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FINAL REPORT ON MACHINABILITY OF MATERIALS

Norman Zlatin
Michael Field
William P. Koster
et al

Metcut Research Associates Inc.

Technical Report AFML-TR-65-444

January 1966

Advanced Fabrication Techniques Branch
Manufacturing Technology Division
Air Force Materials Laboratory
Research and Technology Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

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Subject: "Final Report on Machinability of Materials", Technical Report Nr. AFML TR-65-444

In a post-publication review of this report, an error was found in Figure 246, page 223.

A reprint of the corrected figure, which has been made on pressure sensitive paper, is enclosed for your convenience to paste over the incorrect Figure 246 on page 223.

A related correction is also necessary in Table 17, page 215. The cutting speed for peripheral end milling should be changed from 75 feet/minute to 17 feet/minute.

We appreciate your cooperation in making these changes to your copy of the above referenced report.

METCUT RESEARCH ASSOCIATES INC.

Norman Zlatin

Norman Zlatin, Vice-President

NZ/cf
Enc.

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FINAL REPORT ON MACHINABILITY OF MATERIALS

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Michael Field
William P. Koster
et al

FOREWORD

This Final Technical Report covers work performed under Contract AF 33(615)-1385 from 15 May 1964 to 31 December 1965. The manuscript was released by the author in December 1965 for publication as an AFML Technical Report.

This contract with Metcut Research Associates Inc., Cincinnati, Ohio, was initiated under Manufacturing Methods Project 8-240, "Machinability of Materials." It is being accomplished under the technical direction of Mr. Robert T. Jameson of the Advanced Fabrication Techniques 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: Dr. Michael Field, Dr. William P. Koster, and Messrs. John Christopher and L. R. Gatto. This project has been given the Metcut Research Internal Number 750-6000.

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. The program encompasses the following technical areas:

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

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

This technical report has been reviewed and is approved.

Melvin E. Fields

MELVIN E. FIELDS, COLONEL, USAF
Chief, Manufacturing Technology Division
Air Force Materials Laboratory

ABSTRACT

FINAL REPORT ON MACHINABILITY OF MATERIALS

Norman Zlatin, Michael Field, William P. Koster, et al

In this program the machining characteristics were determined for a variety of ultra high strength steels, titanium alloys, nickel base alloys and cobalt base alloys of current production interest to the Air Force. This group of alloys was the result of a field survey intended to select the most difficult to machine materials presently being fabricated in aerospace components.

Most of the conventional machining operations on these alloys can be performed with reasonable tool life, providing that specific machining conditions are followed. This report presents recommendations for particular machining operations. It should be noted, however, that even small departures from suggested variables, such as cutting speed, feed, cutting fluid, as well as tool material and geometry, may result in a significant reduction in tool life.

High speed edge milling tests were also run on a select group of materials. This particular operation is becoming increasingly important in airframe fabrication. In addition, residual stress and distortion studies were run on four high strength structural alloys. The data developed give an indication of the large variations possible in surface integrity as a function of machining conditions employed.

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1. INTRODUCTION

Advances in aircraft and missile performance are tied closely to the capabilities and limitations of materials from which these vehicles are to be built. Higher performance aircraft as well as propulsion systems require both alloys and non-metallics having increased structural characteristics and/or ability to withstand higher and higher operating temperatures. To be in keeping with this need, much effort has been expended in developing vastly improved structural materials as well as new materials systems.

Almost without exception, higher strength materials as well as higher temperature materials are more difficult to fabricate and machine than their counterparts of lesser ability. The Air Force Manufacturing Methods Program, however, has been keeping pace with aerospace materials development by providing production know-how in advance of extensive production requirements. The subject MMP project is concerned primarily with the conventional machining of these materials. It has the following objectives:

1. To provide conventional machining data which have not been made available previously for new and important aerospace materials.

2. To extend the development of standardized machining data into new areas which may be advantageous to aerospace production.

3. To supply data to help solve specific machining problems in the aerospace industry.

Phase I of this program consisted of a survey intended to isolate significant machining problems, followed by the formulation of a suitable machining program.

Phase II consisted of development of machinability data on a group of ultra high strength steels, titanium alloys and nickel base alloys. Data was also developed on a single cobalt base alloy and a fiber reinforced plastic.

The results of the program are summarized in this report.

2. EQUIPMENT AND TESTING PROCEDURES USED

2.1 Turning

All of the turning tests described in this report were conducted on an American Pacemaker 16" x 30" lathe 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. Carbide and high speed steel tools were used in the turning tests. The turning test bars were 3" to 4" in diameter by 18" long. A skin cut of .100" depth was taken on each test bar prior to making a turning test to remove any surface effects. Both throwaway insert and brazed carbide tools were used.

The nomenclature for the single point lathe tools is shown in Appendix A, page 437.

2.2 Face Milling

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

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" thick by 4" wide by 10" long. In most tests the 2" side was milled; thus, the width of cut was 2". A clean-up machining cut of 0.100" 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" diameter single tooth inserted cutter. A 4" diameter 8 tooth face milling cutter with inserted carbide tipped blades was used for multiple tooth milling tests. The nomenclature for a typical face milling cutter is shown in Appendix B, page 438.

2.3 Side Milling

The Cincinnati No. 3 Horizontal Dial Type Milling Machine shown in Figure 2, page 7, was also used in the side milling tests. The same size bars and setup used in the face milling tests were also employed in the side milling tests.

2.3 Side Milling (continued)

Several tool materials were evaluated over a range of cutting speeds and feeds using a 4" diameter single tooth inserted tooth cutter. The nomenclature for a typical cutter is shown in Appendix B, page 438.

2.4 Peripheral End Milling and End Mill Slotting

The end milling tests were made on the Cincinnati No. 2 Dial Type Vertical Milling Machine shown in Figure 3, page 8. The test bar was clamped in an 8" heavy duty vise attached to the milling machine table. Straight shank end mills were used and held in the machine with an adapter. In addition to the standard integral cutting fluid system, the machine was equipped with a spray mist applicator system in order to evaluate cutting fluid application methods.

The test bars were 2" x 4" x 10" long. All heat treated bars were first face milled to a depth of 0.100" to remove any surface effects on the bars.

Full width cuts 3/4" deep were made in 10" long test bars as shown in Figure 5, page 10. Tool life is expressed in inches work travel to obtain the specified wearland on the tool.

High speed steel end milling cutters were used. The cutters were 3/4" diameter, 4 flute right hand spiral, right hand cut. The nomenclature for end mills is illustrated in Appendix C, page 439.

2.5 Drilling

The drilling tests were performed on a 25" Fosdick Upright Drill Press and a Cincinnati 16" Sliding Head Box Column Drilling Machine equipped with a continuously variable speed drive 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 6, page 11. The drilling test samples were 1/2" thick plates cut from the 2" x 4" milling bar stock. A face milling cut of 0.060" 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" diameter high speed steel drills. Some tests were performed with smaller size drills. Drills made from several types of high speed steels were used.

2.5 Drilling (continued)

The drill nomenclature for standard point and crankshaft point grind is illustrated in Appendix D, page 440.

2.6 Reaming

The Cincinnati 16" Sliding Head Box Column Drilling Machine shown in Figure 6, page 11, was also used for the reaming tests. The reaming test samples were the 1/2" thick plates that had been used in the drilling tests.

Most of the reaming tests were conducted with letter I (.272" dia.) 6 flute high speed steel reamers. Four flute carbide reamers were used on several of the metals reamed. Reamer sizes were used to obtain 60% and 75% threads. The nomenclature for the reamers is shown in Appendix E, page 441.

2.7 Tapping

A special tapping machine with a variable speed drive and a 25" Fosdick Upright Drill Press shown in Figures 6 and 7, pages 11 and 12, were used for the tapping tests. The tapping test samples were 1/2" thick plates with the previously reamed holes. The tapping tests were run with 4/16-24 NF taps made from several high speed steels. Tap nomenclature is indicated by Appendix F, page 442.

2.8 Grinding

A Norton 8" x 24" 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" x 2" x 6" 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) were evaluated.

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

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

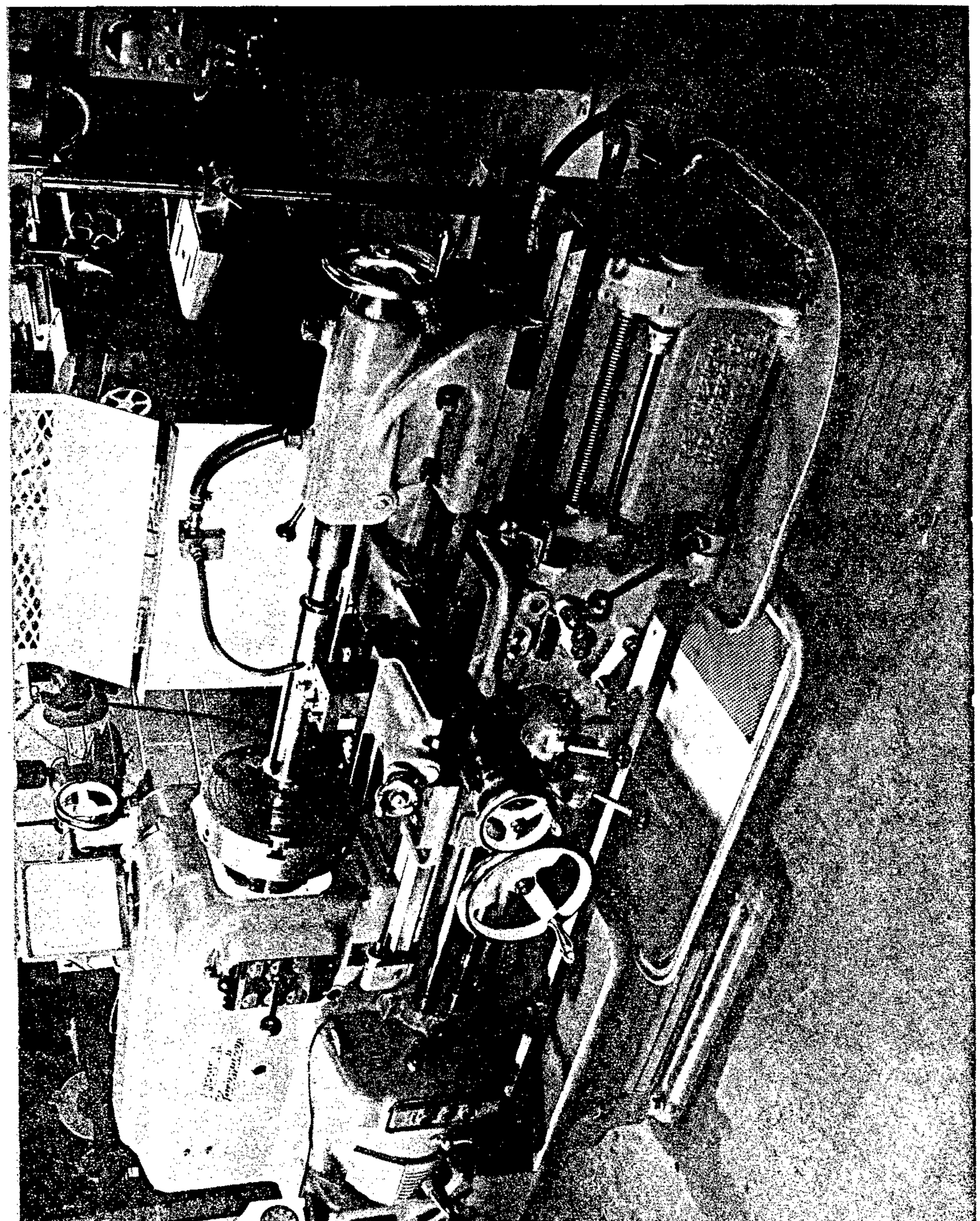
A wheel size of 10" x 1" x 3" was used for all tests.

2.8 Grinding (continued)

The following procedure was used for grinding tests. Before the grinding tests were started, a 0.030" deep by 1/2" wide step was dressed in the grinding wheel; see Figure 9, page 14. This step was used as a reference in measuring wheel wear. A 0.0001" 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" or after .050" 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 0.050" stock removal.

2.9 Cutting Tool Nomenclature

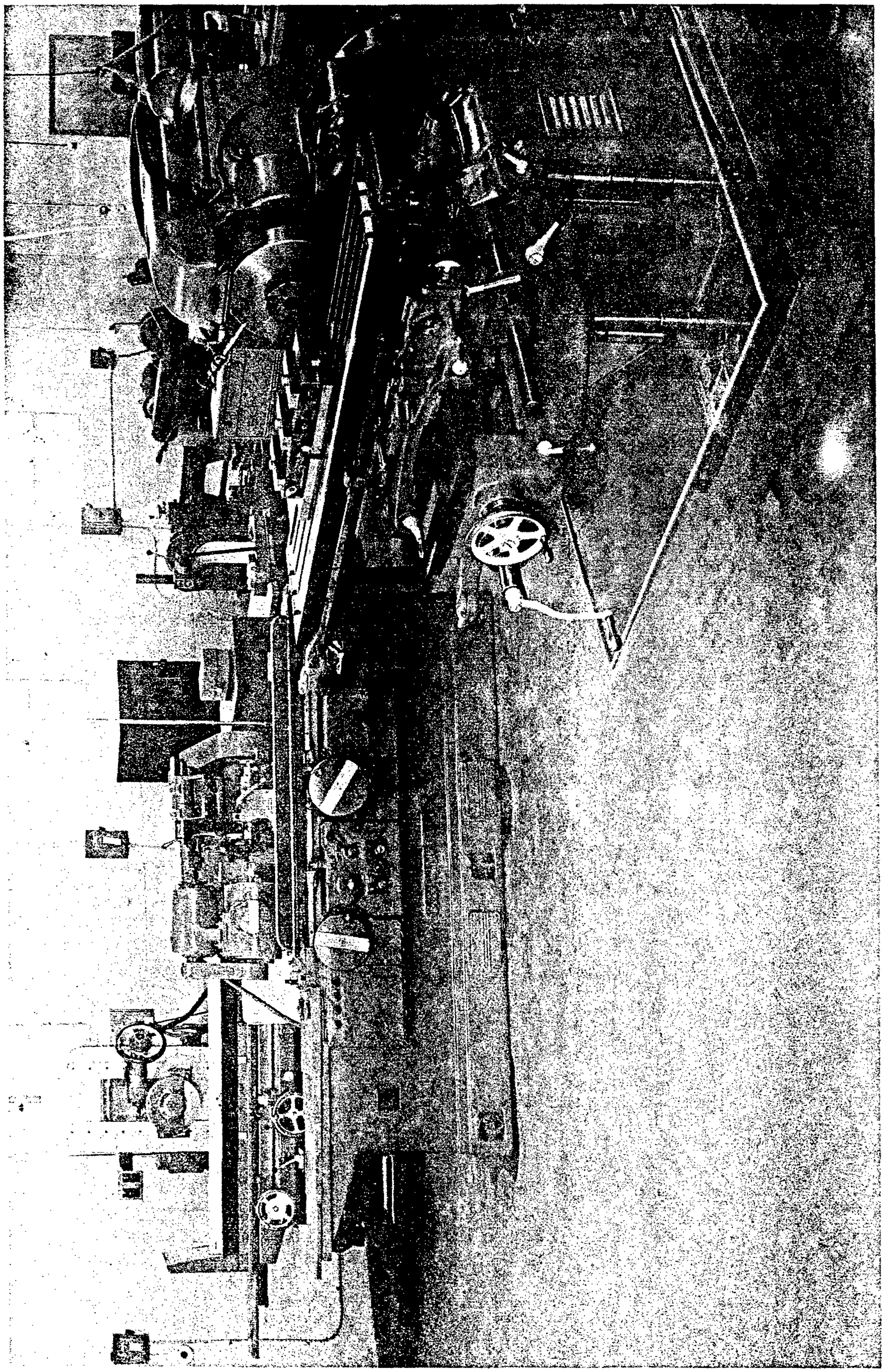
High speed steel and carbide cutting tools were used for this program. In general, the commercial designation for these materials is used throughout this report. An identification of these cutting tool materials is presented in Appendices G and H, pages 443 and 444. A hardness conversion chart is shown in Appendix J, page 446.



16" x 30" American Pacemaker Lathe equipped with a 30 H.P. continuously variable speed drive to provide exact cutting speed control for turning tests.

See Text, page 2

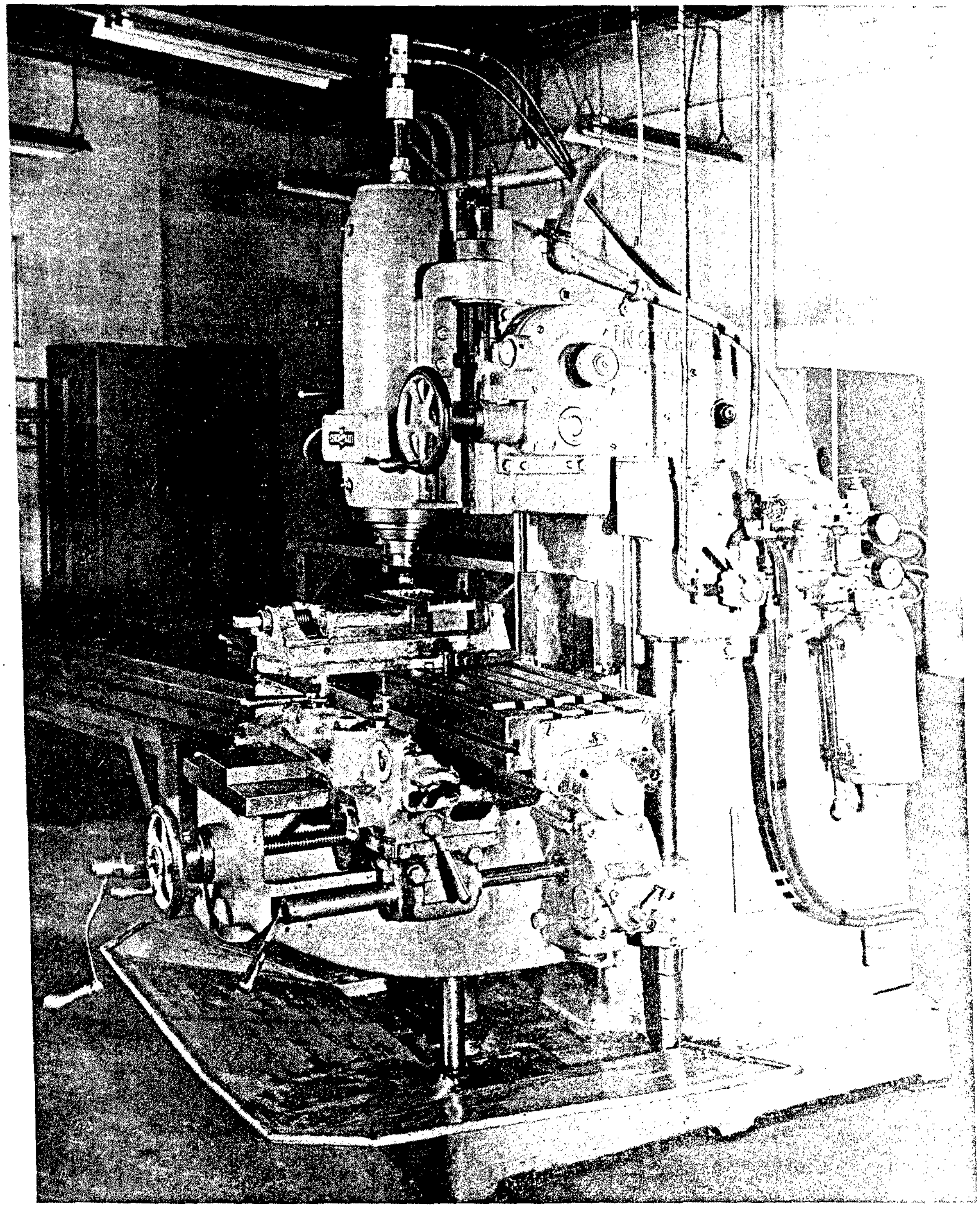
Figure 1



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.

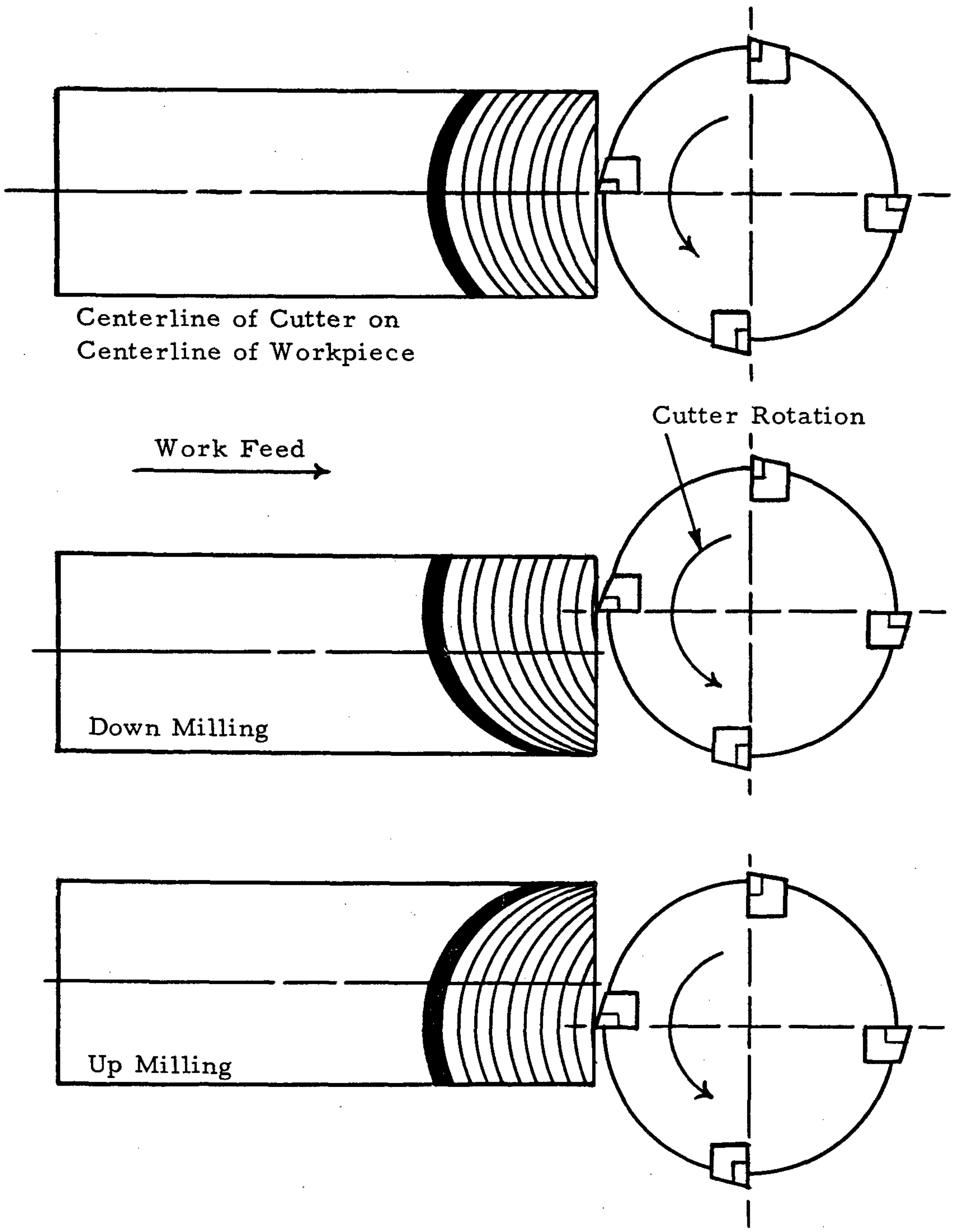
See Text, page 2

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.

Face Milling Setups
Illustrating Up and Down Milling



See Text, page 2

Figure 4

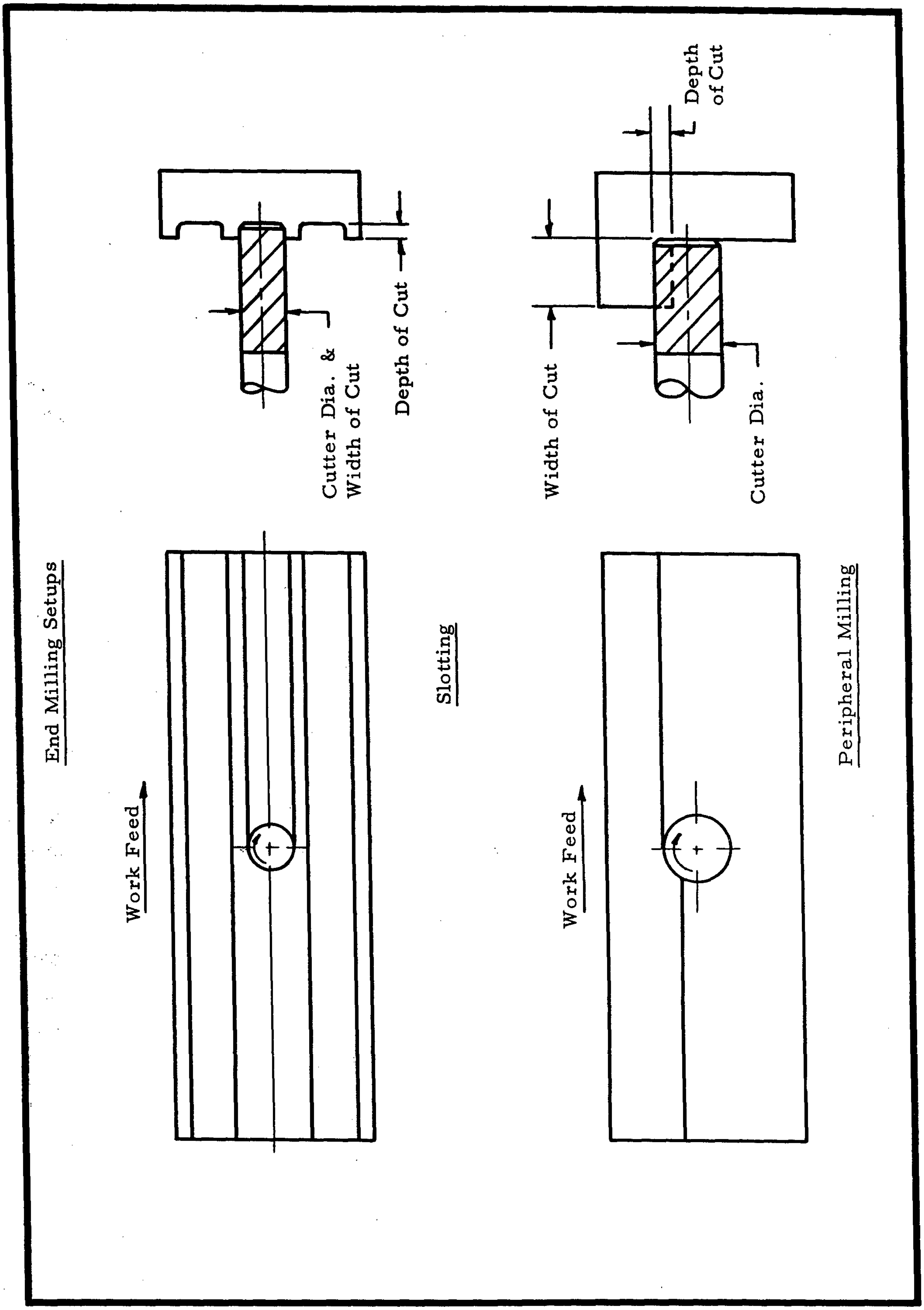
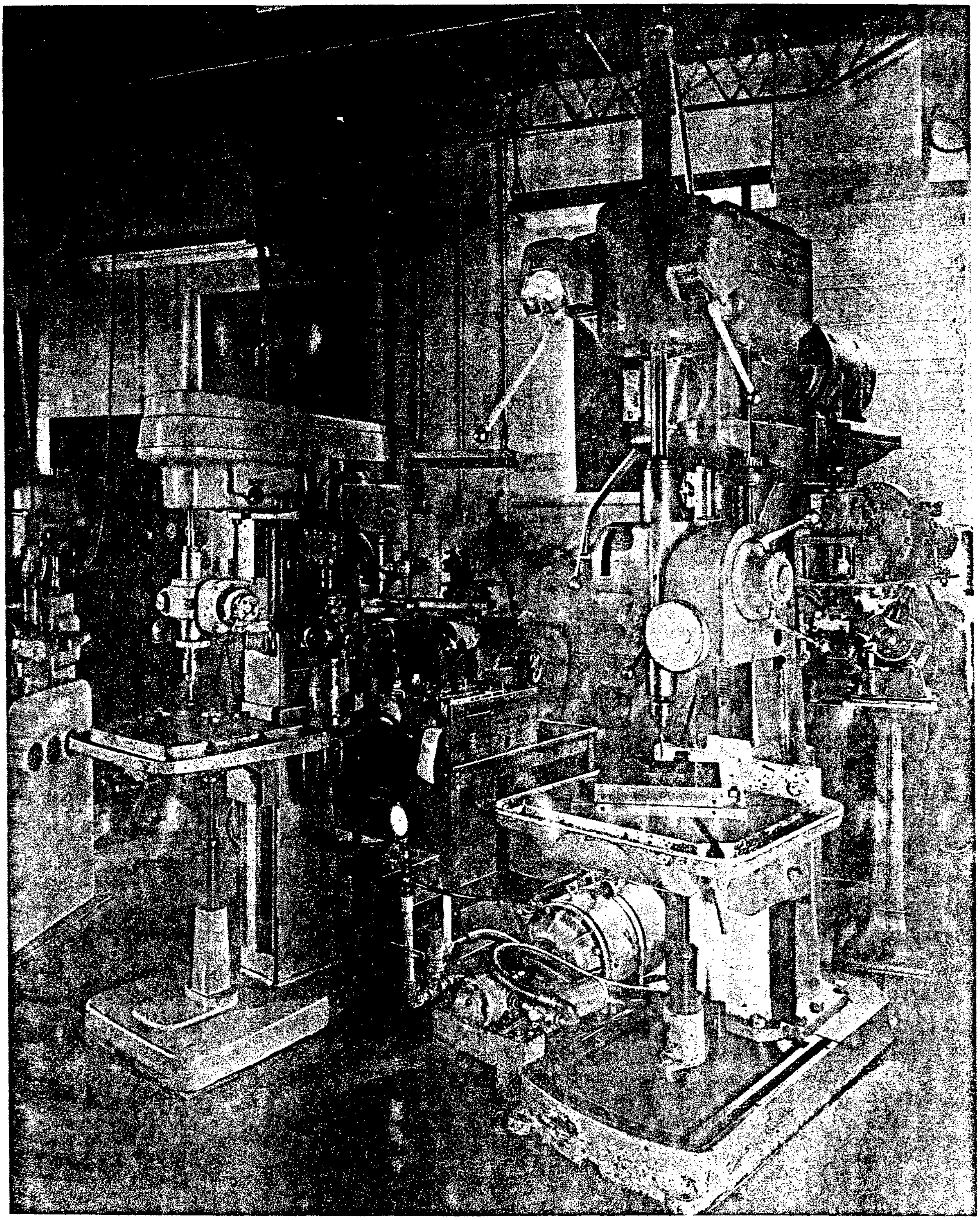
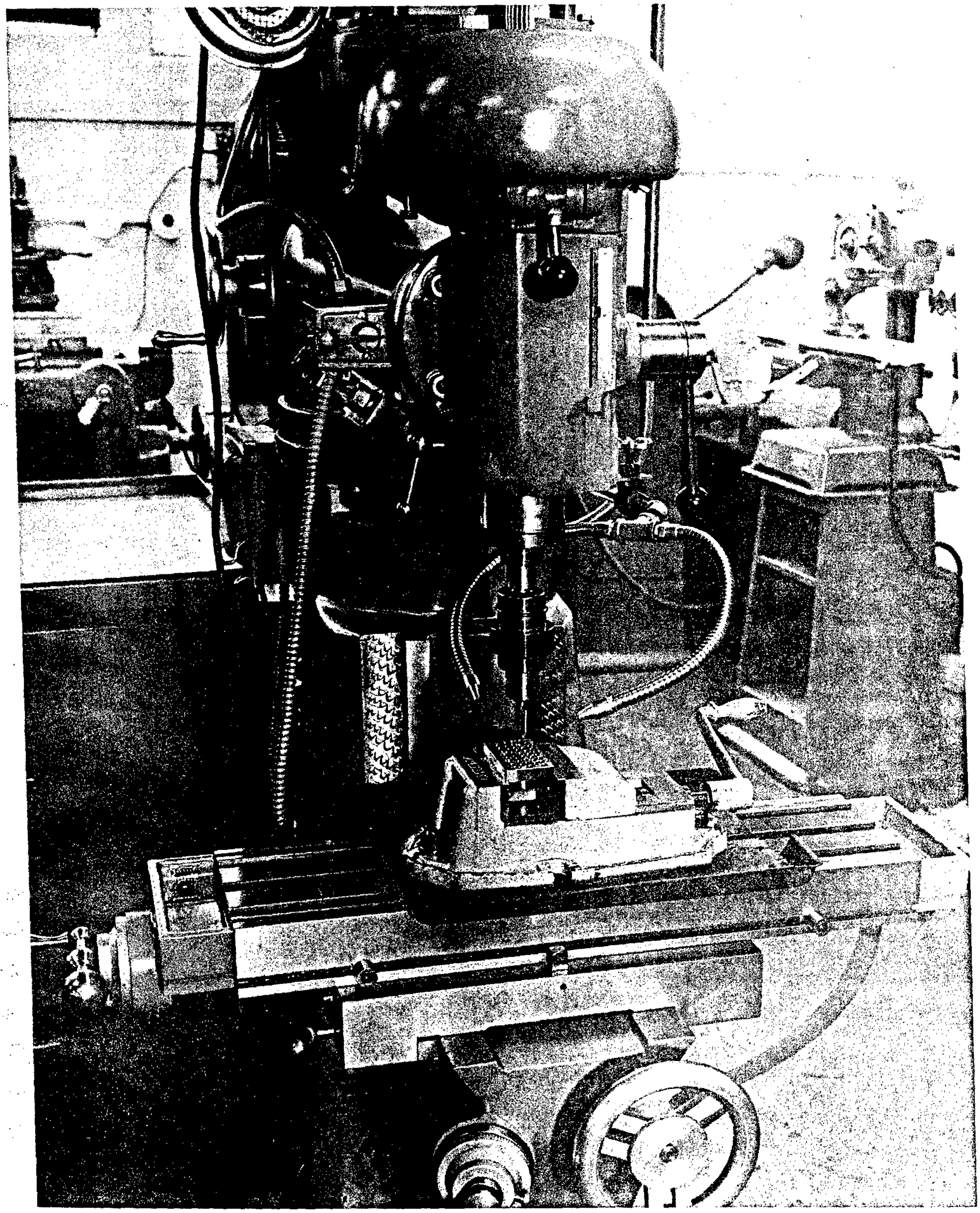


Figure 5

See Text, page 3



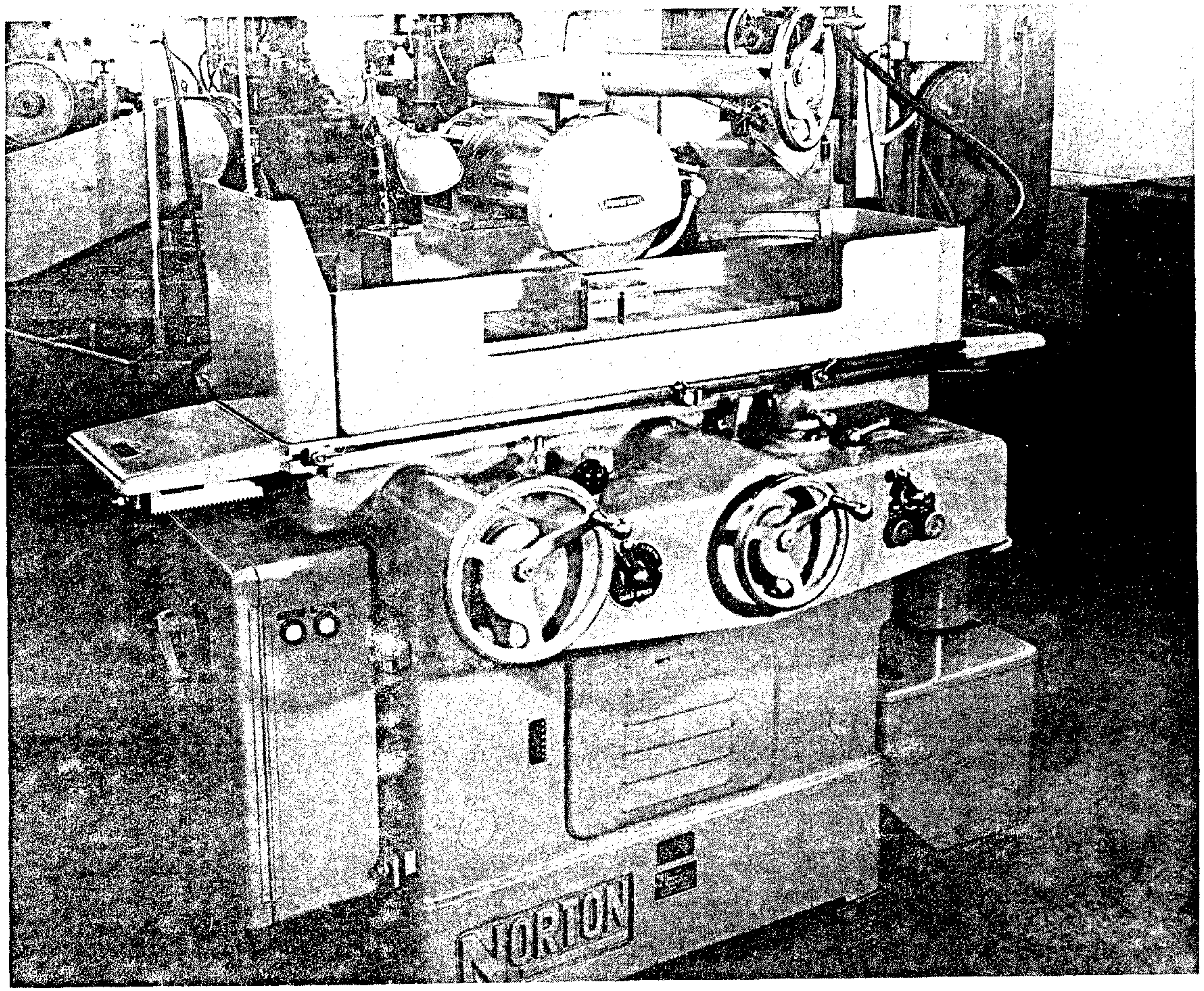
Drilling tests were performed on a Fosdick 25" Upright Box Column Drill Press (right) and a Cincinnati 16" Box Column Drilling Machine. Both machines are equipped with continuously variable feed drive units to provide feeds from .0001 to .025 inches/rev.



Tapping tests were performed on a special tapping machine equipped with a continuously variable speed drive. Available spindle speeds range from 70 to 4000 rpm.

Figure 7

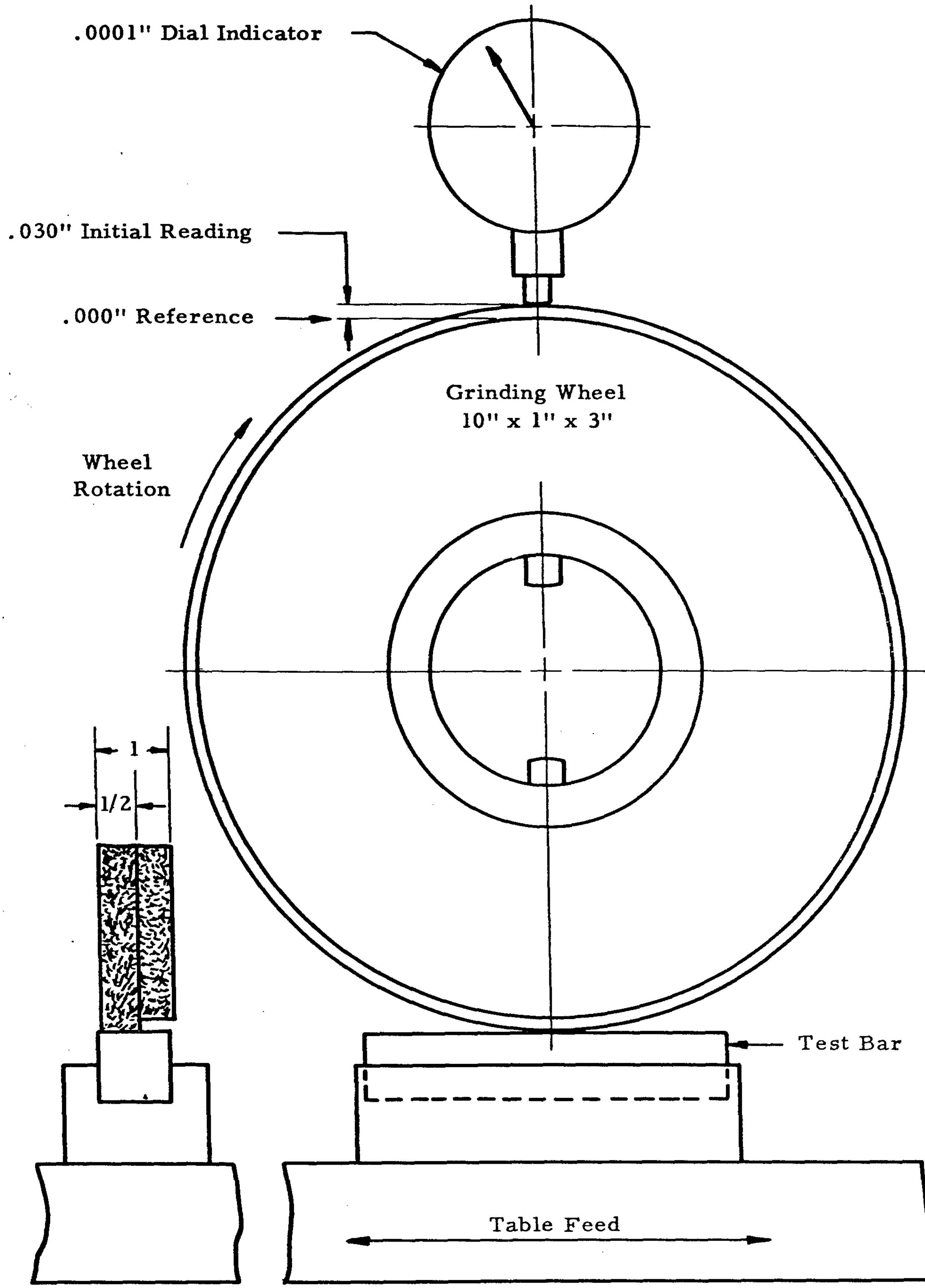
See Text, page 4



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.

Figure 8

See Text, page 4



GRINDING TEST SETUP

See Text, page 4

Figure 9

3. MACHINING ULTRA-HIGH STRENGTH STEELS

Within the aerospace industry the ultra-high strength steels are used for a wide variety of structural parts which operate at temperatures as high as 600-800°F. Major use is found in applications calling for maximum strength and maximum rigidity. Typical components include landing gears, ribs, spars, struts and fasteners. Because of strength-weight-toughness requirements, ultra-high strength steels are also used for rocket motor cases, fuel cells and similar pressure vessels. A fairly new class of materials within this group, the maraging steels, is used for the same range of applications, but predominantly in situations requiring an absolute minimum of distortion during processing.

3.1 AISI 4340 Steel

Alloy Identification

The nominal analysis of AISI 4340 is as follows:

Fe-0.8Cr-1.8Ni-0.4C

Material for milling tests was procured as 2" x 4" bar stock in the hot rolled-annealed condition. Drilling stock was obtained as 1/2" x 4" bar stock in the cold drawn-annealed condition.

Part of the material was subsequently re-annealed in annealing carbon with the following cycle:

1650°F/1 hour/furnace cool at 50°F per hour to 1450°F/air cool

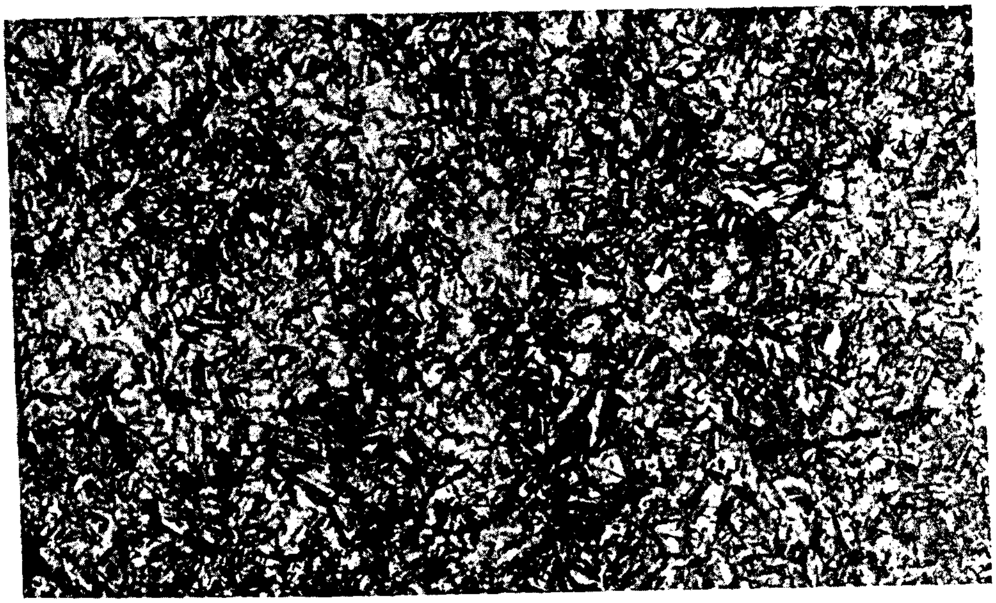
The resulting hardness was 207-217 BHN. The microstructure, consisting of ferrite and fine pearlite which have been partially spheroidized, is illustrated below:

AISI 4340, Annealed

Etchant: Nital   Mag: 1000X

3.1 AISI 4340 Steel (continued)

The remainder of the material was normalized from 1600°F, resulting in a hardness of 321-341 BHN. The structure, consisting of a martensite matrix with some dispersed acicular bainite, is illustrated below:



AISI 4340, Normalized

Etchant: Nital Mag: 500X

Peripheral End Milling (Annealed, 207-217 BHN)

A comparison of conventional milling with climb milling AISI 4340 steel annealed to 207-217 BHN is presented in Figure 10, page 19. The setup used is shown in Figure 5, page 10. Cutter life was almost 2-1/2 times longer with climb milling than with conventional milling at a cutting speed of 190 ft./min. and a feed of .004 in./tooth. As shown in Figure 11, page 19, cutter life was maximum at a feed of about .004 in./tooth for peripheral end milling AISI 4340 steel in the annealed condition.

A further improvement in cutter life was obtained when the cutting fluid was changed from soluble oil to an active sulfurized oil. An increase of more than 50% in cutter life resulted when the active oil was used as compared to the soluble oil at a cutting speed of 190 ft./min., see Figure 12, page 20.

3.1 AISI 4340 Steel (continued)

End Mill Slotting (Annealed, 207-217 BHN)

The tool life curves for two feeds over a range of cutting speeds for slotting are shown in Figure 13, page 20. Note that while the tool life was somewhat greater at a feed of .002 in./tooth than at .004 in./tooth, the fact that at the higher feed the metal removal rate was double that at .002 in./tooth more than justifies using the feed of .004 in./tooth. See Figure 5, page 10 for the setup used.

