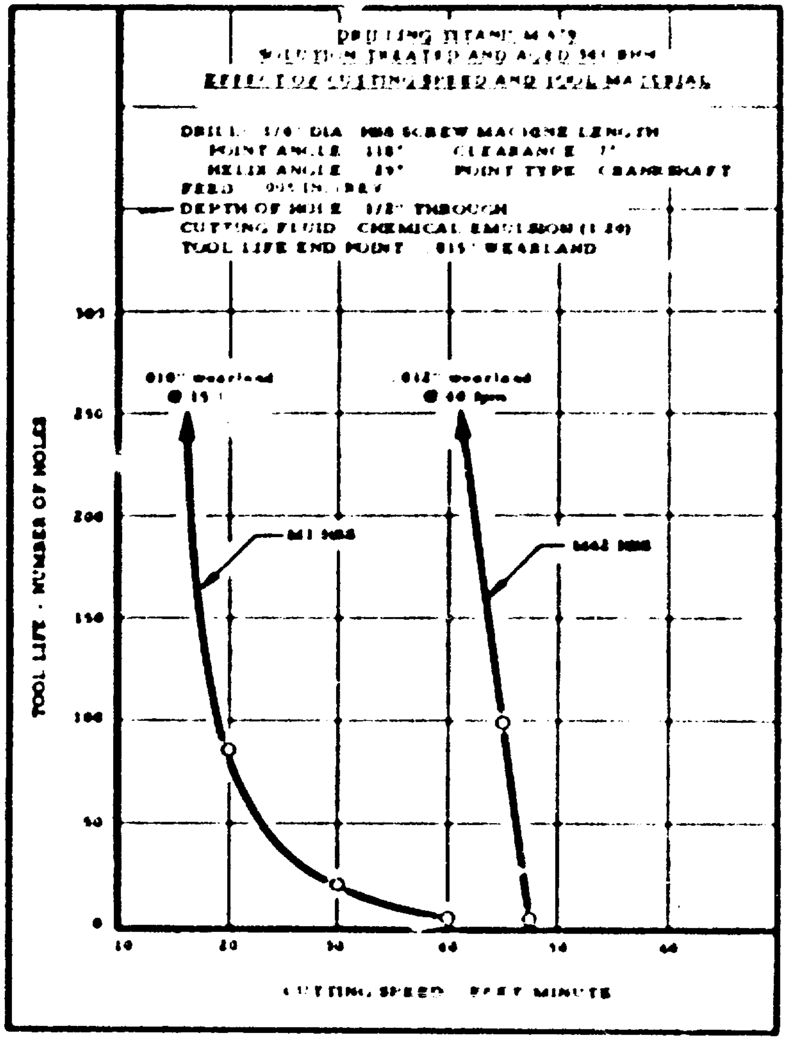
PERIPHERAL END MILLING TITANIUM 679
SOLUTION TREATED AND AGED 352 BHN
EFFECT OF CUTTING SPEED AND DEPTH OF CUT

CUTTER: 1" DIA. M42 HSS 4-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2"
RADIAL RAKE: 10° END CLEARANCE: 5°
CA: 45° x .060" PER. CLEARANCE: 7°

FEED: .002 IN./TOOTH
WIDTH OF CUT: .500"
CUTTING FLUID: CHEMICAL EMULSION (1:20)
SET UP: CLIMB MILLING
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 168

Figure 166

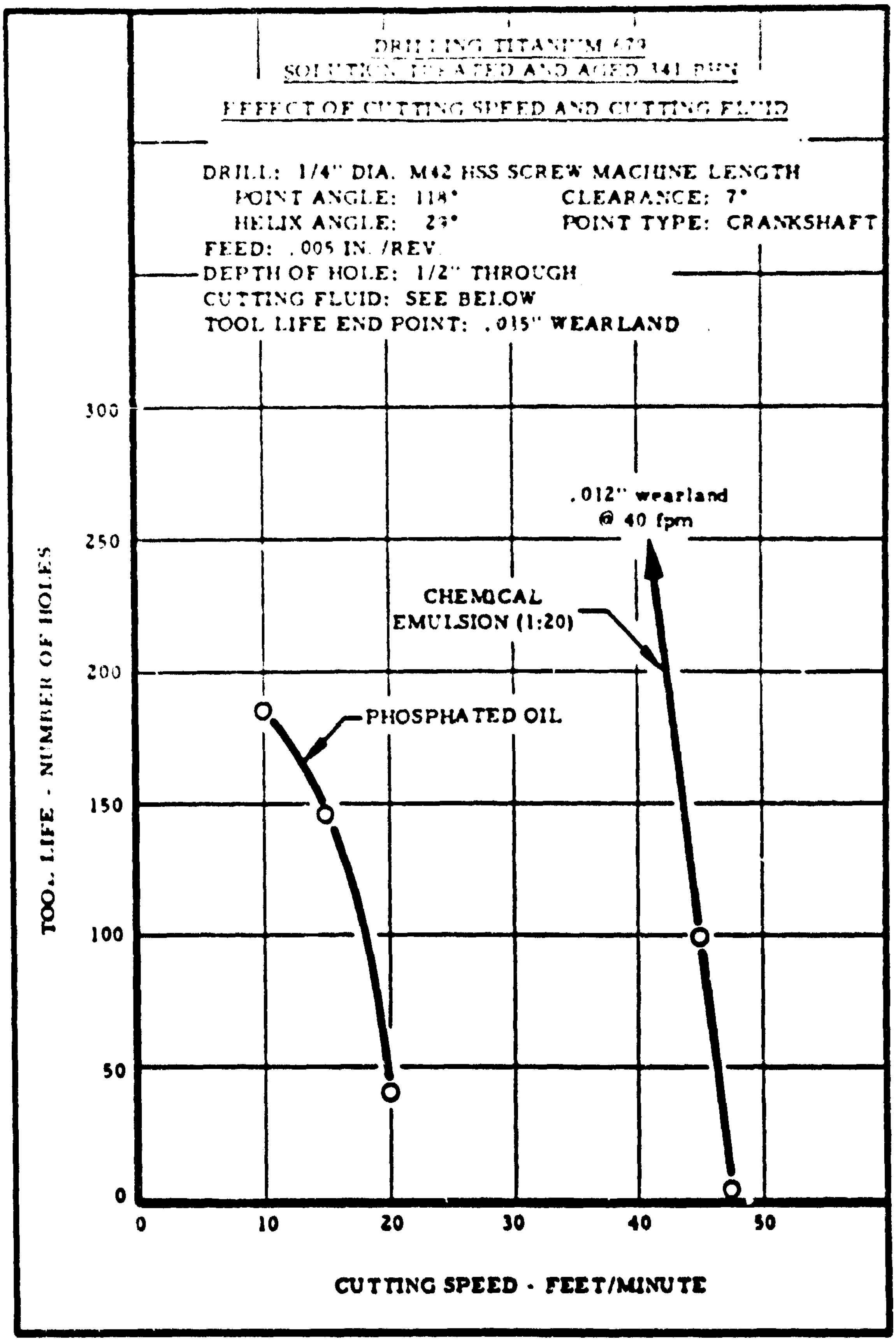


DRILLING TITANIUM 679
SOLUTION TREATED AND AGED 341 BHN
EFFECT OF CUTTING SPEED AND TOOL MATERIAL

DRILL: 1/4" DIA. HSS SCREW MACHINE LENGTH
POINT ANGLE 118° CLEARANCE 7°
HELIX ANGLE 29° POINT TYPE CRANKSHAFT
FEED .005 IN./REV
DEPTH OF HOLE 1/2" THROUGH
CUTTING FLUID CHEMICAL EMULSION (1:20)
TOOL LIFE END POINT .015" WEARLAND

See text, page 168

Figure 167



See text, page 148

Figure 168

5. MACHINING NICKEL BASE ALLOYS

5.1 Inconel 718, Solution Treated and Aged

Alloy Identification

Inconel 718 is a high temperature alloy useful in the intermediate temperature range up to about 1400°F. The material has the following nominal composition:

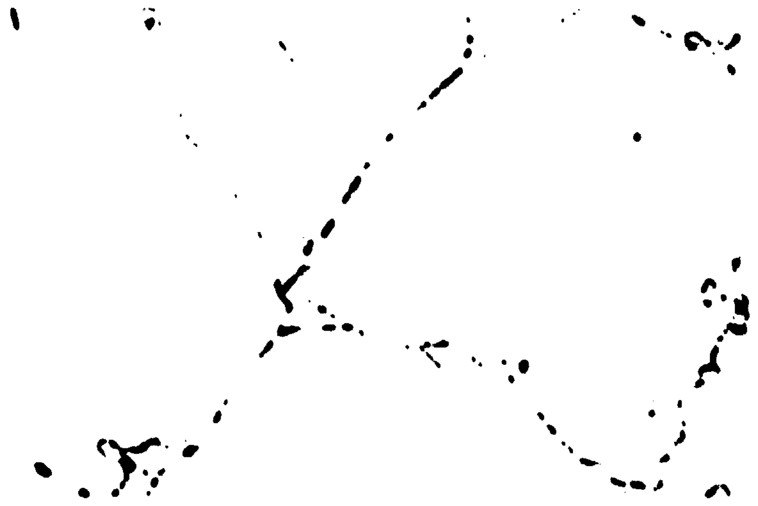
Ni-19Cr-3Mo-5.2Cb+Ta-0.8Ti-0.6Al-18Fe-.06C

Bars 4 in. square by 12 in. long were procured in the forged, solution treated and aged condition for the machining tests. The material was given the following heat treatment:

Solution: 1750°F/1 hour/air cool
Age: 1325°F/8 hours/furnace cool to 1150°F
Hold at 1150°F for 8 hours/air cool

The hardness as the result of the above treatment was determined as 41 R_c.

The microstructure of the alloy shown consists of large, equiaxed grains with complex carbides precipitated along the grain boundaries. Some twinning characteristics are evidenced in the austenitic matrix.



Inconel 718, Solution Treated and Aged

Etchant: Kalling's **Mag.: 500X**

5.1 Inconel 718, Solution Treated and Aged (continued)

Peripheral End Milling (45 R_c)

A comparison of climb cutting with conventional cutting when peripheral end milling Inconel 718 is shown in Figure 169, page 162. Note that the 1 in. diameter cutter had a flute length of 1 in. and that, for the machining conditions used, climb milling was far superior to conventional milling. As a matter of fact, for a tool life of 60 inches of work travel, the cutting speed with climb milling was two and one-half times that with conventional milling. However, as shown in Figure 170, page 162, when the flute length was 2 in., conventional milling was slightly better than climb milling. Apparently, the impact of climb cutting was too severe for the longer cutter, and hence the tool life was less.

The effect of flute length when climb cutting is shown in Figure 171, page 163. The importance of a rigid setup is immediately evident from this comparison. For the same feed, depth of cut and width of cut, the shorter end mill provided double the tool life at a cutting speed of 10 feet/minute. For a given tool life, the cutting speed with the 1 in. flute length end mill was more than two and one-half times faster than when machining with the 2 in. flute length end mill. It should be pointed out that this comparison was made using climb milling. Note in Figure 172, page 163, that when conventional milling was used, the effect of flute length in this range was not very significant.

As has been pointed out many times in the past, when machining a difficult-to-machine alloy such as Inconel 718, the setup must be rigid before it is possible to obtain a reasonable tool life. Figure 173, page 164, shows the tool life curves obtained at two different depths of cut. At the lighter depth of cut, the tool life was more than two and one-half times longer than that obtained at the .125 in. depth of cut. Also, it should be pointed out that while the depth of cut was only half as great with the .062 in. depth, the cutting speed for a 50-in. tool life was more than two and one-half times faster and hence the metal removal rate was greater under these conditions than with the greater depth of cut.

From the two tool life curves shown in Figure 174, page 164, it is apparent that the width of cut in the range of .375 to .750 in. was not too critical with respect to tool life. For at a cutting speed of 10 feet/minute, the tool life for these two widths of cut was the same. Only at the higher cutting speeds was there a difference. Note that these results were obtained with a cutter having a flute length of 2 in.

5.1 Inconel 718, Solution Treated and Aged (continued)

Peripheral End Milling (45 R_c) (continued)

Tool life curves for three different grades of high speed steel are shown in Figure 175, page 165. The type M42 HSS was far better than either the M2 or the T15. The T15 HSS was the poorest of the three, principally because it tended to chip more readily. Note that at a cutting speed of 20 feet/minute, the tool lives for the M42, the M2 and the T15 HSS were respectively 144, 72 and 36 inches of work travel. The depth of cut in all the tests shown in this figure was .062 in. Increasing the depth of cut to .125 in. resulted in an even greater difference in the performances of the M42 and the M2 tools. For as shown in Figure 176, page 165, the cutter life with the M42 tool was more than three times that obtained with the M2 HSS.

The effect of feed on tool life is shown in Figure 177, page 166, for both the M42 and the M2 HSS tools. The lighter feed of .0025 in./tooth was the best for both tools at the speeds shown. Not only was the tool life less at the higher feeds, but there was more tendency for the cutting edge to chip as the feed was increased.

A comparison of climb cutting with conventional cutting with type M42 HSS tools is presented in Figure 178, page 166. In this case, the climb cutting was far superior to conventional cutting even when the flute length was 2 in.

Also as shown in Figure 179, page 167, increasing the depth of cut reduces the tool life appreciably. For example, at a cutting speed of 15 feet/minute, the tool life decreased 50 percent when the depth of cut was increased from .062 to .125 in.

In an attempt to increase the production rate in peripheral milling Inconel 718 in the solution treated and aged condition, carbide end mills were used. It should be first pointed out that, in order to use carbides in machining an alloy such as Inconel 718 (which work hardens readily), positive rake angles must be used on the cutter. This requirement immediately eliminates most of the commercially available cutters since they generally utilise negative rake angles. The cutter that was used in these tests had a helix angle of 0° and a radial rake of 0°.

Figure 180, page 167, shows a comparison for a large number of different grades of carbides that were used to attempt to find the best carbide for the conditions employed. At the feed of .002 in./tooth

5.1 Inconel 718, Solution Treated and Aged (continued)

Peripheral End Milling (45 R_c) (continued)

and the cutting speed of 200 feet/minute, the K6 (C-2) grade proved to be best of the large number tested. A comparison of two C-2 grades is presented in Figure 181, page 168, at a feed of .002 in./tooth and over a range of cutting speeds. Note that the K6 grade provided a tool life of 275 inches of work travel at a cutting speed of 150 feet/minute, while the tool life with the 883 grade was 155 inches of work travel. It should be pointed out that tool failure resulted primarily from chipping and not tool wear. This is usually the condition when attempts are made to mill these highly work hardenable alloys.

As one might expect, the depth of cut has even a greater influence on the tool life when using carbide than when using high speed steel, the reason being that increasing the depth of cut tends to increase the rate of chipping of the cutting edge. Note in Figure 182, page 168, that the cutter life decreased from 275 inches to 60 inches of work travel when the depth of cut was increased from .062 to .125 in. at a cutting speed of 150 feet/minute.

However, at the heavier depth of cut of .125 in., the 883 grade proved to be less prone to chipping than the K6. Hence, as shown in Figure 183, page 169, the cutter life at a cutting speed of 150 feet/minute increased from 120 inches with the K6 tool to 145 inches of work travel with the 883 tool.

The effect of depth of cut on tool life is presented in Figure 184, page 169, using an 883 grade of carbide. The cutter life decreased from 275 to 145 inches of work travel when the depth of cut was increased from .062 to .125 in.

The two tool life curves shown in Figure 185, page 170, demonstrate how critical the selection of machining conditions is when machining the high nickel base alloys. For example, at a cutting speed of 100 feet/minute, the tool life dropped from 275 to 105 inches of work travel when the feed was increased from .002 to .003 in./tooth. At the same cutting speed, if the feed was decreased to .001 in./tooth, the tool life was 202 inches of work travel. At a higher cutting speed of 200 feet/minute, the best tool life was reached at .001 in./tooth.

A comparison of a K6 and an 883 grade of carbide over a range of feeds at the cutting speed of 200 feet/minute indicates that the feed

5.1 Inconel 718, Solution Treated and Aged (continued)

Peripheral End Milling (45 R_c) (continued)

of .002 in./tooth would be the best with the K6 grade of carbide (see Figure 186, page 170).

The advantages of carbide tools over high speed steel tools are clearly indicated in Figure 187, page 171. Note that the tool life with the M2 high speed steel tool at a cutting speed of 10 feet/minute was only 50 inches of work travel, while with the C-2 grade of carbide (K6) a tool life of 275 inches was obtained at a cutting speed of 150 feet/minute. The type M42 HSS tool provided a tool life of 130 inches at a cutting speed of 15 feet/minute. The difference in the width of cut with the HSS and carbide cutters was not believed to be a significant factor affecting tool life. It also should be noted that the high speed steel tool had four teeth, while the carbide cutter only had three teeth.

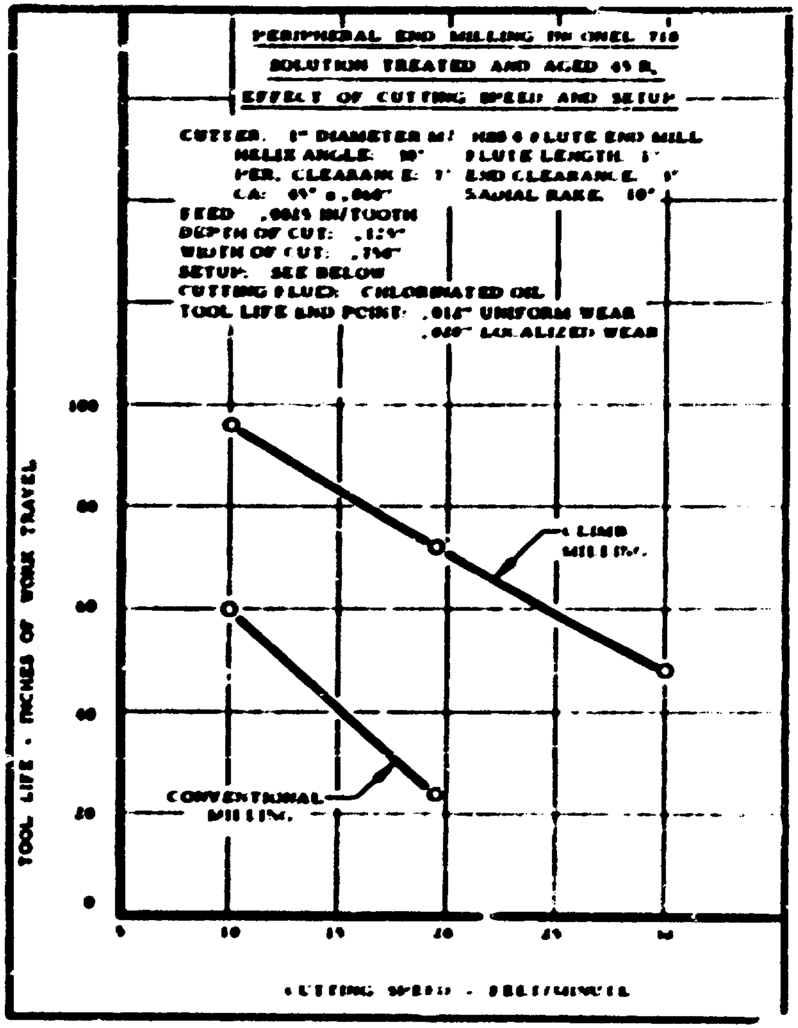
TABLE XII

RECOMMENDED CONDITIONS FOR MACHINING INCONEL 718, SOLUTION TREATED AND AGED 45 R_c

Nominal Chemical Composition, Percent

Ni	Cr	Mo	Cb	Ti	Al	Fe
Bal.	19	3	5.2	0.8	0.6	18

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT INCHES	WIDTH OF CUT INCHES	FEED	CUTTING SPEED FT./MIN.	TOOL LIFE	WEAR-LAND INCHES	CUTTING FLUID
Peripheral End Milling	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	1" Diameter 4 Flute HSS End Mill	.125	.750	.0025 in/tooth	15	96" work travel	.012	Chlorinated Oil
Peripheral End Milling	C-2 Carbide	Helix Angle: 0° RR: 0° Clearance: 10° NR: .030"	1-3/8" Diameter 3 Tooth Carbide Insert End Mill	.062	.375	.002 in/tooth	150	275" work travel	.012	Chlorinated Oil



PERIPHERAL END MILLING INCONEL 718

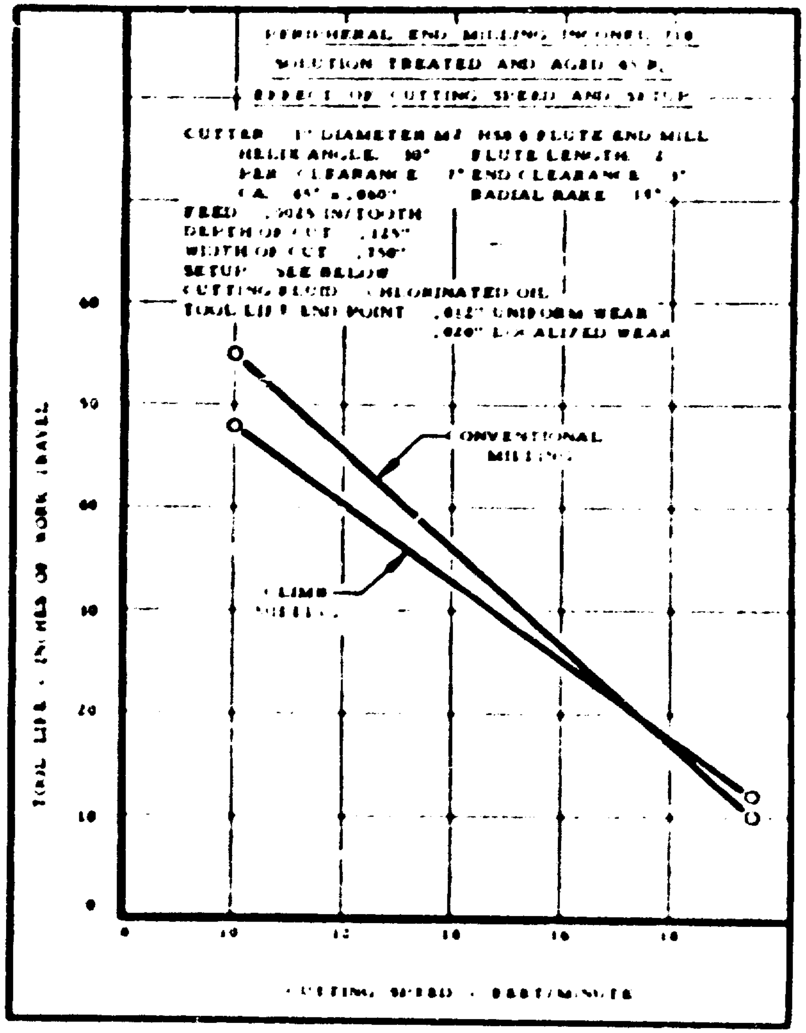
SOLUTION TREATED AND AGED 45 R

EFFECT OF CUTTING SPEED AND SETUP

CUTTER: 1" DIAMETER M2 HSS 4 FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 1"
PER. CLEARANCE: 7° END CLEARANCE: 3°
C.A.: 45° x .060" RADIAL RAKE: 10°
FEED: .0025 IN/TOOTH
DEPTH OF CUT: .125"
WIDTH OF CUT: .750"
SETUP: SEE BELOW
CUTTING FLUID: CHLORINATED OIL
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text page 151

Figure [illegible]



PERIPHERAL END MILLING INCONEL 718

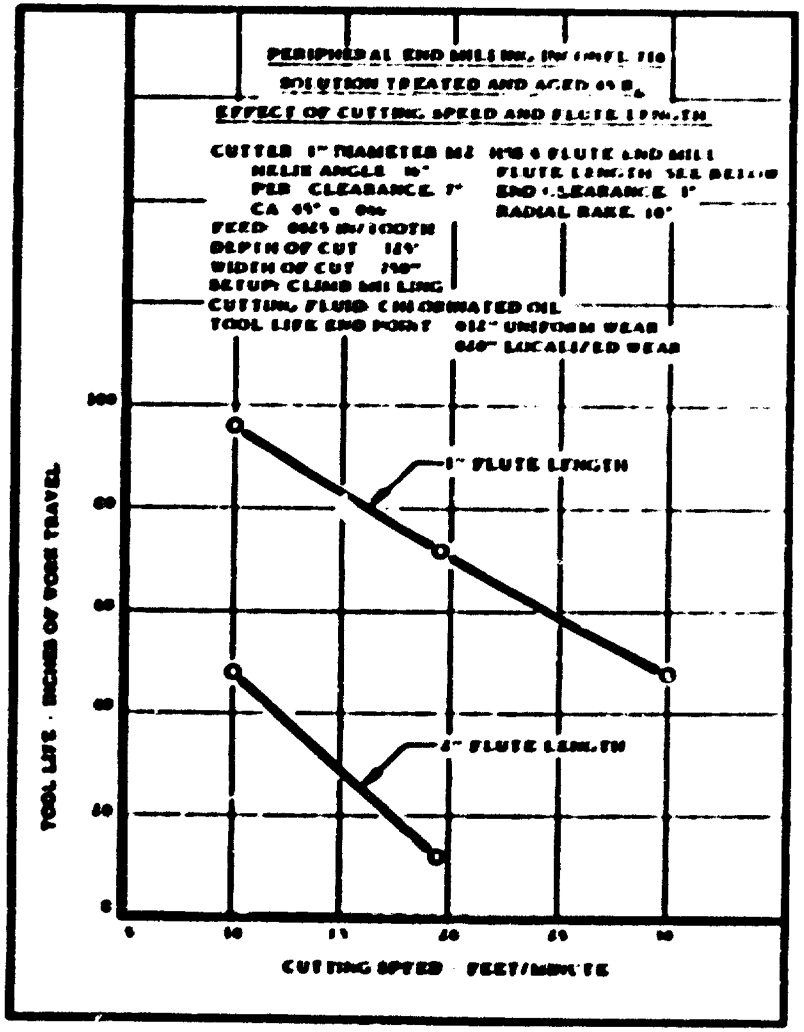
SOLUTION TREATED AND AGED 45 R

EFFECT OF CUTTING SPEED AND SETUP

CUTTER: 1" DIAMETER M2 HSS 4 FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 1"
PER. CLEARANCE: 7° END CLEARANCE: 3°
C.A.: 45° x .060" RADIAL RAKE: 10°
FEED: .0025 IN/TOOTH
DEPTH OF CUT: .125"
WIDTH OF CUT: .750"
SETUP: SEE BELOW
CUTTING FLUID: CHLORINATED OIL
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

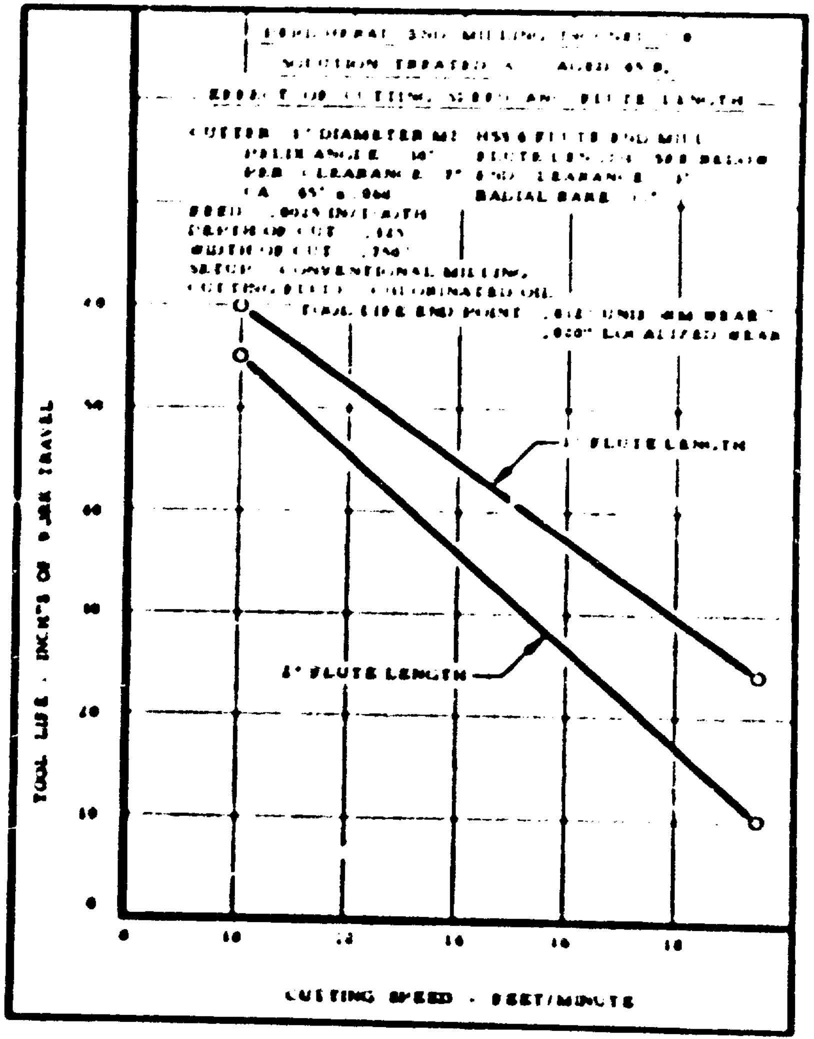
See text page 151

Figure [illegible]



See text page 157

Figure 178



See text page 157

Figure 179

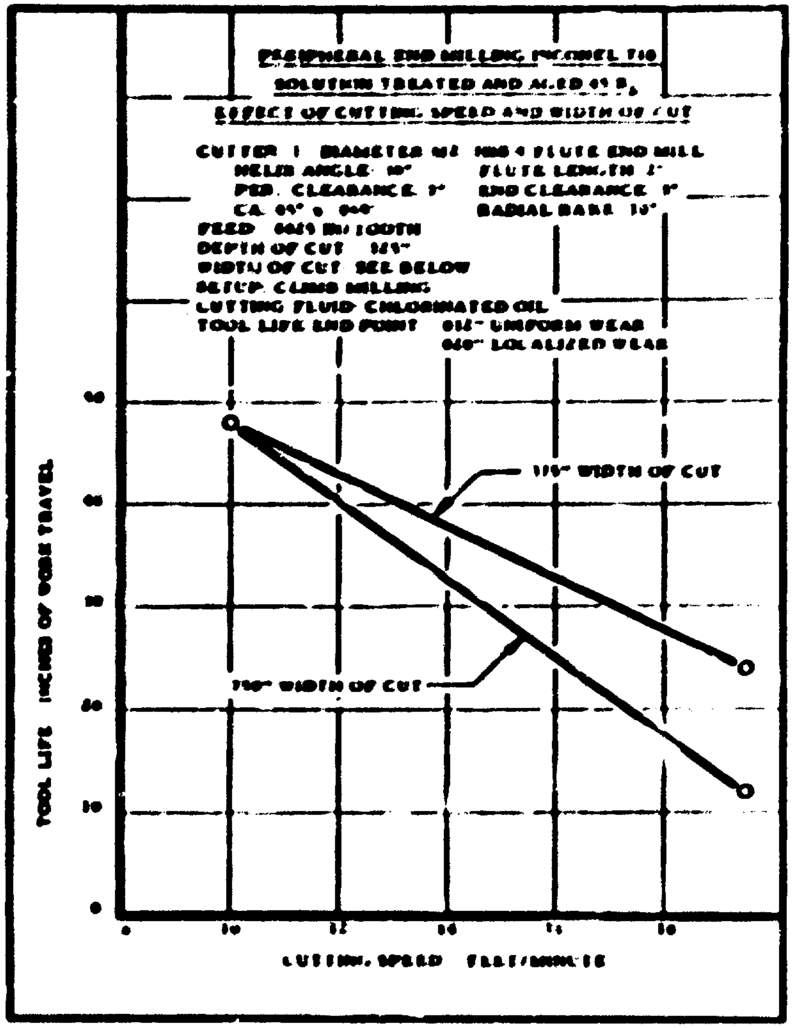


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Figure [illegible]

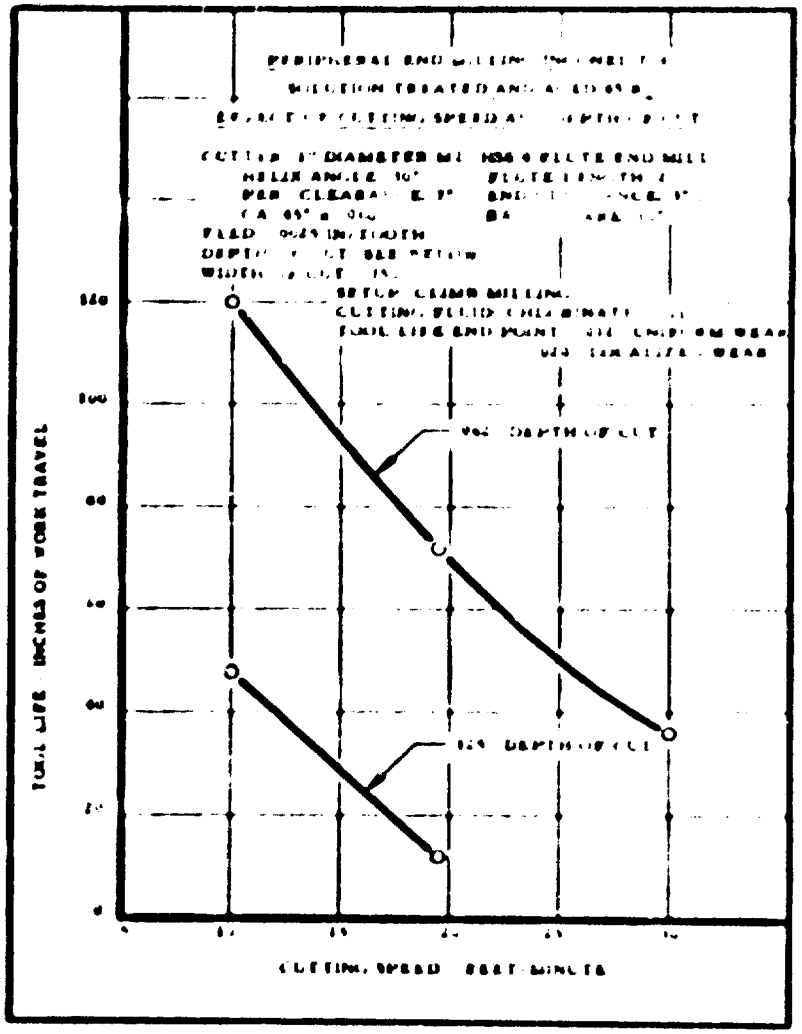

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Figure [illegible]

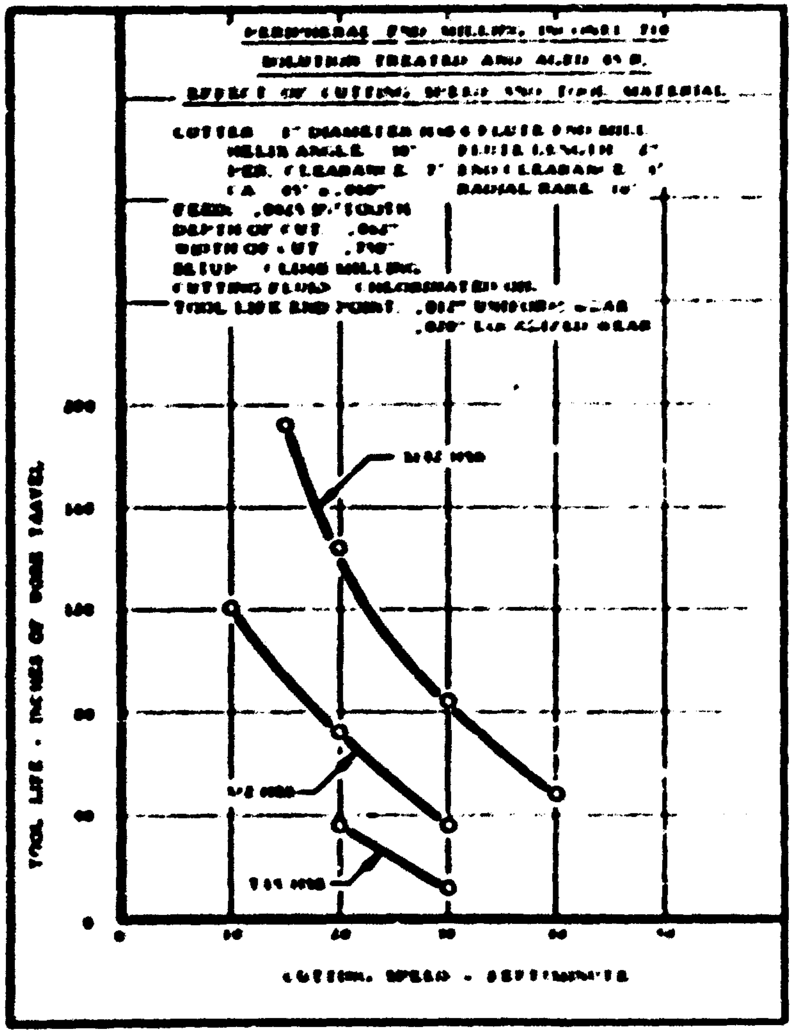

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Figure [illegible]

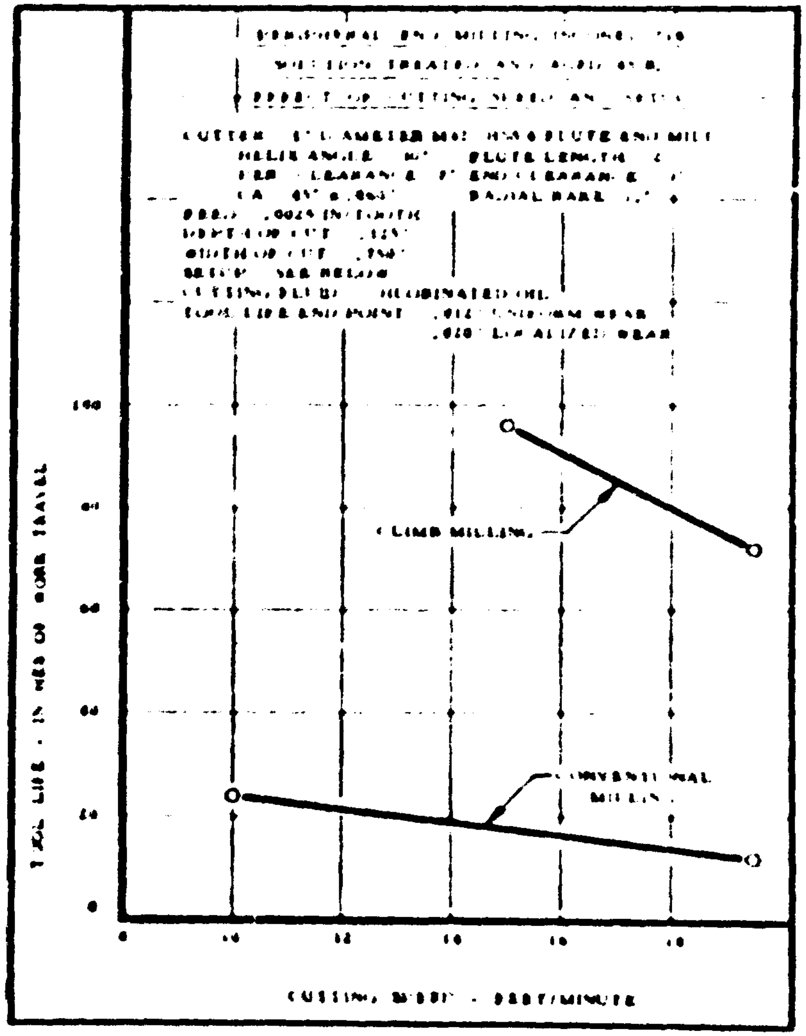

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Figure [illegible]

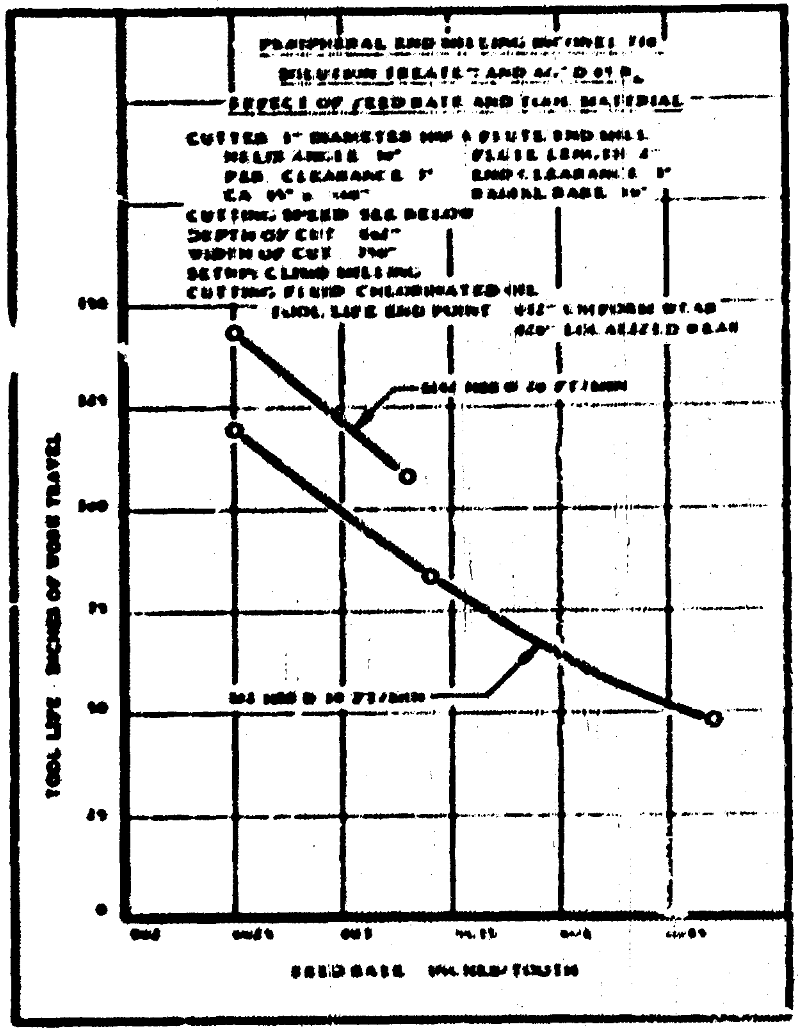

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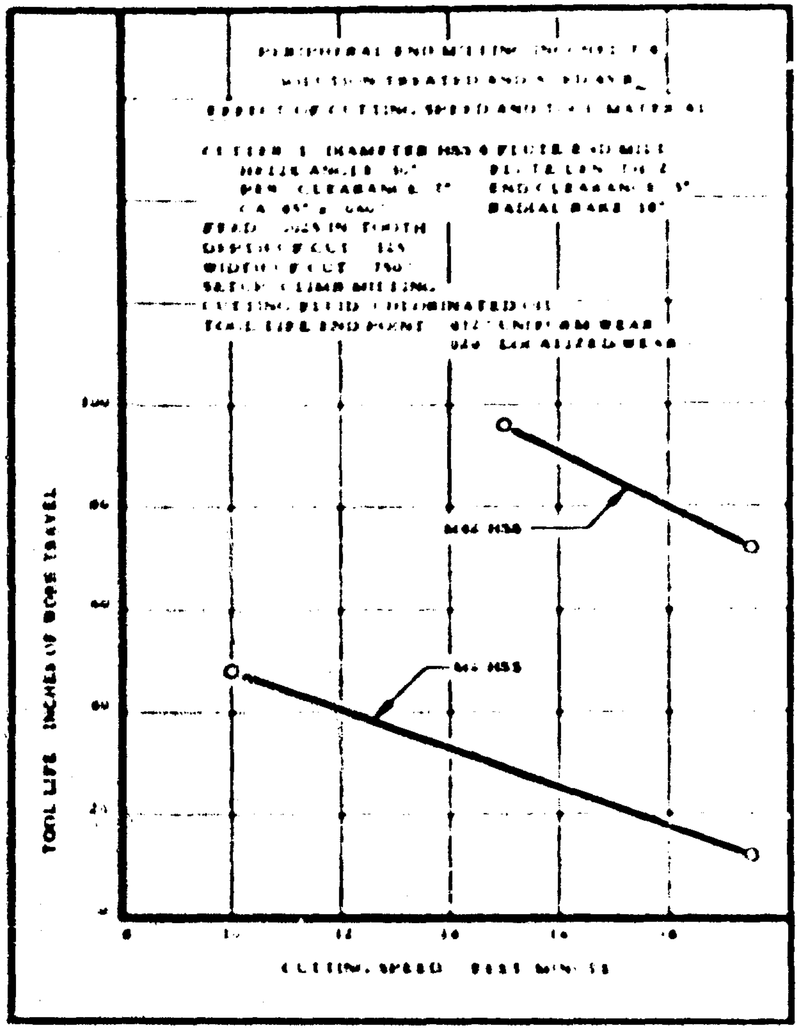
Figure 177



See text page 1??

Figure 1??

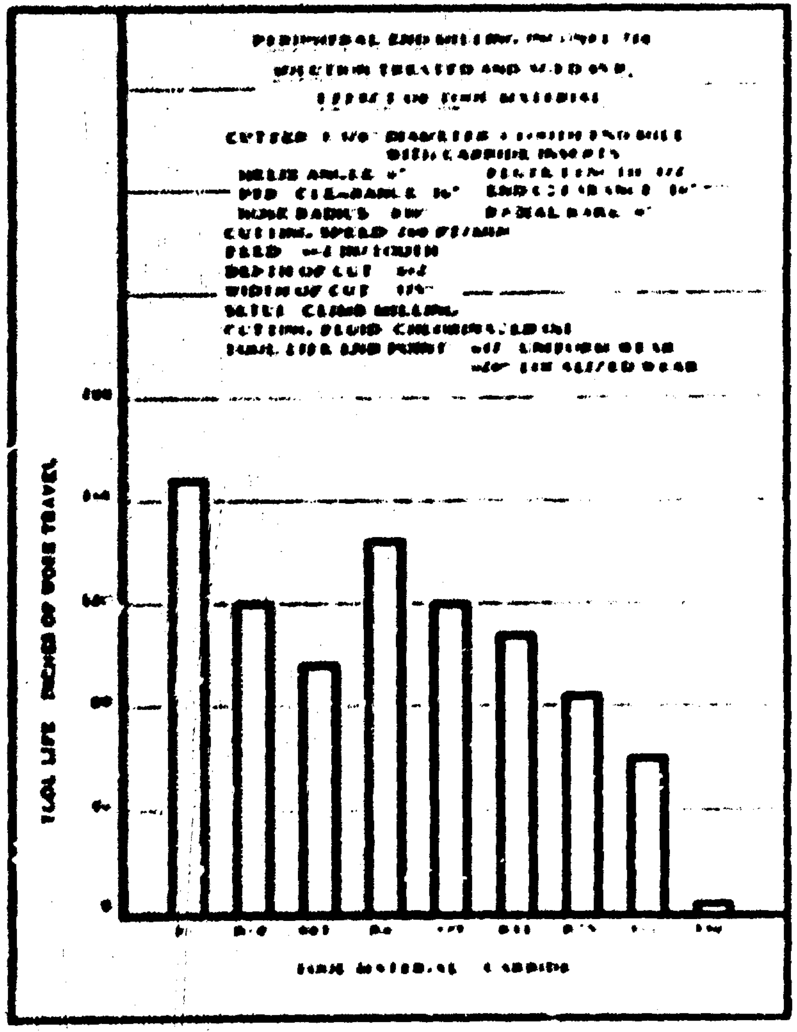


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Figure [illegible]

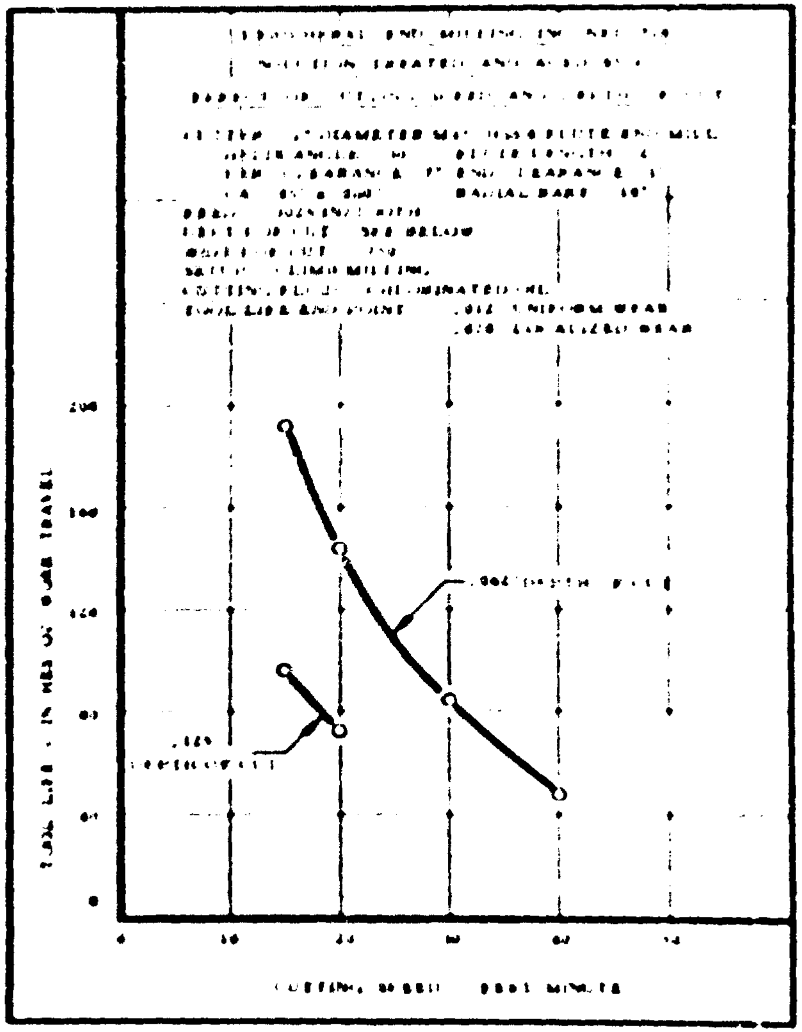

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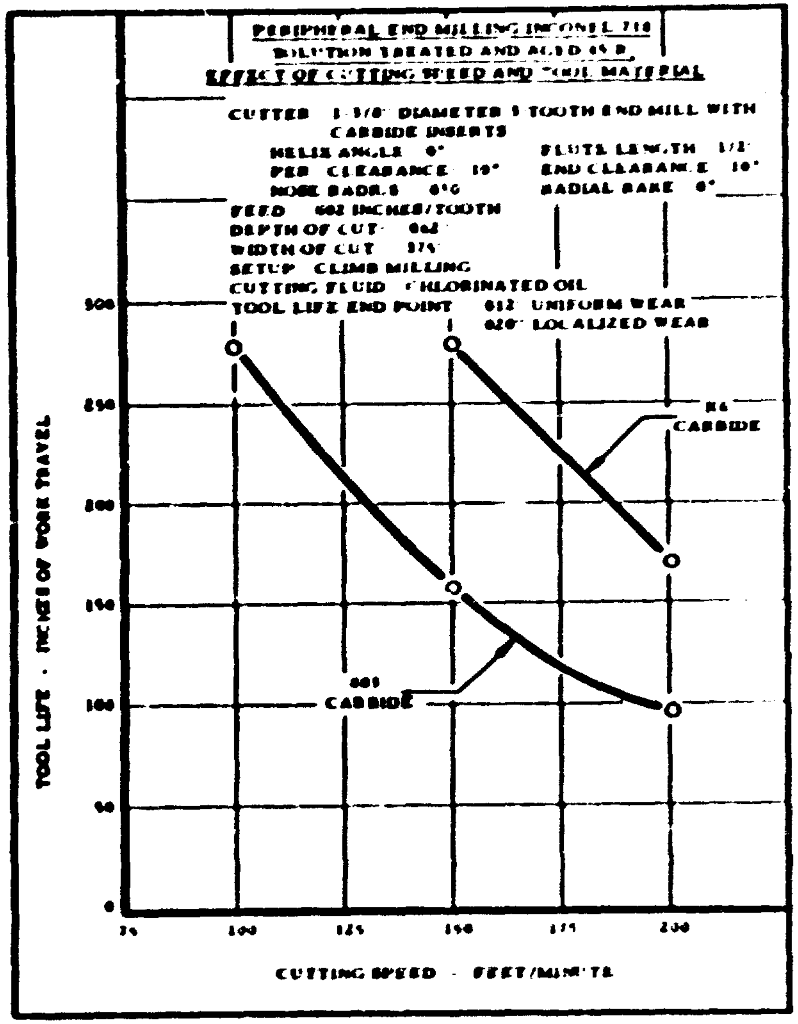
Figure [illegible]



See text, page 159

Figure 1[illegible]

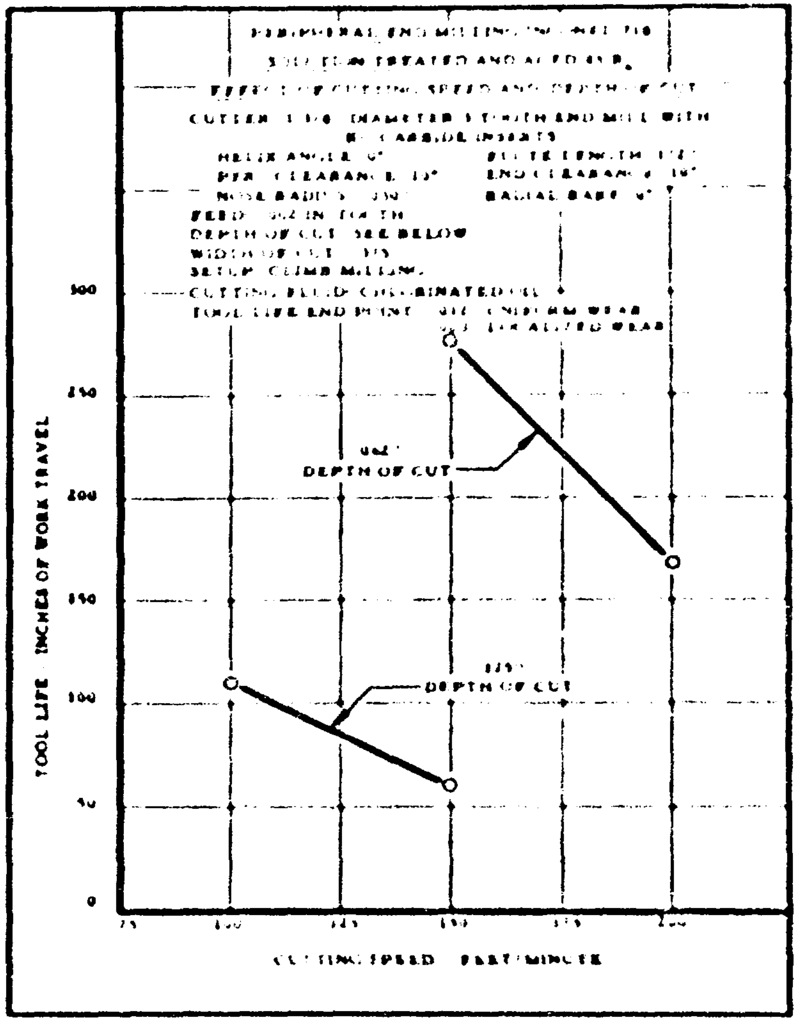


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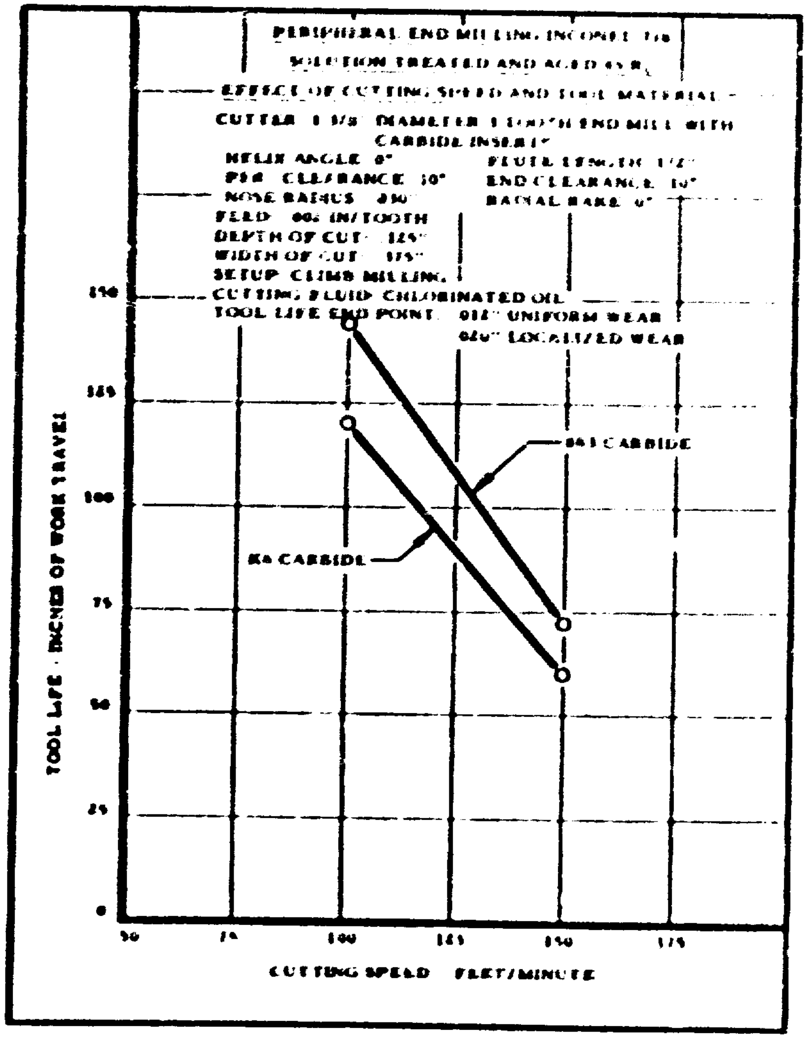
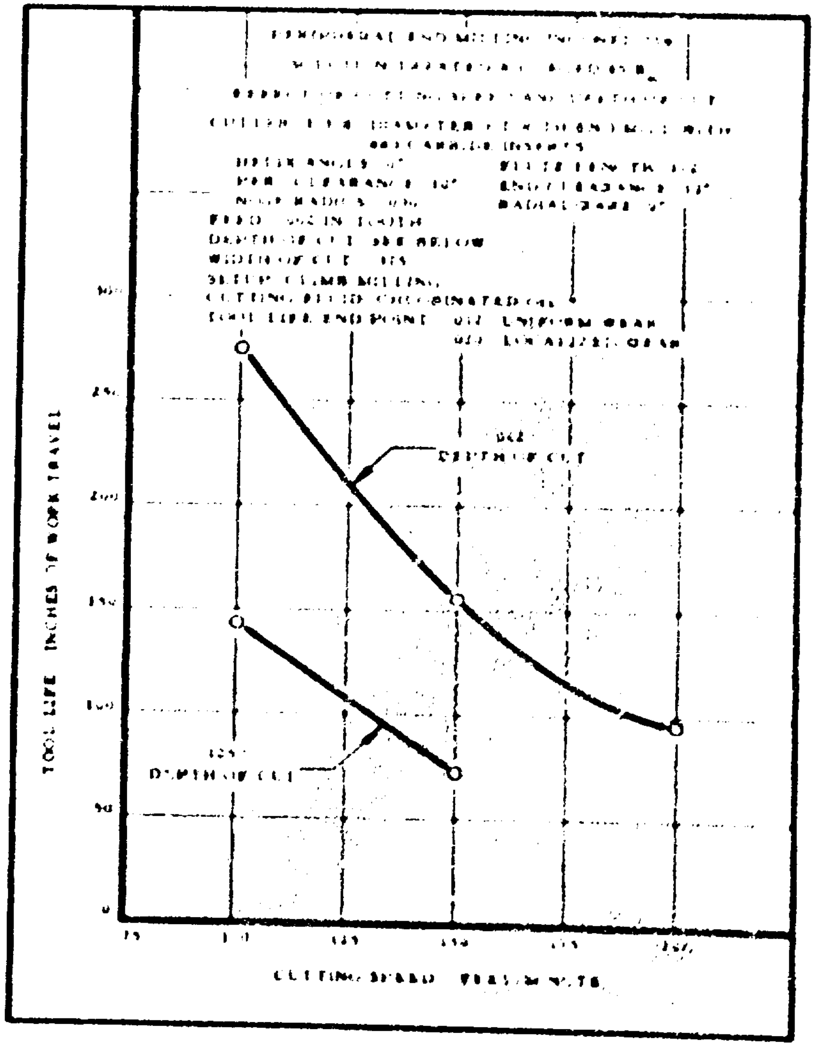
Figure 1[illegible]