Figure 14, page 21, illustrates the effect of feed on tool life for several cutting speeds. Even at a cutting speed of 153 ft./min., the decrease in cutter life for the higher feed was only minor compared to doubling the metal removal rate at the feed of .004 in./tooth.

As shown in Figure 15, page 21, a 15 to 20% increase in tool life was obtained by substituting an active sulfurized oil for the soluble oil. The comparison is shown for a light feed of .002 in./tooth.

Drilling (Annealed, 207-217 BHN)

The drill life in drilling AISI 4340 steel in the annealed condition (207-217 BHN) is substantially greater when using a highly sulfurized oil compared to a soluble oil. As shown in Figure 16, page 22, at a drill life of 250 holes, the cutting speed with a highly sulfurized oil was over 60% faster than with a soluble oil.

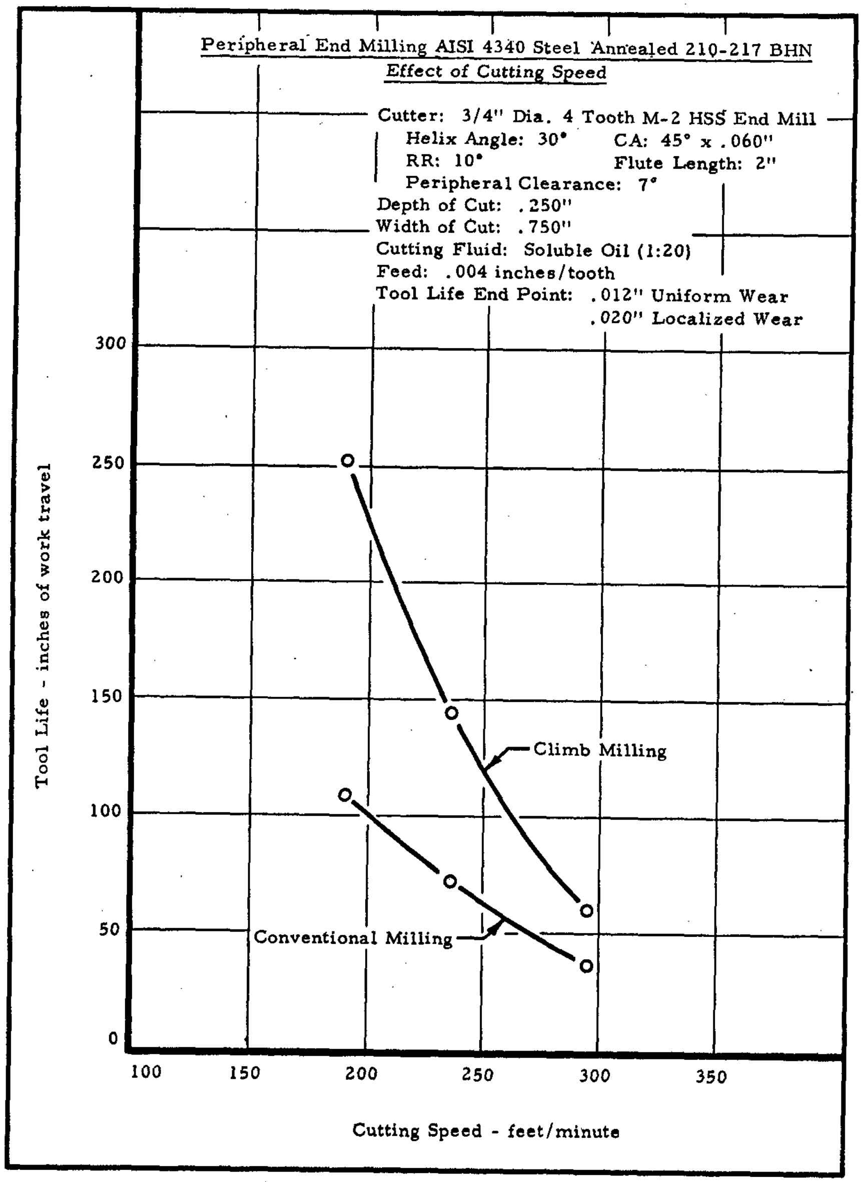
It is interesting to note in Figure 17, page 22, that when soluble oil was used the drill life was considerably lower at a feed of .005 in./rev. as compared to .002 in./rev. However, as presented in Figure 18, page 23, with an active sulfurized oil the drill life was approximately the same for the two feeds. From these results, a feed of .005 in./rev. would be recommended at a cutting speed of 100 to 125 ft./min. with an active cutting oil.

TABLE 1

RECOMMENDED CONDITIONS FOR MACHINING
AISI 4340 STEEL - ANNEALED 200-217 BHN

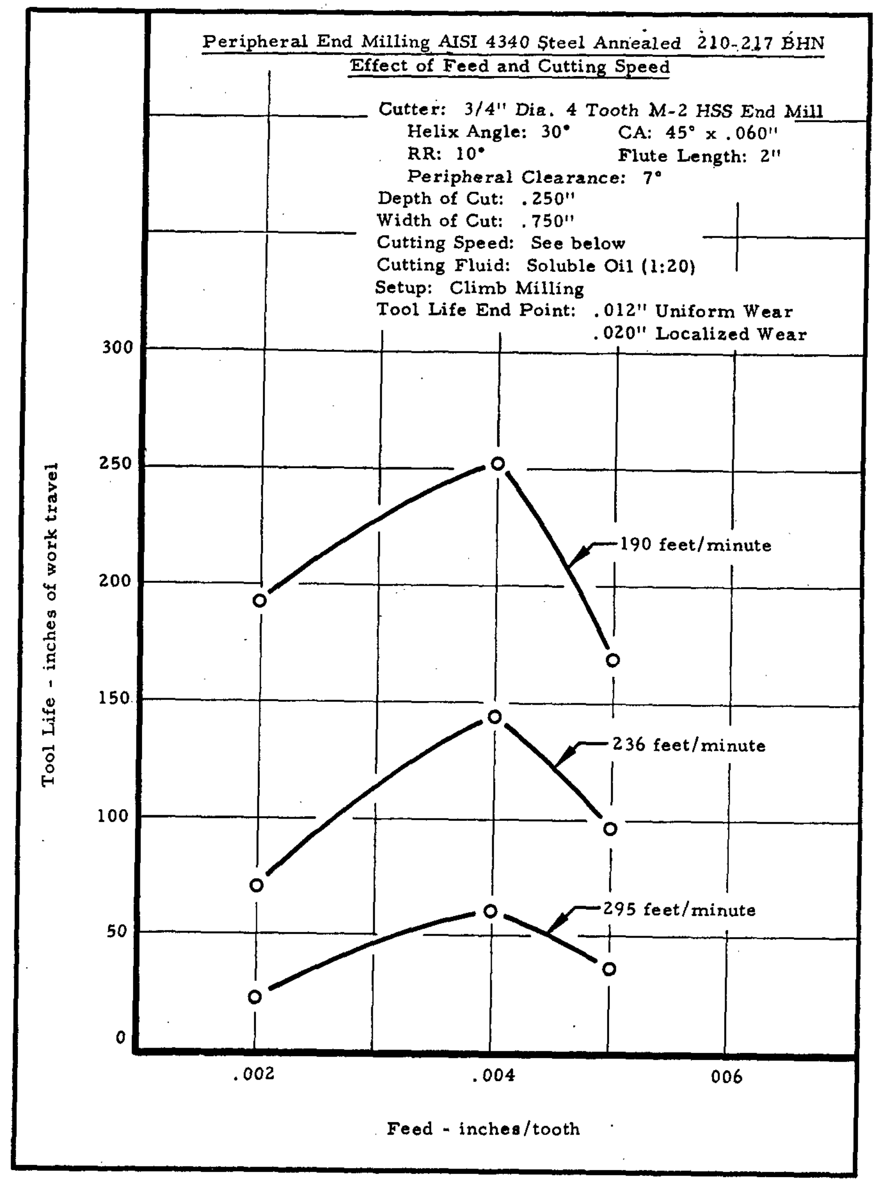
Cr	Ni	C	Fe
0.8	1.8	0.4	Bal

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	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.004 in./tooth	190	250" work travel	.012	Highly Sulphurized Oil
End Mill Slotting	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.004 in./tooth	124	180" work travel	.012	Highly Sulphurized Oil
Drilling	M-1 HSS	118° Plain Point 7° Clearance Angle	1/4" diameter drill 2-1/2" long	.500 thru	-	.005 in./rev.	125	250 holes	.015	Highly Sulphurized Oil



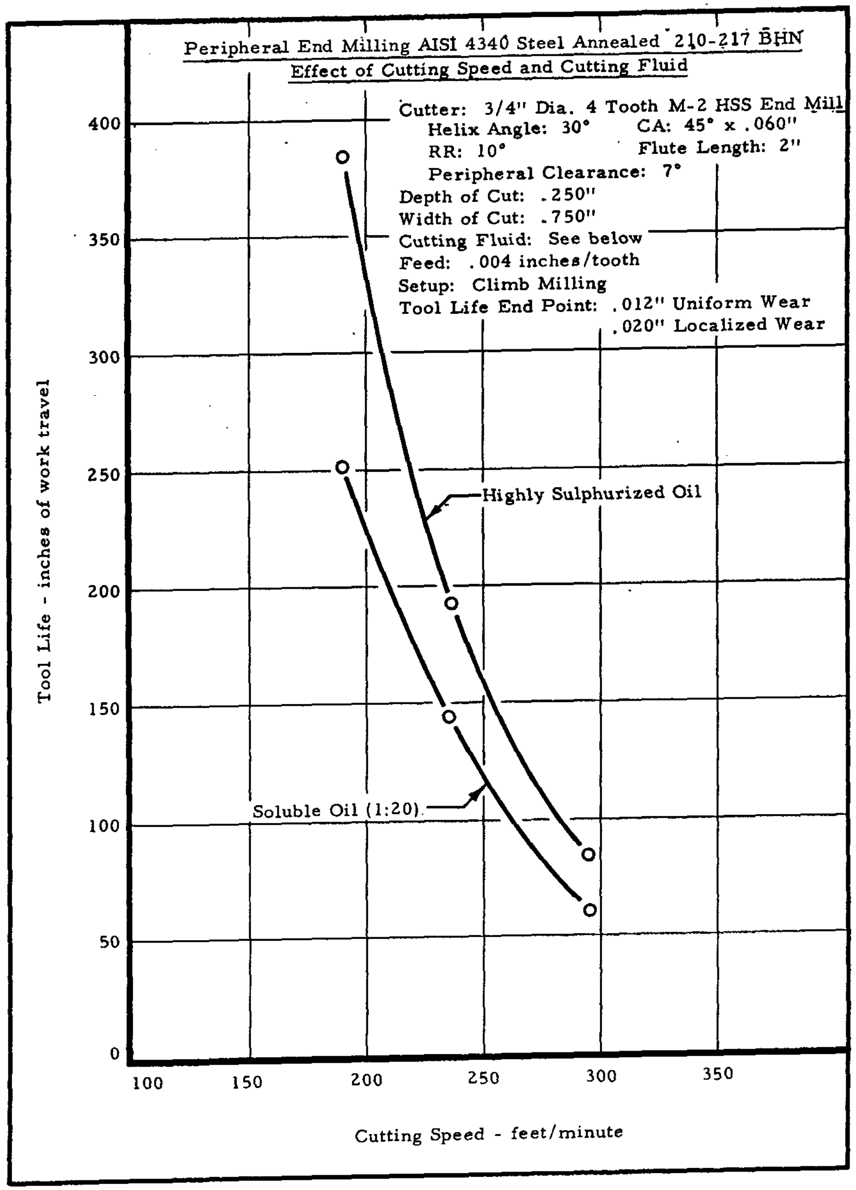
See Text, page 16

Figure 10



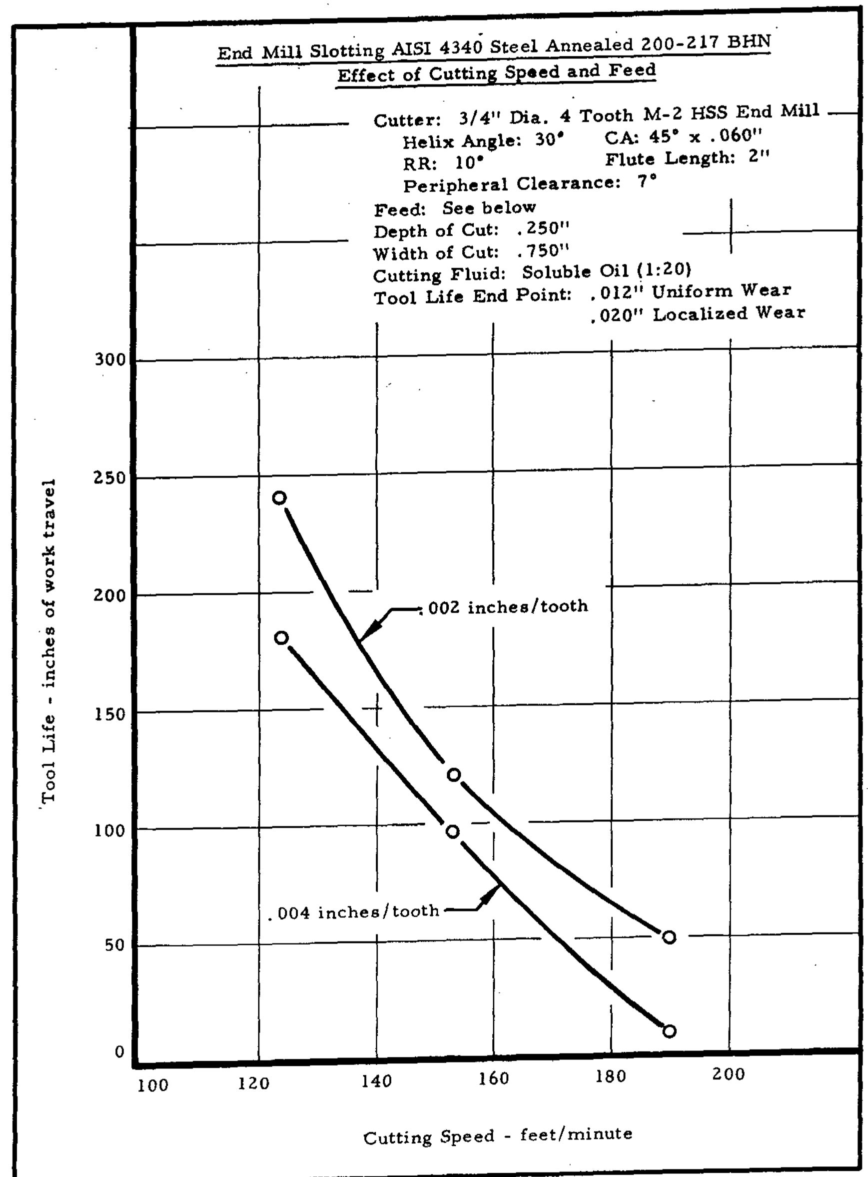
See Text, page 16

Figure 11



See Text, page 16

Figure 12



See Text, page 17

Figure 13

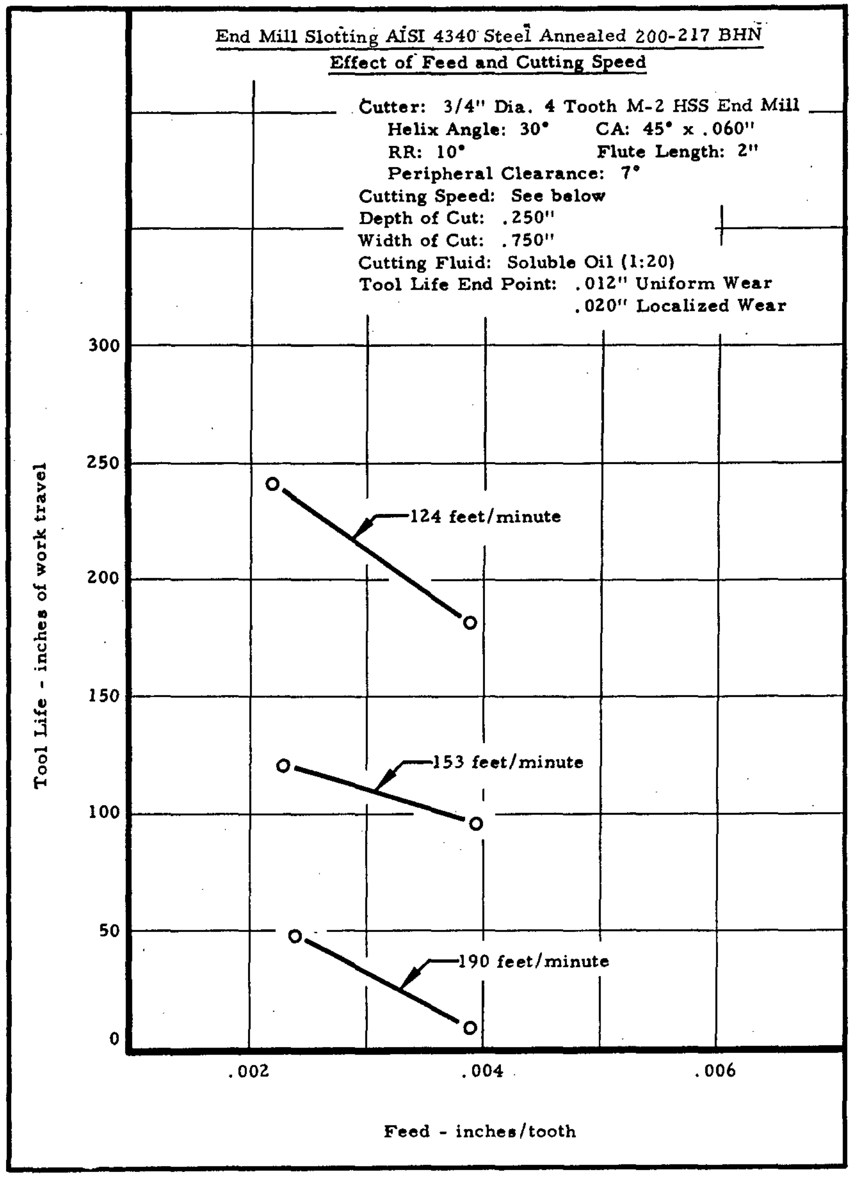


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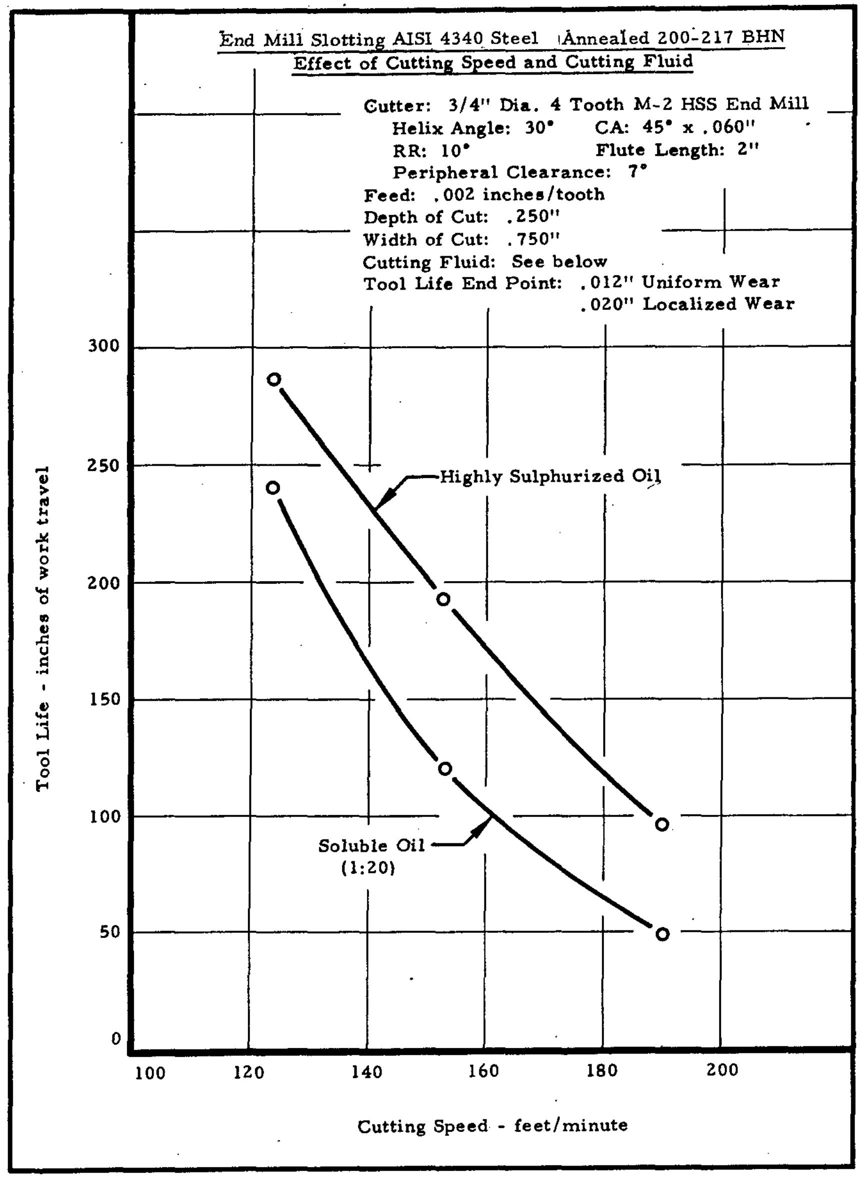
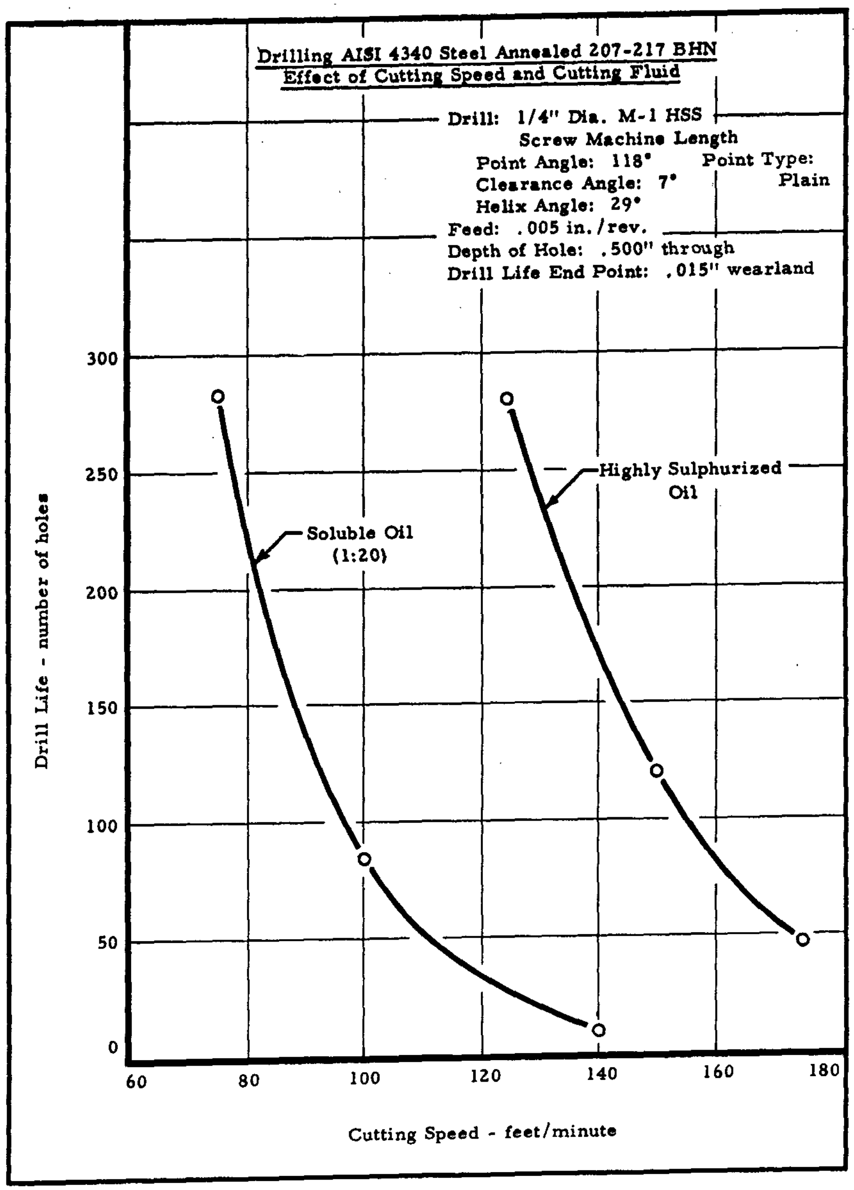
Figure 14



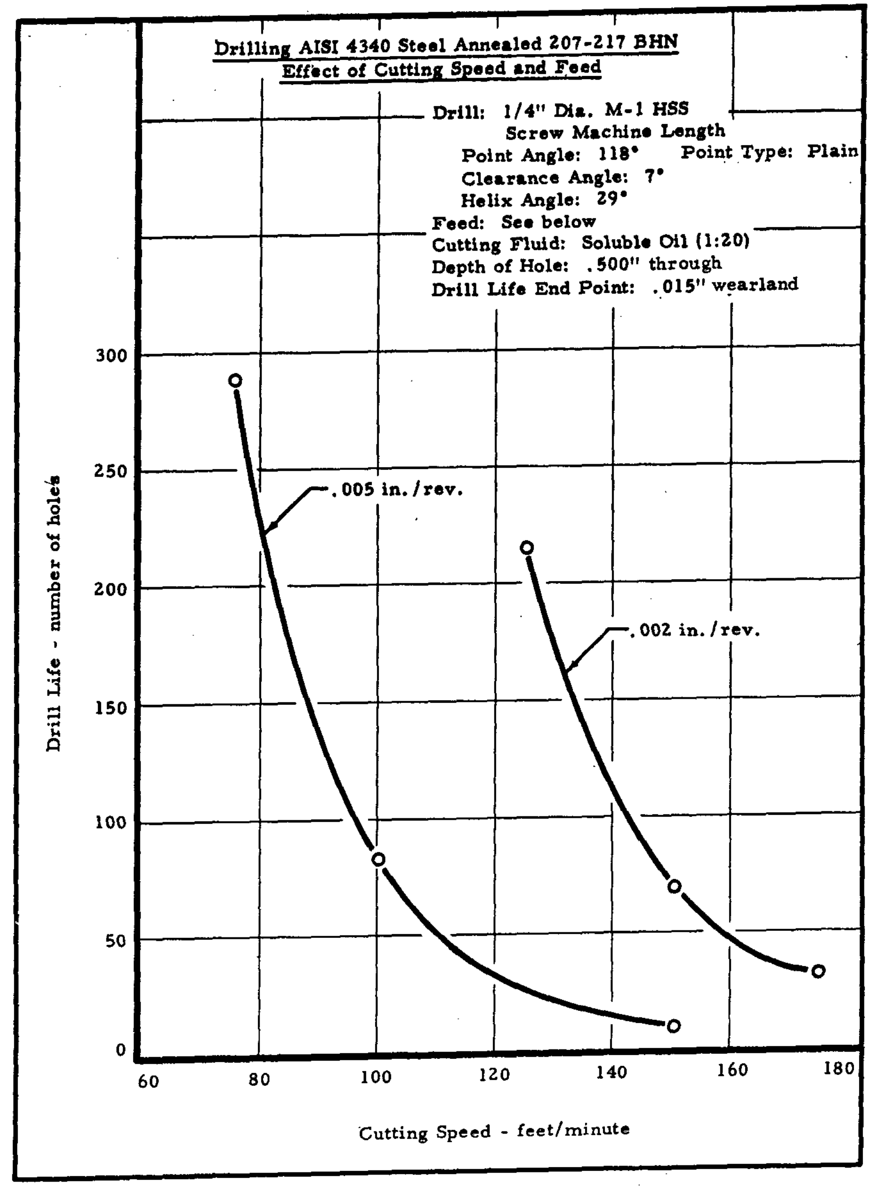
See Text, page 17

Figure 15



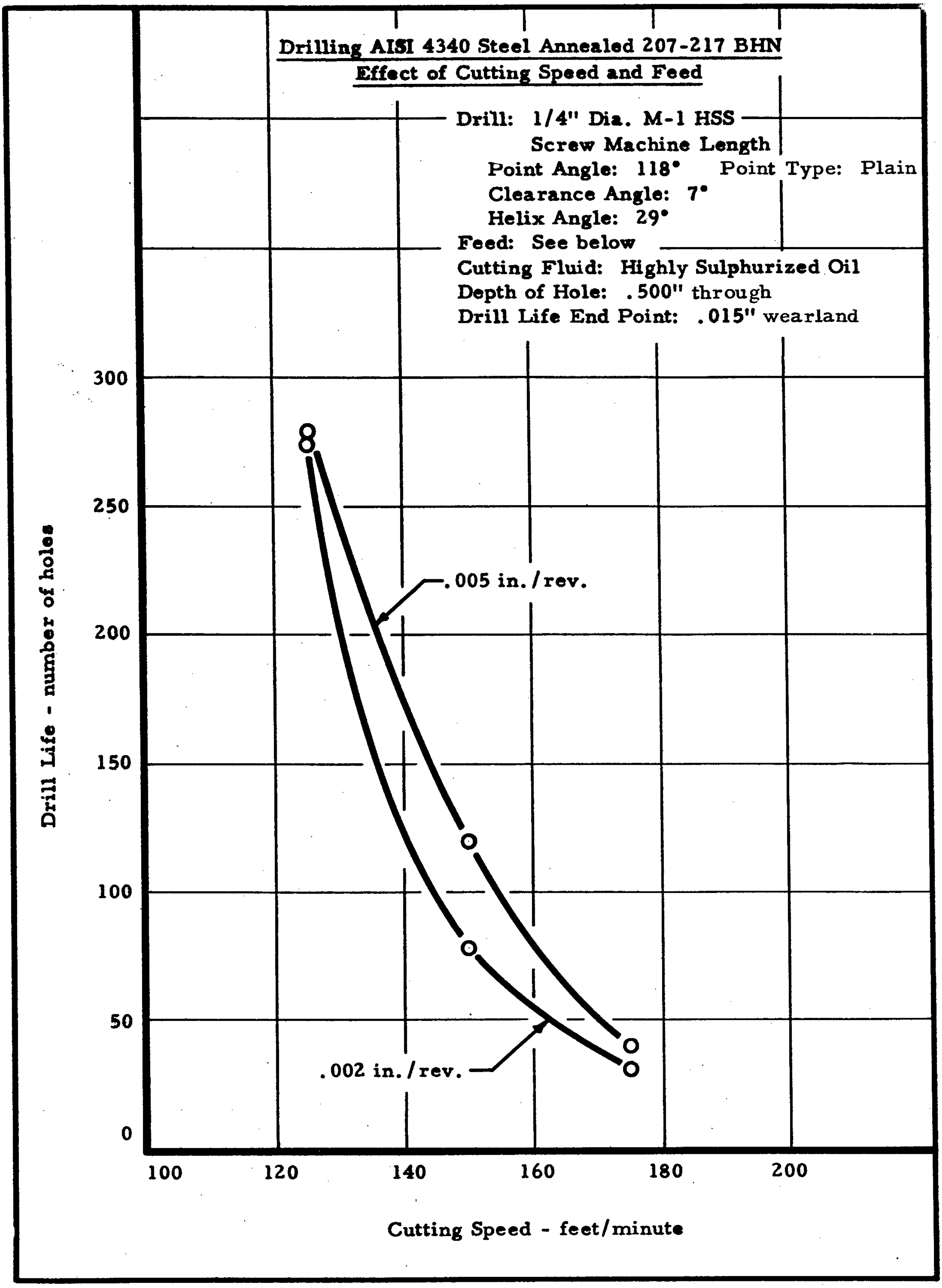
See Text, page 17

Figure 16



See Text, page 17

Figure 17



See Text, page 17

Figure 18

Peripheral End Milling (Normalized, 321-341 BHN)

The results of peripheral end milling of AISI 4340 steel normalized to 321-341 BHN with both water base and oil base cutting fluids are presented in Figure 19, page 27. Climb milling was used throughout these tests, since it was found in similar tests on the annealed steel that climb milling was superior to conventional milling. Under the conditions employed in these tests, there were no significant differences between the tool life results obtained with (1) highly sulfurized oil, (2) soluble oil (flood), or (3) soluble oil (spray mist).

Figure 20, page 27, shows a comparison of peripheral end milling AISI 4340 steel in two heat treated conditions, namely annealed and normalized. The importance of selecting the proper heat treated form before starting the rough machining is quite evident from this comparison. Note that for a tool life of 200 inches of work travel, the normalized 4340 steel must be peripheral end milled at 70 ft./min. as compared to 210 ft./min. for the annealed steel; a 300% increase in cutting speed.

End Mill Slotting (Normalized, 321-341 BHN)

The effect of cutting speed and cutting fluid on tool life in end mill slotting 4340 steel in the normalized condition is demonstrated in Figure 21, page 28. The soluble oil (1:20) was far superior to the highly sulfurized oil. For a tool life of 150 inches the cutting speed with the soluble oil was more than double that used with the highly sulfurized oil. As shown in Figure 22, page 28, the cutting speed at which a 4340 steel in the annealed condition (207-217 BHN) can be end mill slotted is far higher than that for a 4340 steel in the normalized condition. The cutting speed for the annealed 4340 steel was over 300% faster than for the normalized 4340 steel at a tool life of 200 inches of work travel.

It is demonstrated in Figure 23, page 29, that the feed should not exceed .002 in./tooth in slotting normalized 4340 steel with an end mill. The tool life decreased more than 40% when the feed was increased from .002 to .004 in./tooth.

3.1 AISI 4340 Steel (continued)

Drilling (Normalized, 321-341 BHN)

Comparisons of the results obtained in drilling the 4340 steel in the normalized condition (321-341 BHN) with two cutting fluids and at two feeds are shown in Figures 24 through 28, pages 29 through 31. As shown in Figure 24, page 29, the drill life was approximately the same for both the soluble oil (1:20) and the highly sulfurized oil at a feed of .002 in./rev. and a cutting speed of 50 ft./min. However, in the cutting speed range of 20 to 30 ft./min. and a feed of .005 in./rev. the soluble oil was appreciably better, see Figure 30, page 36. For a drill life of 175 holes, the cutting speed with the soluble oil was 30 ft./min. as compared to 20 ft./min. with the sulfurized oil.

Comparisons of the drill life results at the two feeds of .002 and .005 in./rev. for each of the cutting fluids are shown in Figures 26 and 27, pages 30 and 31. While the drill life with the lighter feed of .002 in./rev. was considerably greater than at a feed of .005 in./rev., the production rate was about 60% greater at the .005 in./rev. feed than at the lighter feed with equivalent drill life with the soluble oil.

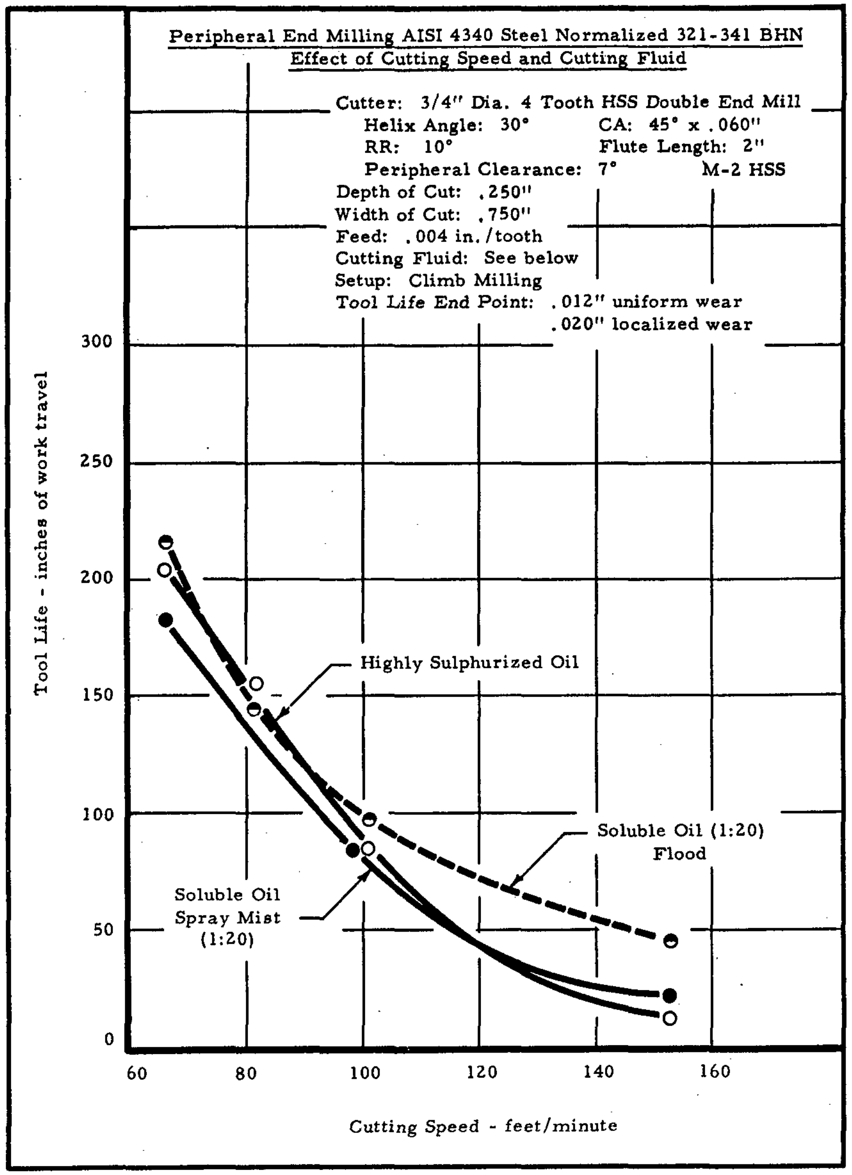
The advantage of machining in the annealed condition, although not as great as in the milling operations, also exists in drilling, see Figure 28, page 31. The cutting speed for a drill life of 175 holes was over 50% higher on the annealed steel as compared to the normalized steel.

TABLE 2

RECOMMENDED CONDITIONS FOR MACHINING
AISI 4340 STEEL - NORMALIZED 321-341 BHN

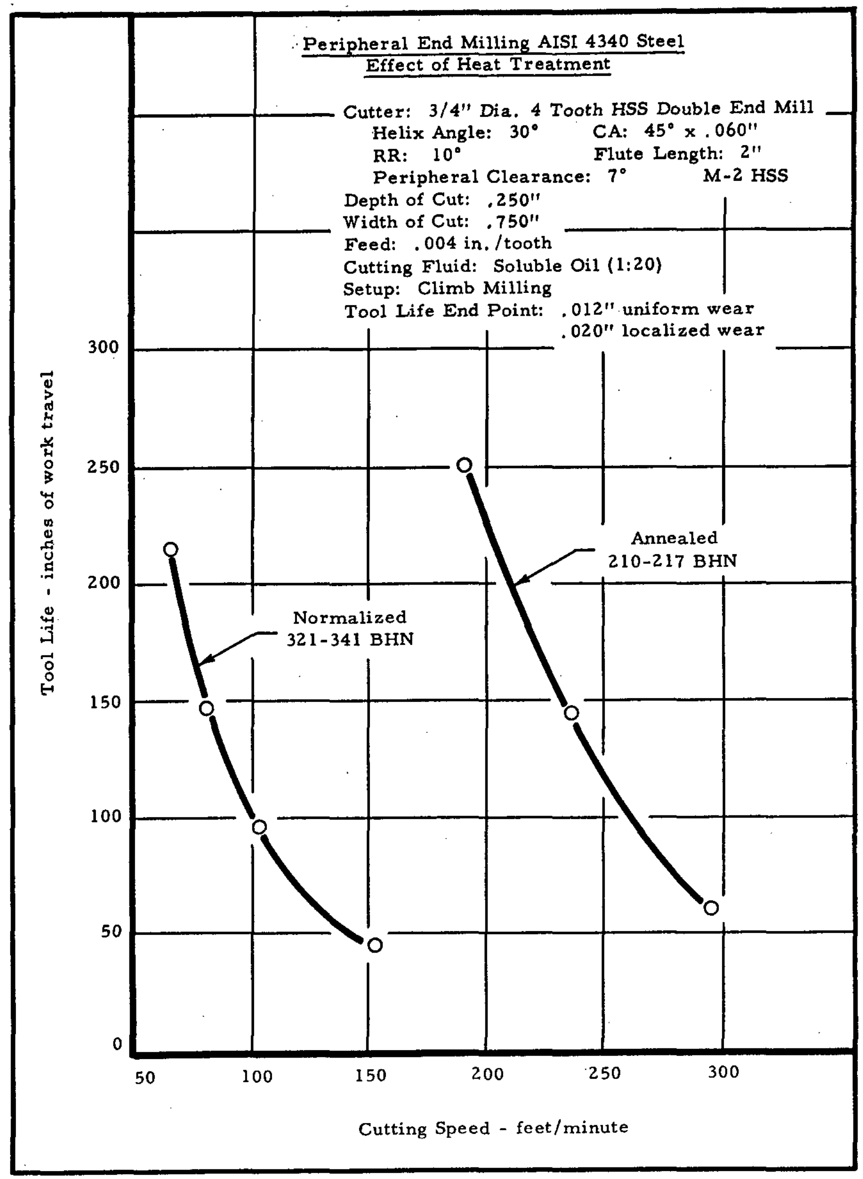
Cr	Ni	C	Fe
0.8	1.8	0.4	Bal

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	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.004 in./ tooth	70	220" work travel	.012	Soluble Oil (1:20)
End Mill Slotting	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.002 in./ tooth	45	180" work travel	.012	Soluble Oil (1:20)
Drilling	M-1 HSS	118° Plain Point 7° Clearance Angle	1/4" diameter drill 2-1/2" long	.500	-	.005 in./ rev.	30	175 holes	.015	Soluble Oil (1:20)



See Text, page 24

Figure 19



See Text, page 24

Figure 20

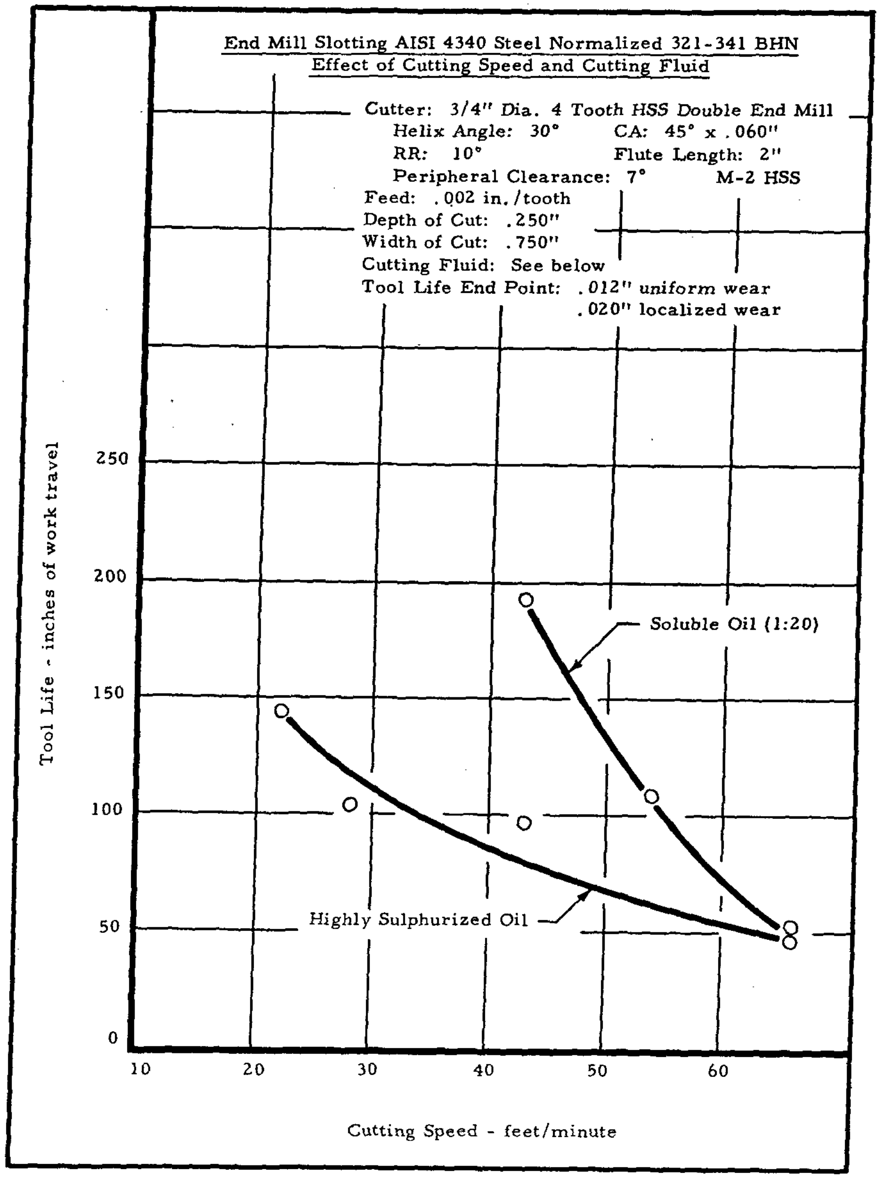


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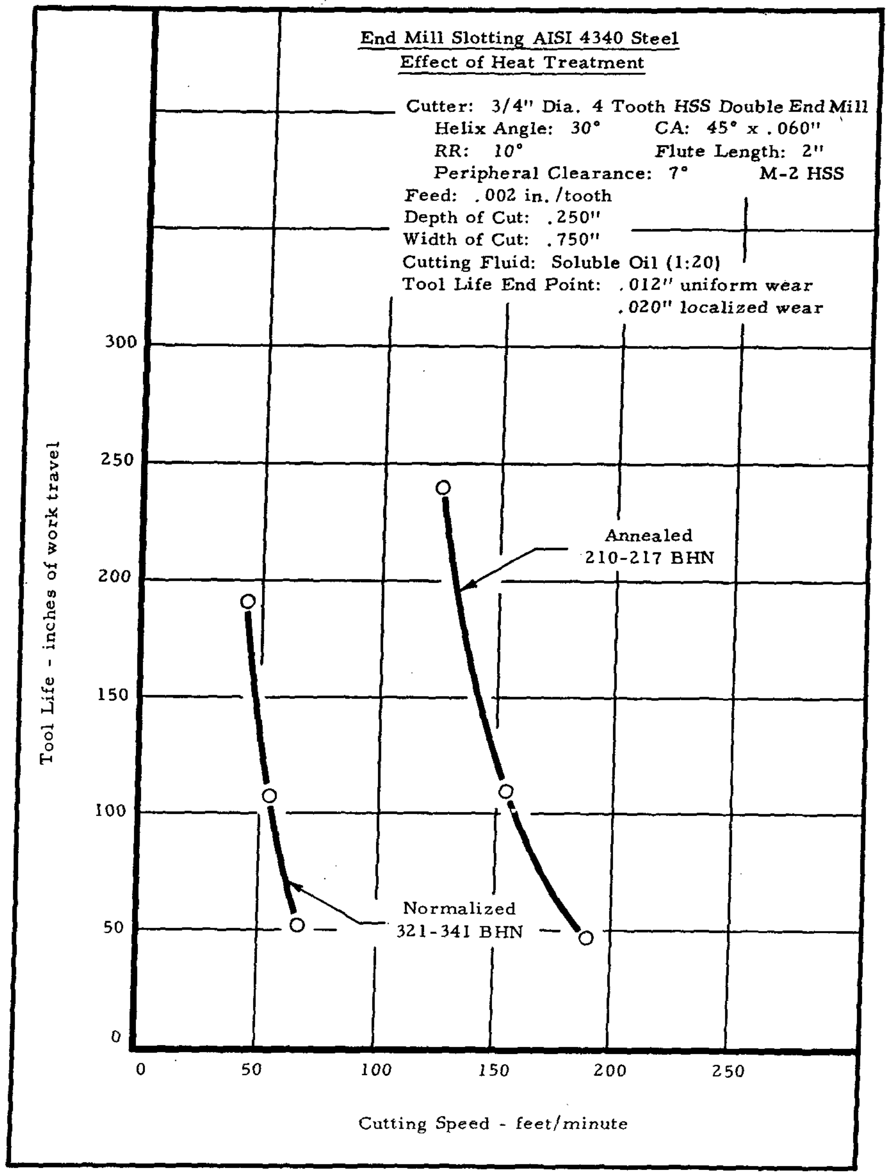
Figure 21