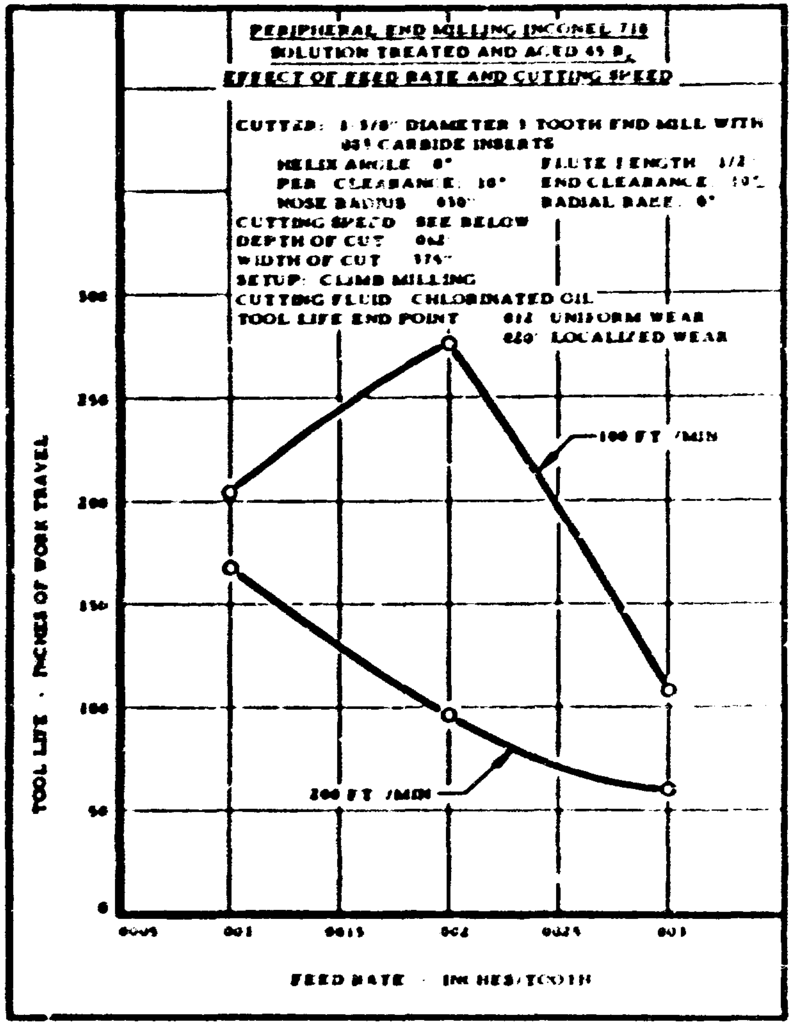
See text, page 159

Figure 185



See text, page 155

Figure 184



See text, page 559

Figure 185

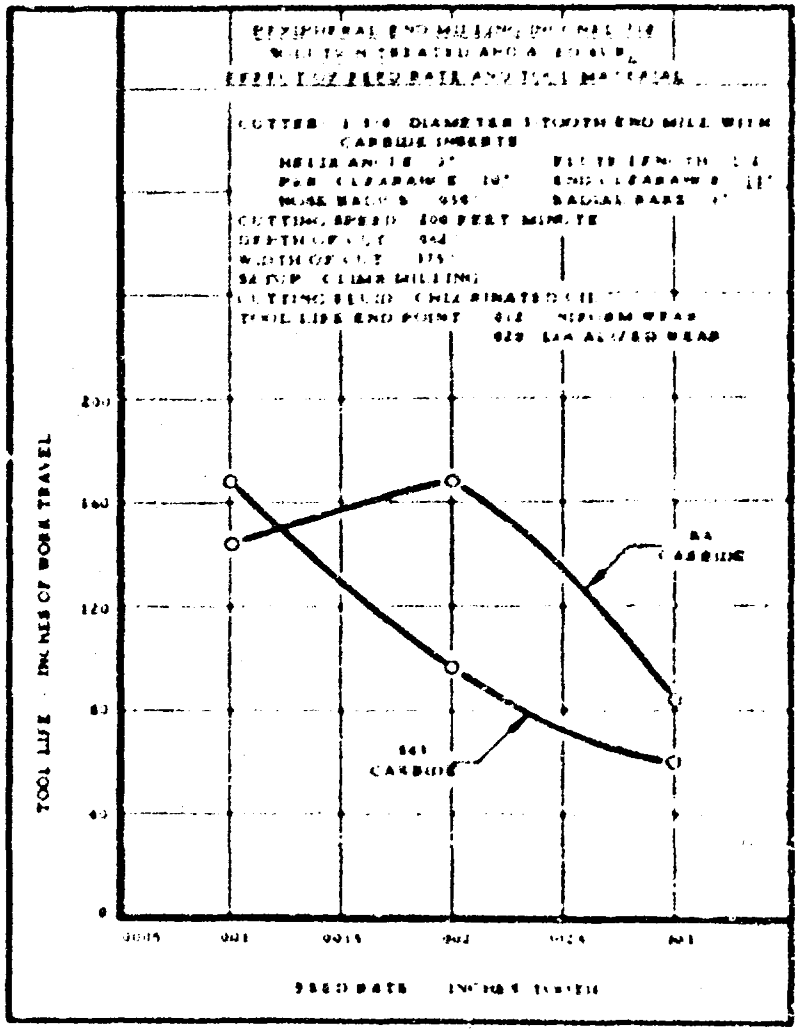


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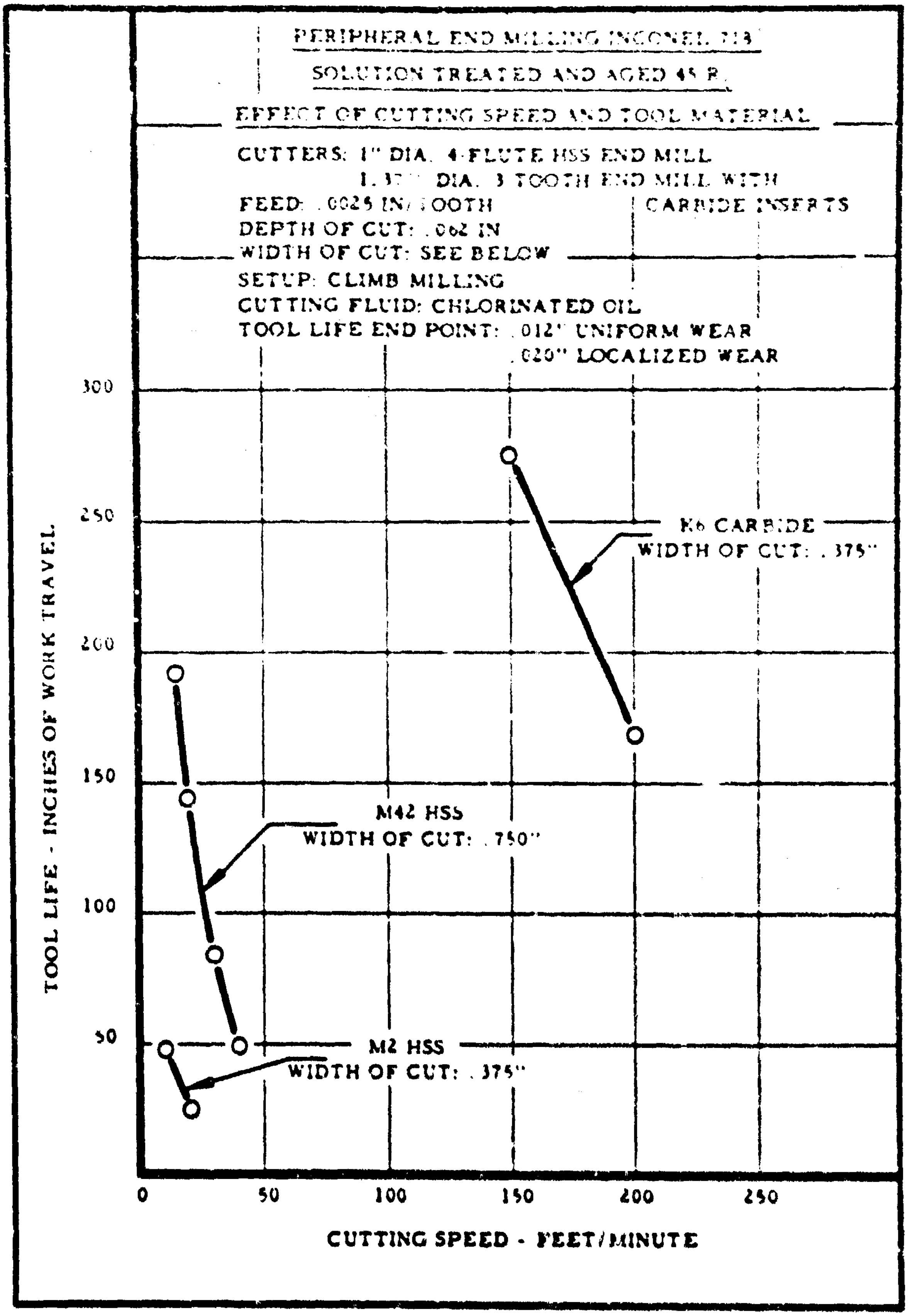
Figure [illegible]



PERIPHERAL END MILLING INCONEL 718

SOLUTION TREATED AND AGED 45 R_c

EFFECT OF CUTTING SPEED AND TOOL MATERIAL

CUTTERS: 1" DIA. 4-FLUTE HSS END MILL
1.375" DIA. 3 TOOTH END MILL WITH CARBIDE INSERTS
FEED: .0025 IN/TOOTH
DEPTH OF CUT: .062 IN
WIDTH OF CUT: SEE BELOW
SETUP: CLIMB MILLING
CUTTING FLUID: CHLORINATED OIL
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 160

Figure 187

5.2 Inconel 625, Annealed

Alloy Identification

Inconel 625 is a nickel base, high temperature alloy which is highly resistant to oxidation and corrosion. It exhibits excellent rupture and toughness characteristics up to 1700°F. Additions of molybdenum and columbium are utilized to solution strengthen the nickel-rich matrix. The alloy has been used in aerospace and marine applications as well as chemical processing equipment.

The nominal composition of the alloy is as follows:

Ni-22Cr-9Mo-3.5Cb+Ta-2.5Fe-.25Al-.25Ti-.05C

The material for the milling tests was procured as 1 in. by 4 in plate in the mill annealed condition. The annealing treatment performed at the mill was as follows:

1650°F/1 hour/air cool

The as-received hardness of the material was 277 BHN. As shown below, the material exhibits a duplex austenitic grain structure.

Inconel 625, Annealed

Etchant: Kalling's **Mag.: 00X**

5.2 Inconel 625, Annealed (continued)

Face Milling (277 BHN)

Figure 188, page 175, shows a comparison of the tool life curves for both a single-tooth and a multiple-tooth cutter over a range of cutting speeds. At a cutting speed of 30 feet/minute, the tool life with the single-tooth cutter was 134 inches of work travel per tooth, while with the 14-tooth cutter under the same conditions the tool life was 75 inches of work travel per tooth. However, the 14-tooth cutter at this cutting speed cut a total of 1,050 inches of work travel.

Multiple-tooth cutters with two different grades of HSS are compared in Figure 189, page 175. The M42 HSS cutter permitted cutting speeds 12 percent higher than those with the M2 HSS cutter.

End Mill Slotting (277 BHN)

As shown in Figure 190, page 176, the M42 HSS cutter provided a tool life that was double the tool life obtained with the M2 HSS cutter at a cutting speed of 40 feet/minute. For a given tool life, the cutting speed with the M42 HSS cutter was 15 percent faster than with the M2 HSS cutter.

Within a range of feed rates of .001 to .002 in./tooth, the magnitude of the feed rate is not critical in end mill slotting. Note in Figure 191, page 176, that in this range the tool life did not drop appreciably when the feed rate was increased. However, increasing the feed rate to .003 resulted in decreasing the tool life from 85 inches of work travel to less than 15 inches of work travel.

Doubling the depth of cut from .125 to .250 in. required a 20 percent decrease in cutting speed in order to maintain the same tool life, see Figure 192, page 177. The relationship between depth of cut and tool life in end mill slotting is further demonstrated in Figure 193, page 177. The cutter life did not change appreciably when the depth of cut was increased from .062 to .125 in. However, it did decrease drastically when the depth of cut was further increased from .125 to .250 in.

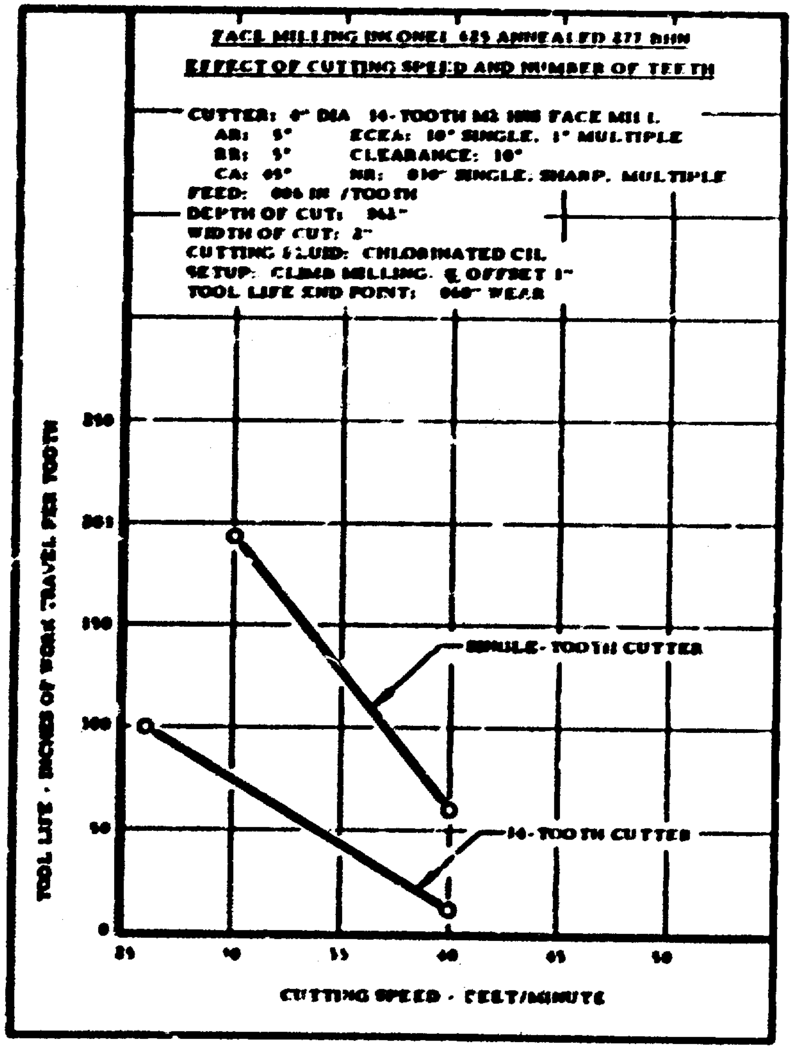
TABLE XIII

RECOMMENDED CONDITIONS FOR MACHINING INCONEL 625, ANNEALED 277 BHN

Nominal Chemical Composition, Percent

Ni	Cr	Mo	Cb+Ta	Fe	Al	Ti	C
Bal.	22	9	3.5	2.5	.25	.25	.05

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Face Milling	M2 HSS	AR: 5° ECEA: 1° RR: 5° CA: 45° Clearance: 10°	4" Diameter 14 Tooth HSS Face Mill	.060	2	.006 in/tooth	26	1400" work travel	.060	Chlorinated Oil
End Mill Slotting	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" Diameter 4 Flute HSS End Mill	.125	.750	.002 in/tooth	40	215" work travel	.012	Chlorinated Oil



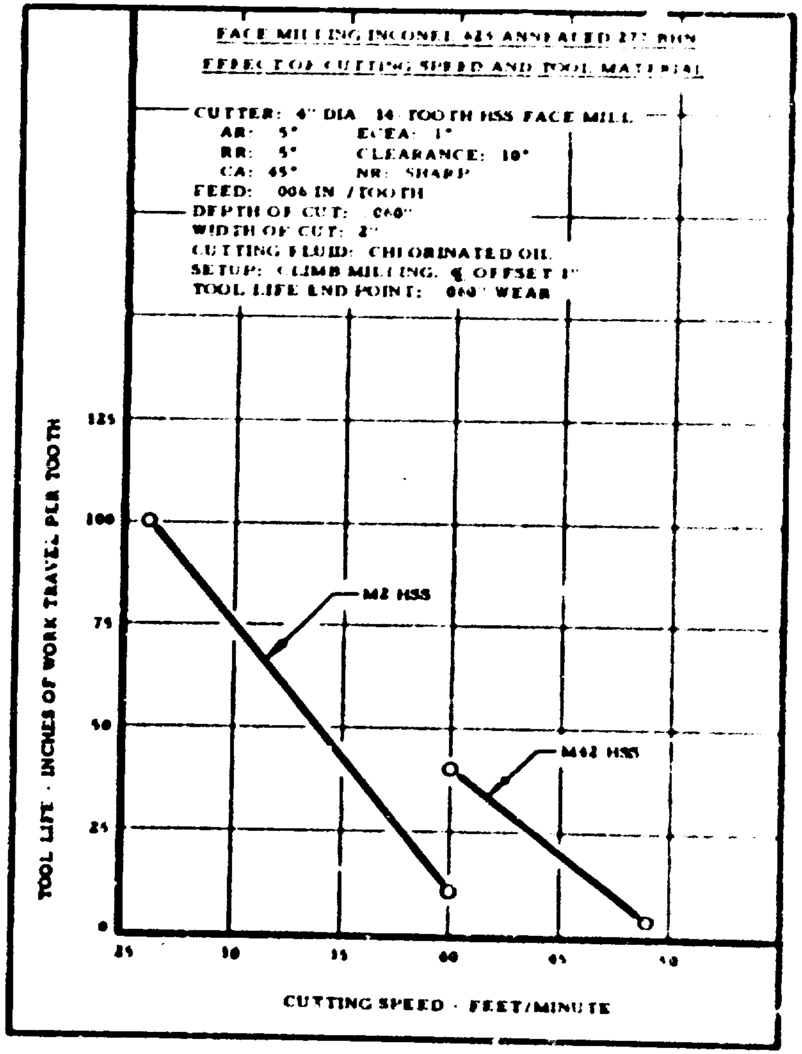
FACE MILLING INCONEL 625 ANNEALED 277 BHN

EFFECT OF CUTTING SPEED AND NUMBER OF TEETH

CUTTER: 4" DIA 14-TOOTH M2 HSS FACE MILL
AR: 5° ECEA: 10° SINGLE, 1° MULTIPLE
RR: 5° CLEARANCE: 10°
CA: 45° NR: .010" SINGLE; SHARP, MULTIPLE
FEED: .006 IN./TOOTH
DEPTH OF CUT: .060"
WIDTH OF CUT: 2"
CUTTING FLUID: CHLORINATED OIL
SETUP: CLIMB MILLING, ℄ OFFSET 1"
TOOL LIFE END POINT: .060" WEAR

See text, page 175

Figure 164



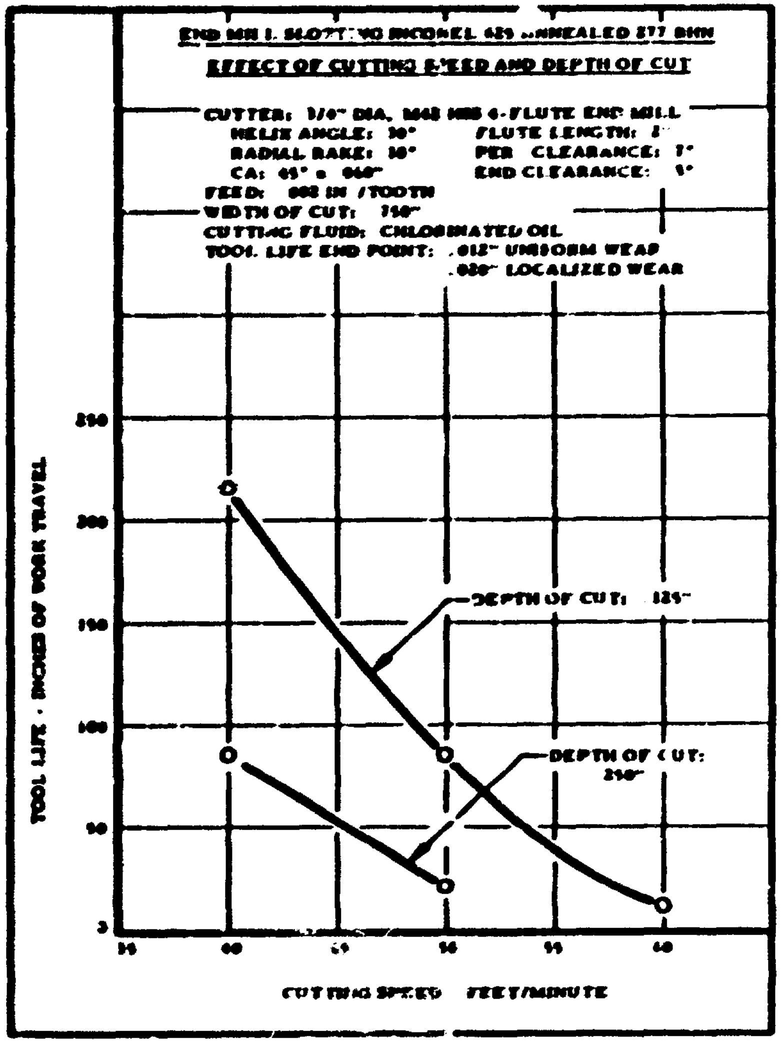
FACE MILLING INCONEL 625 ANNEALED 277 BHN

EFFECT OF CUTTING SPEED AND TOOL MATERIAL

CUTTER: 4" DIA 14-TOOTH HSS FACE MILL
AR: 5° ECEA: 1°
RR: 5° CLEARANCE: 10°
CA: 45° NR: SHARP
FEED: .006 IN./TOOTH
DEPTH OF CUT: .060"
WIDTH OF CUT: 2"
CUTTING FLUID: CHLORINATED OIL
SETUP: CLIMB MILLING, ℄ OFFSET 1"
TOOL LIFE END POINT: .060" WEAR

See text, page 175

Figure 165



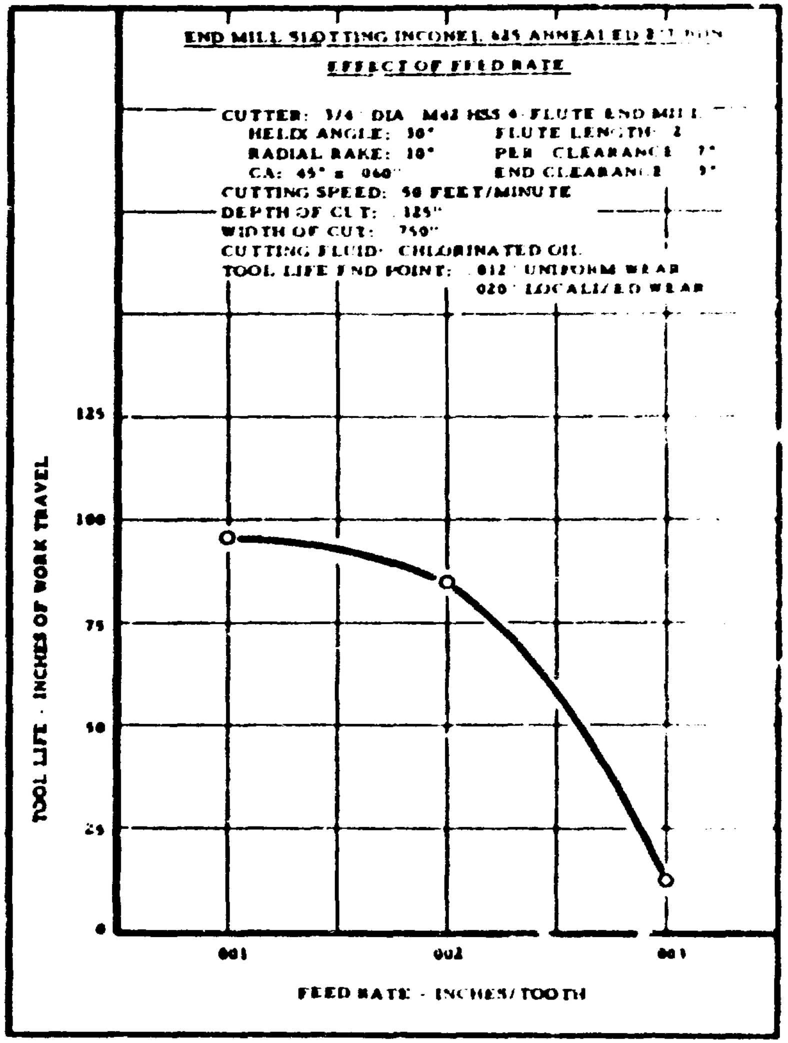
END MILL SLOTTING INCONEL 625 ANNEALED 277 BHN

EFFECT OF CUTTING SPEED AND DEPTH OF CUT

CUTTER: 3/4" DIA. M42 HSS 4-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2"
RADIAL RAKE: 10° PER CLEARANCE: 7°
CA: 45° x .060" END CLEARANCE: 5°
FEED: .002 IN /TOOTH
WIDTH OF CUT: .750"
CUTTING FLUID: CHLORINATED OIL
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 173

Figure 190



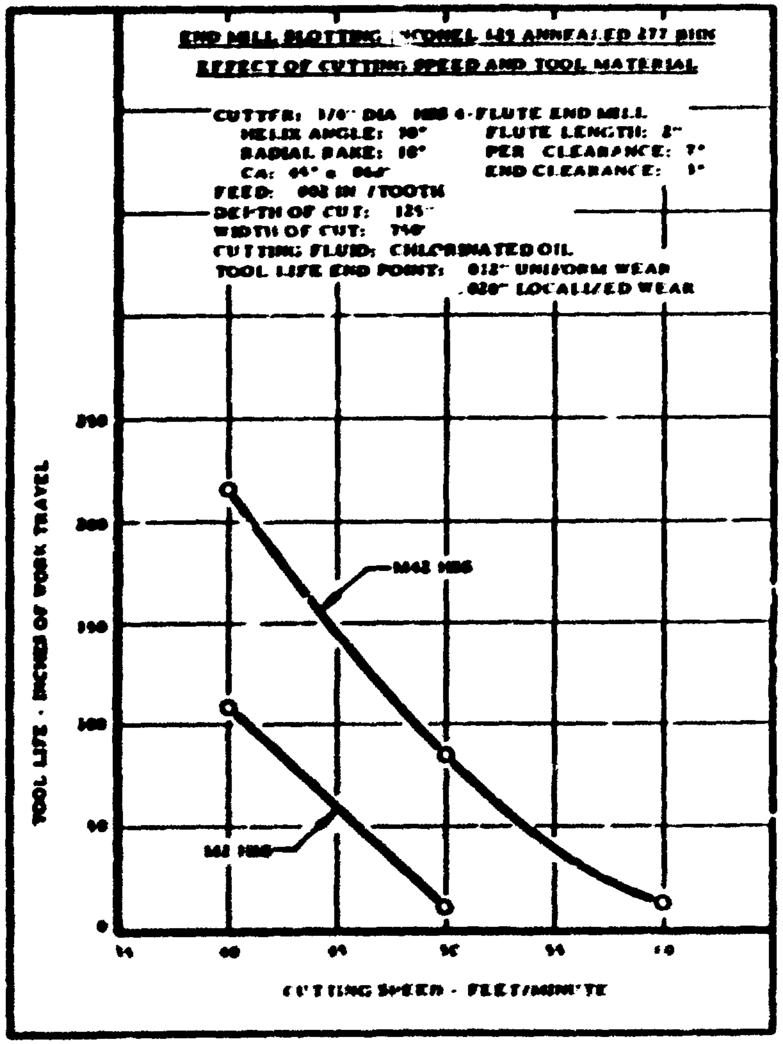
END MILL SLOTTING INCONEL 625 ANNEALED 277 BHN

EFFECT OF FEED RATE

CUTTER: 3/4" DIA. M42 HSS 4-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2"
RADIAL RAKE: 10° PER CLEARANCE: 7°
CA: 45° x .060" END CLEARANCE: 5°
CUTTING SPEED: 50 FEET/MINUTE
DEPTH OF CUT: .125"
WIDTH OF CUT: .750"
CUTTING FLUID: CHLORINATED OIL
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 173

Figure 191



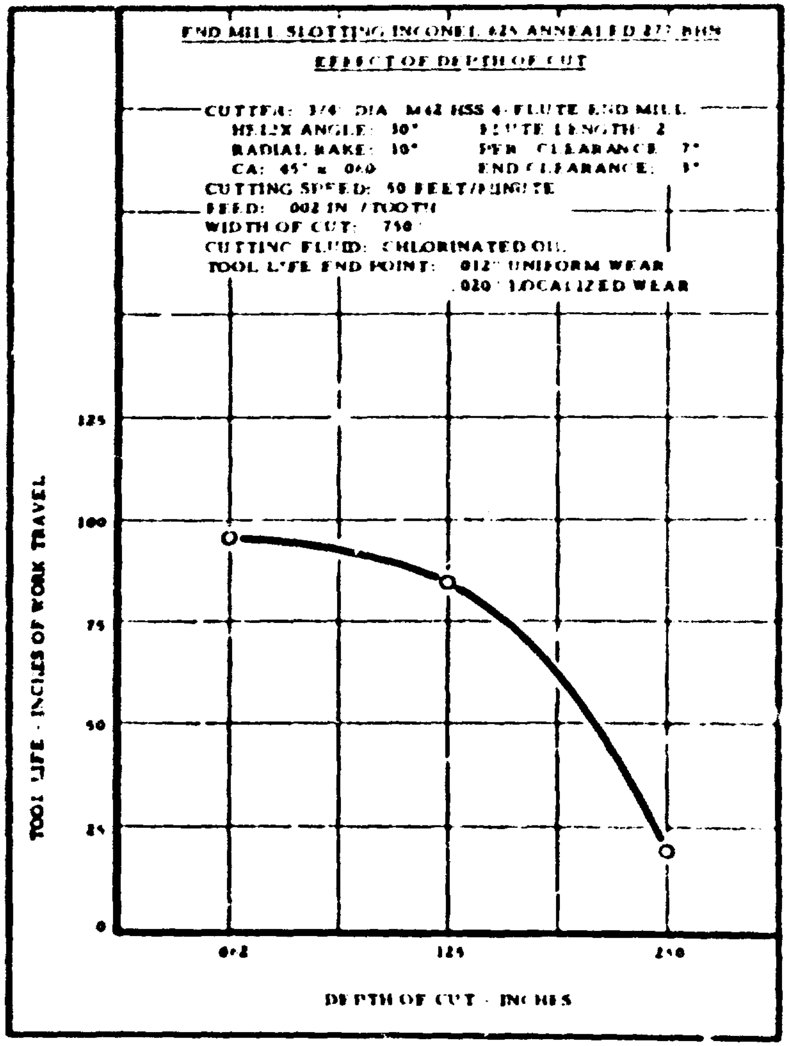
END MILL SLOTTING INCONEL 625 ANNEALED 277 BHN

EFFECT OF CUTTING SPEED AND TOOL MATERIAL

CUTTER: 3/4" DIA HSS 4-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2"
RADIAL RAKE: 10° PER CLEARANCE: 7°
CA: 45° x .060" END CLEARANCE: 3°
FEED: .002 IN /TOOTH
DEPTH OF CUT: .125"
WIDTH OF CUT: .750"
CUTTING FLUID: CHLORINATED OIL
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 171

Figure 112



END MILL SLOTTING INCONEL 625 ANNEALED 277 BHN

EFFECT OF DEPTH OF CUT

CUTTER: 3/4" DIA M42 HSS 4-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2
RADIAL RAKE: 10° PER CLEARANCE: 7°
CA: 45° x .060 END CLEARANCE: 3°
CUTTING SPEED: 50 FEET/MINUTE
FEED: .002 IN /TOOTH
WIDTH OF CUT: .750"
CUTTING FLUID: CHLORINATED OIL
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 171

Figure 113

5.3 As Cast Udimet 700

Alloy Identification

Udimet 700 is a vacuum induction melted, highly alloyed nickel base alloy exhibiting excellent mechanical properties at elevated temperature. In the cast form, the alloy has been used for industrial gas turbine buckets and in some jet engine applications. The nominal composition of this alloy is as follows:

Ni-15Cr-15Co-4Mo-3.5Ti-4Al-.05C

The material for the machining tests was procured as 2 in. by 4 in. cast bars. No heat treatment was performed on this material prior to use.

The hardness of the alloy as received was 302 BHN.

The microstructure of the alloy is illustrated below. It consists of a gamma matrix containing gamma prime precipitate and complex carbides. The unevenly shaded areas of gamma prime are indicative of the original dendritic pattern of the alloy.

Udimet 700, As Cast

Etchant: Kalling's Mag.: 500X

5.3 As Cast Udimet 700 (continued)

Peripheral End Milling (302 BHN)

Tool life curves with three different grades of HSS end mills having 2 in. flute lengths are shown in Figure 194, page 184. The tool life with the T15 HSS cutters was abnormally low because the cutters chipped badly. The M2 HSS cutters provided a tool life of 84 inches of work travel at a cutting speed of 11 feet/minute, while the M42 HSS cutters provided a tool life of 96 inches of work travel at a cutting speed of 15 feet/minute. The relationships between cutting speed and tool life at two different feeds are shown in Figure 195, page 184, for an M42 HSS cutter. At a cutting speed of 15 feet/minute, the tool life at a feed of .004 in./tooth was over twice that obtained at a feed of .002 in./tooth.

It is interesting to note in Figure 196, page 185, how rapidly the tool life increased as the feed was increased with the M42 HSS cutters, while with the M2 HSS cutters the cutter life decreased as the feed was increased from .002 to .004 in./tooth. The data shown were obtained at a constant cutting speed of 15 feet/minute.

As shown in Figure 197, page 185, even at a feed of .002 in./tooth, the cutter life decreased drastically when the depth of cut was increased from .060 to .125 in. For example, at a cutting speed of 15 feet/minute, the cutter life at a depth of cut of .060 in. was 96 inches of work travel as compared to 22 inches of work travel at a depth of cut of .125 in.

Tool life curves with stub-length (1 in. flute length) cutters are shown in Figure 198, page 186, for two different grades of HSS. Note that at a cutting speed of 15 feet/minute, the tool life with the M42 HSS cutter was 205 inches of work travel, while with the M2 HSS cutter the tool life was 25 inches of work travel. The feed was .002 in./tooth. This feed rate was used since the depth of cut was .125 in.

A comparison is made in Figure 199, page 186, of the tool life curves obtained with 1 in. flute length cutters and cutters having a flute length of 2 in. Note that the feed was .002 in./tooth and the depth of cut was .125 in. At this heavier depth of cut, the cutter having the 1 in. flute length provided a tool life of 205 inches at a cutting speed of 15 feet/minute, while the longer cutter provided a tool life of less than 25 inches of work travel.

The stub length cutter is compared with a cutter with the 2 in. flute length for a feed of .004 in./tooth and a depth of cut of .060 in. in

5.3 As Cast Udimet 700 (continued)

Peripheral End Milling (302 BHN) (continued)

Figure 200, page 187. Note that at a cutting speed of 30 feet/minute the tool life with the cutter having a 1 in. flute length was 132 inches as compared to a tool life of 72 inches for the cutter having a 2 in. flute length.

Several new types of carbides have been made available to the industry. In general, these new types of carbides contain submicron grains. Two groups of inserts made from these materials are the Baxtron-DBW and Ramet 1. A comparison is shown in Figure 201, page 187, of the two groups with a C-2 grade of carbide. Note that there was improvement in tool life. For example, at a cutting speed of 200 feet/minute, the tool life with the C-2 grade of carbide was 150 inches of work travel as compared to 160 for the Ramet 1 tool and 192 inches for the Baxtron-DBW tool. Actually, these two new tool materials have their best application in those operations where impact on the tool usually results in chipping of the carbide. In the instance shown in Figure 201, the feed and depth of cut were quite small, hence chipping was not a serious problem. Also the clamping of the insert in the tool holder was not satisfactory for feeds above about .002 in./tooth. Hence, these new type carbide tools could not be used to their fullest advantage.

From the results shown in Figure 202, page 188, the chlorinated oil proved to be far superior to the soluble oil in peripheral end milling with the Baxtron-DBW inserts. For a tool life of 100 inches, the cutting speed was two and one-half times greater with the chlorinated oil than with the soluble oil.

The effect of depth of cut on tool life when using the submicron carbides is shown in Figure 203, page 188. It is quite possible that the large decrease in tool life with an increase in depth of cut was partially due to the fact that the tool holders available for this operation were not satisfactory for the higher depths of cut. Nevertheless, the results show that a decrease of more than 50 percent resulted when the depth of cut was increased from .030 to .060 inches.

An interesting comparison is made in Figure 204, page 189, showing the tool life results with the submicron carbide cutters at a feed of .002 in./tooth and the results obtained with an M42 HSS cutter at a feed of .004 in./tooth. Note that for a tool life of approximately 100 inches of work travel, the cutting speeds with the carbide tool were two to three times faster than that with the M42 HSS tool. However, it should be pointed out that the feed with the carbide tool was only half of that with the HSS tool.

5.5 As Cast Udimet 700 (continued)

End Mill Slotting (302 BHN)

As shown in Figure 205, page 189, the M42 HSS cutter provided considerably longer tool life than the M2 HSS cutter. At a cutting speed of 15 feet/minute, the tool life with the M42 HSS cutter was 84 inches of work travel as compared to 12 inches of work travel with the M2 HSS cutter.

The results presented in Figure 206, page 190, indicate how critical the feed rate is when end mill slotting this alloy. For example, at a feed of .002 in./tooth, the tool life was 84 inches of work travel. Approximately a 40 percent decrease in tool life resulted when the feed rate was increased to .003 in./tooth and also when the feed rate was decreased to .0015 in./tooth. Several interesting comparisons are shown in Figure 207, page 190, regarding the effect of flute length and depth of cut on tool life. Note for example that when the depth of cut was increased from .060 to .125 in., the tool life with the cutter having the 1 in. flute length decreased from 145 inches of work travel to 107 inches of work travel. In the case of the cutters with the 2 in. flute length, the tool life decreased from 120 inches of work travel to 85 inches of work travel. Also at a depth of cut of .060 in., the 1 in. flute length cutter provided a cutter life of 145 inches of work travel as compared to 120 inches of work travel with the 2 in. flute length cutter. At the higher depth of cut, the cutter life with the 1 in. flute length was 107 inches as compared to 85 inches with the cutter having the 2 in. flute length.

Drilling (302 BHN)

A comparison of the tool life results obtained with two different grades of HSS drills is shown in Figure 208, page 191. At a cutting speed of 15 feet/minute and a feed of .003 in./rev., the tool life with the M42 HSS drills was 83 holes as compared to 50 holes with the T15 HSS drill.

The relationship between drill life and cutting speed for two different feeds are shown in Figure 209, page 191. The results indicate that a feed of .003 in./rev. is more desirable than a feed of .005 in./rev. For example, at a cutting speed of 10 feet/minute, the drill life with the feed of .003 in./rev. was 182 holes, while at the same cutting speed but at a feed of .005 in./rev. the tool life was 56 holes.

5.3 As Cast Udimet 700 (Continued)

Reaming (302 BHN)

As shown in Figure 210, page 192, the HSS reamer life over a range of cutting speeds and feeds was not very long. The best reamer life was 25 holes, obtained at a cutting speed of 20 feet/minute and a feed of .009 in./rev.

A more reasonable reamer life was obtained with a carbide-tipped four-flute reamer (see Figure 211, page 192). With this reamer at a cutting speed of 10 feet/minute and a feed rate of .015 in./rev., the reamer life was 60 holes. This feed was better than the feeds of .005 and .009 in./rev.

An interesting comparison of the cutter life obtained with the carbide-tipped and the M33 HSS reamer is presented in Figure 212, page 193. Note that at a cutting speed of 10 feet/minute, the reamer life with the carbide-tipped four-flute reamer was more than double that obtained with the M33 HSS six-flute reamer.

Tapping (302 BHN)

The importance of selecting the proper machining conditions for tapping as cast Udimet 700 is clearly demonstrated in Figures 213 and 214, page 194. Note in Figure 213 how the tap life increased from 6 holes at a cutting speed of 15 feet/minute to 47 holes at 5 feet/minute and then decreased rapidly as the cutting speed was reduced below 5 feet/minute.

Also note the wide range of tap life values obtained for the various taps tested. At the cutting speed of 5 feet/minute, the two-flute standard tap provided a tap life of 47 holes, while the maximum tap life for any one of the other taps involved was 2 holes.

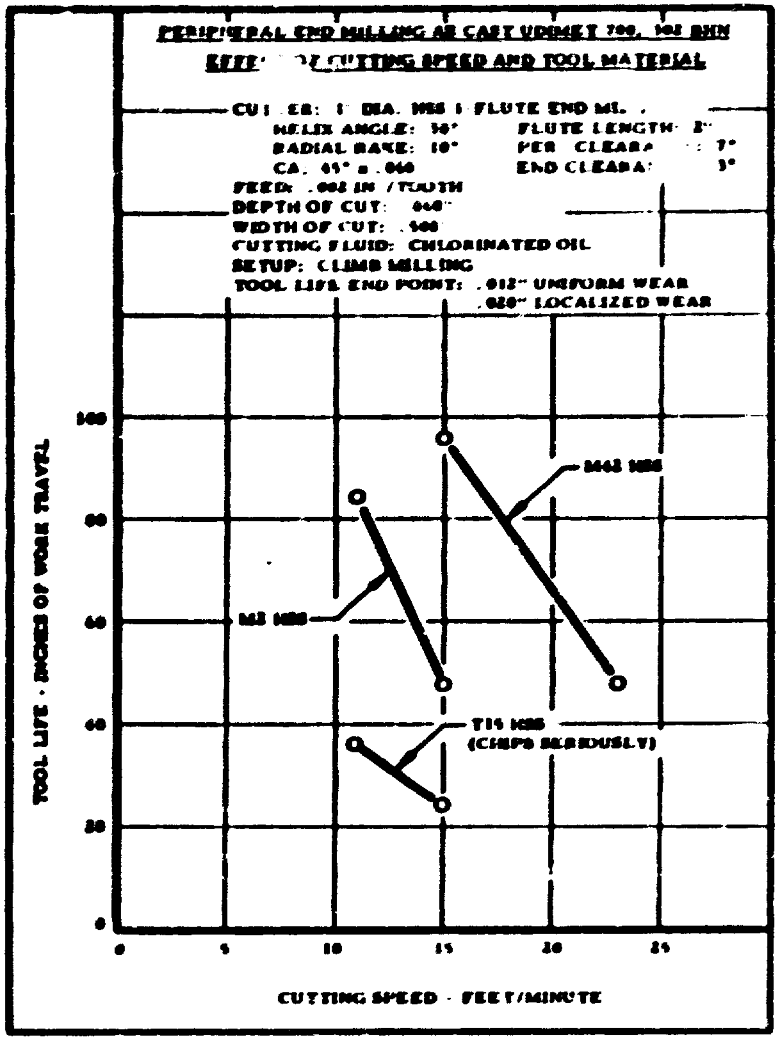
TABLE XIV

RECOMMENDED CONDITIONS FOR MACHINING UDIMET 700, AS CAST 302 BHN

Nominal Chemical Composition, Percent

Ni	Cr	Co	Mo	[illegible]	Al	C
Bal.	15	15	4	3.5	4	.05

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft. min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Peripheral End Milling	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	Diameter 4 Flute HSS End Mill	.060	.500	.004 in/tooth	15	200" work travel	.012	Chlorinated Oil
Peripheral End Milling	Baxtron DBW	Helix Angle: 0° RR: 0° Clearance: 10° NR: .030"	1.5" Diameter 3 Tooth Carbide Insert End Mill	.030	.375	.002 in/tooth	200	190" work travel	.012	Chlorinated Oil
End Mill Slotting	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" Diameter 4 Flute HSS End Mill	.060	.750	.002 in/tooth	15	144" work travel	.012	Chlorinated Oil
Drilling	M42 HSS	118° Crankshaft Point Helix Angle: 29° Clearance: 7°	1/4" Diameter HSS Drill 2-1/2" Long	.500 thru	--	.003 in/rev	10	180 holes	.015	Chlorinated C
Reaming	C-2 Carbide	Helix Angle: 0° CA: 45° Clearance: 7°	.272" Dia. 4-Flute Carbide-Tipped Chucking Reamer	.500 thru	--	.015 in/rev	10	60 holes	.006	Chlorinated Oil
Tapping	M1 HSS	2 Flute Plug Spiral Point 75% Thread	5/16-24 NF Tap	.500 thru	--	--	5	47 holes	Under-size Thread	Chlorinated Oil

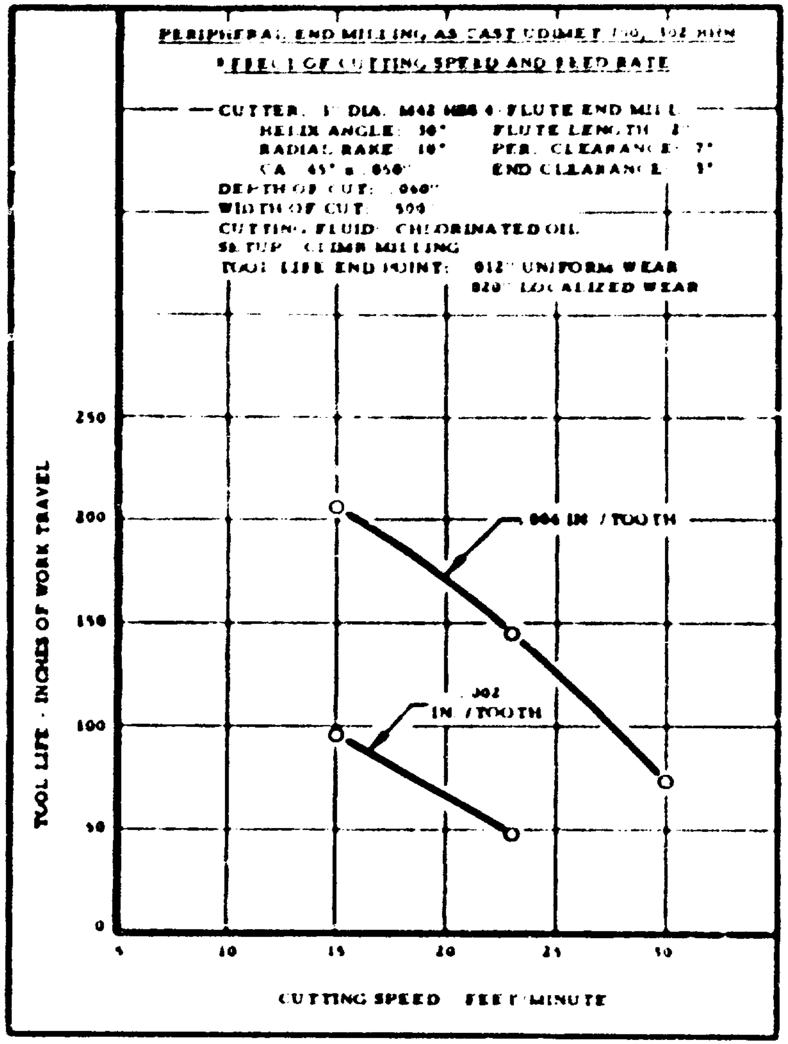

PERIPHERAL END MILLING AS CAST UDIMET 700, 302 BHN

EFFECT OF CUTTING SPEED AND TOOL MATERIAL

CUTTER: 1" DIA. HSS 4 FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2"
RADIAL RAKE: 10° PER. CLEARANCE: 7°
CA: 45° x .060 END CLEARANCE: 3°
FEED: .002 IN./TOOTH
DEPTH OF CUT: .060"
WIDTH OF CUT: .500
CUTTING FLUID: CHLORINATED OIL
SETUP: CLIMB MILLING
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 174

Figure 146

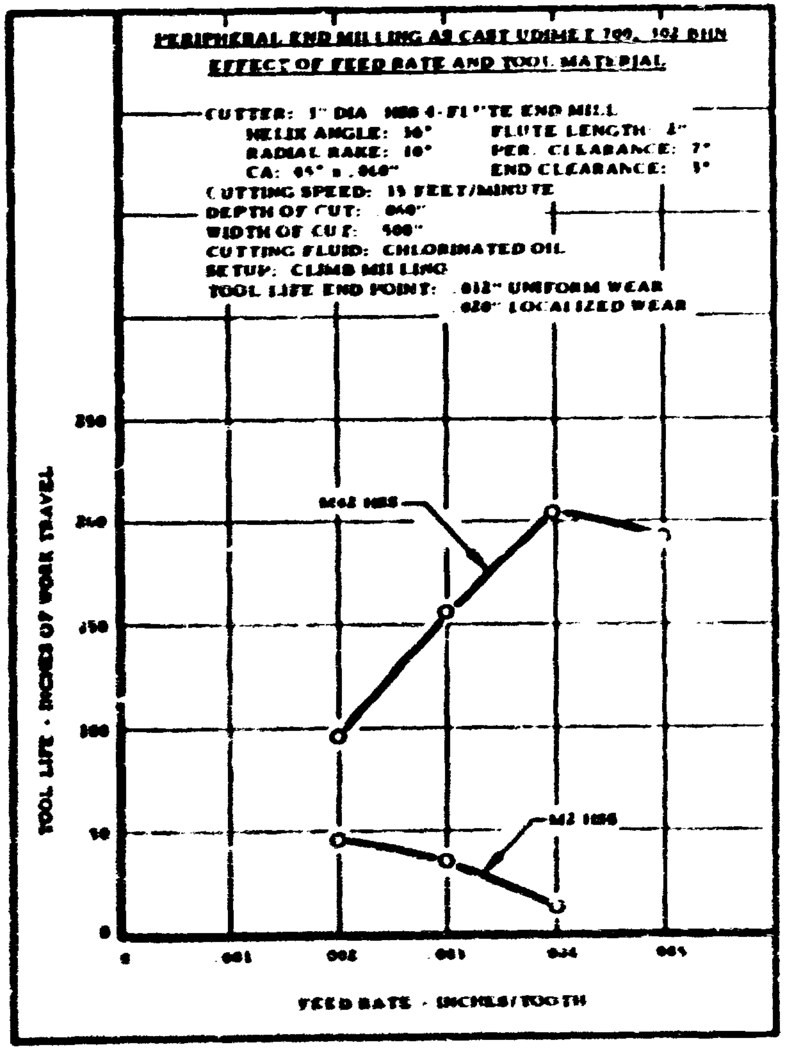

PERIPHERAL END MILLING, AS CAST UDIMET 700, 302 BHN

EFFECT OF CUTTING SPEED AND FEED RATE

CUTTER: 1" DIA. M42 HSS 4 FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2"
RADIAL RAKE: 10° PER. CLEARANCE: 7°
CA: 45° x .050" END CLEARANCE: 3°
DEPTH OF CUT: .060"
WIDTH OF CUT: .500
CUTTING FLUID: CHLORINATED OIL
SETUP: CLIMB MILLING
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 174

Figure 145

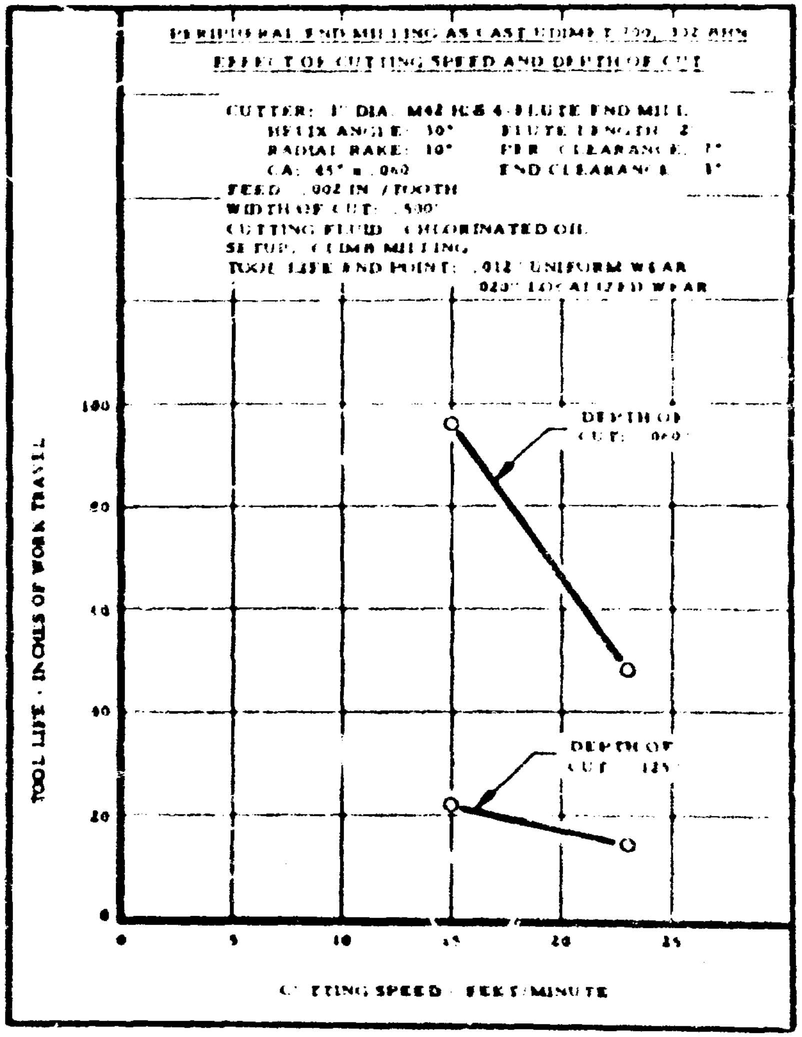

PERIPHERAL END MILLING AS CAST UDIMET 700, 302 BHN

EFFECT OF FEED RATE AND TOOL MATERIAL

CUTTER: 1" DIA HSS 4-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2"
RADIAL RAKE: 10° PER. CLEARANCE: 7°
CA: 45° x .060" END CLEARANCE: 3°
CUTTING SPEED: 15 FEET/MINUTE
DEPTH OF CUT: .060"
WIDTH OF CUT: .500"
CUTTING FLUID: CHLORINATED OIL
SETUP: CLIMB MILLING
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 179

Figure 192

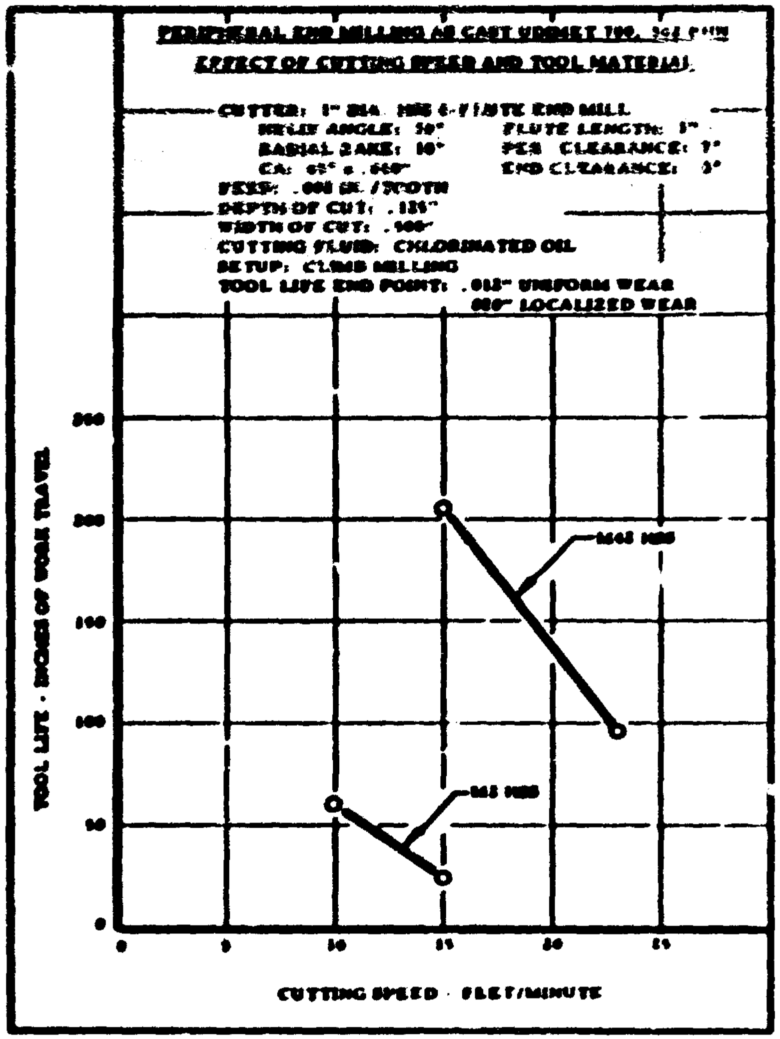

PERIPHERAL END MILLING AS CAST UDIMET 700, 302 BHN

EFFECT OF CUTTING SPEED AND DEPTH OF CUT

CUTTER: 1" DIA. M42 HSS 4-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2
RADIAL RAKE: 10° PER. CLEARANCE: 7°
CA: 45° x .060 END CLEARANCE: 3°
FEED: .002 IN./TOOTH
WIDTH OF CUT: .500"
CUTTING FLUID: CHLORINATED OIL
SETUP: CLIMB MILLING
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 179

Figure 193



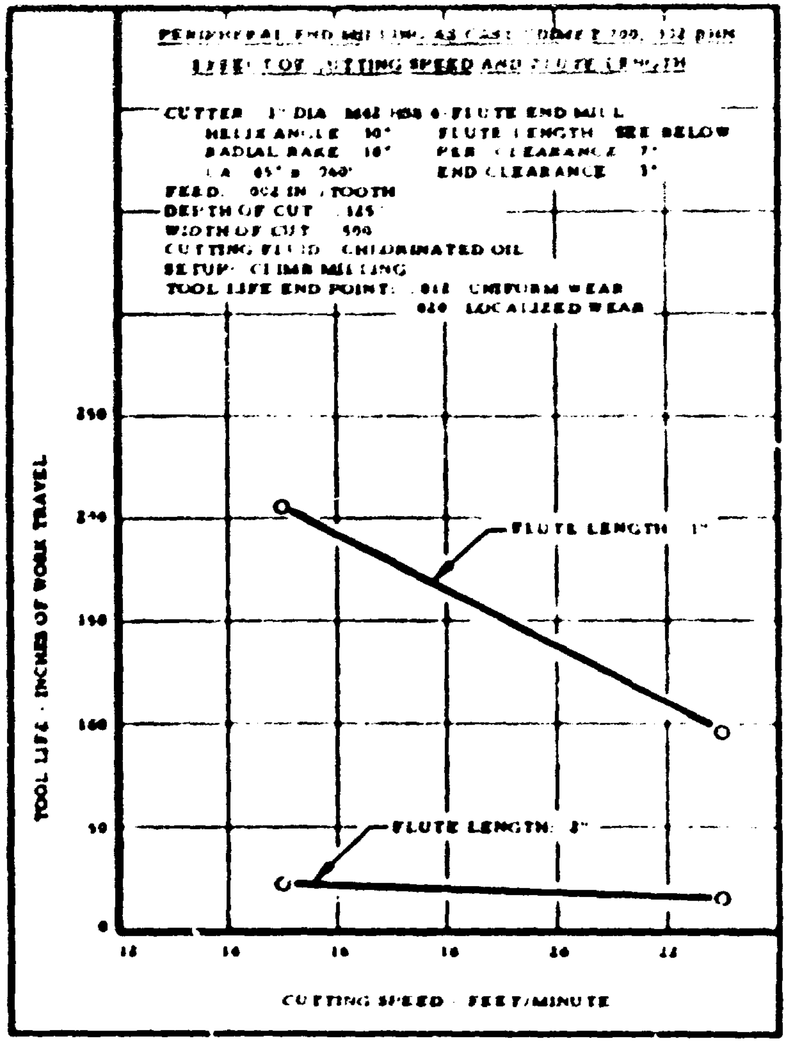
PERIPHERAL END MILLING AS CAST UDIMET 700, 364 BHN

EFFECT OF CUTTING SPEED AND TOOL MATERIAL

CUTTER: 1" DIA. HSS 6-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 1"
RADIAL RAKE: 10° PER. CLEARANCE: 7°
CA: 45° x .060" END CLEARANCE: 3°
FEED: .006 IN./TOOTH
DEPTH OF CUT: .125"
WIDTH OF CUT: .100"
CUTTING FLUID: CHLORINATED OIL
SETUP: CLIMB MILLING
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 179