See Text, page 24

Figure 22

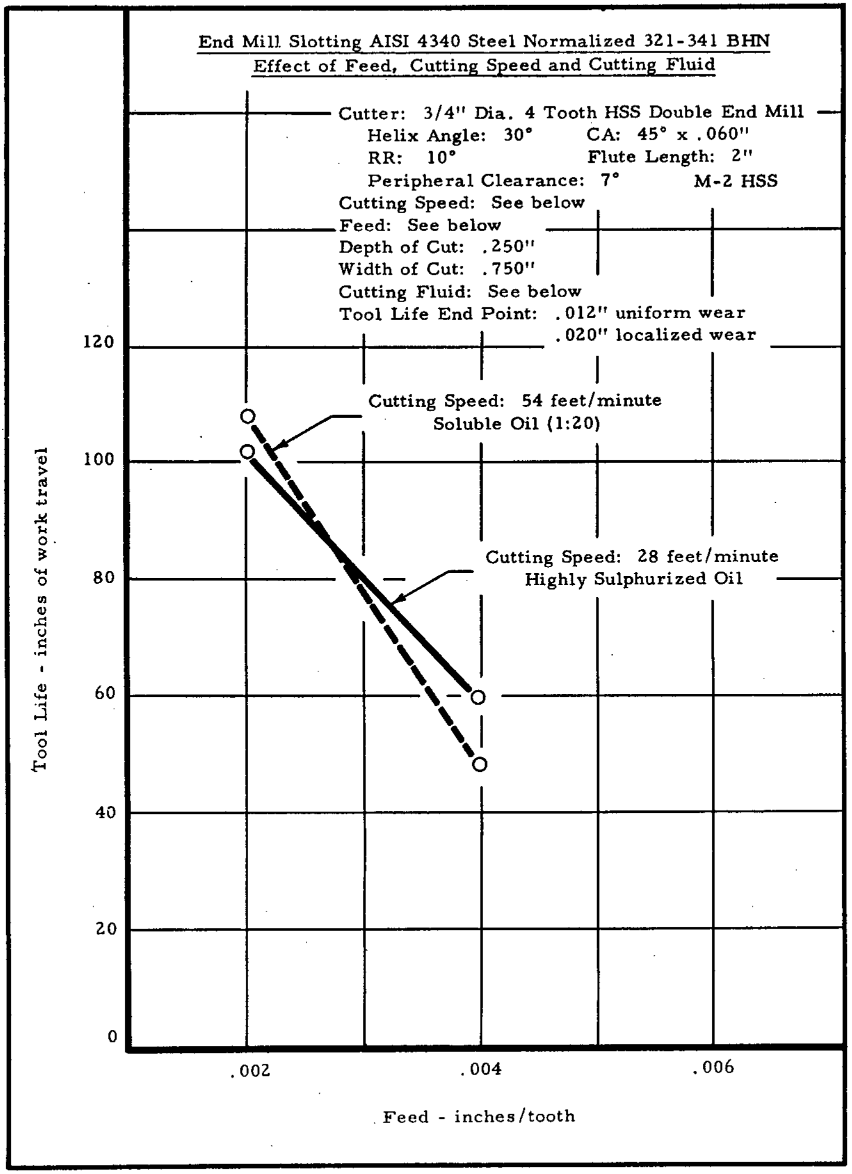


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Figure 23

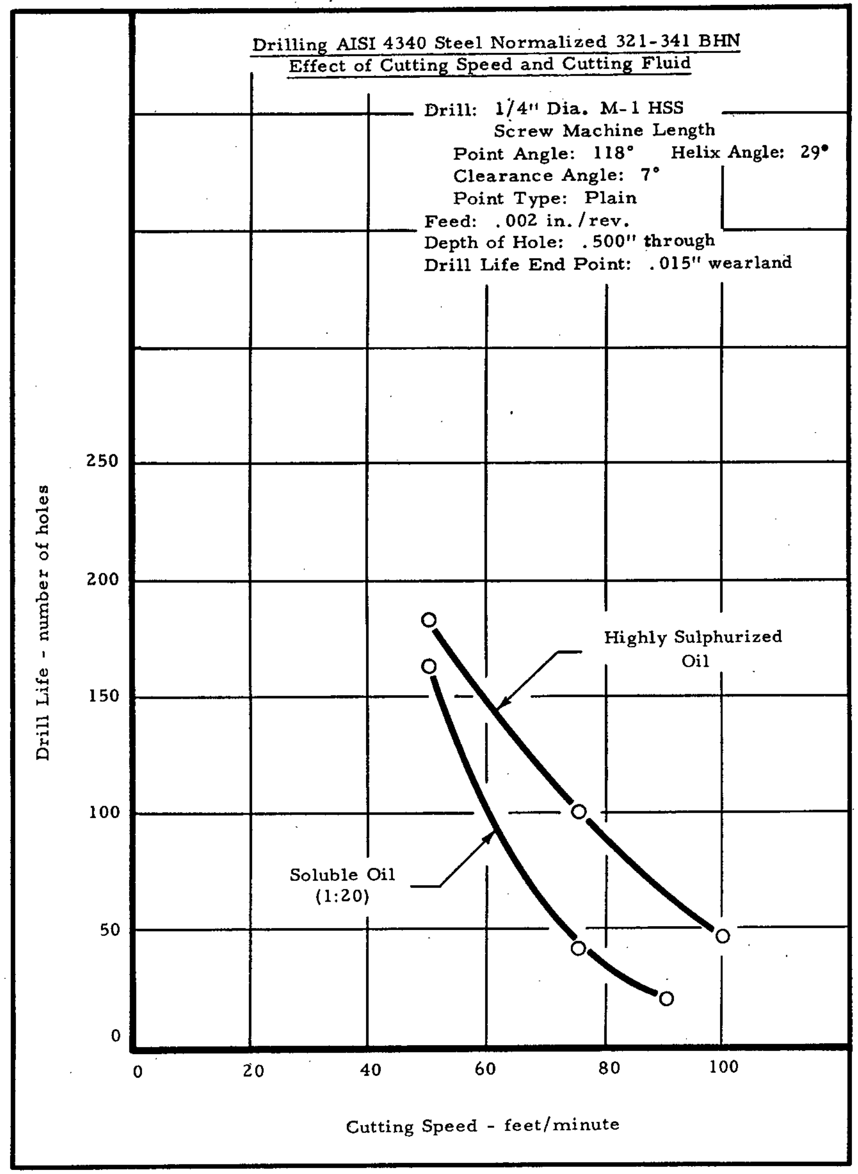

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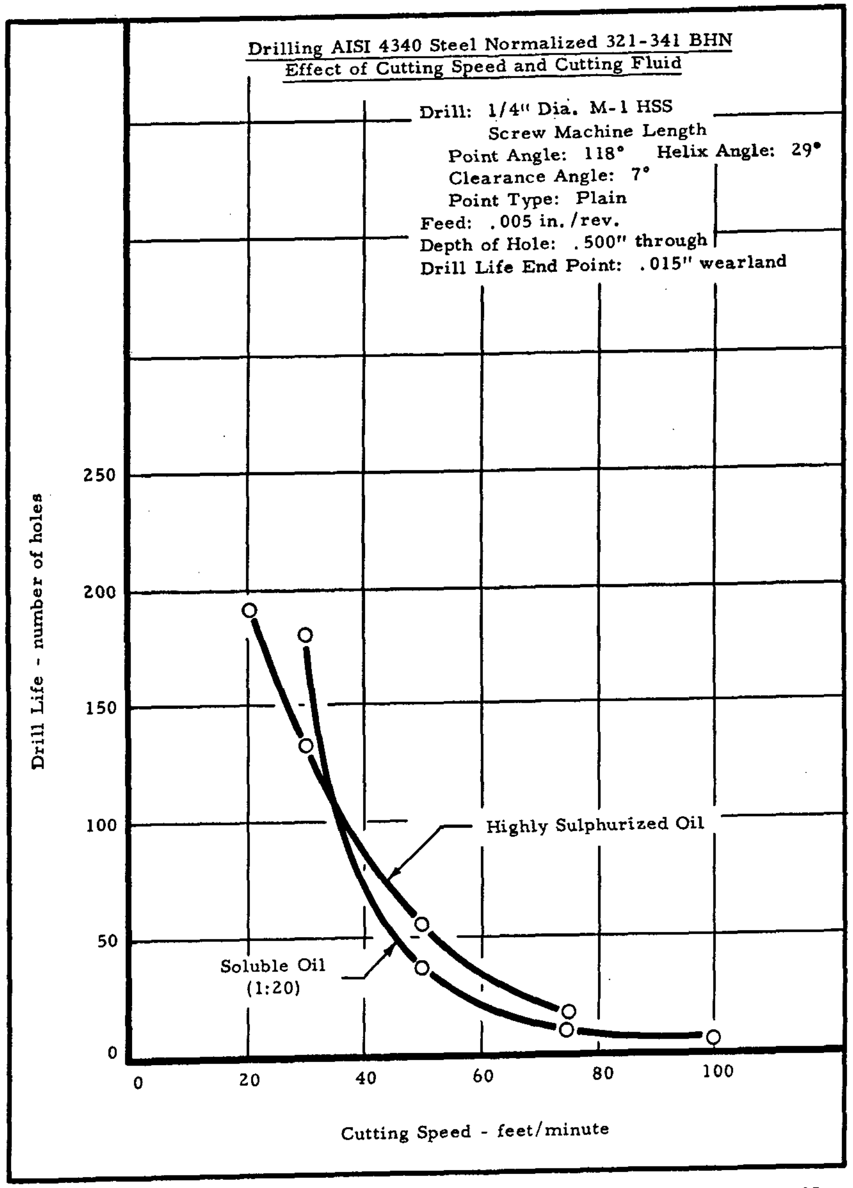
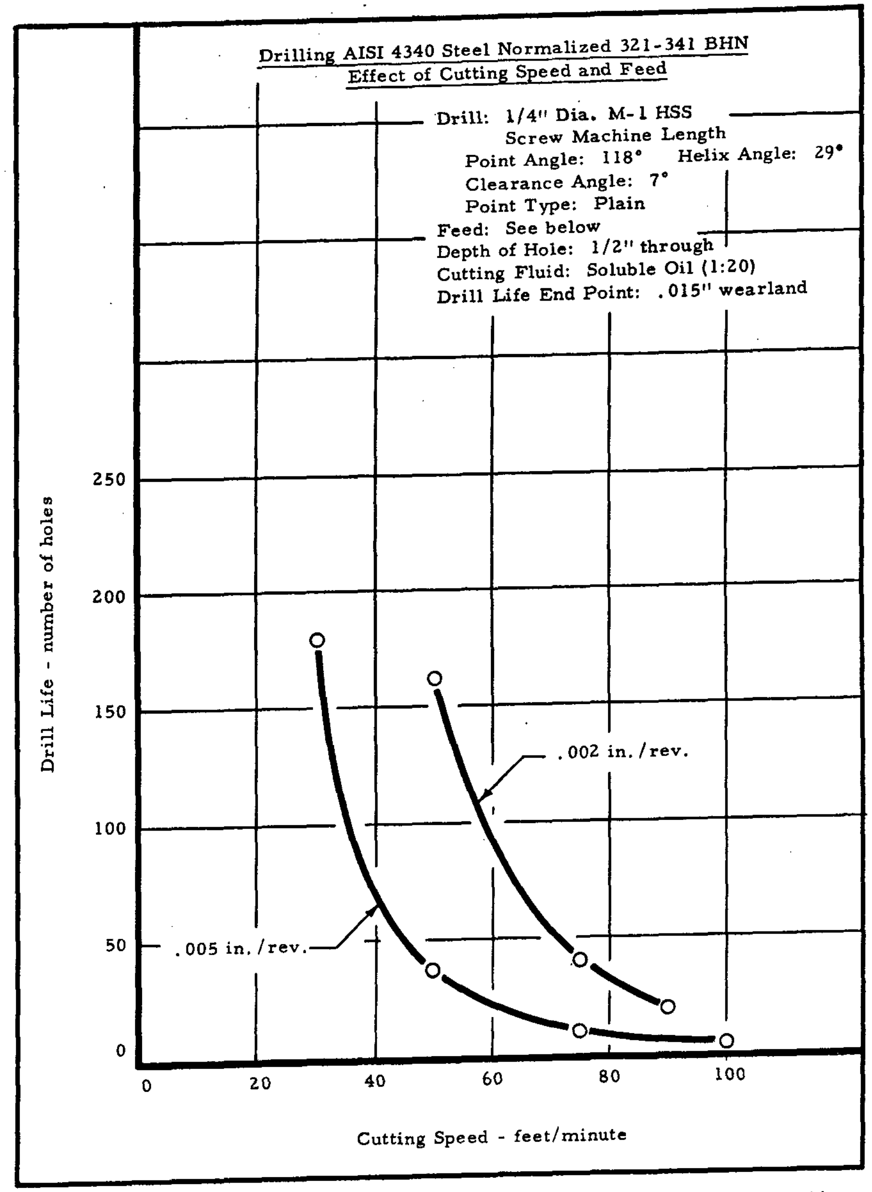
Figure 24



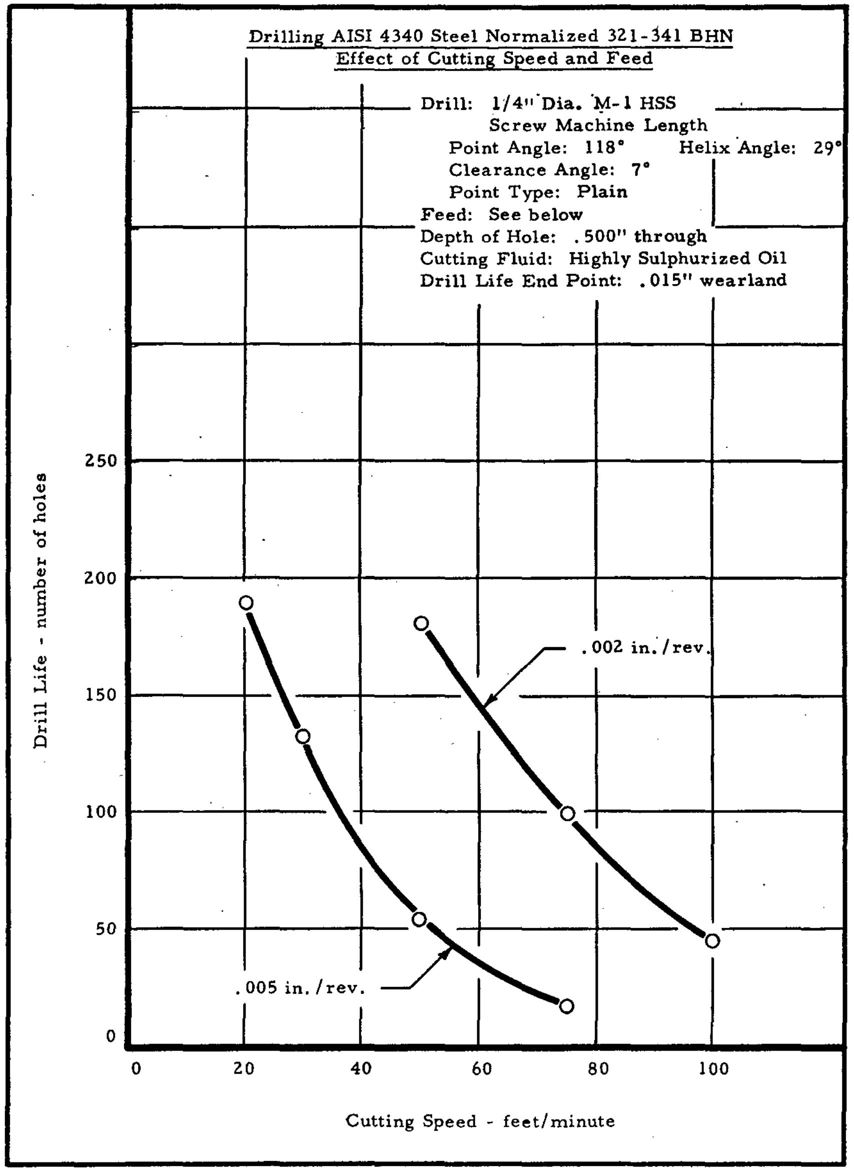
See Text, page 25

Figure 25



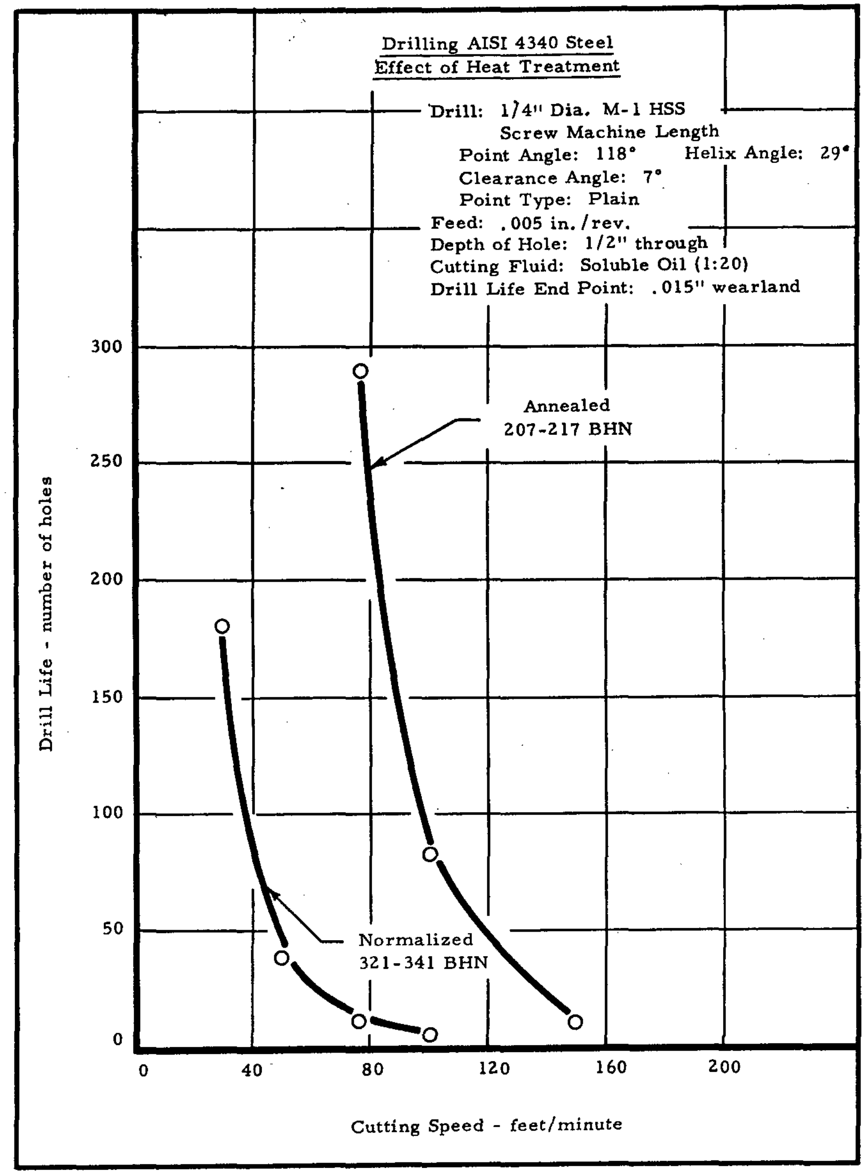
See Text, page 25

Figure 26



See Text, page 25

Figure 27



See Text, page 25

Figure 28

3.2 D6AC Steel

Alloy Identification

The nominal analysis of D6AC is as follows:

Fe - 1 Cr - 0.5 Ni - 1 Mo - 0.46 C

The material for the tests described in this report was procured as 2" x 4" bar stock in the hot rolled-annealed condition. To assure uniformity, the bars were re-annealed in annealing carbon as follows:

1450F/4 hours/furnace cool to 1200F/air cool

The resulting hardness was 217-229 BHN. The microstructure obtained, ferrite plus very fine pearlite, somewhat segregated, is illustrated below.

D6AC, Annealed

Etchant: Nital Mag: 1000X

Peripheral End Milling (Annealed, 217-229 BHN)

A comparison of conventional and climb milling is made in Figure 29, page 35, in peripheral end milling D6AC steel in the annealed condition having a hardness of 217-229 BHN. A 60% increase in cutting speed was accomplished by using climb milling over conventional milling.

The difference in cutter life when using a highly sulfurized oil or a soluble oil either in flooding the cutting tool or as a spray mist is negligible. As shown in Figure 30, page 35, cutter life was slightly longer when flooding the tool with soluble oil.

The test results presented in Figure 31, page 36, show that a feed of .004 in./tooth was optimum using either a soluble oil or a highly sulfurized oil. Cutter life decreased approximately 30% at a feed of .002 in./tooth and 20% at .005 in./tooth compared to a feed of .004 in./tooth.

End Mill Slotting (Annealed, 217-229 BHN)

Tool life curves for a range of cutting speeds using soluble oil and highly sulfurized oil are shown in Figure 32, page 36. Note that for equivalent tool life, the cutting speed with the soluble oil was approximately 20% faster than with the highly sulfurized oil. Note that in peripheral end milling the sulfurized oil was far superior to the soluble oil.

Figure 33, page 37, indicates the rapid decline in tool life as the feed was increased beyond .002 in./tooth. With the soluble oil at a cutting speed of 124 ft./min. cutter life decreased from 215 inches of work travel to 132 inches as the feed was increased from .002 to .004 in./tooth.

Drilling (Annealed, 217-229 BHN)

Figures 34 and 35, pages 37 and 38, present the tool life curves for drilling D6AC steel annealed (217-229 BHN) using feeds of .002 and .005 in./rev. with two different cutting fluids. Note in Figure 34, page 37, that for a given cutting speed the drill life with the .002 in./rev. feed was more than double that obtained with the feed of .005 in./rev. However, if the cutting speed is reduced approximately 30%, the higher feed of .005 in./rev. will produce the same number of holes as the lighter feed and at a much higher production rate. Almost the same situation existed when a soluble oil was used, see Figure 35, page 38.

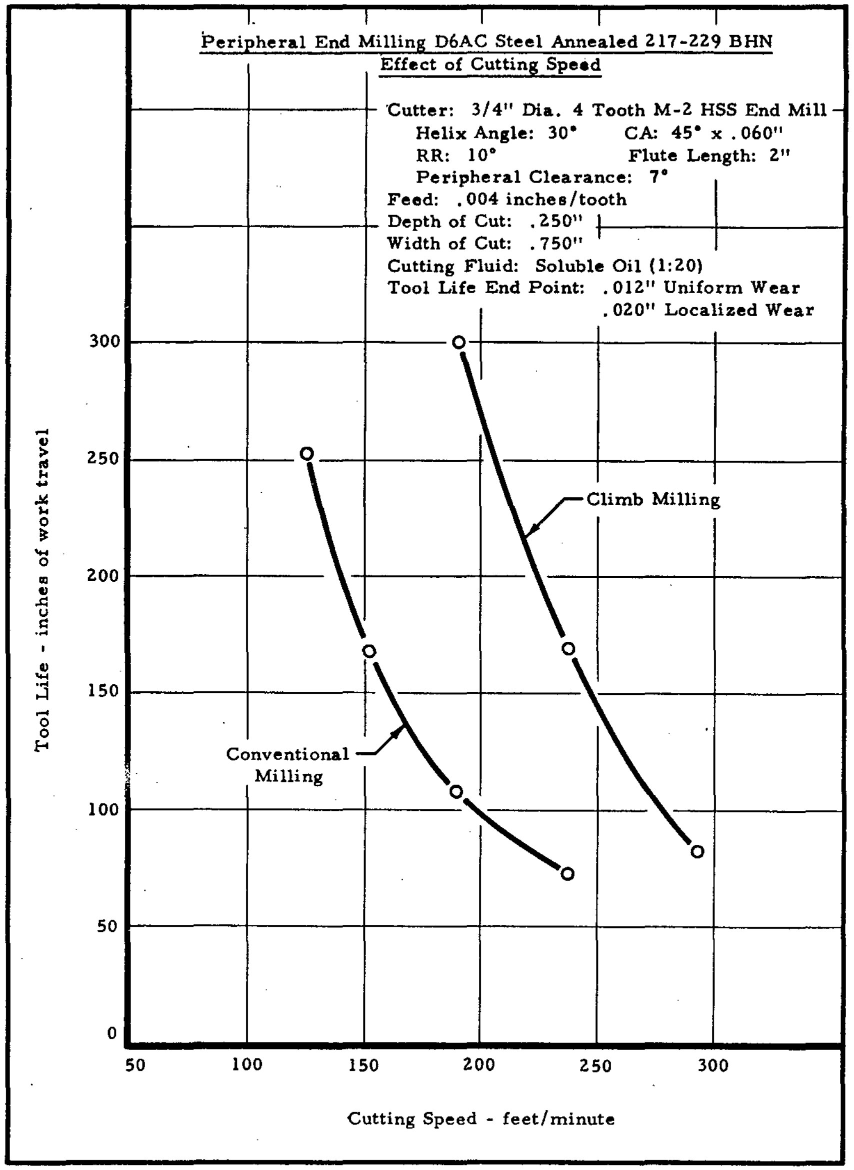
A comparison is also shown in Figure 34, page 37, of the tool life results obtained with a soluble oil and a highly sulfurized oil at a feed of .005 in./rev. An appreciable increase in drill life resulted when the highly sulfurized oil was used.

TABLE 3

RECOMMENDED CONDITIONS FOR MACHINING
D6AC STEEL - ANNEALED 217-229 BHN

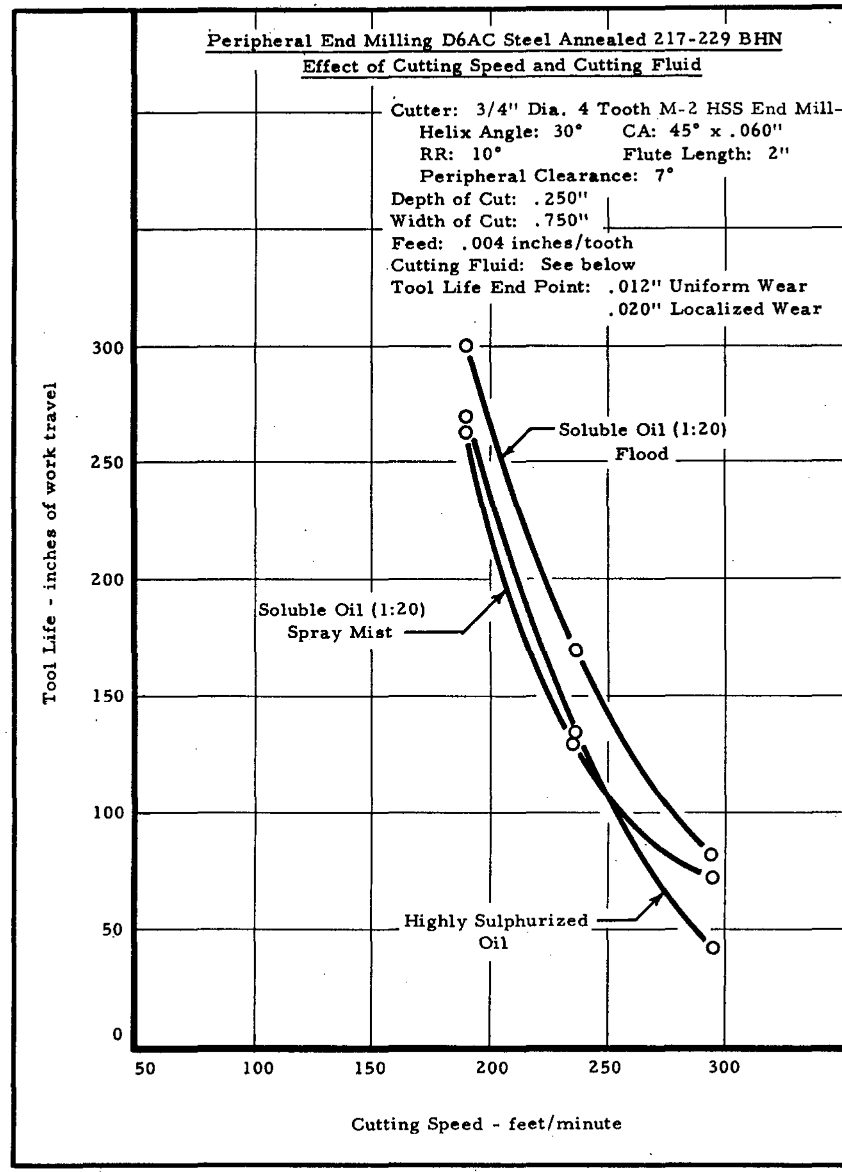
Cr	Ni	Mo	C	Fe
1.0	0.5	1.0	0.46	Bal

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	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.004 in./tooth	190	300" work travel	.012	Soluble Oil (1:20)
End Mill Slotting	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.002 in./tooth	125	220" work travel	.012	Soluble Oil (1:20)
Drilling	M-1 HSS	118° Plain Point 7° Clearance Angle	1/4" diameter drill 2-1/2" long	.500 thru	-	.005 in./rev.	90	175 holes	.015	Highly Sulphurized Oil



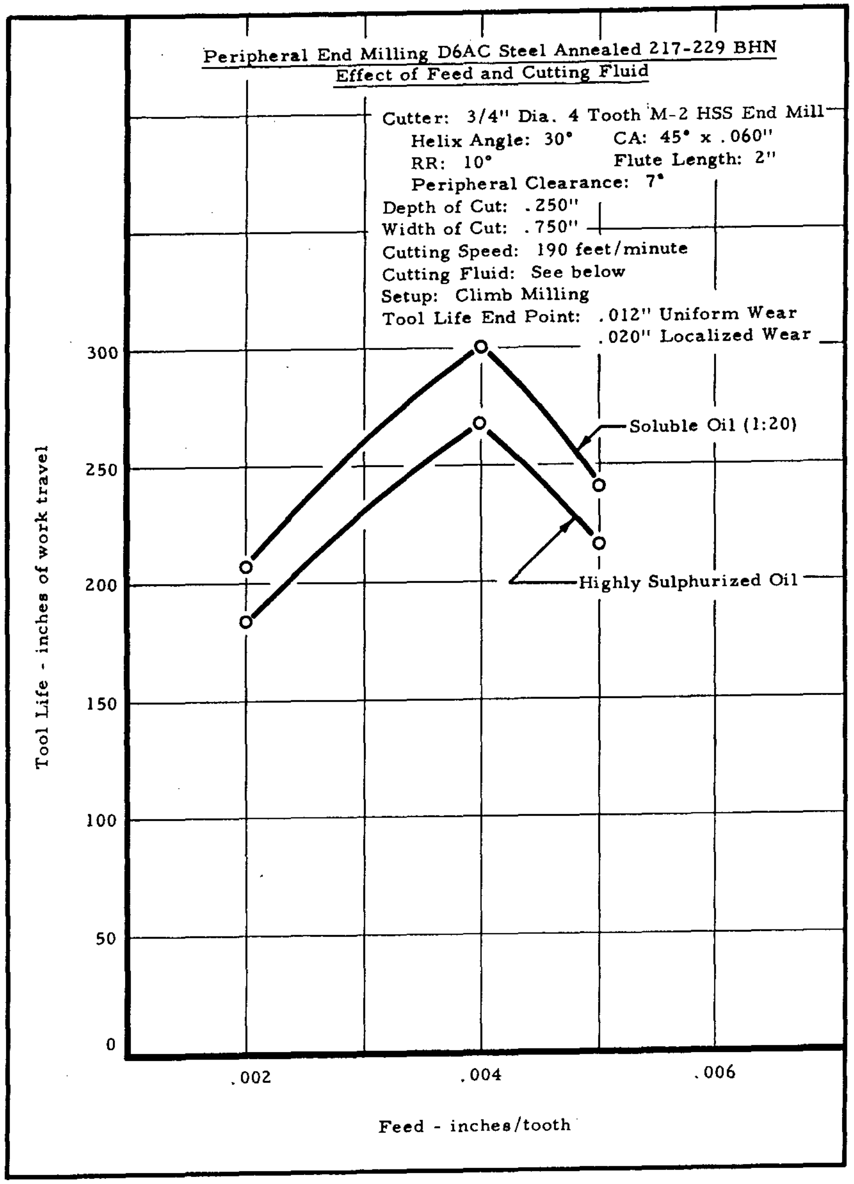
See Text, page 33

Figure 29



See Text, page 33

Figure 30



See Text, page 33

Figure 31

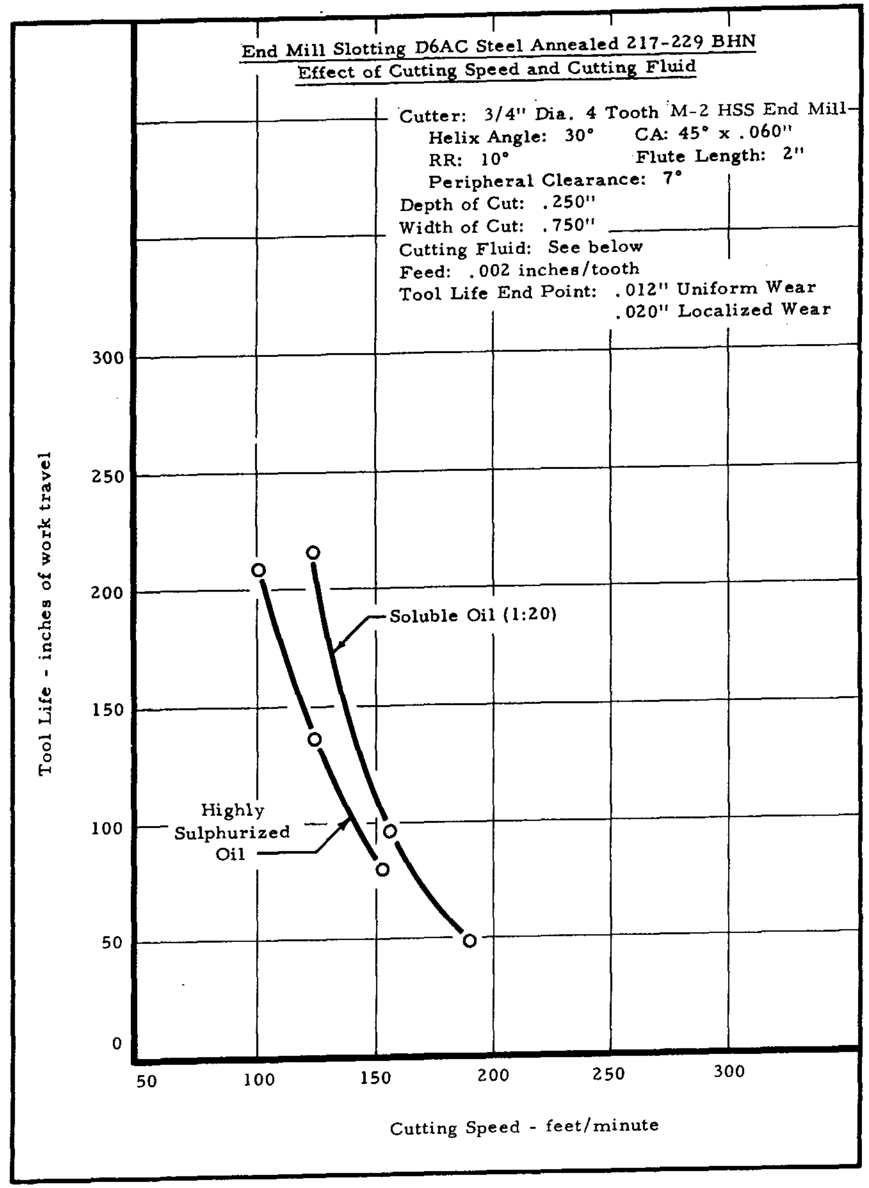


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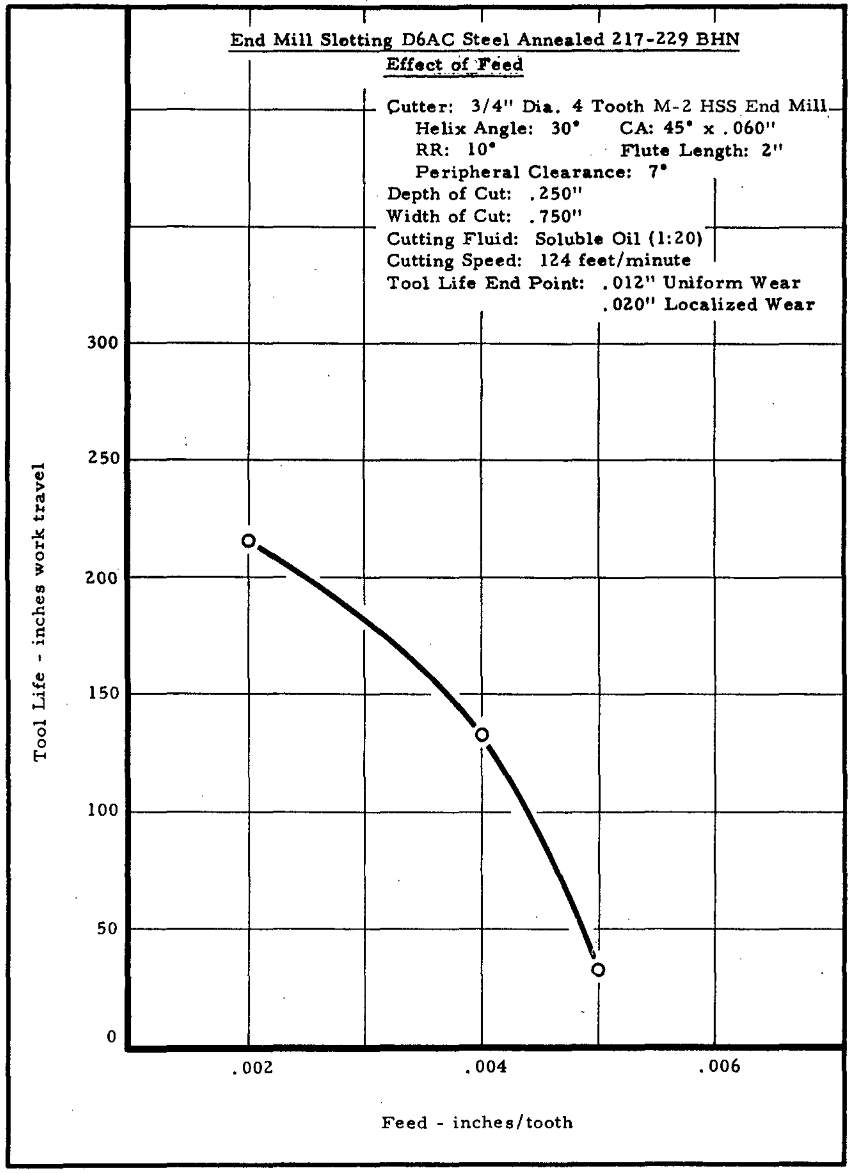
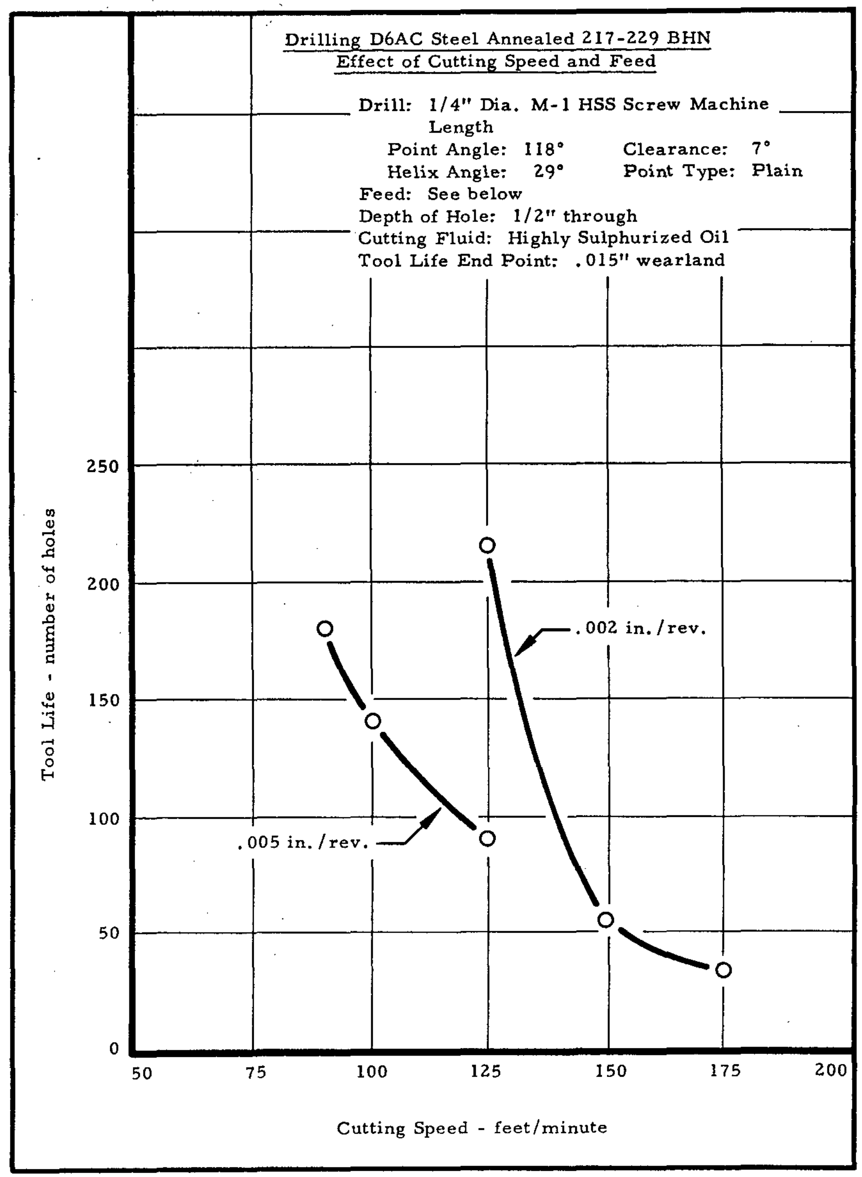
Figure 32



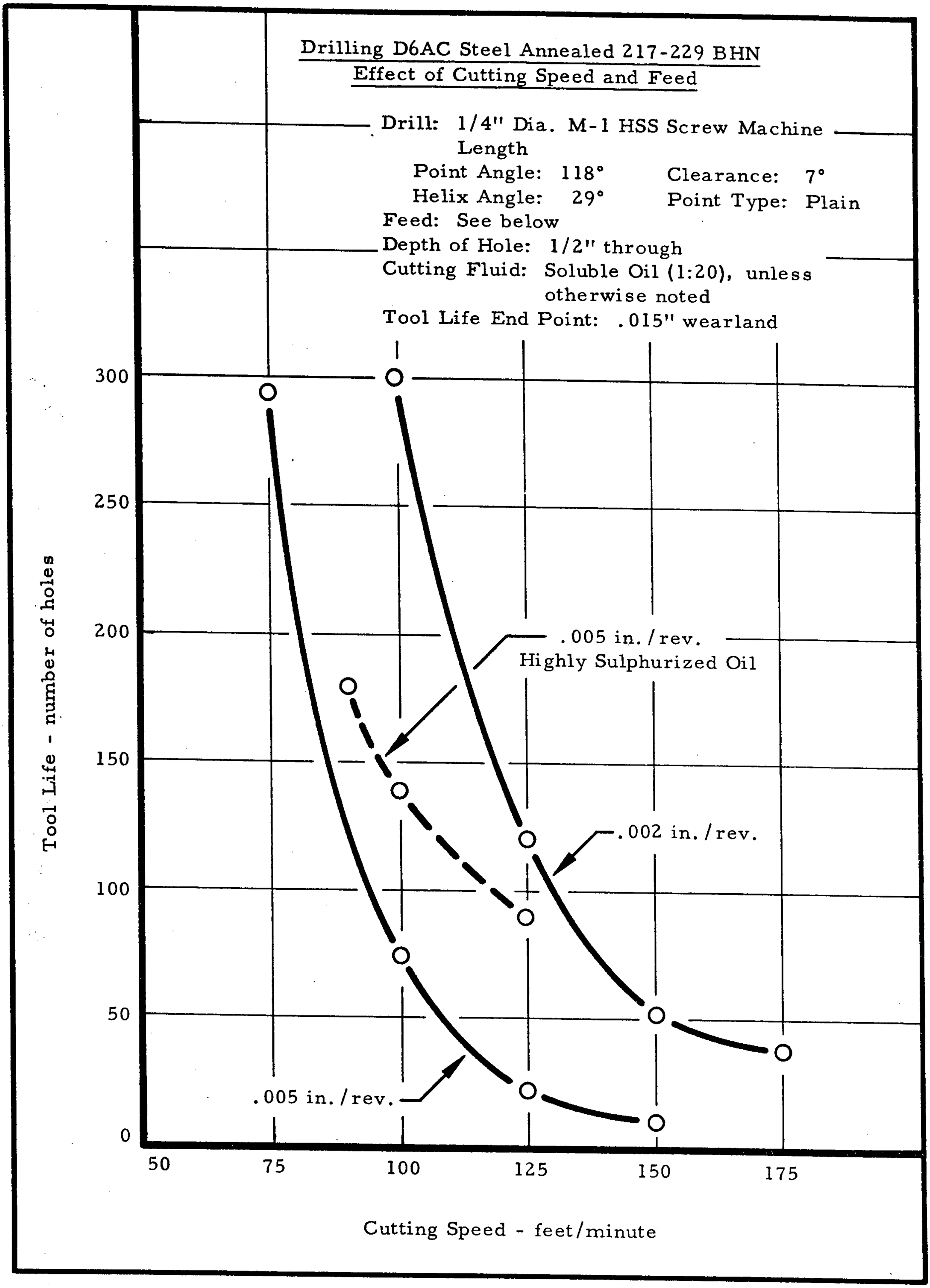
See Text, page 33

Figure 33



See text, page 33

Figure 34



See text, page 33

Figure 35

3.3 18% Nickel 250 Grade Maraging Steel

Alloy Identification

The nominal analysis of the 250 grade maraging steel is as follows:

Fe-18Ni-7.8Co-4.9Mo-.02C-.5Ti-.1Al

The alloy is normally martensitic and may be further strengthened by an aging process known as maraging.

The material for the machining tests was procured as 4" square bars in the hot rolled-annealed condition. This material had been solution annealed at the mill as follows:

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

The resulting solution annealed hardness was 311-341 BHN. The microstructure of the annealed material, consisting of roughly equiaxed plate-like martensite, is shown below.

18% Nickel 250 Grade Maraging Steel, Annealed

Etchant: $FeCl_3$ Mag: 500X

A portion of this material was also evaluated in the aged condition, using the standard maraging treatment, as follows:

900°F/3 hours/air cool

3.3 18% Nickel 250 Grade Maraging Steel (continued)

This treatment resulted in a hardness of 50-53 R_C. The microstructure of the aged grade, which is illustrated below, consists of a martensitic matrix strengthened by intermetallics precipitated from the aging operation.

18% Nickel 250 Grade Maraging Steel, Aged

Etchant: $FeCl_3$ Mag: 500X

Turning (Annealed, 341 BHN)

The effect of cutting fluid on tool life in turning the 18% nickel 250 grade maraging steel in the annealed condition with HSS tools is shown in Figure 36, page 48. The soluble oil (1:20) used in turning this steel with type M-2 HSS tools permitted a 10% higher cutting speed than the highly chlorinated oil for a given tool life. A comparison of the two types of cutting fluids at a cutting speed of 80 ft./min. shows that the tool life with the highly chlorinated oil was only 36 minutes as compared to 82 minutes with the soluble oil (1:20).

The results of turning with two types of HSS tools are plotted in Figure 37, page 48. The T-15 HSS tools permitted a 7% higher cutting speed than the M-2 HSS tools for a tool life of 60 minutes. The cutting speed was 84 ft./min. with the M-2 tool and 90 ft./min. with the T-15 tool.

3.3 18% Nickel 250 Grade Maraging Steel (continued)

Four grades of carbides are compared in Figure 38, page 49, in turning. Note the steepness of the tool life curves. Increasing the cutting speed from 490 ft./min. to 500 ft./min. with the K-8 (the best of the group tested) carbide resulted in decreasing the tool life from over 40 minutes to less than 10 minutes. The 883, 370 and K-68 tools did not perform as well as the K-8 carbide.

As indicated in Figure 39, page 49, a 20% increase in cutting speed was obtained by using a soluble oil (1:20) instead of cutting dry in turning the 250 grade steel in the annealed condition with a carbide tool.

Face Milling (Annealed 321 BHN)

A comparison of T-15 and M-2 high speed steels is shown in Figure 40, page 50, in face milling 250 grade maraging steel annealed to 321 BHN over a range of feeds. The average tool life was about 30% higher with the T-15 over the M-2. Also, both types of high speed steels produced appreciably higher tool life at the lighter feeds. However, as shown in Figure 41, page 50, if the cutting speed is reduced about 25%, a reasonable cutter life can be obtained at a feed of .005 in./tooth with both types of high speed steels. Thus, for equivalent tool life, the production rate would be appreciably higher by using a cutting speed of 142 ft./min. and a feed of .005 in./tooth than at a cutting speed of 178 ft./min. and a feed of .003 in./tooth. The difference in the performances of the T-15 and M-2 high speed steels was not significant at the lower cutting speed and a feed of .005 in./rev.

Note in Figure 42, page 51, that the tool life with the highly chlorinated oil was about 30% longer at a cutting speed of 142 ft./min. than that obtained with a soluble oil using an M-2 high speed steel cutter.

Figure 43, page 51, shows the effect of tool geometry on tool life in face milling the skin of the annealed 250 grade maraging steel. It is quite apparent that axial rake should be positive, while the radial rake should be about 0° for the longest tool life. The combination of 10° positive axial rake with a 0° radial rake angle produced a 60% longer tool life than that obtained with -7°, -7° axial and radial rake angles. In Figure 44, page 52, a comparison is made of face milling both the skin and under the skin over a range of feeds. Note that a different cutting speed was used for each curve. The effect of feed on tool life is more critical when cutting the skin. The tool life dropped from 140 to 12 inches of work travel as the feed was increased from .003 to .008 in./tooth, while when face milling under the skin for the same feed range, the tool life dropped less than 50%. Again, by using a slower cutting speed, as shown in Figure 45, page 52, a reasonable tool life can be obtained at a feed of .005 in./tooth. Note in Figure 45, page 52, that for a given tool life the cutting speed under the skin was almost double that when face milling the skin.

It is quite obvious from Figure 46, page 53, that the annealed 250 grade maraging steel should be face milled dry. At a given cutting speed, the tool life was almost double that obtained with a soluble oil.

A comparison is made in Figure 47, page 53, between a single tooth and an eight tooth cutter in face milling 250 grade maraging steel annealed to 321 BHN. It is quite apparent from these curves that the cutter life per tooth was appreciably less with the multiple tooth cutter. However, it should be noted that while, for a given tool life per tooth the single tooth cutter performed at twice the cutting speed at which the eight tooth cutter performed, the eight tooth cutter was still producing chips four times as fast as the single tooth cutter. Since the cutter had eight teeth and was cutting at approximately half the cutting speed, the production rate was four times as great.

Side Milling (Annealed 321 BHN)

Figure 48, page 54, shows the effect of tool geometry on tool life in side milling 250 grade maraging steel annealed to 321 BHN. The differences in the tool life values obtained were not very great for the three tool geometries used. However, the tool with the positive rake angles did produce the longest tool life. Using a tool with 5° positive axial and radial rake angles, it was found as shown in Figure 49, page 54, that the tool life was longer for the lighter feeds. At a feed of .003 in./tooth a tool life of 145 inches of work travel was obtained, while at a feed of .005 in./tooth the tool life was 95 inches of work travel. Nevertheless, it was found that by reducing the cutting speed, a reasonable tool life could be obtained with a feed of .005 in./tooth. For example, as shown in Figure 50, page 55, with the K-6 carbide a tool life of 180 inches of work travel was obtained at a cutting speed of 675 ft./min. using a feed of .005 in./tooth.

Peripheral End Milling (Annealed 321 BHN)

A feed of about .004 in./tooth was found to be the optimum for the conditions shown in Figure 51, page 55, for peripheral end milling 250 grade maraging steel in the annealed condition. This feed produced the longest tool life with both the soluble oil and the highly chlorinated cutting fluids. The tool life at a feed of .006 in./tooth was only 50% of that obtained at a feed of .004 in./tooth. Note also that the tool life was 50% better using a soluble oil over that obtained using a highly chlorinated oil. Figure 52, page 56, illustrates how the tool life changes with cutting speed when using a feed of .004 in./tooth. This chart indicates that the cutting speed should be about 175 ft./min. when peripheral end milling the annealed maraging steel.

Cutter deflection is one of the more serious problems in peripheral end milling of deep pockets. When this occurs, the machined surface along the axial length of the cutter (width of cut) is tapered. This condition is illustrated by Figure 53, page 56.

A comparison is shown in Figure 54, page 57, of the cutter deflection that occurred for various flute lengths as the tool became dull at a depth of cut of .125" for 3/4" dia. cutters. Note that the deflection with a cutter having a 3" flute length was almost six times greater than that with a cutter having a 3/4" flute length when the wearland was .008". It is also interesting to note that the deflection with both of the cutters having 3/4" and 1-5/8" flute lengths remained constant as the wearland increased up to .008".

In Figure 55, page 57, with a depth of cut of .250" the deflection of the cutter increased rapidly as the wearland on the cutter developed. For example, with the cutter having 3/4" flute length the deflection was .005" at a wearland of .004" and .008" deflection at a wearland of .008". Note also that the flute length of the cutter was more critical for the higher depth of cut.

Figure 56, page 58, shows the deflection that resulted with a cutter having a 3" flute length for various depths of cut as a tool became dull. Note that the deflection of the cutter was from 2-1/2 to 4 times greater at a depth of cut of .250" as compared to a depth of cut of .062" for a 3/4" dia. cutter.

End Mill Slotting (Annealed 321 BHN)

Cutter life in end mill slotting 250 grade maraging steel in the annealed condition is sensitive to the feed. As shown in Figure 57, page 58, the cutter life was negligible at .003 in./tooth using soluble oil at a speed of 143 ft./min., while at .002 in./tooth 62 inches of work was slotted. The feed was less critical when using the highly chlorinated oil, for the tool life at .002 in./tooth was 84 inches as compared to 72 inches for .003 in./tooth feed. A more drastic change in tool life occurred, however, when the feed was increased still further to .004 in./tooth.

In order to get a reasonable cutter life one should use an active cutting oil such as a highly chlorinated oil. As shown in Figure 58, page 59, a maximum tool life even at a cutting speed of 115 ft./min. was only 65 inches of work travel when using a soluble oil. However, with the highly chlorinated oil, at a cutting speed of 142 ft./min. a cutter life of 200 inches of work travel was obtained.

As shown in Figure 59, page 59, the T-15 high speed steel cutter produced appreciably longer tool life than the M-2 high speed steel cutter when using a soluble oil. At a cutting speed of 145 ft./min., the cutter life with the M-2 high speed steel tool was 60 inches of work travel as compared to 120 inches with the T-15 high speed steel cutter.

Drilling (Annealed 321 BHN)

A comparison of the tool life curves obtained with three different types of cutting fluids over a range of feeds is shown in Figure 60, page 66. Note that drill life dropped sharply when the feed was decreased from .005 in./rev. to .002 in./rev. using a high sulfurized oil. Under the same conditions but with a highly chlorinated oil, a sharp increase in drill life resulted when the feed was decreased to .002 in./rev. A further comparison of the three cutting fluids is shown in Figure 61, page 60, for a range of cutting speeds. A feed of .005 in./rev. was used in these tests. The highly sulfurized oil was superior to both of the other two types of cutting fluids. For a drill life of 125 holes, the cutting speed was 10% higher with the highly sulfurized oil as compared to the highly chlorinated oil. The soluble oil was the poorest of the three.

The curves in Figure 62, page 61, compare the results obtained in drilling 1/2" deep through holes with 1/2" deep blind holes. Note that for a given drill life the through holes could be drilled 10% faster than the blind holes. Also, at a cutting speed of 100 ft./min. the drill life on the blind holes was 25 holes as compared to 125 through holes.

Data is presented in Figure 63, page 61, for deep hole drilling the 250 grade maraging steel in the annealed condition. The drill diameter was 1/8" and the depth of hole 1/2". A drill life of 75 holes was obtained at a cutting speed of 55 ft./min. when the hole was drilled in one step. The cutting speed could be increased to 75 ft./min. with the same drill life when the hole was drilled in two steps (1/4" deep each step). By drilling the hole in three steps, namely 1/4", 1/8" and 1/8", the drilling speed could be further increased to 85 ft./min.

3.3 18% Nickel 250 Grade Maraging Steel (continued)

Reaming (Annealed 321 BHN)

Active cutting oils appear to be much more effective in reaming 250 grade maraging steel in the annealed condition than soluble oil. As shown in Figure 64, page 62, with either the highly sulfurized or highly chlorinated oil the cutting speed for a given number of holes reamed was more than double that obtained with a soluble oil. At a feed of .009 in./rev., this steel could be reamed at a cutting speed of 150 ft./min. using one of the active cutting oils.

Tapping (Annealed 321 BHN)

A tool life curve showing a relationship between tool life and number of holes tapped and cutting speed is presented in Figure 65, page 62. With the highly sulfurized oil it was possible to tap 175 holes at a cutting speed of 150 ft./min.

TABLE 4

RECOMMENDED CONDITIONS FOR MACHINING
18% NICKEL 250 GRADE MARAGING STEEL - ANNEALED 321-341 BHN

Ni	Co	Mo	C	Ti	Al	Fe
18	7.8	4.9	.02	.5	.1	Bal

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	M-2 HSS	BR: 0° SCEA: 15° SR: 10° ECEA: 5° Relief: 5° NR: .030"	5/8" square tool bit	.060	-	.009 in./rev.	80	85 min.	.060	Soluble Oil (1:20)
Turning	C-3 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square throwaway insert	.060	-	.009 in./rev.	475	40 min.	.010	Soluble Oil (1:20)
Face Milling	M-2 HSS	AR: 5° ECEA: 10° RR: 5° CA: 45° Clearance: 8°	4" diameter single tooth face mill	.060	2	.005 in./tooth	140	200" work travel	.060	Highly Chlorinated Oil
Face Milling	C-2 Carbide	AR: 10° ECEA: 10° RR: 0° CA: 45° Clearance: 8°	4" diameter single tooth face mill	.060	2	.005 in./tooth	330	150" work travel	.015	Dry
Side Milling	C-2 Carbide	AR: 5° ECEA: 10° RR: 5° CA: 45° Clearance: 8°	4" diameter single tooth face mill	.100	1	.005 in./tooth	670	175" work travel	.015	Dry
Peripheral End Milling	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.004 in./tooth	225	150" work travel	.012	Soluble Oil (1:20)

TABLE 4 (continued)
RECOMMENDED CONDITIONS FOR MACHINING

18% NICKEL 250 GRADE MARAGING STEEL - ANNEALED 321 - 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
End Mill Slotting	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.002 in/tooth	140	200" work travel	.012	Highly Chlorinated Oil
Drilling	M-1 HSS	118° Plain Point Clearance: 7°	1/4" diameter HSS drill 2 1/2" long	.500 thru	-	.005 in/rev	100	140 holes	.015	Highly Sulphurized Oil
Reaming	M-2 HSS	Helix Angle: 0° CA: 45° Clearance: 7°	.272" diameter 6 flute chucking reamer	.500 thru	-	.009 in/rev	60	170 holes	.006	Highly Sulphurized Oil
Tapping	M-1 HSS	2 Flute Plug 75% thread	5/16 - 24 NF tap	.500 thru	-	-	150	175 holes	Under-size threads	Highly Sulphurized Oil