Figure 110



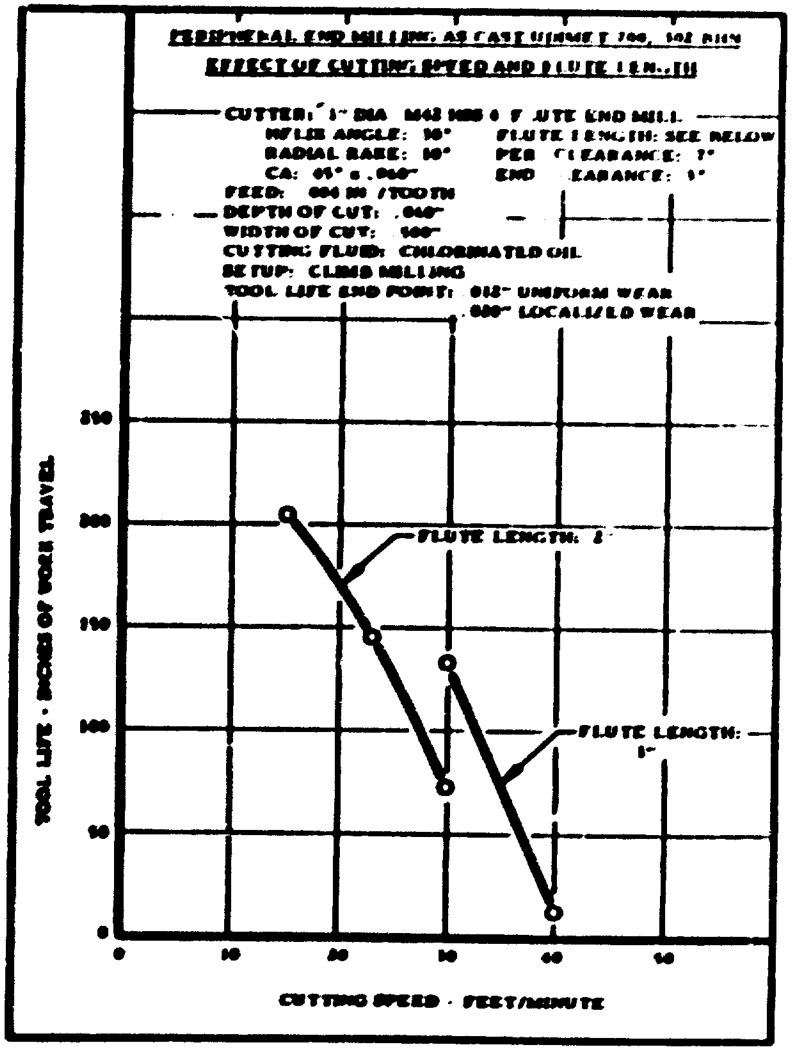
PERIPHERAL END MILLING AS CAST UDIMET 700, 332 BHN

EFFECT OF CUTTING SPEED AND FLUTE LENGTH

CUTTER: 1" DIA. M42 HSS 6-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: SEE BELOW
RADIAL RAKE: 10° PER. CLEARANCE: 7°
CA: 45° x .060" END CLEARANCE: 3°
FEED: .004 IN./TOOTH
DEPTH OF CUT: .125"
WIDTH OF CUT: .500"
CUTTING FLUID: CHLORINATED OIL
SETUP: CLIMB MILLING
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

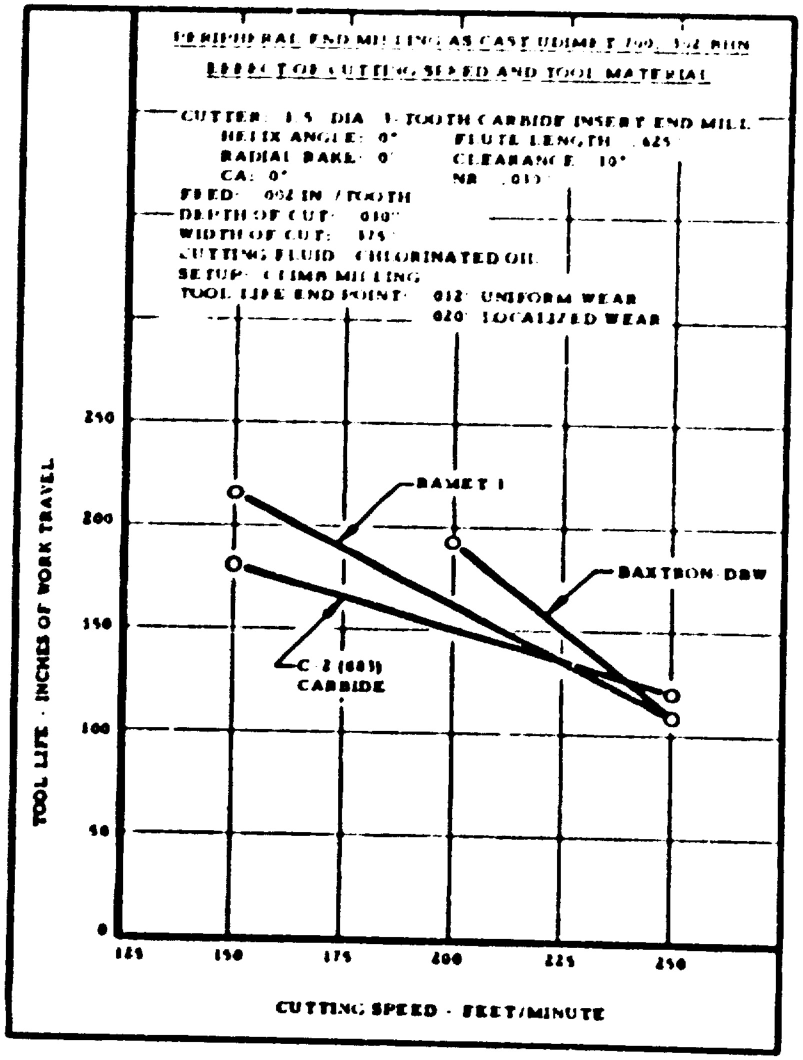
See text, page 179

Figure 109



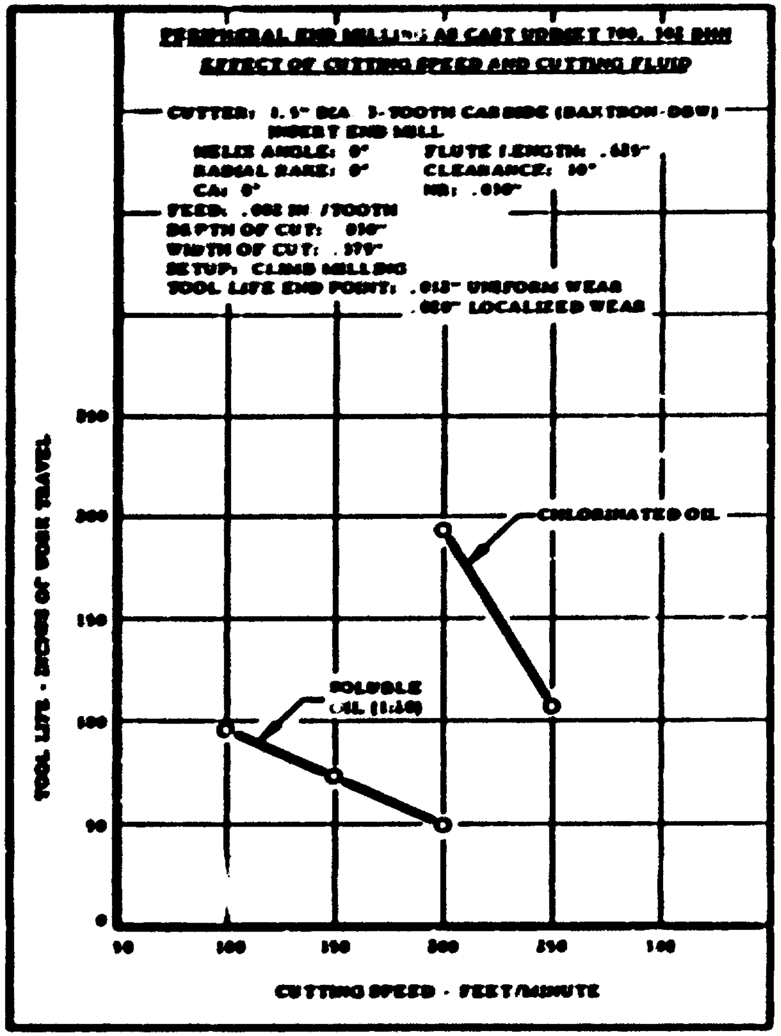
See text, page 100

Figure 200



See text, page 100

Figure 201



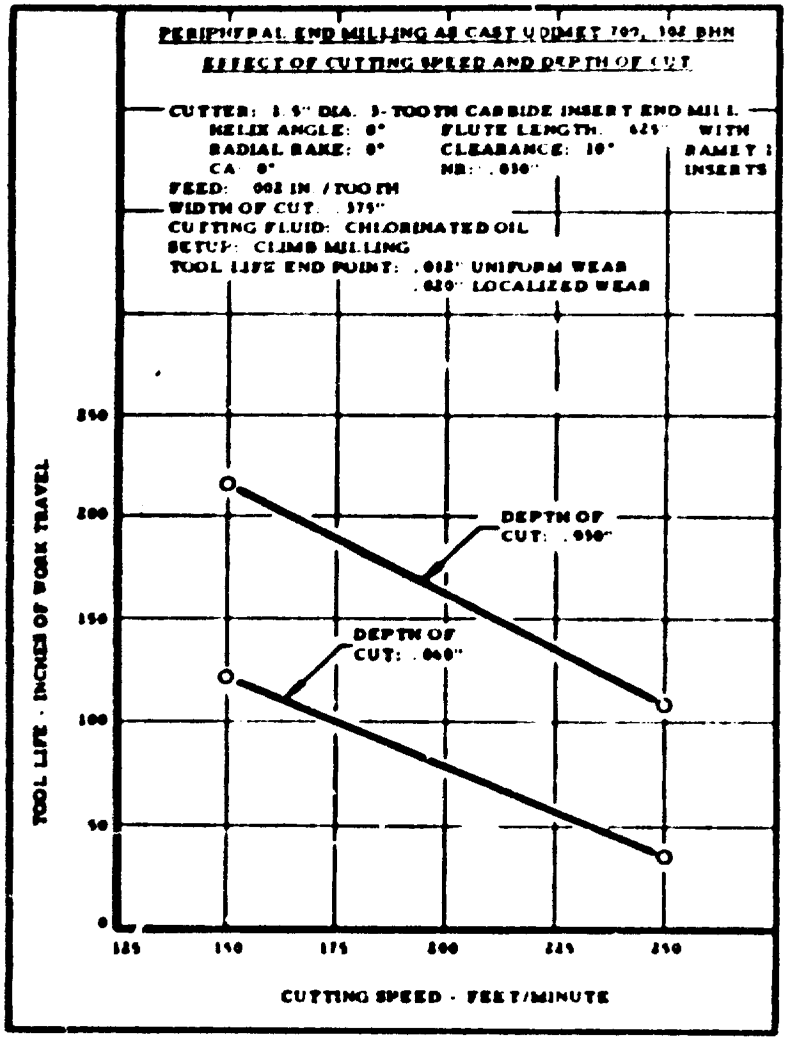
PERIPHERAL END MILLING AS CAST UDIMET 700, 302 BHN

EFFECT OF CUTTING SPEED AND CUTTING FLUID

CUTTER: 1.5" DIA. 3-TOOTH CARBIDE (BAXTRON-DBW) INSERT END MILL
HELIX ANGLE: 0° FLUTE LENGTH: .625"
RADIAL RAKE: 0° CLEARANCE: 10°
CA: 0° NR: .030"
FEED: .002 IN /TOOTH
DEPTH OF CUT: .030"
WIDTH OF CUT: .375"
SETUP: CLIMB MILLING
TOOL LIFE END POINT: .015" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 180

Figure 262



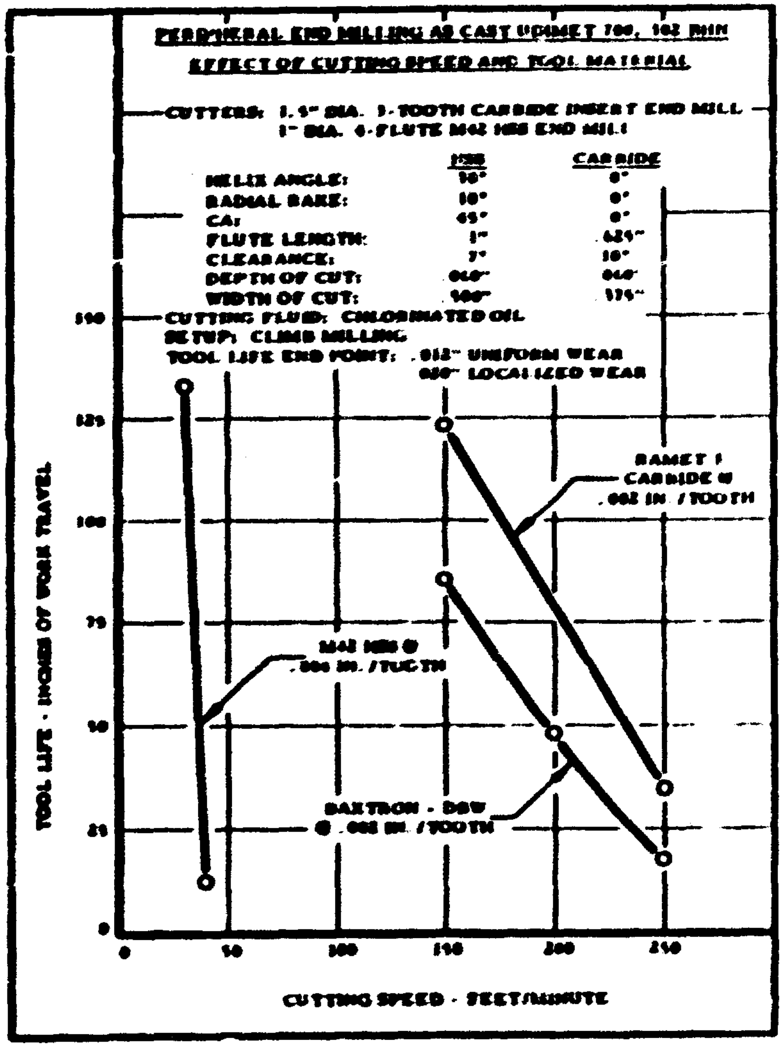
PERIPHERAL END MILLING AS CAST UDIMET 700, 302 BHN

EFFECT OF CUTTING SPEED AND DEPTH OF CUT

CUTTER: 1.5" DIA. 3-TOOTH CARBIDE INSERT END MILL
HELIX ANGLE: 0° FLUTE LENGTH: .625" WITH
RADIAL RAKE: 0° CLEARANCE: 10° RAMET 1
CA: 0° NR: .030" INSERTS
FEED: .002 IN /TOOTH
WIDTH OF CUT: .375"
CUTTING FLUID: CHLORINATED OIL
SETUP: CLIMB MILLING
TOOL LIFE END POINT: .015" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 180

Figure 263



PERIPHERAL END MILLING AS CAST UDIMET 700, 302 BHN

EFFECT OF CUTTING SPEED AND TOOL MATERIAL

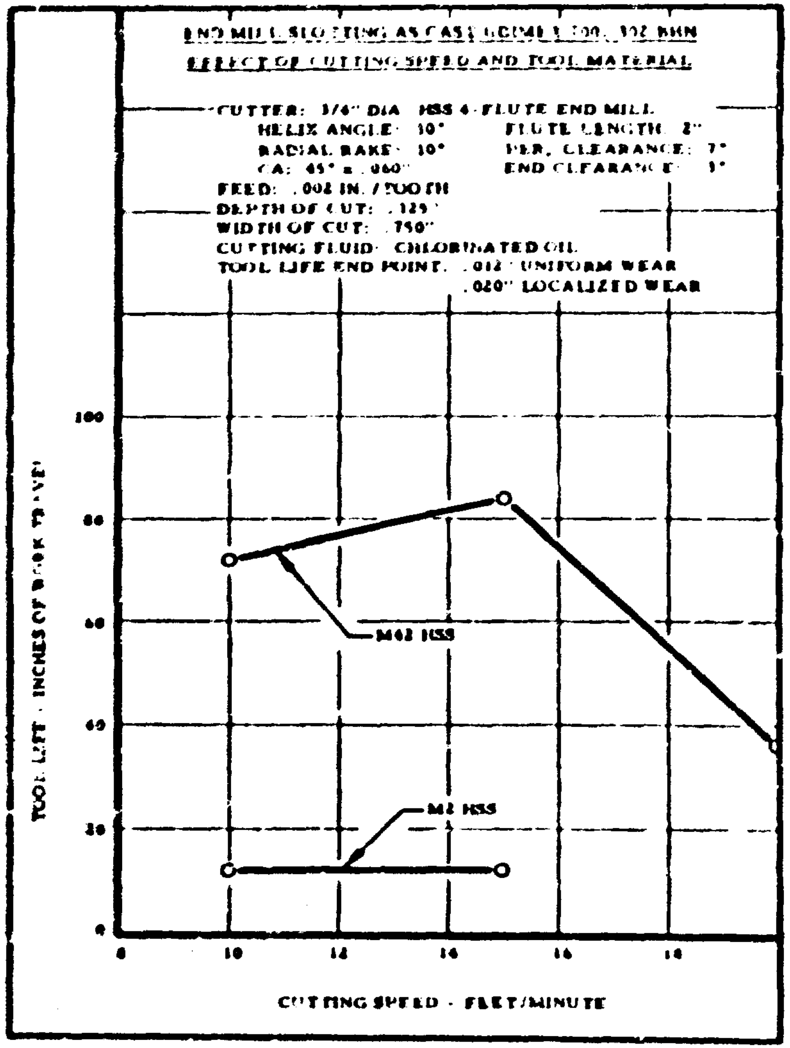
CUTTERS: 1.5" DIA. 3-TOOTH CARBIDE INSERT END MILL
1" DIA. 4-FLUTE M42 HSS END MILL

	HSS	CARBIDE
HELIX ANGLE:	30°	0°
RADIAL RAKE:	10°	0°
CA:	45°	0°
FLUTE LENGTH:	1"	.625"
CLEARANCE:	7°	10°
DEPTH OF CUT:	.060"	.060"
WIDTH OF CUT:	.500"	.375"

CUTTING FLUID: CHLORINATED OIL
SETUP: CLIMB MILLING
TOOL LIFE END POINT: .012" UNIFORM WEAR
.030" LOCALIZED WEAR

See text, page 100

Figure 204



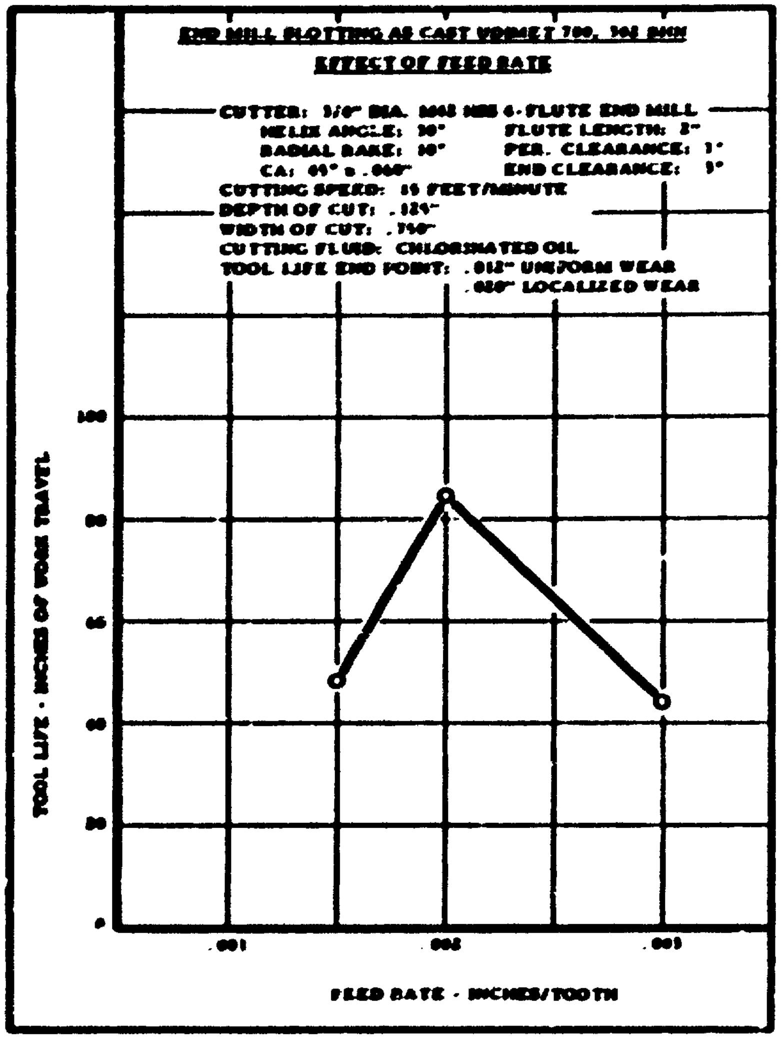
END MILL SLOTTING AS CAST UDIMET 700, 302 BHN

EFFECT OF CUTTING SPEED AND TOOL MATERIAL

CUTTER: 3/4" DIA HSS 4-FLUTE END MILL
HELIX ANGLE: 30°
RADIAL RAKE: 10°
CA: 45° x .060"
FLUTE LENGTH: 2"
PER. CLEARANCE: 7°
END CLEARANCE: 3°
FEED: .002 IN. /TOOTH
DEPTH OF CUT: .125"
WIDTH OF CUT: .750"
CUTTING FLUID: CHLORINATED OIL
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

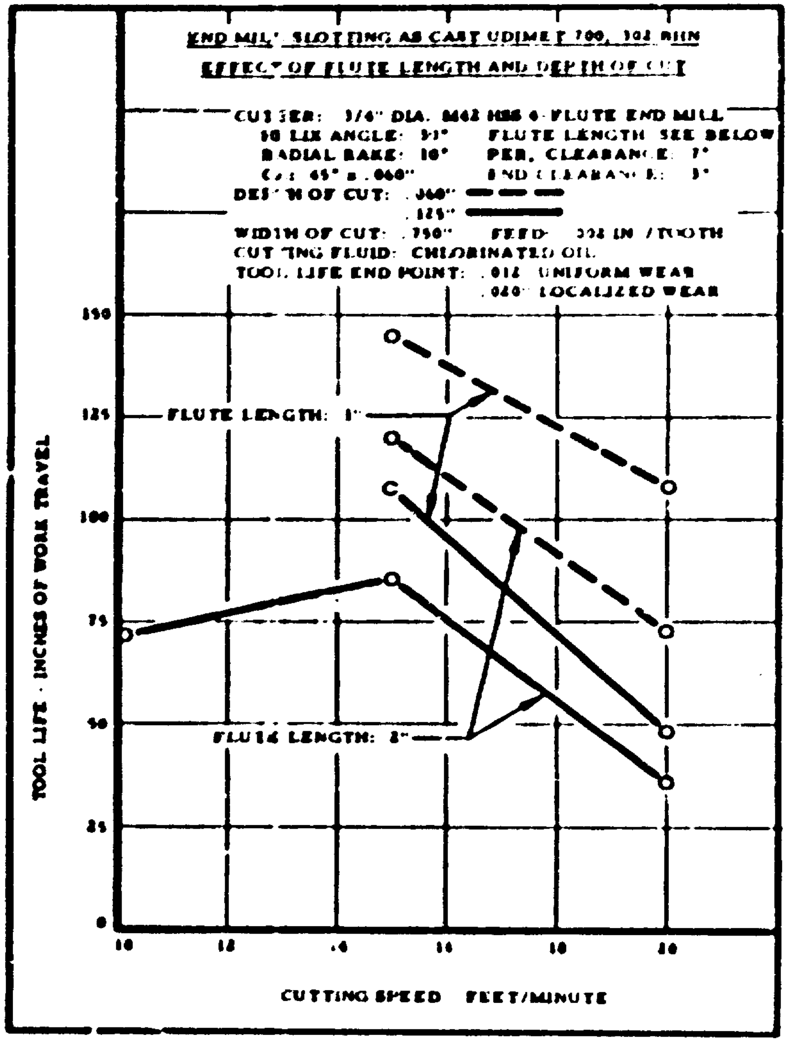
See text, page 101

Figure 205



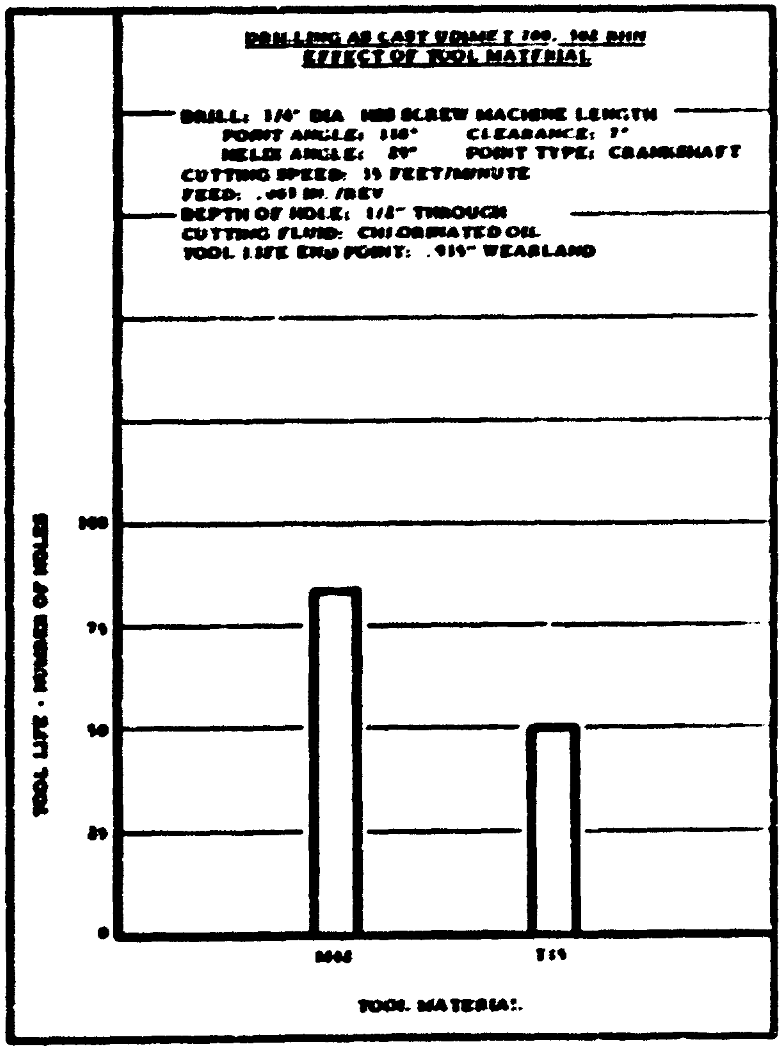
See text, page

Figure 206



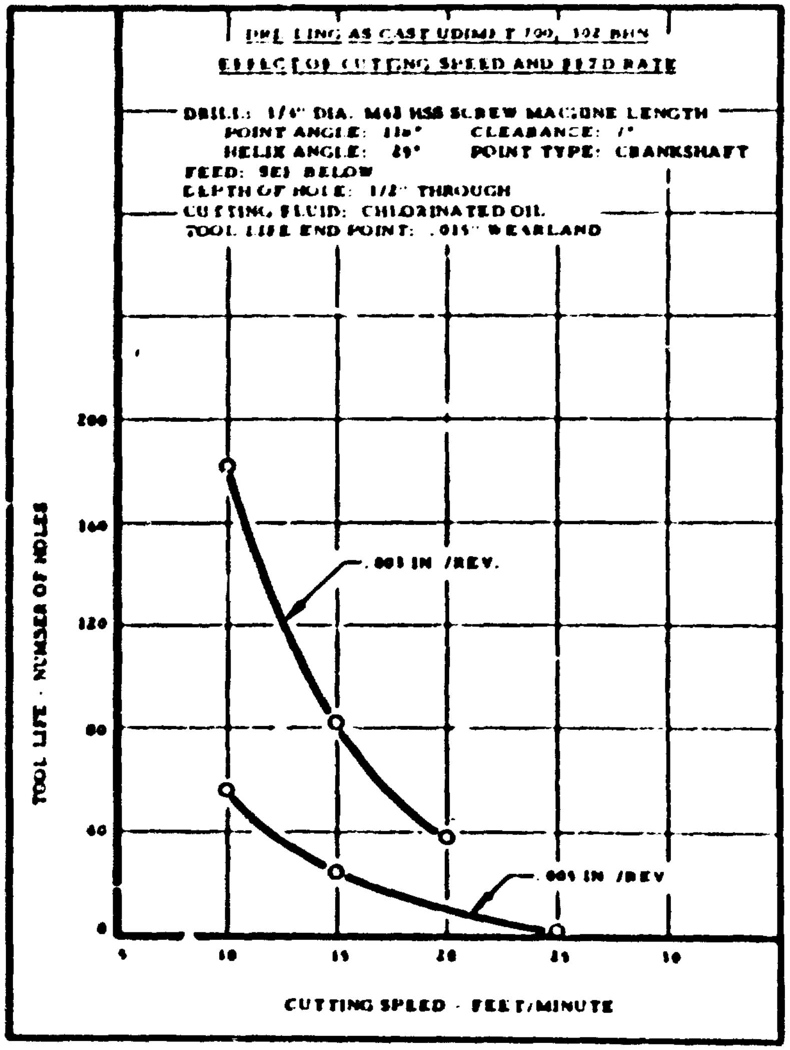
See text, page 181

Figure 207



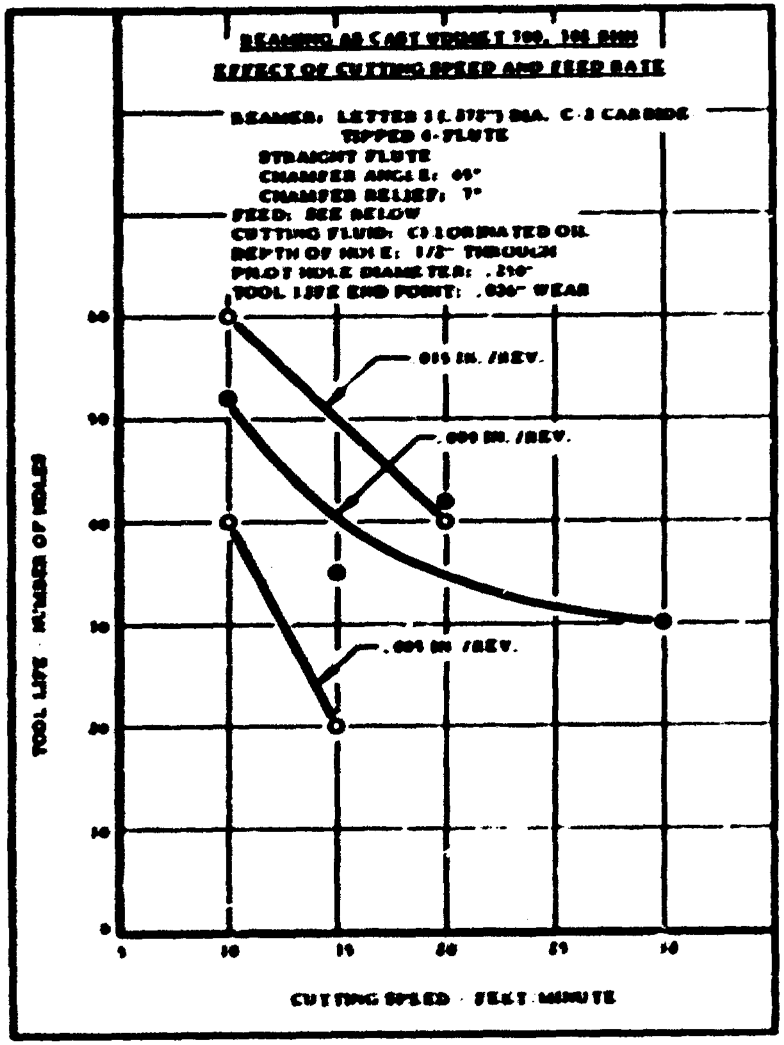
See text, page 181

Figure 24a



See text, page 181

Figure 24b



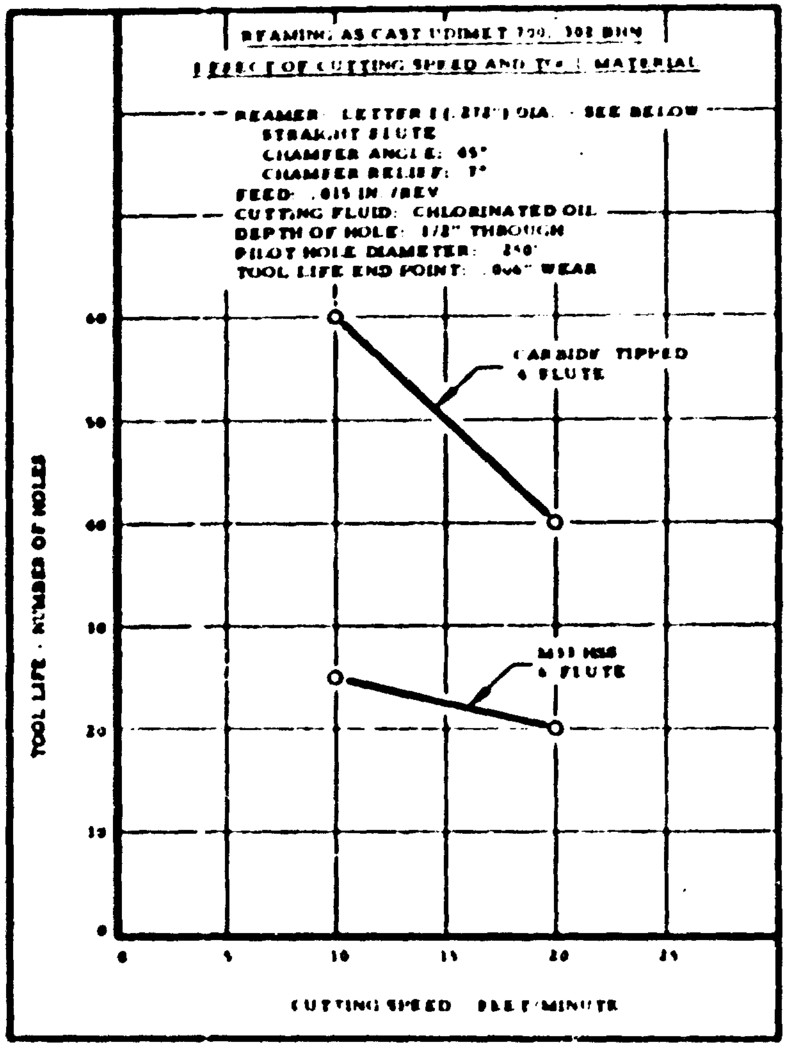
REAMING AS CAST UDIMET 700, 302 BHN

EFFECT OF CUTTING SPEED AND FEED RATE

REAMER: LETTER S (.348") DIA. C-2 CARBIDE
TIPPED 6-FLUTE
STRAIGHT FLUTE
CHAMFER ANGLE: 45°
CHAMFER RELIEF: 7°
FEED: SEE BELOW
CUTTING FLUID: CHLORINATED OIL
DEPTH OF HOLE: 1/2" THROUGH
PILOT HOLE DIAMETER: .310"
TOOL LIFE END POINT: .030" WEAR

See text, page 162

Figure 214



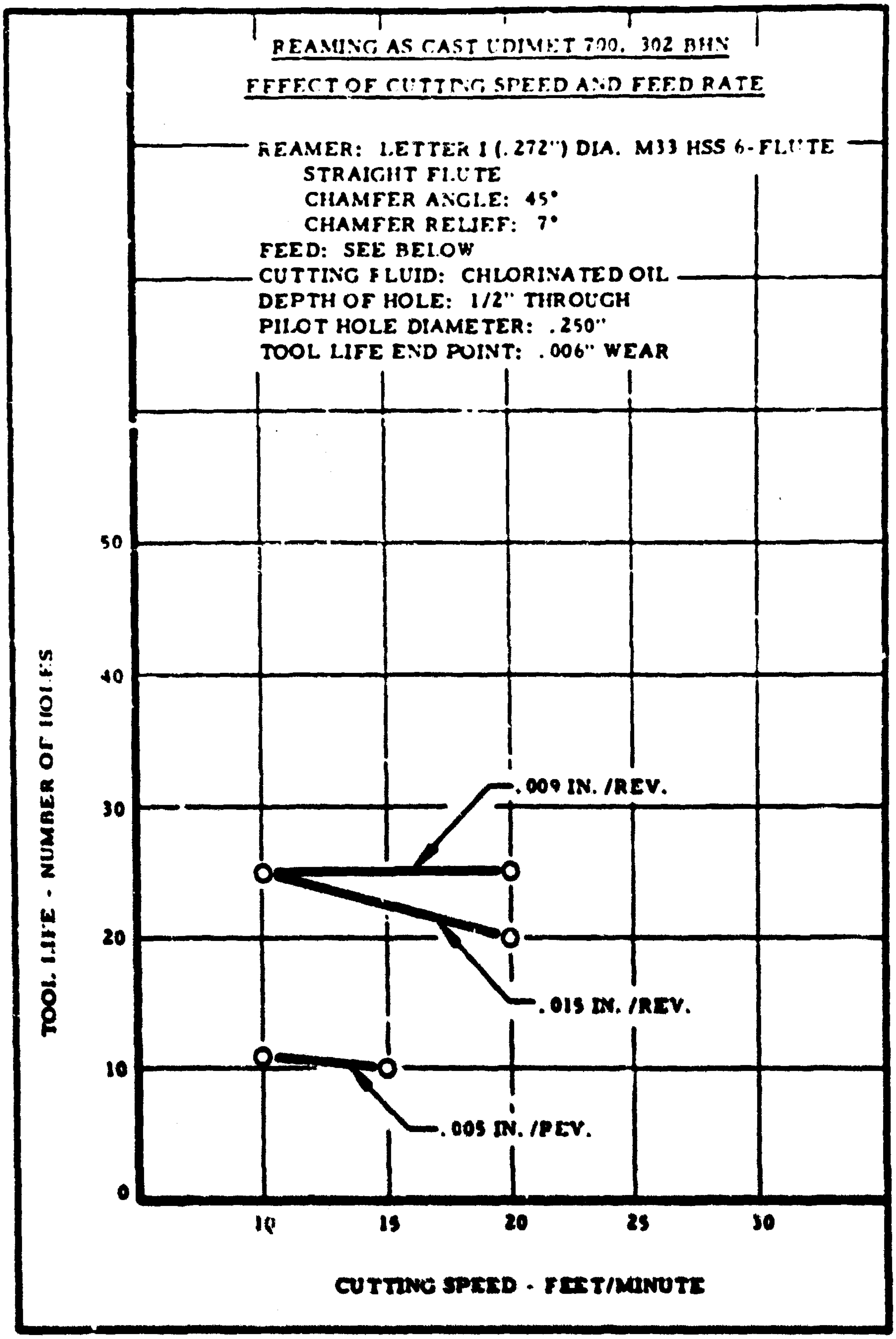
REAMING AS CAST UDIMET 700, 302 BHN

EFFECT OF CUTTING SPEED AND TOOL MATERIAL

REAMER: LETTER S (.348") DIA. - SEE BELOW
STRAIGHT FLUTE
CHAMFER ANGLE: 45°
CHAMFER RELIEF: 7°
FEED: .015 IN. /REV
CUTTING FLUID: CHLORINATED OIL
DEPTH OF HOLE: 1/2" THROUGH
PILOT HOLE DIAMETER: .310"
TOOL LIFE END POINT: .030" WEAR

See text, page 162

Figure 211



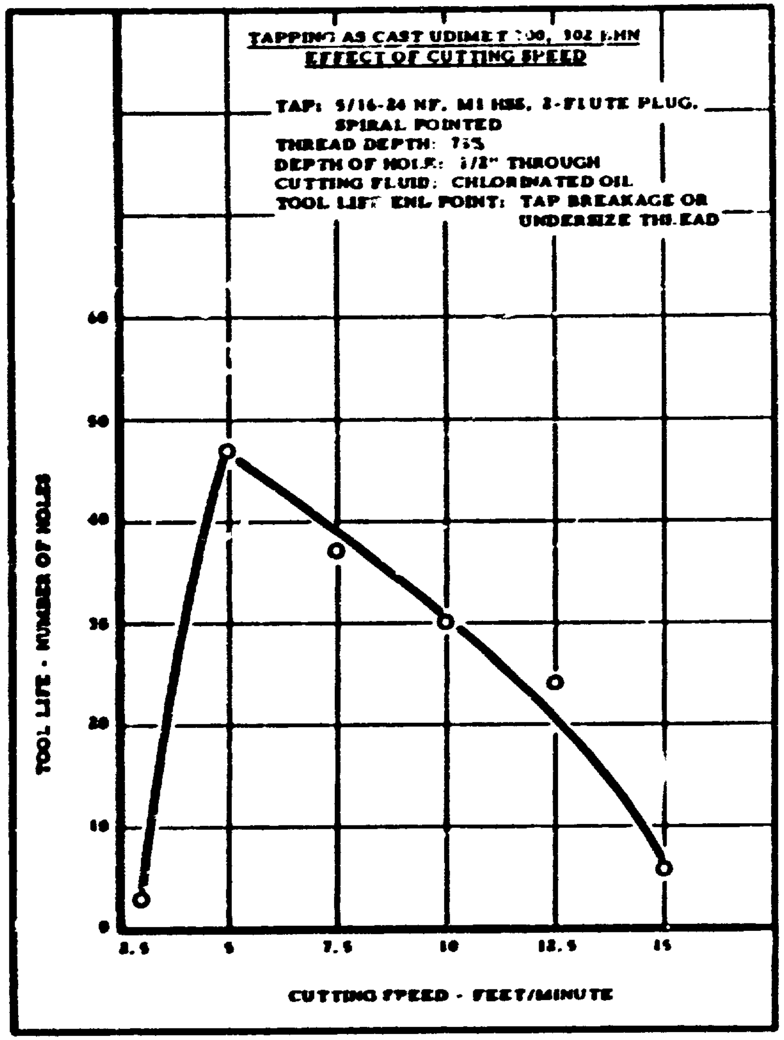
REAMING AS CAST UDIMET 700, 302 BHN

EFFECT OF CUTTING SPEED AND FEED RATE

REAMER: LETTER I (.272") DIA. M33 HSS 6-FLUTE
STRAIGHT FLUTE
CHAMFER ANGLE: 45°
CHAMFER RELIEF: 7°
FEED: SEE BELOW
CUTTING FLUID: CHLORINATED OIL
DEPTH OF HOLE: 1/2" THROUGH
PILOT HOLE DIAMETER: .250"
TOOL LIFE END POINT: .006" WEAR

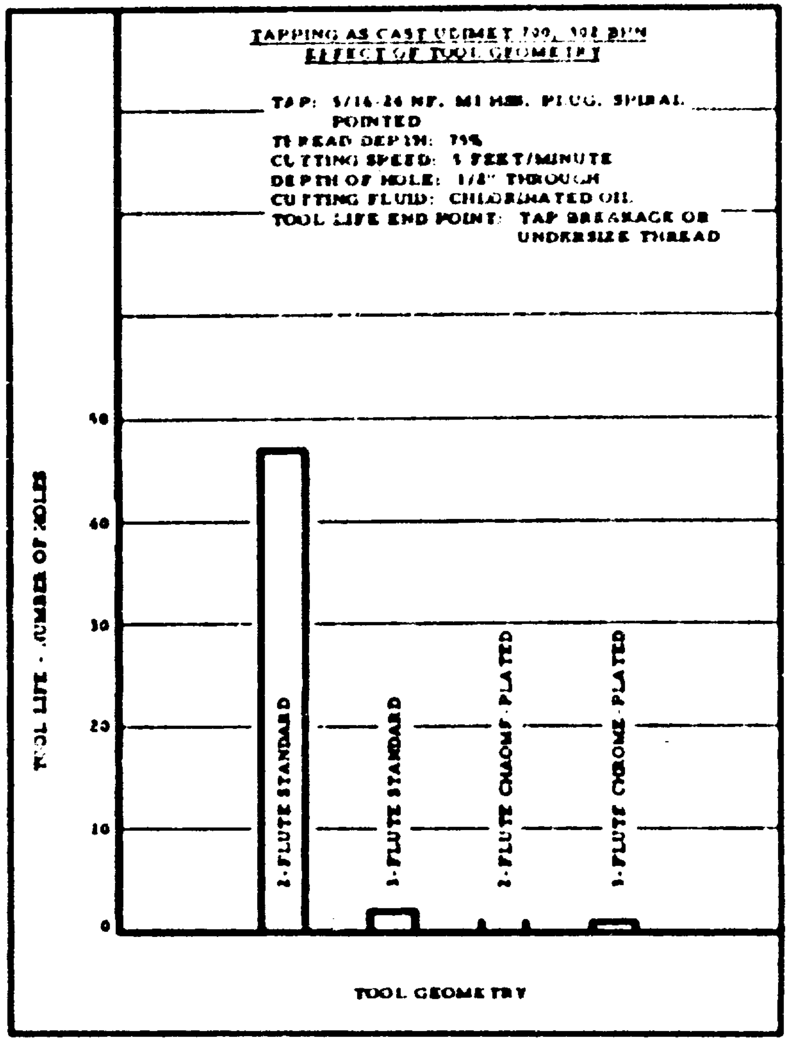
See text, page 182

Figure 212



See text, page 182

Figure 215



See text, page 182

Figure 216

5.4 Cast Inconel 718, As Cast

Alloy Identification

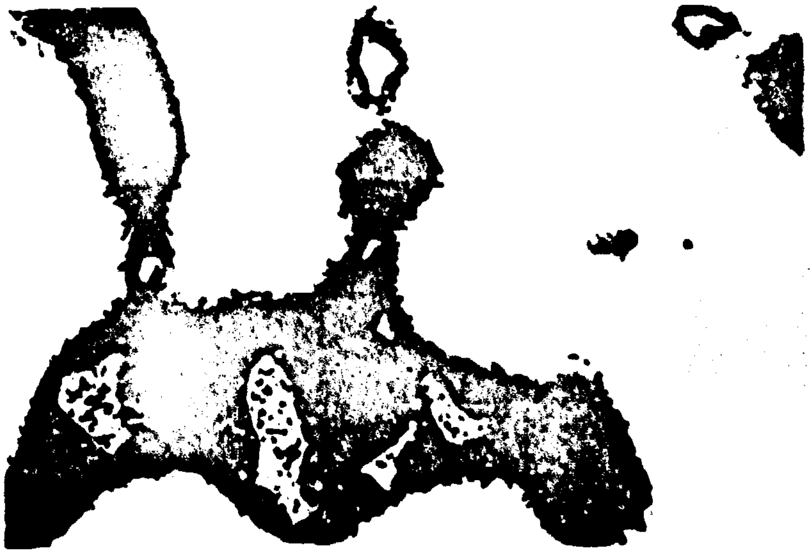
Inconel 718 is a precipitation hardening nickel base alloy which exhibits high strength at elevated temperatures as well as excellent cryogenic characteristics. The alloy is strengthened primarily by the precipitation of columbium intermetallics.

The material has the following nominal composition:

Ni-19Cr-18Fe-5.2Cb+Ta-3Mo-0.8Ti-0.6Al-.06C

The material for the milling tests was procured as 2 in. by 4 in. cast bars. No heat treatment was performed on this material prior to use. The hardness of the material was 269 BHN.

The microstructure of the alloy is evidenced below. The nickel-rich matrix contains irregularly-shaped Laves phases and blocky-shaped carbides and nitrides. The dark acicular phase is probably Ni_3Cb.



Inconel 718, As Cast

Etchant: Kalling's **Mag.: 500X**

[illegible] Cast Inconel 713, As Cast (continued)

Peripheral End Milling (269 BHN)

Tool life curves with three different grades of carbides are shown in Figure 215, page 198. Note that at a cutting speed of 150 feet/minute and a feed of .002 in./tooth the two new types of carbides -- Baxtron-DBW and Ramet 1 -- provided the longest tool life. The tool life values for the Baxtron-DBW, Ramet 1 and the C-2 grades of carbide were 300, 275 and 215 inches of work travel, respectively, at a cutting speed of 150 feet/minute. At a higher cutting speed of 250 feet/minute the tool life results for the C-2 grade of carbide, Ramet 1 and Baxtron-DBW were 170, 155 and 70 inches of work travel.

End Mill Slotting (269 BHN)

A 20 percent increase in cutting speed was obtained by using the M42 HSS cutter in place of the M2 HSS cutter, see Figure 216, page 198. A comparison of the two tool life curves shows that at a cutting speed of 60 feet/minute, the tool life with the M42 HSS cutter was 110 as compared to 49 inches of work travel with the M2 HSS cutter. The feed used in end mill slotting is somewhat critical. Note in Figure 217, page 199, that while a tool life of 77 inches of work travel was obtained at a feed of .002 in./tooth, the tool life dropped to 25 inches at a feed of .003 and 60 inches at a feed of .001 in./tooth. The cutting speed was 25 feet/minute.

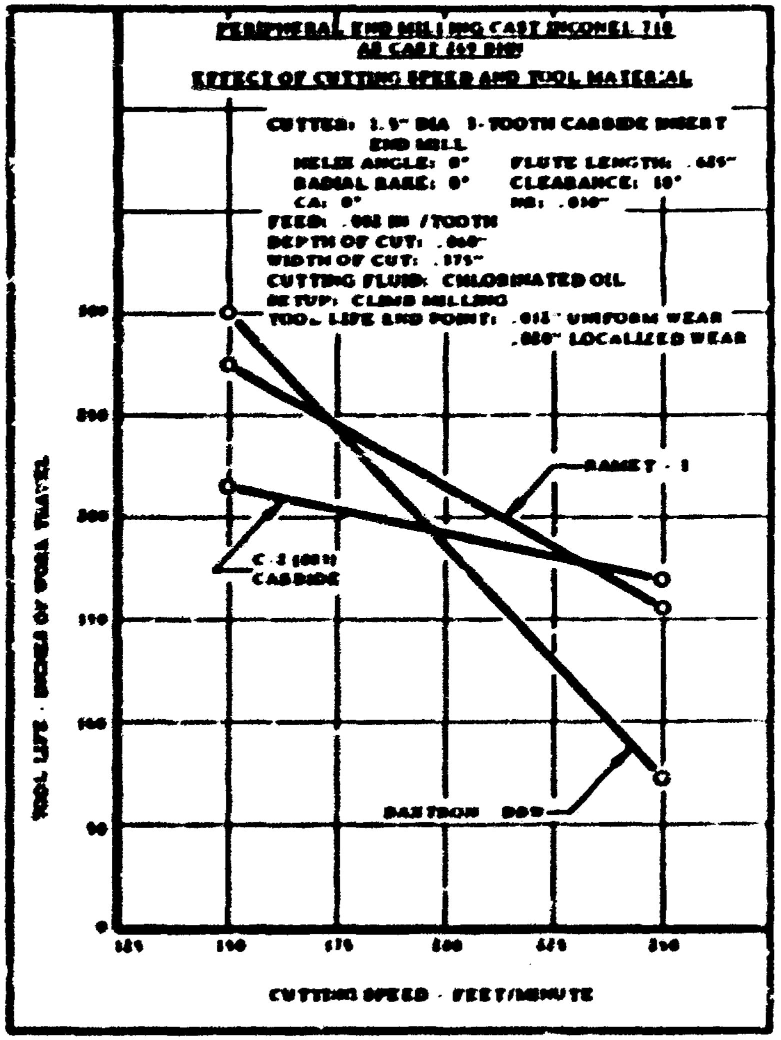
TABLE XV

RECOMMENDED CONDITIONS FOR MACHINING INCONEL 718, AS CAST 269 BHN

Nominal Chemical Composition, Percent

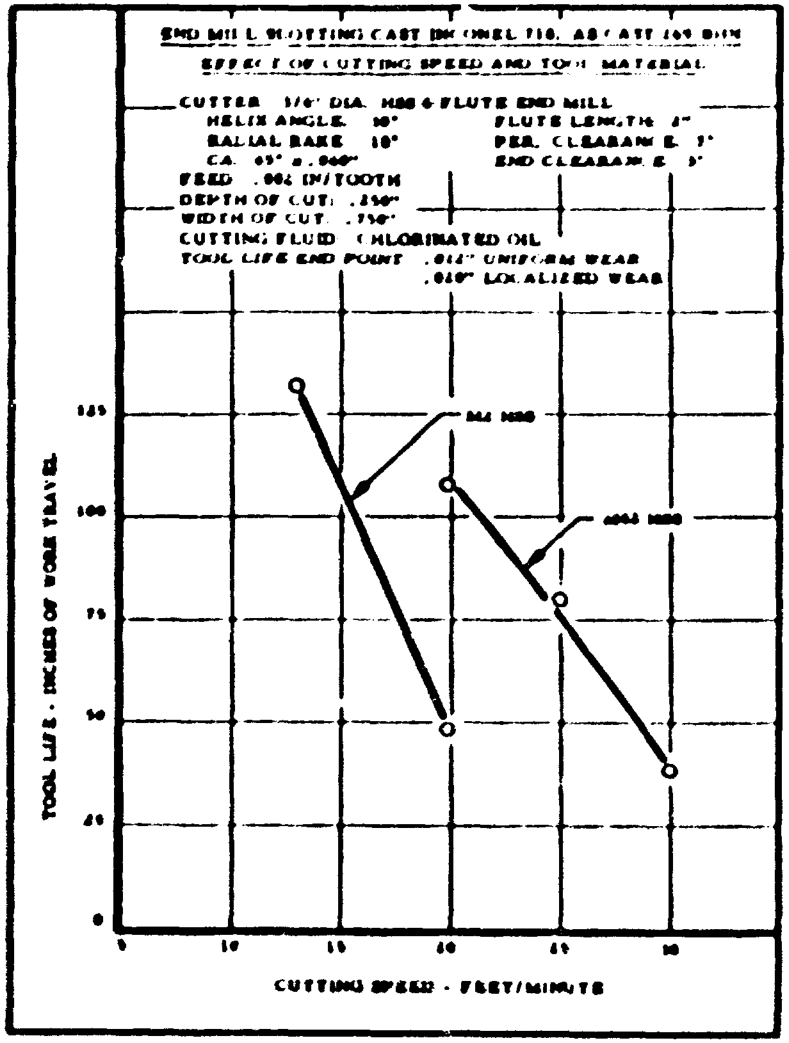
Ni	Cr	Mo	Cb	Ti	Al	Fe
Bal.	19	3	5.2	0.8	0.6	18

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Peripheral End Milling	C-2 Carbide Insert	Helix Angle: 0° RR: 0° Clearance: 10° NR: .032"	1.5" Diameter 3 Tooth Carbide Insert End Mill	.060	.375	.002 in/tooth	150	300" work travel	.012	Chlorinated Oil
End Mill Slotting	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	1" Diameter 4 Flute HSS End Mill	.250	.750	.002 in/tooth	20	108" work travel	.012	Chlorinated Oil



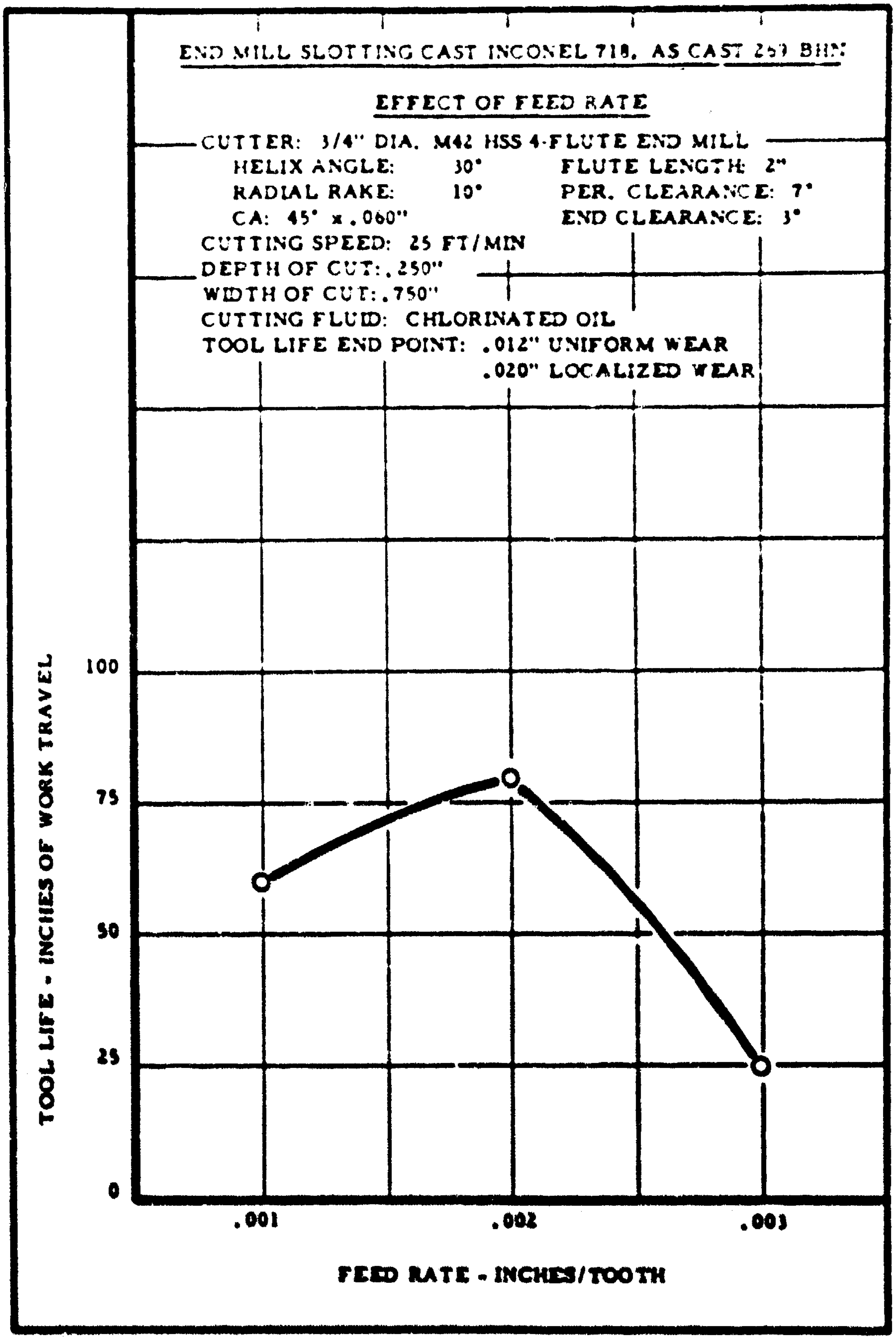
See text, page 196

Figure 215



See text, page 196

Figure 216



See text, page 196

Figure 217

6. MACHINING STAINLESS STEEL

6.1 Greek Ascoloy, Quenched and Tempered

Alloy Identification

Greek Ascoloy is a chromium-nickel-tungsten alloy steel used in medium high temperature applications. The nominal composition of this alloy is as follows:

Fe-13Cr-3.0W-2.0Ni-.3Mn-.2Si-.18C

The material for the machining tests was procured as 2 in. by 4 in. rectangular bars in the quenched and tempered condition. The heat treatment to which the material had been subjected was as follows:

Austenitize:	1850°F/2 hours/oil quench
Temper:	1100°F/4 hours/air cool

The resulting hardness was 352 BHN. As evidenced below, the microstructure consists of roughly equiaxed tempered martensite.

Greek Ascoloy, Quenched and Tempered

Etchant: Kalling's **Mag.: 500X**

6.1 Greek Ascoloy, Quenched and Tempered (continued)

Turning (352 BHN)

Note in Figure 218, page 208, that a tool life of more than 60 minutes was obtained at a cutting speed of 70 feet/minute using an M2 HSS tool at a feed of .010 in./rev. Using a C-6 grade of carbide, the tool life was 22 minutes at a cutting speed of 400 feet/minute; see Figure 219, page 208. A feed of .010 in./rev. was also used with the carbide tool.

Face Milling (352 BHN)

A comparison of two HSS tools is shown in Figure 220, page 209, for face milling Greek Ascoloy, quenched and tempered to 352 BHN. Note that, for a given tool life, the cutting speeds with the M42 tools were about 25 percent higher than with the M2 HSS tools. For example, at a tool life of 200 inches of work travel, the cutting speed with the M2 tool was 80 feet/minute, as compared to 100 feet/minute for the M42 tool. It should be pointed out, however, that a single-tooth face mill was used at a feed of .010 in./tooth.

Figure 221, page 209, shows the relationship between feed rate and tool life at a cutting speed of 120 feet/minute for a single-tooth cutter. At this cutting speed, with the single-tooth face mill, a feed rate of .008 in./tooth was the best of the three feeds used. The tool life dropped very rapidly when the feed was increased to .010 in./tooth and decreased about 30 percent when the feed was decreased to .006 in./tooth.