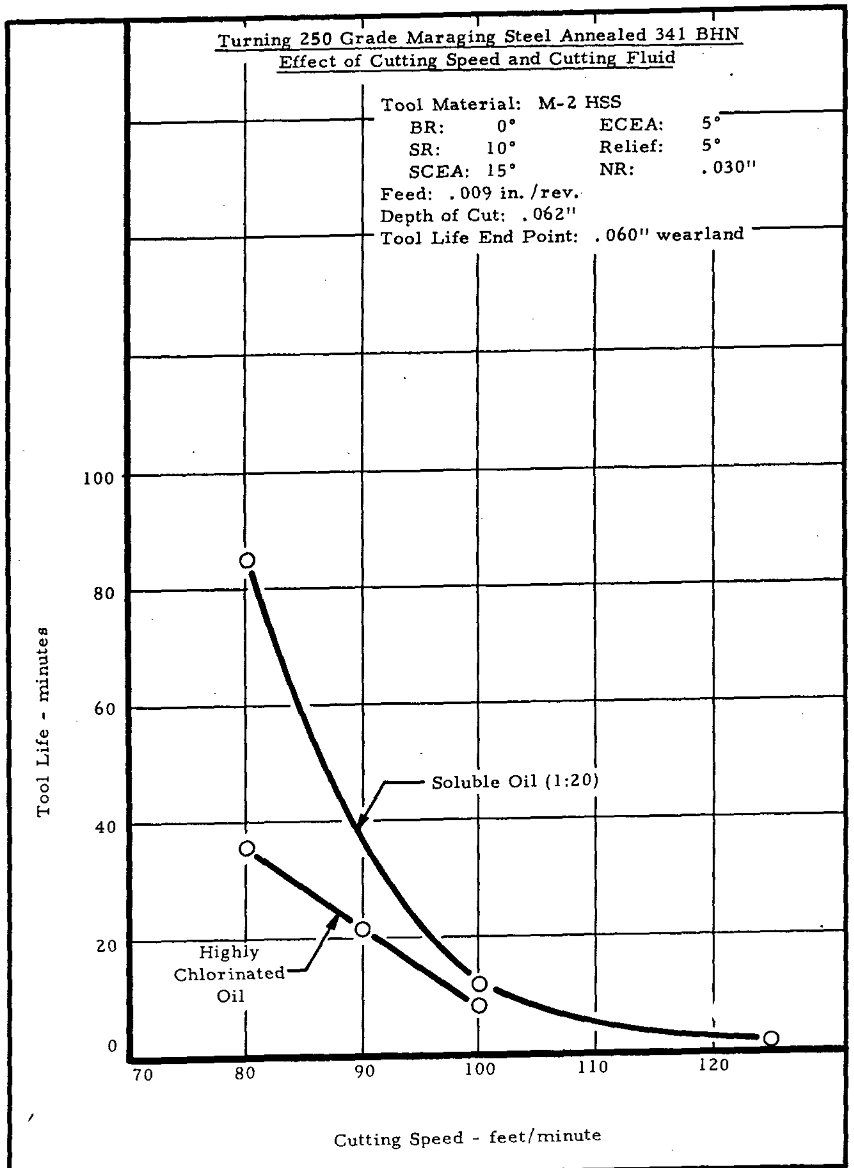


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Figure 36

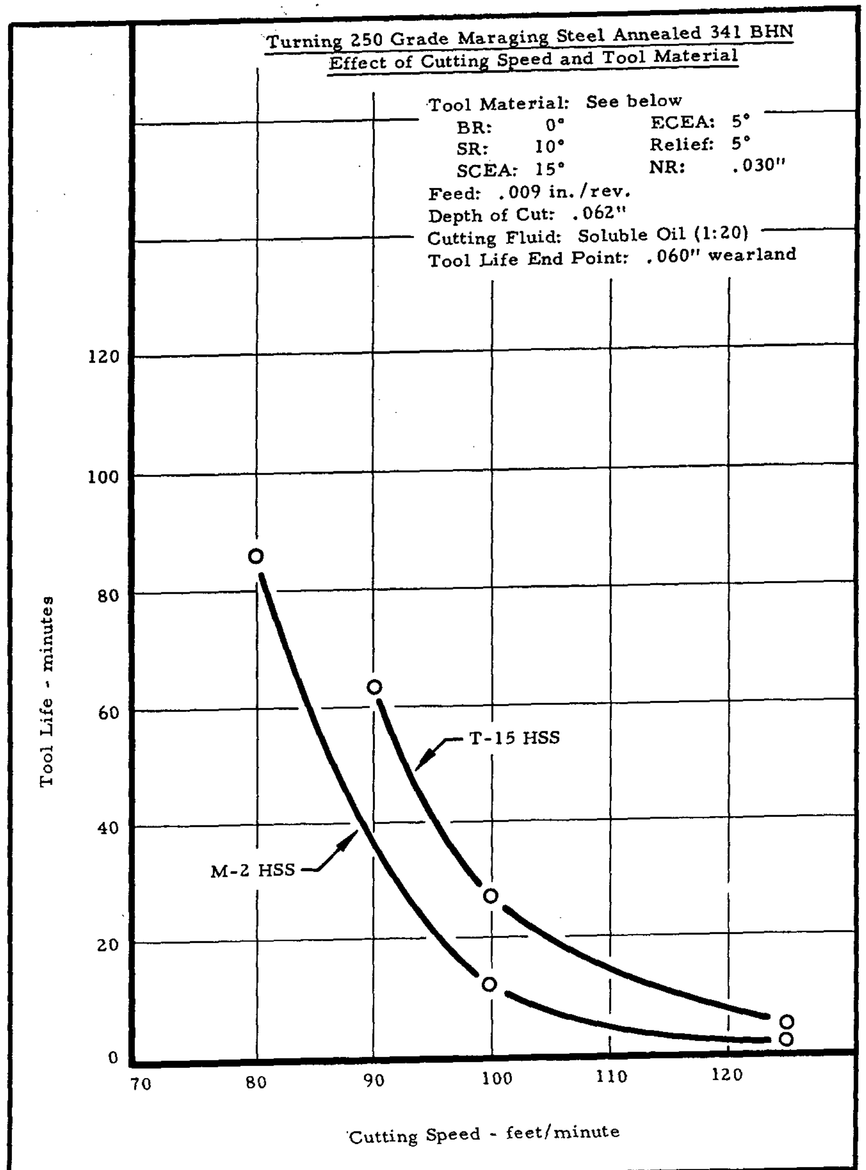

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Figure 37

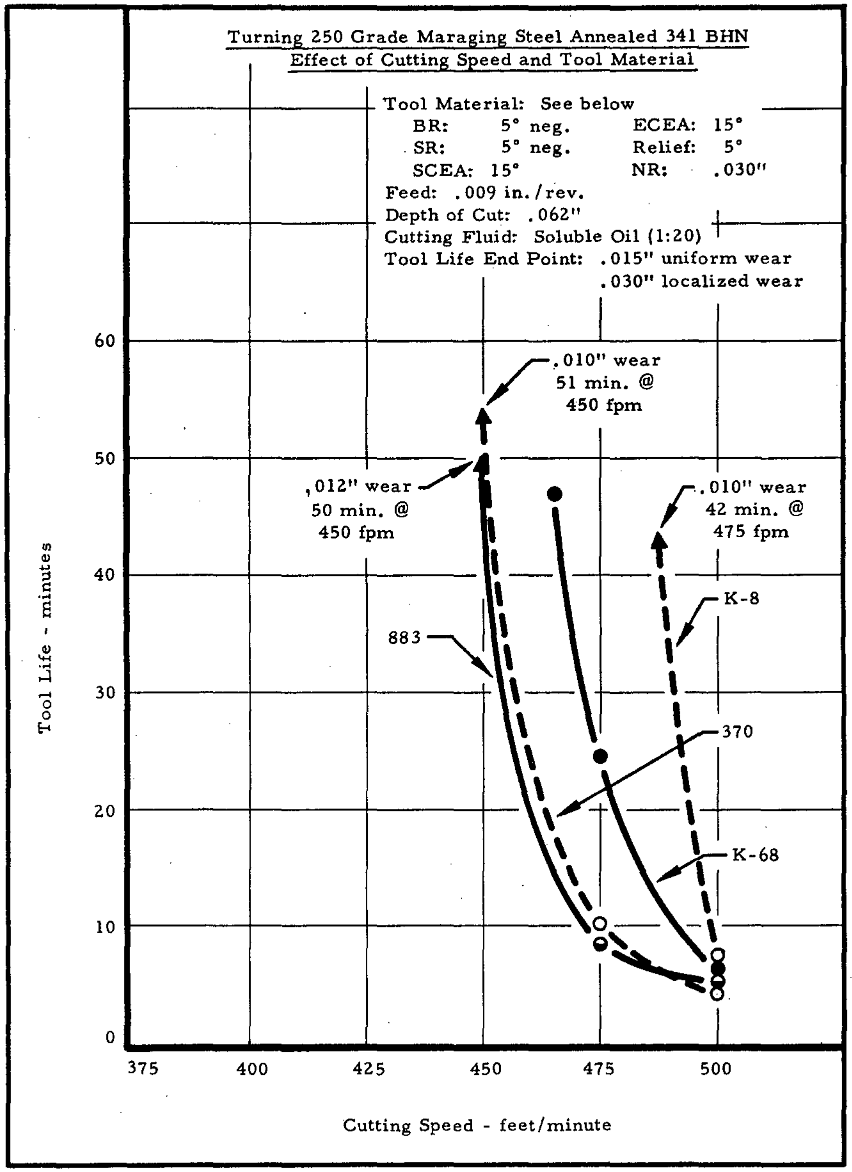

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Figure 38

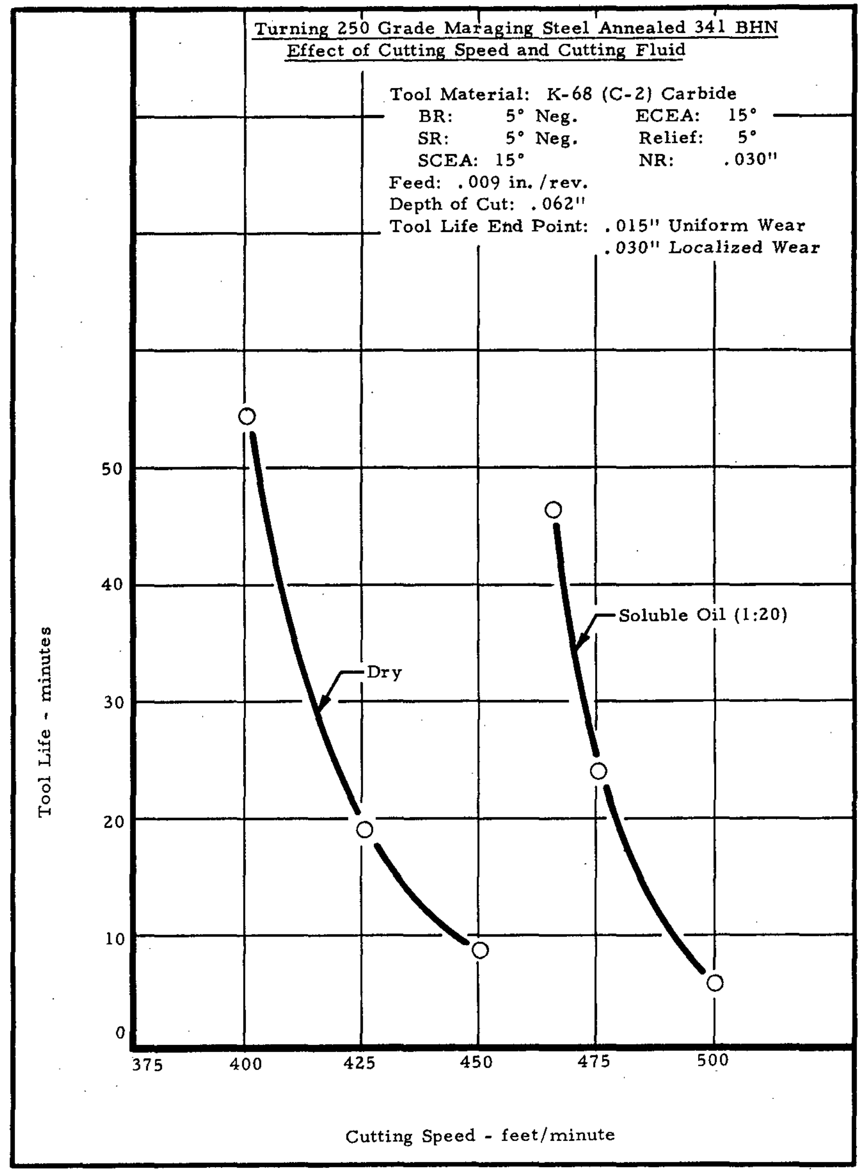

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Figure 39

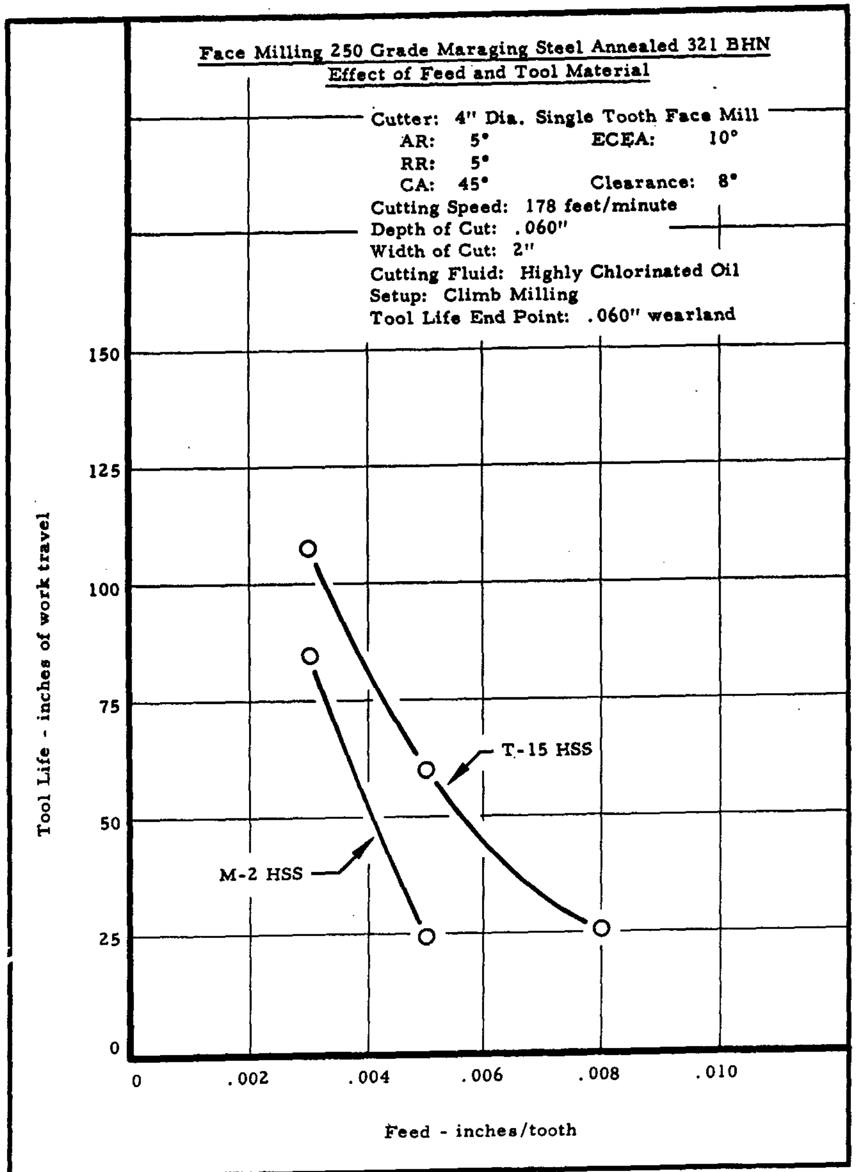

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Figure 40

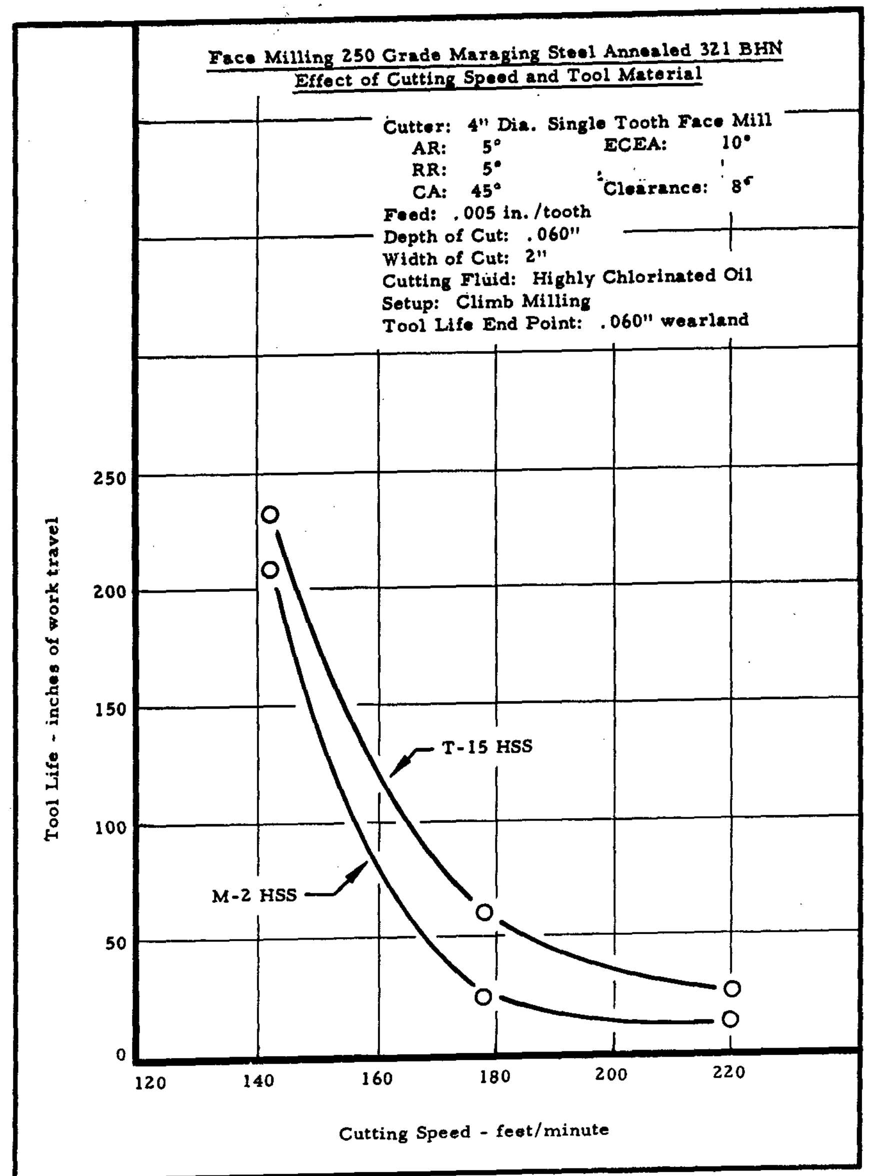

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Figure 41

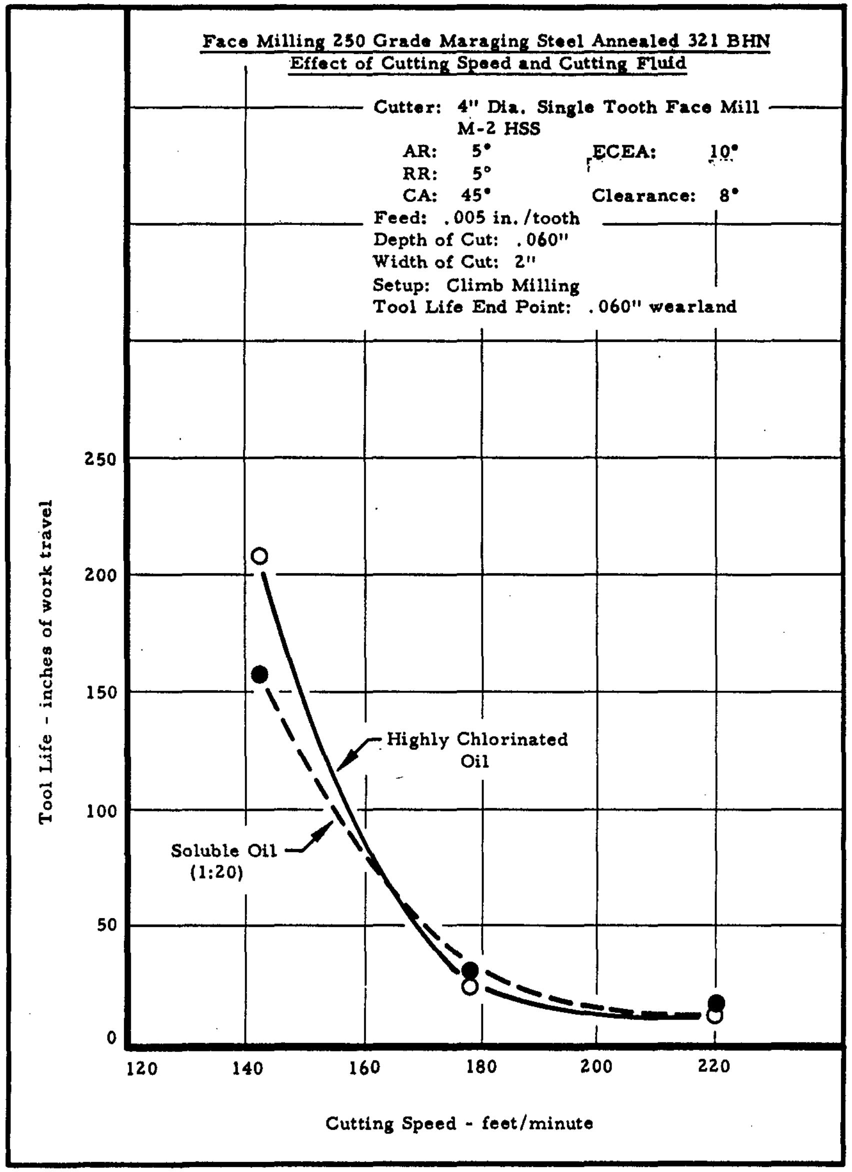

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Figure 42

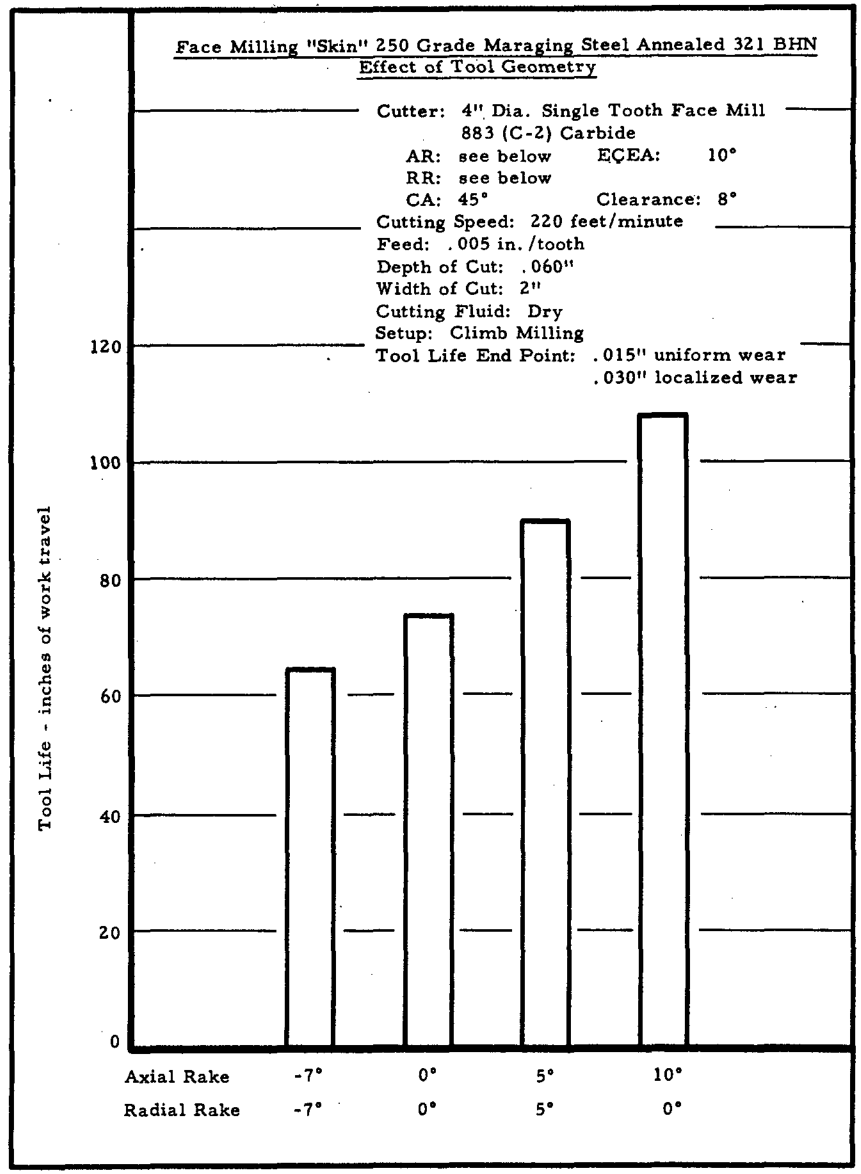

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Figure 43

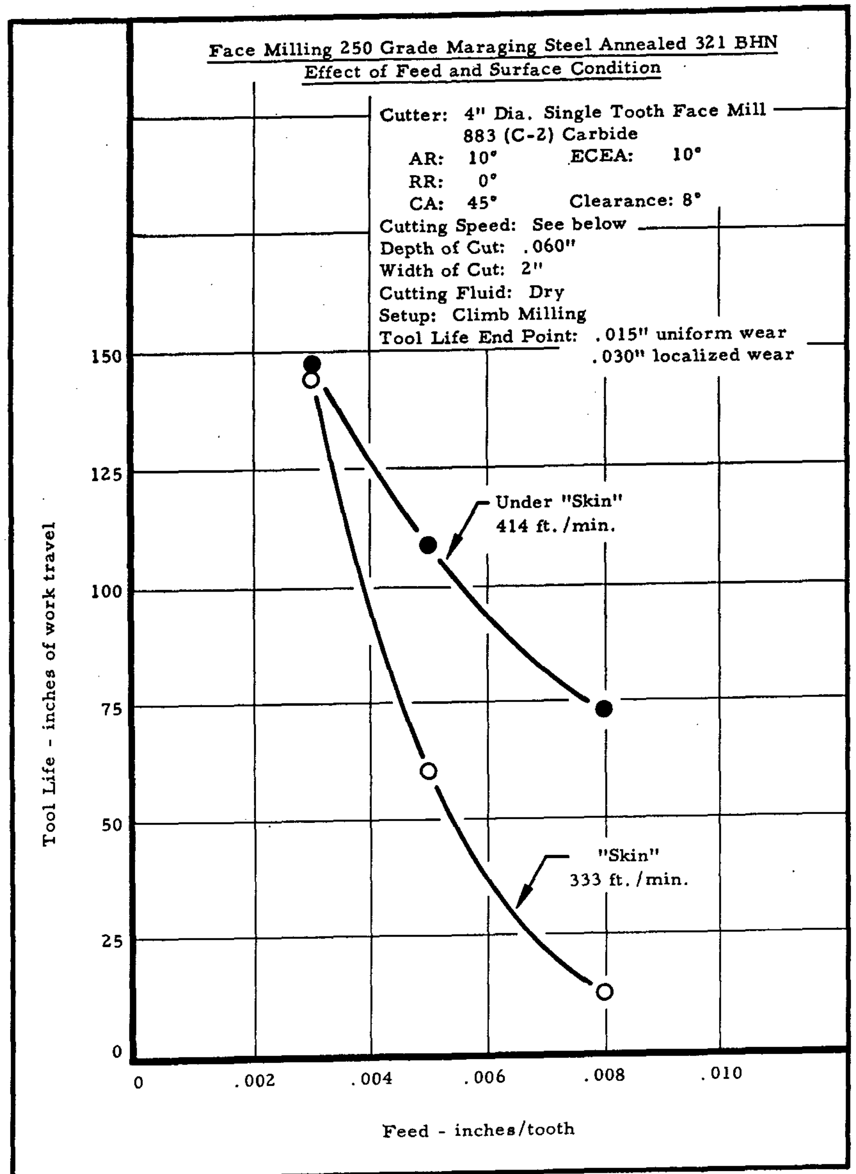

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Figure 44

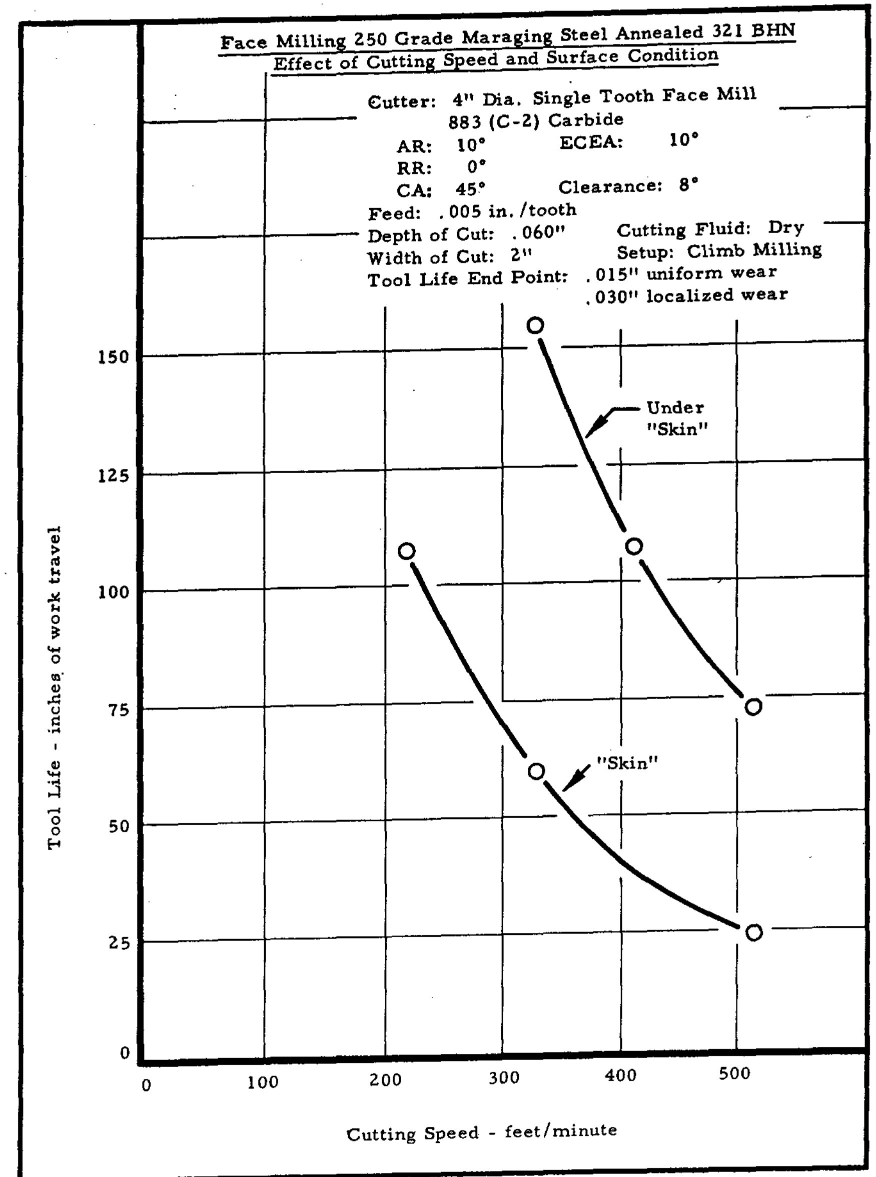

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Figure 45

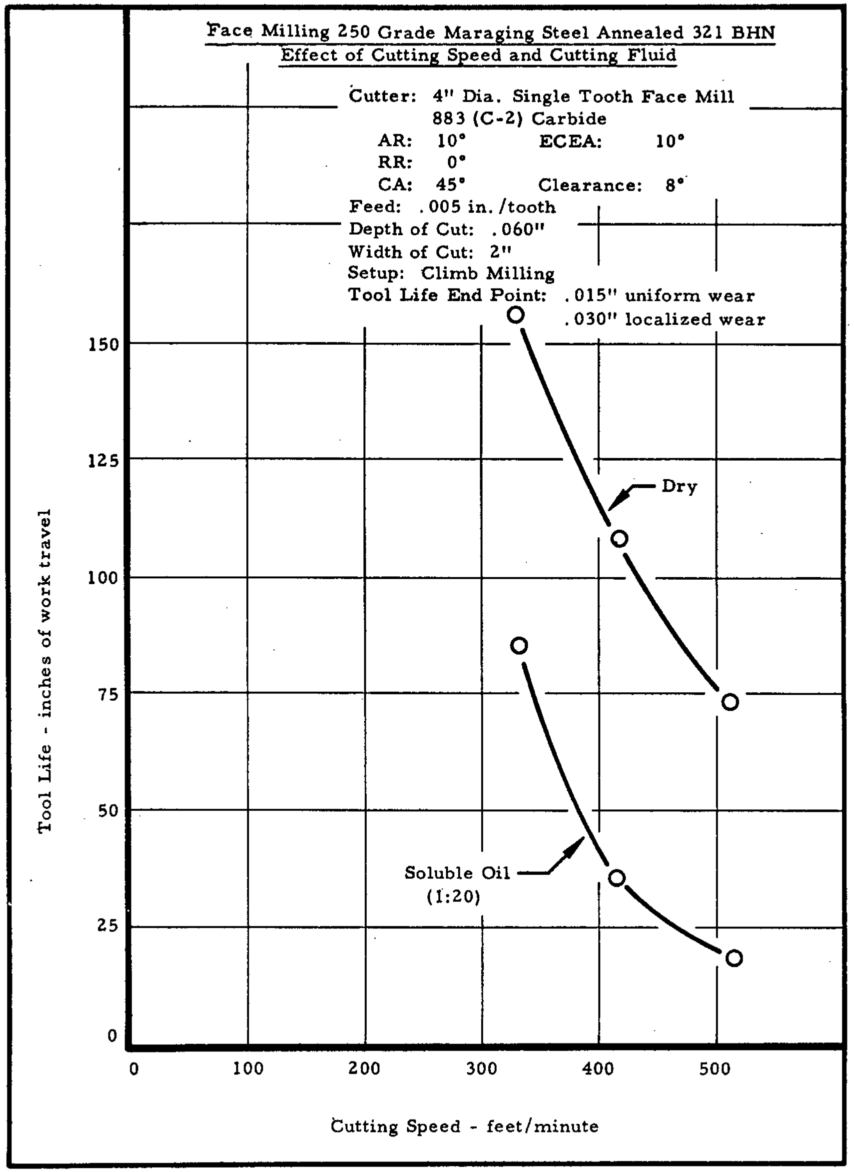

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Figure 46

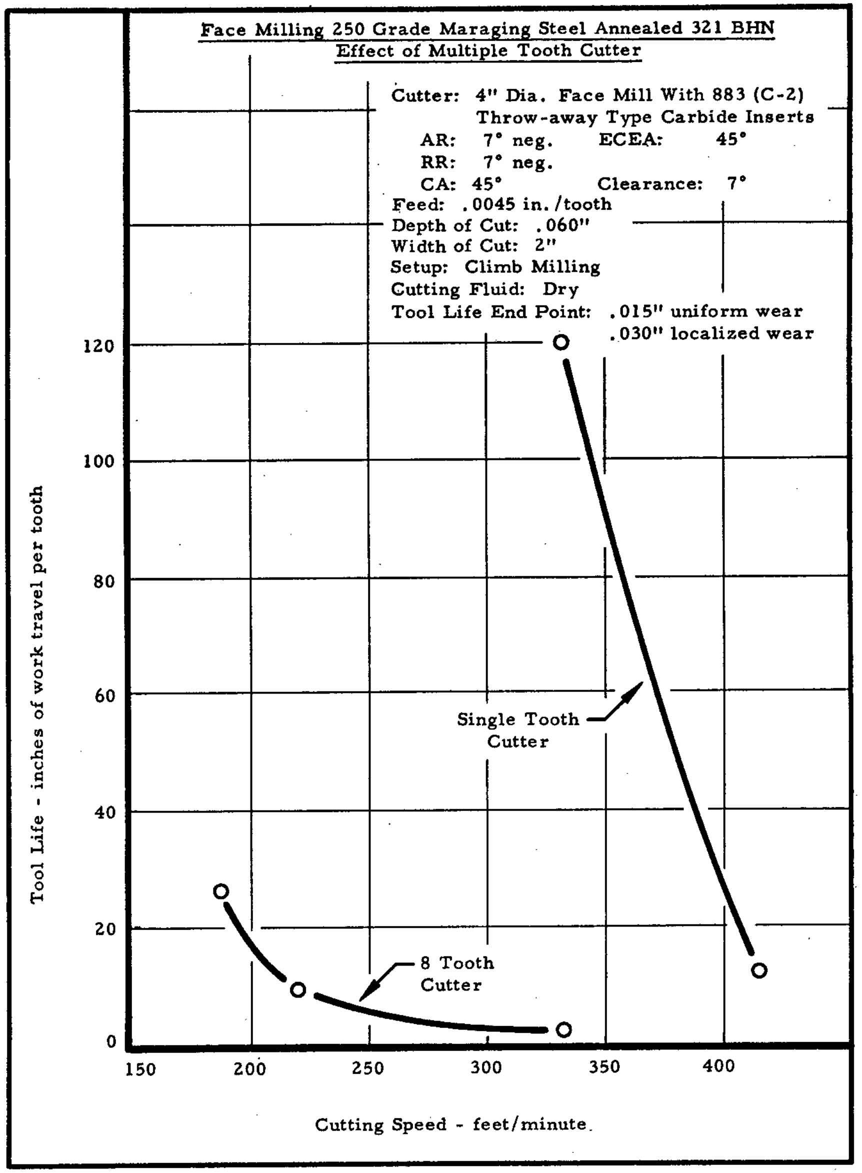

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Figure 47

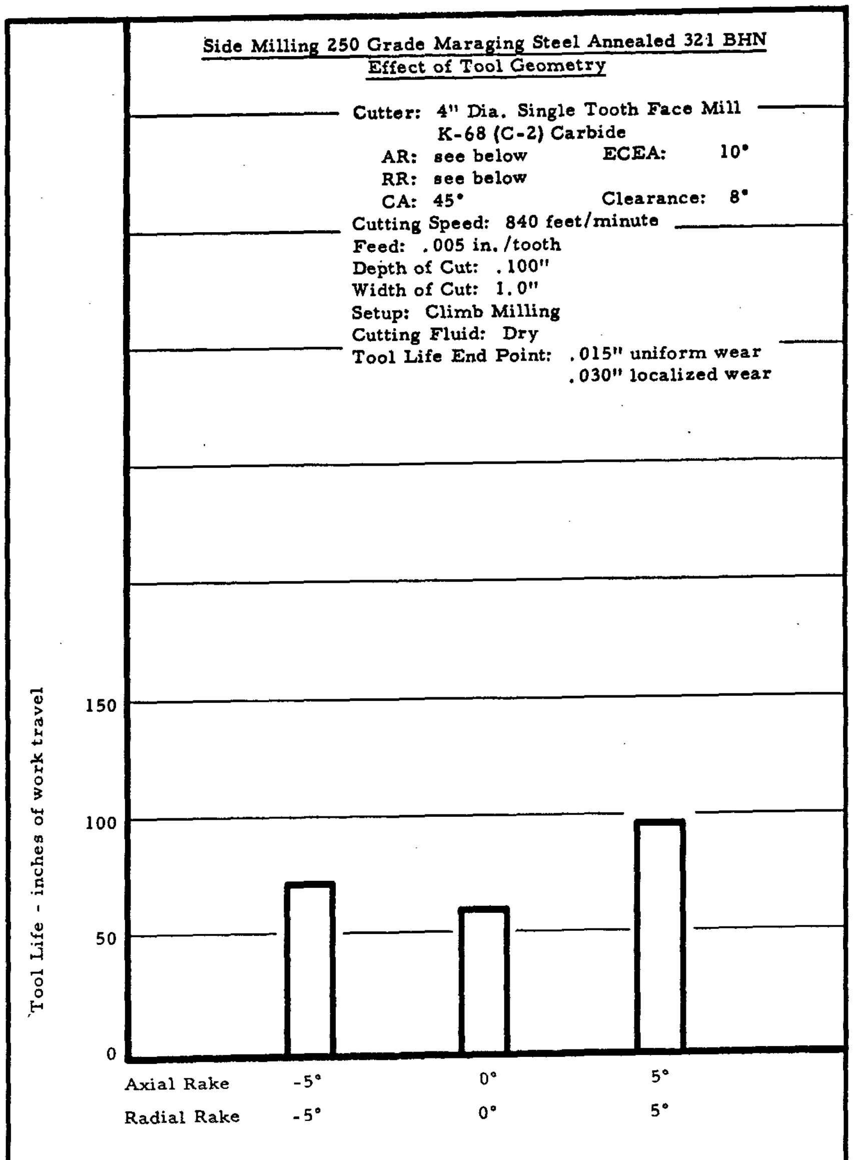

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Figure 48

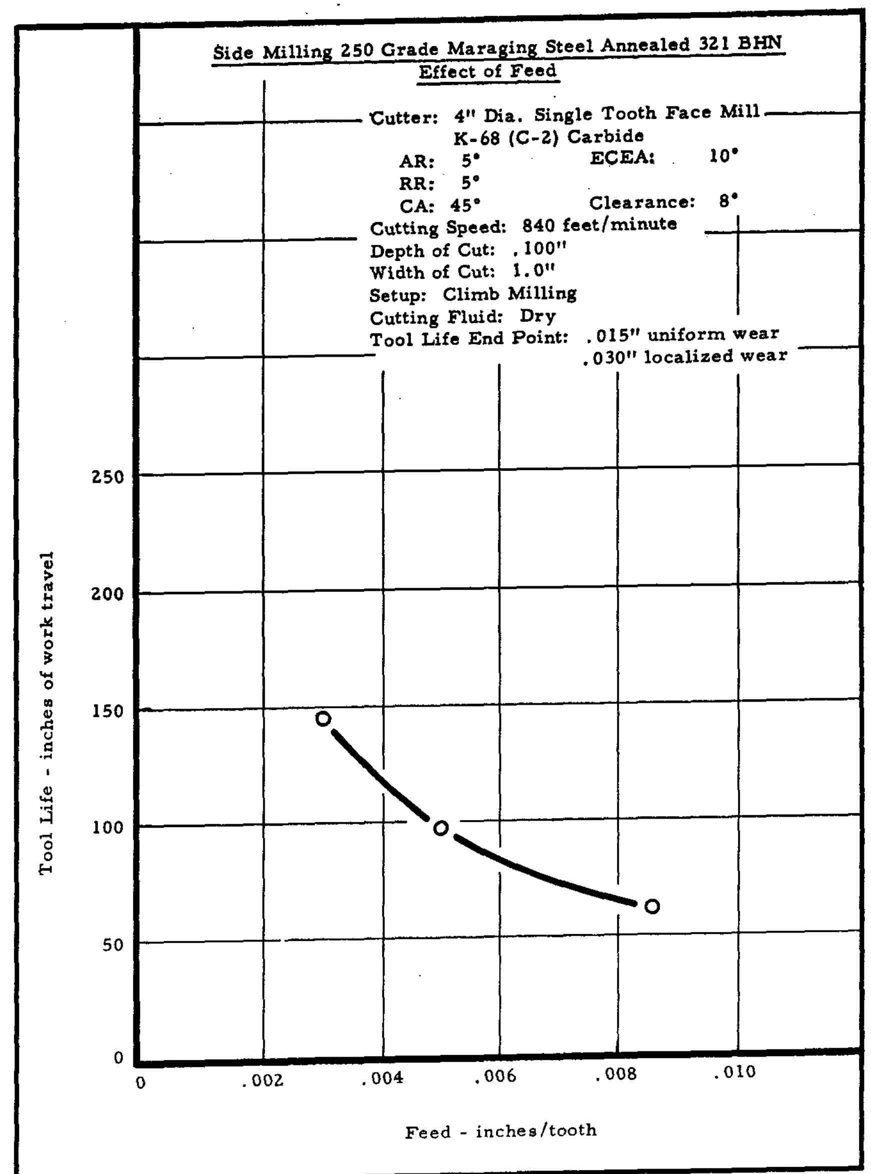

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Figure 49

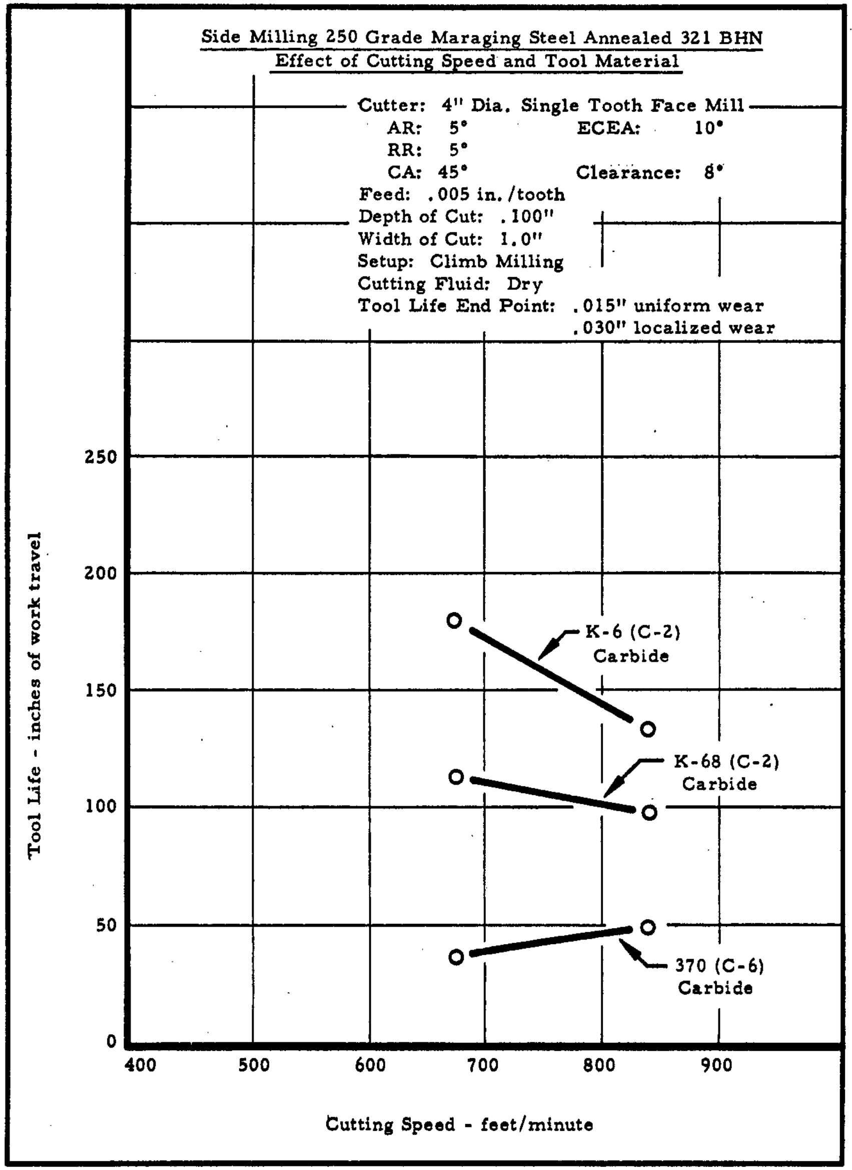

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Figure 50

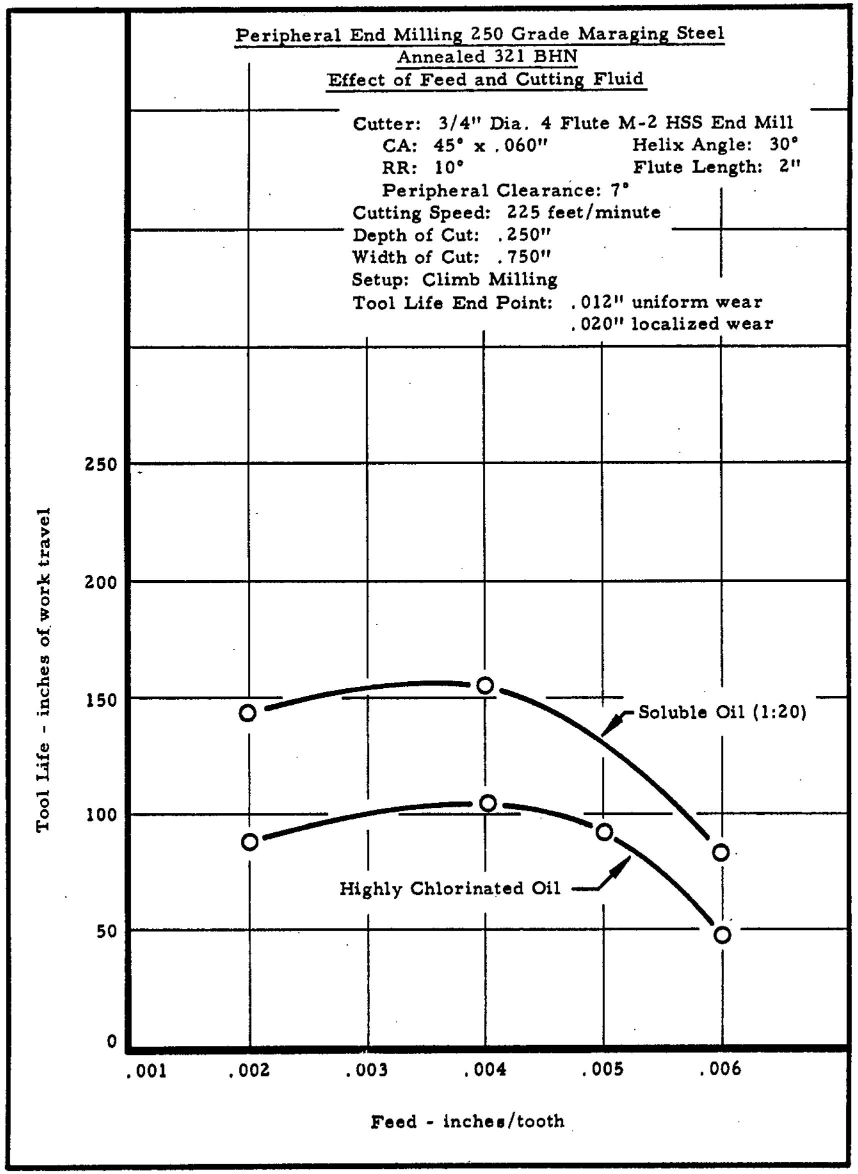

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Figure 51

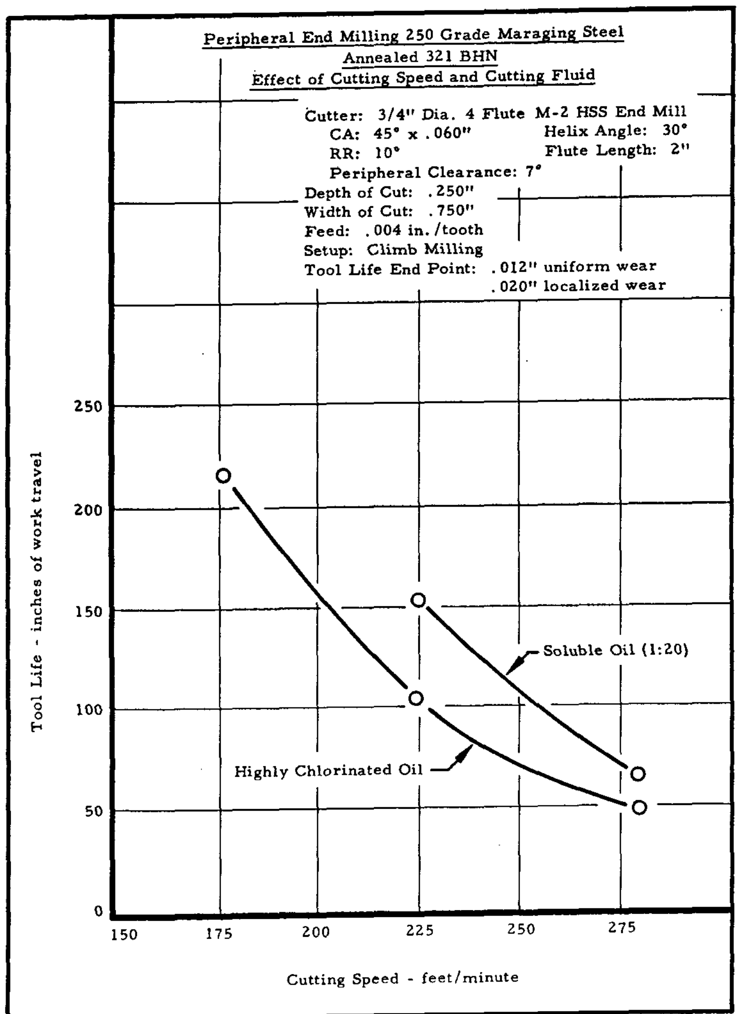

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Figure 52

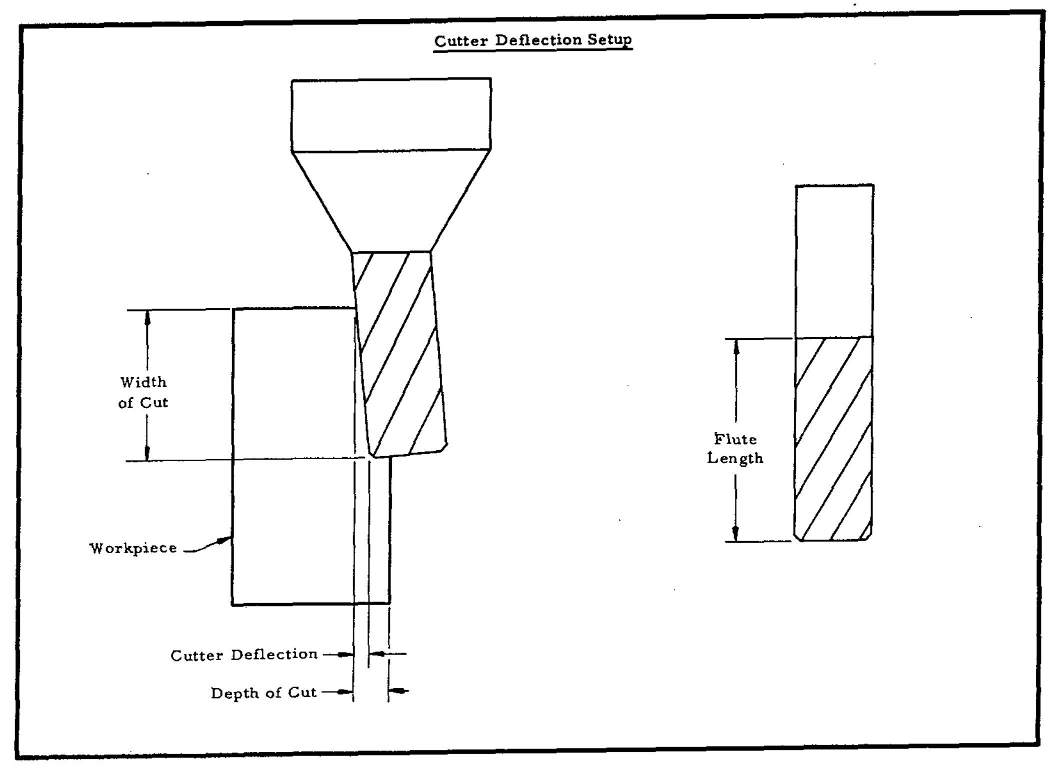

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Figure 53

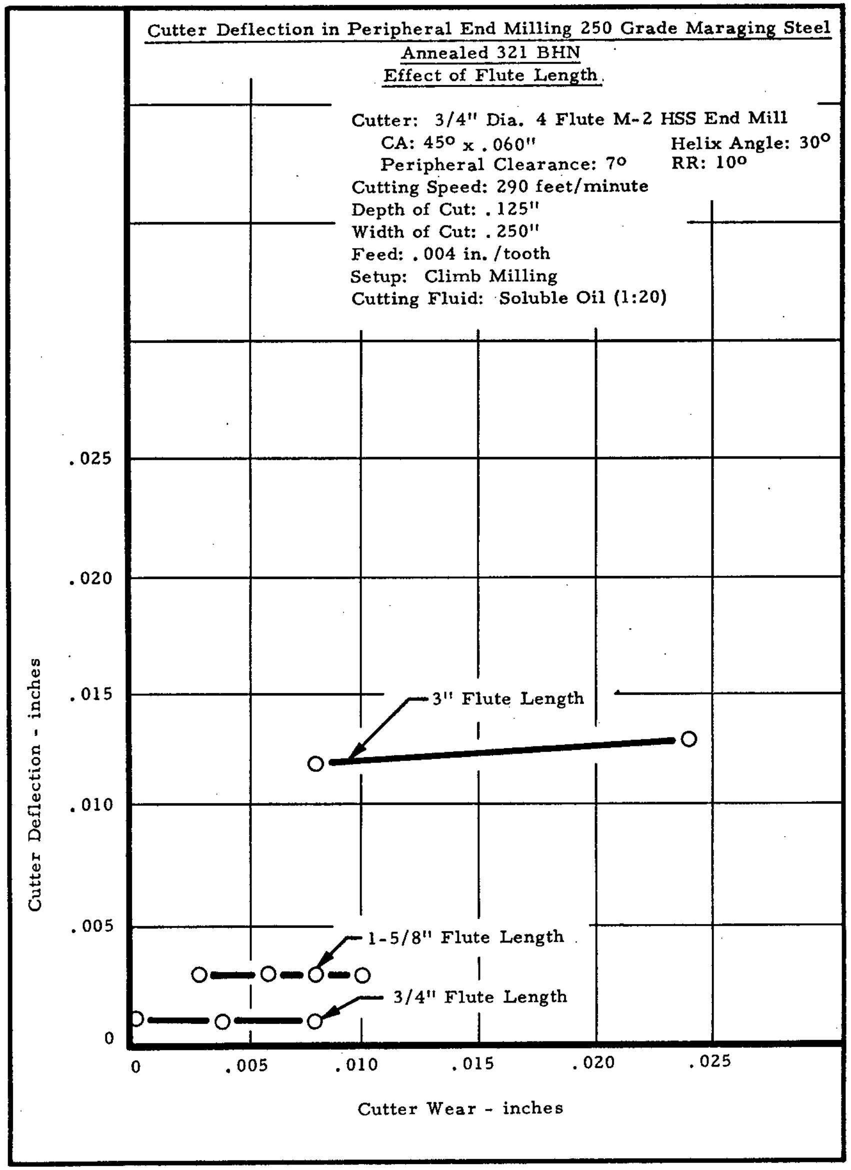

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Figure 54

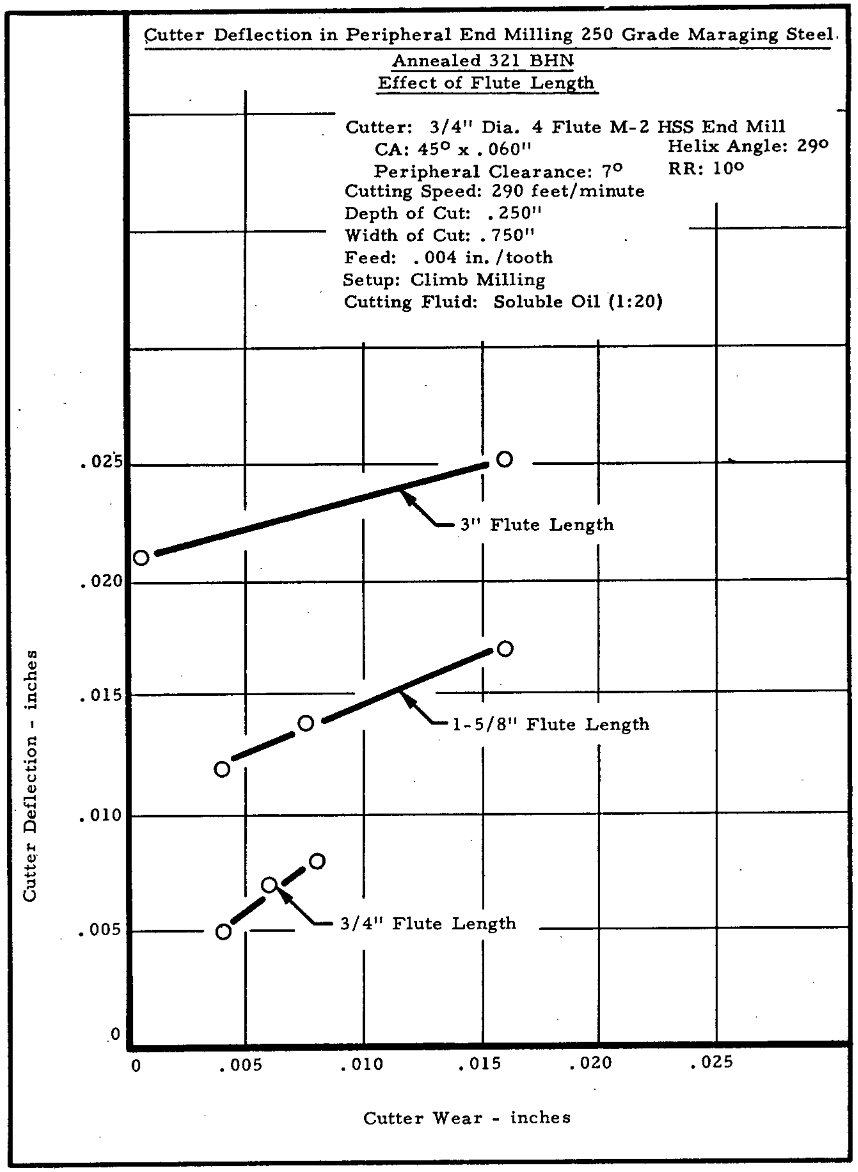

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Figure 55

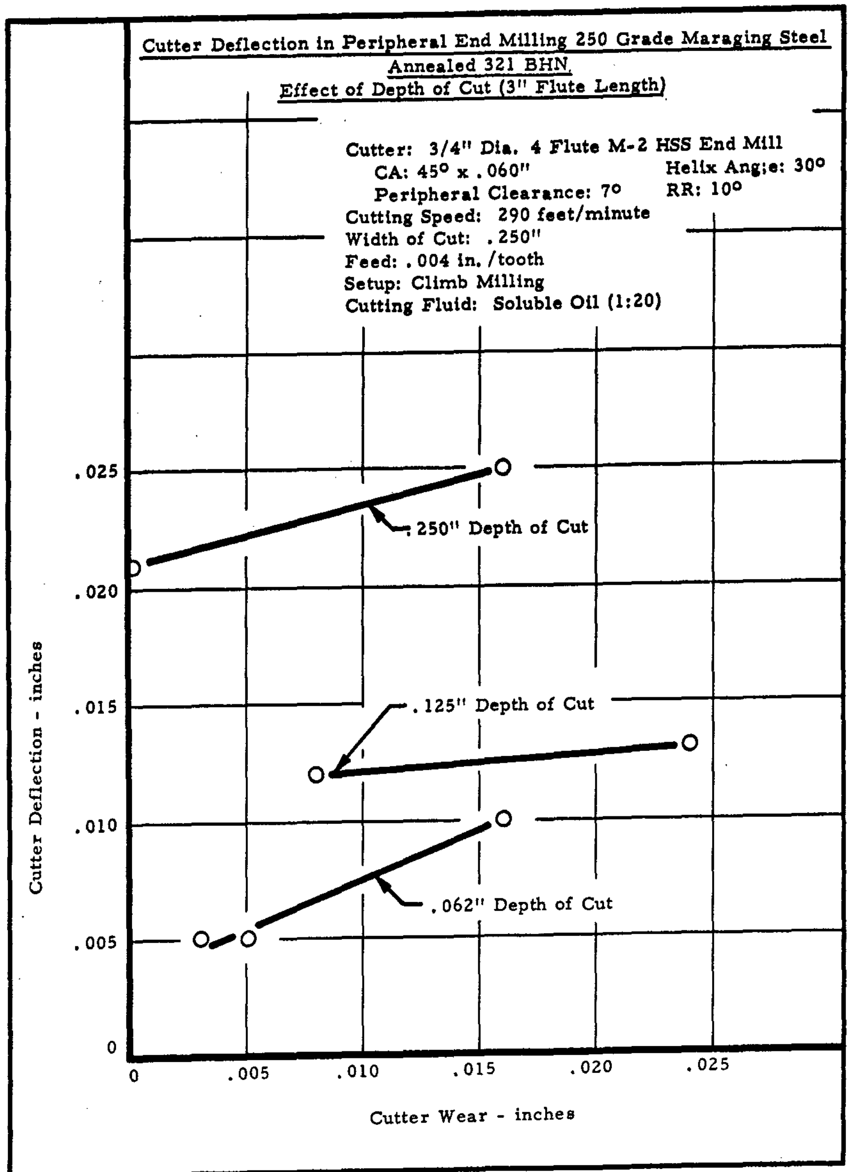

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Figure 56

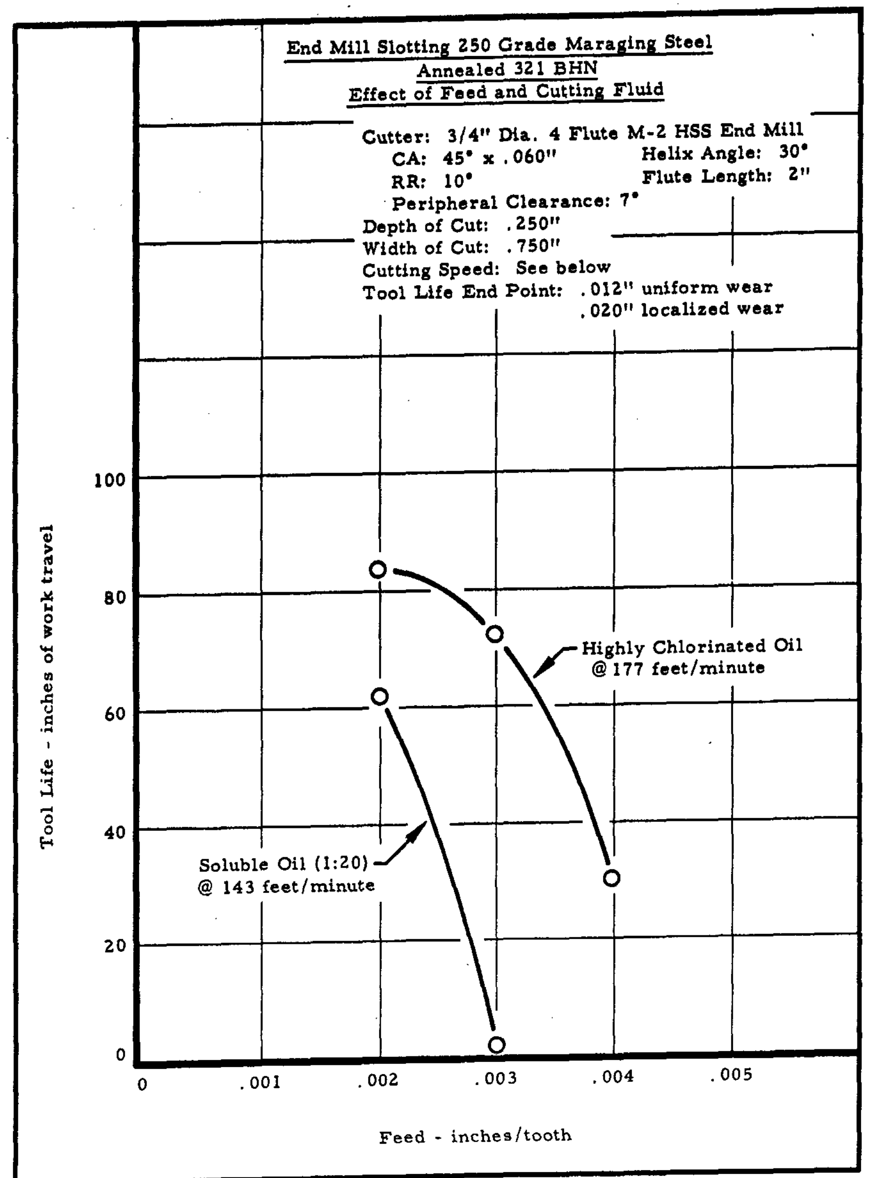

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Figure 57

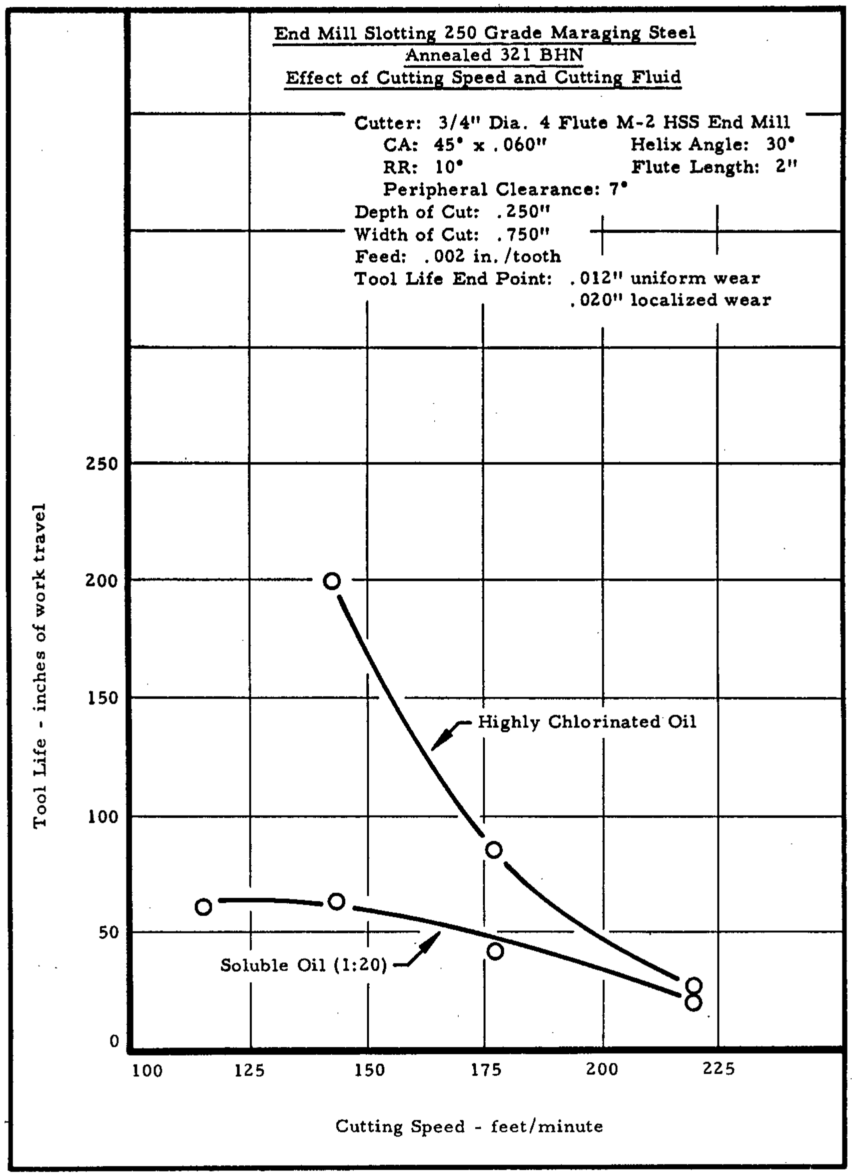

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Figure 58

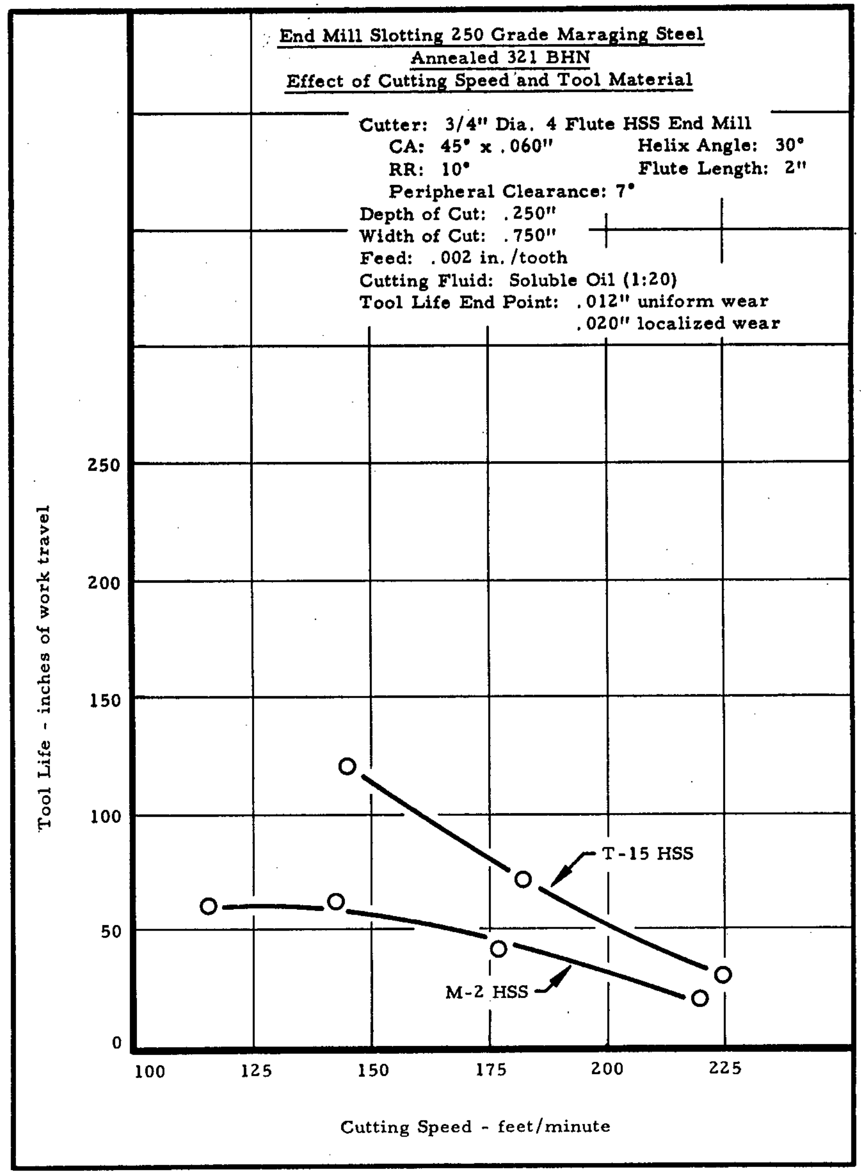

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Figure 59

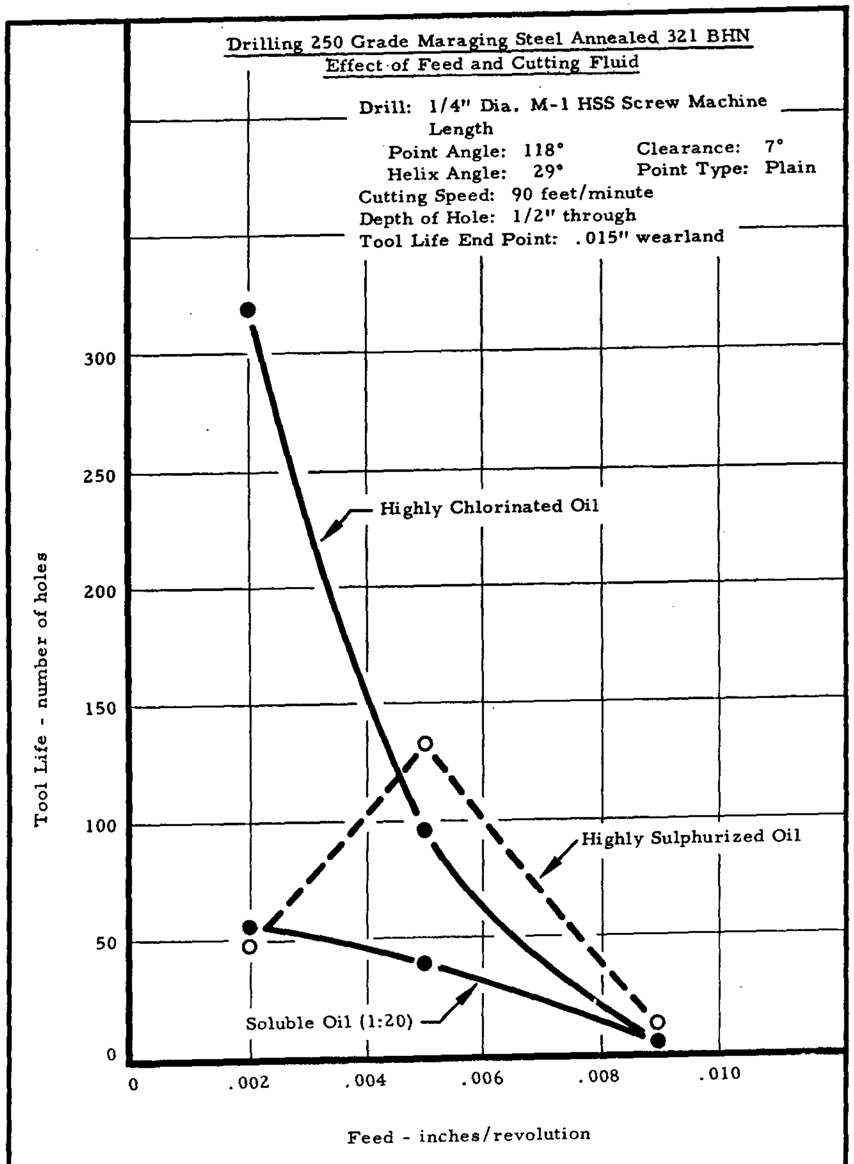

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Figure 60

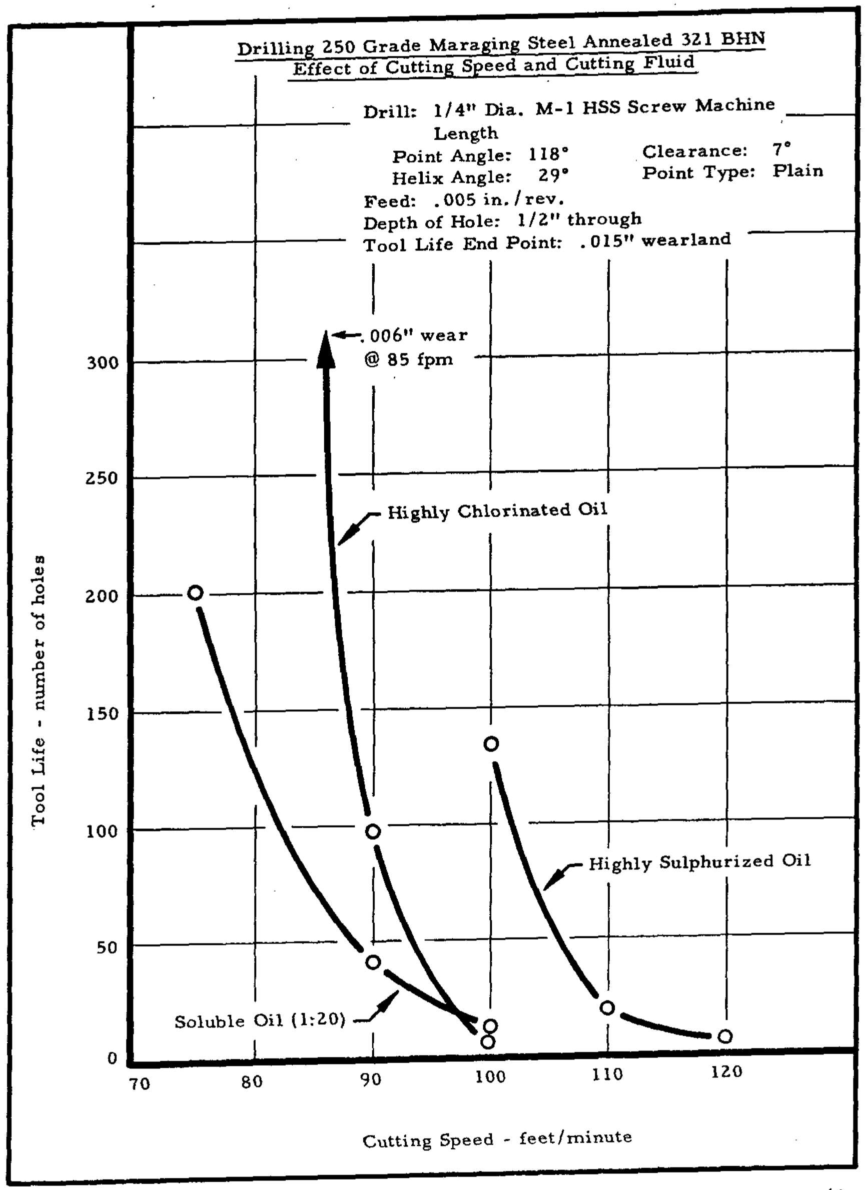

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Figure 61

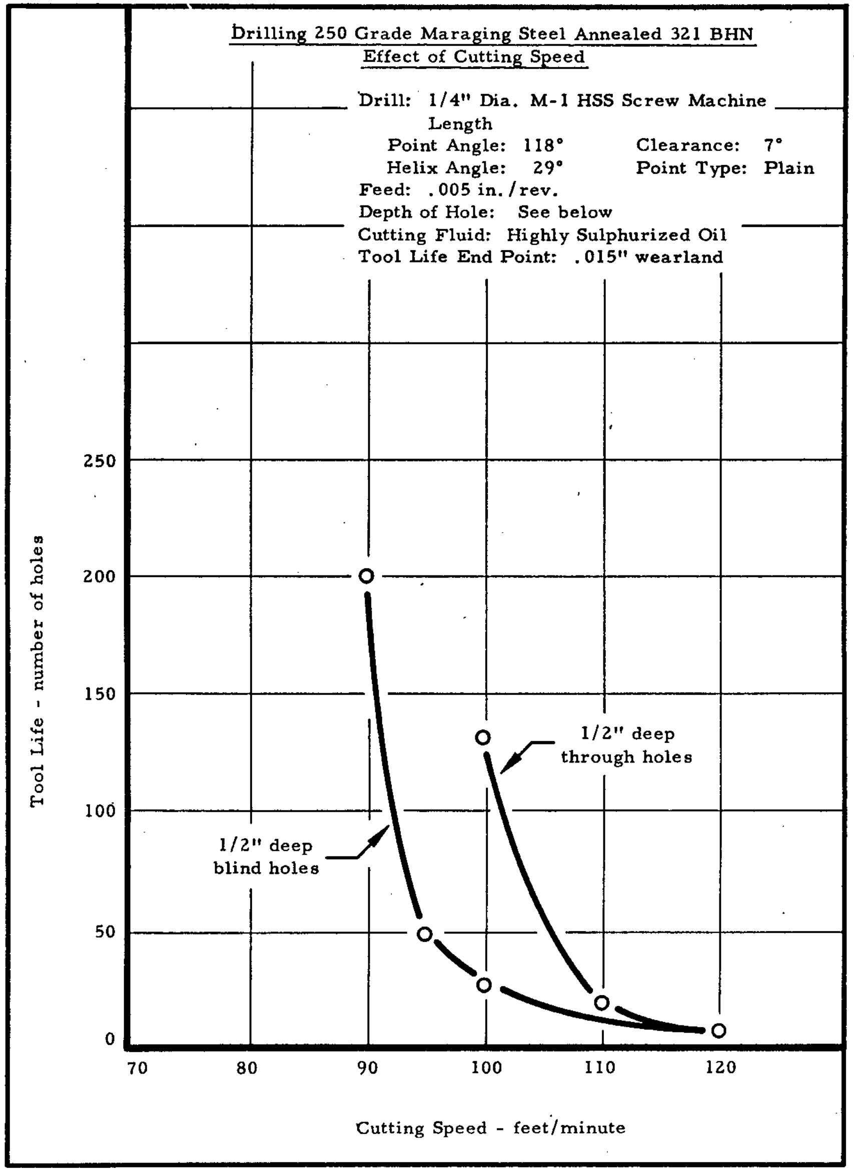

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Figure 62

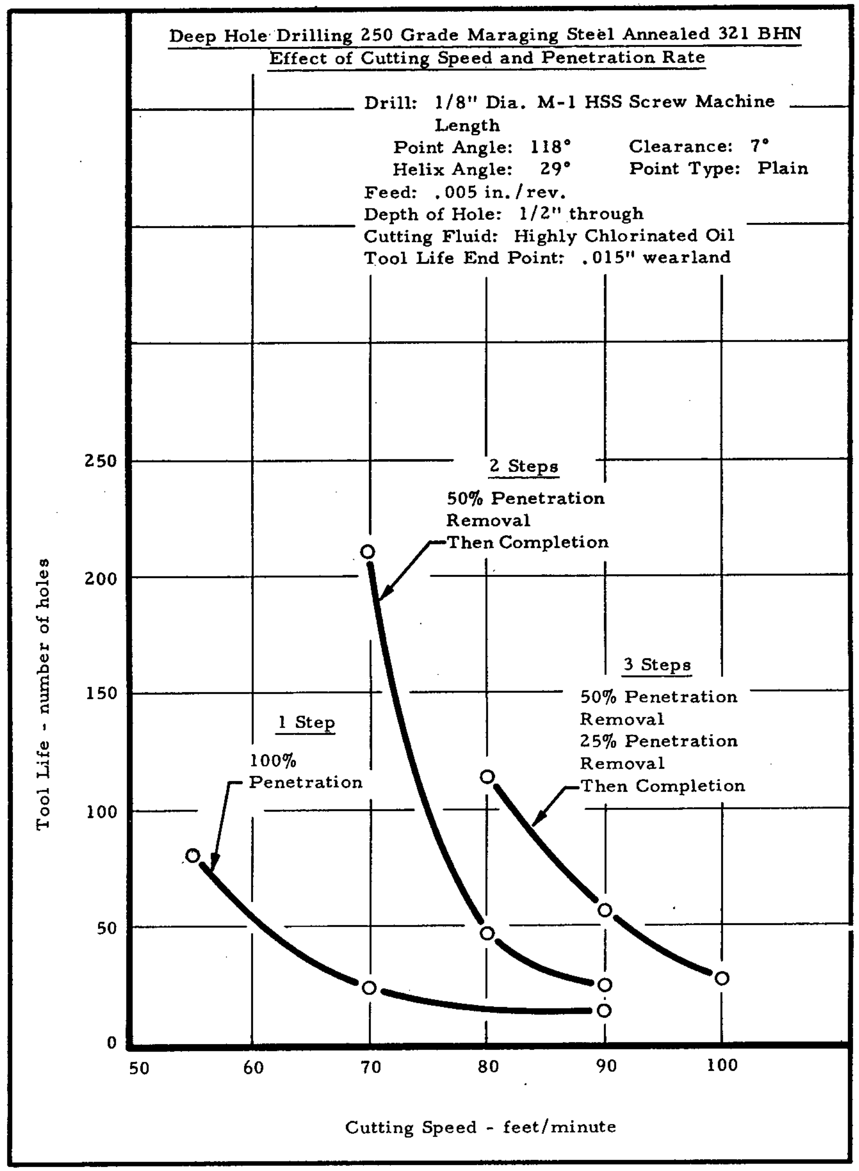

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Figure 63

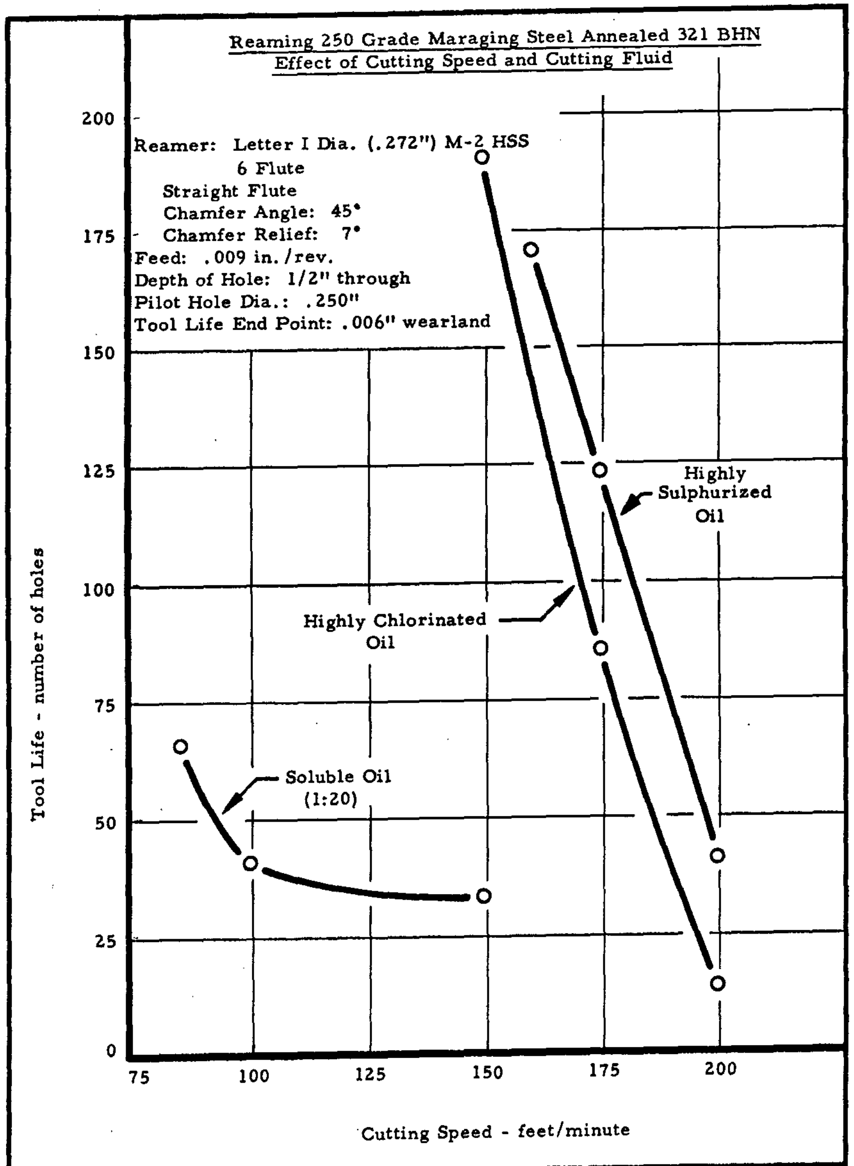

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Figure 64

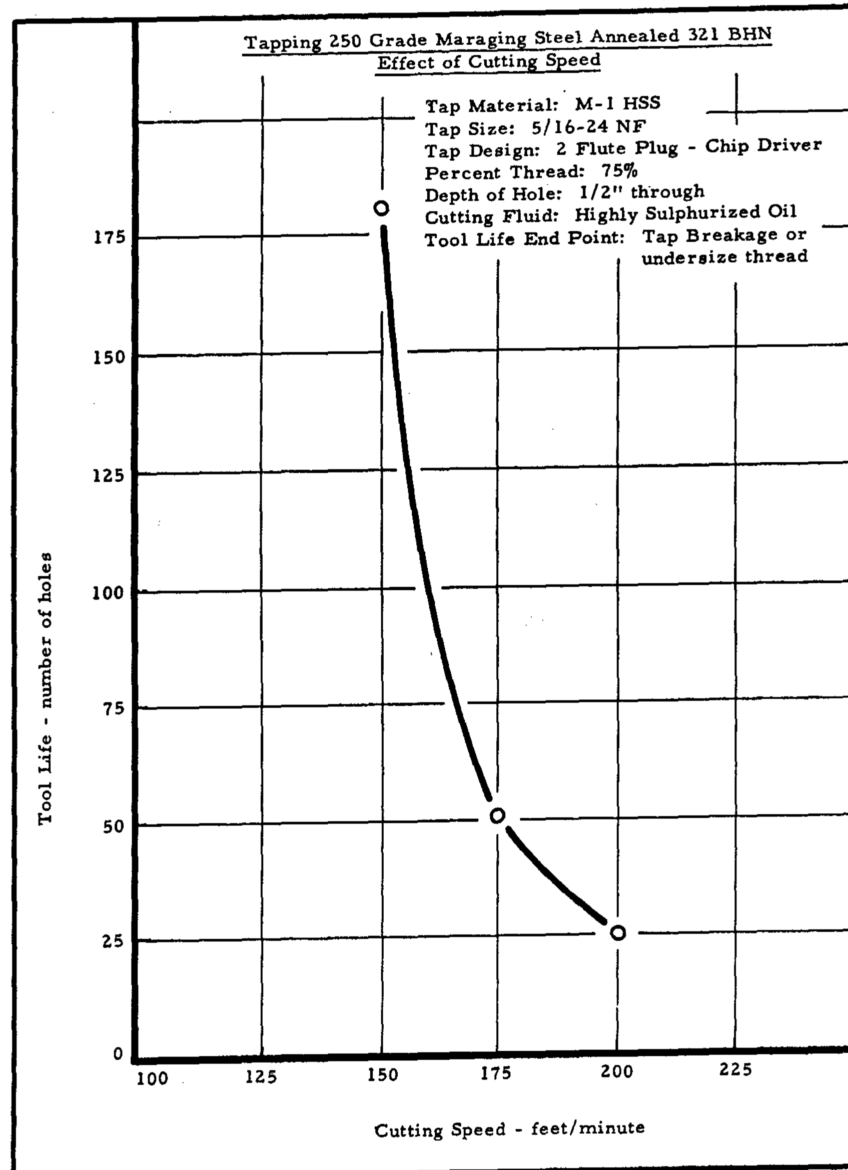

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Figure 65

3.3 18% Nickel 250 Grade Maraging Steel (continued)

Turning (Aged 52-53 R_c)

A comparison of several types of high speed steel tools is presented in Figure 66, page 72, in turning the 18% nickel maraging steel 250 grade aged to a hardness of 52-53 R_c. The cutting speeds with the two premium grades %-15 and M-44 were approximately 30% higher than with the type M-2 high speed steel tool. The difference in the cutting speeds for a given tool life with the T-15 and M-44 tools was negligible, however, at a cutting speed of 60 ft./min. the tool life with the T-15 high speed steel tool was more than 50% greater than with the M-44 tool.

The tool life curves shown in Figure 67, page 72, indicate the advantage of using a soluble oil (1:20) over a highly chlorinated oil in turning the aged 250 grade of maraging steel. The cutting speed was 40% higher with the soluble oil.

Note in Figure 68, page 73, how critical the feed is when turning a steel at a hardness level of 52-53 R_c with a high speed steel tool. The tool life at a feed of .003 in./rev. was 67 minutes, which was double that obtained at a feed of .005 in./rev. At a feed of .009 in./rev. the tool life was less than 5 minutes.

The results of turning the aged 250 grade maraging steel with several different grades of carbides are plotted in Figure 69, page 73. The harder grade of carbide K-8 was superior to the grade 883. The cutting speed with the K-8 carbide was about 50% faster than with the 883 carbide. The tool life was even less with the 370 and K-2S grades. A comparison of the performance of the best high speed steel tool tested, T-15 (see Figure 66, page 72), with that of the K-8 carbide tool shown in Figure 69, page 73, reveals that not only can the carbide tool be used at a cutting speed that is at least 4 times faster but the feed is also 80% greater.

The feed curve in Figure 70, page 74, indicates that feeds up to about .009 in./rev. are suitable with carbide tools. While a lighter feed of .005 in./rev. provided an appreciably longer tool life in terms of minutes, the feed of .009 in./rev. is 80% faster. As a matter of fact, as shown in Figure 69, page 73, a 20% reduction in cutting speed at the higher feed would result in about the same tool life in terms of minutes. In addition, the combination of slightly lower cutting speed and the higher feed would have the advantage of a higher production rate.

3.3 18% Nickel 250 Grade Maraging Steel (continued)

The relative production rates at which the 250 grade maraging steel in the annealed (341 BHN) compared to the aged (53 R_c) conditions can be turned with high speed steel tools are indicated in Figure 71, page 74. Note that not only is the cutting speed on the steel in the aged condition 30 to 50% less than that on the annealed steel, but the feed is also 40% less.

A comparison is presented in Figure 72, page 75, of turning with carbide tools the 250 grade maraging steels in two heat treated conditions: 1) annealed 341 BHN, and 2) aged 52-53 R_c. The annealed steel (341 BHN) could be machined about 70% faster than the aged steel (53 R_c). This fact should be noted when the decision must be made regarding rough turning in the annealed conditions and finish turning in the aged condition.

Face Milling (Aged 50 R_c)

The longest tool life in face milling 250 grade maraging steel aged to 50 R_c was obtained at the lighter feeds. As shown in Figure 73, page 75, there was an appreciable decrease in tool life as the feed was increased from .003 in./tooth to .008 in./tooth. This occurred both with the highly chlorinated oil and the soluble oil in face milling with a T-15 high speed steel cutter. However, it should again be noted that a higher production rate can be obtained by reducing the cutting speed 20% using a feed of .005 in./tooth. A comparison of the T-15 and M-2 high speed steels is shown in Figure 74, page 76. The cutter life was about 75% longer with the T-15 over the M-2 high speed steel at a cutting speed of 74 ft./min. For an equivalent tool life, the cutting speeds were about 15% higher when using the T-15 high speed steel instead of the M-2. Also, as shown in Figure 75, page 76, the highly chlorinated oil is superior to the soluble oil. The highly chlorinated oil permitted 10% higher cutting speeds than the soluble oil.

Figure 76, page 77, shows a comparison of the results obtained with four grades of carbide in face milling the 250 grade maraging steel in the aged condition. The C-2 grade appeared to be by far superior to the C-6 grade. Of the C-2 grades used, the 883 grade produced the longest tool life. A tool life curve for this grade of carbide is shown in Figure 77, page 77. At a cutting speed of 115 ft./min., tool life was 120 inches. As one might expect, the tool geometry is critical when the metal to be machined has a hardness of 50 R_c or higher. This is illustrated in Figure 78, page 78. While in the annealed condition, the tool geometry having a 10^o positive axial and 0^o radial rake was superior; on the material in the aged condition, the reverse was true. A tool geometry of -15° axial rake and -7° radial rake was far superior to any of the other tool geometries used. At a cutting speed of 220 ft./min., the light feeds were far superior to the heavier feeds. The tool life curve showing the relation between feed and tool life in Figure 79, page 78, shows that increasing the feed from .002 to .004" resulted in decreasing tool life 60%. The tool life curve shown in Figure 80, page 79, indicates that cutting dry is far superior to either face milling with soluble oil or with the highly chlorinated oil.

A single tooth cutter is compared with an 8 tooth cutter in face milling 250 grade maraging steel aged to 50 R_C in Figure 81, page 79. In order to obtain a cutter life of 18 inches of work travel per tooth at a cutting speed of 286 ft./min., a feed of .005 in./tooth could be used with the single tooth cutter, while the feed would have to be reduced to .002 in./tooth with the multiple tooth cutter. In spite of this reduction in feed per tooth, the multiple tooth cutter would be advancing at the rate of .016 in./rev., while the single tooth cutter would advance only at the rate of .005 in./rev. In other words, the eight tooth cutter would be cutting a little over three times as fast as the single tooth cutter. A further comparison of the multiple tooth cutter with the single tooth cutter is presented in Figure 82, page 80, at a feed of .004 in./tooth. In this case, for a tool life of 30 inches of work travel per tooth, the cutting speed with the single tooth cutter would be 270 ft./min. as compared to 170 ft./min. with the multiple tooth cutter. However, the production rate with the multiple tooth cutter would be four times higher than the single tooth cutter, and thus, the use of the multiple tooth cutter would be justified.

Side Milling (Aged 50 R_C)

The results shown in Figure 83, page 80, indicate that a high negative rake should be used for both the radial and axial rake angles in side milling 250 grade maraging steel aged to 50 R_C. Note that a cutter having a 15° negative axial rake and a 7° negative radial rake angle produced three times the tool life that a cutter having a 0° axial rake and a 0° radial rake angle produced. Also note in Figure 84, page 81, that the cutter life in side milling decreased rapidly at feeds other than .004 in./tooth. For example, the cutter life decreased from 72 inches of work travel at a feed of .004 in./tooth to 24 inches of work travel at a feed of .006 in./tooth. Also, when the feed was decreased to .002 in./tooth, the cutter life dropped to 60 inches of work travel.

The C-2 grades of carbide should be used in side milling. The cutter life with a C-2 grade was several times better than that obtained with the C-5 or C-6 grades of carbide, as shown in Figure 85, page 81. Also, it is desirable to side mill the 250 grade maraging steel in the aged condition dry rather than using a soluble oil. Figure 86, page 82, shows the results of such a comparison. The cutting speed for a given tool life was more than double when the material was side milled without a cutting fluid, as compared to that obtained when using a soluble oil.

Peripheral End Milling (Aged 50 R_c)