A highly chlorinated oil provided a longer tool life than the soluble oil at a cutting speed of 100 feet/minute, as shown in Figure 222, page 210. Under these conditions, the tool life was 165 inches of work travel with the soluble oil and 245 inches of work travel with the highly chlorinated oil. However, it should be pointed out that, when milling at a cutting speed of 100 feet/minute or more, problems could arise as a result of the smoke generated by the oil, especially with multiple-tooth cutters.

A comparison of the tool life curves obtained with a single-tooth and a 14-tooth cutter is shown in Figure 223, page 210. The cutter life per tooth was 72 inches of work travel with the single-tooth cutter and 48 inches of work travel per tooth for the 14-tooth cutter. It should be noted, however, that the 14-tooth cutter cut a total of 672 inches of work travel. Note in spite of the fact that the feed with the single-tooth cutter was .010 in./tooth and .008 in./tooth with

Face Milling (352 BHN) (continued)

the multiple-tooth cutter, the metal removal rate was eleven times faster with the multiple-tooth cutter.

The M42 HSS multiple-tooth cutter provided a slightly higher tool life than the M2 HSS cutter. For example, at a tool life of 36 inches of work travel per tooth, the M42 HSS cutter permitted a 5 percent higher cutting speed than the M2 HSS cutter see Figure 224 page 211.

As shown in Figure 225, page 211, the magnitude of the feed rate was not critical over the range shown. Note at the cutting speeds shown in the chart, namely 110 and 125 feet/minute, the decrease in tool life with the multiple-tooth cutter was less than 10 percent when the feed rate was increased from .005 to .008 in./tooth.

Face milling Greek Ascoloy in the quenched and tempered condition (352 BHN) was particularly poor with carbide tools because of the tendency of the carbide to chip. As a result of the chipping, tool life was low and somewhat erratic. Also, as shown in Figure 226, page 212, the selection of cutting speed was critical. For example, at a cutting speed of 250 feet/minute, the life of the single-tooth cutter was 275 inches of work travel. Increasing or decreasing the cutting speed resulted in a marked drop in tool life. While this may be expected when increasing the cutting speed to 450 feet/minute, it is unusual when decreasing the cutting speed. Also, the tool life was even more erratic and much lower when a soluble oil was used.

The C-6 grade of carbide provided appreciably longer tool life than the C-2 grade; see Figure 227, page 212. As a matter of fact, for a given tool life, the cutting speeds with the C-6 grade were about 30 percent faster than with the C-2 grade. Note in Figure 228, page 213, that at the cutting speed of 250 feet/minute for the conditions shown, the tool life dropped rapidly when the feed was increased from .005 to .008 in./tooth.

The effect of tool geometry on tool life is indicated in Figures 229 and 230, pages 213 and 214. Note in Figure 229 that at a feed of .008 in./tooth the single-tooth cutter having the 5° positive axial rake and 5° negative radial rake angles provided the longest tool life as compared to a double negative or a double positive tool geometry, while at a feed of .005 in./tooth (Figure 230), the tool life with the cutter having the 5° double positive rake angles was slightly greater

Face Milling (352 BHN) (continued)

than the one with the 5° positive axial rake and 5° negative radial rake angles at a feed of .005 in./tooth.

The problem of chipping of the carbide tool increased when the multiple-tooth cutter was used. Hence, the feed had to be reduced to .005 in./tooth. A tool life curve was obtained as shown in Figure 231, page 214, for a six-tooth cutter with double negative and double positive rake angles. The cutter with the 5° negative axial and radial rake angles was superior to the one having the positive rake angles. This superiority existed over a range of feeds as shown in Figure 232, page 215. Note also that the tool life did not change appreciably as the feed rate increased from .003 to .005 in./tooth.

The chipping of the carbide tool was primarily the result of the chips welding to the cutting edge of the tool. Hence, an investigation was made regarding the use of various types of cutting fluids to alleviate this situation. As shown in Figure 233, page 215, the tool life with the soluble oil was even less than that cutting dry. However, the chlorinated oil did provide a tool life that was double that obtained while cutting dry. Nevertheless, it may not be practical to use this cutting oil since smoke is generated and an exhaust system would have to be used to make the operation practical.

Tool life curves showing the relationship between cutter life and cutting speed for two different feeds while cutting dry are shown in Figure 234, page 216. Note that as the cutting speed was increased, the tool life per tooth increased to about 70 inches of work travel per tooth at a speed of 350 feet/minute and a feed of .005 in./tooth. Increasing the speed beyond this point resulted in a decrease in tool life.

An interesting comparison is made in Figure 235, page 216, between a single-tooth carbide cutter and a six-tooth carbide cutter. Note that with the multiple-tooth cutter the maximum tool life was 150 inches of work travel per tooth at a cutting speed of 350 feet/minute. This amounted to 900 inches of work travel in total for the multiple-tooth cutter. The single-tooth cutter provided a tool life of 180 inches of work travel at a cutting speed of about 540 feet/minute.

Peripheral End Milling (352 BHN)

A curve showing the relationship between tool life, in terms of inches of work travel, versus cutting speed is shown in Figure 236, page 217, for a 1 in. diameter M42 HSS end mill. Note that at a cutting speed of 150 feet/minute and a feed of .003 in./tooth, 500 inches of work was machined before the cutter required regrinding.

A comparison of an M42 and an M2 HSS end mill is shown in Figure 237, page 217. The cutting speed was 200 feet/minute over the range of feeds used. At a given feed rate, the M42 HSS cutter produced about 20 percent longer tool life than the M2 HSS end mill.

End Mill Slotting (352 BHN)

Tool life curves for both the M2 HSS and M42 HSS end mills are presented in Figure 238, page 218. Note that for a given tool life the cutting speeds with the M42 HSS end mill were 10 percent higher than the M2 HSS end mill.

As shown in Figure 239, page 218, as the feed was increased from .001 to .002 in./tooth, the tool life dropped from 190 inches of work travel to 130 inches of work travel. Increasing the feed still further to .004 in./tooth resulted in decreasing tool life to 85 inches of work travel.

Drilling (321 BHN)

Good tool life was obtained with both the M1 and M42 HSS drills at reasonably high cutting speed. For example, as shown in Figure 240, page 219, at a cutting speed of 70 feet/minute the tool life with the M1 HSS drill was 215 holes. With the M42 HSS drill, the tool life was over 250 holes at a cutting speed of 75 feet/minute.

A chlorinated oil provided about a 7 percent increase in cutting speed over a chemical emulsion in drilling; see Figure 241, page 219.

Reaming (321 BHN)

Tool life curves are presented in Figure 242, page 220, for both M2 and M33 HSS reamers. Note that the tool life was almost the same for both grades of HSS.

6.1 Greek Ascoloy, Quenched and Tempered (continued)

Tapping (321 BHN)

As shown in Figure 243, page 220, unless an active chlorinated oil was used, both the cutting speed and tap life was very low. For example, at a cutting speed of 10 feet/minute, the tap life with a soluble oil was 24 holes. With the sulfurized oil at a cutting speed of 40 feet/minute, the tap life was 37 holes, while with a chlorinated oil 250 holes were tapped at a cutting speed of 70 feet/minute.

TABLE XVI

RECOMMENDED CONDITIONS FOR MACHINING GREEK ASCOLOY, QUENCHED AND TEMPERED 352 BHN

Nominal Chemical Composition, Percent

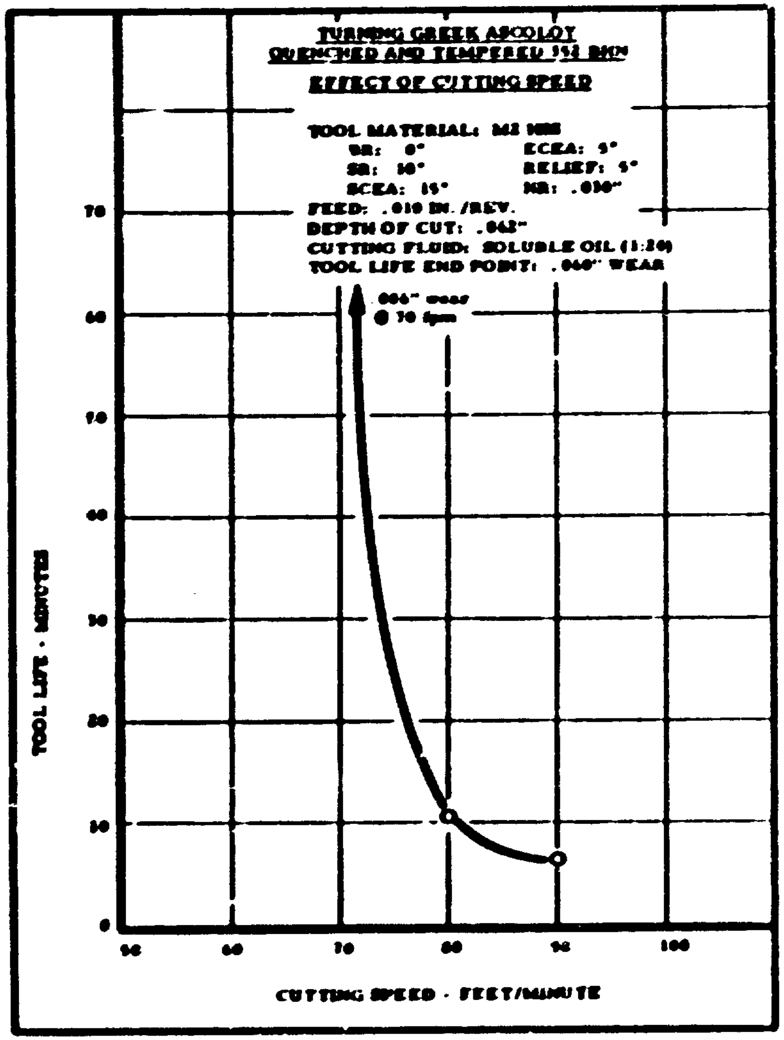
Fe	Cr	W	Ni	Mn	Si	C
Bal.	13	3.0	2.0	.3	.2	.18

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Turning	M2 HSS	BR: 0° SCEA:15° SR:10° ECEA:5° Relief: 5° NR: .030"	5/8" Square Tool Bit	.002	-	.010 in/rev	70	60 min.	.006	Soluble Oil (1:20)
Turning	C-2 Carbide	BR:-5° SCEA:15° SR:-5° ECEA:15° Relief: 5° NR: .030"	SNG 432 Insert	.062	-	.010 in/rev	400	22 min.	.015	Soluble Oil (1:20)
Face Milling	M42 HSS	AR:5° ECEA:1° RR:5° CA:45° Clearance: 10°	4" Diameter 14 Tooth HSS Face Mill	.060	2	.008 in/tooth	110	672" work travel	.060	Soluble Oil (1:20)
Face Milling	C-2 Carbide	AR:-5° ECEA:45° RR: -5° CA: 45° Clearance: 5°	4" Diameter 6 Tooth Face Mill	.060	2	.005 in/tooth	350	900" work travel	.015	Chlorinated Oil
Peripheral End Milling	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	1" Diameter 4 Flute HSS End Mill	.125	.500	.003 in/tooth	200	245" work travel	.012	Soluble Oil (1:20)
End Mill Slotting	M42 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" Diameter 4 Flute HSS End Mill	.125	.750	.002 in/tooth	100	325" work travel	.012	Soluble Oil (1:20)

TABLE XVI (continued)

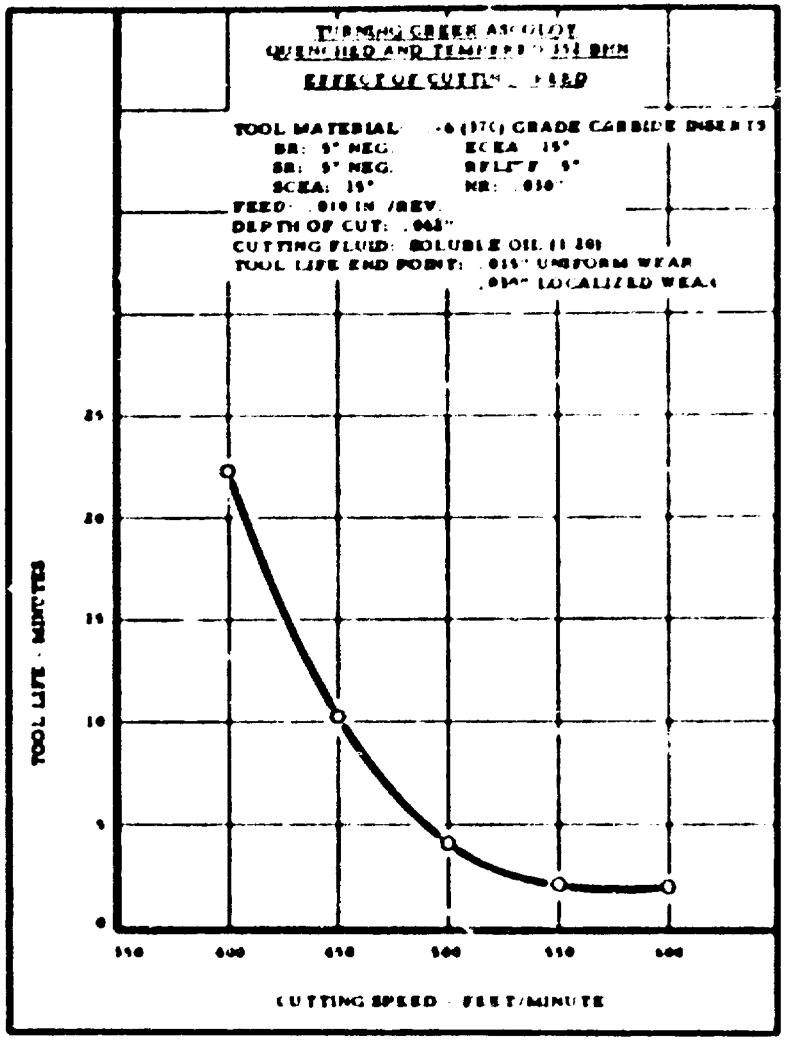
RECOMMENDED CONDITIONS FOR MACHINING GREEK ASCOLOY, QUENCHED AND TEMPERED 352 BHN

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min.	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Drilling	M42 HSS	118° Crankshaft Point Helix Angle: 29° Clearance: 7°	1/4" Diameter HSS Drill 2-1/2" Long	.500 thru	--	.005 in/rev	80	250+ holes	.013	Chlorinated Oil
Reaming	M2 HSS	Helix Angle: 0° CA: 45° Clearance: 7°	.272" Diameter 6 Flute Chucking Reamer	.500 thru	--	.009 in/rev	90	250+ holes	.004	Chlorinated Oil
Tapping	M1 HSS	2 Flute Plug Spiral Point 75% Thread	5/16-24 NF Tap	.500 thru	--	--	70	250+ holes	--	Chlorinated Oil



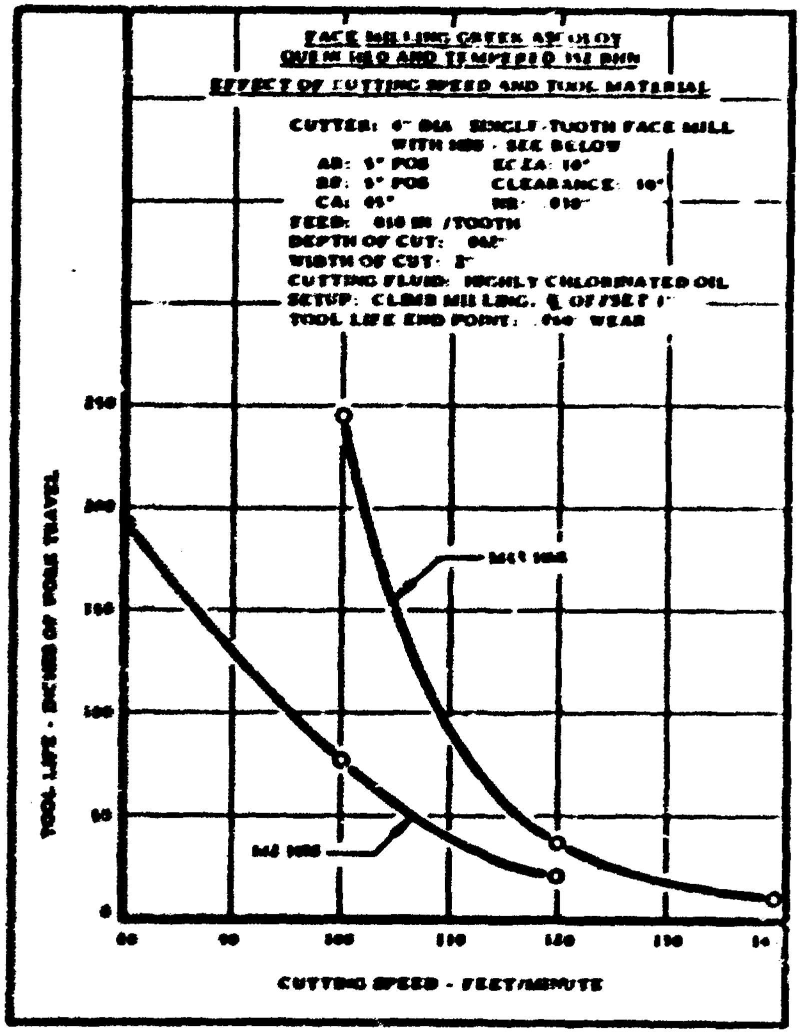
See text, page 201

Figure 210



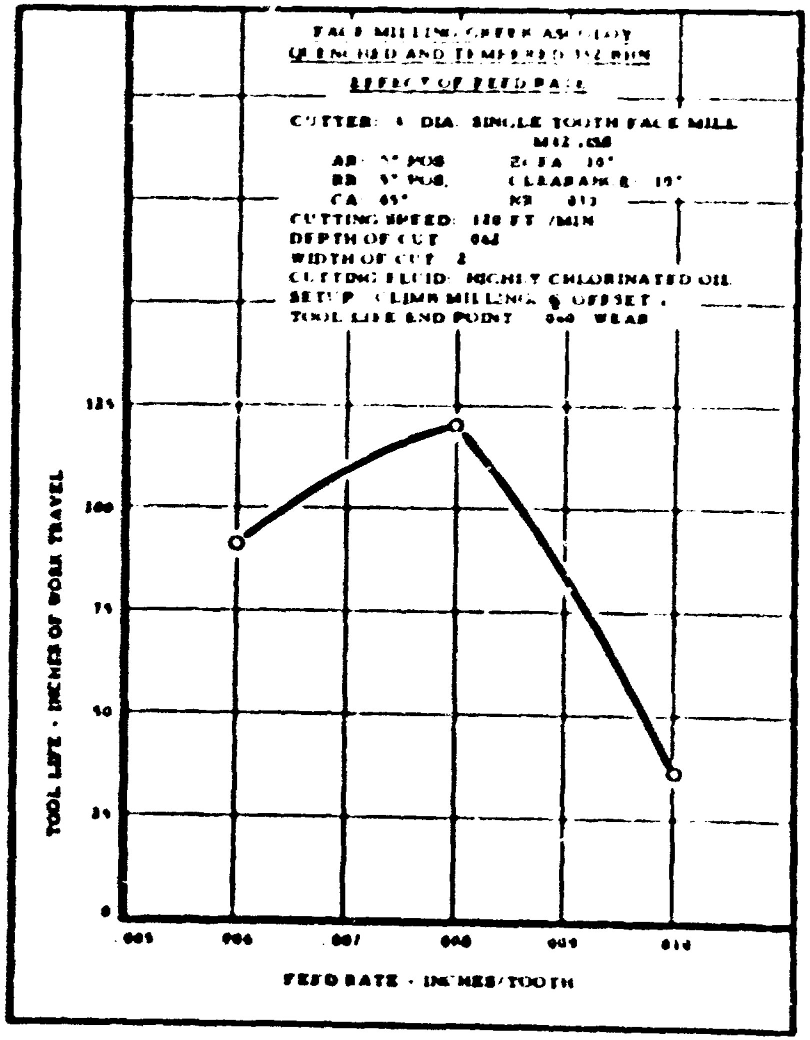
See text, page 231

Figure 211



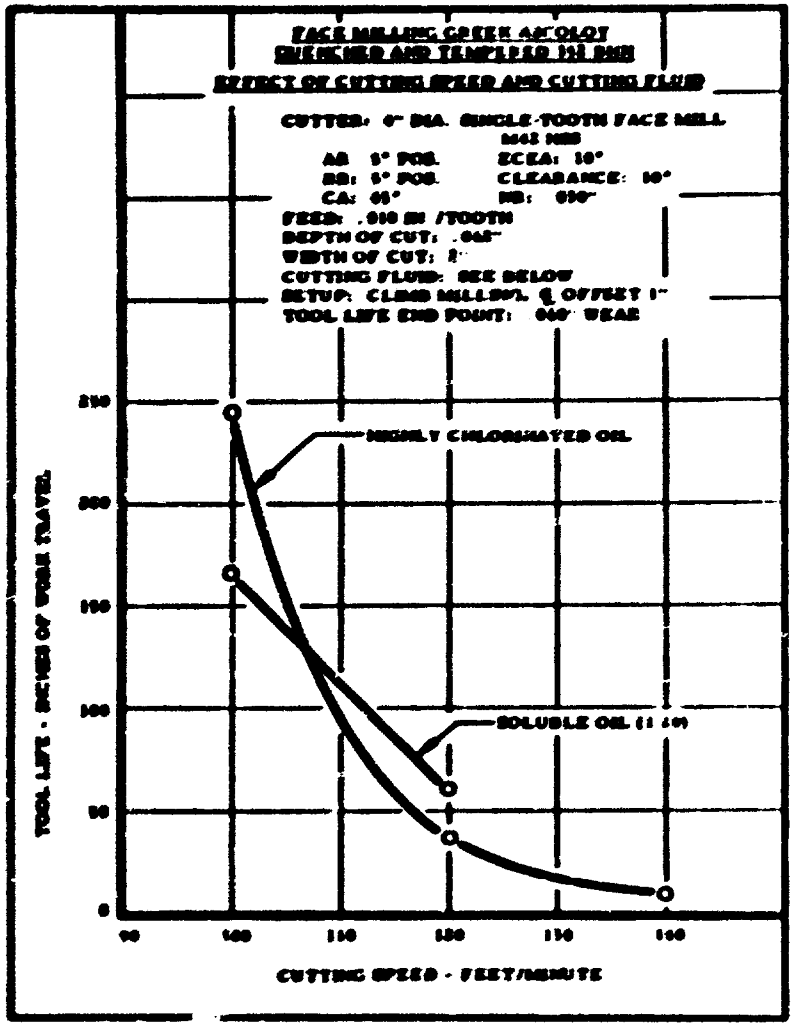
See text, page 201

Figure 220



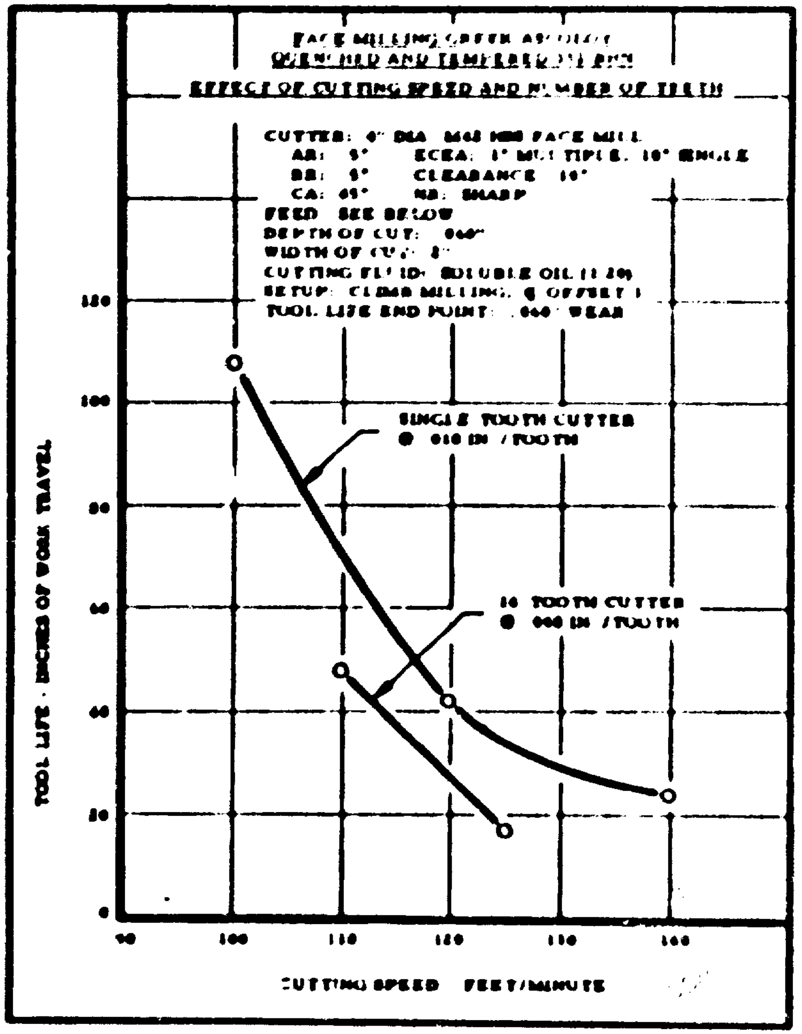
See text, page 201

Figure 221



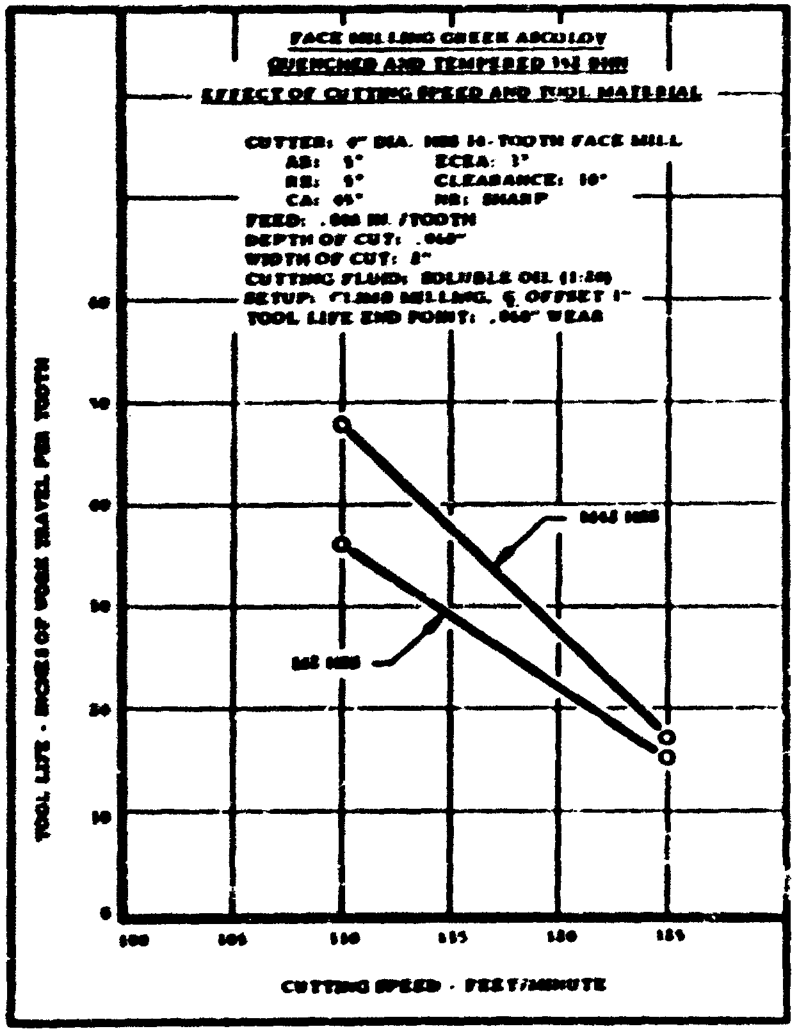
See text, page 241

Figure 222



See text, page 201

Figure 221

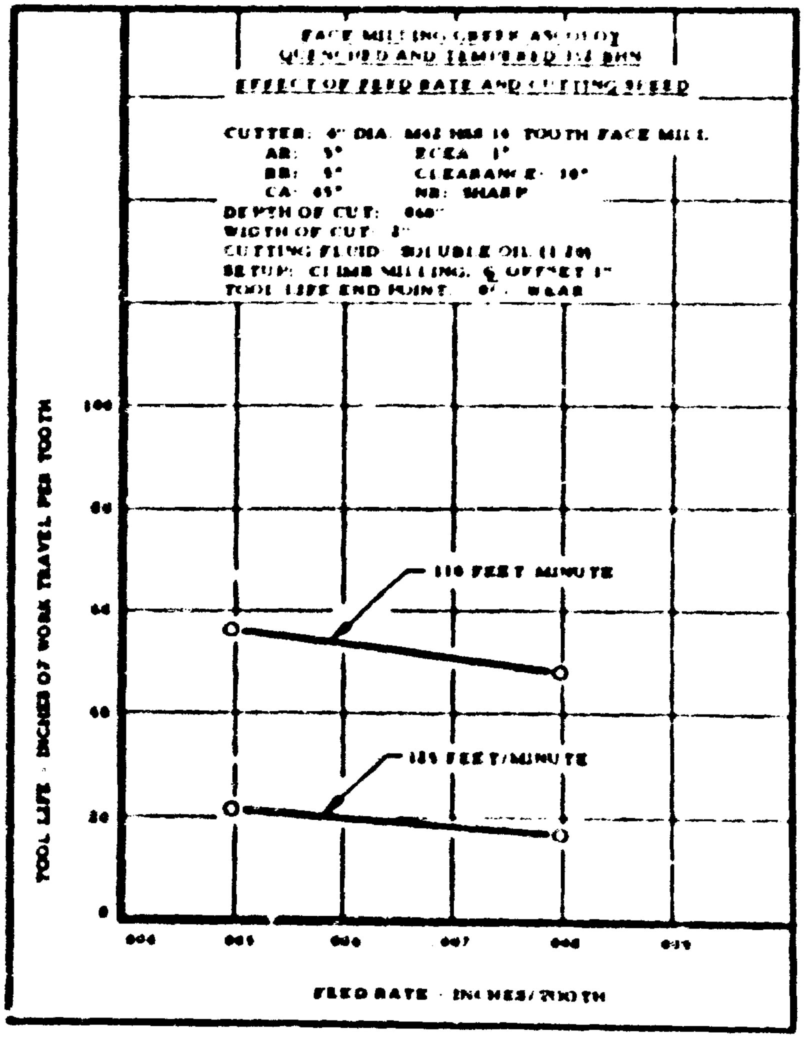


FACE MILLING GREEK ASCOLOY
QUENCHED AND TEMPERED [illegible] BHN
EFFECT OF CUTTING SPEED AND TOOL MATERIAL

CUTTER: 4" DIA. HSS 14-TOOTH FACE MILL
AR: 5° ECEA: 1°
RR: 5° CLEARANCE: 10°
CA: 45° NR: SHARP
FEED: .008 IN./TOOTH
DEPTH OF CUT: .060"
WIDTH OF CUT: 2"
CUTTING FLUID: SOLUBLE OIL (1:20)
SETUP: CLIMB MILLING, ℄ OFFSET 1"
TOOL LIFE END POINT: .060" WEAR

See text, page 306

Figure 220

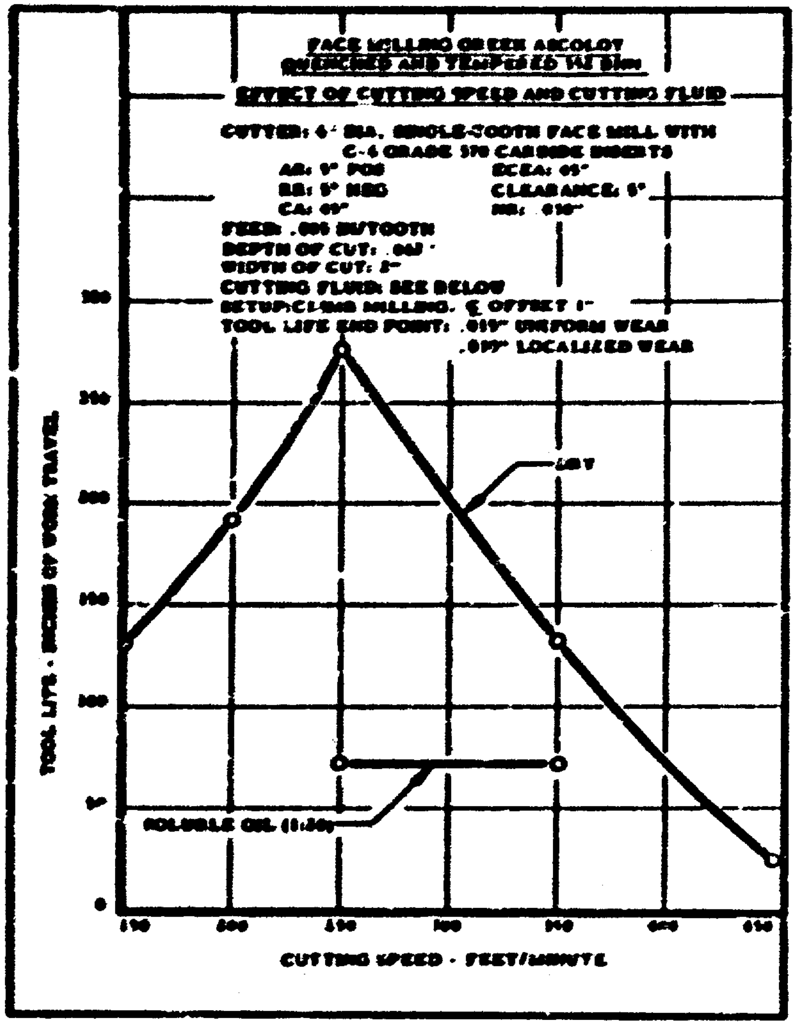


FACE MILLING GREEK ASCOLOY
QUENCHED AND TEMPERED [illegible] BHN
EFFECT OF FEED RATE AND CUTTING SPEED

CUTTER: 4" DIA. M42 HSS 14-TOOTH FACE MILL
AR: 5° ECEA: 1°
RR: 5° CLEARANCE: 10°
CA: 45° NR: SHARP
DEPTH OF CUT: .060"
WIDTH OF CUT: 2"
CUTTING FLUID: SOLUBLE OIL (1:20)
SETUP: CLIMB MILLING, ℄ OFFSET 1"
TOOL LIFE END POINT: .060" WEAR

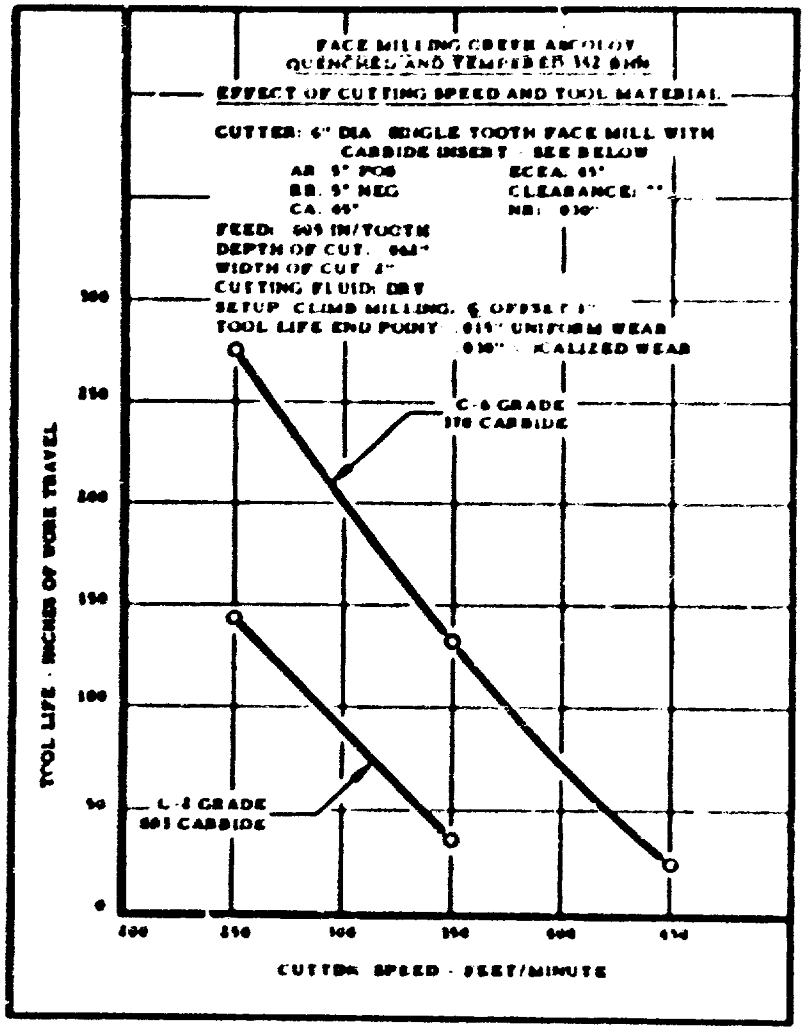
See text, page 308

Figure 221



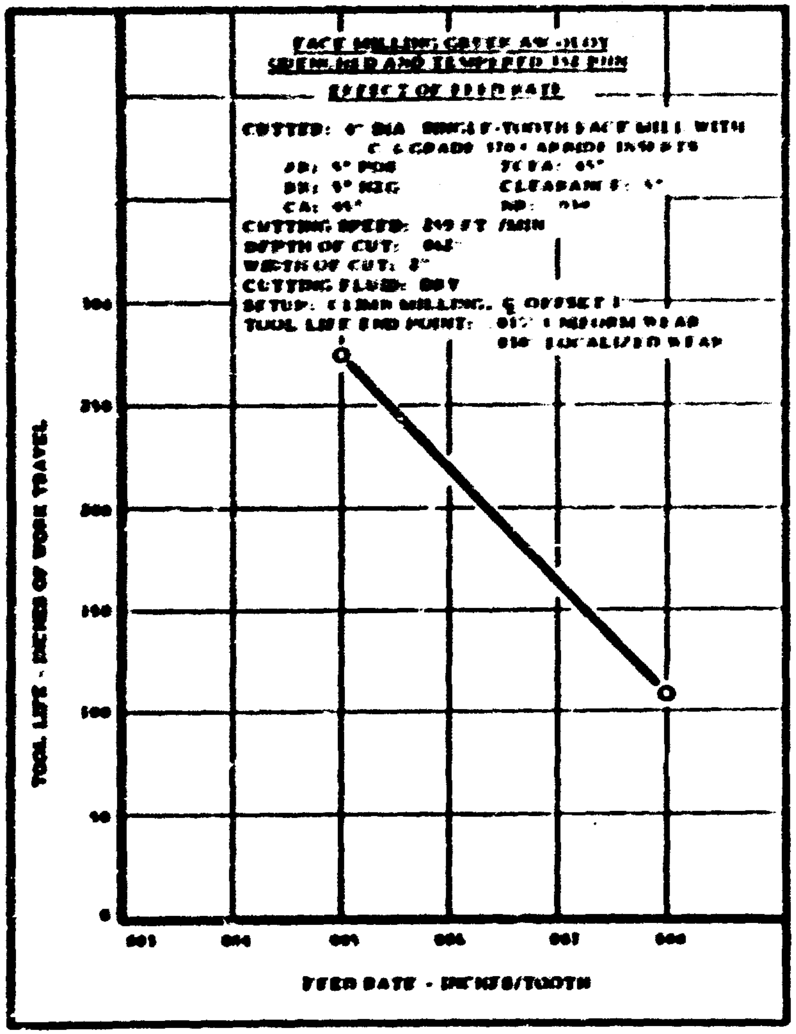
See text, page 208

Figure 226



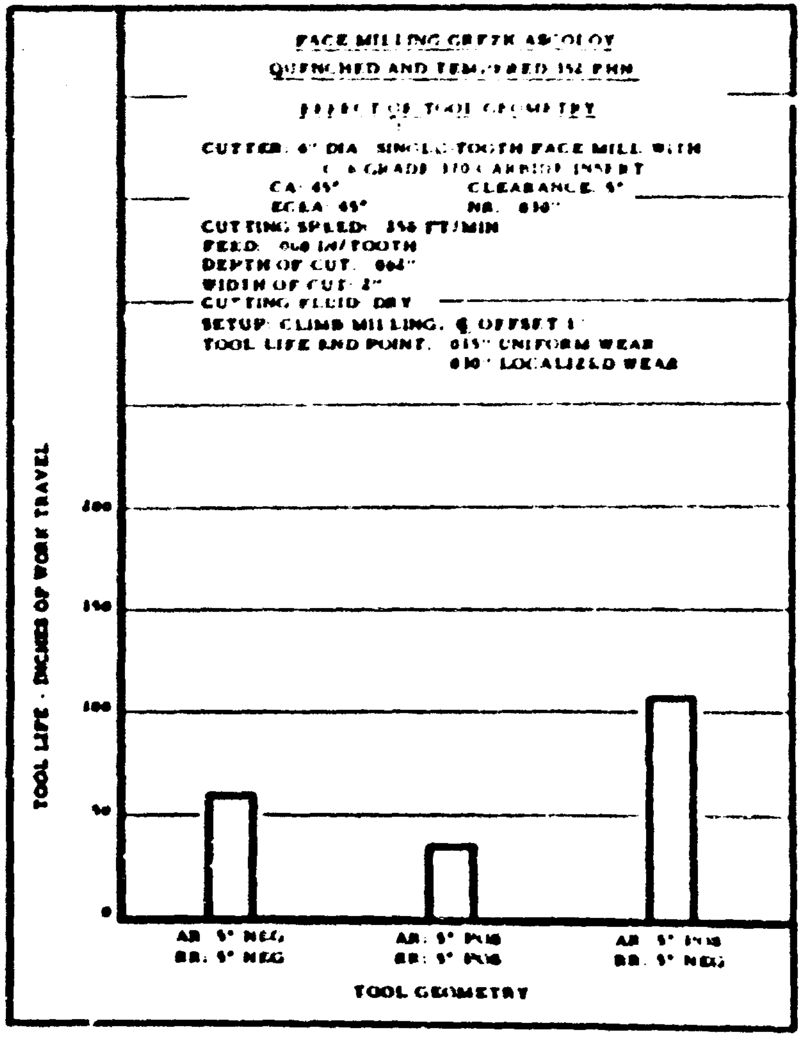
See text, page 208

Figure 227



See text, page 202

Figure 220



See text, page 202

Figure 221

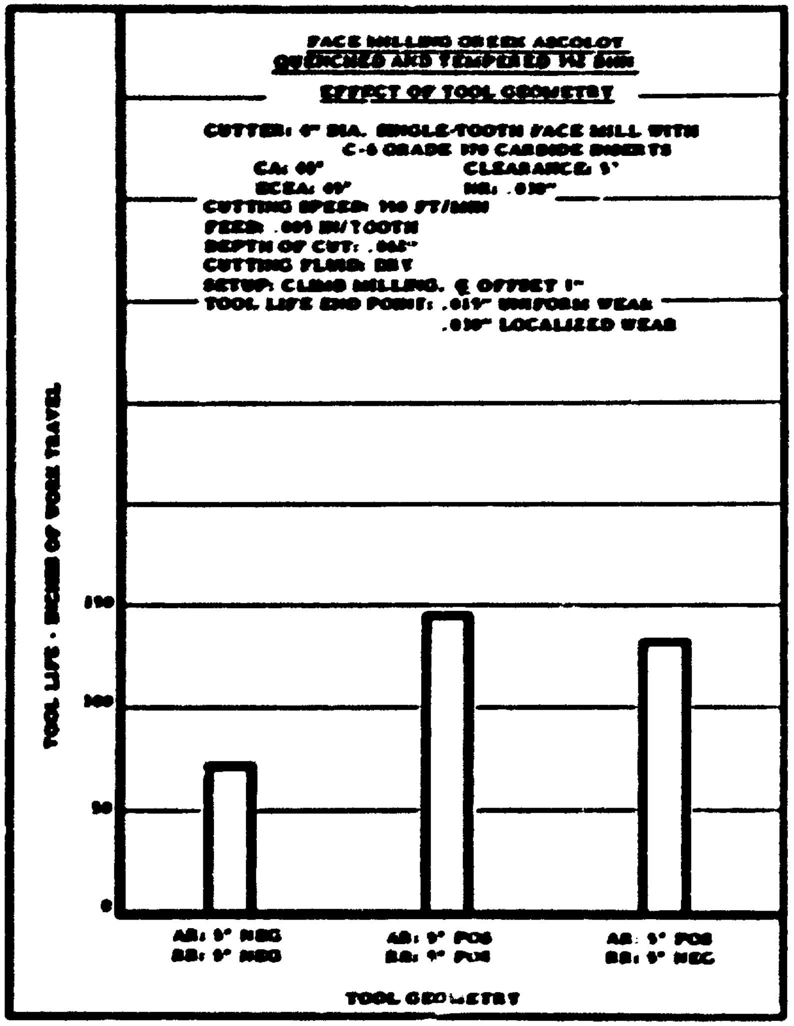


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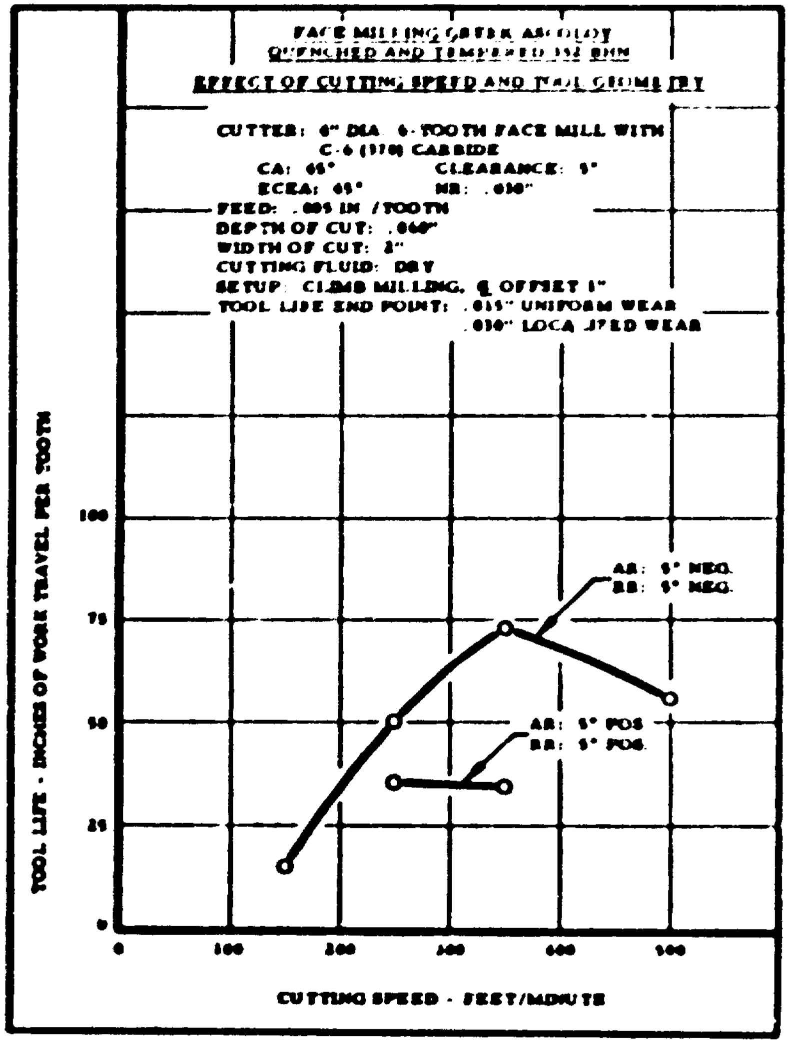
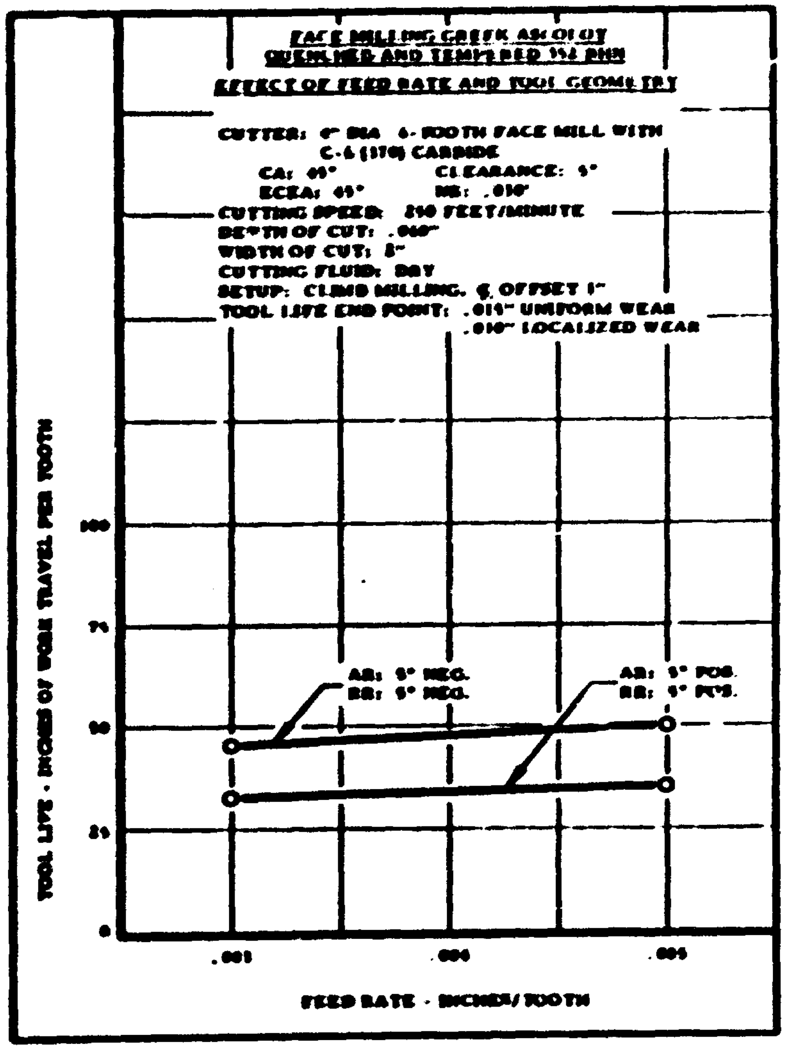
Figure 210



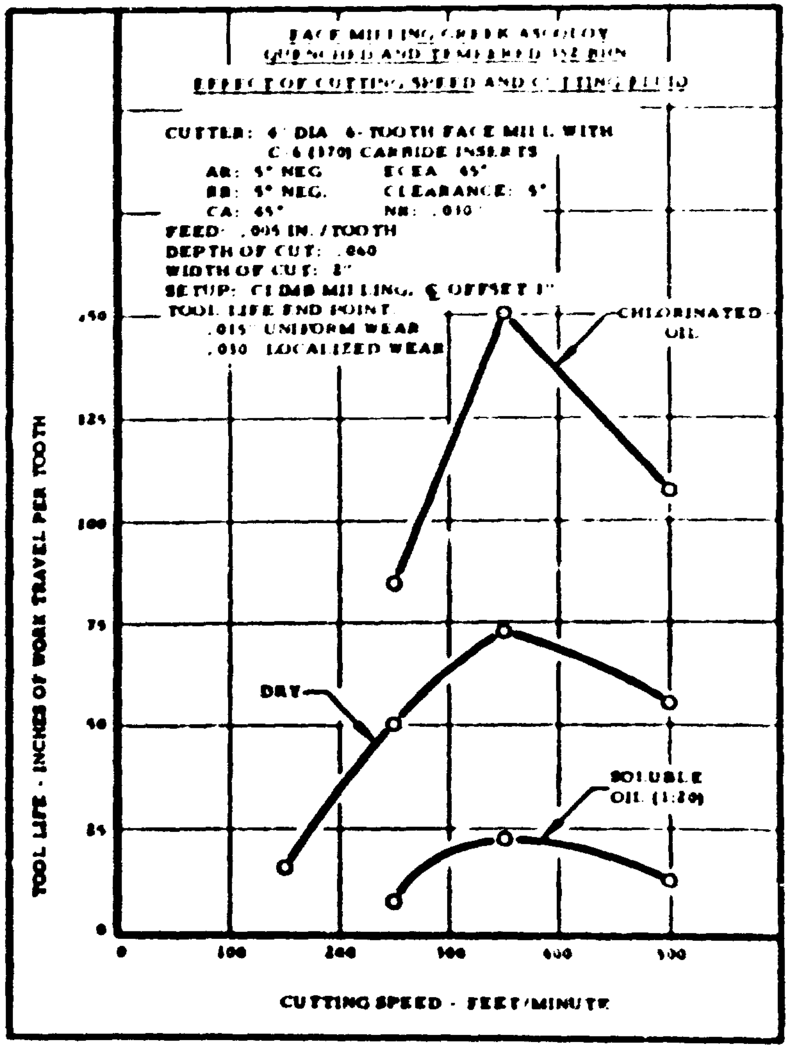
See text, page 301

Figure 211



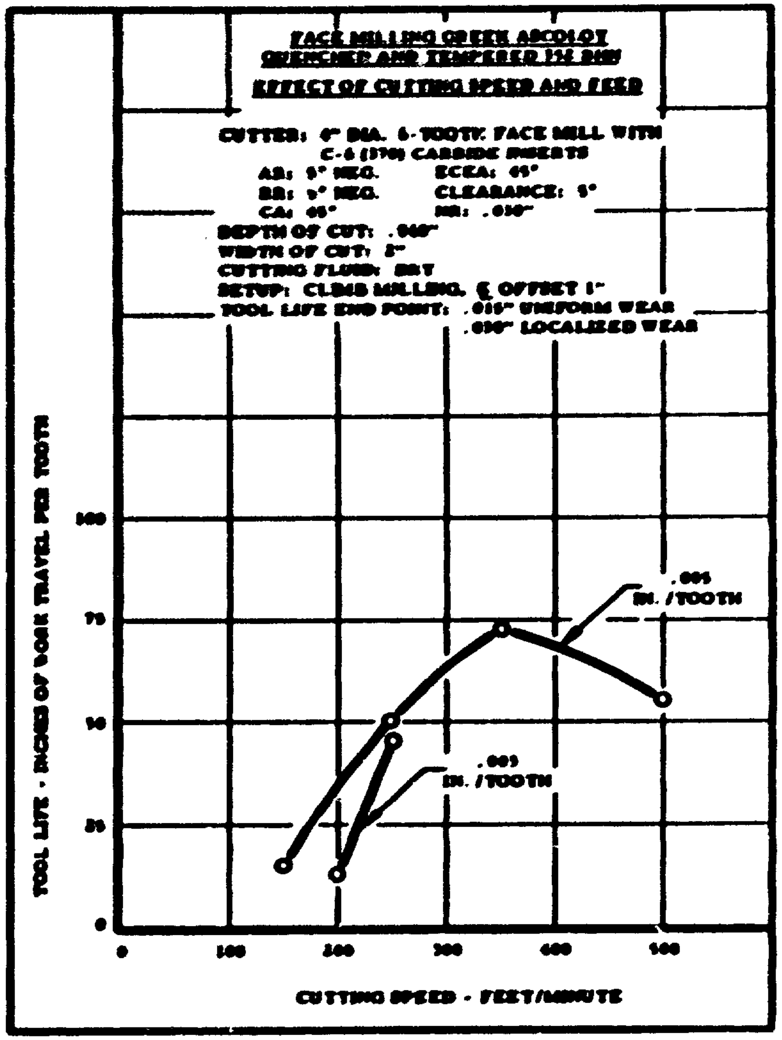
See text, page 201

Figure 212



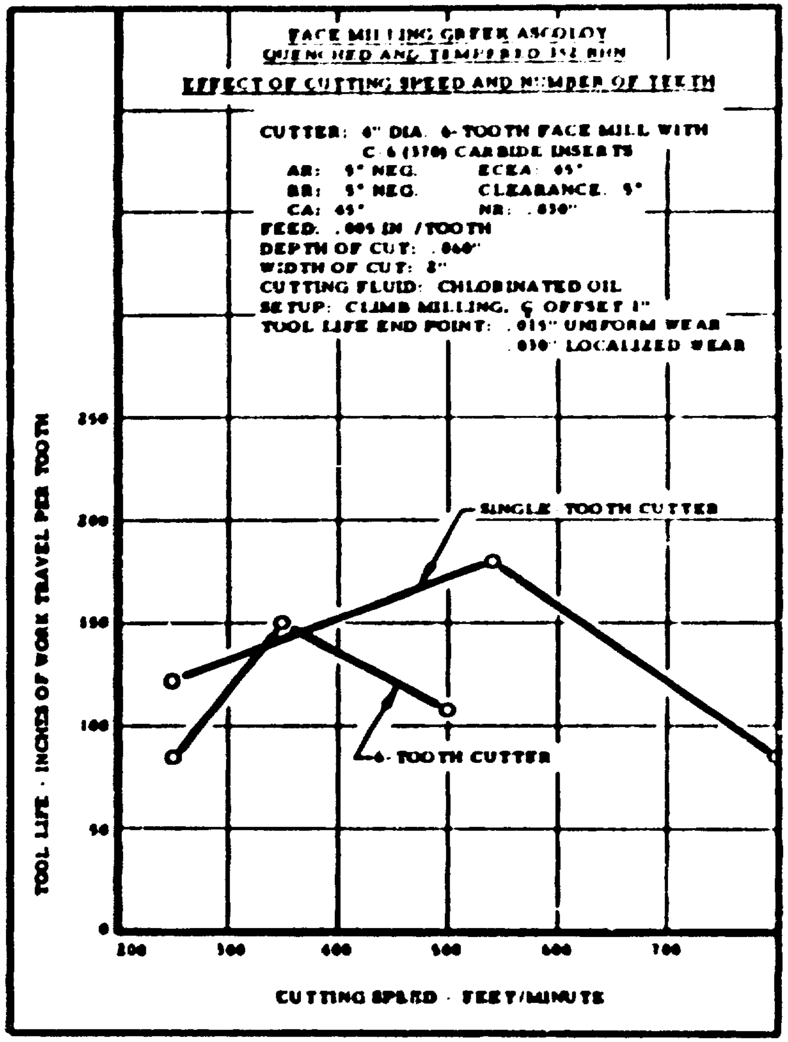
See text, page 201

Figure 211



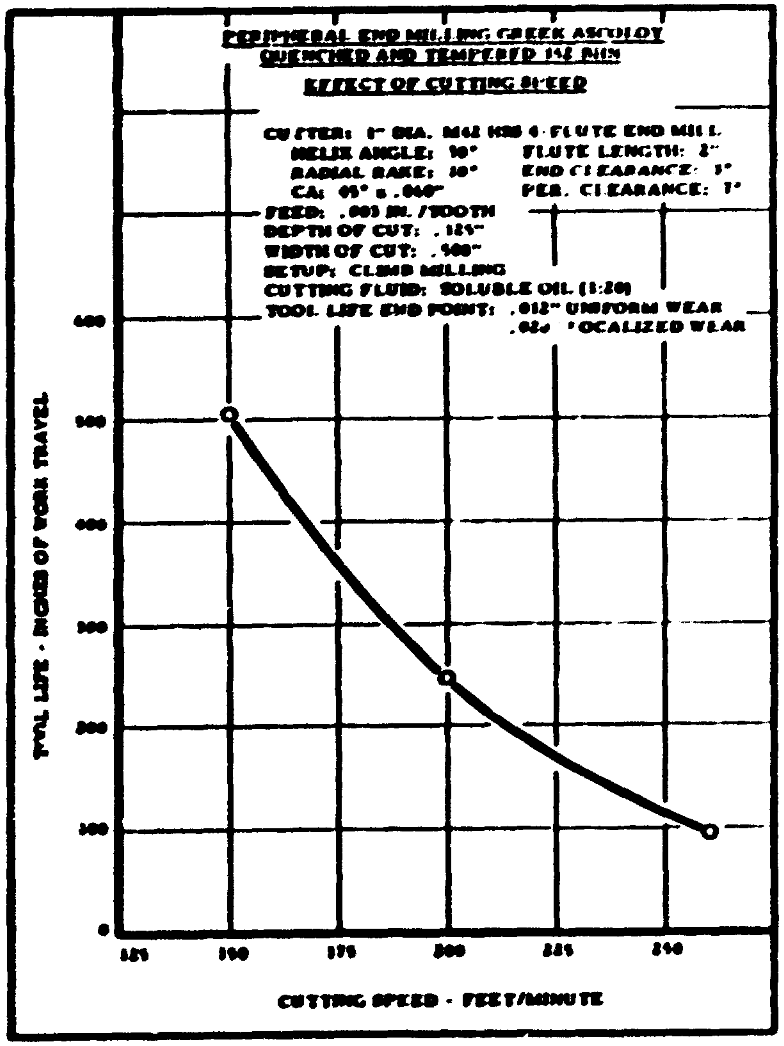
See text, page 203

Figure 216



See text, page 201

Figure 215

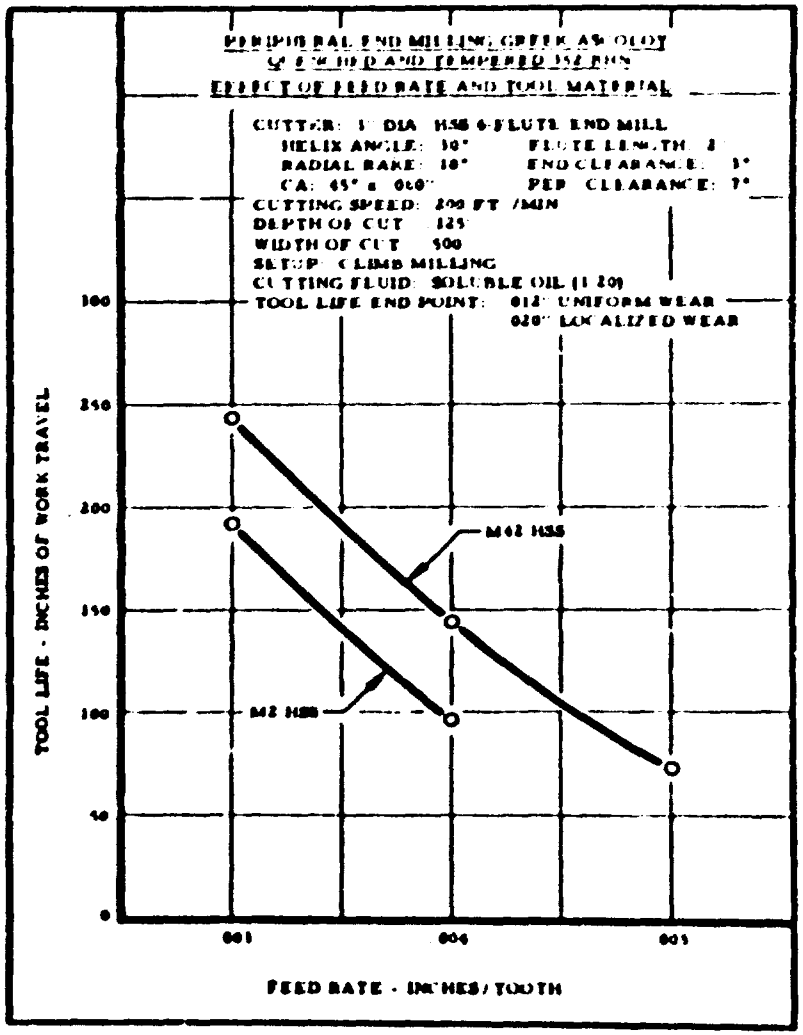


PERIPHERAL END MILLING GREEK ASCOLOY
QUENCHED AND TEMPERED 352 BHN
EFFECT OF CUTTING SPEED

CUTTER: 1" DIA. M42 HSS 4-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2"
RADIAL RAKE: 10° END CLEARANCE: 3°
CA: 45° x .060" PER. CLEARANCE: 7°
FEED: .003 IN./TOOTH
DEPTH OF CUT: .125"
WIDTH OF CUT: .500"
SETUP: CLIMB MILLING
CUTTING FLUID: SOLUBLE OIL (1:20)
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 206