The effectiveness of each of two types of cutting fluids is shown in Figure 87, page 82, in peripheral end milling 250 grade maraging steel aged to 50 R_c. Note that the curves are drawn for a range of feeds at different cutting speeds. Cutter life decreased rapidly with increased feed using the highly chlorinated oil at a cutting speed of 101 ft./min. In the light feed range, tool life did not change for the feed range of .001 to .002 in./tooth when a soluble oil was used at a speed of 65 ft./min. However, beyond this point, tool life decreased rapidly. A further comparison is made between the highly chlorinated oil and the soluble oil over a range of cutting speeds in Figure 88, page 83. Note that for a tool life of 150 inches of work travel the cutting speed was 46 ft./min. with the soluble oil and 85 ft./min. with the highly chlorinated oil.

The vast difference in the machinability of the annealed 250 grade maraging steel and the aged is shown in Figure 89, page 83. For a given tool life, not only was the cutting speed with the annealed steel over twice as fast, but the feed was four times as great.

End Mill Slotting (Aged 50 R_c)

Very light feeds, approximately .001 in./tooth should be used in end mill slotting 250 grade maraging steel aged to 50 R_c. As shown in Figure 90, page 84, tool life drops off rapidly as the feed is increased from .001 to .002 in./tooth with a highly chlorinated oil. Unless an active cutting oil of this type is used, the tool life is poor regardless of the feed (see Figure 90, page 84). Using a feed of .001 in./tooth and a cutting speed of 44 ft./min., a tool life of 180 inches of work travel was obtained as shown in Figure 91, page 84. When the cutting speed was increased to 61 ft./min., tool life decreased rapidly to 60 inches of work travel.

A comparison of several grades of carbide used in end milling this steel aged to 50 R_c is shown in Figure 92, page 85. The two C-2 grades, K-68 and 883, prove to be the best of the six that were used. With a 1" dia., 2 tooth end mill using throwaway inserts, cutter life from 140 to 170 inches of work travel was obtained with these two grades of carbide, at a feed of .002 in./tooth and a cutting speed of 312 ft./min. These results were obtained without the use of a cutting fluid. Note also that the feed was twice that used with the high speed steel cutter and the cutting speed was six times faster.

Drilling (Aged 50 R_c)

The curves in Figure 93, page 85, show the relationship between drill life and cutting speed for two different types of cutting oils. For a tool life of 100 holes, the cutting speed with the highly sulfurized oil was about 50% greater than that with the highly chlorinated oil. Using the sulfurized oil, the T-15 high speed steel drills permitted a cutting speed that was double that used with the M-1 high speed steel drills. For example, as shown in Figure 94, page 86, for 100 holes with the M-1 high speed steel drill, the cutting speed was 24 ft./min. as compared to 50 ft./min. with the T-15 high speed steel drill.

Figure 95, page 86, presents tool life curves showing the relationship between drill life and feed at two different cutting speeds. Note that in general the drill life at the speeds shown decreased about 50% when the feed was increased from .001 to .002 in./rev. However, using a .002 in./rev. feed at a speed of 50 ft./min., it was possible to obtain a reasonable drill life, as shown in Figure 94, page 86. Also, the production rate was appreciably higher than could be obtained at a feed of .001 in./rev. and a cutting speed of 60 ft./min.

Various types of drill materials were used to obtain the tool life results shown in Figure 96, page 87. First note that the split point T-15 high speed steel drill was appreciably better than the same drill material having a plain point. The cutting speed was about 25% faster with the split point drill. There was no significant difference between the T-15 and the M-42 high speed steel drill performances.

A comparison of drilling the 250 grade maraging steel in the annealed and aged conditions is shown in Figure 97, page 87. Note that for a drill life of 100 holes the annealed steel was not only drilled four times as fast, but the feed per revolution was 2-1/2 times as great.

3.3 18% Nickel 250 Grade Maraging Steel (continued)

Reaming (Aged 50 R_c)

A comparison of two different cutting oils used in the reaming of the 250 grade maraging steel in the aged condition is shown in Figure 98, page 88. The highly sulfurized oil permitted cutting speeds that were almost 80% faster than that with the highly chlorinated oils for a given tool life.

The tool life curve showing the relationship between reamer life and feed is shown in Figure 99, page 88. Increasing the feed from .005 to .009 in./rev. resulted in a decrease in reamer life of 30%.

By using an M-33 high speed steel reamer, a 60% increase in cutting speed was obtained over the M-2 high speed steel reamer for a given reamer life. These results are shown in Figure 100, page 89.

Tapping (Aged 50 R_c)

In order to tap the 250 grade maraging steel aged, having a hardness of 50 R_c, very low cutting speeds must be used. As shown in Figure 101, page 89, with a highly chlorinated oil, a cutting speed of 8 ft./min. had to be used in order to tap 100 holes, while with a sulfurized oil, a cutting speed of about 5 to 6 ft./min. was used.

Surface Grinding (Aged 52-53 R_c)

The effect of wheel speed on the G Ratio in grinding the 250 grade maraging steel is shown in Figure 102, page 90. The results are indicated for both an H and a K hardness wheel at a down feed of .002 in./pass, a table speed of 40 ft./min. and a cross feed of .050 in./pass, using a soluble oil grinding fluid. The G Ratio increased with increased wheel speed for both wheels. The K wheel seemed to provide less wheel wear; that is provided a higher G Ratio than the H hardness wheel, except at the higher wheel speed of 6000 ft./min.

The effect of down feed on G Ratio is shown in Figure 103, page 90, for wheel speeds of 4000 and 6000 ft./min. The grinding ratio increased with increasing down feed, and it again should be observed that higher G Ratios were obtained with 6000 ft./min. compared to the 4000 ft./min. grinding speed.

The G Ratio was observed to be constant at cross feeds of .025 to .050 in./pass, but an appreciable increase in the grinding ratio was obtained at .100 in./pass, Figure 104, page 91. Here it should be observed that the G Ratio increased from 7.5 to 28 as the cross feed increased from .050 to .100 in./pass. This data was obtained with a wheel speed of 6000 ft./min. and a down feed of .001 in./pass, using a K hardness grinding wheel.

The G Ratio increased with increasing table speed, Figure 105, page 91. At a table speed of 60 ft./min. the G Ratio was 11 compared to 6.8 at a table speed of 20 ft./min.

The effect of the grinding fluid on G Ratio is indicated in Figure 106, page 92. This data, obtained at a wheel speed of 6000 ft./min., a down feed of .002 in./pass with a K hardness grinding wheel, indicates that the straight oils resulted in less wheel wear than the soluble oil.

The recommended conditions for surface grinding the 250 grade maraging steel are given in Table 5, page 71.

In roughing, conditions can be used which produce maximum G Ratio. These include a K hardness wheel, a wheel speed of 6000 ft./min., a cross feed of .100 in./pass, a down feed of .001 in./pass and a table speed of 40-60 ft./min. Under these conditions, a G Ratio of approximately 30 should be obtained. However, there is a distinct danger of obtaining a soft white layer of resolutioned austenite in using these roughing conditions, especially if the cutting fluid should be accidentally cut off or if the wheel were to become loaded. To insure a finish ground surface with high integrity, the last .010" should be ground using the finish grinding conditions indicated in Table 5, page 71. These conditions are those of "low stress" grinding and will insure a minimum of surface damage and a minimum of residual stress, as described in Chapter 7, pages 317-378. The "low stress" conditions include:

Grinding Wheel: 32A46H8VBE

Wheel Speed: 3000-4000 ft./min.

Down Feed: Last .010" removed at feeds of .0005 to .0002 in./pass

Cutting Fluid: Highly Sulfurized Oil

The surface finish obtained in grinding the 250 grade maraging steel was 10 to 20 microinches, arithmetical average, under finishing conditions, and 15 to 60 microinches, arithmetical average, under roughing conditions.

TABLE 5

RECOMMENDED CONDITIONS FOR MACHINING
18% NICKEL 250 GRADE MARAGING STEEL - AGED 50-53 R_c

Ni	Co	Mo	C	Ti	Al	Fe
18	7.8	4.9	.02	.5	.1	Bal

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	T-15 HSS	BR: 0° SCEA: 15° SR: 10° ECEA: 5° Relief: 5° NR: .030"	5/8" square tool bit	.062	-	.005 in. / rev.	60	90 min.	.016	Soluble Oil (1:20)
Turning	C-3 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square throwaway insert	.062	-	.009 in. / rev.	275	35 min.	.015	Soluble Oil (1:20)
Face Milling	T-15 HSS	AR: 5° ECEA: 10° RR: 5° CA: 45° Clearance: 8°	4" diameter single tooth face mill	.060	2	.005 in. / tooth	75	140" work travel	.060	Highly Chlorinated Oil
Face Milling	C-2 Carbide	AR: -15° ECEA: 10° RR: -7° CA: 45° Clearance: 8°	4" diameter single tooth face mill	.060	2	.004 in. / tooth	180	210" work travel	.015	Dry
Side Milling	C-2 Carbide	AR: -15° ECEA: 10° RR: -7° CA: 45° Clearance: 8°	4" diameter single tooth face mill	.100	1.25	.004 in. / tooth	300	80" work travel	.015	Dry
Peripheral End Milling	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.001 in. / tooth	80	160" work travel	.012	Highly Chlorinated Oil

TABLE 5 (continued)
RECOMMENDED CONDITIONS FOR MACHINING

18% NICKEL 250 GRADE MARAGING STEEL - AGED 50-53 R_c

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	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 Tooth HSS End Mill	.250	.750	.001 in/ tooth	40	175" Work Travel	.012	Highly Chlorinated Oil
End Mill Slotting	C-2 Carbide	AR:-7° ECEA:45° RR:-7° NR:.045" CA: 45° Clearance: 7°	1" dia. 2 tooth end mill with carbide throw-away inserts	.125	1.0	.002 in/ tooth	312	160" Work Travel	.015	Dry
Drilling	T-15 HSS	118° Split Point 7° Clearance Angle	1/4" diameter HSS Drill 2 1/2" long	.500 thru	-	.002 in/rev	50	100 holes	.015	Highly Sulphurized Oil
Reaming	M-33 HSS	Helix Angle: 0° CA: 45° Clearance: 7°	.272" diameter 6 Flute chucking reamer	.005 thru	-	.005 in/rev	100	90 holes	.006	Highly Sulphurized Oil
Tapping	M-1 HSS Nitrided	2 Flute Plug Spiral Point 75% thread	5/16 - 24 NF Tap	.500 thru	-	-	7	125 holes	Under size threads	Highly Chlorinated Oil

SURFACE GRINDING

Operation	Wheel Grade	Grinding Fluid	Wheel Speed Ft./Min.	Table Speed Ft./Min.	Down Feed In./Pass.	Cross Feed In./Pass.	G Ratio
Finishing	32A46H8VBE	Highly Sulphurized Oil	4000	60	.0005	.050	7
Roughing	32A46K8VBE	Highly Sulphurized Oil or Soluble Oil (1:20)	6000	60	.001	.100	30

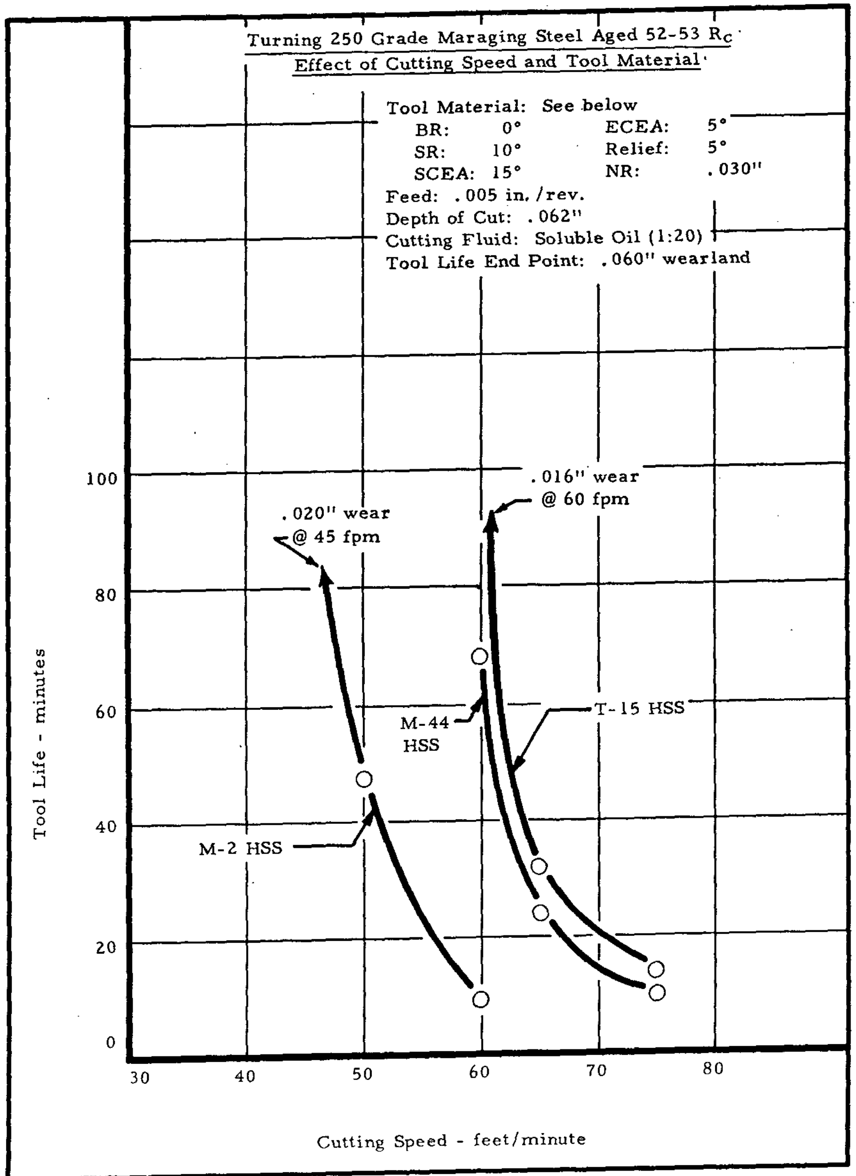

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Figure 66

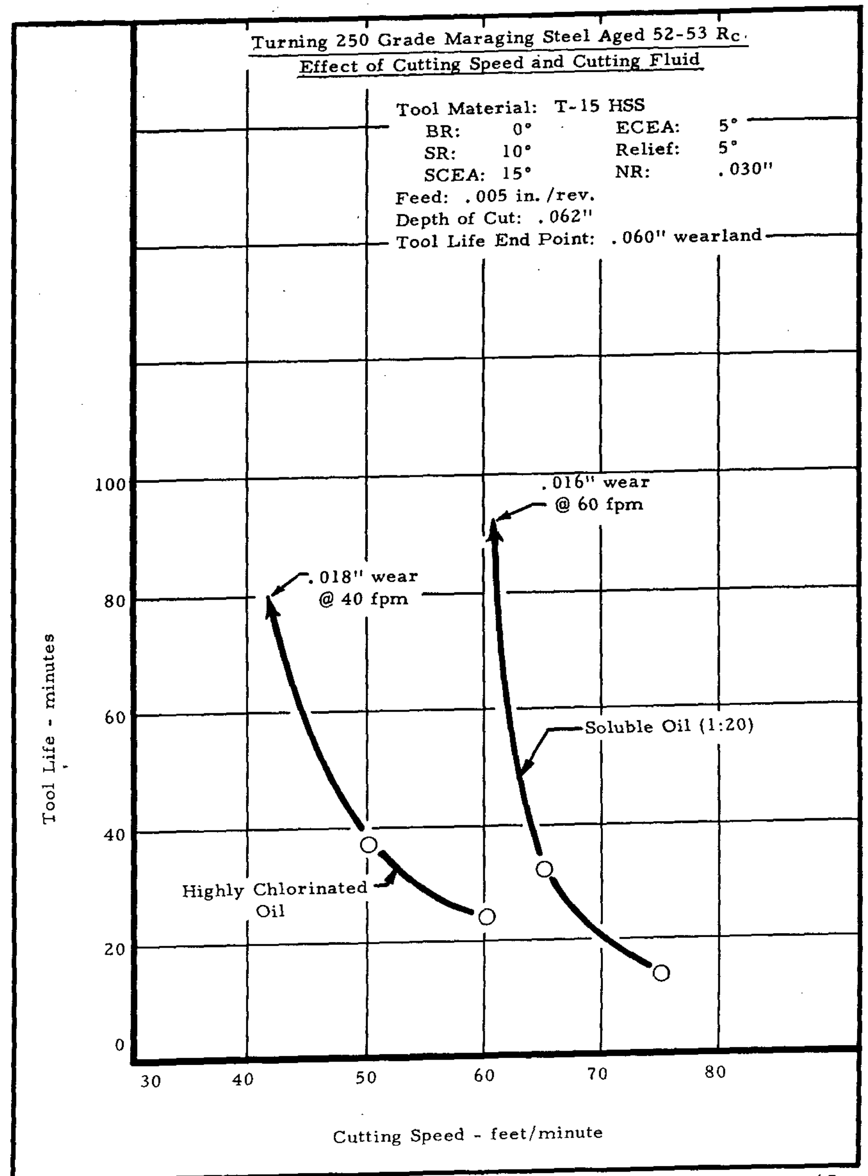

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Figure 67

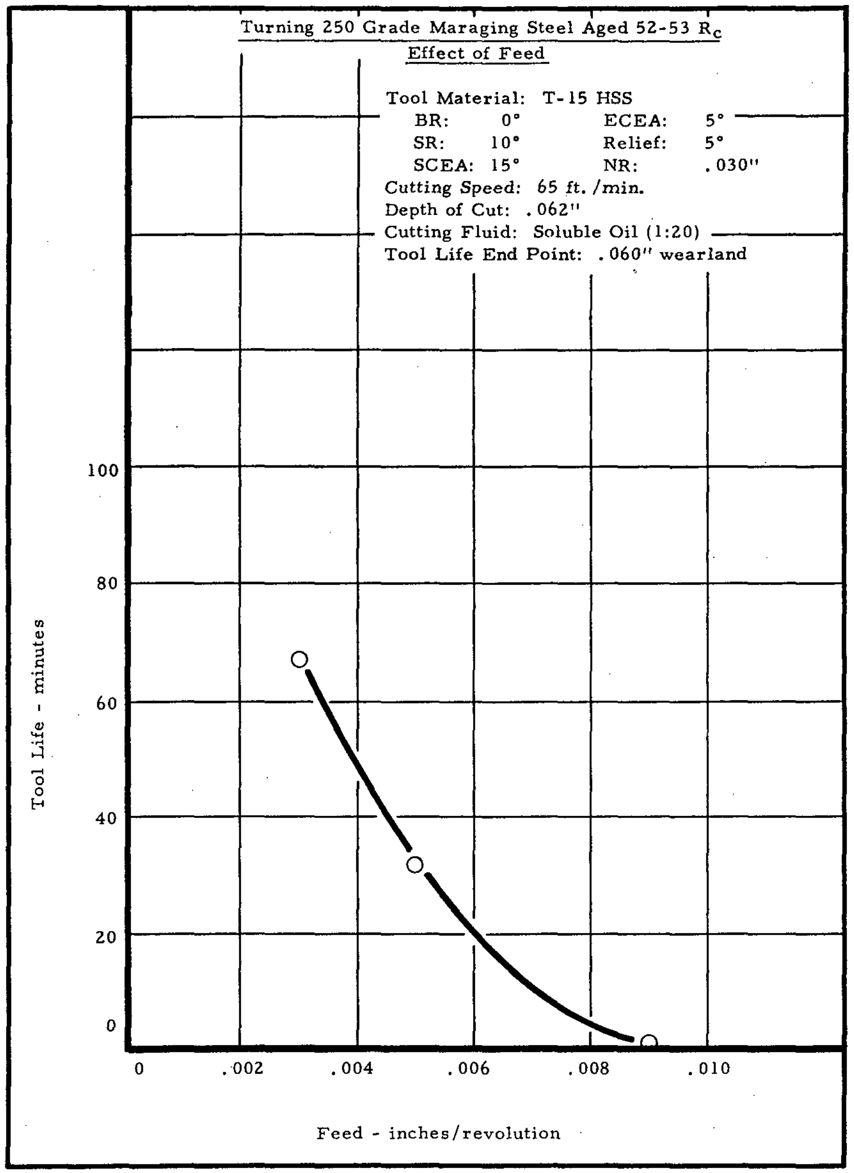

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Figure 68

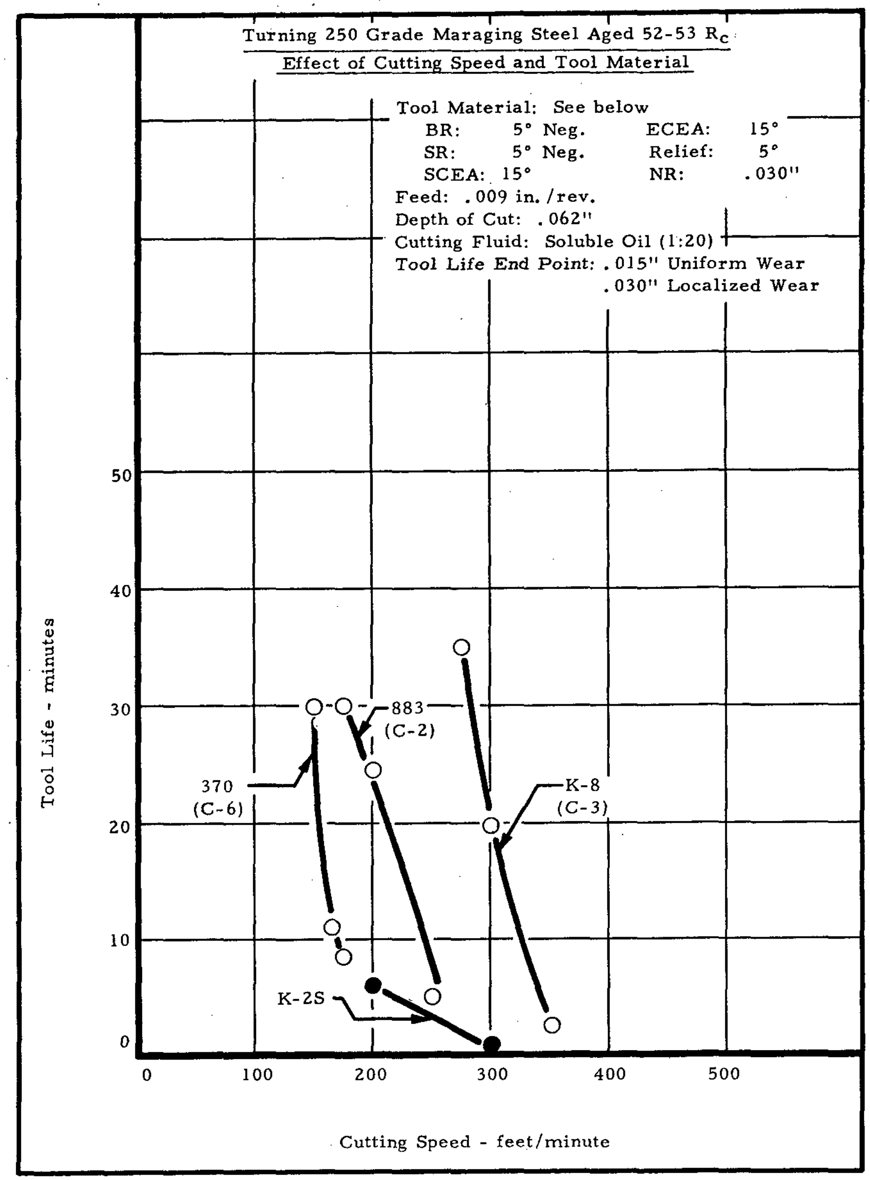

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Figure 69

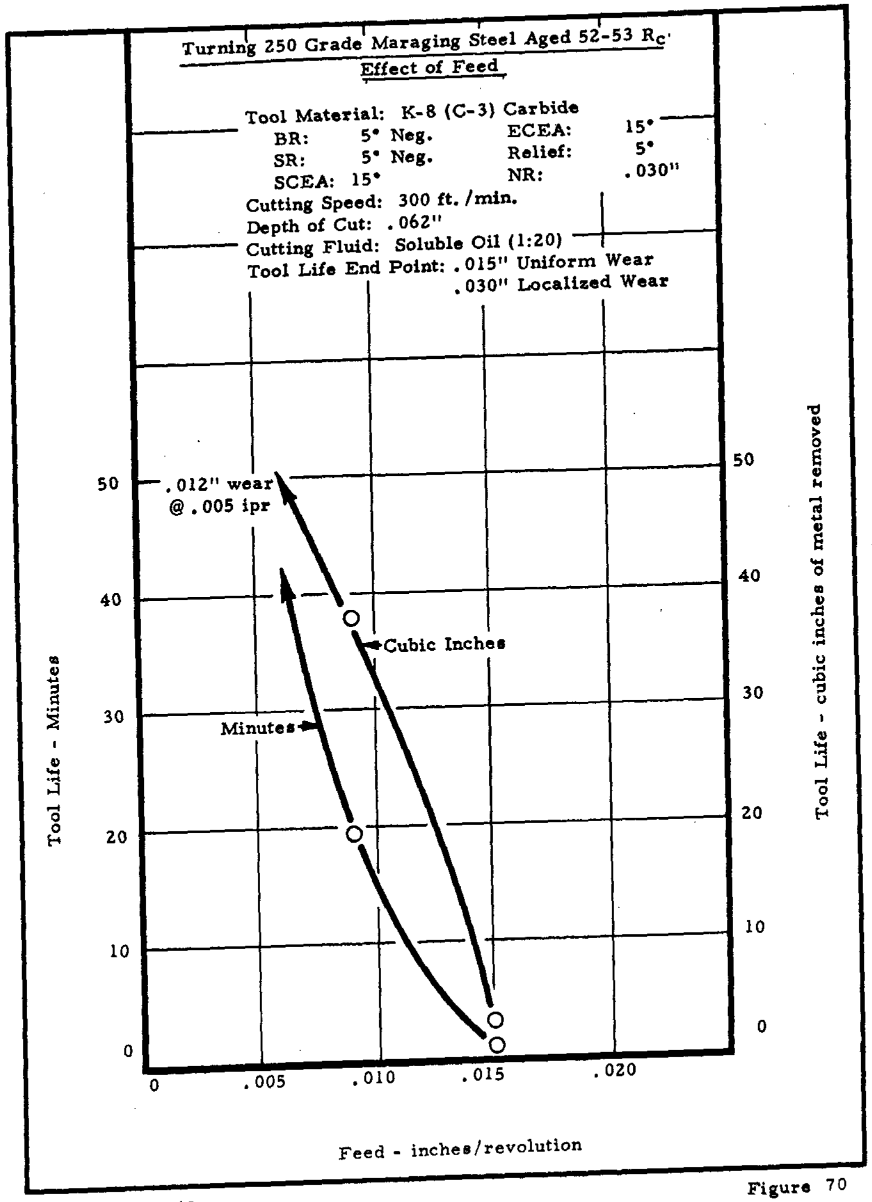

Figure 70

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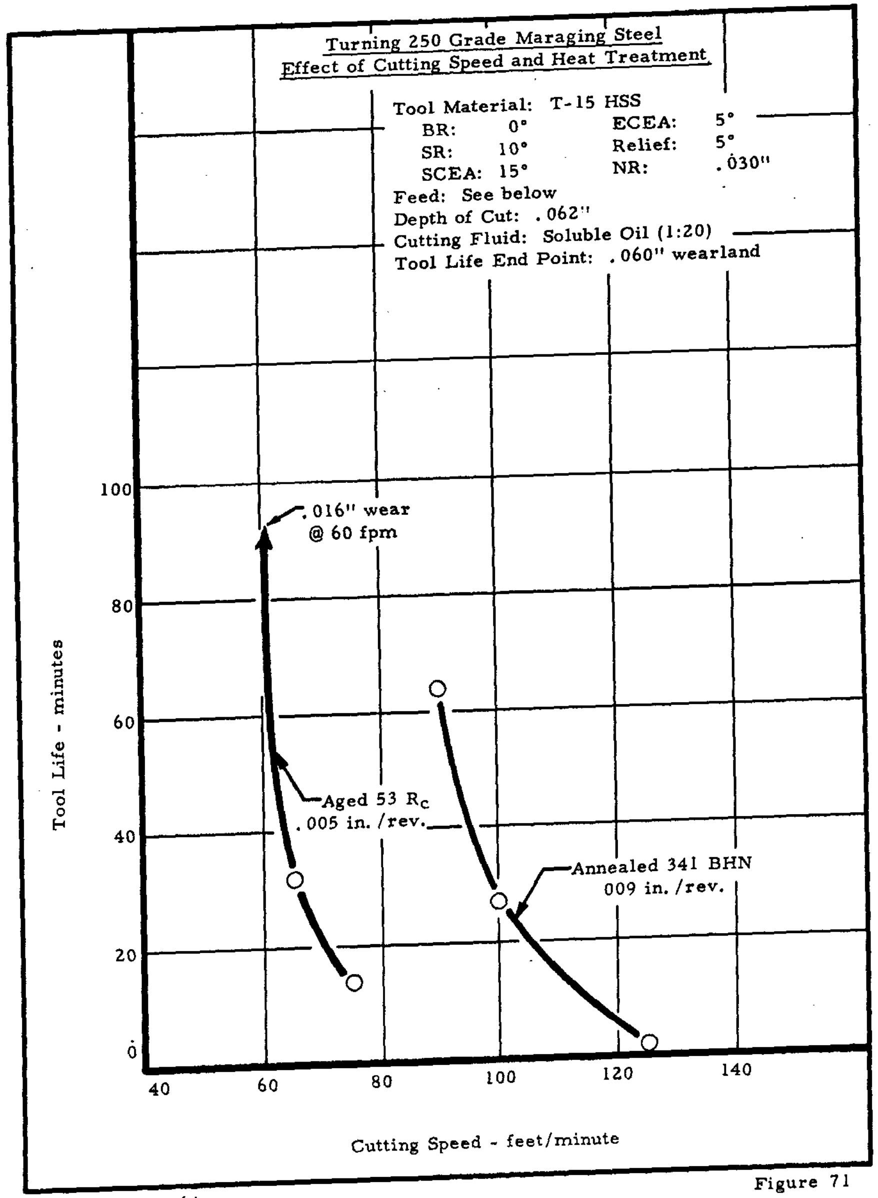

Figure 71

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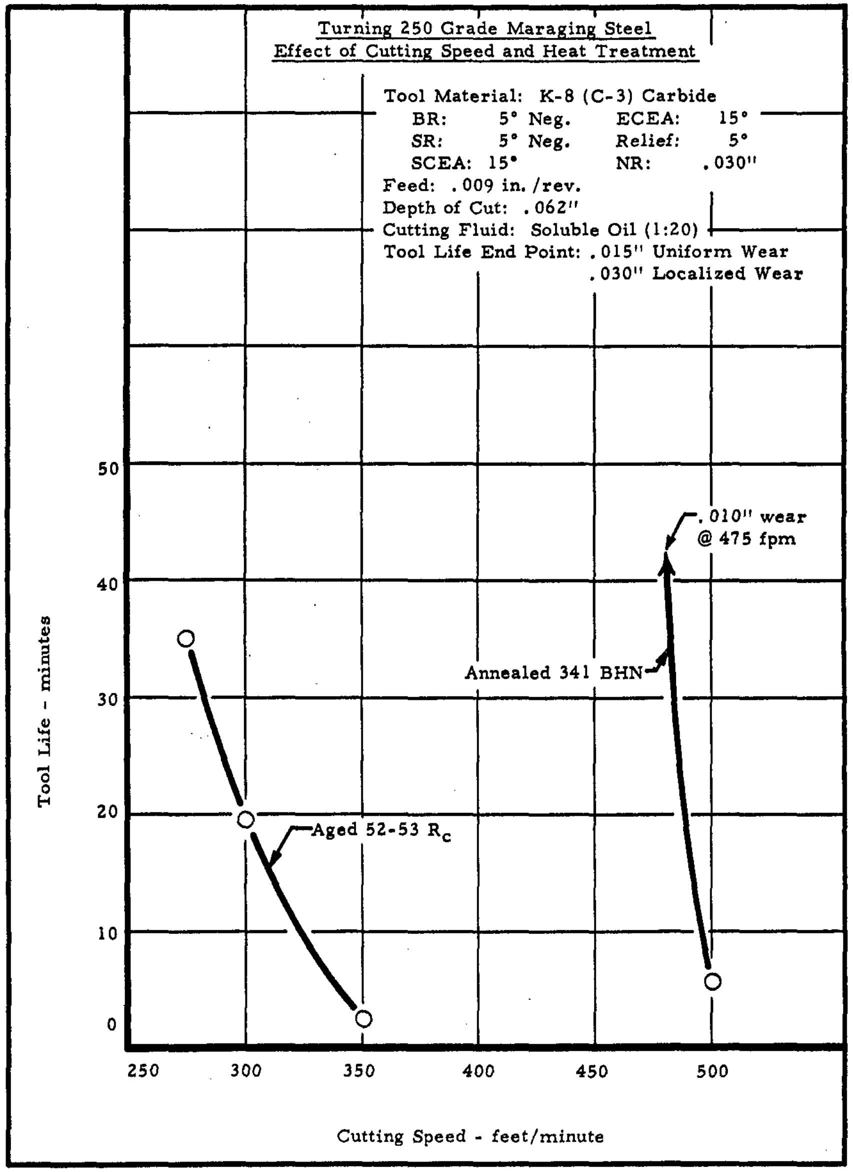