Figure 236

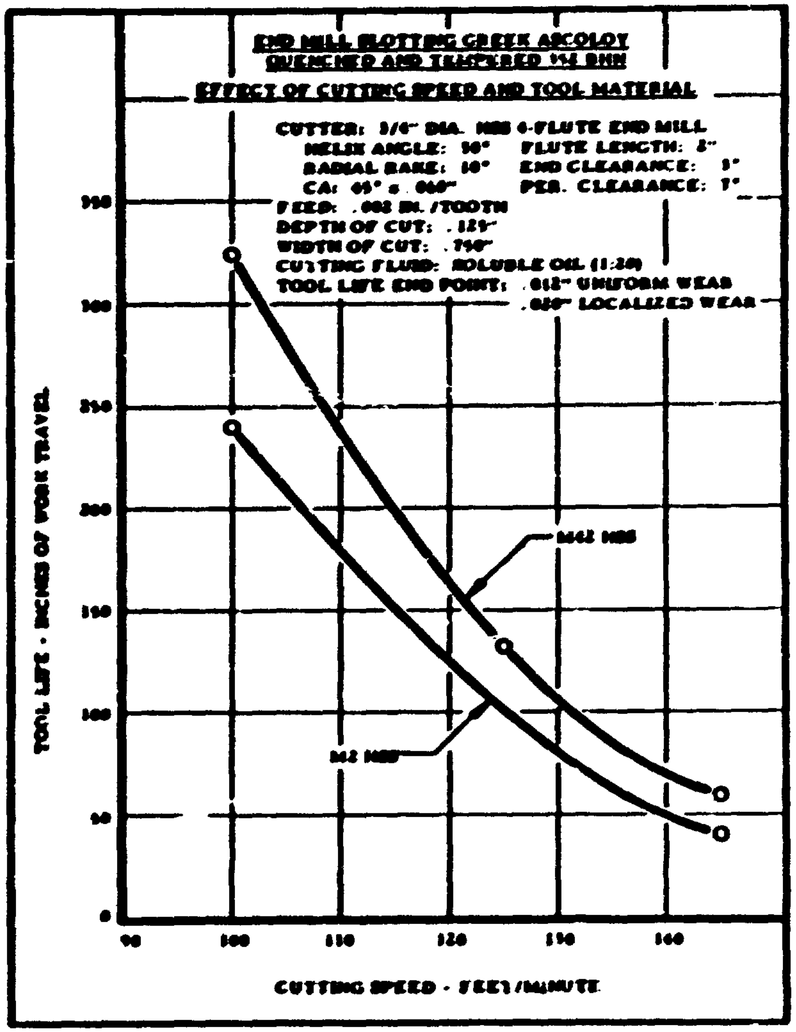


PERIPHERAL END MILLING GREEK ASCOLOY
QUENCHED AND TEMPERED 352 BHN
EFFECT OF FEED RATE AND TOOL MATERIAL

CUTTER: 1" DIA HSS 4-FLUTE END MILL
HELIX ANGLE: 30° FLUTE LENGTH: 2"
RADIAL RAKE: 10° END CLEARANCE: 3°
CA: 45° x .060" PER CLEARANCE: 7°
CUTTING SPEED: 200 FT./MIN
DEPTH OF CUT .125"
WIDTH OF CUT .500"
SETUP: CLIMB MILLING
CUTTING FLUID: SOLUBLE OIL (1:20)
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR

See text, page 206

Figure 237



See text, page 204

Figure 218

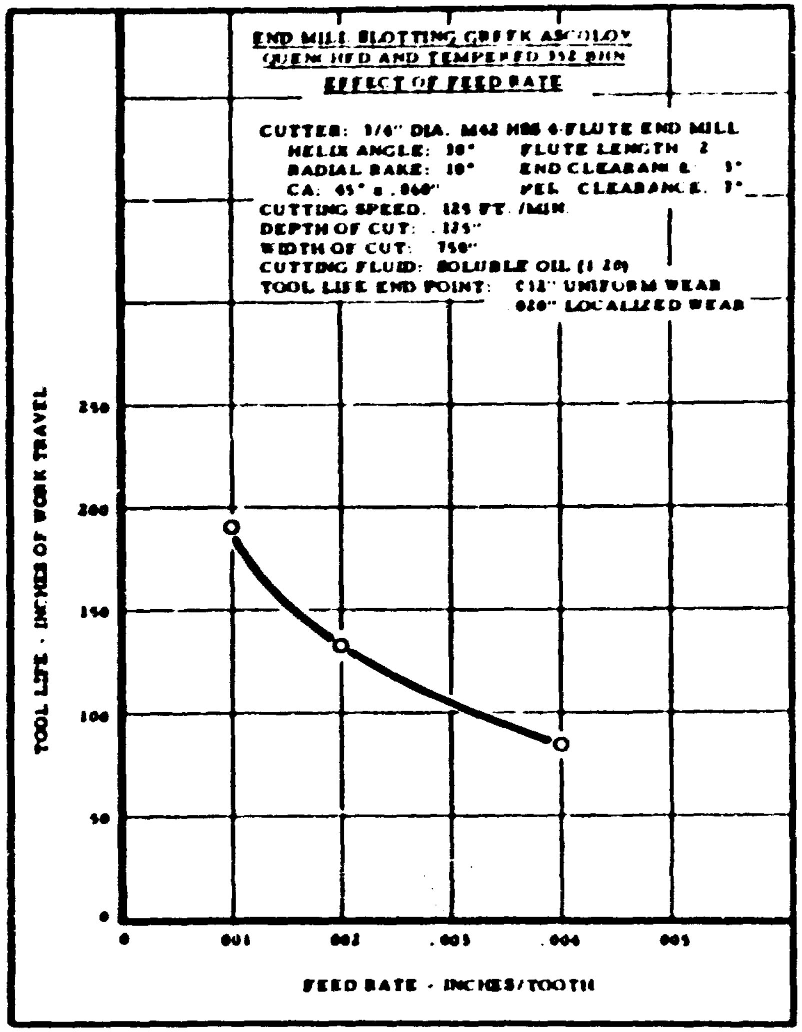


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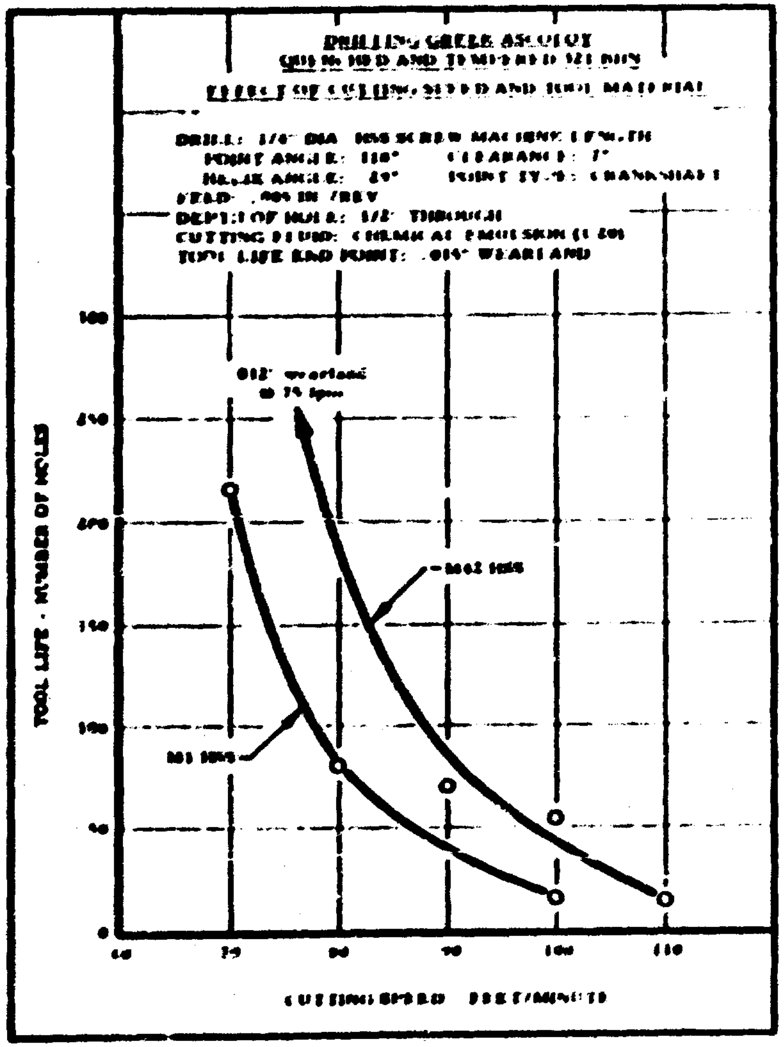
Figure 219



See text, page 248

Figure 240

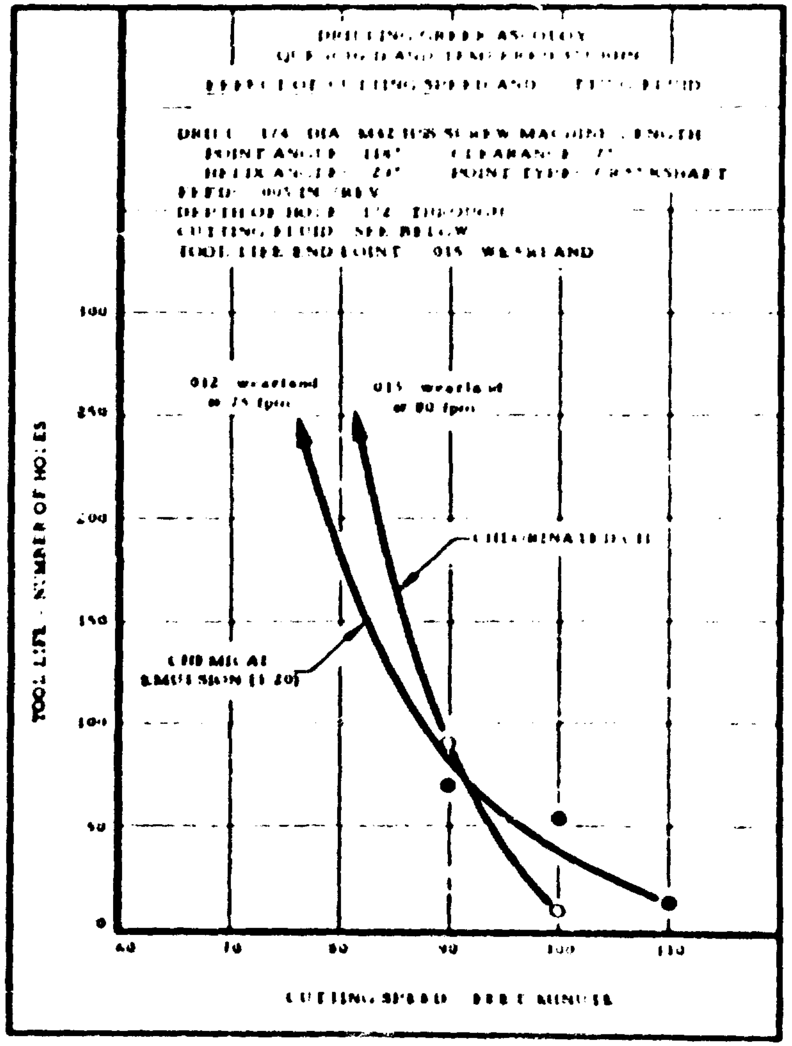


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Figure 241

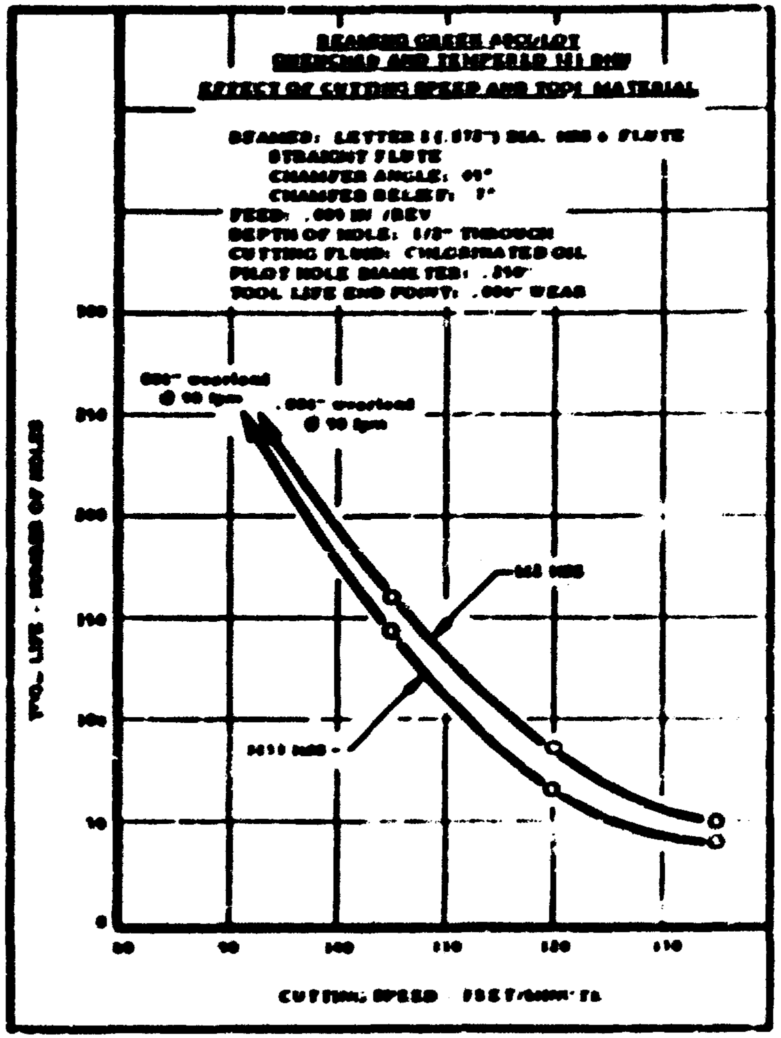

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Figure [illegible]

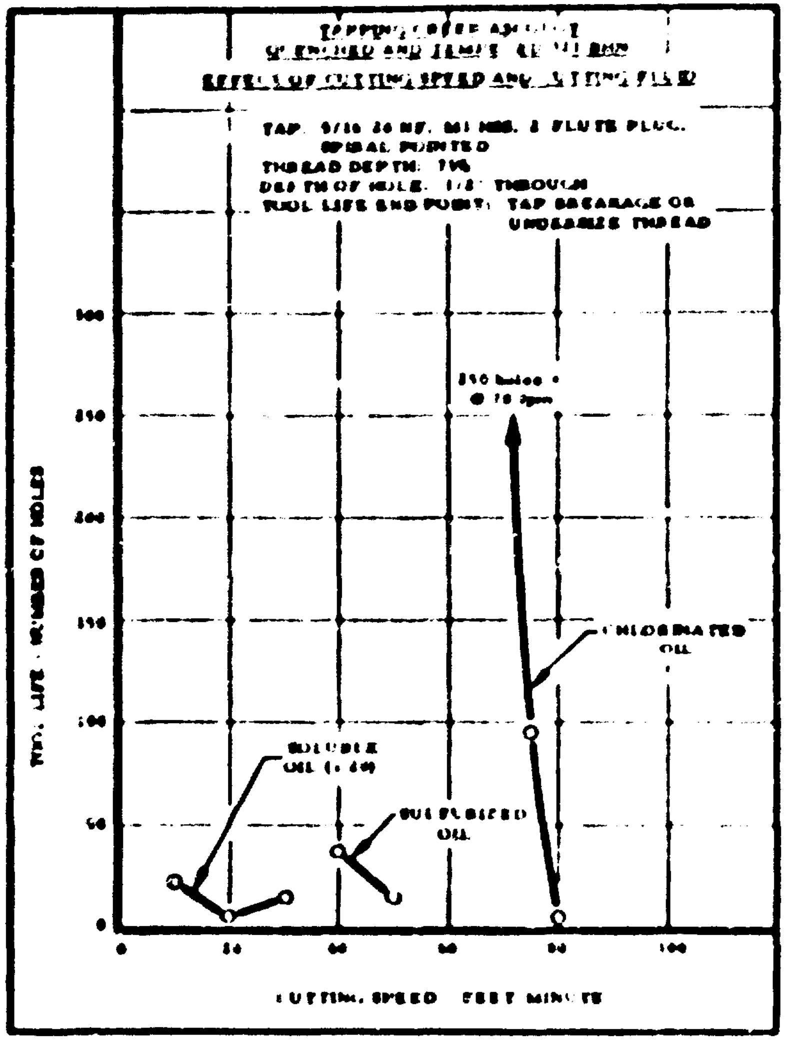

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Figure [illegible]

7. DISTORTION AND RESIDUAL STRESS STUDIES OF MILLED AND GROUND SURFACES

The results of various milling and surface grinding conditions in producing distortion and residual stresses were determined using four alloys: ultra high strength steel HP 9-4-45 (51 R_c), Ti-6Al-4V beta rolled (322 BHN), Ti-6Al-2Sn-4Zr-2Mo (321 BHN), and Inconel 625 (200 BHN).

Heat Treatment and Test Specimen Preparation

The HP 9-4-45 alloy was received from the mill in the normalized condition. A martempered state was produced by heating specimen blanks to 1475°F, holding for 1/4 hour, transferring to a furnace at 475°F, holding for 7 hours, followed by air cooling to room temperature. The resulting hardness was 51 R_c.

Both of the titanium alloys were received in the heat treated condition. The Ti-6Al-4V beta rolled was aged two hours at 1100°F followed by an air cool, and the Ti-6Al-2Sn-4Zr-2Mo was given a standard duplex anneal of 1650°F for one-half of an hour, air cool, then one-quarter of an hour at 1450°F with an air cool. The resulting hardness was 322 BHN and 321 BHN respectively.

The Inconel 625 was annealed by heating to 1650°F, holding for 1/4 hour, then air cooling. A hardness of 200 BHN was obtained.

In the preparation of the test specimens, care was exercised to assure uniform quality and composition. A "low stress" grinding technique was used for finish grinding. The specimens were 3/4 in. wide, 4-1/4 in. long, with a thickness of .070 in. for grinding and .100 in. for milling tests. A sketch of the specimen geometry is shown in Figure 244, page 223. The sample thickness after test machining was .060 in. for all specimens.

Distortion and Residual Stress Analysis Procedure

The curvature of each specimen over a 3.5 in. gage length was measured before and after test machining. A sketch, Figure 245, page 224, shows how the deflection measurements were obtained on this fixture. Through this procedure the change in curvature, or the distortion resulting from the machining operation, was obtained.

Residual stress analyses were made on selected test specimens from the distortion studies to determine the types and magnitude of the stresses induced by milling or grinding.

Distortion and Residual Stress Analysis Procedure (continued)

The procedure used in the stress analysis was one of progressively etching off the test surface in uniform small increments and noting the change in deflection of the specimen. For the HP 9-4-45 and titanium alloys, etching was accomplished by immersing the specimens in acid solution after coating the back of each specimen with lacquer. A solution of 20% HNO_3 was used for the HP 9-4-45 and one of 10% HF for the titanium alloys.

It was necessary to use an electrolytic technique for the removal of layers from the Inconel 625 specimens. The electrolyte was a 25% HCl solution. Figure 246, page 225, shows the setup used for the electrolytic etching.

Deflection measurements after each etching step were made using the same fixture as in the distortion studies. The thickness of the sample was measured to the nearest .0001 in. with an indicating micrometer. The depth of stock removed versus change in deflection data were then used to calculate the residual stresses at any depth below the surface of the specimen. The uniaxial stress in the longitudinal direction of the test specimen was calculated using an equation developed by F. Stablein.[*]

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

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 delfection versus stock removed curve.

sub-n = Readings after subsequent etchings

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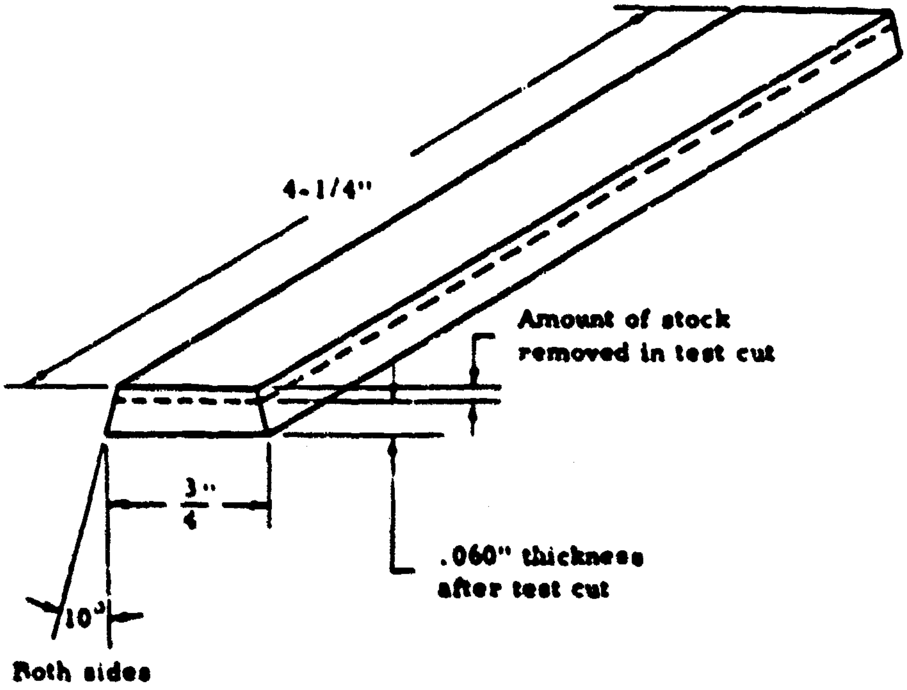
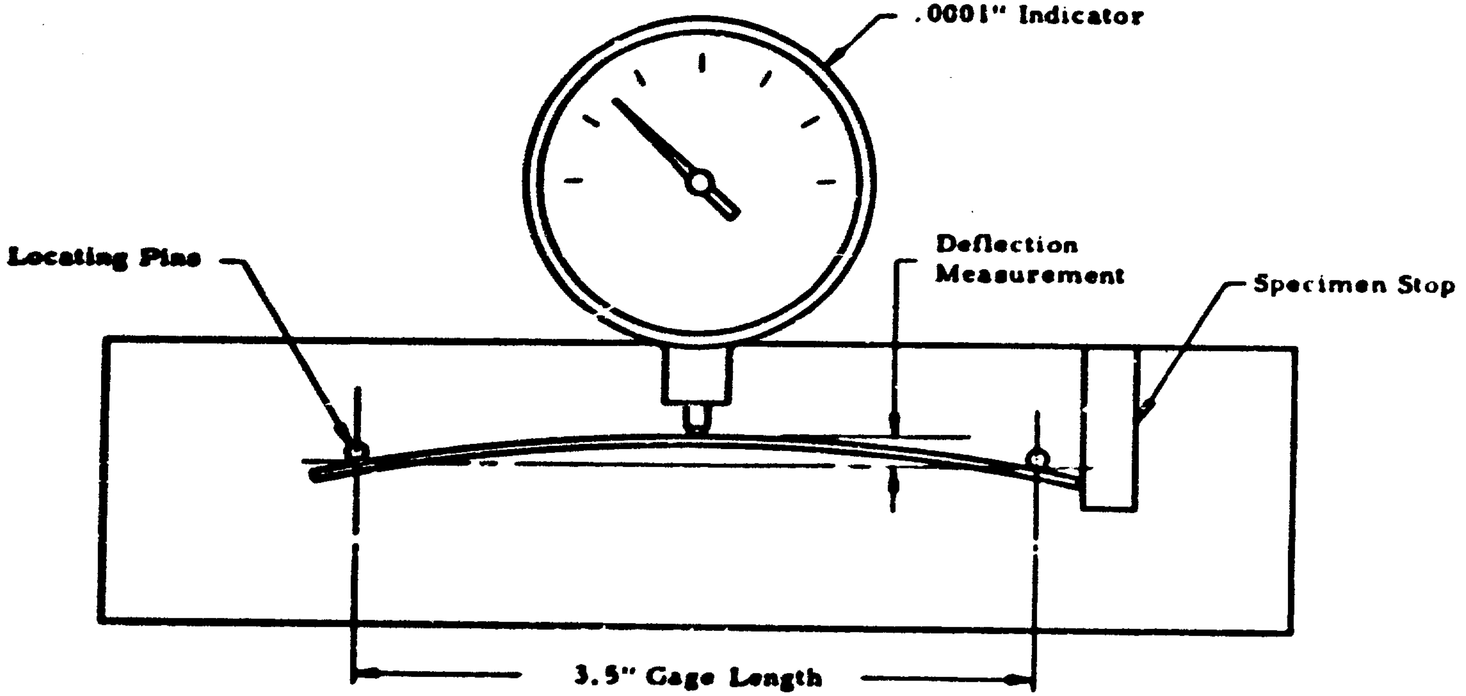
[*] Stablein, F. - "Spannungsmessungen an einseitig abgeloeschten Knuppeln" - Kruppsche Monatshefte, Vol. 12 (1931) pp. 93-98.



DISTORTION AND RESIDUAL STRESS TEST SPECIMEN

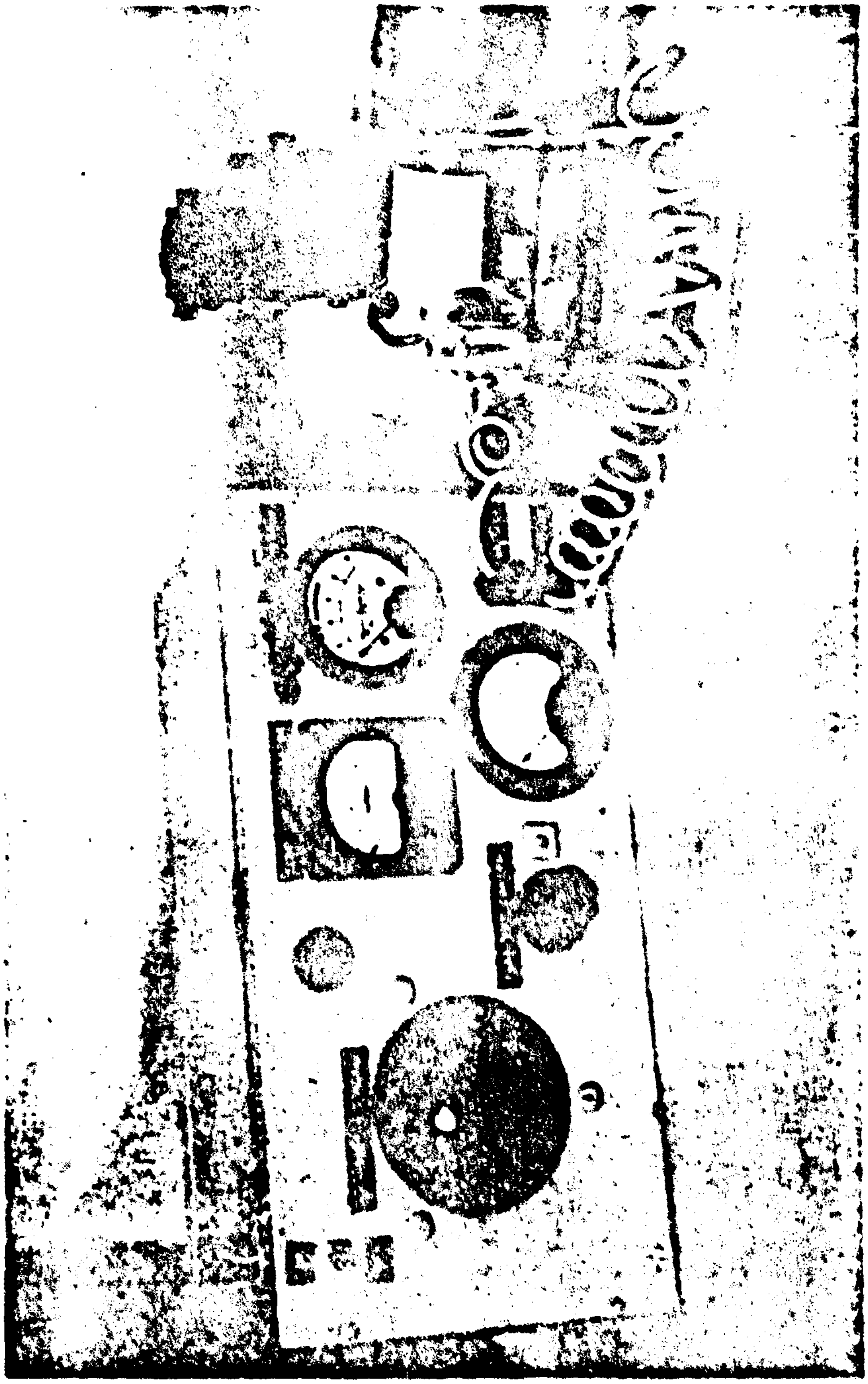
Figure 244

DEFLECTION MEASUREMENT FIXTURE



The above fixture is used to measure deflection of the test specimen in both the distortion and the residual stress analyses

Figure 245



ELECTROLYTIC APPARATUS USED FOR DIFFERENTIAL ETCHING OF RESIDUAL STRESS SPECIMENS

Figure 246

7.1 Ultra High Strength Steel HP 9-4-45, Martempered, 51 R_c

Face Milling - Carbide Cutter

The distortion produced by using a C-6 (370) carbide cutter with various degrees of tool wearland is shown in Figure 247, page 232. For a 0.040 in. depth of cut, increasing tool wear produced more distortion with both dry cutting and soluble oil as the cutting fluids. However, the 0.010 in depth of cut when cutting dry showed maximum distortion at the intermediate wearland of 0.016 in. and the same distortion with a sharp cutter as with one having 0.032 in. wearland.

The residual stress curves obtained with different degree of tool wear can be found in Figure 248, page 232. Cutting was done dry with a 0.040 in. depth of cut. For all three wearland conditions, some tensile stresses were found at the surface, decreasing rapidly to maximum compressive stresses at .001-.002 in. below the surface. As will be noted, the main portion of the stressed layer is compressive in nature. The largest tool wearland, 0.032 in., produced the highest tensile stress at the surface, 60,000 psi, the largest compressive stress below the surface, over 70,000 psi, and the greatest depth of penetration of the compressive stressed layer, 0.011 in.

The effect of cutting fluid and depth of cut may be seen in Figure 249, page 233. A higher maximum compressive stressed condition resulted with soluble oil as the cutting fluid than cutting dry, but the depth of penetration was about the same in both cases. Increasing the depth of cut from .010 in. to .040 in. had relatively little effect on the characteristics of the residual stress curves.

Surface finish, in terms of microinches AA, for the various cutting conditions, is given in Table XVII.

Face Milling - HSS Cutter

Distortion and residual stress curves for face milling HP 9-4-45 with an HSS cutter are shown in Figures 250, 251 and 252, pages 233 and 234. Distortions at various wearland values were obtainable only when milling dry. About the same degree of distortion was produced at the .016 in. and .032 in. wearlands. A sharp cutting tool gave the least distortion, see Figure 250, page 233. With a sharp cutter, milling with a greater depth of cut or with a highly chlorinated oil yielded about the same distortion.

The residual stress curves with various tool wearlands are shown in Figure 251, page 234. As will be noted, the residual stresses are

Face Milling - HSS Cutter (continued)

predominantly compressive with about the same stress pattern at 0.016 in. tool wearland as with 0.032 in. wearland. The sharp cutting tool produced only a shallow stressed layer.

Figure 252, page 234, shows three residual stress curves: two for milling dry with different depths of cut and one for milling when using highly chlorinated oil as the cutting fluid. In all three cases, a sharp cutter was used.

A summary of surface roughness values obtained when milling with T15 high speed steel is given in Table XVIII.

Surface Grinding

The primary purpose of the grinding studies was to show the effect of wheel grade, wheel speed, down feed and grinding fluid on the resulting distortion and residual stresses produced. Graphs covering this phase of the work may be found in Figures 253 through 261, pages 235 through 239.

As will be noted in Figures 253 and 254, page 235, increasing the wheel speed increases the distortion, with the greatest distortion being associated with large down feeds. As the wheel hardness is increased from the H to the K grade, the distortion is increased; see Figure 253, page 235. With reference to Figure 254, page 235, it will be observed that at a down feed of .002 in./pass and a wheel speed of 6000 feet per minute, the use of highly chlorinated oil gave more distortion than did soluble oil or highly sulfurized oil.

Residual stress curves associated with a number of these grinding conditions are shown in Figures 255 through 261, pages 236 through 239. With the soft 32A46H8VBE wheel, increasing the wheel speed from 4000 feet/minute to 6000 feet/minute increased the magnitude of the tensile residual stresses; see Figure 255, page 236.

Figures 256 and 257, pages 236 and 237, illustrate the effect of the harder wheel grade, 32A46K8VBE, in not only the magnitude of the tensile stresses but also the depth to which tensile stresses were found for two different down feed conditions. Maximum tensile stresses of over 80,000 psi and depths of penetration in excess of 0.004 in. were obtained. It will be noted that when the wheel speed

Surface Grinding (continued)

was increased from 4000 feet/minute to 6000 feet/minute there was no significant increase in the residual stresses. The "low stress" down feed involves the removal of the .010 in. of material at .0005 in./pass for the first .008 in. and for the last .002 in. two passes at .0004 in./pass, with the final six passes of .0002 in./pass.

The use of a "low stress" down feed condition markedly reduced the residual stress condition at wheel speeds of 4000 feet/minute and 6000 feet/minute. In fact, the residual stresses in the sample ground at 6000 feet/minute were less than those found in the one ground at 4000 feet/minute; see Figure 258, page 237.

When a comparison is made of the residual stress patterns produced by using wheels of three different hardness levels, Figure 259, page 238, the pronounced tendency to produce higher tensile stresses and a greater depth of penetration of such stresses is readily evident. A "low stress" down feed produces low residual stresses. As may be seen in Figure 260, page 238, increasing the down feed gives rise to higher tensile residual stresses. In Figure 261, page 239, the residual stress pattern produced by using a soft wheel, low-wheel speed, highly sulfurized oil and a "low stress" down feed may be observed. Here a predominantly compressive stress was obtained.

The surface finish in surface grinding the HP 9-4-45 steel averaged about 10 microinches AA in the direction parallel to the grind and 15 to 25 microinches AA perpendicular to the grinding direction.

A summary of the surface finishes produced is given in Table XIX.

TABLE XVII

SURFACE ROUGHNESS PRODUCED BY FACE MILLING HP 9-4-45 MARTEMPERED 51 R_c

Cutter: 4" Dia. Single-Tooth Face Mill
With C-6 (370) Carbide

AR:	-7°	Incl.:	0°
RR:	-7°	ECEA:	0°
CA:	45°	Clearance:	8°
TR:	-10°		

Cutting Speed: 150 feet/minute
Feed: .008 in. /tooth

Cutting Fluid	Depth of Cut (inches)	Wearland (inches)	Surface Finish - Microinches AA	
			Parallel to Cutting Direction	Perpendicular to Cutting Direction
Dry	.010	0	12-14	30-35
		0.016	6-7	65-68
		0.032	5-8	20-25
Dry	.040	0	6-12	25-30
		0.016	10-12	25-30
		0.032	8-12	35-38
Soluble Oil (1:20)	.040	0	8-14	22-25
		0.016	7-12	70-78
		0.032	8-12	38-44

TABLE XVIII

SURFACE ROUGHNESS PRODUCED BY FACE MILLING HP 9-4-45 MARTEMPERED 51 R_C

Cutter: 4" Dia. Single-Tooth Face Mill
With T15 HSS

AR: 5° Incl.: 0°
RR: 5° ECEA: 0°
CA: 45° Clearance: 8°
TR: 7°

Cutting Speed: 70 feet/minute
Feed: .005 in. /tooth

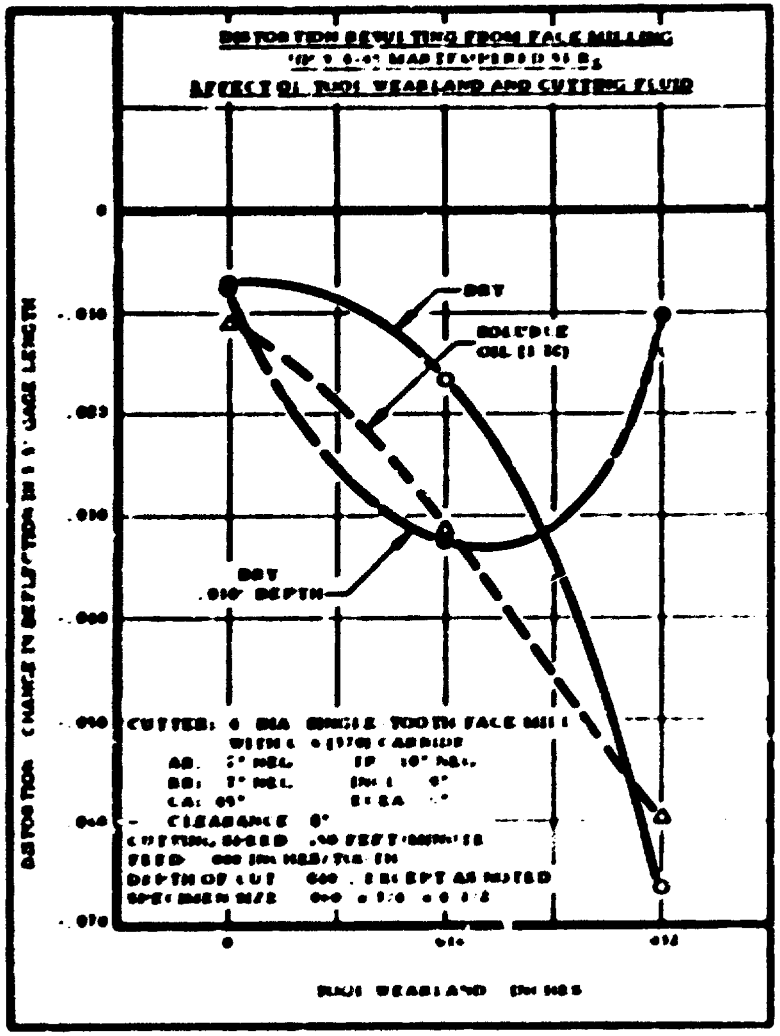
Cutting Fluid	Depth of Cut (inches)	Wearland (inches)	Surface Finish - Microinches AA: Parallel to Cutting Direction	Surface Finish - Microinches AA: Perpendicular to Cutting Direction
Dry	.010	0	22-25	45-50
		0.016	18-20	28-32
		0.032	10-13	50-60
Dry	.040	0	25-30	55-60
Highly Chlorinated Oil	.040	0	20-25	37-42

TABLE XIX

SURFACE ROUGHNESS PRODUCED BY SURFACE GRINDING
HP 9-4-45 MARTEMPERED 49 R_c

Cross Speed: .050 inches/pass
Table Speed: 40 feet/minute
Depth of Grind: .010 in.

Wheel	Down Feed (Inches)	Cutting Fluid	Wheel Speed	Surface Finish - Microinches AA	
				Parallel to Grinding Direction	Perpendicular to Grinding Direction
32A46H8VBE	.002	Soluble Oil (1:20)	2000	9-12	30-34
			4000	10-13	22-27
			6000	14-19	33-37
32A46K8VBE	.002	Soluble Oil (1:20)	2000	6-8	15-18
			4000	8-13	28-34
			6000	10-14	23-28
	.001	Soluble Oil (1:20)	2000	7-10	23-27
			4000	7-11	21-32
			6000	6-9	20-24
	LS	Soluble Oil (1:20)	2000	5-6	13-17
			4000	6-9	16-19
			6000	5-7	13-16
	.002	Highly Chlorinated Oil	6000	10-16	30-36
	.002	Highly Sulfurized Oil	6000	7-11	28-33
32A46H8VBE	LS	Highly Sulfurized Oil	2000	5-6	23-30
			4000	5-7	15-19
			6000	5-6	15-19
32A46N8VBE	.002	Soluble Oil (1:20)	6000	7-10	20-23



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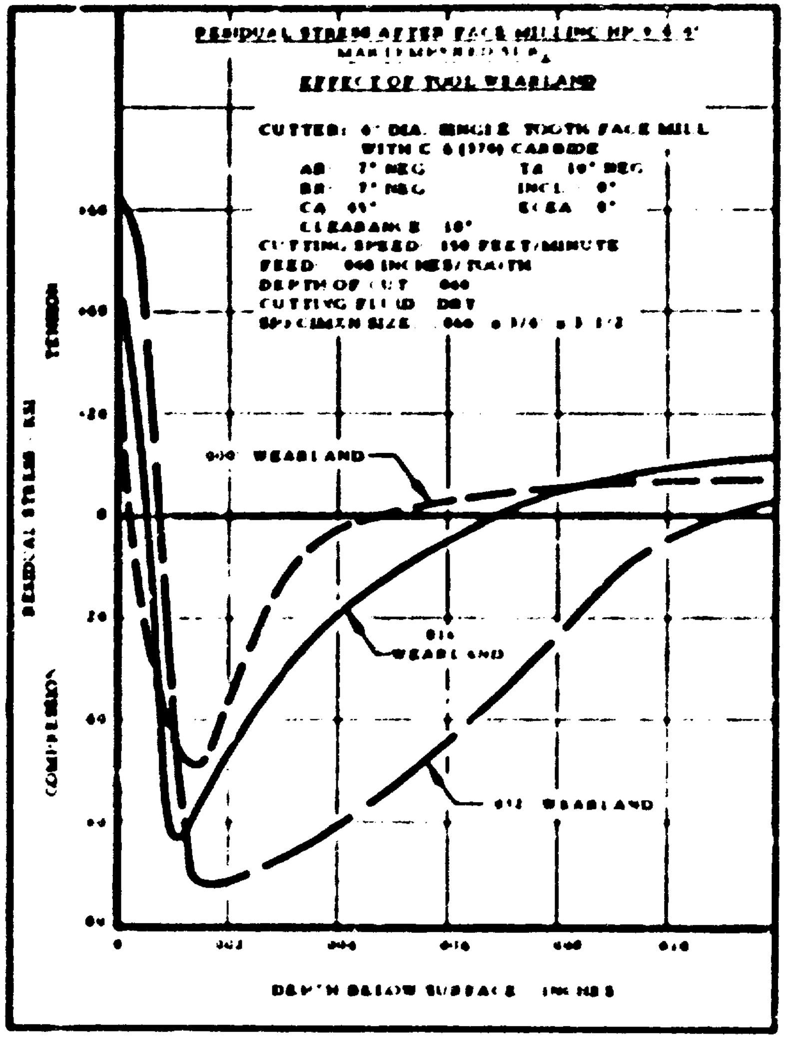

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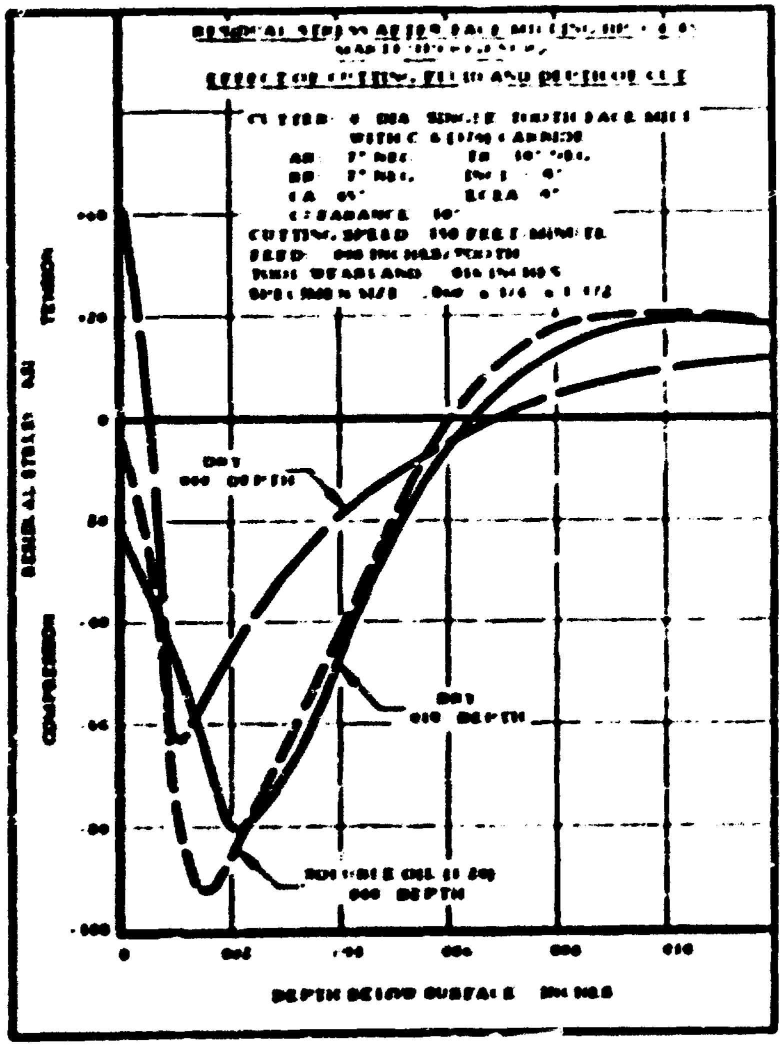
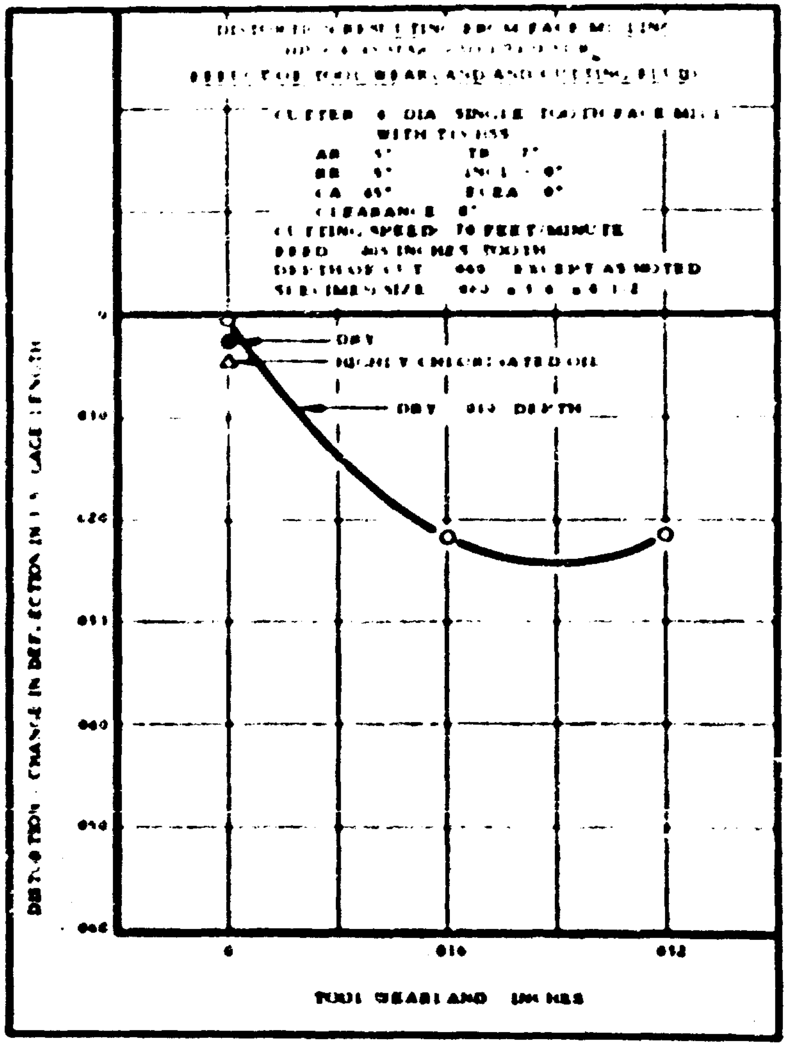
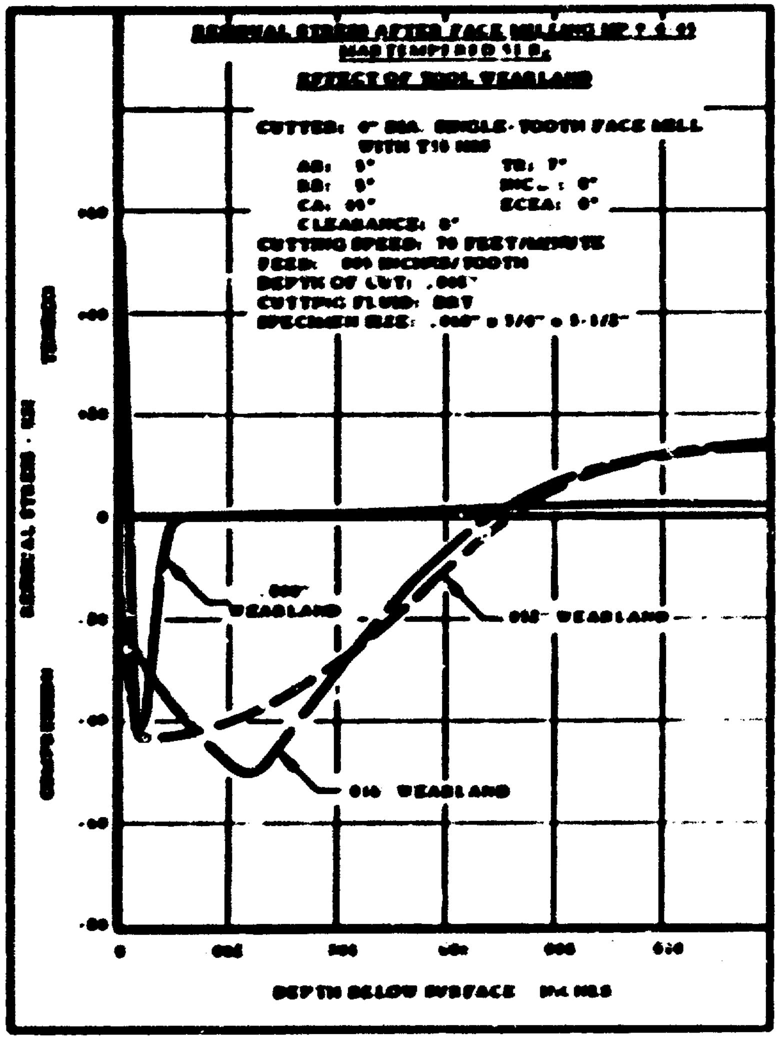


See text, page 226 Figure 249



See text, page 226 Figure 250



See text, page 227

Figure 191

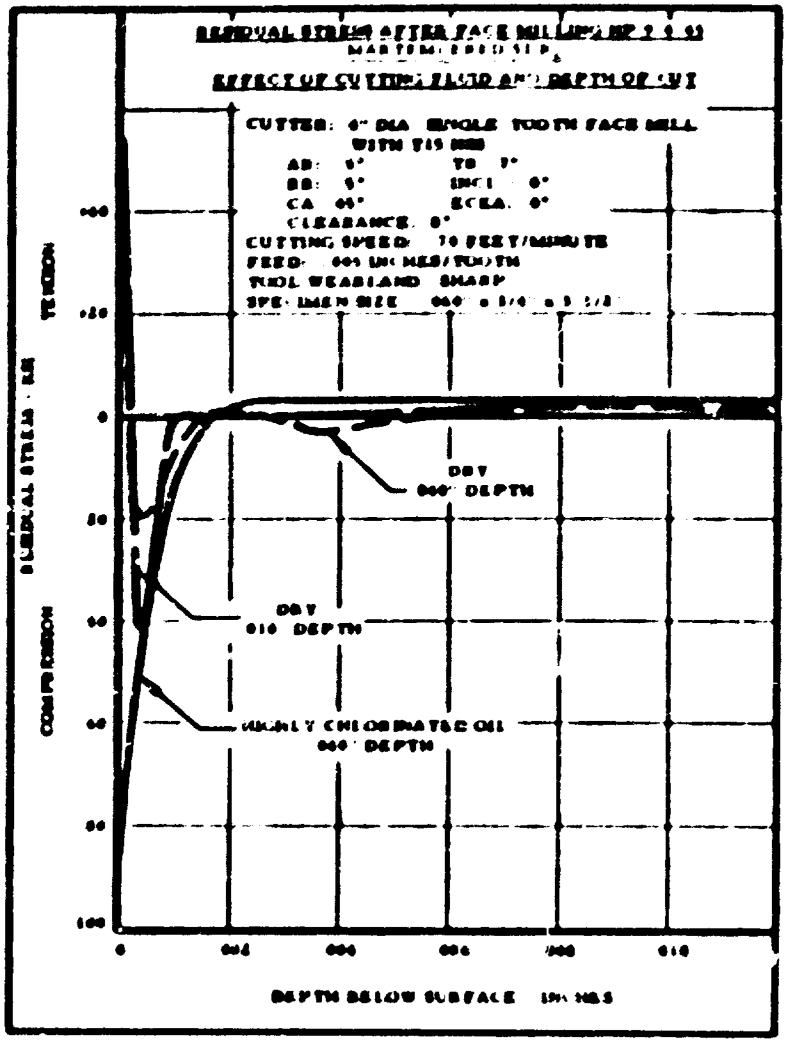


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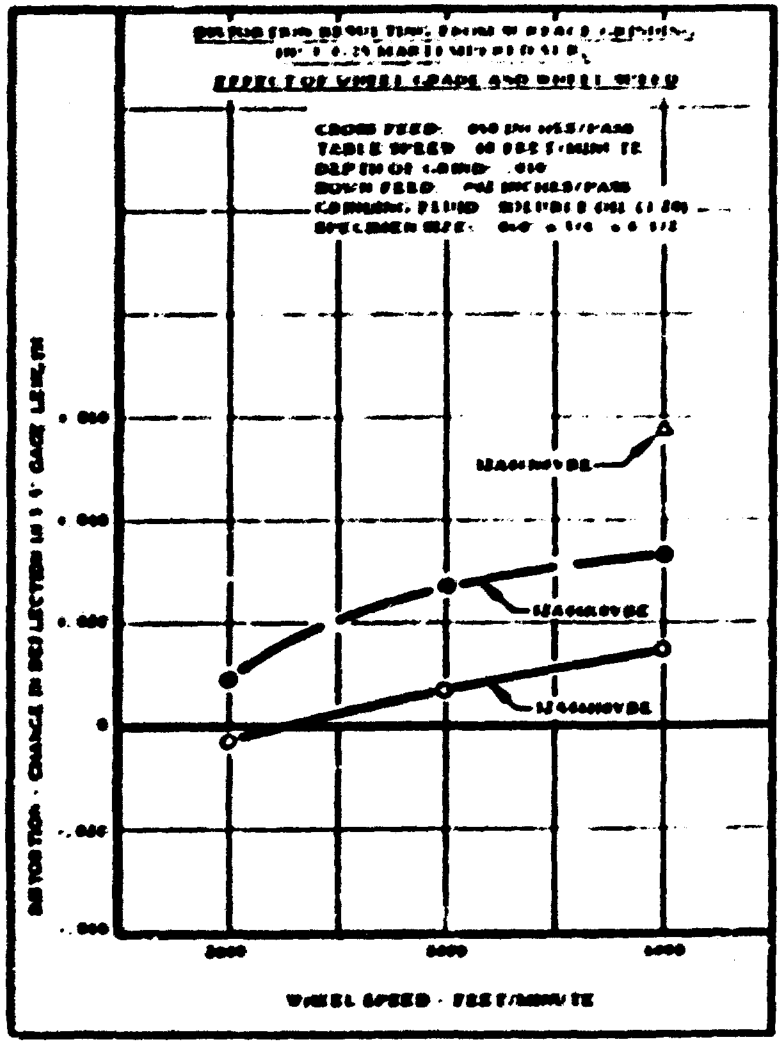
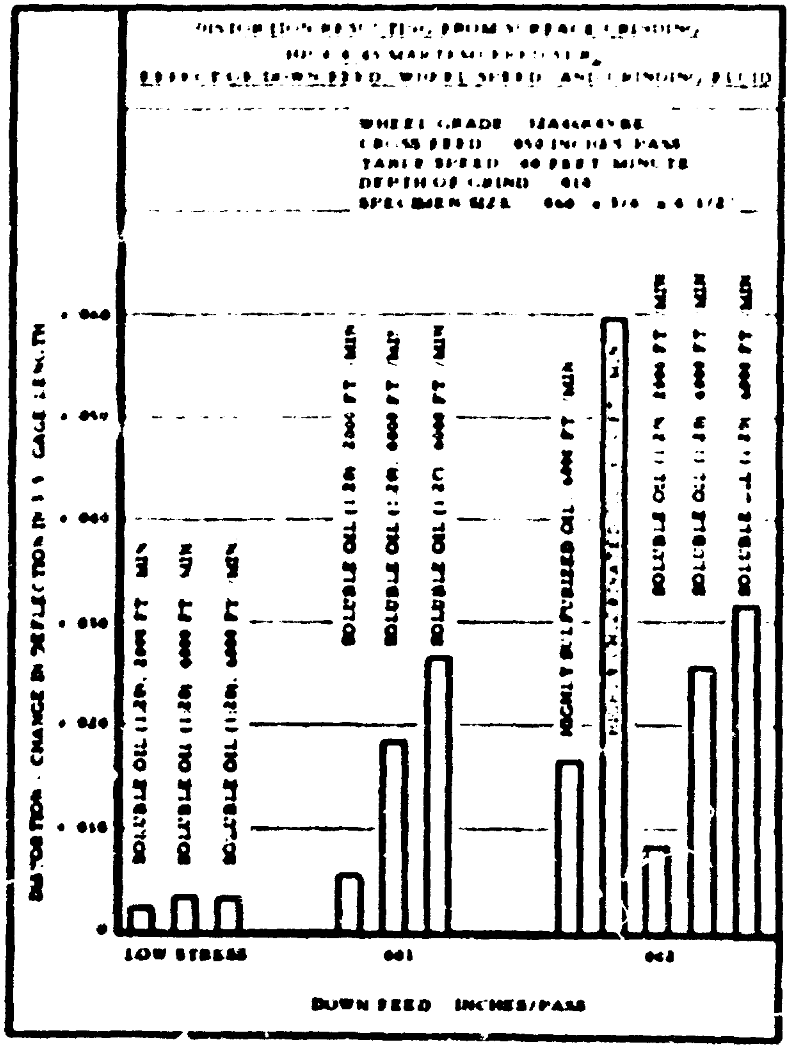
Figure 192



See text, page 227

Figure 255



See text, page 227

Figure 256

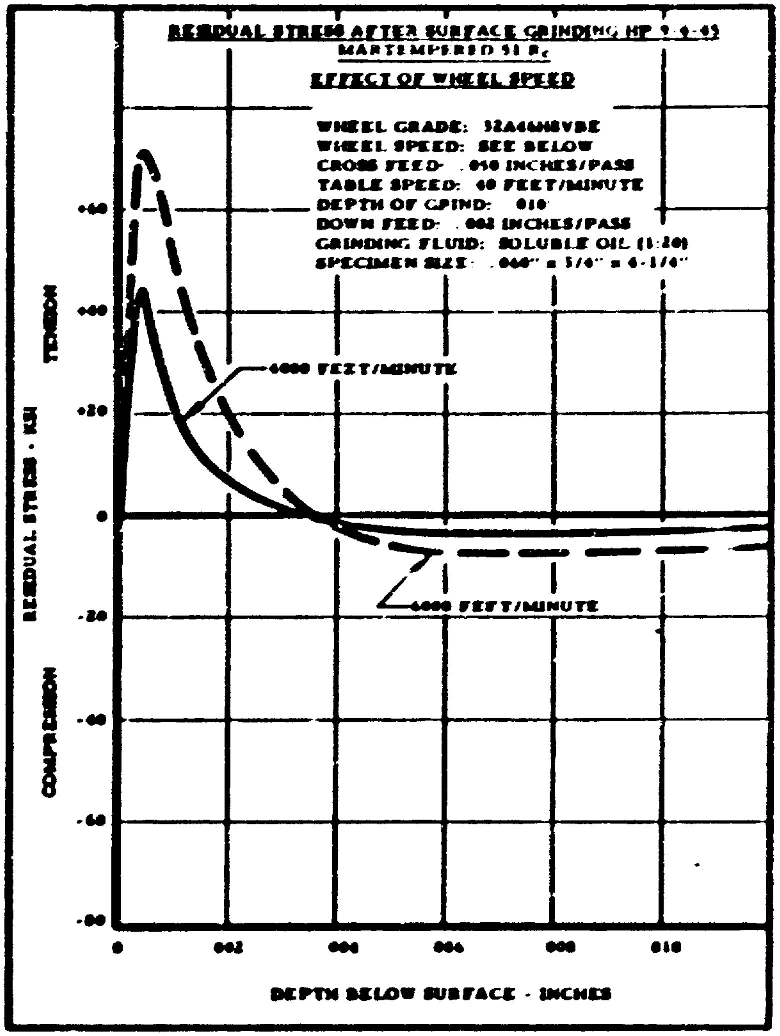


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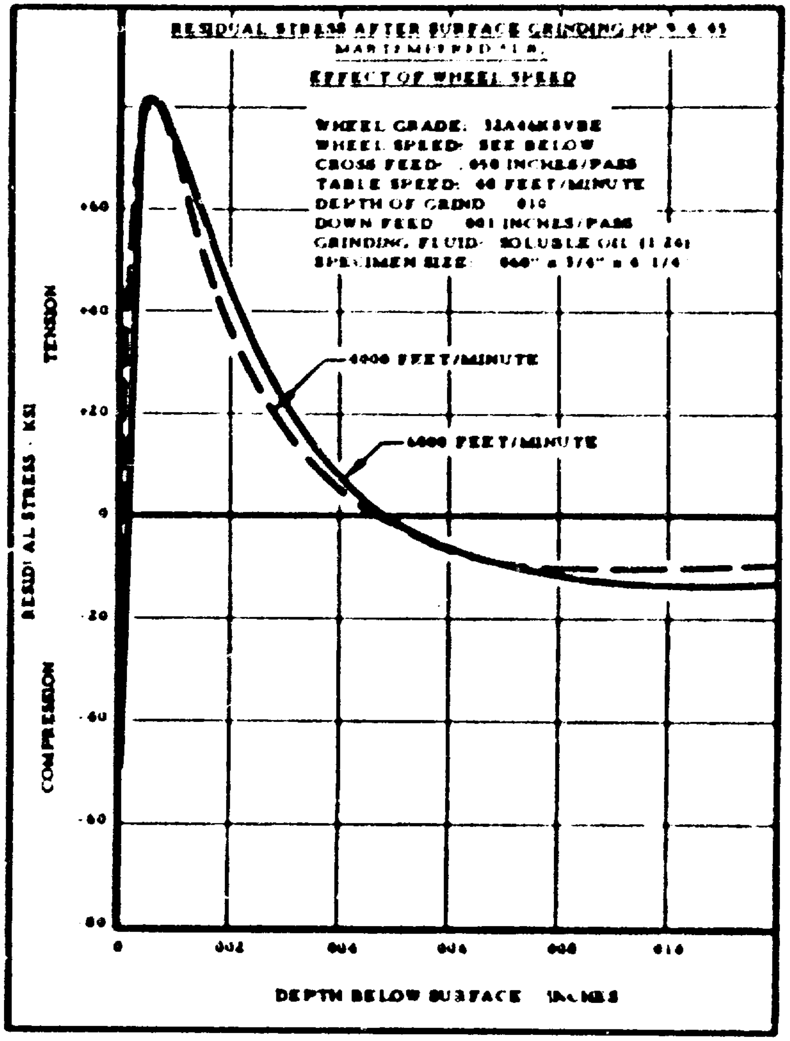
Figure 255



See text, page 227

Figure 256

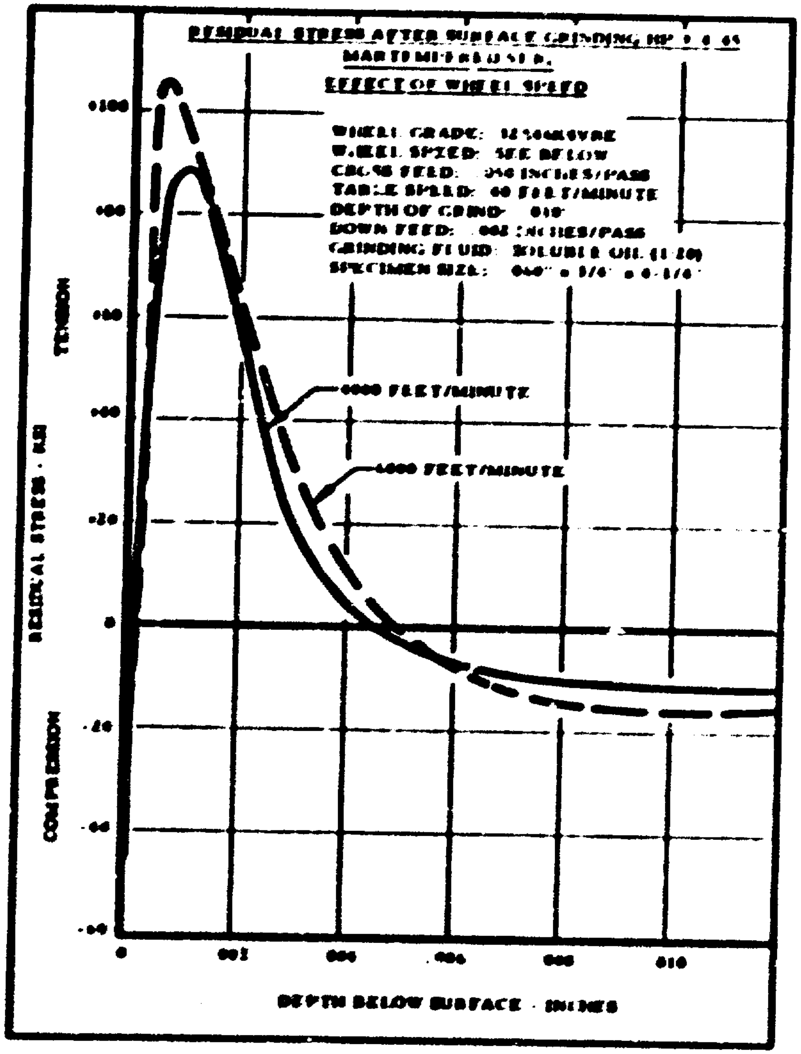


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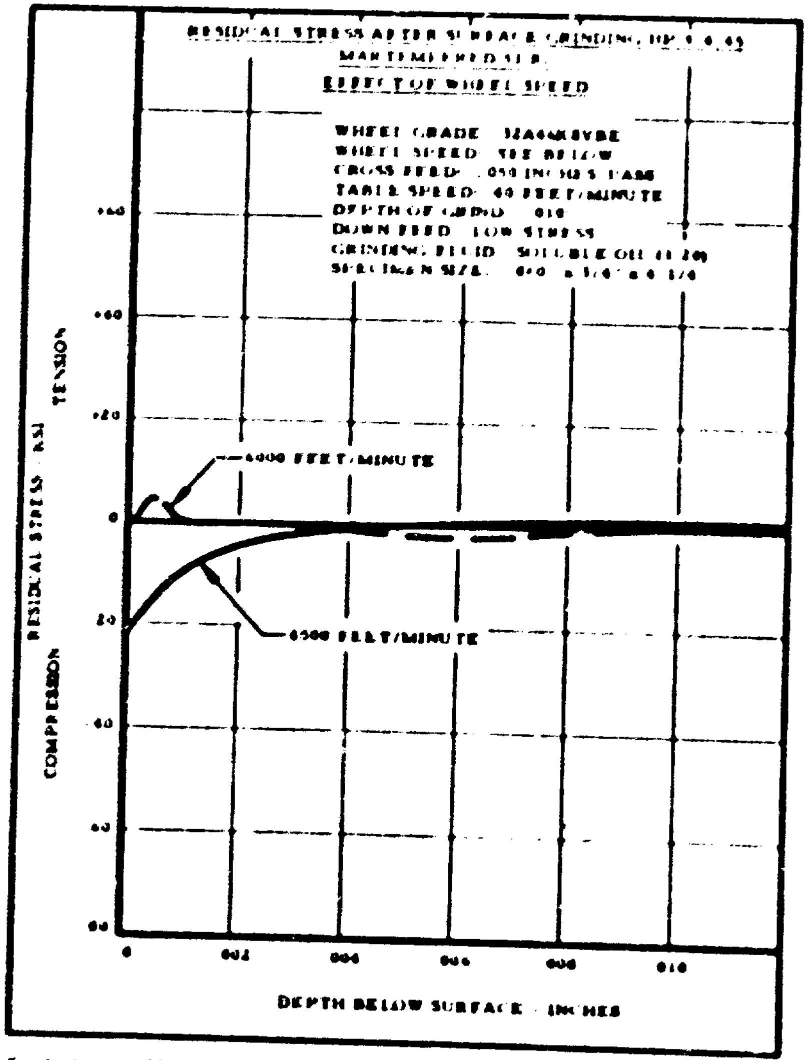
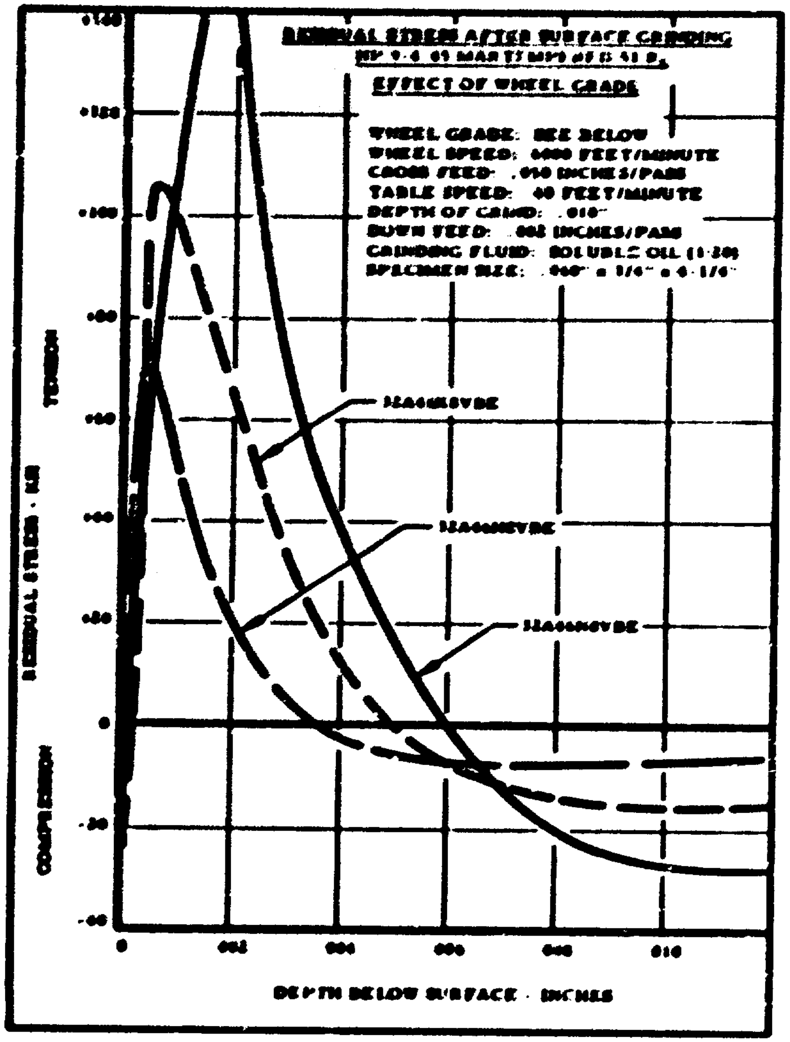
Figure 257



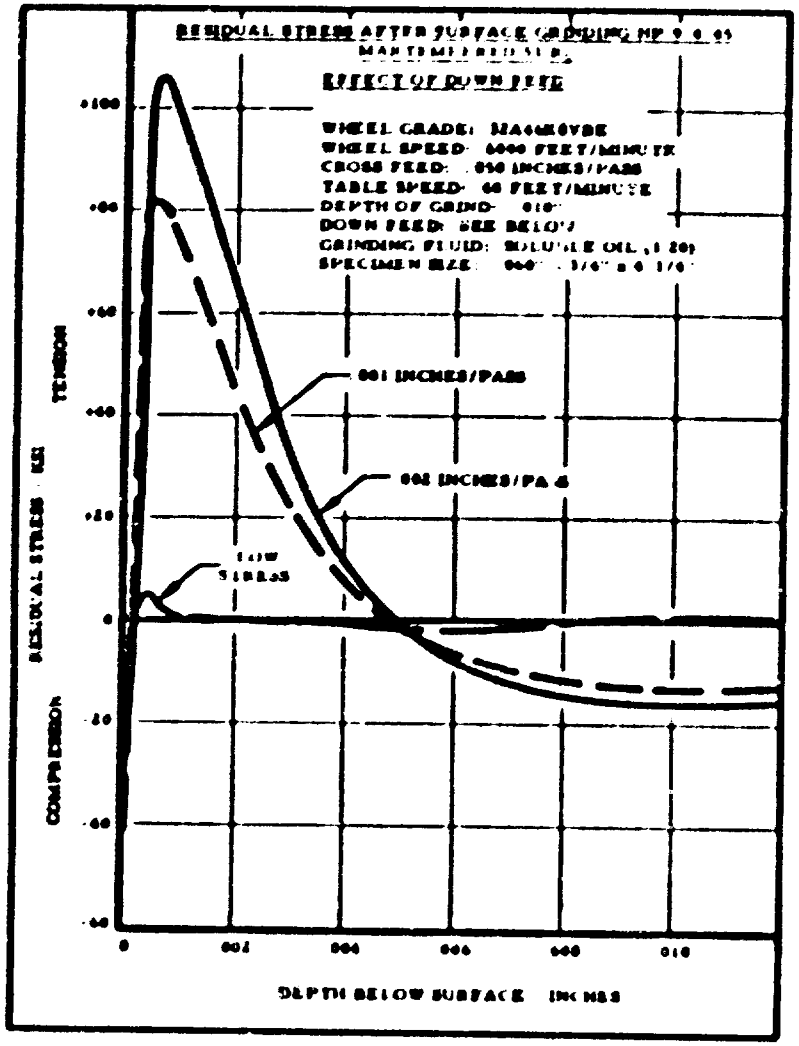
See text, page 228

Figure 258



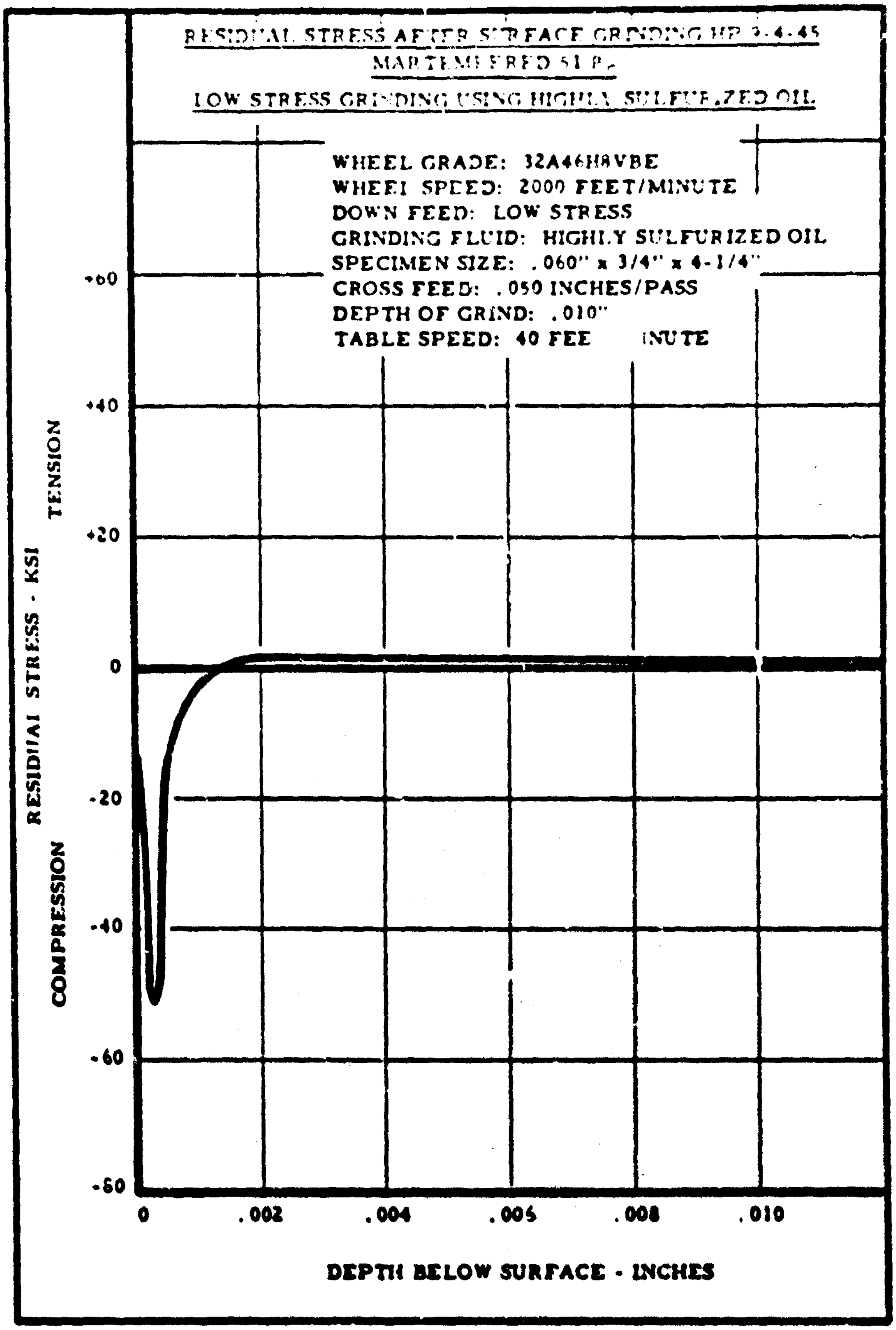
See text, page 226

Figure 259



See text, page 226

Figure 260



See text, page 228

Figure 261

7.2 Ti-6Al-4V, Beta Rolled, 322 BHN

Face Milling - Carbide Cutter

The effect of tool wearland and type of cutting fluid on the distortion when using type C-2 carbide cutter is shown in Figure 262, page 247. In all cases, the greatest distortion occurred at the intermediate degree of tool wear (.016 in. tool wearland). The heavy-duty chemical emulsion cutting fluid gave less distortion than the barium compounded oil or the dry cutting conditions. The negative sign of the deflection readings indicates the introduction of compressive stresses by the machining operation. The depth of cut appears to have only a minor effect on the distortion produced. At .016 in. wearland, the distortion is extensive, .070 to .100 in. in a 3.5 in. span, while a tool with twice the wearland gave distortions of the same order of magnitude as that found when using a sharp tool.

Residual stress determinations, Figures 263 and 264, pages 247 and 248, show the order of magnitude and depth of the more highly stressed layer. With a sharp cutter, a maximum of 50,000 psi compressive stress was found at .001 in. depth, and the compressive layer only extended to a depth of .002 in.; see Figure 263, page 247. The intermediate wearland condition (.016 in.) did not yield as high a stress level, but did result in the stress layer extending to a much greater depth, .010 in. The .032 in. wearland had a stress depth of .004 in., which was less than that for the .016 in. wearland; see Figure 263.

The effect of changing cutting fluid conditions may be observed in Figure 264. Dry, heavy-duty chemical emulsion, and barium compounded oil are compared. In all these cases, a more highly stressed compressive layer exists to a depth of about .010 in., with a maximum stress of 36,000 to 38,000 psi occurring .003 to .004 in. below the surface. All three curves are similar in characteristics. At the surface, no stress was found when using either dry cutting or a barium compounded oil, while 20,000 psi compression was observed when milling with the heavy-duty chemical emulsion.

Surface roughness readings are listed in Table XX for carbide cutters.

Face Milling - HSS Cutter

Distortion and residual stress results obtained with a T15 HSS cutter under various tool wear and cutting fluid conditions are presented graphically in Figures 265 and 266, pages 248 and 249. As the tool wear increased, the distortion increased in the compressive direction; see Figure 265. The residual stress curves obtained for various

Face Milling - HSS Cutter (continued)

degrees of tool wear when using a heavy-duty chemical emulsion cutting fluid are shown in Figure 266. A sharp cutting tool limited the compressive stressed layer to within .003 in. of the surface, while wear on the tool (.016 and .032 in. wearlands) yielded compressive stresses to a depth of .010 in.

It will be noted that the residual stress curves for the .016 and .032 in. wearland conditions exhibit only minor differences, results which are consistent with the distortion values. Maximum compressive stresses produced ranged from 36,000 to 46,000 psi.

At .016 in. wearland and .040 in. depth of cut, a comparison of cutting fluids, Figure 267, page 249, showed the heavy-duty chemical emulsion producing more distortion than either the barium compounded or the highly chlorinated oils. Even though the residual stress curves associated with these conditions do not differ greatly (Figure 267), the area under the stress curve for the heavy-duty chemical emulsion is somewhat greater than that found when using the other two fluids.

Surface roughness readings are listed in Table XXI for HSS cutters.

Surface Grinding

The effects of wheel grade, down feed, wheel speed, and grinding fluid on the distortion and residual stress patterns were investigated; see Table XXII. It will be noted in Figure 268, page 250, that increasing the wheel speed increases the distortion in the direction associated with tensile stresses. In general, a softer H-grade wheel gives less distortion that the harder J or K grades in both the silicon carbide (39C60) and aluminum oxide (32A46) types. All of these tests were run with KNO_2 (1:20) as the grinding fluid. Greater distortion, indicating a greater stressed condition, occurs when using an aluminum oxide wheel in place of a silicon carbide wheel of the same hardness.

In Figure 269, page 250, the effect of the three grinding fluids -- highly chlorinated oil, highly sulfurized oil, and KNO_2 (1:20) -- on the resulting distortion is shown. Only at high wheel speeds, 6000 feet/minute, was a noticeable difference obtained. At this speed, highly chlorinated oil gave the greatest distortion.

7.2 Ti-6Al-4V, Beta Rolled, 322 BHN (continued)

Surface Grinding (continued)

A bar graph in Figure 270, page 251, summarizes the distortion results at 2000 and 4000 feet/minute wheel speeds for various down feeds and grinding fluids when using the 39C60H8VK silicon carbide wheel. The greater down feeds usually gave some increase in deflection in the direction which would indicate compressive stresses in the surface layer.

The residual stress profiles for a number of grinding conditions are shown in Figures 271, 272 and 273, pages 251 and 252. The effect of wheel speed is noted in Figure 271 when using KNO_2 and a silicon carbide wheel. As the wheel speed increases, there tends to be some increase in the tensile stressed layer. At 6000 feet/minute, tensile stresses were found to a depth of .002 in. below the surface, while at 2000 feet/minute, they were confined to less than .0004 in. below the surface.

The "low stress" down feed resulted in a shallow tensile stressed layer as noted in Figure 272.

When an aluminum oxide wheel was used at a high wheel speed of 6000 feet/minute, an extensive tensile stressed condition resulted as may be seen in Figure 272. The tensile stressed state existed to a depth of .006 in., with a maximum value of 70,000 psi .001 in. below the surface.

The effect of using a grinding fluid other than KNO_2 solution on the residual stress patterns may be observed by comparing the curves in Figure 273. Even though the surface stress was a high tensile value when a highly chlorinated oil was used, the distortion and general characteristics are similar to those obtained when using KNO_2 solution.

Table XXII lists surface roughness readings for various grinding conditions.

TABLE XX

SURFACE ROUGHNESS PRODUCED BY FACE MILLING TITANIUM 6Al-4V BETA ROLLED, 322 BHN

Cutter: 4" Dia. Single Tooth Face Mill with
C-2 (883) Carbide

AR:	0°	Incl.:	0°
RR:	-10°	ECEA:	0°
CA:	45°	Clearance:	10°
TR:	7°		

Cutting Speed: 150 feet/minute
Feed: .005 inches/tooth

Cutting Fluid	Depth of Cut (Inches)	Wearland (Inches)	Surface Finish - Microinches AA Parallel to Cutting Direction	 Perpendicular to Cutting Direction
Chemical Emulsion	.010	0	10-12	18-20
		.016	18-20	30-34
		.032	15-18	20-22
	.040	0	10-12	18-20
		.016	20-25	50-60
		.032	15-18	30-32
Dry	.040	0	10-12	18-20
		.016	20-24	25-28
		.032	15-18	30-32
Barium Compounded Oil	.040	0	10-12	18-20
		.016	14-16	24-25
		.032	15-16	25-28

TABLE XXI

SURFACE ROUGHNESS PRODUCED BY FACE MILLING
TITANIUM 6Al-4V BETA ROLLED, 322 BHN

Cutter: 4" Dia. Single Tooth Face Mill with
T15 HSS

AR:	0°	Incl.:	0°
RR:	0°	ECEA:	0°
CA:	45°	Clearance:	8°
TR:	0°		

Cutting Speed: 75 feet/minute
Feed: .005 inches/tooth

Cutting Fluid	Depth of Cut (Inches)	Wearland (Inches)	Surface Finish - Microinches AA Parallel to Cutting Direction	Surface Finish - Microinches AA Perpendicular to Cutting Direction
Chemical Emulsion	.010	0	8-10	9-10
		.016	15-17	23-25
		.032	14-16	27-30
	.040	0	10-12	10-12
		.016	12-14	20-23
		.032	14-16	28-30
Highly Chlorinated Oil	.040	0	8-10	6-7
		.016	12-15	28-30
		.032	10-12	20-22
Barium Compounded Oil	.040	0	10-12	12-14
		.016	15-17	28-30
		.032	13-15	24-25

TABLE XXII

SURFACE ROUGHNESS PRODUCED BY SURFACE GRINDING
TITANIUM 6Al-4V BETA ROLLED, 322 BHN

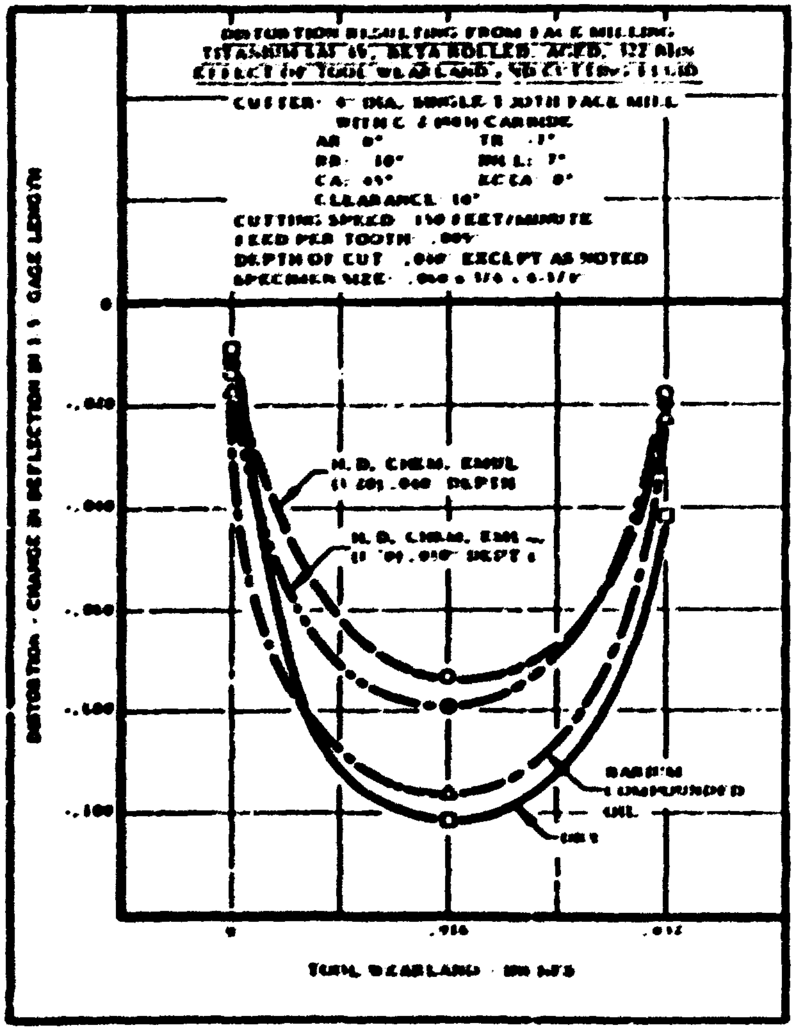
Cross Speed: .050 inches/pass
Table Speed: 40 feet/minute
Depth of Grind: .010 in.

Wheel	Down Feed (Inches)	Cutting Fluid	Wheel Speed	Surface Finish - Microinches AA Parallel to Grinding Direction	Surface Finish - Microinches AA Perpendicular to Grinding Direction
32A46H8VBE	.002	KNO_2(1:20)	2000	45-50	135-140
			4000	20-25	48-52
			6000	28-32	78-82
32A46K8VBE	.002	KNO_2 (1:20)	2000	20-26	50-54
			4000	25-30	46-50
			6000	23-24	48-50
39C60J8VK	.002	KNO_2(1:20)	2000	35-45	95-100
			4000	42-48	115-125
			6000	24-26	55-60
39C60H8VK	.002	KNO_2(1:20)	2000	55-57	152-157
			4000	30-32	85-90
			6000	25-27	55-56
	LS	KNO_2(1:20)	2000	15-17	26-28
			4000	43-44	34-35
	.001	KNO_2(1:20)	2000	32-38	80-85
			4000	38-40	75-80
	LS	Highly Sulfurized Oil	4000	14-18	29-30
	.001	Highly Sulfurized Oil	4000	20-23	60-61

TABLE XXII

SURFACE ROUGHNESS PRODUCED BY SURFACE GRINDING TITANIUM 6Al-4V BETA ROLLED, 32[illegible] BHN (continued)

Wheel	Down Feed (Inches)	Cutting Fluid	Wheel Speed	Surface Finish - Microinches AA Parallel to Grinding Direction	Surface Finish - Microinches AA Perpendicular to Grinding Direction
39C60H8VK	.002	Highly Sulfurized Oil	2000	52-57	145-153
			4000	45-49	83-85
			6000	40-45	125-135
	.002	Highly Chlorinated Oil	2000	28-36	138-142
			4000	52-55	150-155
			6000	20-22	49-50



See text, page 260

Figure 262

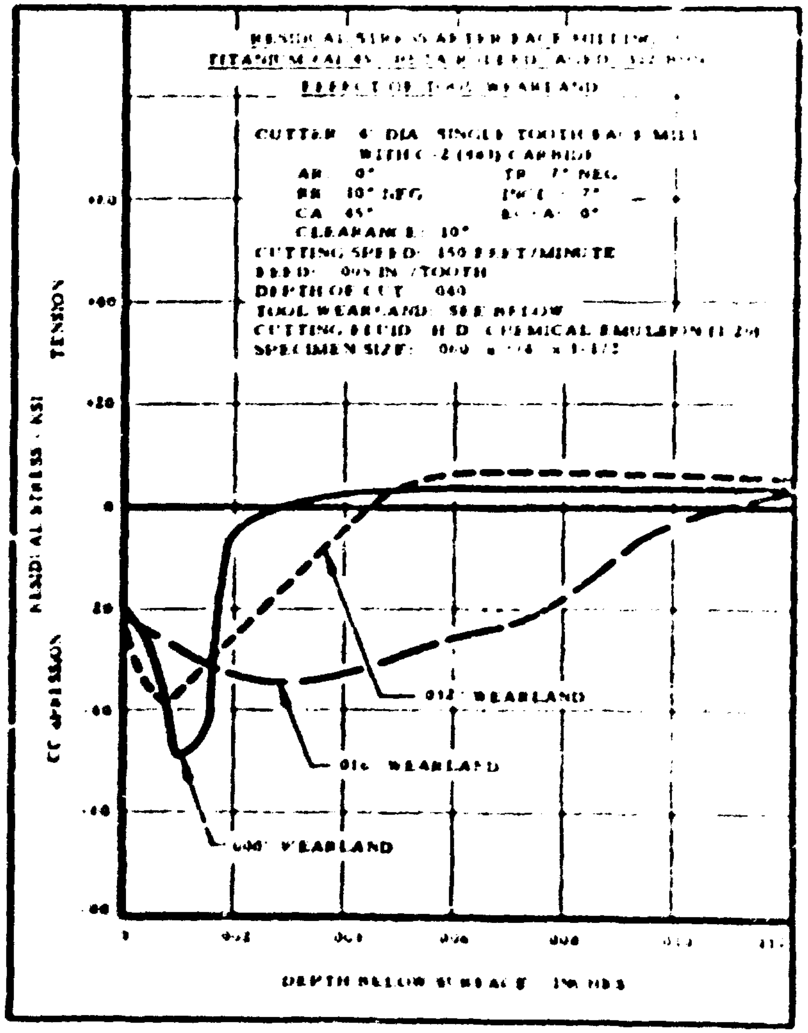


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Figure 263

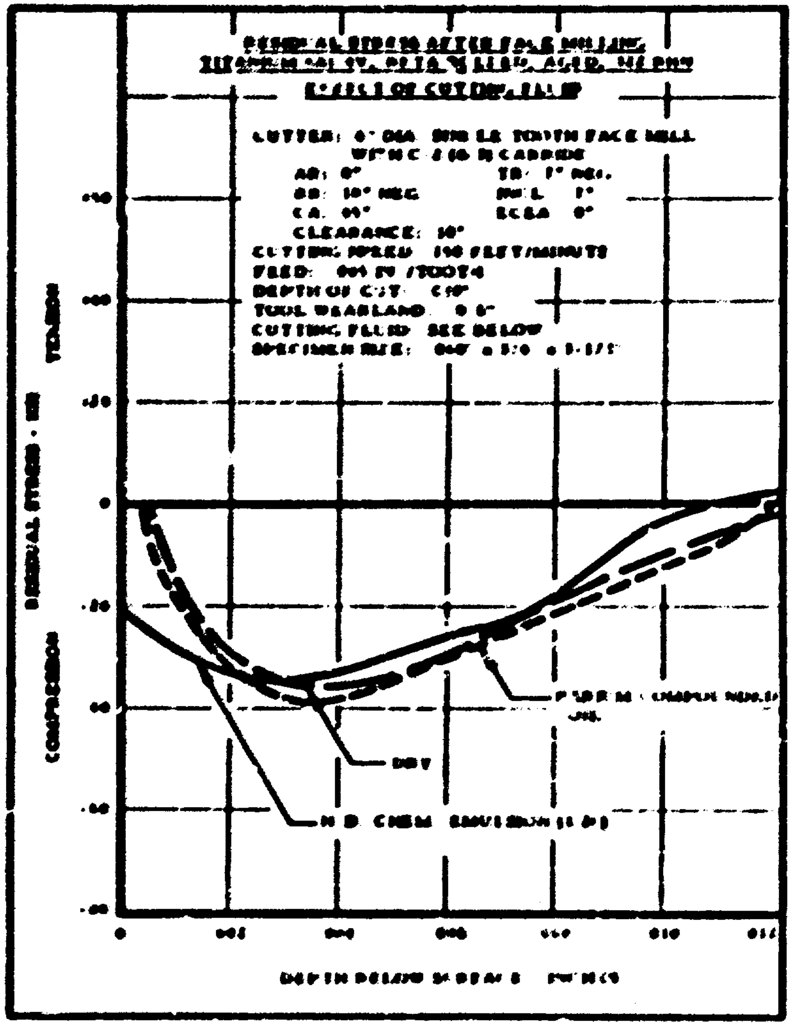

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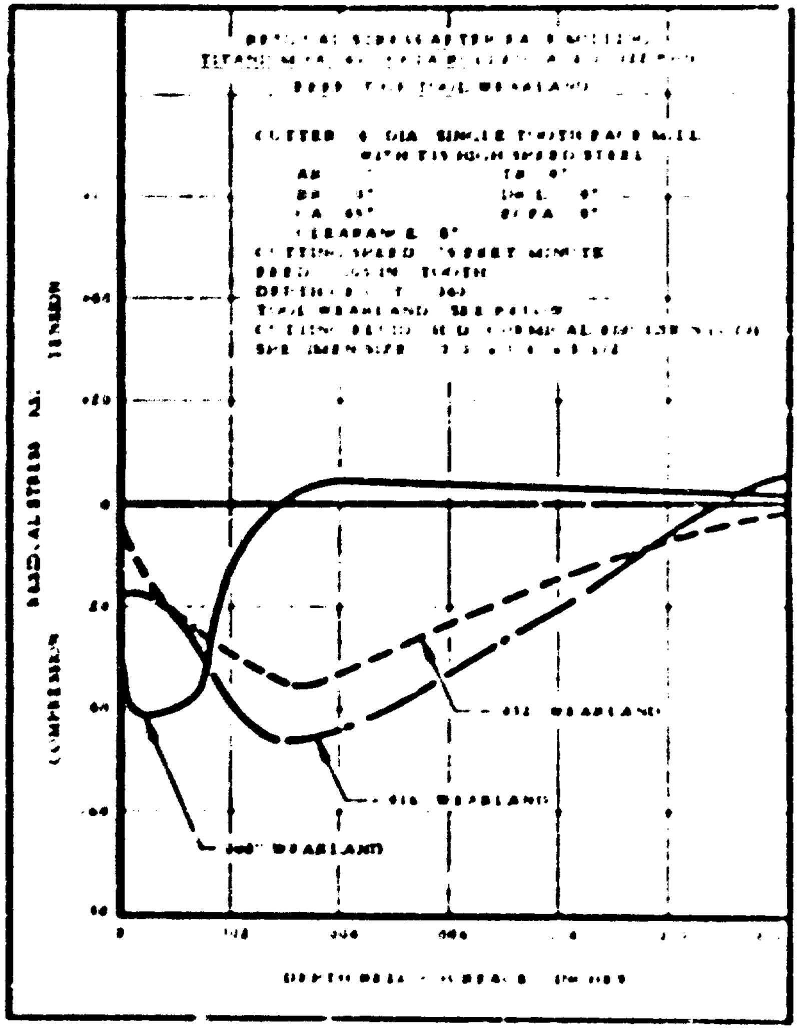
Figure [illegible]



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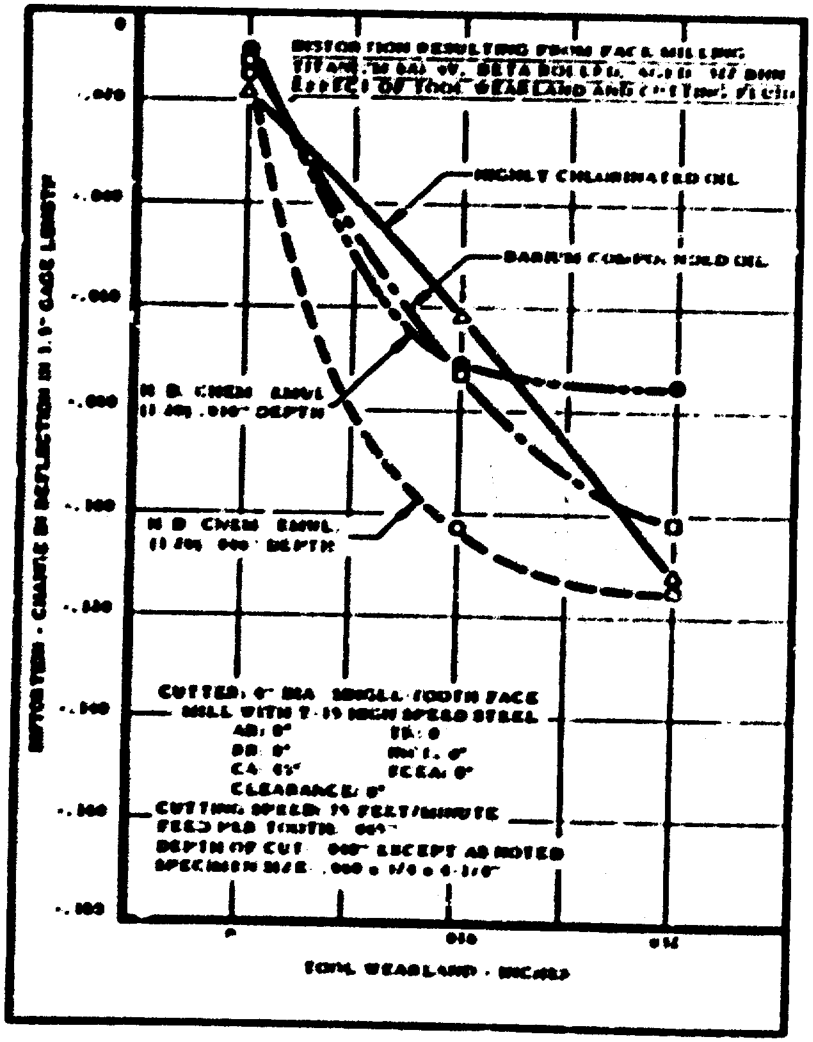

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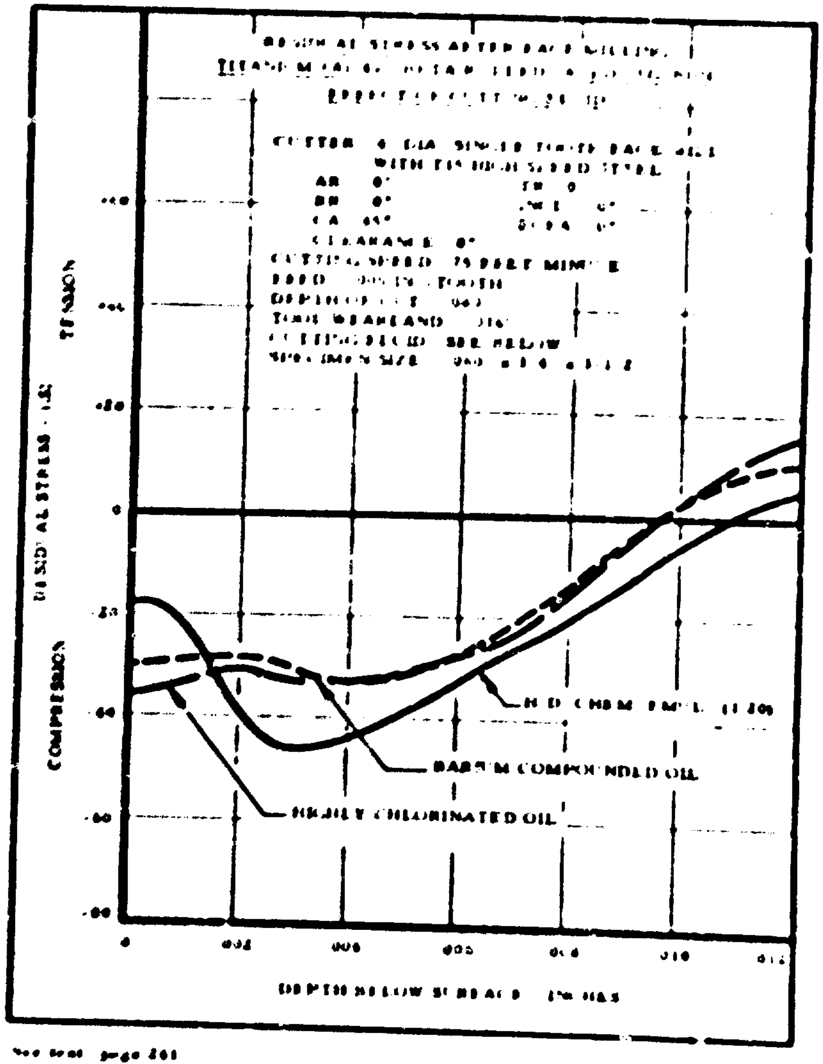
Figure [illegible]



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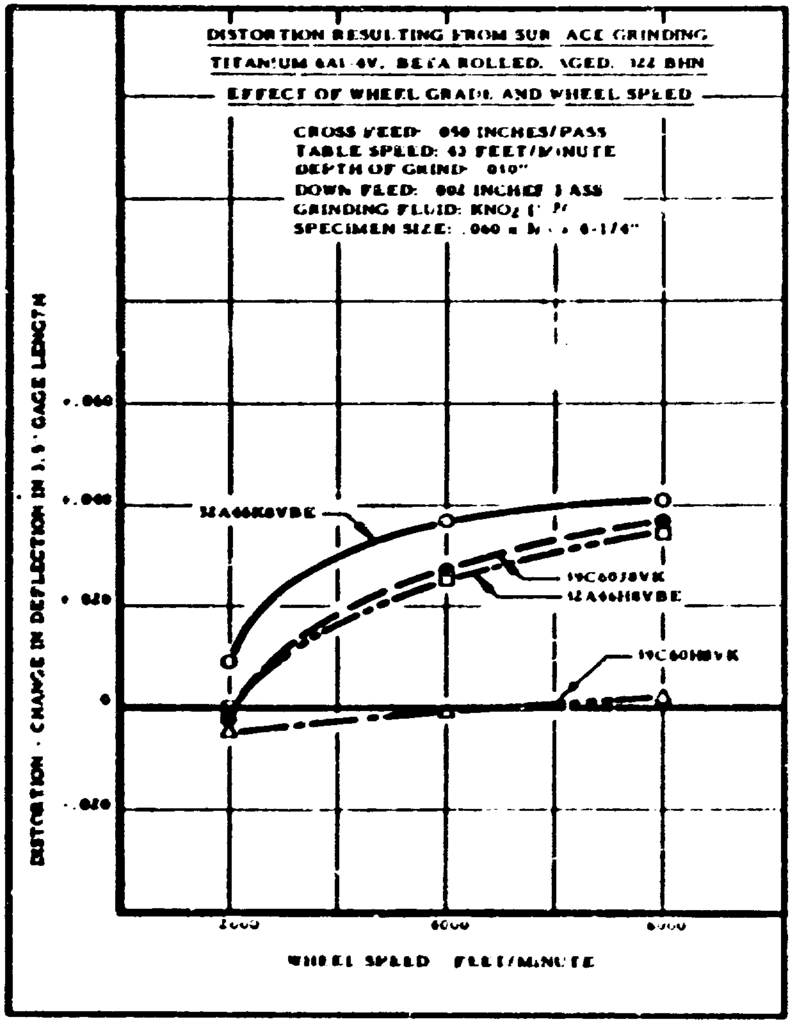
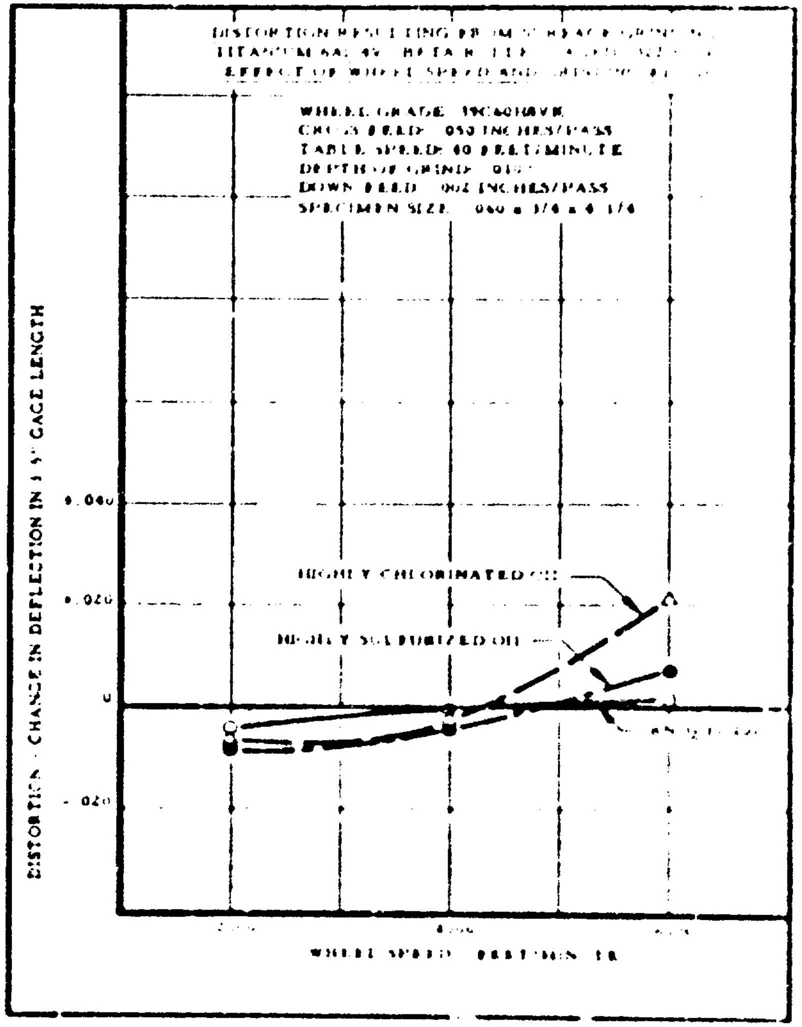


See text page 241 Figure 2[illegible]



See text page 241 Figure [illegible]

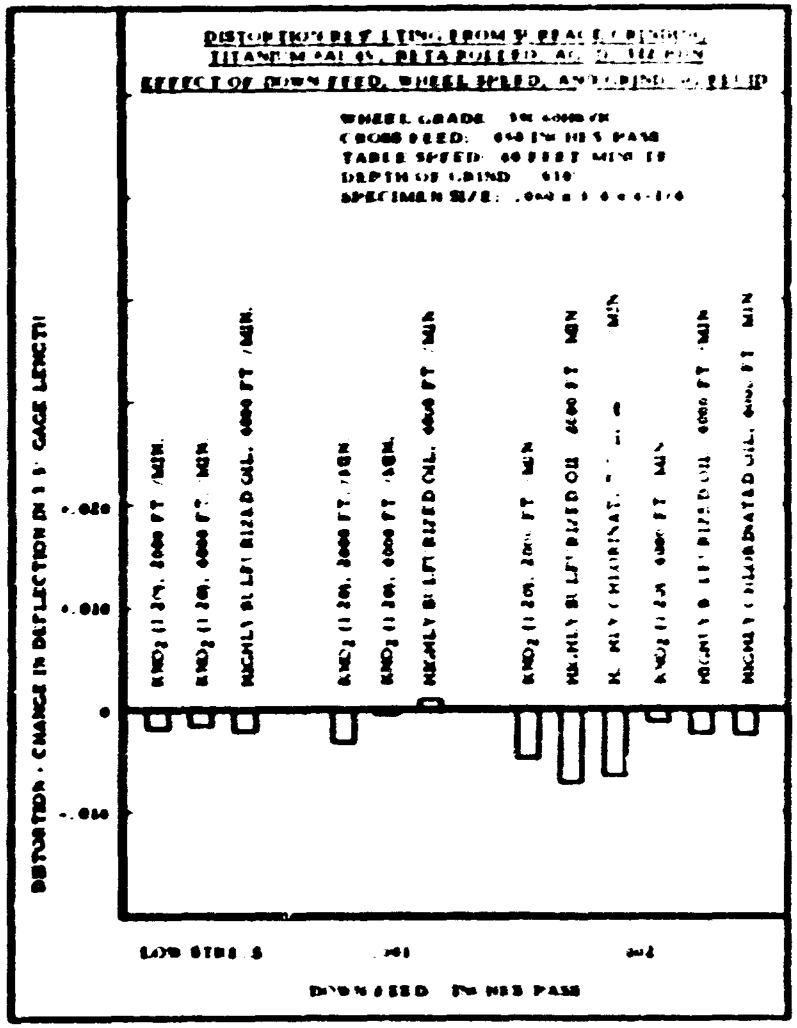


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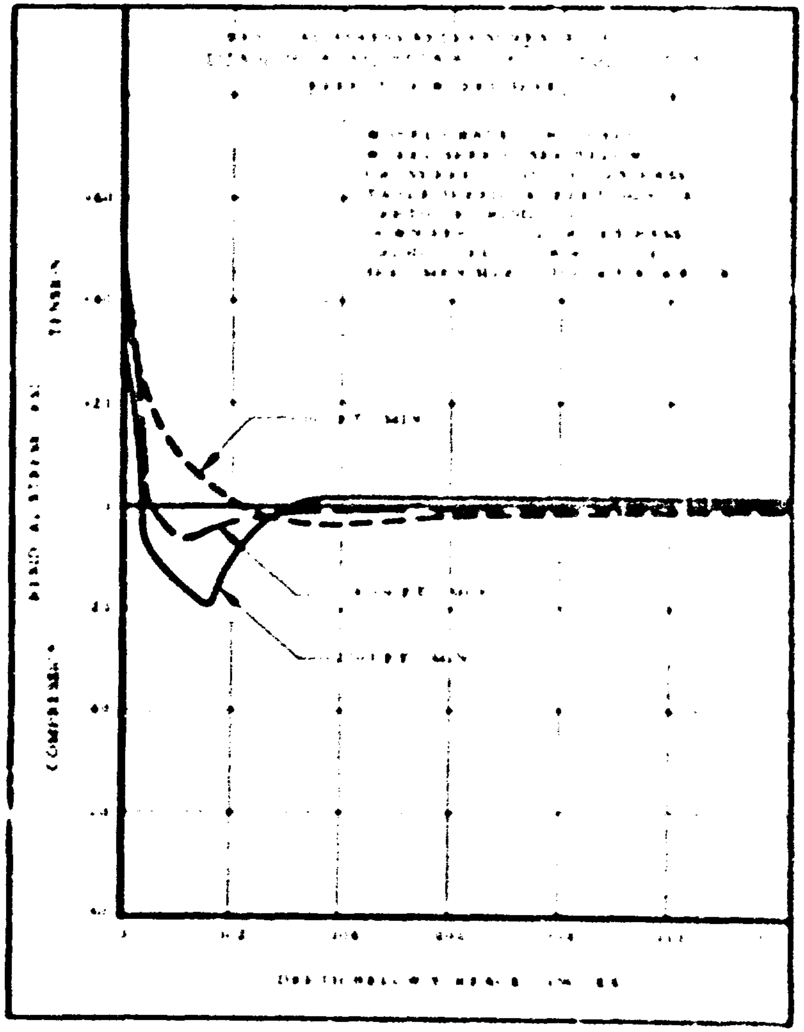
Figure 4



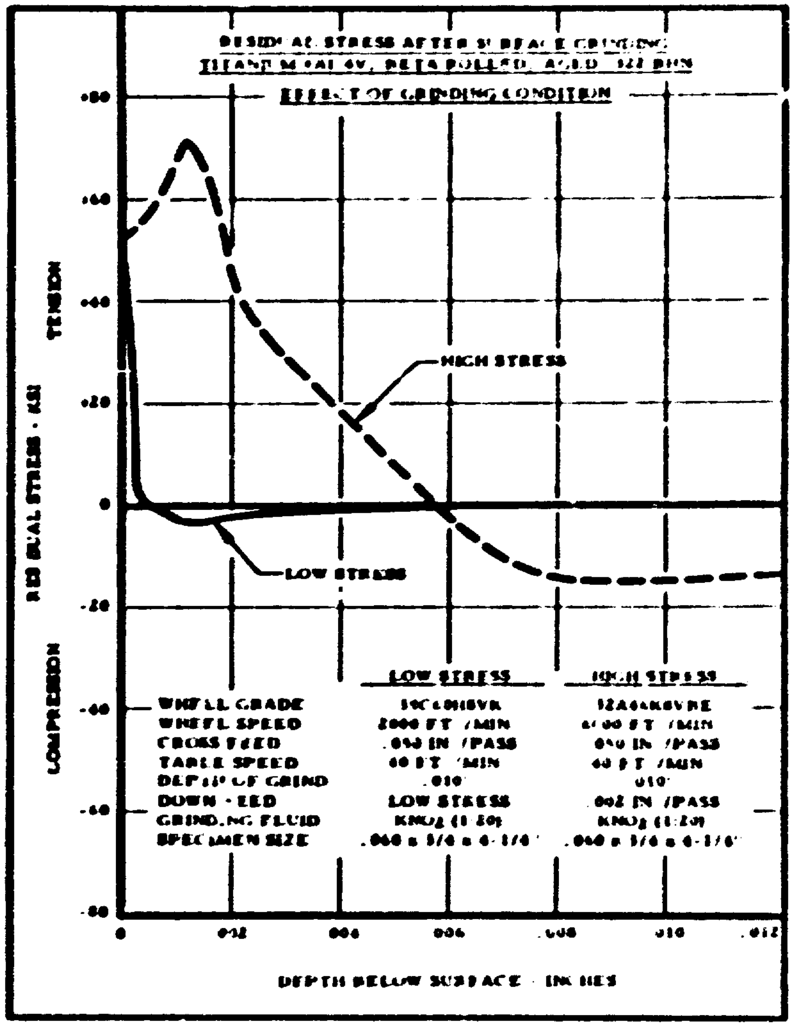


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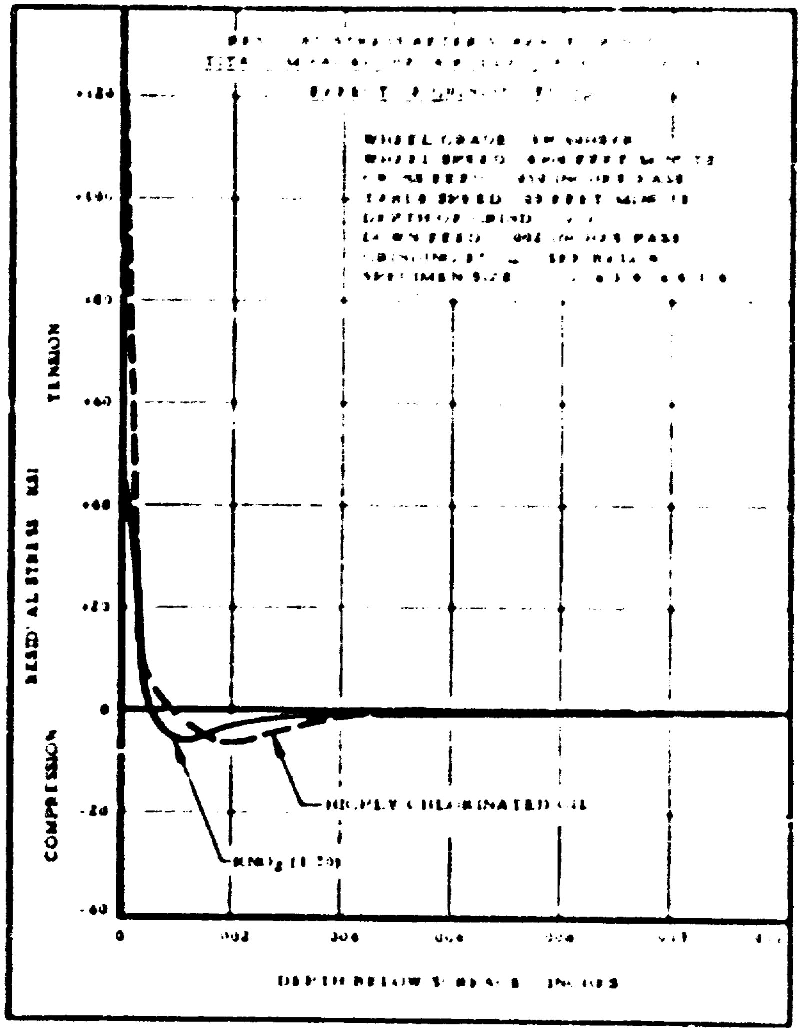
Figure 272



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[illegible] Ti-6Al-2Sn-4Zr-2Mo, Annealed 321 BHN

Face Milling - Carbide Cutter

Distortion and residual stress results when face milling with a carbide cutter with various milling conditions are found in Figures 274, 275 and 276, pages 261 and 262. Also see Table XXIII.

With a C-2 (883) carbide cutter, the distortions produced with .016 or .032 in. wearlands were greater than that found with a sharp cutter, see Figure 274, page 261. There was some tendency for less distortion at .032 in. wearland than at .016 in. wearland. All distortion values indicate compressive residual stresses in the layers. The residual stress patterns related to these results are given in Figures 275 and 276, pages 261 and 262.

A sharp tool gave a compressive stressed layer of a greater magnitude to a greater depth than either of the other two wear conditions, see Figure 275, page 261. The greatest wear, .032 in. wearland, showed no measurable residual stress within the first .001 in. below the surface, with only small stress values below that point. The intermediate wearland produced a shallow (less than .001 in.) compressive stressed layer, with a maximum value of 90,000 psi at the surface. A heavy-duty chemical emulsion was used as the cutting fluid in all these tests.

The effect of cutting fluids on residual stress patterns is shown in Figure 276, page 262. The heavy-duty chemical emulsion, the barium compounded oil, and milling dry produced similar results. The compressive surface stress values ranged from 50,000 to 90,000 psi, decreasing rapidly within the first .001 in. below the surface. These results are in agreement with the distortions; see Figure 274.

For the same cutting fluid (heavy-duty chemical emulsion), less distortion was found when using a light cut (.010 in.) than when using the deeper cut of .040 in., see Figure 274.

The surface roughness readings obtained when face milling with the C-2 carbide cutter are summarized in Table XXIII.

Face Milling - HSS Cutter

A T15 HSS cutter was used under various cutting fluid, wearland, and depth of cut conditions. The distortion produced under these various milling conditions and the resulting residual stress patterns

7.3 Ti-6Al-2Sn-4Zr-2Mo, Annealed 321 BHN (continued)

Face Milling - HSS Cutter (continued)

associated with some of these conditions are found in Figures 277, 278 and 279, pages 262 and 263.

A T15 HSS cutter gave greater distortions for greater tool wear, Figure 277, page 262, over the range 0.00 in. (sharp tool) to .032 in. tool wearland. In the same figure, the effect of depth of cut and cutting fluid may be seen. There were three different cutting fluids used -- a heavy duty chemical emulsion, a barium compounded oil and a highly chlorinated oil. Even though some greater distortion resulted with the highly chlorinated oil at .016 in. tool wearland, in general, the differences between the curves are small.

The two curves reported for the heavy-duty chemical emulsion as the cutting fluid show the effect of two different depths of cut (.010 and .040 in.). It will be noted that slightly less distortion occurred with the greater depth of cut.

The residual stress profiles with different degrees of tool wearland are presented in Figure 278, page 263. The compressive-stressed area under the curve for .032 in. wearland is the greatest, while that under the .000 in. wearland is least. Such results are in agreement with the distortion values in Figure 277. With both the .016 and .032 in. wearland conditions, the compressive stressed layer extended to a depth of greater than .010 in.

When the residual stress curves produced by three different cutting fluids are compared, Figure 279, page 263, the difference is not considered significant. Shapes are similar, and the compressive stressed layer extends to at least .010 in. in all cases. The three fluids compared are heavy-duty chemical emulsion, highly chlorinated oil, and barium compounded oil.

In Table XXIV, the surface roughness values of surfaces machined with the T15 cutter are listed.

Surface Grinding

The surface grinding parameters investigated when grinding the Ti-6Al-2Sn-4Zr-2Mo alloy were wheel speed, wheel grade, and grinding fluid. Graphical results on distortion and residual stress characteristics are shown in Figures 280 through 286, pages 264 through 267.

7.3 Ti-6Al-2Sn-4Zr-2Mo Annealed, 321 BHN (continued)

Surface Grinding (continued)

Increasing wheel speed and increasing wheel hardness increased the distortion see Figure 280 page 264. With the silicon carbide wheel at 4000 feet/minute wheel speed, practically no distortion was found. However increasing the wheel speed to 6000 feet/minute resulted in a distortion of .020 in. in 3.5 in. Aluminum oxide wheels produce a greater degree of distortion than silicon carbide wheels. At 4000 feet/minute wheel speed the distortion increased from zero with a 39C60H8VK (silicon carbide, H hardness) wheel to .023 in. with the harder 39C60J8VK wheel. With aluminum oxide (32A46) wheels at 4000 feet/minute increasing the wheel hardness from H to K increased the distortion only a small amount, from .033 to .035 in. in 3.5 in.

The effect of using highly chlorinated oil, highly sulfurized oil, and KNO_2 (1:20) solution showed only a minor difference between the distortion values when using the two oils and a somewhat-reduced distortion when using KNO_2 solution, see Figure 281, page 264.

The bar graph in Figure 282, page 265, summarizes the effect of wheel speed, grinding fluid, and down feed on distortion. With a "low stress" down feed, only a small degree of distortion resulted. At .002 in./pass down feed, the degree of distortion increased with the direction of the distortion, giving an indication of compressive stresses at a wheel speed of 2000 feet/minute and tension stresses at a wheel speed of 4000 feet/minute.

Figure 283, page 265, shows the residual stress patterns obtained when varying the wheel speed for KNO_2 as the grinding fluid. Wheel speeds of 2000 feet/minute and 4000 feet/minute gave similar patterns. At 6000 feet/minute, tensile stresses existed to a depth of .003 in.

At a wheel speed of 4000 feet/minute, more distortion was obtained with highly chlorinated oil as the grinding fluid than with KNO_2 solution. The residual stress curves for these two conditions are shown in Figure 284, page 266, where the greater quantity of tensile stressed layer in the sample ground using highly chlorinated oil as the fluid is observed.

At a high wheel speed (6000 feet/minute) and using an aluminum oxide wheel (32A46K8VBE), tensile stresses extended to .005 in. below the surface, as may be observed in Figure 285, page 266.

7.3 Ti-6Al-2Sn-4Zr-2Mo, Annealed 321 BHN (continued)

Surface Grinding (continued)

The same wheel speed with a silicon carbide wheel (6000 sfpm) also produced a tensile stressed layer, but both the magnitude and depth were less.

In Figure 286, page 267, the residual stress curves for a "low stress" grinding condition (silicon carbide wheel, low wheel speed, and "low stress" down feed) and for a more abusive grinding condition (aluminum oxide wheel, high wheel speed, and heavy down feed) are shown. The greater tensile stressed layer of the abusive condition is readily evident. The "low stress" down feed condition involves the removal of .010 in. of material at .0005 in./pass for the first .008 in., and for the last .002 in. two passes at .0004 in./pass, with the final six passes of .0002 in./pass.

The surface finish produced by these grinding studies are recorded in Table XXV.

TABLE XXIII

SURFACE ROUGHNESS PRODUCED BY FACE MILLING
TITANIUM 6Al-2Sn-4Zr-2Mo, ANNEALED, 321 BHN

Cutter: 4" Dia. Single Tooth Face Mill with
C-2 (883) Carbide

AR: 0° IncL.: 7°
RR: -10° ECEA: 0°
CA. 45° Clearance: 10°
TR: -7°

Cutting Speed: 150 feet/minute
Feed: .005 inches/tooth

			Surface Finish - Microinches AA	
Cutting Fluid	Depth of Cut (Inches)	Wearland (Inches)	Parallel to Cutting Direction	Perpendicular to Cutting Direction
Heavy-duty Chemical Emulsion	.010	0	18-20	45-47
		.016	15-17	35-37
		.032	14-16	34-36
	.040	0	25-27	33-36
		.016	25-27	38-43
		.032	27-29	40-42
Dry	.040	0	20-22	29-31
		.016	17-19	42-44
		.032	17-19	48-52
Barium Compounded Oil	.040	0	18-20	28-32
		.016	15-17	35-38
		.032	13-15	28-30

TABLE XXIV

SURFACE ROUGHNESS PRODUCED BY FACE MILLING
TITANIUM 6Al-2Sn-4Zr-2Mo, ANNEALED, 321 BHN

Cutter: 4" Dia. Single Tooth Face Mill with
T15 HSS

AR:	0°	Incl.:	0°
RR:	0°	ECEA:	0°
CA:	45°	Clearance:	8°
TR:	0°		

Cutting Speed: 75 feet/minute
Feed: .005 inches/tooth

Cutting Fluid	Depth of Cut (Inches)	Wearland (Inches)	Surface Finish - Microinches AA: Parallel to Cutting Direction	Surface Finish - Microinches AA: Perpendicular to Cutting Direction
Heavy-duty Chemical Emulsion	.010	0	13-15	15-17
		.016	14-15	33-35
		.032	28-30	50-55
	.040	0	14-15	18-20
		.016	18-20	40-42
		.032	23-27	64-67
Highly Chlorinated Oil	.040	0	13-15	20-22
		.016	14-15	28-30
		.032	15-17	30-32
Barium Compounded Oil	.040	0	15-17	15-17
		.016	14-15	30-32

TABLE XXV

SURFACE ROUGHNESS PRODUCED BY SURFACE GRINDING
TITANIUM 6Al-2Sn.-4Zr-2Mo, 321 BHN

Cross Speed: .050 inches/pass
Table Speed: 40 feet/minute
Depth of Grind: .010 in.

Wheel	Down Feed (Inches)	Cutting Fluid	Wheel Speed	Surface Finish - Microinches AA: Parallel to Grinding Direction	Surface Finish - Microinches AA: Perpendicular to Grinding Direction
32A46H8VBE	.002	KNO_2(1:20)	2000	24-25	35-37
			4000	19-20	48-50
			6000	25-27	58-60
32A46K8VBE	.002	KNO_2(1:20)	2000	22-24	36-38
			4000	22-24	45-47
			6000	22-24	48-50
32A46J8VK	.002	KNO_2(1:20)	2000	22-24	36-38
			4000	25-27	68-70
			6000	28-32	68-70
39C60H8VK	.002	KNO_2(1:20)	2000	45-48	98-100
			4000	45-48	80-84
			6000	25-27	67-69
	LS	KNO_2(1:20)	2000	15-17	20-21
			4000	18-20	33-35
	.001	KNO_2(1:20)	2000	18-20	32-33
			4000	24-25	29-31
	LS	Highly Sulfurized Oil	4000	14-16	28-30
	.001	Highly Sulfurized Oil	4000	17-19	40-42

TABLE XXV

SURFACE ROUGHNESS PRODUCED BY SURFACE GRINDING

TITANIUM 6Al-2Sn-4Zr-2Mo, 321 BHN (Continued)

Wheel	Down Feed (Inches)	Cutting Fluid	Wheel Speed	Surface Finish - Microinches AA: Parallel to Grinding Direction	Surface Finish - Microinches AA: Perpendicular to Grinding Direction
39C60H8VK	.002	Highly Sulfurized Oil	2000	45-47	95-100
			4000	60-65	80-85
			6000	20-21	43-45
	.002	Highly Chlorinated Oil	2000	38-42	190-200
			4000	15-17	40-42
			6000	30-32	42-45
32A46H8VBE	.002	KNO_2(1:20)	2000	33-35	68-72
			4000	24-26	55-60
39C60J8VB	.002	KNO_2(1:20)	2000	38-40	63-65
			4000	43-45	65-68
			6000	35-38	48-52

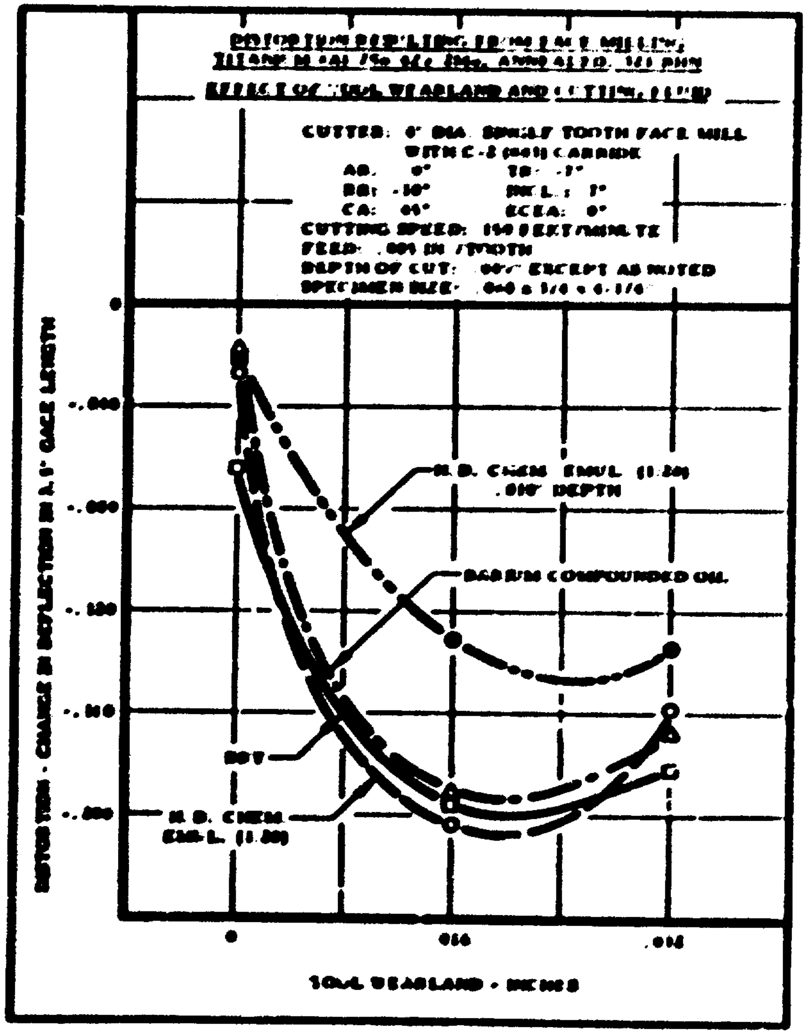

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Figure 276

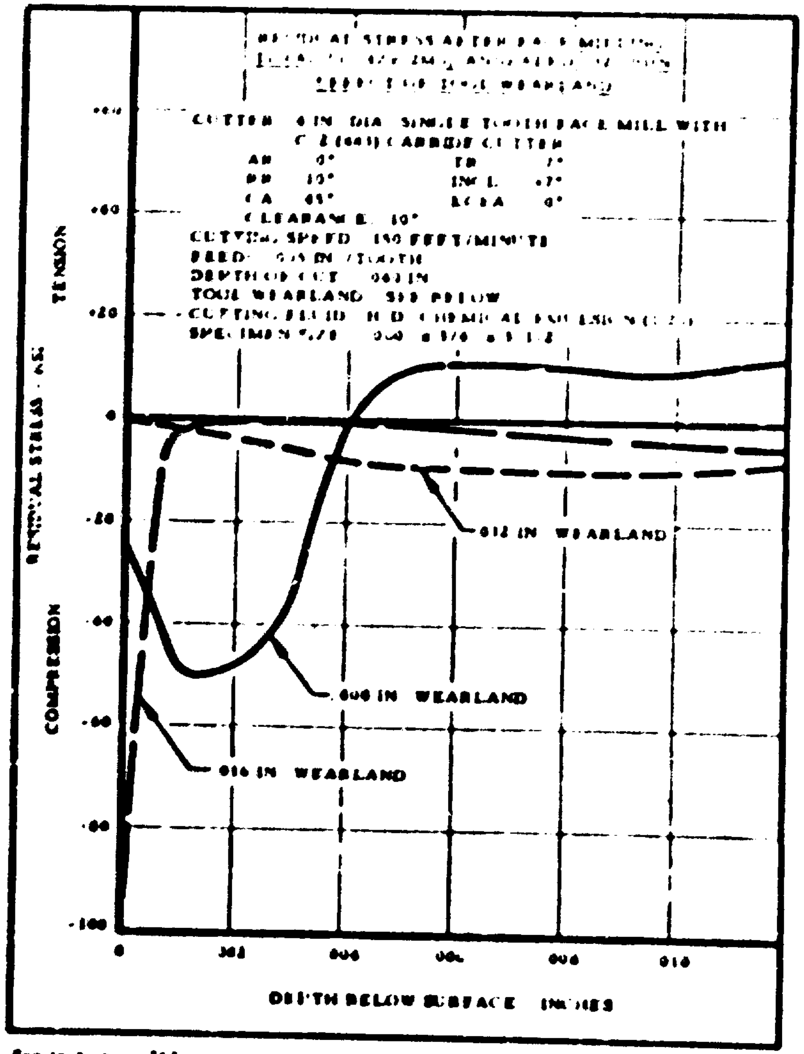

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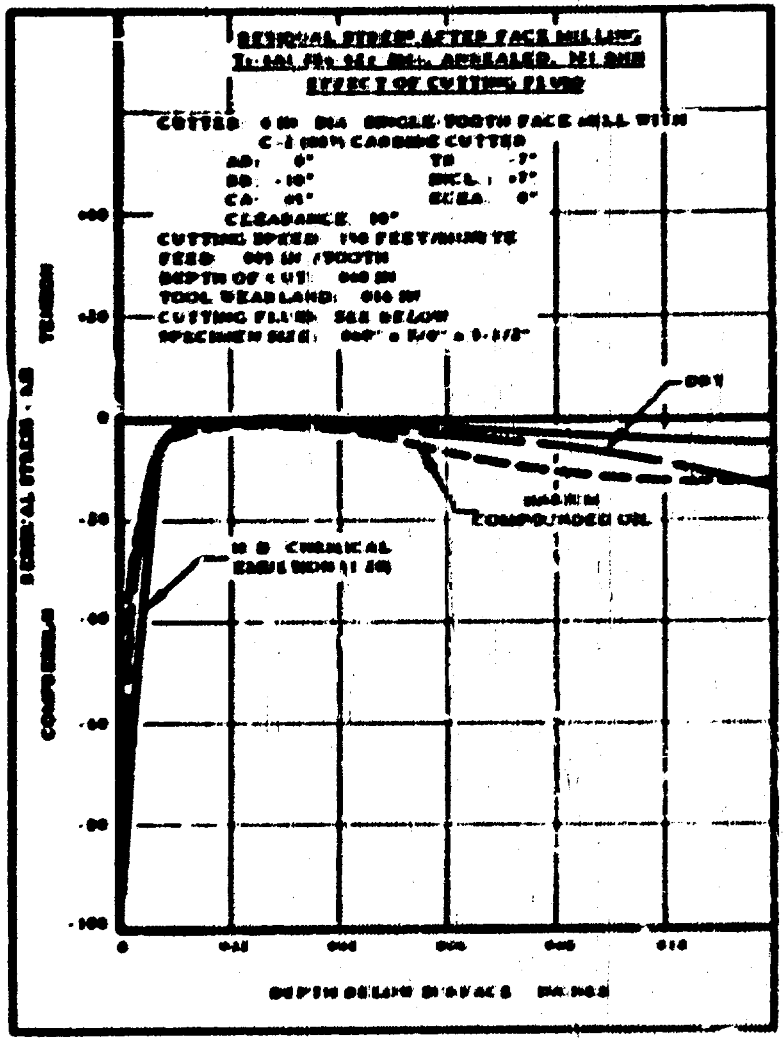
Figure 275



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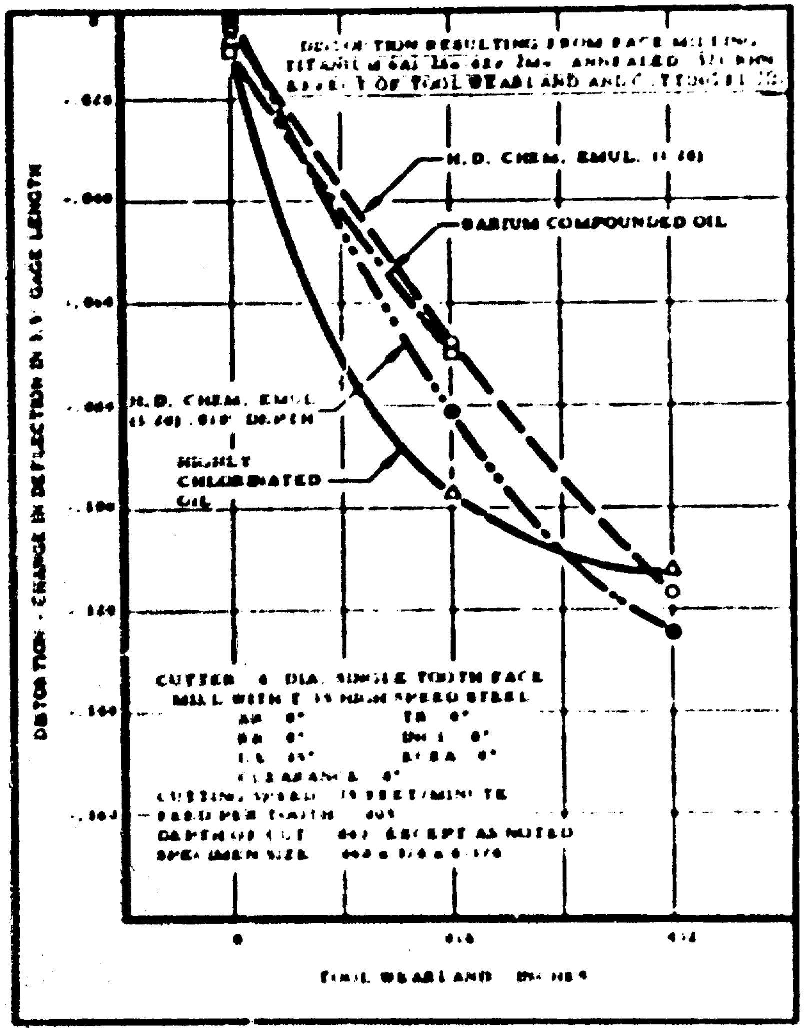

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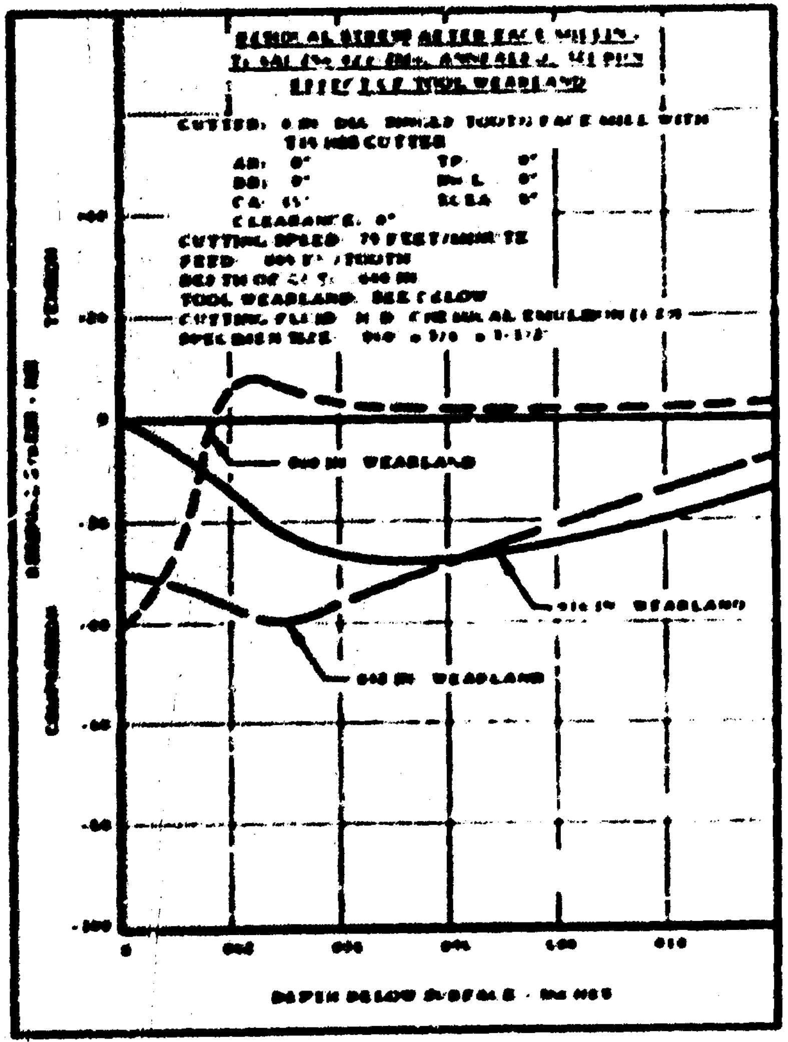

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Figure [illegible]

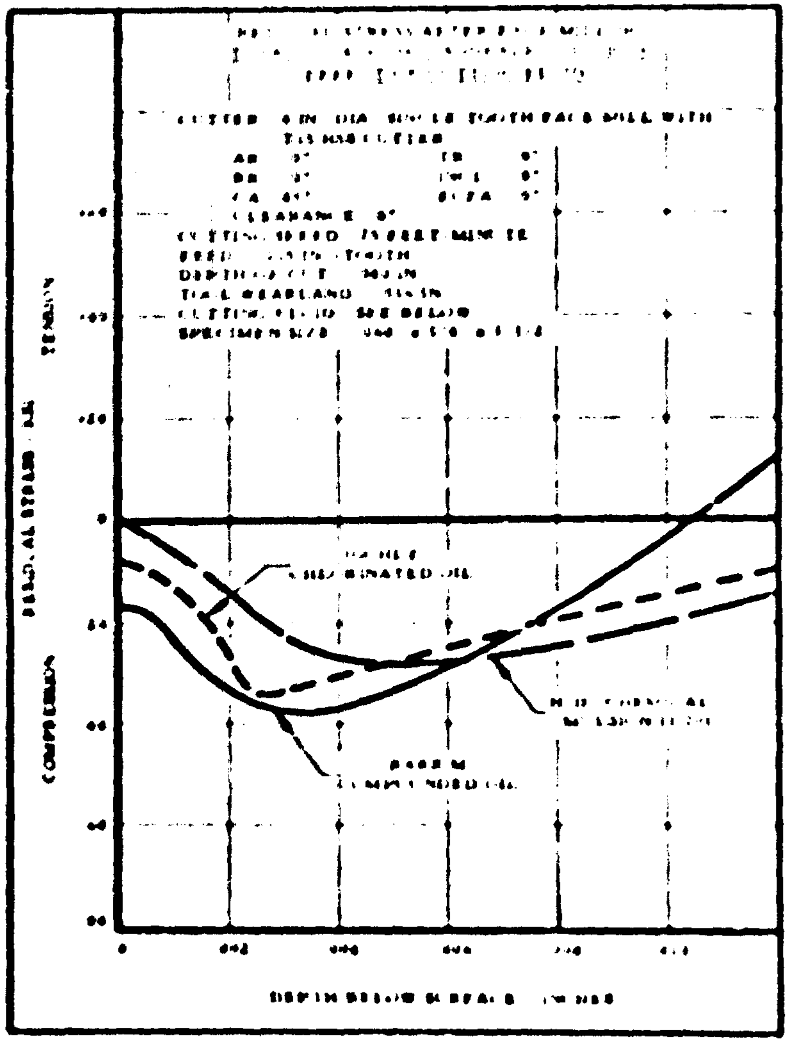

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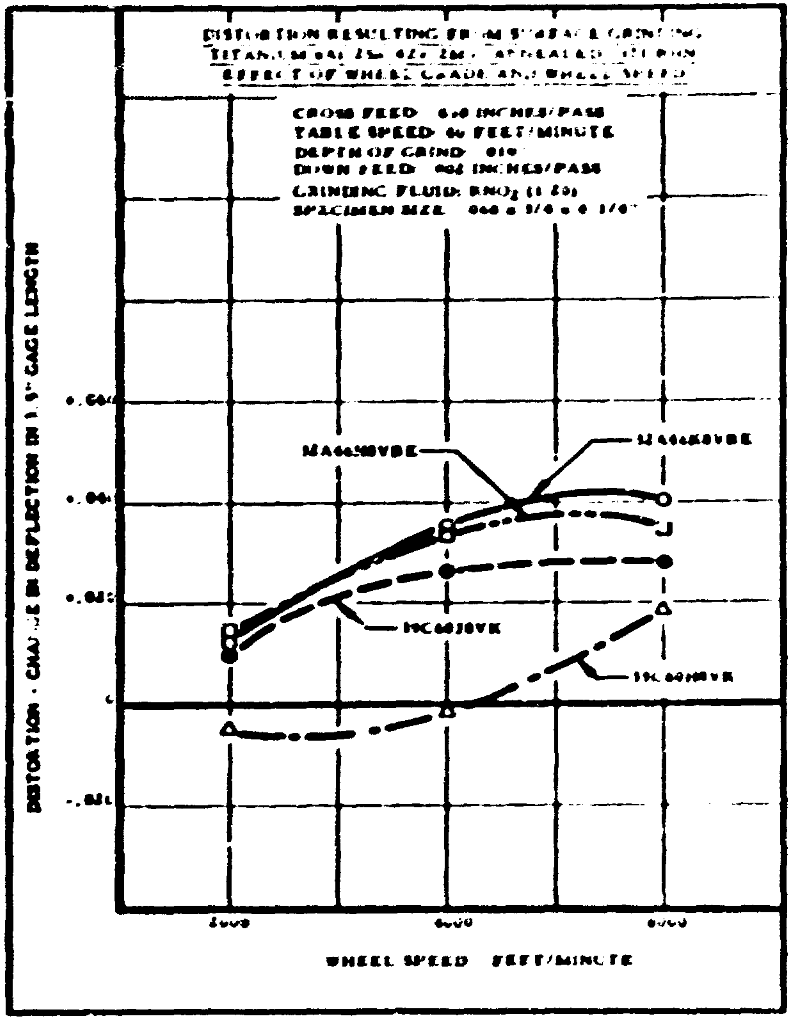
Figure [illegible]



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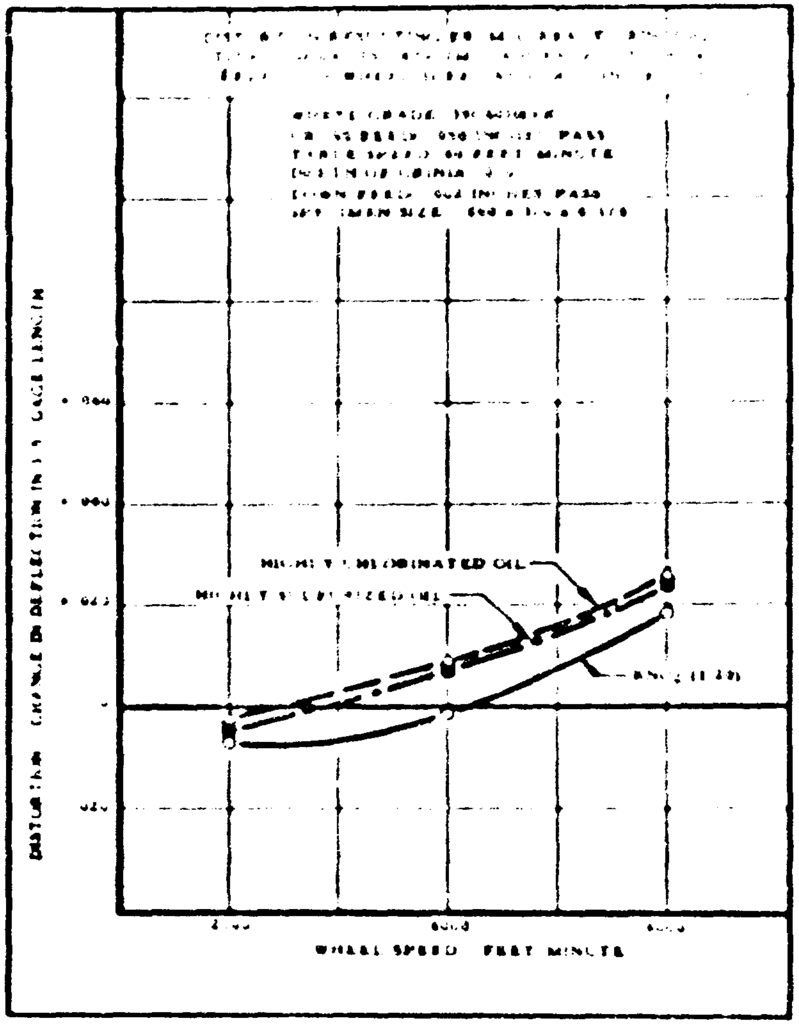

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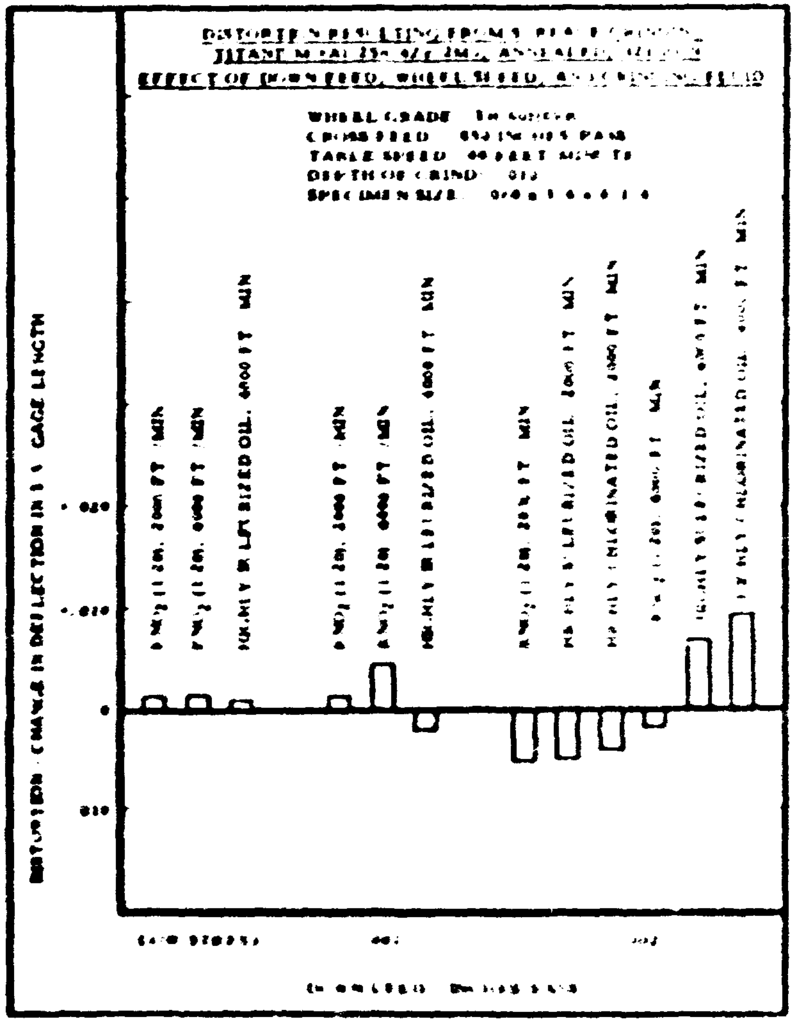
Figure [illegible]


DISTORTION RESULTING FROM SURFACE GRINDING
TITANIUM ALLOY (Ti-6Al-4V) ANNEALED
EFFECT OF DOWNFEED, WHEEL SPEED, AND GRINDING FLUID
WHEEL GRADE
CROSSFEED .050 INCHES/PASS
TABLE SPEED 40 FEET/MINUTE
DEPTH OF GRIND .012
SPECIMEN SIZE
KNO2 (1 1/2% SOL.) 2000 FT/MIN
KNO2 (1 1/2% SOL.) 6000 FT/MIN
HIGHLY SULFURIZED OIL, 6000 FT/MIN
KNO2 (1 1/2% SOL.) 2000 FT/MIN
KNO2 (1 1/2% SOL.) 6000 FT/MIN
HIGHLY SULFURIZED OIL, 6000 FT/MIN
KNO2 (1 1/2% SOL.) 2000 FT/MIN
HIGHLY SULFURIZED OIL, 2000 FT/MIN
HIGHLY CHLORINATED OIL, 2000 FT/MIN
KNO2 (1 1/2% SOL.) 6000 FT/MIN
HIGHLY SULFURIZED OIL, 6000 FT/MIN
HIGHLY CHLORINATED OIL, 6000 FT/MIN
DISTORTION - CHANGE IN DEFLECTION IN 3" GAGE LENGTH
+.020
+.010
0
.010
LOW STRESS
.002
DOWNFEED, INCHES/PASS

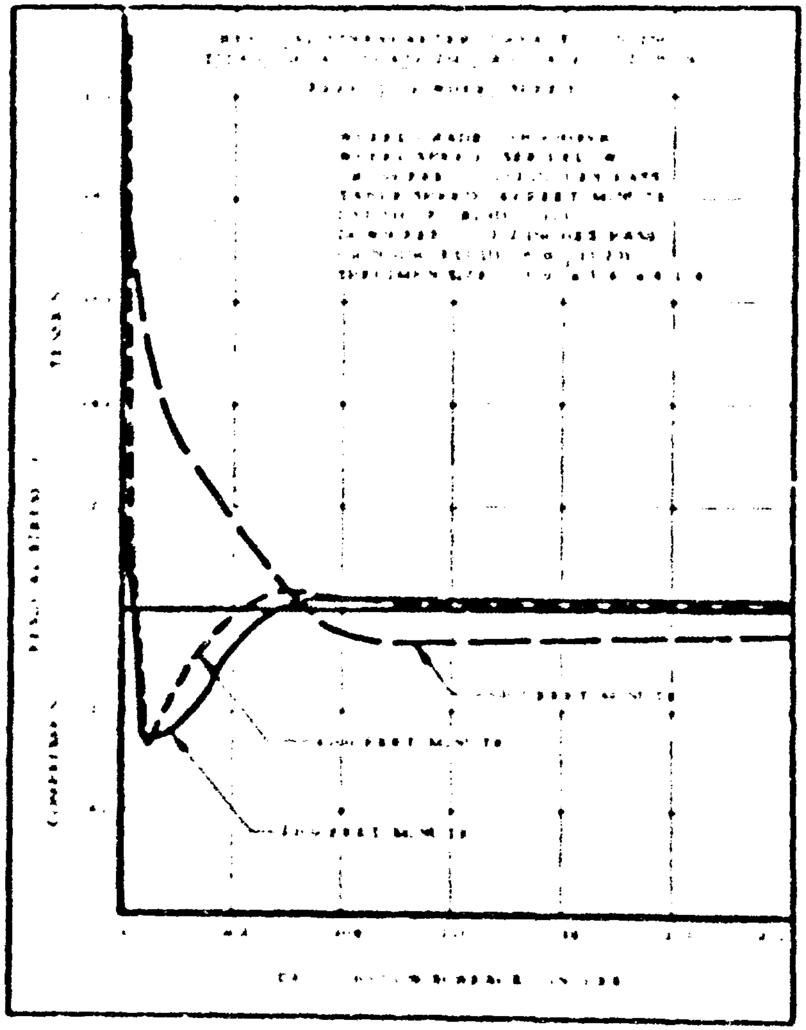
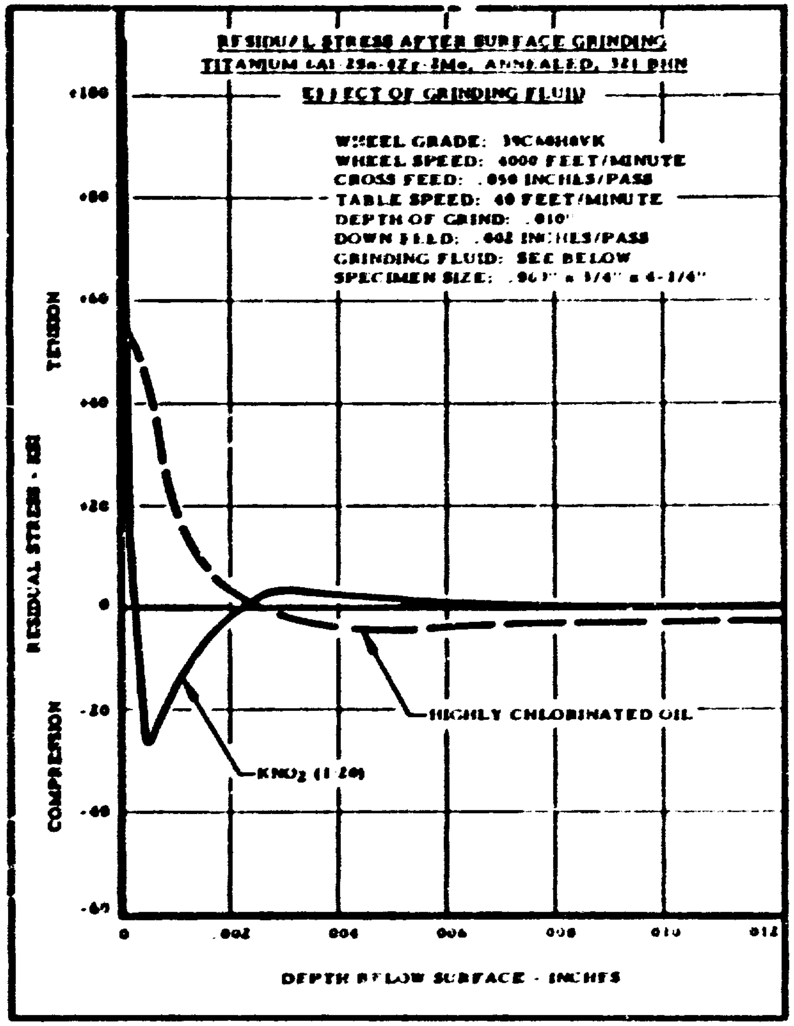
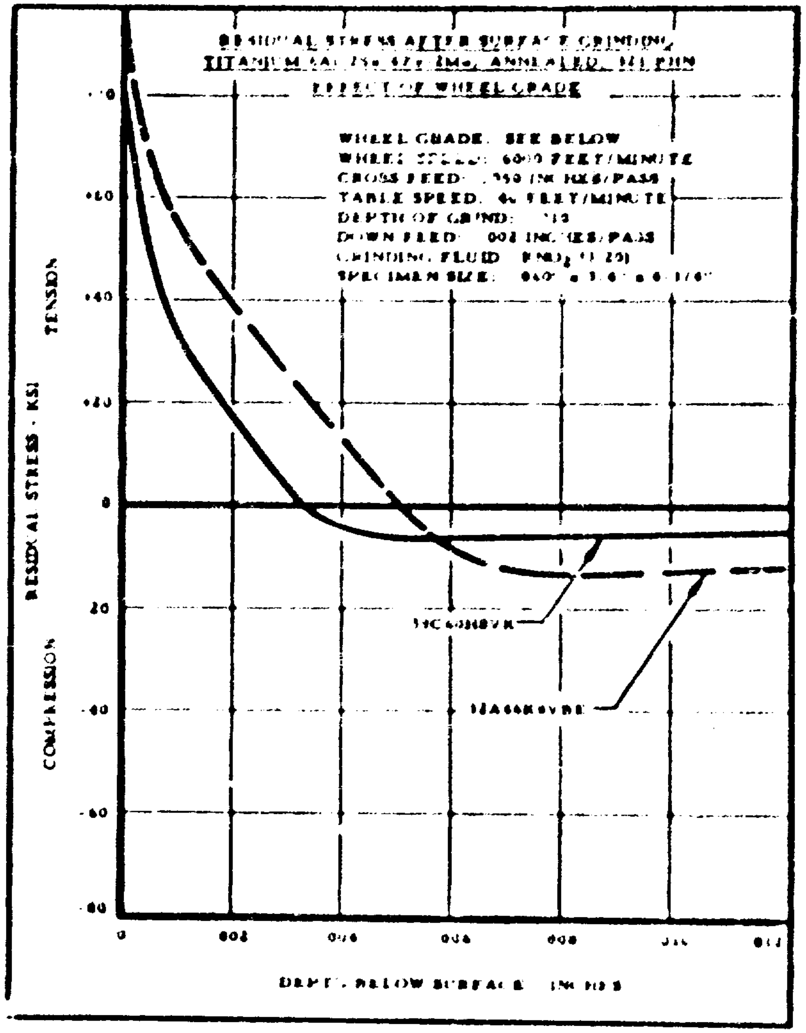


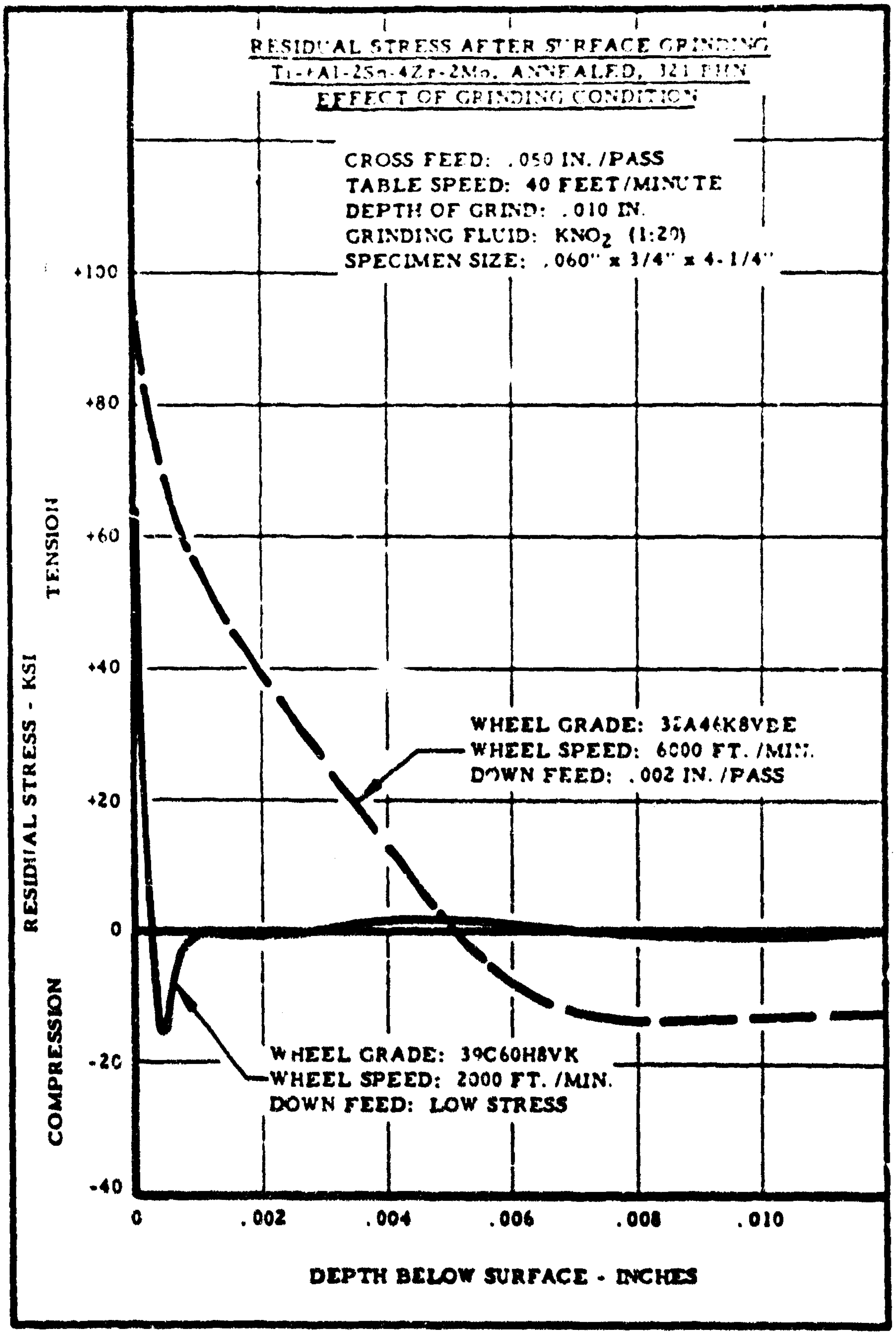
TABLE SPEED 40 FEET/MINUTE
TENSION
COMPRESSION
FEET/MINUTE
FEET/MINUTE
FEET/MINUTE



See text, page 25 Figure 284



See text, page 25 Figure 285



See text, page 256

Figure 286

7.4 Inconel 625, Annealed, 200 BHN

Face Milling - Carbide Cutter

Annealed Inconel 625 of 200 BHN was face milled with C-2 (883) carbide at two different depths of cut and three wearland conditions. Highly chlorinated oil was used as the cutting fluid for all tests. The distortion and residual stress results are found in Figure 287, 288 and 289, pages 274 and 275.

With a 0.010 in. depth of cut, a sharp tool gave the least distortion, the greatest distortion with 0.016 in. wearland, and intermediate distortion at 0.032 in. wearland, see Figure 287, page 274. When the depth of cut was increased to 0.040 in., the distortion was about the same for all wearland conditions.

Residual stress curves for the three wearland levels and a 0.010 in. depth of cut are shown in Figure 288, page 274. The deflection values indicated the major portion of stress in the outer layers as compressive; however, it will be noted that all three curves showed a tensile stress at the surface. Only at depths greater than .001-.002 in. below the surface did compressive stresses prevail. A sharp cutter (.000 in. wearland) restricted the major stress to within 0.010 in. of the surface, while the greater wearlands exhibited compressive stresses at depths greater than this.

Two residual stress curves for a 0.040 in. depth of cut are shown in Figure 289, page 275, the one for a sharp cutter and the other with a 0.016 in. wearland. The curves are quite similar, except for the portion near the surface (less than 0.001 in. below the surface) where some tensile stresses were found in the 0.016 in. wearland specimen.

The surface roughness values of the carbide milled surfaces are listed in Table XXVI.

Face Milling - HSS Cutter

Face milling with a T15 HSS cutter involved using two different depths of cut and three different wearland conditions. The resulting distortions are shown in Figure 290, page 275. At 0.016 in. and 0.032 in. wearlands, the distortions produced were about the same. A sharp cutting tool with a shallow cut (.010 in.) gave less distortion than did the deeper cut (.040 in.).

Residual stress patterns did not differ greatly as may be seen in Figures 291 and 292, page 276. A sharp cutting tool with both a

7.4 Inconel 625, Annealed, 200 BHN (continued)

Face Milling - HSS Cutter (continued)

.010 in. and a .040 in. depth of cut produced some tensile stresses on the surface and a maximum compressive stress of approximately 18,000 psi at 0.001 in. below the surface. In general, the maximum stresses were not very large, but did extend to about .010 in. below the surface.

Table XXVII indicates the surface roughness of the specimens used.

Surface Grinding

The effect of grinding Inconel 625 with aluminum oxide grinding wheels of various hardness values and at various wheel speeds was investigated. Most of the work was done with highly sulfurized oil as the grinding fluid, however, a few tests were run using no fluid, a KNO_2 solution, and a highly chlorinated oil. The distortion results are presented in Figures 293 and 294, page 277, and the residual stresses in Figures 295 and 296, page 278.

The softer "H" wheel gave the least distortion at all wheel speeds; see Figure 293, page 277. The "J" and "L" grades produced about the same degree of distortion. As the wheel speed increases, the distortions tend to increase, with the increase being less for the wheel speed interval 4000 to 6000 feet/minute than the interval 2000 to 4000 feet/minute when the H and J wheels were used.

The residual stress curves in Figure 295, page 278, are in general agreement with the distortion results for the case of a 32A46J8VBE wheel at speeds of 2000, 4000, and 6000 feet/minute.

When the wheel hardness was increased from the H grade to the J grade, the major effect on the residual stress curve was one of extending the tensile stressed layer deeper within the sample; see Figure 296, page 278.

In Figure 297, page 279, the changes in residual stress curves with changing down feed conditions may be observed. When a "low stress" down feed was used, the stress values were lowest and the depth of penetration was less.

A summary of the distortions produced when surface grinding with a 32A46J8VBE wheel under various conditions of down feeds, wheel speeds, and grinding fluids may be found in Figure 294, page 277.

7.4 Inconel 625, Annealed 200 BHN (continued)

Surface Grinding (continued)

At a wheel speed of 4000 feet/minute and a down feed of .001 in./pass, highly chlorinated oil gave the greatest distortion with KNO_2 solution the least. The highly sulfurized oil produced intermediate distortion. Minimum distortion was produced using the low stress down feed.

In Figure 298, page 279, the residual stress curves are given for the two extreme grinding conditions. The more abusive conditions of a harder wheel (L grade), greater down feed (.002 in./pass), high wheel speed (6000 feet/minute) and cutting dry can be compared to the results when a softer wheel (J grade), low stress down feed, a lower wheel speed of 4000 feet/minute, and a grinding fluid were used.

Surface roughness readings were made on all the test ground surfaces. These results are tabulated in Table XXVIII.

The surface finish obtained in grinding the Inconel 625 alloy averaged about 8 microinches AA in a direction parallel to the grind and 15 to 25 microinches AA perpendicular to the grind direction.

TABLE XXVI

SURFACE ROUGHNESS PRODUCED BY FACE MILLING
INCONEL 625, ANNEALED, 200 BHN

Cutter: 4" Dia. Single Tooth Face Mill with
C-2 (883) Carbide

AR:	5°	Incl.:	0°
RR:	5°	ECEA:	0° land
CA:	45°	Clearance:	5°
TR:	7°		

Cutting Speed: 73 feet/minute
Feed: .010 inches/tooth

Cutting Fluid	Depth of Cut (Inches)	Wearland (Inches)	Surface Finish - Microinches AA Parallel to Cutting Direction	Surface Finish - Microinches AA Perpendicular to Cutting Direction
Highly Chlorinated Oil	.010	0	13-16	17-22
		.016	5-7	35-40
		.032	5-7	70-85
	.040	0	5-8	13-15
		.016	6-12	27-33
		.032	5-7	30-38

TABLE XXVII

SURFACE ROUGHNESS PRODUCED BY FACE MILLING

INCONEL 625, ANNEALED, 200 BHN

Cutter: 4" Dia. Single Tooth Face Mill with
T15 HSS

AR:	5°	Incl.:	-7°
RR:	15°	ECEA:	0° land
CA:	45°	Clearance:	10°
TR:	14°		

Cutting Speed: 38 feet/minute
Feed: .010 inches/tooth

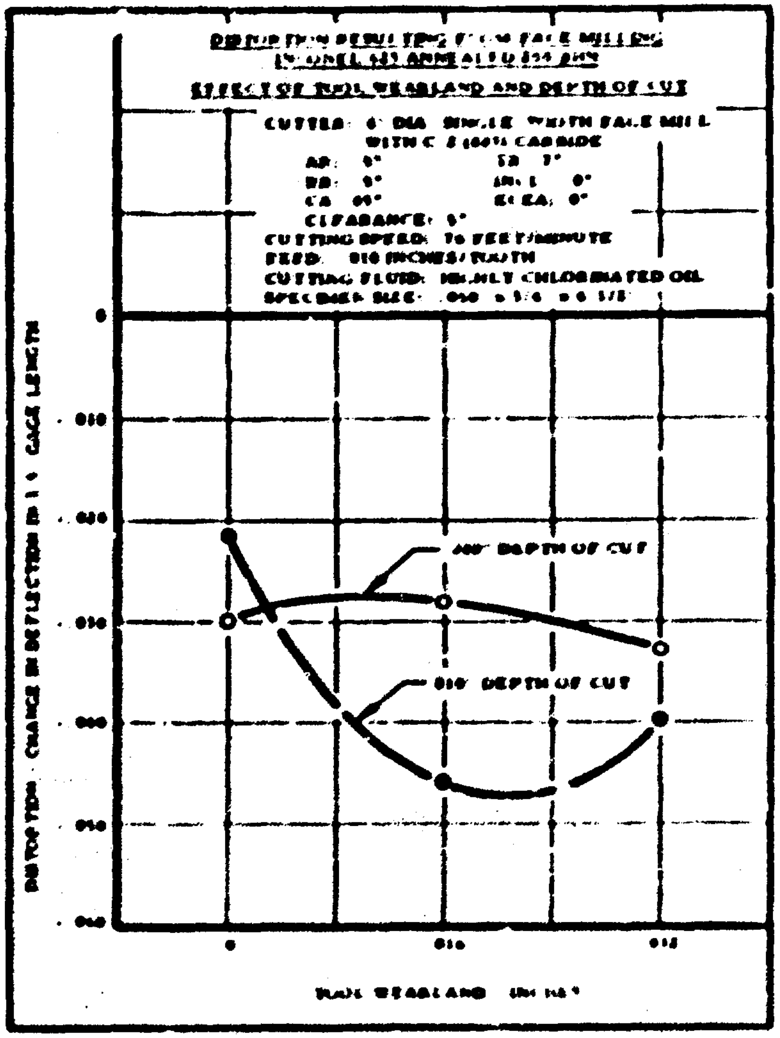
			Surface Finish - Microinches AA	
Cutting Fluid	Depth of Cut (Inches)	Wearland (Inches)	Parallel to Cutting Direction	Perpendicular to Cutting Direction
Highly Chlorinated Oil	.010	0	15-22	60-80
		.016	5-8	13-17
		.032	5-7	11-14
	.040	0	9-12	70-85
		.016	8-11	18-22
		.032	6-8	12-14

TABLE XXVIII

SURFACE ROUGHNESS PRODUCED BY SURFACE GRINDING
INCONEL 625, ANNEALED, 200 BHN

Cross Speed: .050 inches/pass
Table Speed: 40 feet/minute
Depth of Grind: .010 in.

Wheel	Down Feed (Inches)	Cutting Fluid	Wheel Speed	Surface Finish - Microinches AA Parallel to Grinding Direction	Surface Finish - Microinches AA Perpendicular to Grinding Direction
32A46H8VBE	.001	Highly Sulfurized Oil	2000	6-9	13-17
			4000	6-7	17-22
			6000	6-8	24-27
32A46J8VBE	.001	Highly Sulfurized Oil	2000	5-7	20-24
			4000	5-7	17-22
			6000	5-8	22-28
32A46L8VBE	.001	Highly Sulfurized Oil	2000	4-6	20-24
			4000	4-7	15-18
			6000	5-6	13-17
32A46J8VBE	LS	Highly Sulfurized Oil	4000	4-7	10-12
	.002	Highly Sulfurized Oil	4000	4-6	18-23
	.001	Highly Chlorinated Oil	4000	5-6	12-15
	.001	KNO_2(1:20)	4000	7-9	15-17
32A46L8VBE	.002	Dry	6000	9-13	22-27



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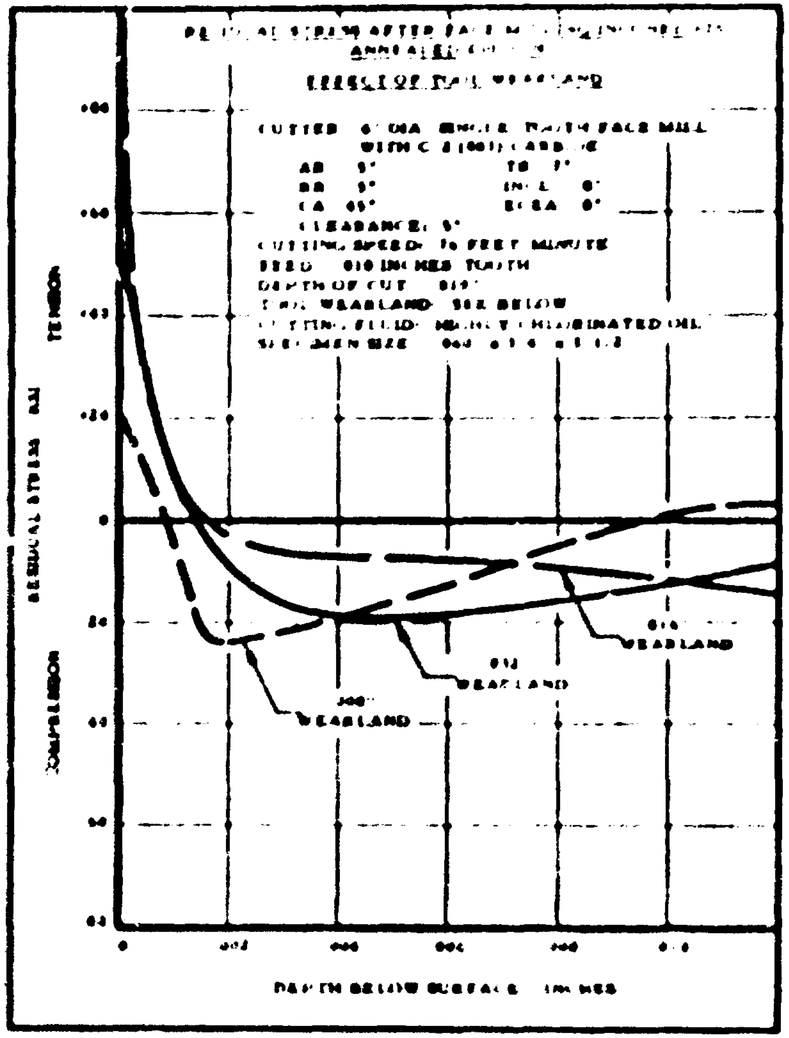

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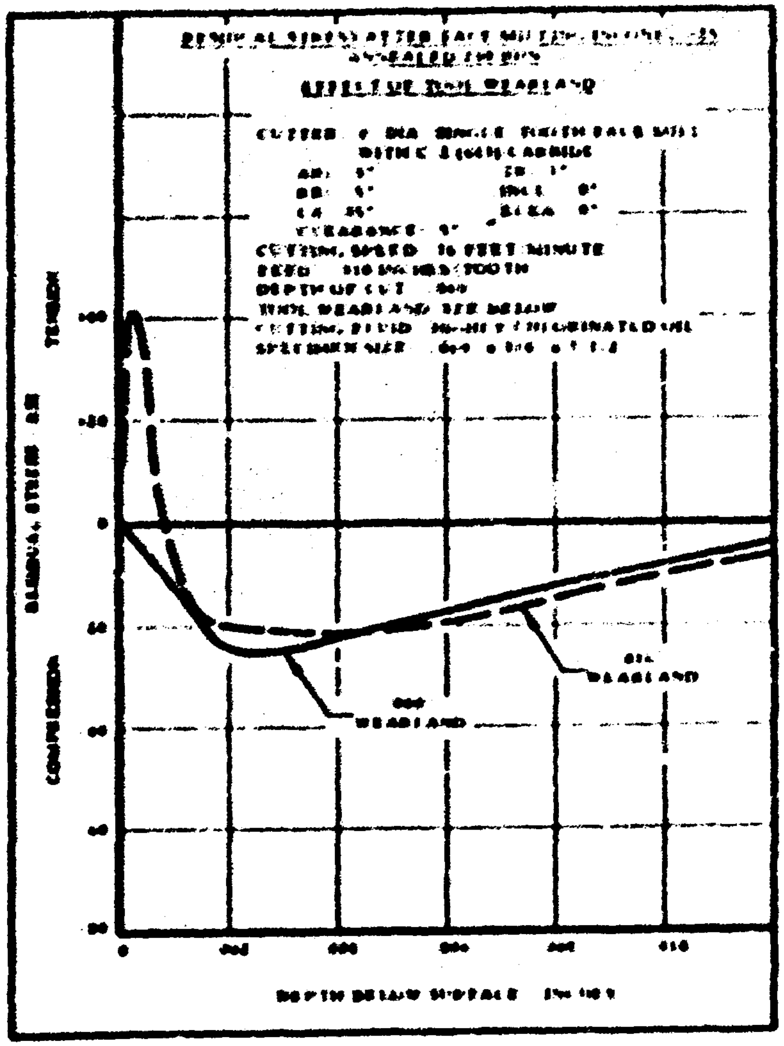

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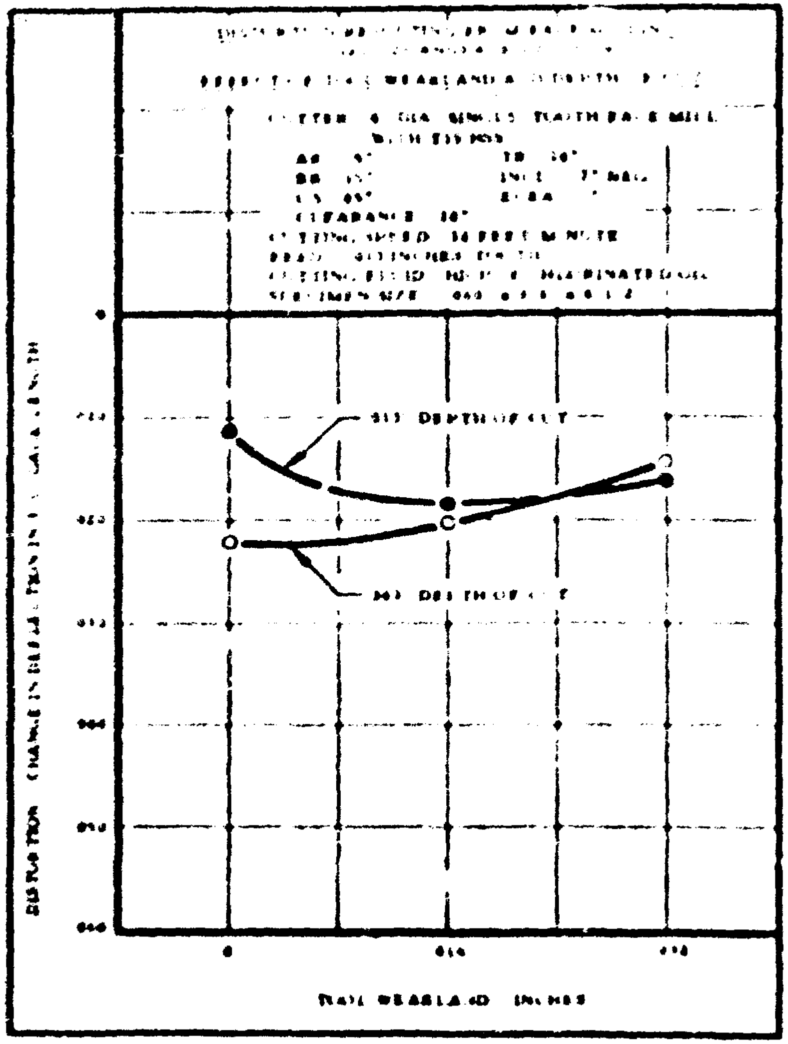

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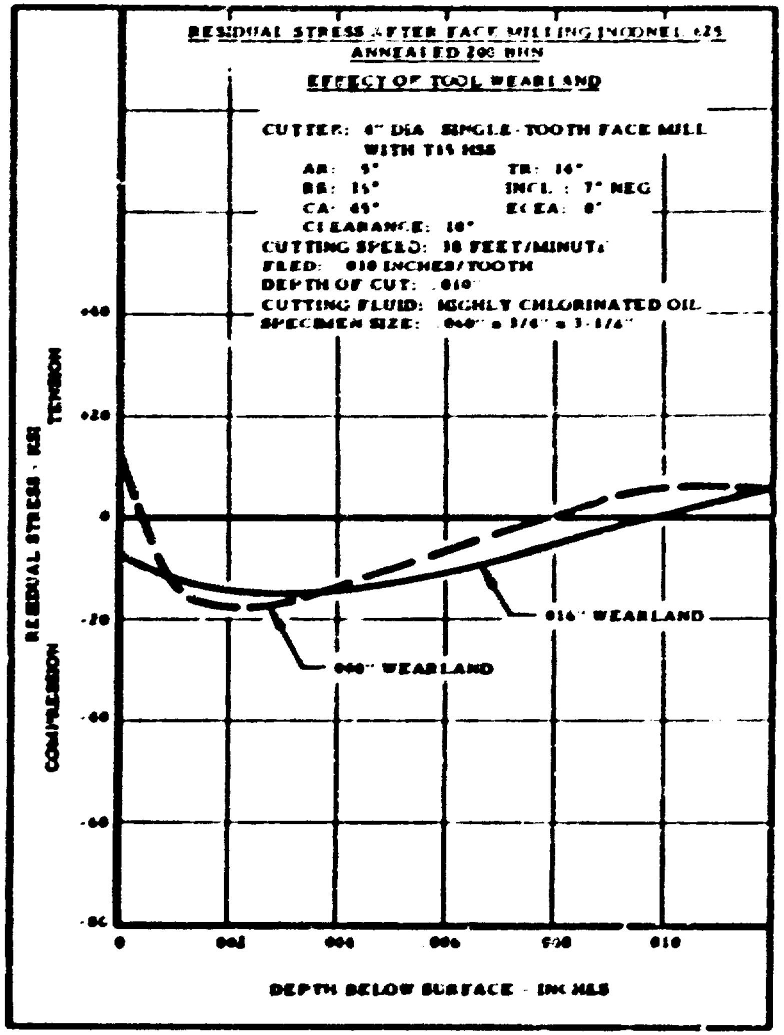

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Figure 291

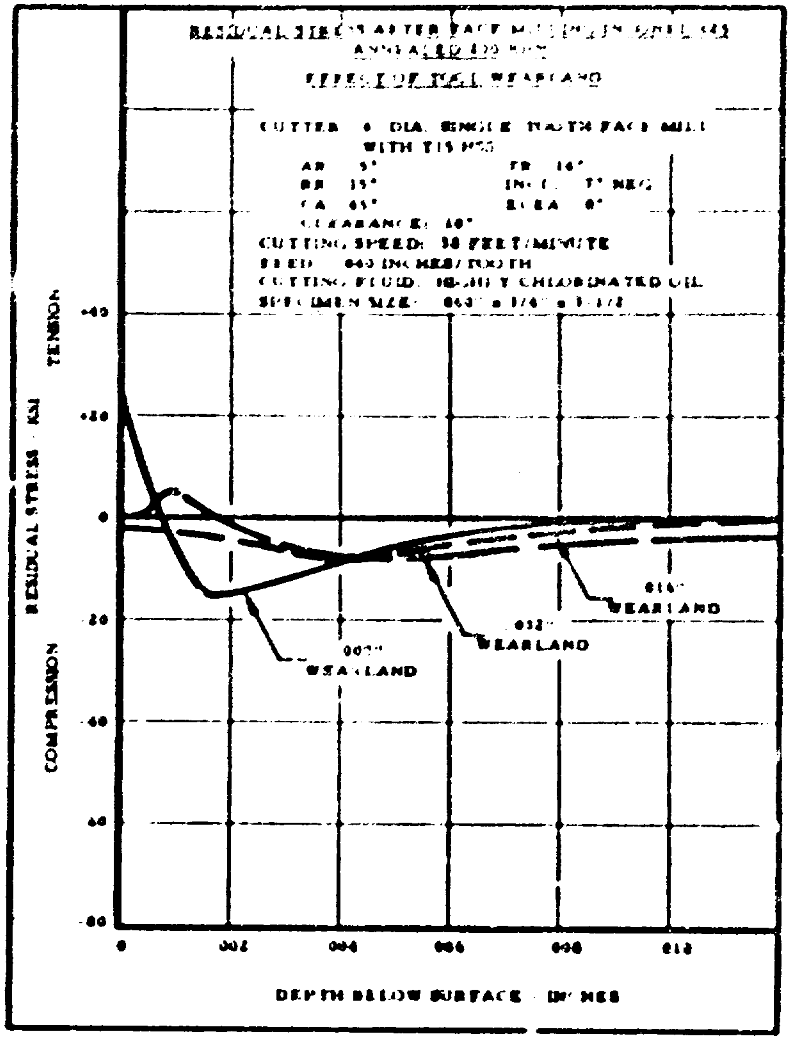

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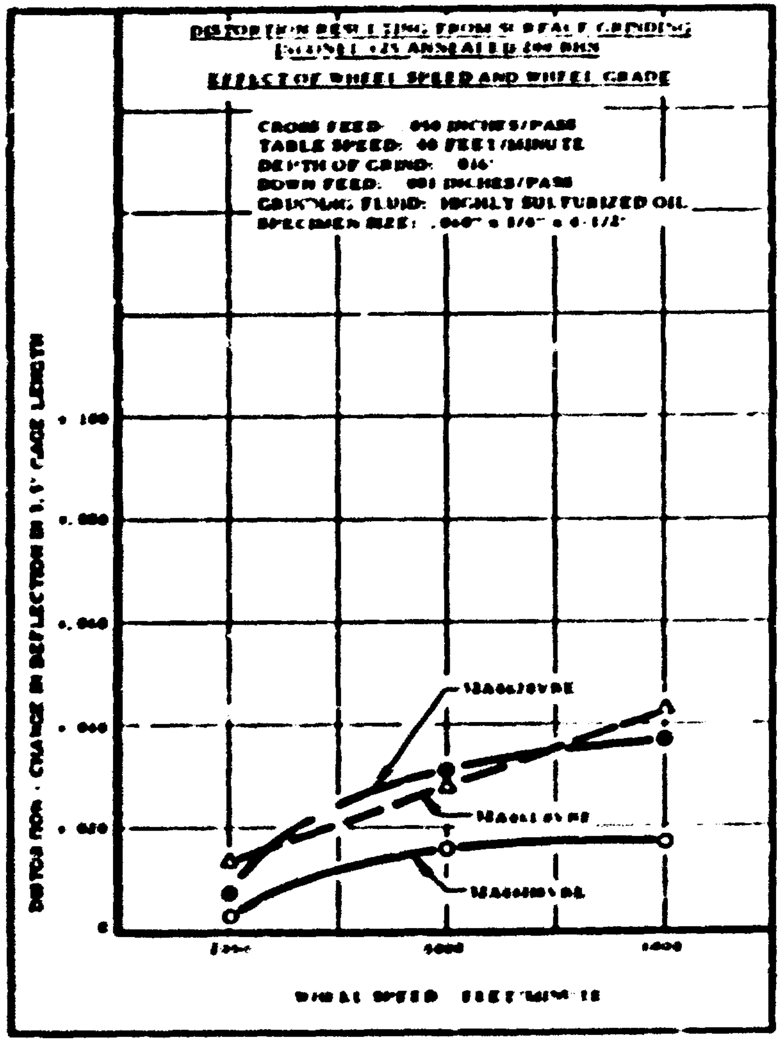
Figure 292



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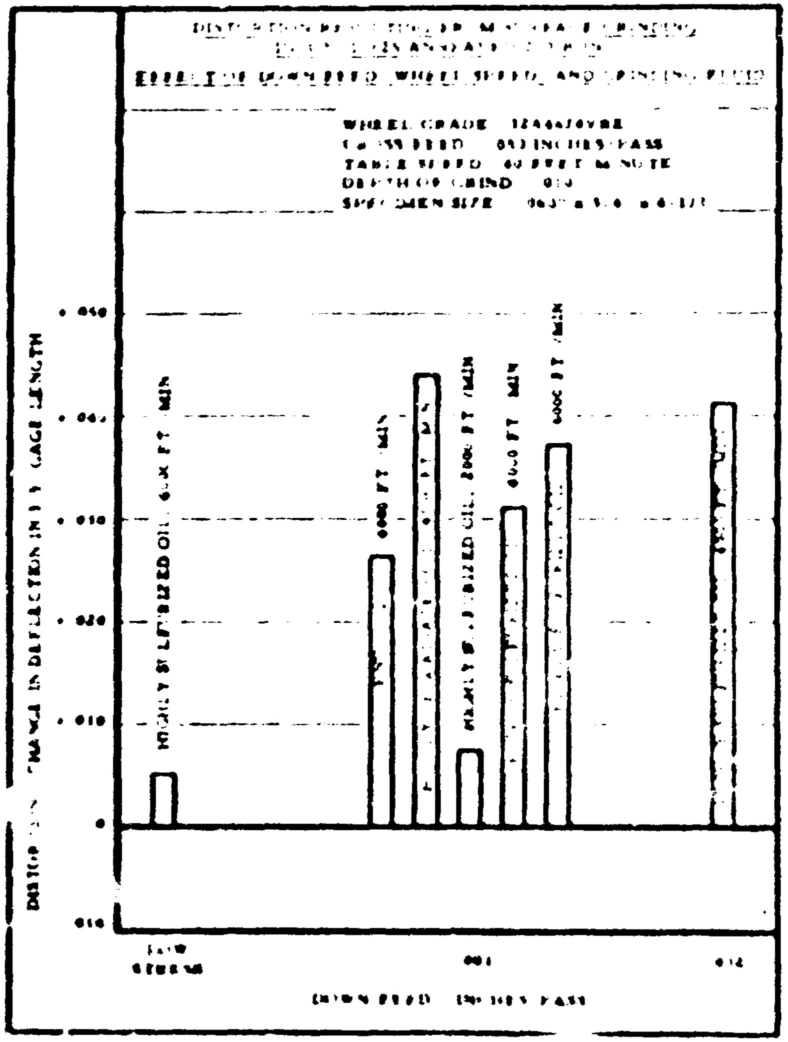

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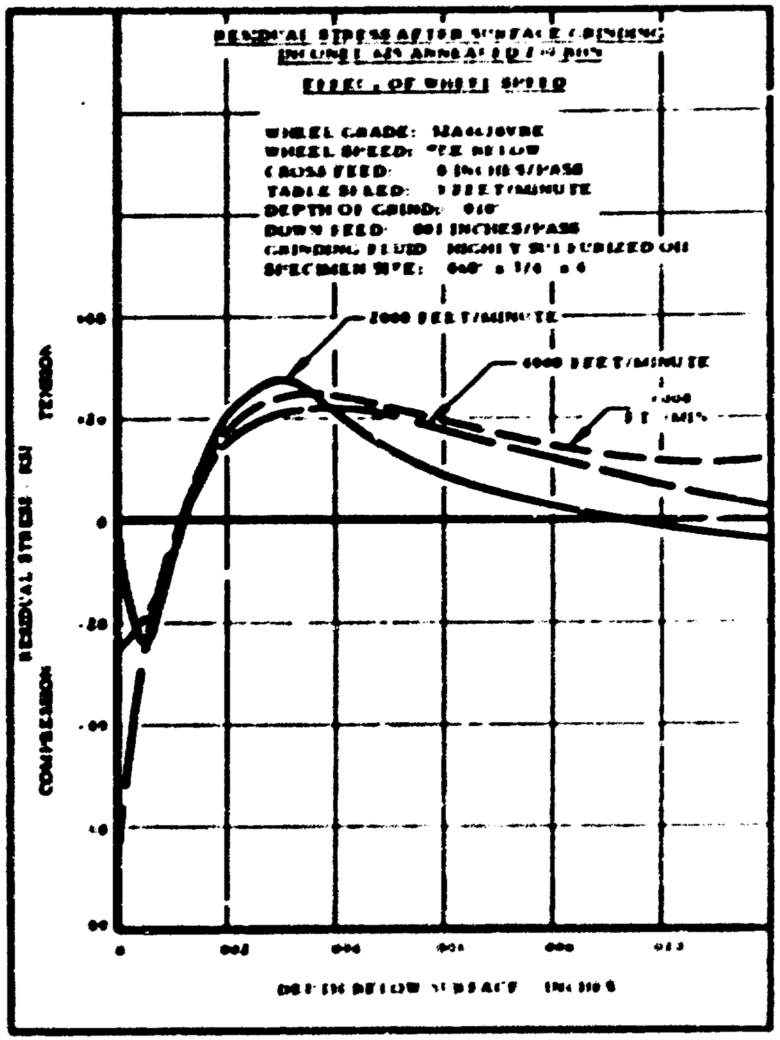

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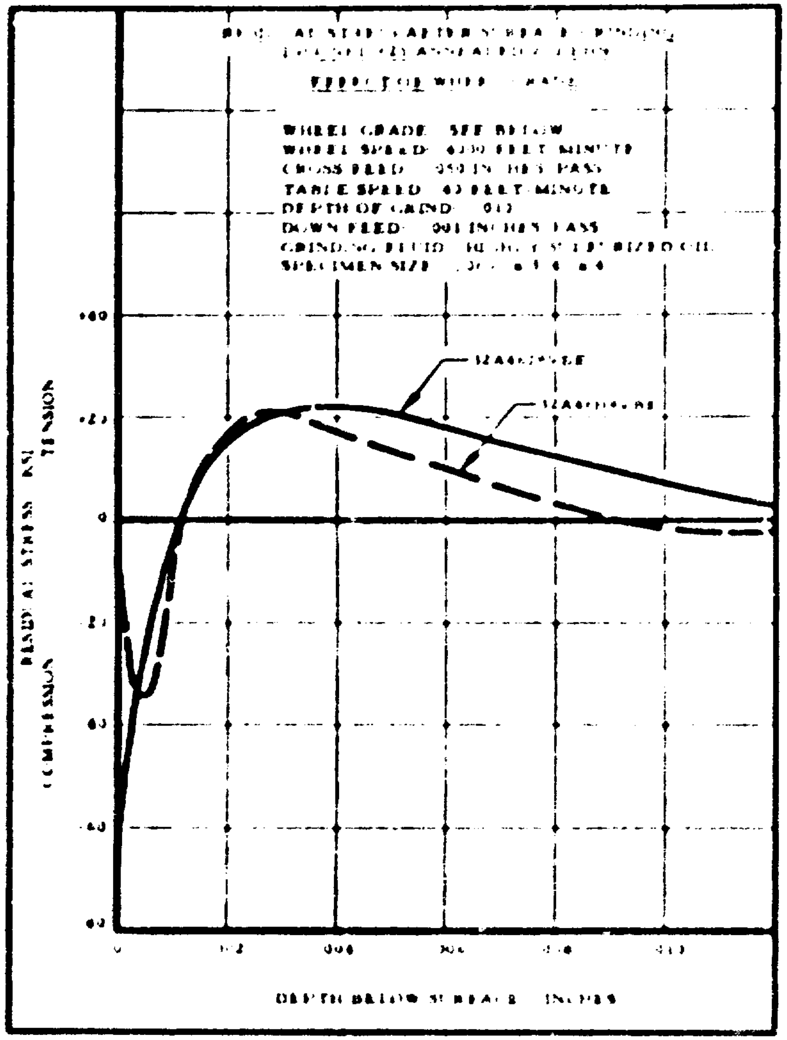

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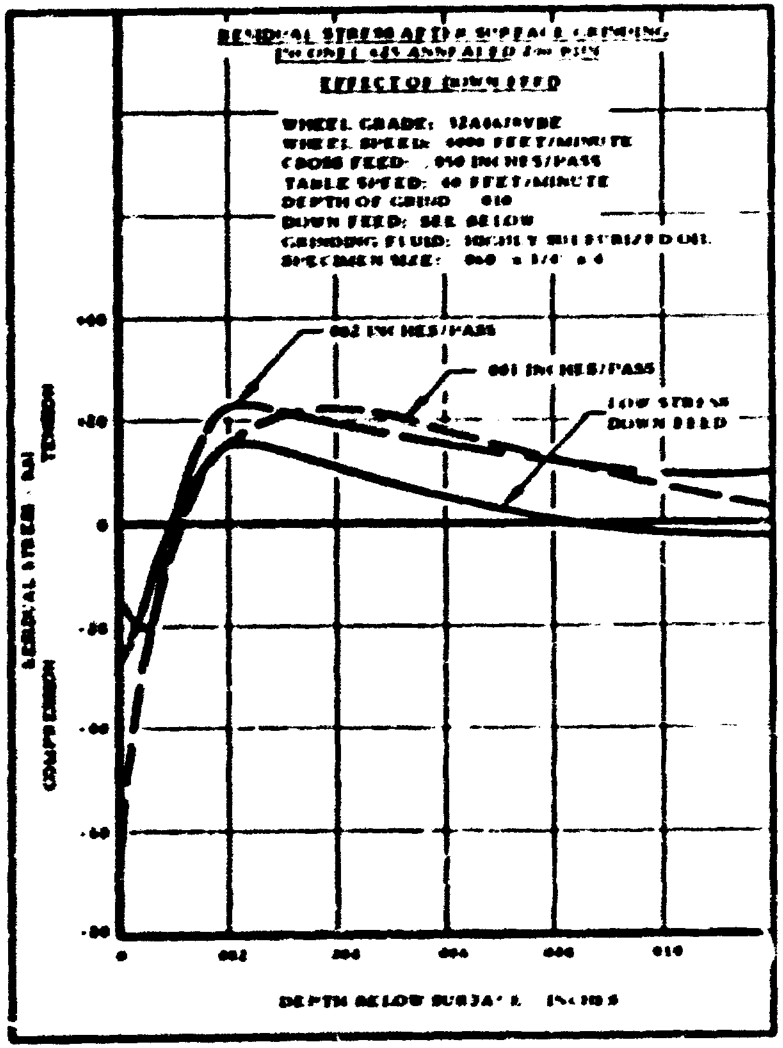

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Figure 241

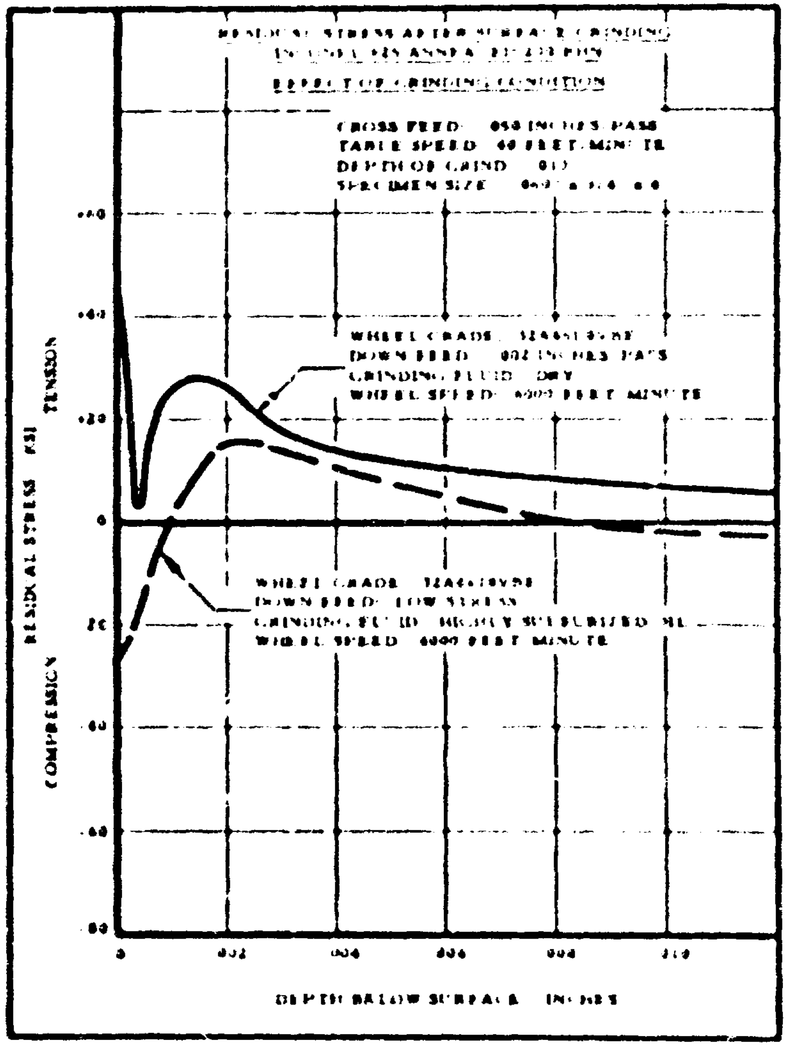

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Figure 240

8. SURFACE FINISH

The surface finishes obtained in face milling, peripheral end milling, and end mill slotting on most of the metals tested in this program are listed in Tables XXIX through XXXI, pages 281 through 287. These measurements were made with a Surfindicator instrument both at the start and end of the tool life tests in which reasonable tool life values were obtained. In general, the high speed steel tools had a wear land of .060 in. and the carbide .015 in. at the end of the tests. It should be noted that the qualities of the surface finishes at the end of the tests with the worn tools were often better than with a sharp tool. Whether the quality of the surface finish improves or deteriorates as the tool dulls depends on the workpiece material and the type of wear that develops on the tool.

TABLE XXIX

SURFACE FINISH MEASUREMENTS IN FACE MILLING

Work Material	Tool Material	Tool Geometry		Cutting Speed ft./min.	Feed in./tooth	Cutting Fluid	Surface Finish microin. AA	
							Sharp Tool	Dull Tool
HP9-4-45 Steel Normalized 341 BHN	M2 HSS	AR: 5° RR: 5°	CA: 45°	160	.003	Soluble Oil 1:20	150	200
	C-6 Carbide	AR: -5° RR: -5°	CA: 45°	350	.005	Dry	150	160
18% Ni Cast Maraging Steel Solution Treated 331 BHN	M2 HSS	AR: 5° RR: 5°	CA: 45°	225	.005	Soluble Oil 1:20	30	45
	C-2 Carbide	AR: -5° RR: -5°	CA: 45°	500	.005	Dry	40	50
17-4 PH Cast Solution Treated and Aged 415 BHN	M42 HSS	AR: 5° RR: 5°	CA: 45°	100	.005	Soluble Oil 1:20	15	25
	C-2 Carbide	AR: -5° RR: -5°	CA: 45°	300	.007	Dry	125	175
Ti 6Al-4V Beta Forged 331 BHN	M42 HSS	AR: 5° RR: 5°	CA: 45°	70	.003	Soluble Oil 1:20	40	50
	C-2 Carbide	AR: -5° RR: -5°	CA: 45°	220	.005	Phosphated Oil 1:20	125	145
Ti 6Al-4V As Cast 341 BHN	M2 HSS	AR: 5° RR: 5°	CA: 45°	80	.005	Chemical Emulsion 1:20	60	50
	C-2 Carbide	AR: -5° RR: -5°	CA: 45°	160	.003	Dry	125	120

TABLE XXIX (continued)

SURFACE FINISH MEASUREMENTS IN FACE MILLING

Work Material	Tool Material	Tool Geometry	Cutting Speed ft./min.	Feed in./tooth	Cutting Fluid	Surface Finish micro-in. - AA	
						Sharp Tool	Dull Tool
Inconel 625 Annealed 277 BHN	M2 HSS	AR: 5° RR: 5° CA: 45°	26	.006	Chlorinated Oil	40	65
Greek Ascoloy Quenched and Tempered 352 BHN	M42 HSS	AR: 5° RR: 5° CA: 45°	110	.008	Soluble Oil 1:20	110	125
	C-2 Carbide	AR: -5° RR: -5° CA: 45°	350	.005	Chlorinated Oil	175	150

TABLE XXX

SURFACE FINISH MEASUREMENTS IN PERIPHERAL END MILLING

Work Material	Tool Material	Tool Geometry	Cutting Speed ft./min.	Feed in./tooth	Cutting Fluid	Surface Finish microin. - AA	
						Sharp Tool	Dull Tool
HP9-4-45 Steel Normalized 341 BHN	M2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	225	.003	Soluble Oil 1:20	27	30
18% Ni Cast Maraging Steel Solution Treated 331 BHN	M2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	275	.005	Soluble Oil 1:20	35	50
17-4 PH Cast Solution Treated and Aged 415 BHN	M42 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	175	.003	Chlorinated Oil	30	40
Almar 362 Annealed 248 BHN	M42 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	250	.004	Soluble Oil 1:20	45	100
Almar 362 Annealed and Temper Aged 375 BHN	M42 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	100	.003	Soluble Oil 1:20	20	60

TABLE XXX (continued)

SURFACE FINISH MEASUREMENTS IN PERIPHERAL END MILLING

Work Material	Tool Material	Tool Geometry	Cutting Speed ft./min.	Feed in./tooth	Cutting Fluid	Surface Finish microin. - AA	
						Sharp Tool	Dull Tool
Ti 6Al-4V Beta Forged 331 BHN	M42 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	150	.004	Soluble Oil 1:20	35	50
Ti 6Al-4V As Cast 341 BHN	M42 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	165	.002	Chemical Emulsion 1:20	25	35
Ti 679 Solution Treat and Aged 352 BHN	M42 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	225	.002	Chemical Emulsion 1:20	30	35
Inconel 718 Solution Treated and Aged 45 R_c	M42 HSS	Helix Angle. 30° RR: 10° CA: 45° x .060"	15	.0025	Chlorinated Oil	55	70
Greek Ascoloy Quenched and Tempered 352 BHN	M42 HSS	Helix Angle: 30° RR: 19° CA: 45° x .060"	200	.003	Soluble Oil 1:20	55	65

TABLE XXX (continued)

SURFACE FINISH MEASUREMENTS IN PERIPHERAL END MILLING

Work Material	Tool Material	Tool Geometry	Cutting Speed ft./min.	Feed in./tooth	Cutting Fluid	Surface Finish microin. - AA	
						Sharp Tool	Dull Tool
Udimet 700 As Cast 302 BHN	M42 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	15	.004	Chlorinated Oil	150	275

TABLE XXXI

SURFACE FINISH MEASUREMENTS IN END MILL SLOTTING

Work Material	Tool Material	Tool Geometry	Cutting Speed ft./min.	Feed in./tooth	Cutting Fluid	Surface Finish microin. - AA	
						Sharp Tool	Dull Tool
HP9-4-45 Steel Normalized	**M2 HSS**	**Helix Angle: 30° RR: 10° CA: 45° x .060"**	150	.002	Soluble Oil 1:20	125	120
17-4 PH Cast Solution Treated and Aged 415 BHN	**M42 HSS**	**Helix Angle: 30° RR: 10° CA: 45° x .060"**	110	.003	Chlorinated Soluble Oil 1:20	70	70
Ti 6Al-4V Beta Forged 331 BHN	**M42 HSS**	**Helix Angle: 15° RR: 10° CA: 45° x .060"**	115	.002	Soluble Oil 20	30	40
Ti 6Al-4V As Cast 341 BHN	**M42 HSS**	**Helix Angle: 30° RR: 10° CA: 45° x .060"**	100	.002	Chemical Emulsion 1:20	35	45
Ti 6Al-2 Sn-4Zr-2Mo Solution Treated and Aged 321 BHN	**M42 HSS**	**Helix Angle: 30° RR: 10° CA: 45° x .060"**	150	.0015	Soluble Oil 1:20	45	45

TABLE XXXI (continued)

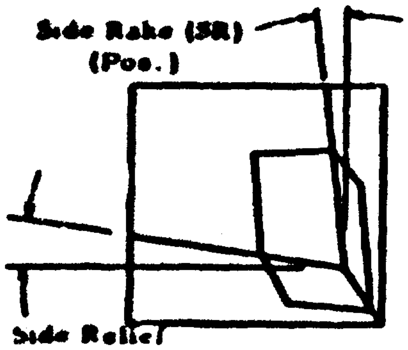
SURFACE FINISH MEASUREMENTS IN END MILL SLOTTING

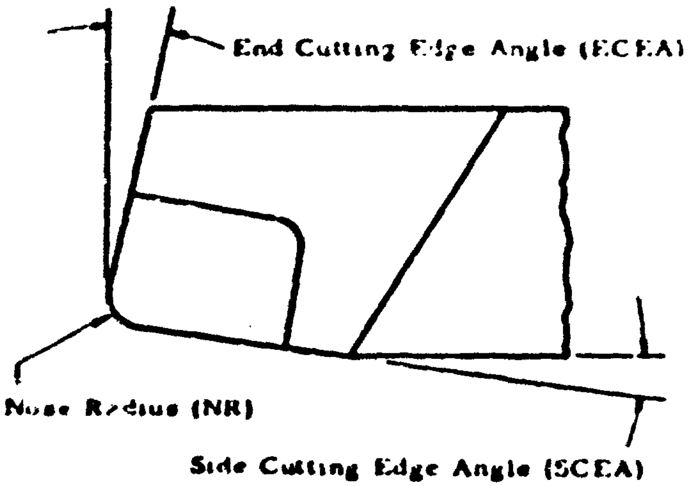
Work Material	Tool Material	Tool Geometry	Cutting Speed ft./min.	Feed in./tooth	Cutting Fluid	Surface Finish microin. - AA	
						Sharp Tool	Dull Tool
Inconel 625 Annealed 277 BHN	M2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	40	.002	Chlorinated Oil	40	45
Greek Ascoloy Quenched and Tempered 352 BHN	M42 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	100	.002	Soluble Oil 1:20	40	80
Udimet 700 As Cast 302 BHN	M42 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	15	.002	Chlorinated Oil	40	50
Inconel 718 Cast 207 BHN	M42 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	20	.002	Chlorinated Oil	100	115

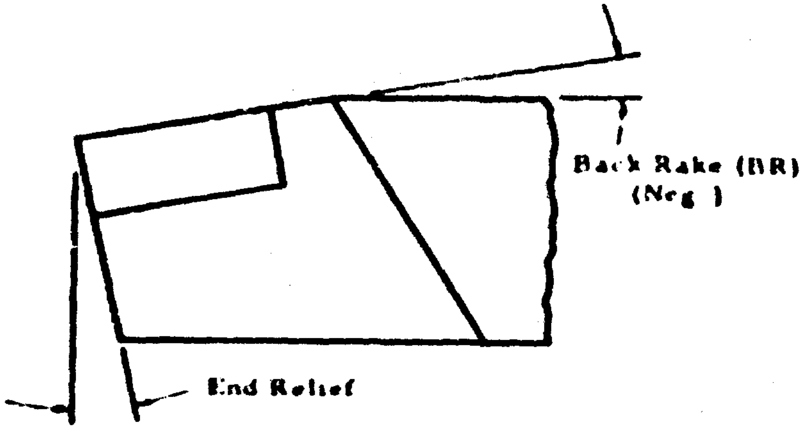
9. APPENDICES

APPENDIX I

LATHE TOOL NOMENCLATURE

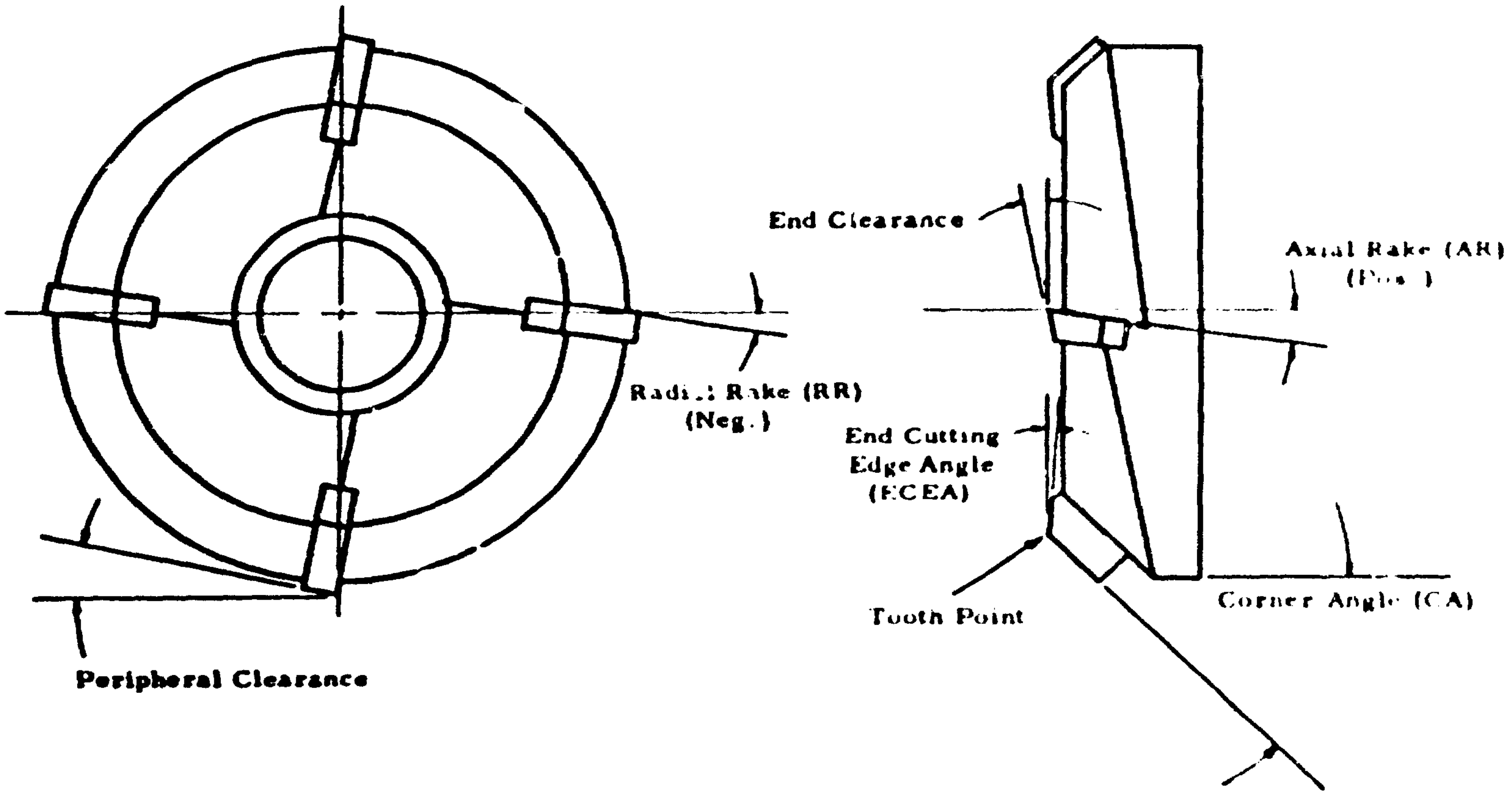






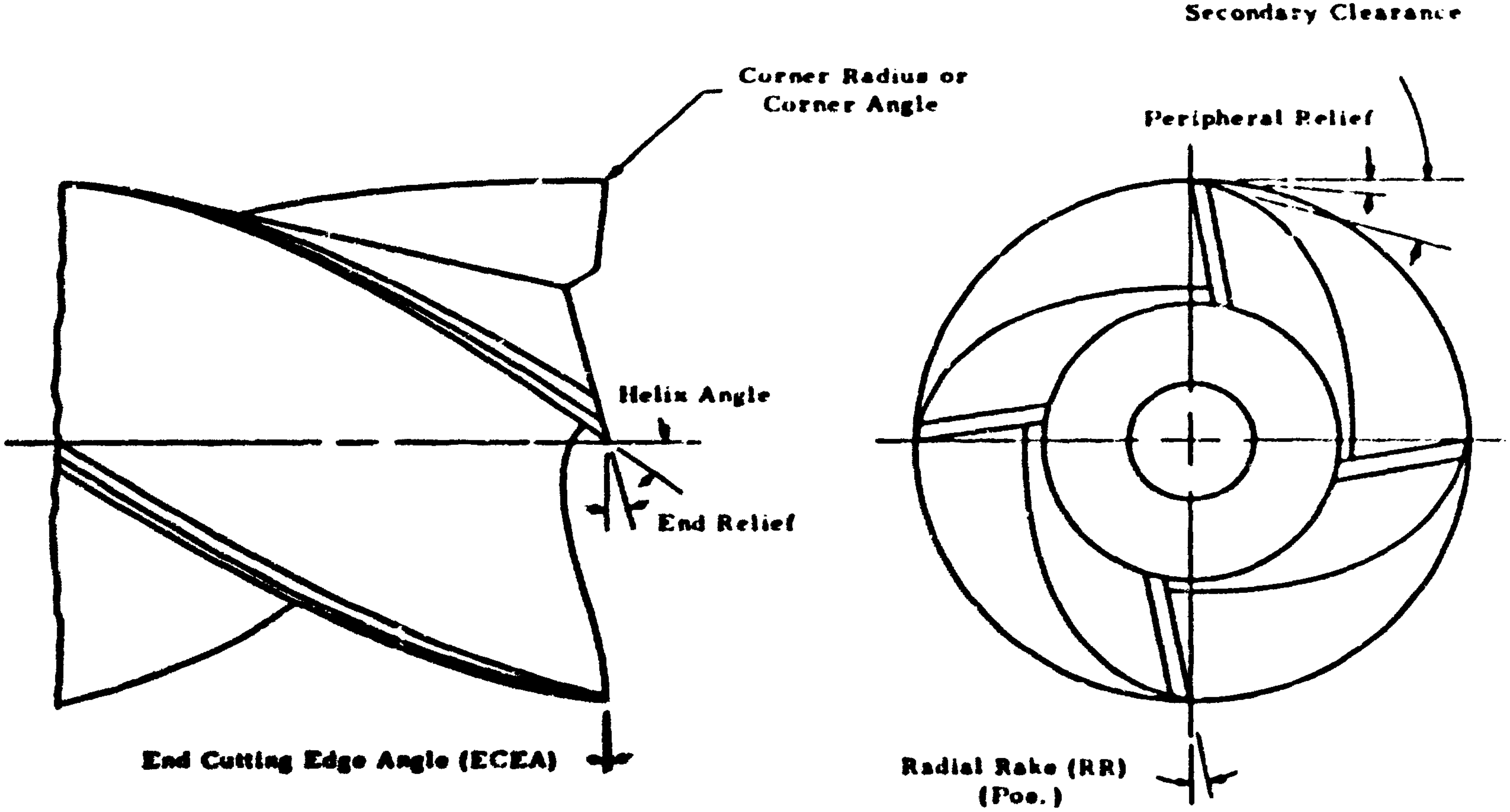
APPENDIX II

FACE MILL NOMENCLATURE



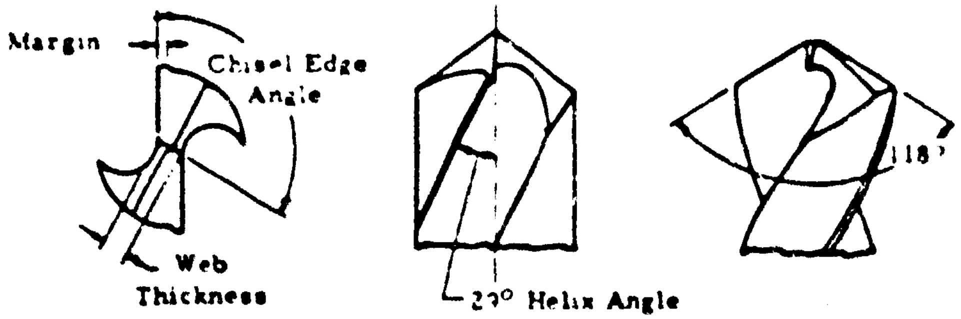
APPENDIX III

END MILL NOMENCLATURE

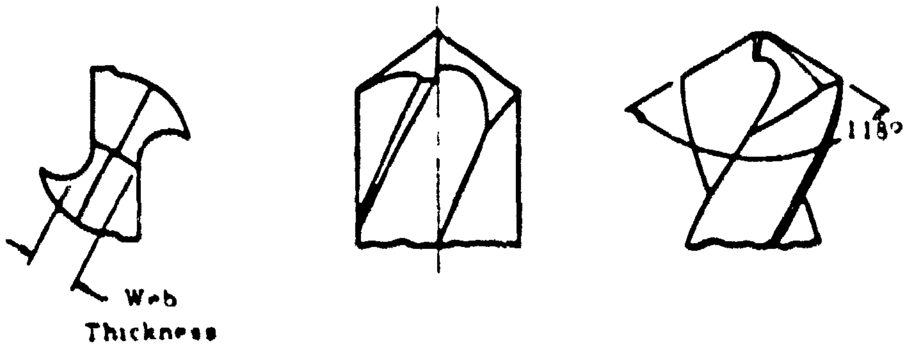


APPENDIX IV

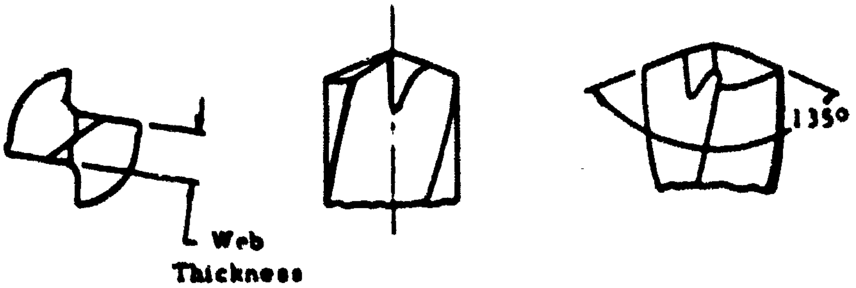
DRILL STYLES



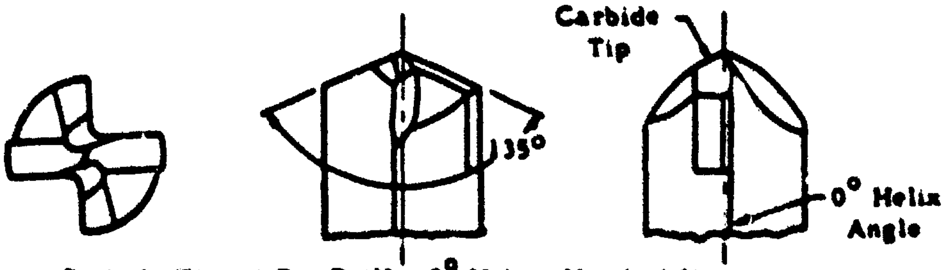
Standard Twist Drill - 29° Helix, Split Point



Heavy Web Drill - 29° Helix, Split Point



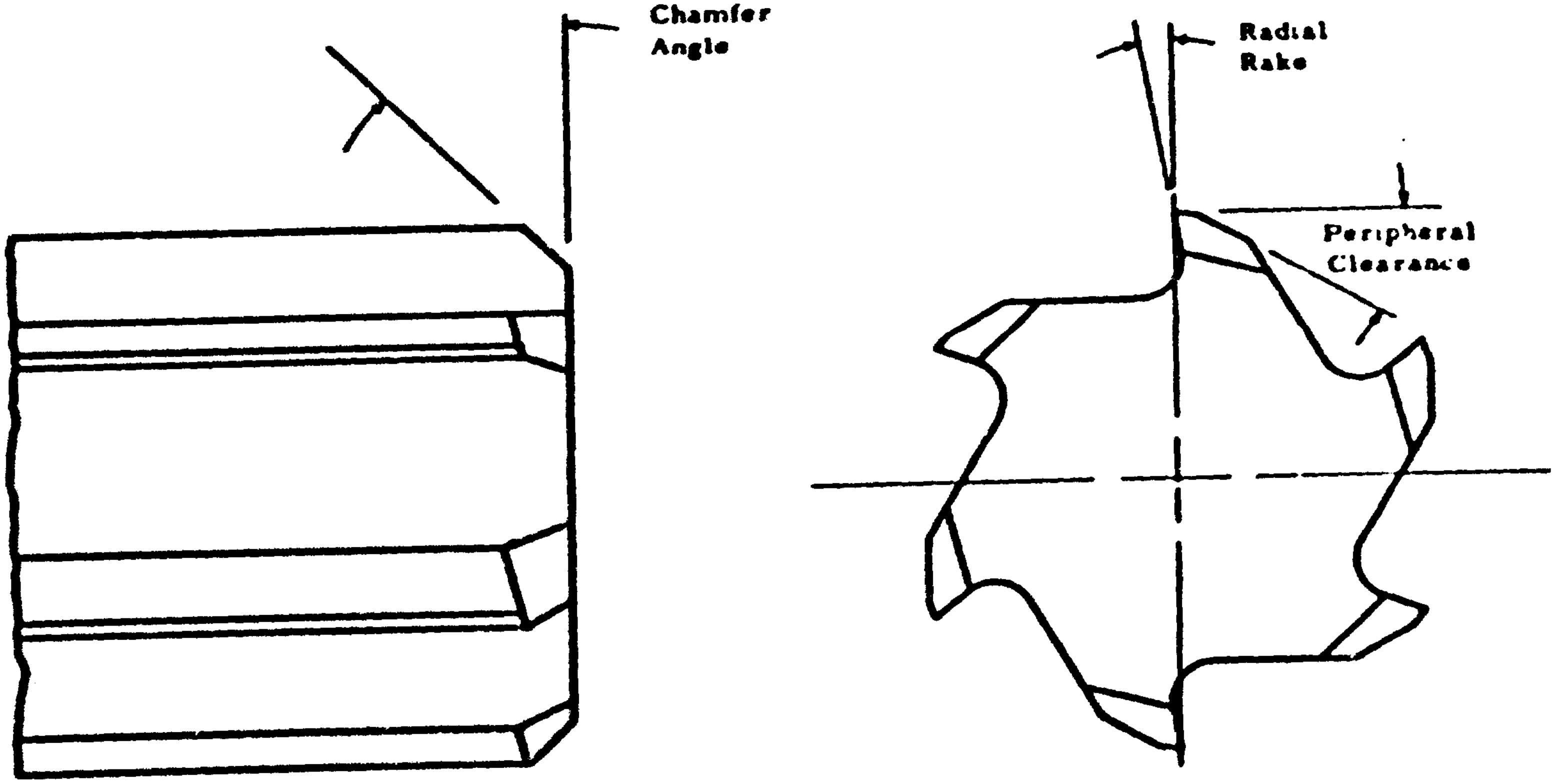
Heavy Web Drill - 12° Low Helix, Notched Point



Carbide Tipped Die Drill - 0° Helix, Notched Point

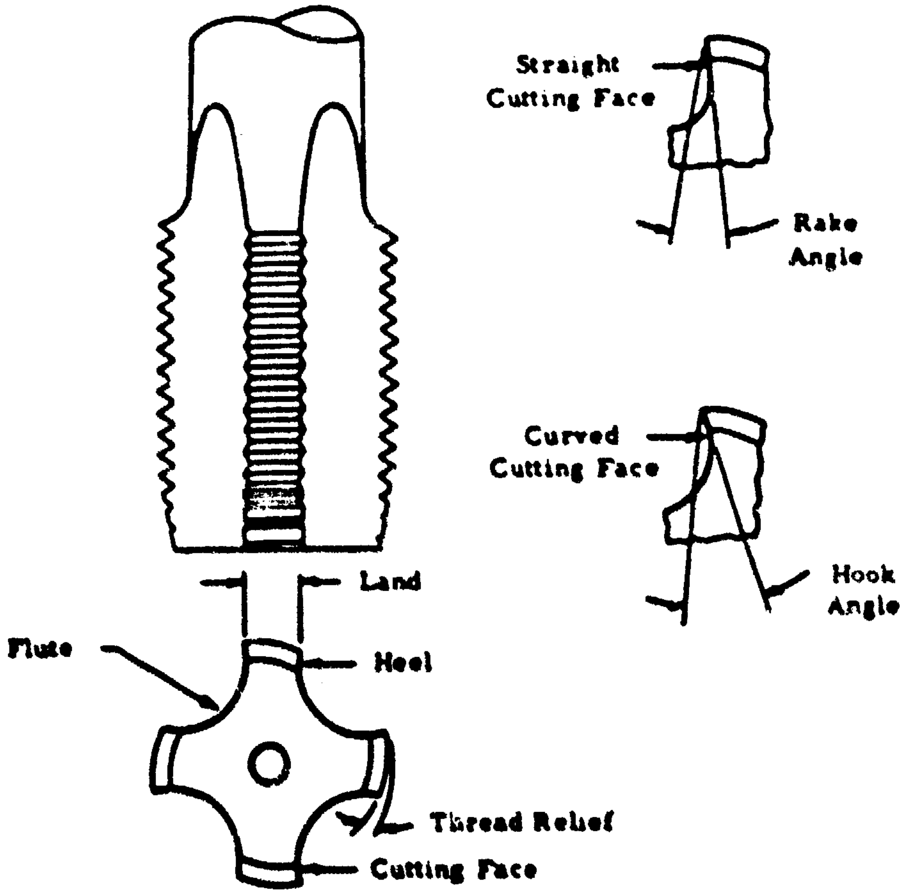
APPENDIX V

REAMER NOMENCLATURE



APPENDIX VI

TAP NOMENCLATURE



APPENDIX VII

IDENTIFICATION OF HIGH SPEED STEEL CUTTING TOOL MATERIALS

Symbol M, Molybdenum Types

Type	Nominal Composition, Percent						Application
	C	W	Mo	Cr	V	Co	
M-1	.80	1.50	8.00	4.00	1.00	-	General Purpose
M-2	.85	6.00	5.00	4.00	2.00	-	General Purpose
M-7	1.00	1.75	8.75	4.00	2.00	-	Fine Edge Tools - Abrasion Resistant
M-33	.90	1.50	9.50	4.00	1.15	8.00	Heavy Cuts - Abrasion Resistant
M-34	.90	2.00	8.00	4.00	2.00	8.00	Heavy Cuts - Abrasion Resistant
M-35	.80	6.00	5.00	4.00	2.00	5.00	Heavy Cuts - Abrasion Resistant
M-36	.80	6.00	5.00	4.00	2.00	8.00	Heavy Cuts - Abrasion Resistant
M-41	1.10	6.75	3.75	4.25	2.00	5.00	Heavy Cuts - Abrasion Resistant
M-42	1.10	1.50	9.50	3.75	1.15	8.00	Heavy Cuts - Abrasion Resistant
M-43	1.25	1.75	8.75	3.75	2.00	8.25	Heavy Cuts - Abrasion Resistant
M-44	1.15	5.25	6.25	4.25	2.25	12.00	Heavy Cuts - Abrasion Resistant

Symbol T, Tungsten Types

Type	C	W	Mo	Cr	V	Co	Application
T-1	.70	18.00	-	4.00	1.00	-	General Purpose
T-15	1.50	12.00	-	4.00	5.00	5.00	Extremely Abrasion Resistant

APPENDIX VIII
CARBIDE GRADE CHART

C 1 to C 8
BASED ON APPLICATIONS

CARBIDE MANUFACTURERS	INDUSTRY CODE							
	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8
ADAMAS	B	A AB PWB	PWB AA	AAA	DD [illegible] 434	[illegible]	[illegible]	CC [illegible]
[illegible]	--	[illegible]	--	--	--	--	--	--
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CARBOLOY	44A	883 [illegible]	883 [illegible] 905	999 [illegible] 370	[illegible]	[illegible]	350 78 370	320
CARMET	CA-3	CA-4 [illegible]	CA-7	CA-8	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FIRTH-LOACH	FA-5	FA-6	FA-7	FA-8	FT-3 FT-4 FT-5	FT-5 FT-62	FT-6 FT-62	FT-7 FT-72*
FIRTH STERLING	H	HA [illegible]	HE	HF	[illegible]	[illegible]	[illegible]	[illegible]
FUTURMILL	--	[illegible]	--	--	[illegible]	[illegible]	[illegible]	--
KENNAMETAL	K1	[illegible]	[illegible]	K11	[illegible]	[illegible]	[illegible]	[illegible]
MULTI METALS	901	902	903	904	[illegible]	--	--	--
NEWCOMER	N10	N20	N30	N40	N50	N60	[illegible]	[illegible]
SINTERCAST	Ferro-Tic [illegible]	Ferro-Tic [illegible]	--	--	Ferro-Tic [illegible]	Ferro-Tic [illegible]	--	--
SPEEDICUT BITS	A	B	C	E	[illegible]	[illegible]	[illegible]	[illegible]
TALIDE	C-88	C-91	C-93	C-95	[illegible]	[illegible]	[illegible]	[illegible]
TUNGSTEN ALLOY	B	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
VALENITE	VC-1	VC-2 [illegible] [illegible]	VC-3	VC-4	[illegible]	[illegible]	VC-7	VC-8 [illegible] [illegible]
VR/WESSON	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WENDT-SONIS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WILLEY'S	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

CAST IRON, NON-FERROUS AND NON-METALLIC MATERIALS		STEEL AND STEEL ALLOYS	
C-1	Roughing	C-5	Roughing
C-2	General Purpose	C-6	General Purpose
C-3	Finishing	C-7	Finishing
C-4	Precision Finishing	C-8	Precision Finishing

Listings do not necessarily imply equivalency of various manufacturer's grades.
This chart is not to be considered an endorsement of or an approved list of any manufacturer's products.
*Grades containing more than [illegible] Titanium Carbide

APPENDIX IX

HARDNESS CONVERSION CHART

Brinell Hardness Number	R_c Hardness Number	R_B Hardness Number
372	40	--
363	39	--
352	38	--
332	36	--
313	34	--
297	32	--
283	30	--
270	28	--
250	24	--
240	22	100
230	20	98
223	--	97
212	--	96
207	--	95
197	--	93
179	--	89
170	--	87
163	--	85
156	--	83
149	--	81

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Metcut Research Associates Inc.
3980 Rosslyn Drive
Cincinnati, Ohio 45209

Unclassified

MACHINABILITY PARAMETERS ON NEW AND SELECTIVE AEROSPACE MATERIALS

Technical Final Report, 1 December 1967 to 1 May 1969

Zlatin, Norman; Field, Michael; Christopher, John D.; Kohls, John B.

May 1969	314	0

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Manufacturing Technology Division
Air Force Materials Laboratory
Wright-Patterson Air Force Base, Ohio

Four groups of alloys of interest to the aerospace industry were selected for the machinability studies from a survey of the industry and a review of the literature. The four groups consisted of (1) high strength steels, (2) titanium alloys, (3) nickel base alloys and (4) stainless steel alloys. Both wrought and cast alloys were included in the first three groups.

In general, the cast nickel base alloys required even lower cutting speeds than the wrought alloys in this category. Recommendations are listed in tables in the report for machining all of the alloys included in this program with commercially available tools. It should be noted, however, that in some instances small departures from the suggested cutting speeds, feeds, cutting fluids, tool geometries or tool materials could result in significant reductions in tool life.

A short study was also made of the machined surfaces obtained by face milling and grinding of two titanium alloys, a high strength steel, and a nickel base alloy.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Machinability						
Machining Operations						
Aerospace Alloys						
Turning						
End Milling						
Drilling						
Face Milling						
High Strength Steels						
Titanium						
Distortion						
Residual Stress						

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