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Figure 72

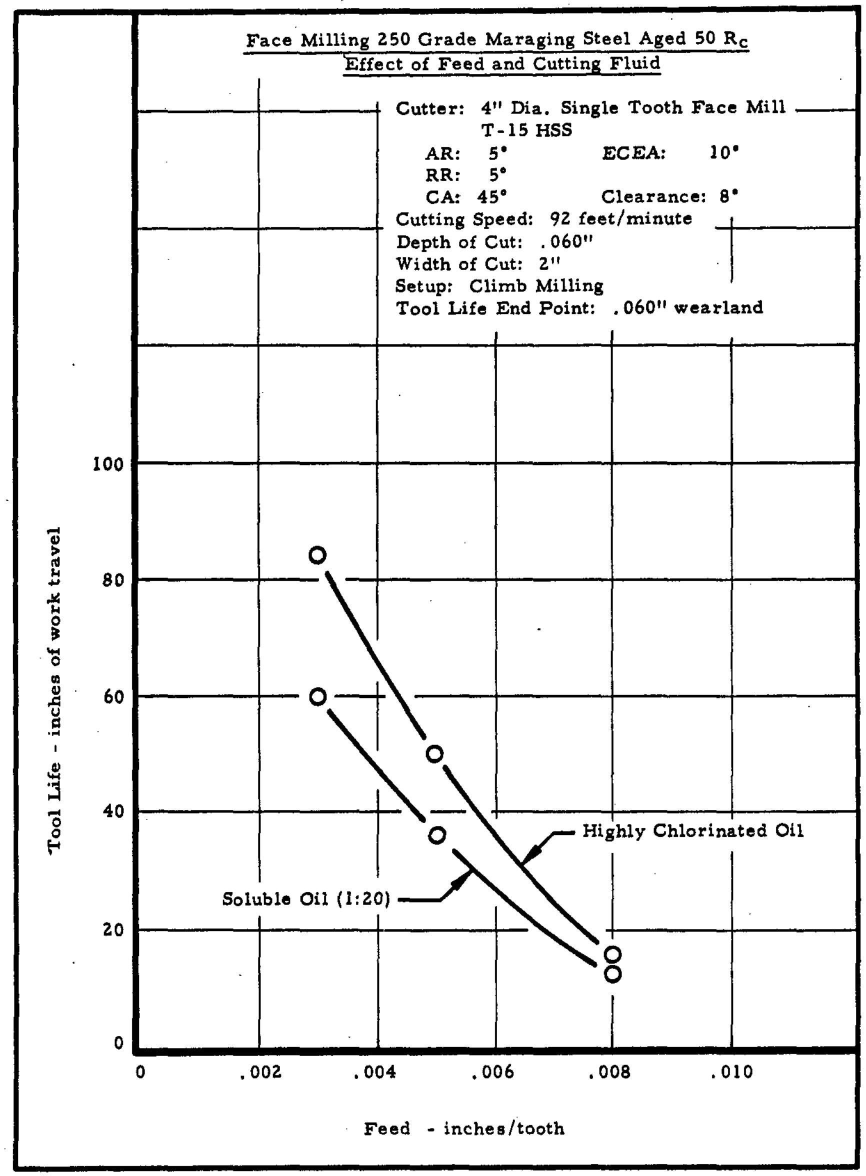

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Figure 73

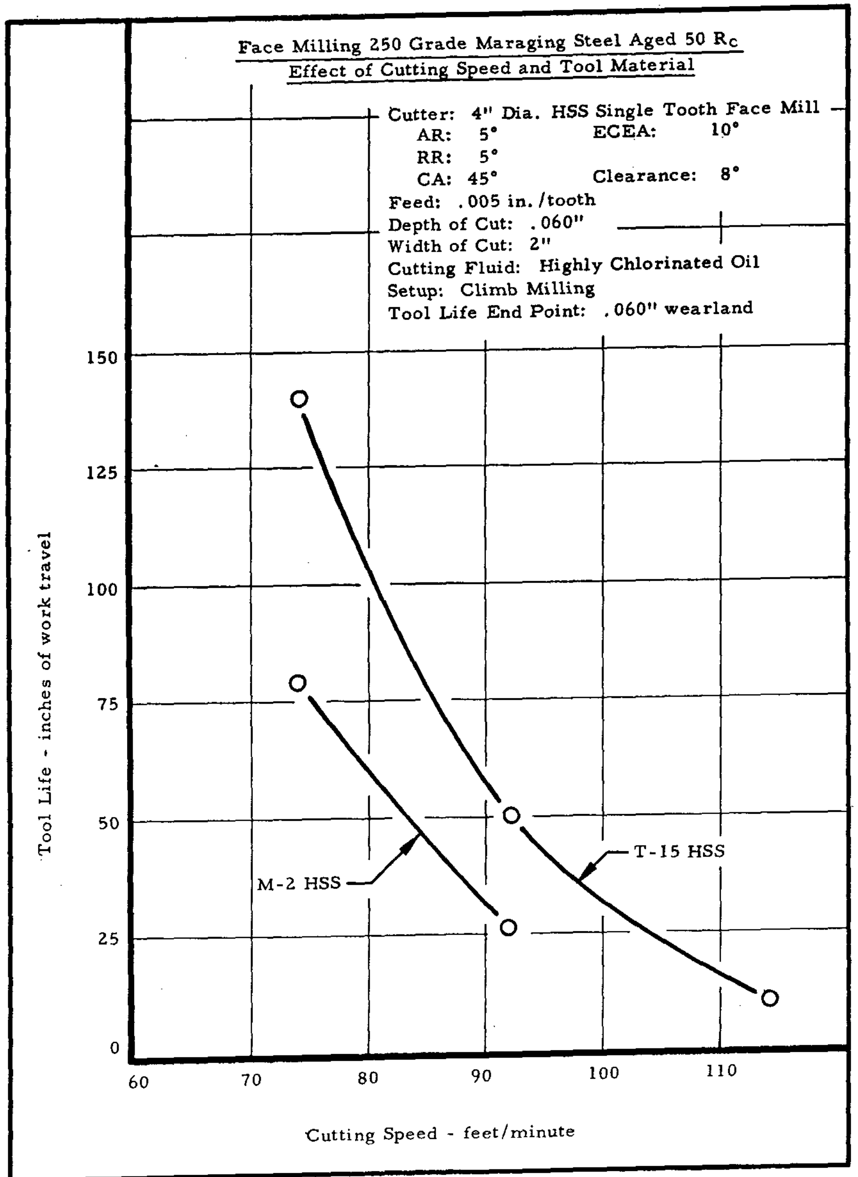

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Figure 74

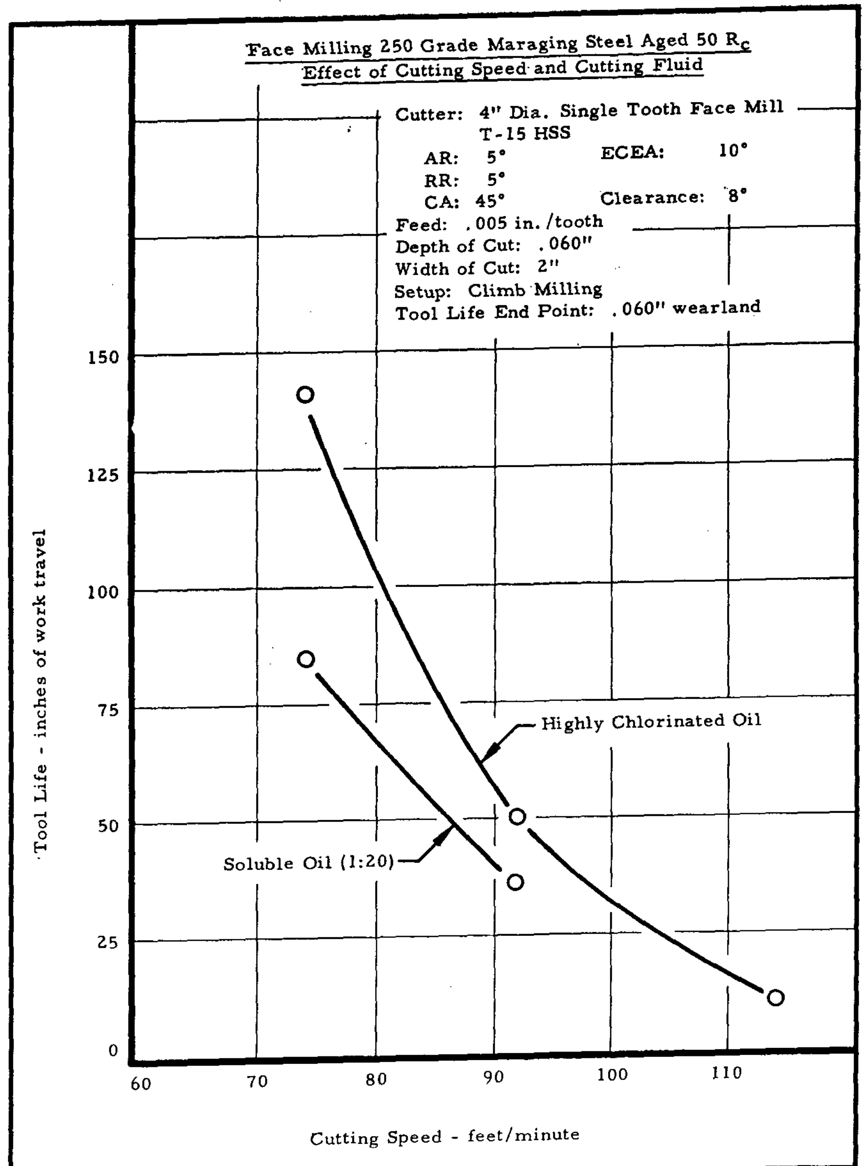

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Figure 75

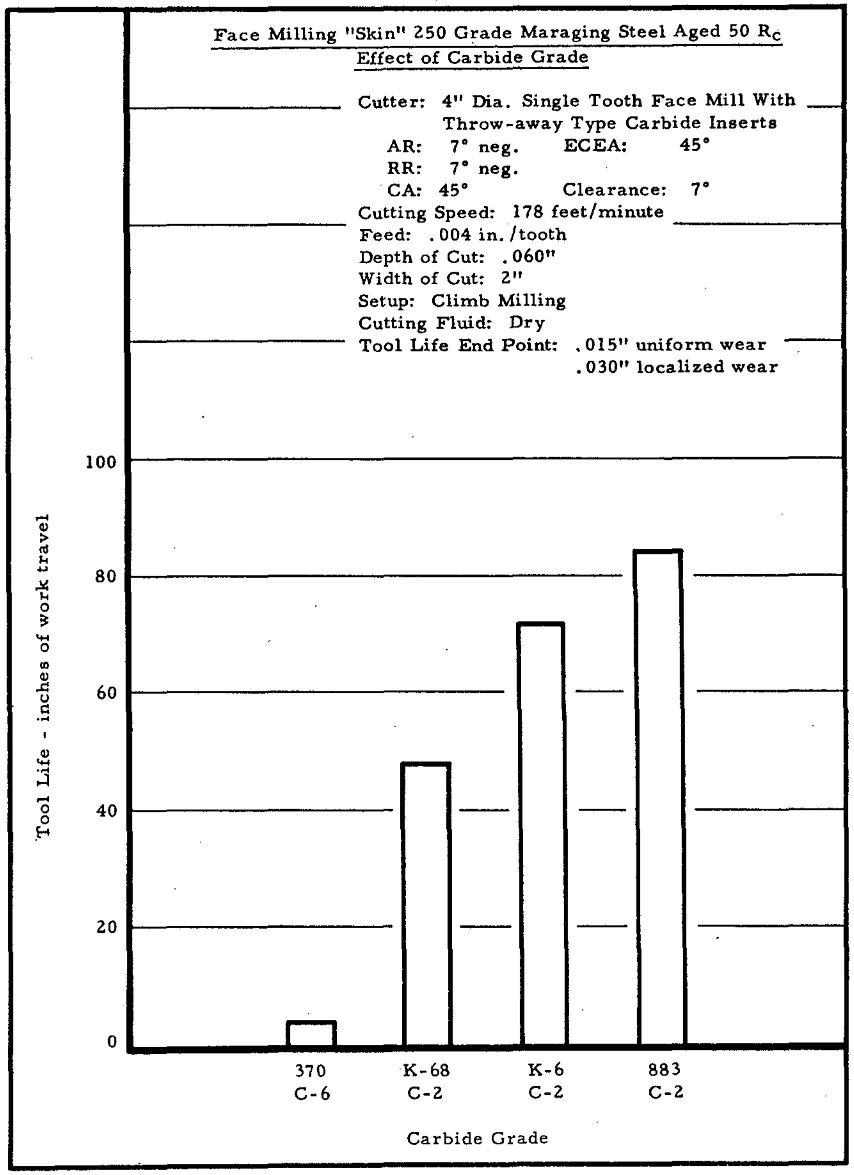

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Figure 76

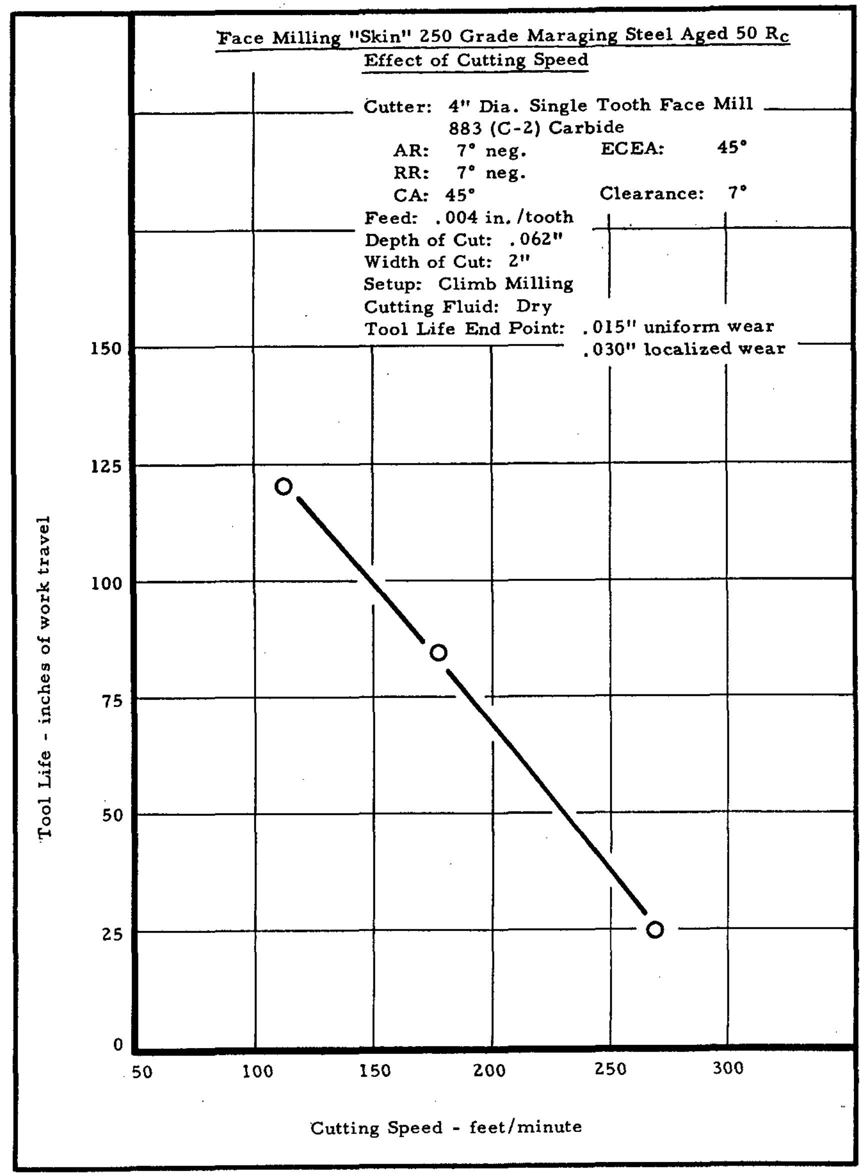

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Figure 77

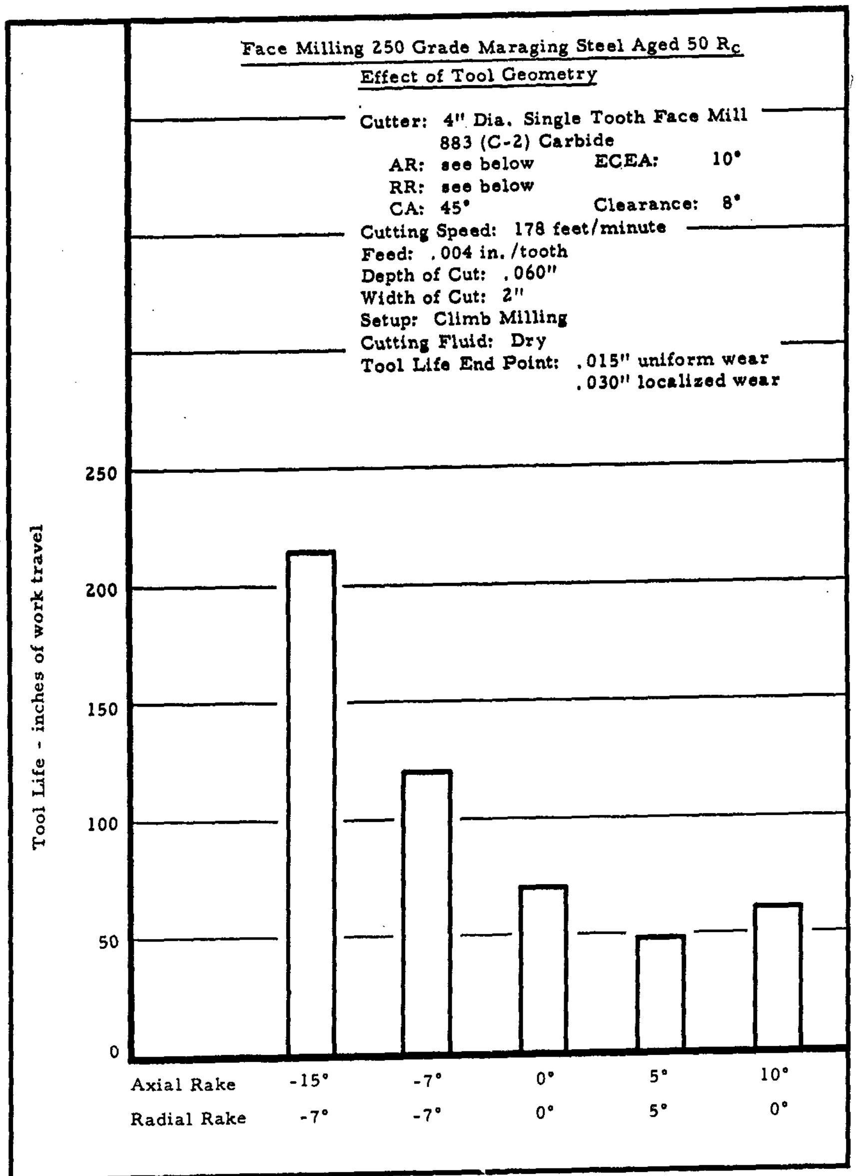

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Figure 78

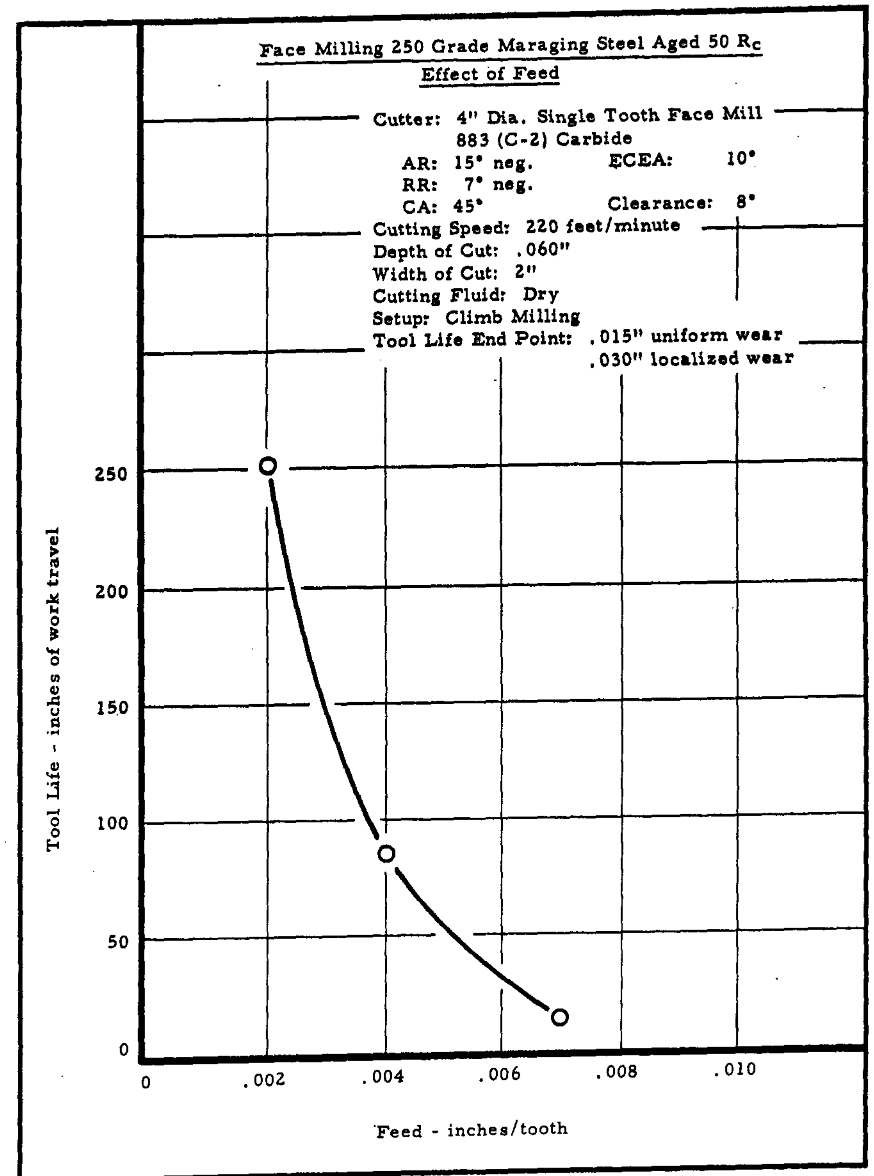

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Figure 79

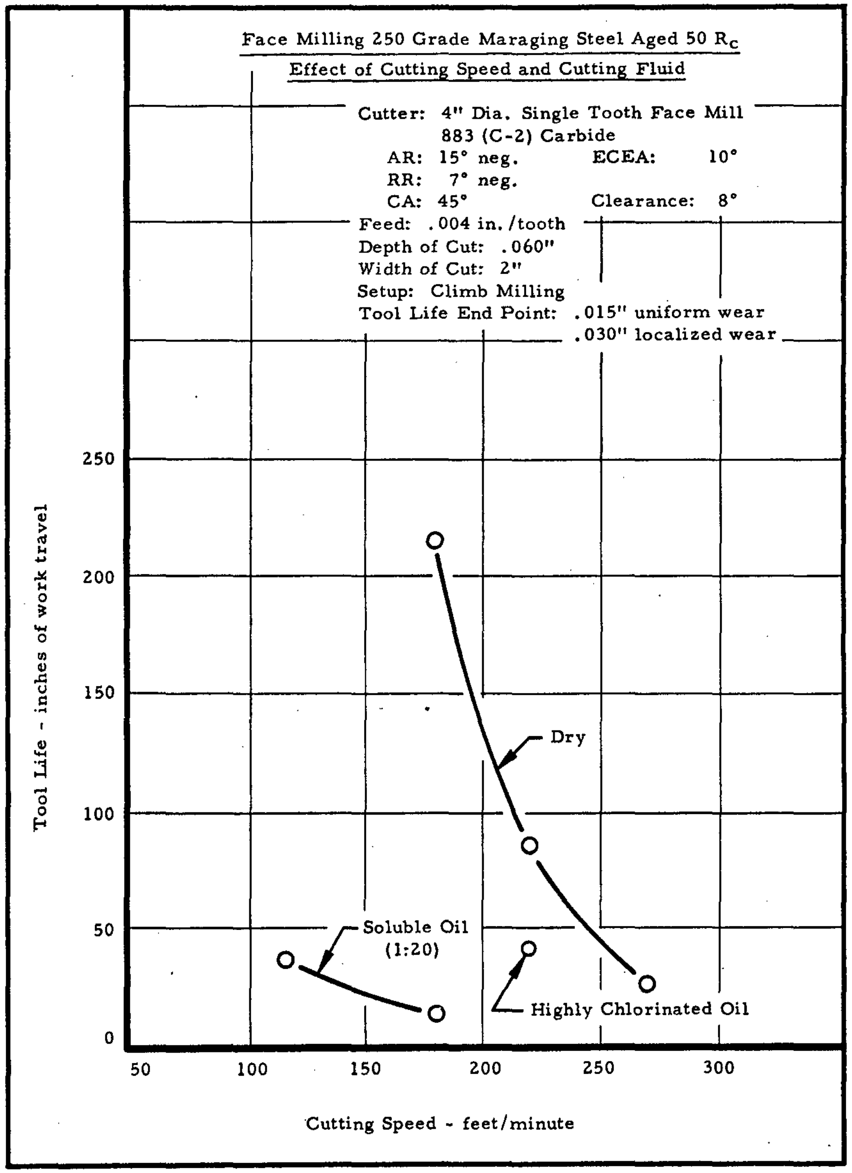

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Figure 80

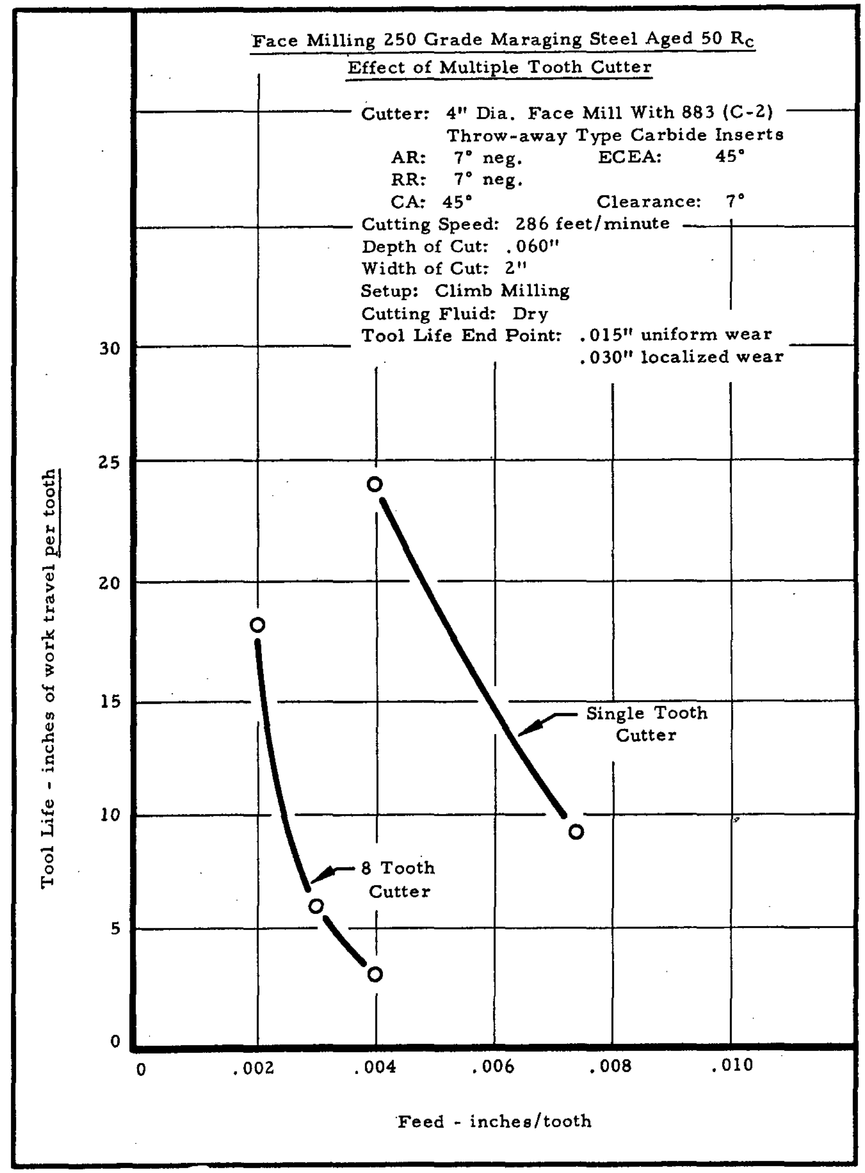

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Figure 81

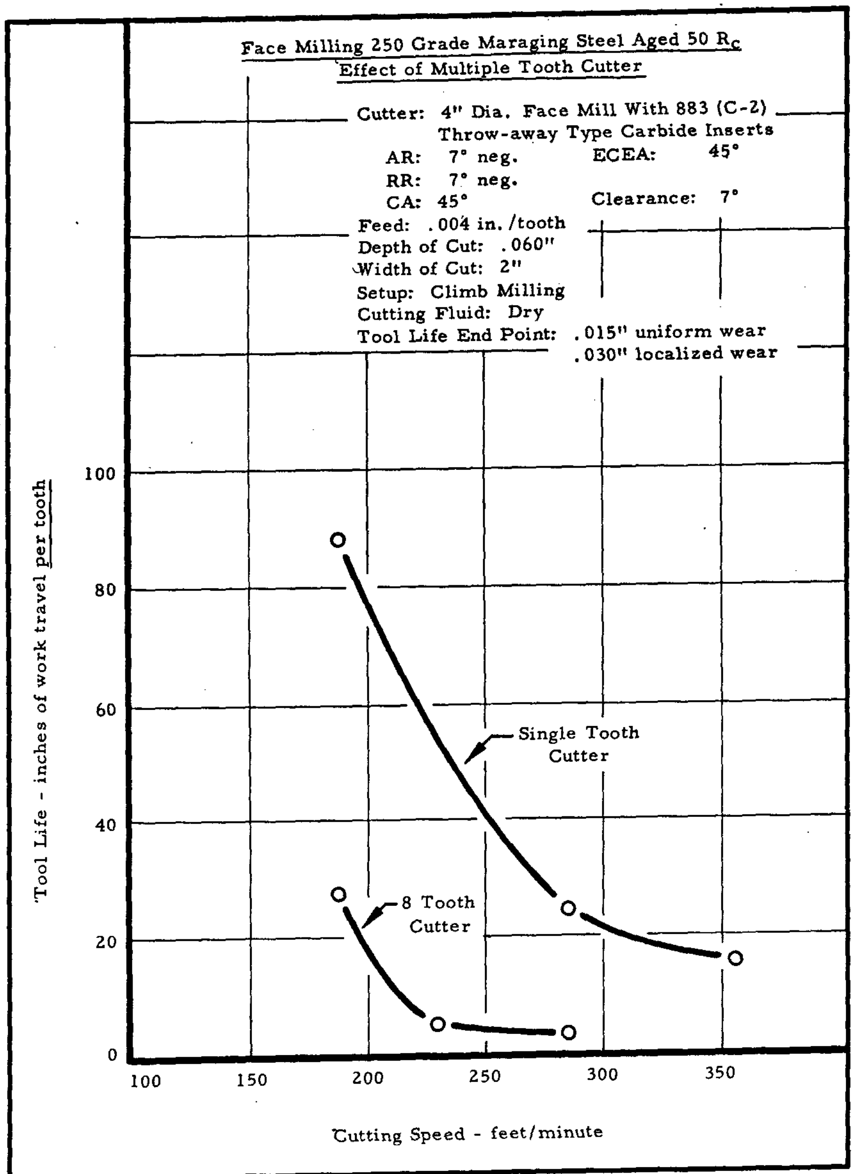

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Figure 82

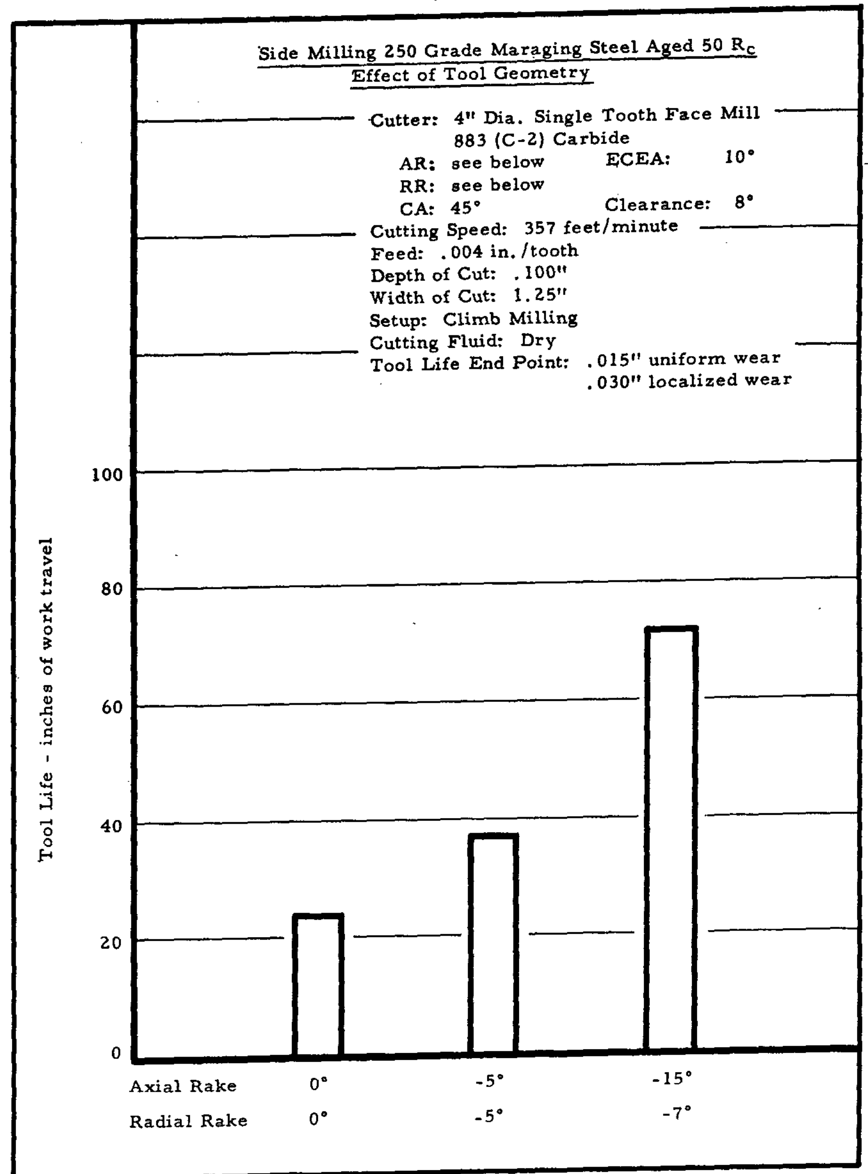

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Figure 83

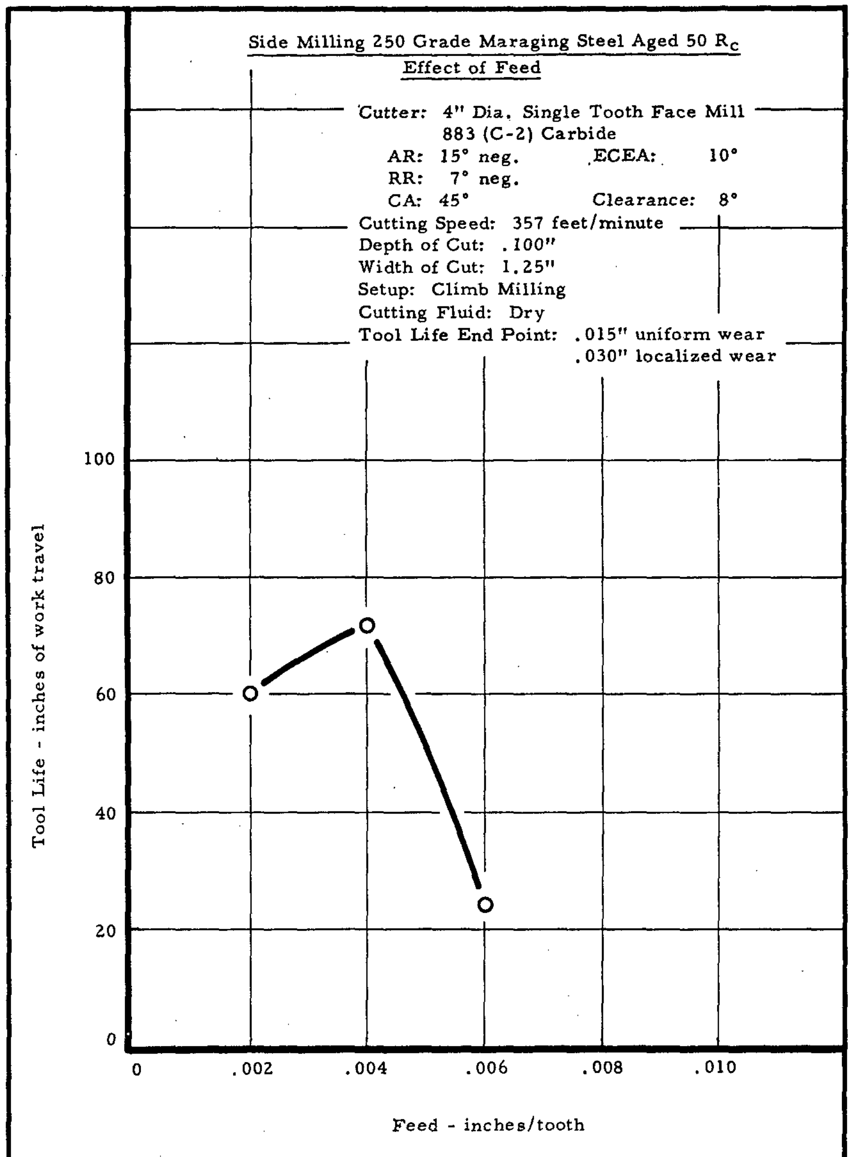

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Figure 84

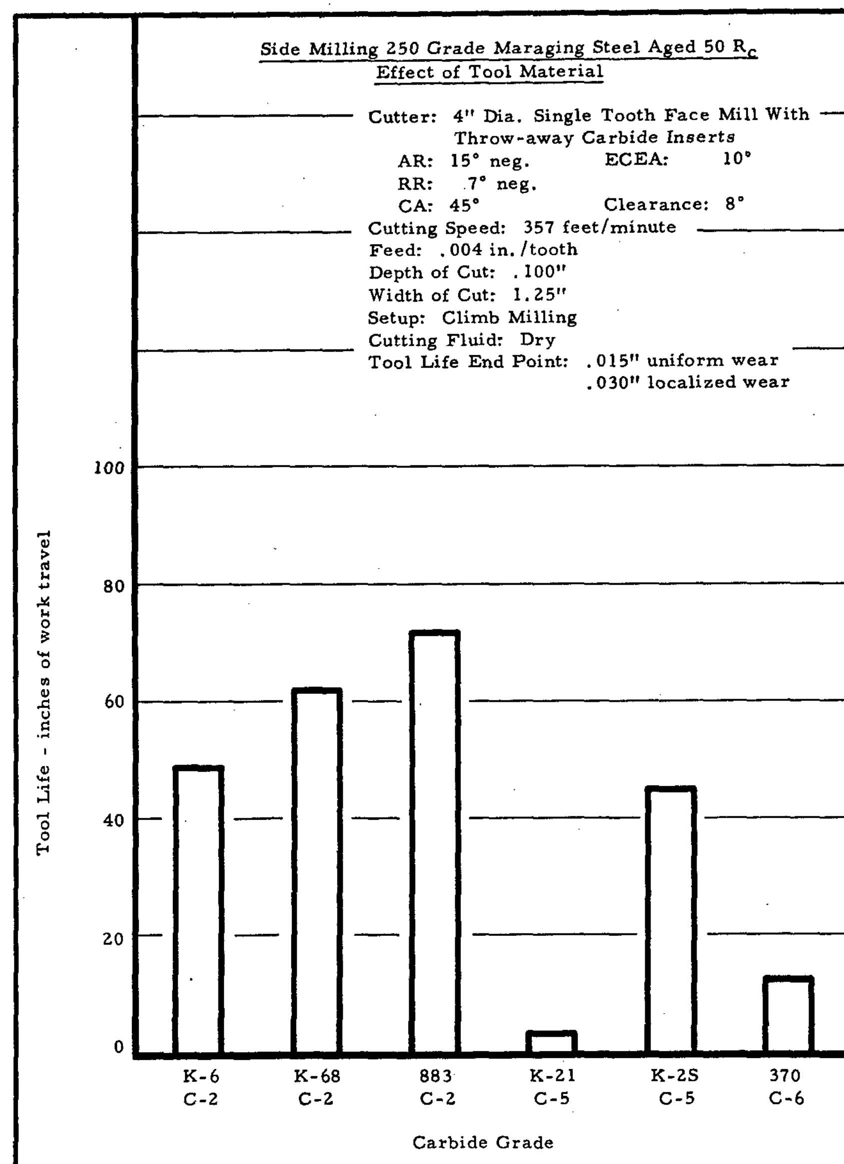

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Figure 85

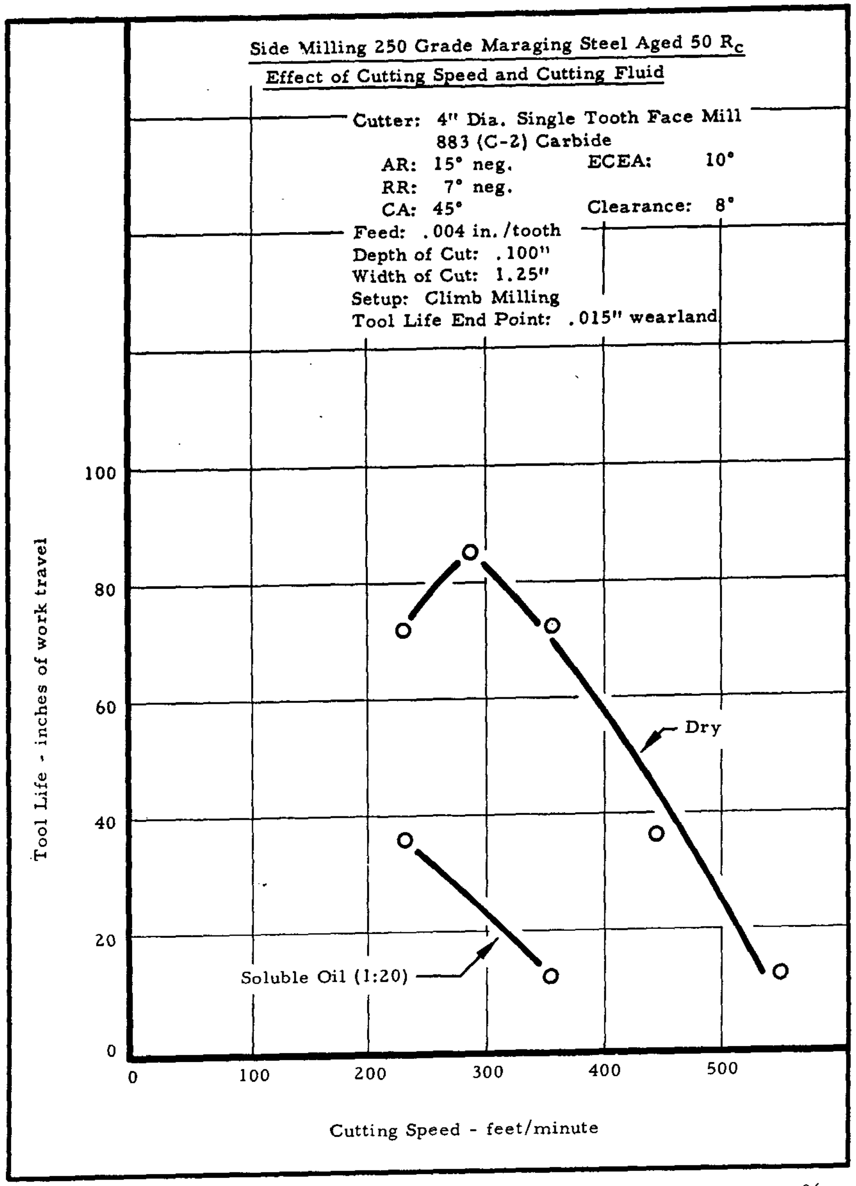

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Figure 86

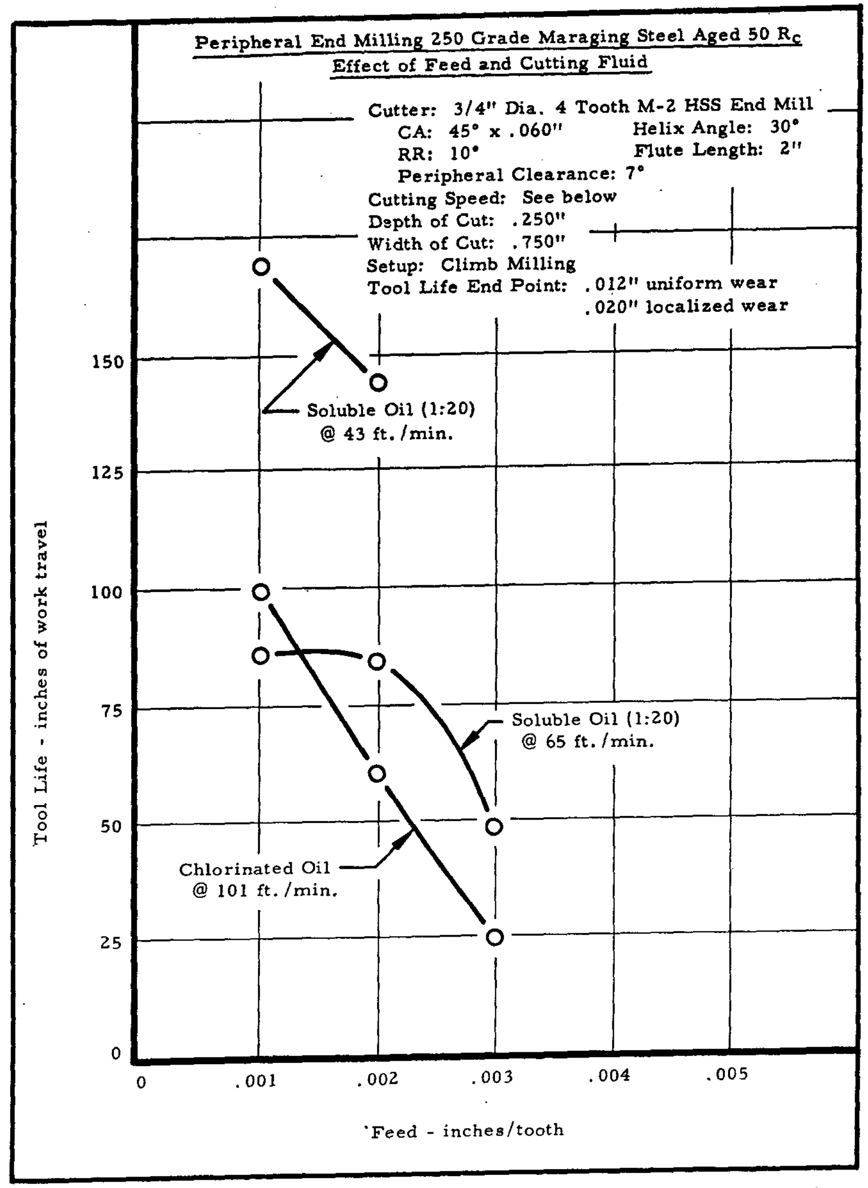

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Figure 87

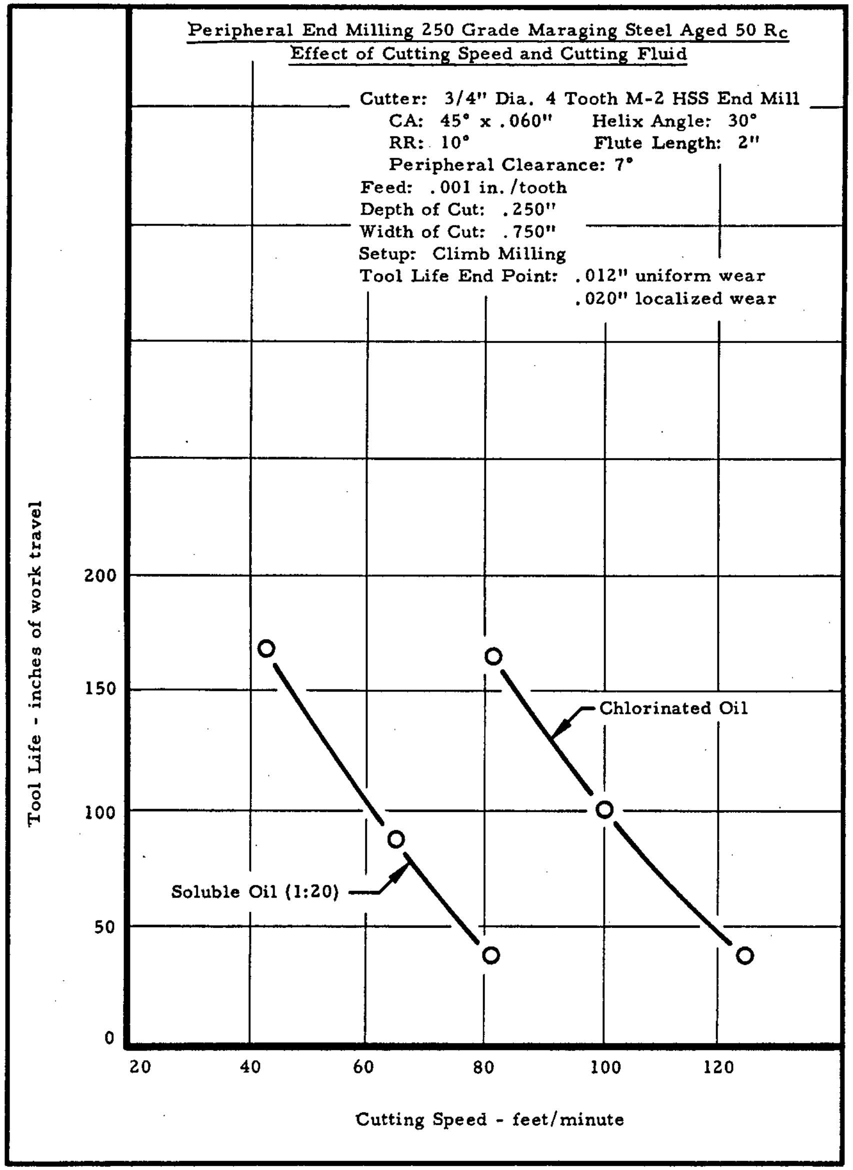

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Figure 88

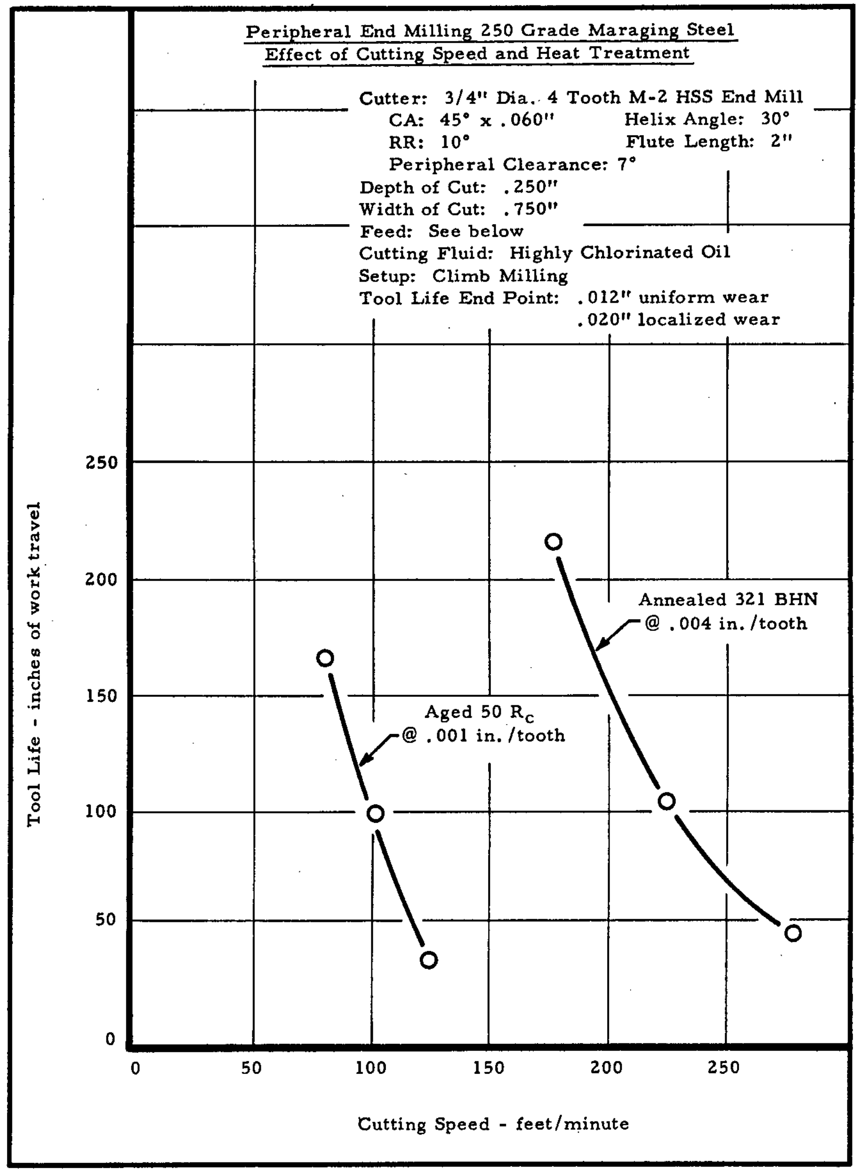

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Figure 89

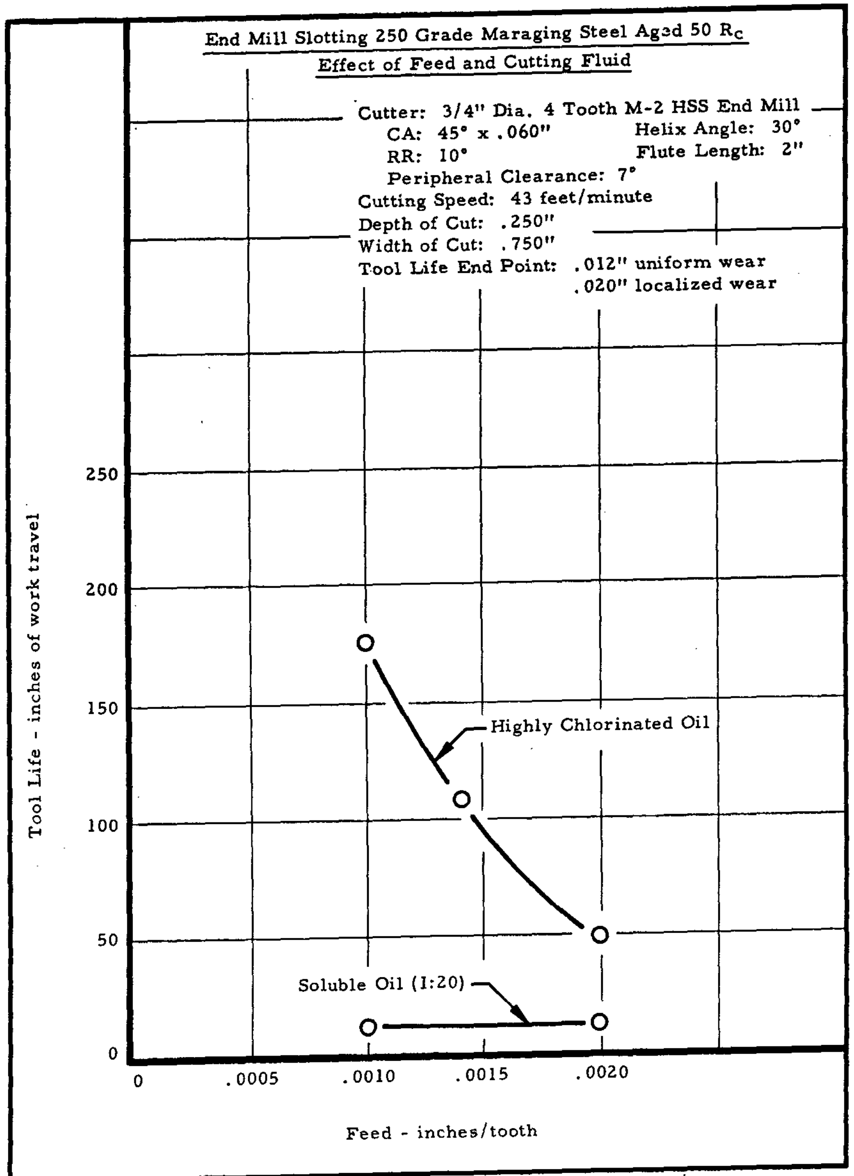

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Figure 90

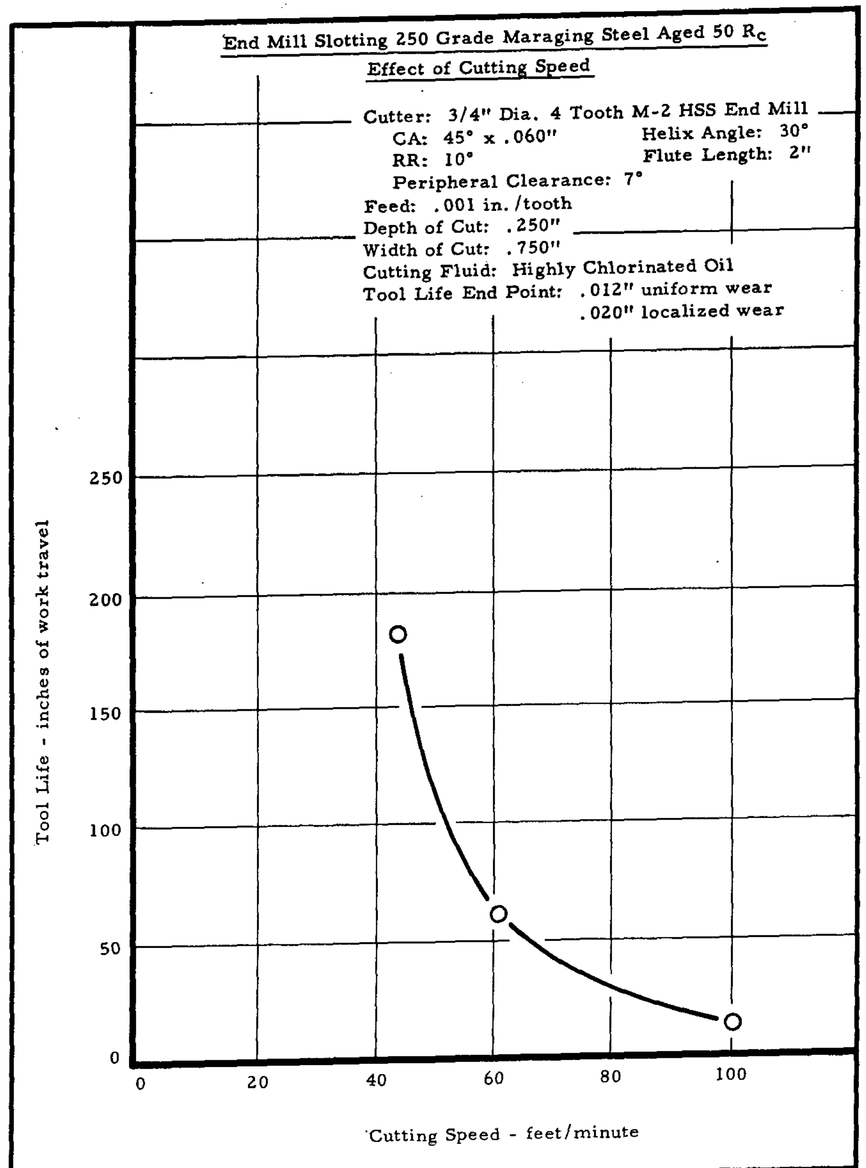

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Figure 91

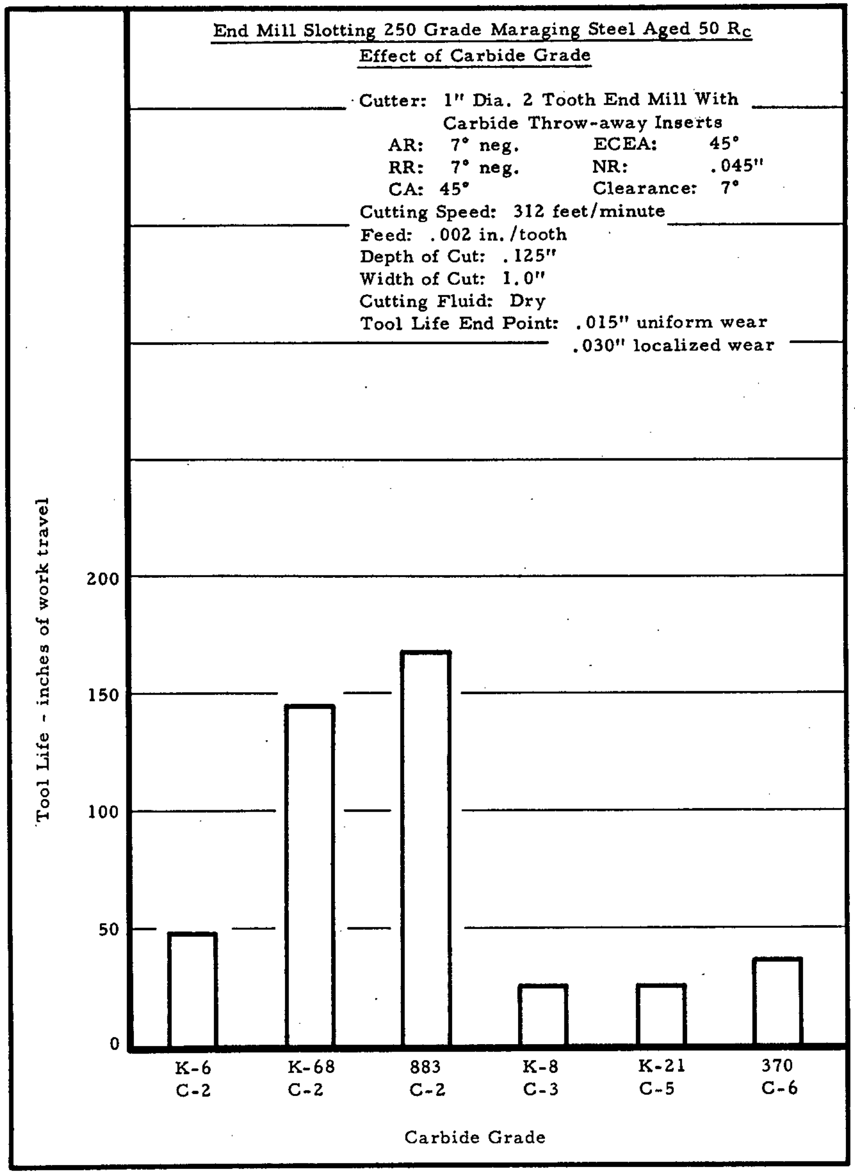

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Figure 92

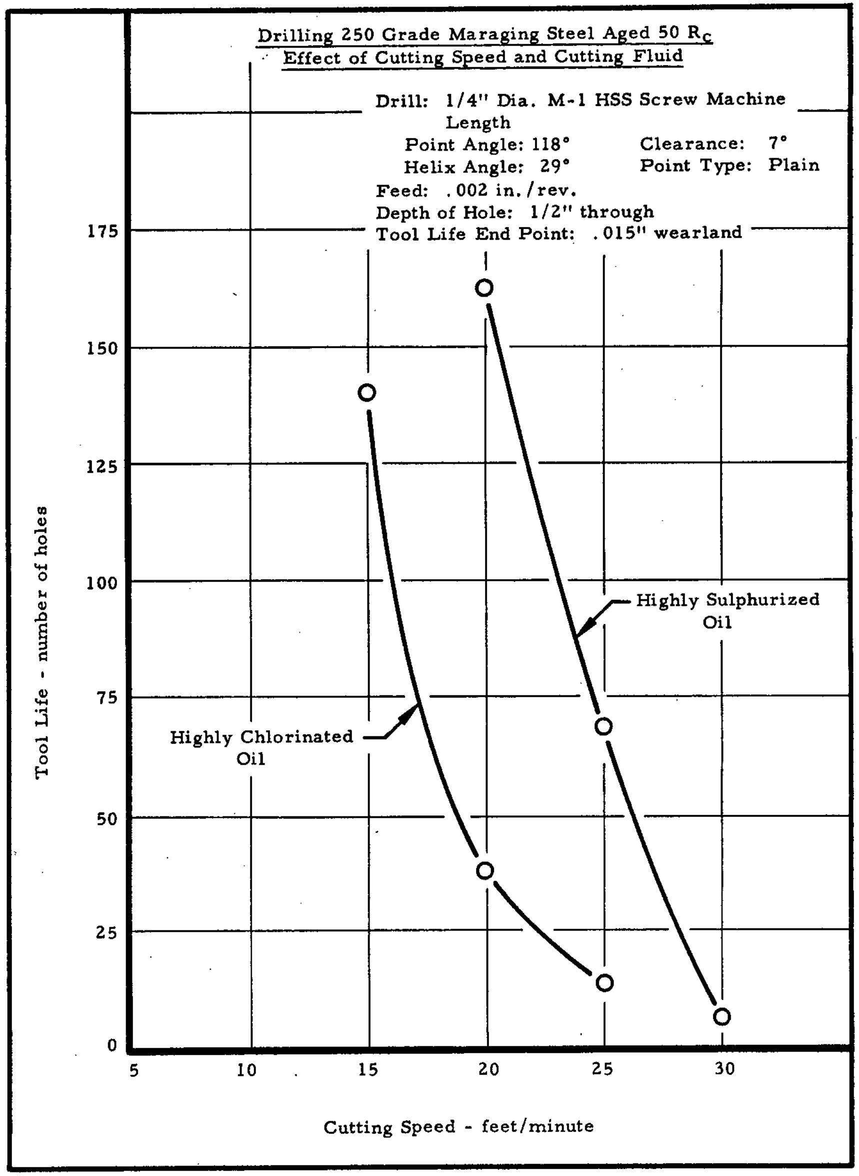

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Figure 93

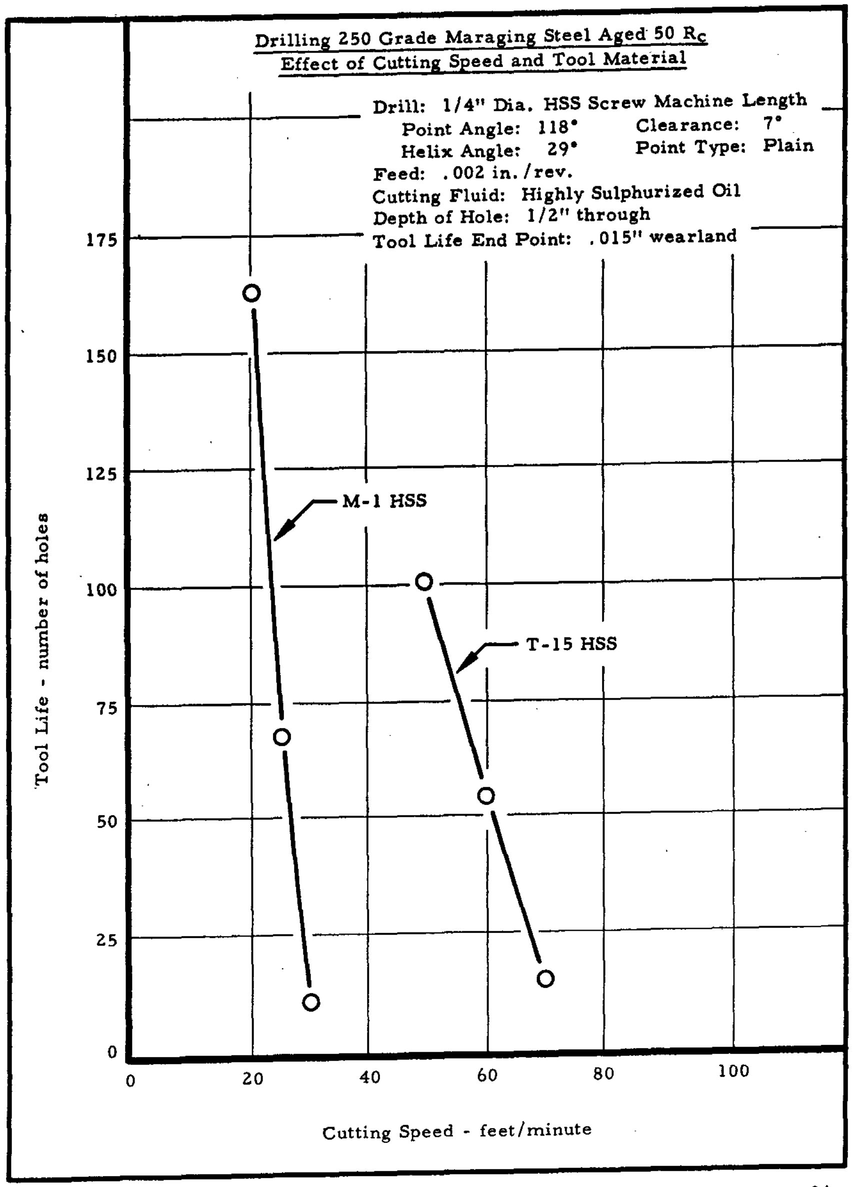

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Figure 94

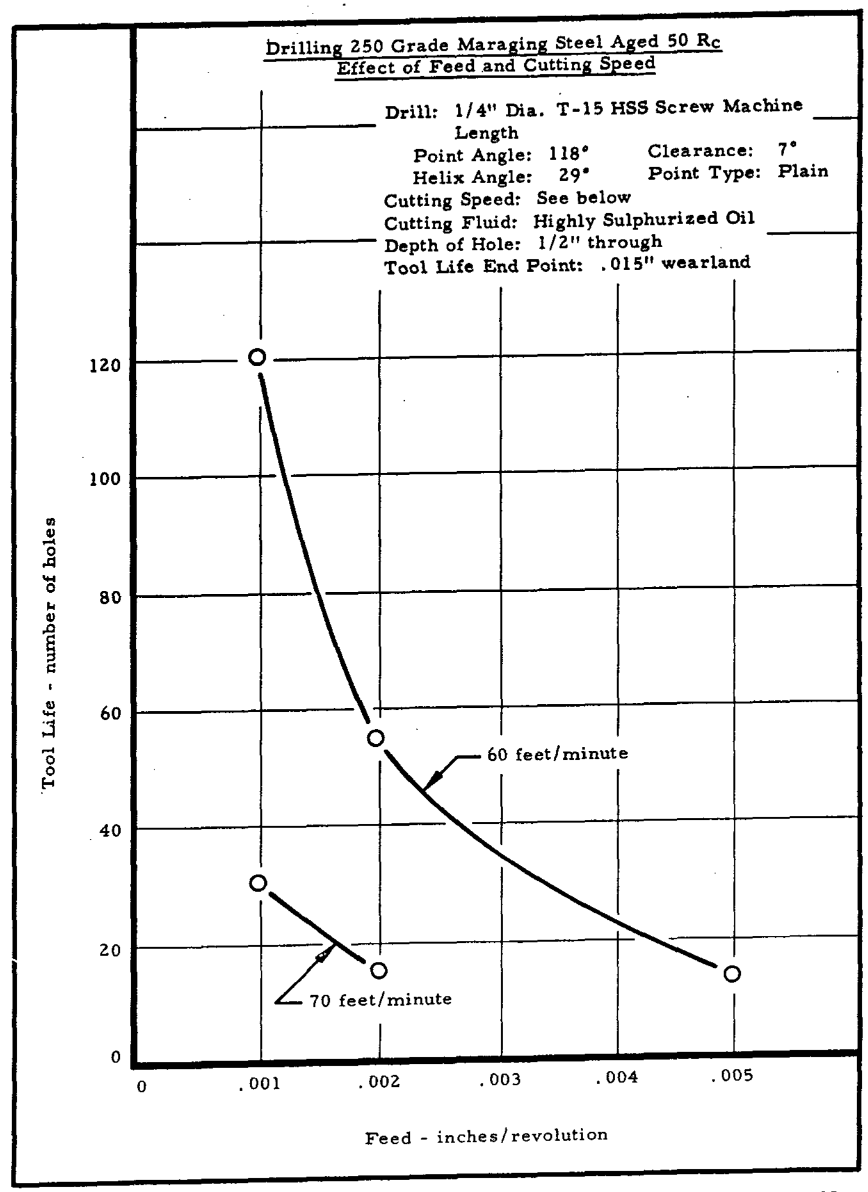

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Figure 95

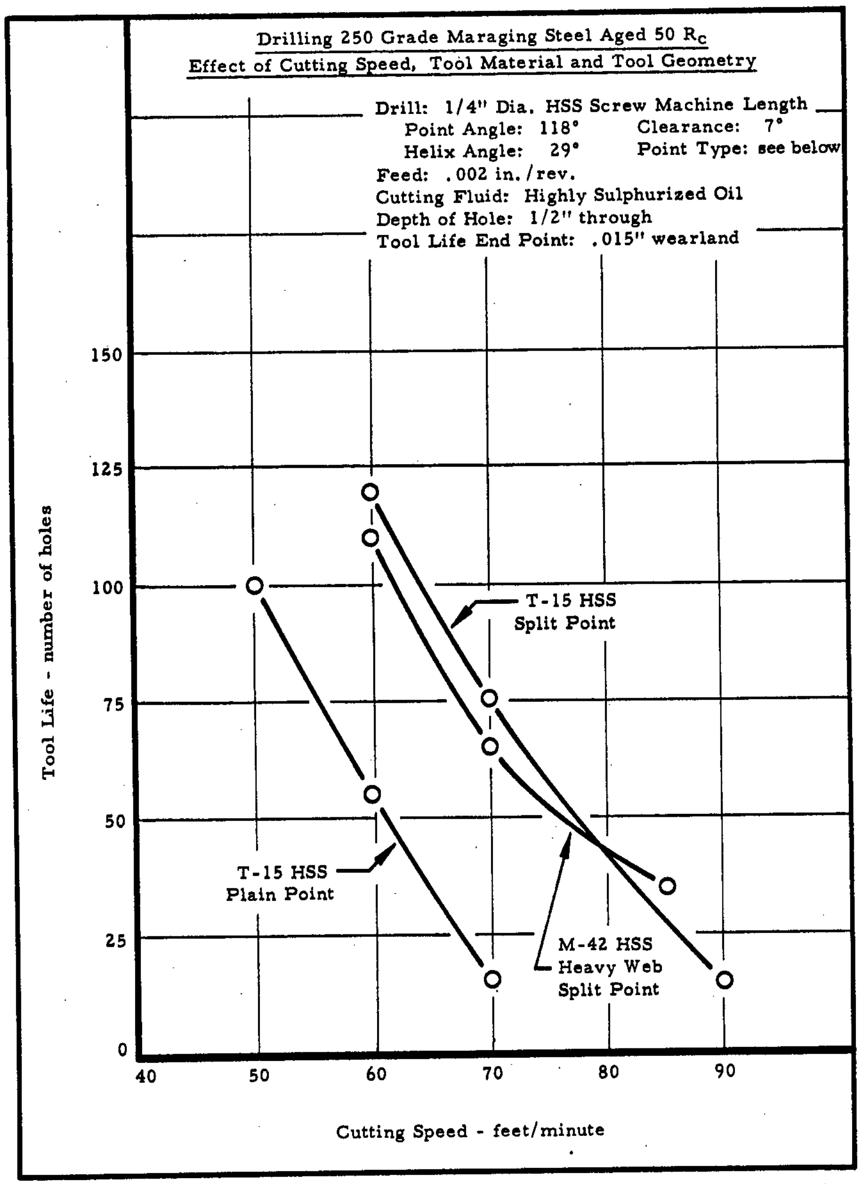

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Figure 96

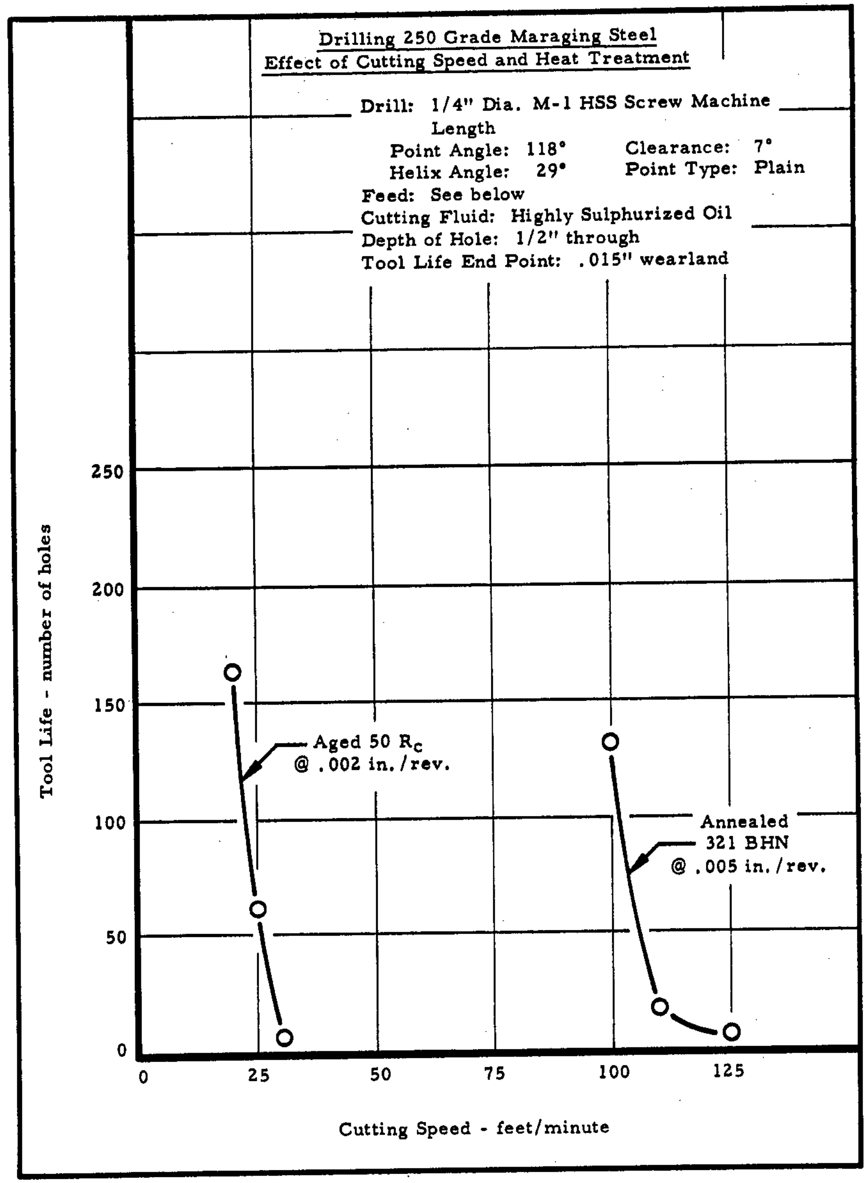

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Figure 97

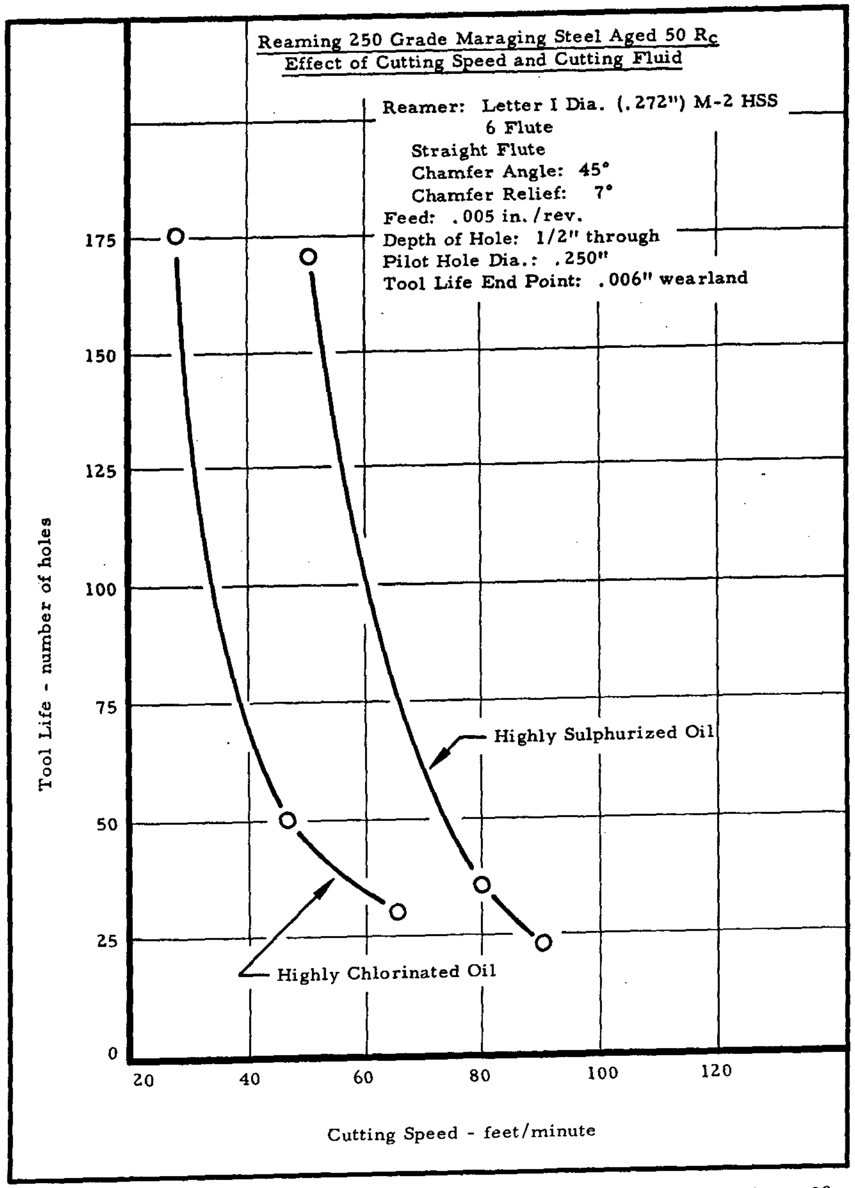

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Figure 98

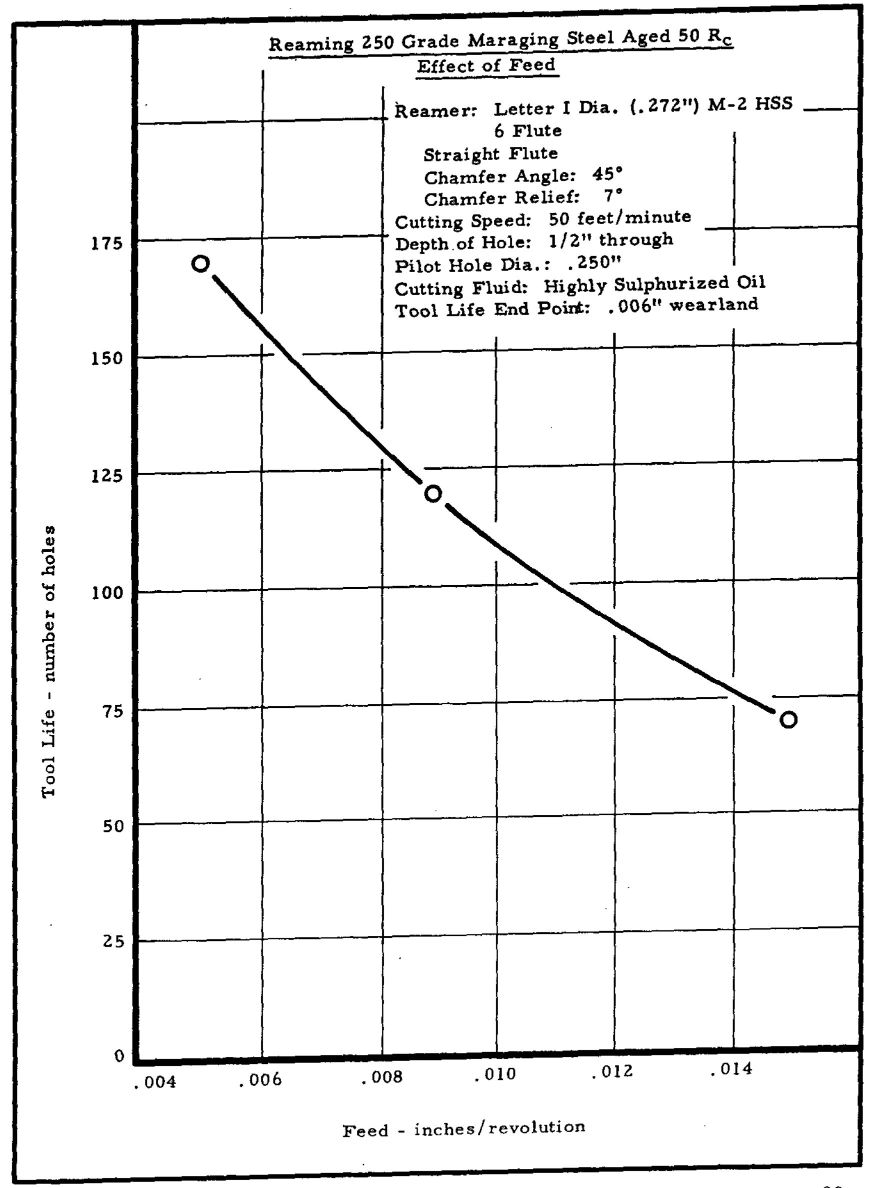

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Figure 99

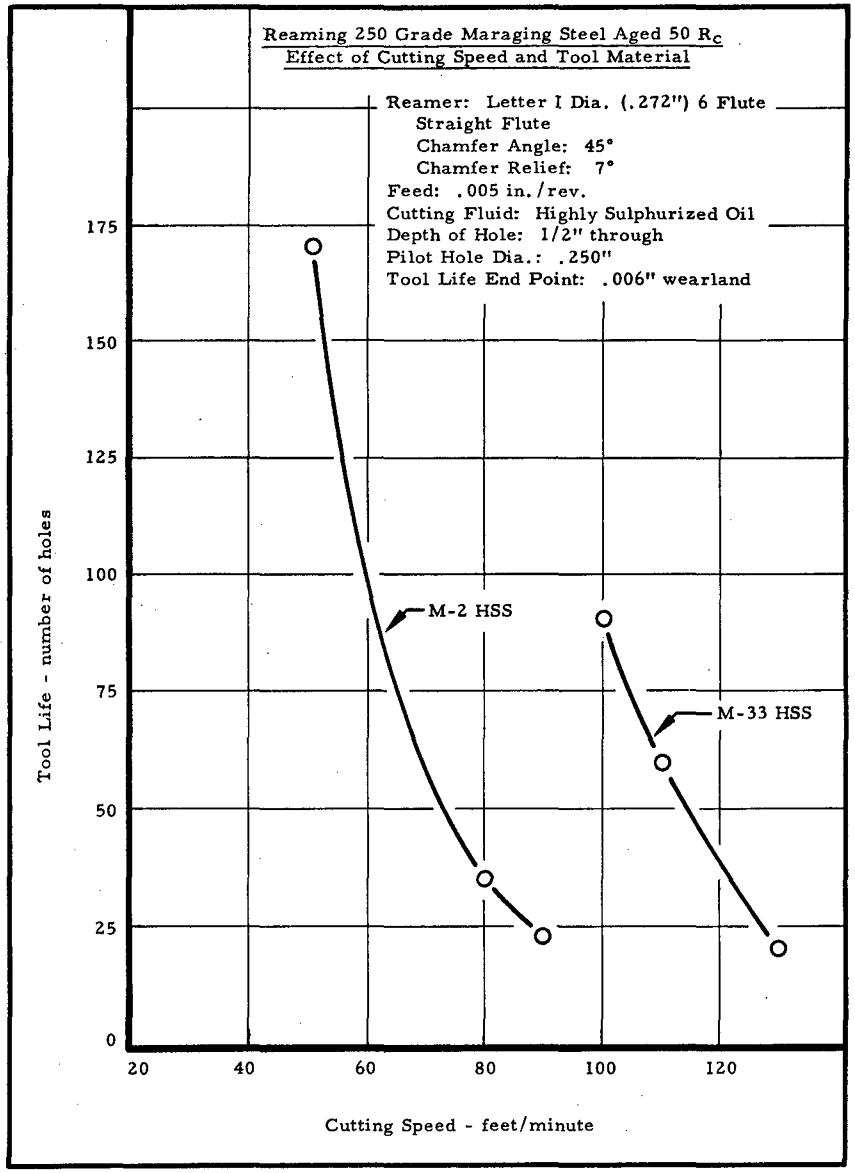

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Figure 100

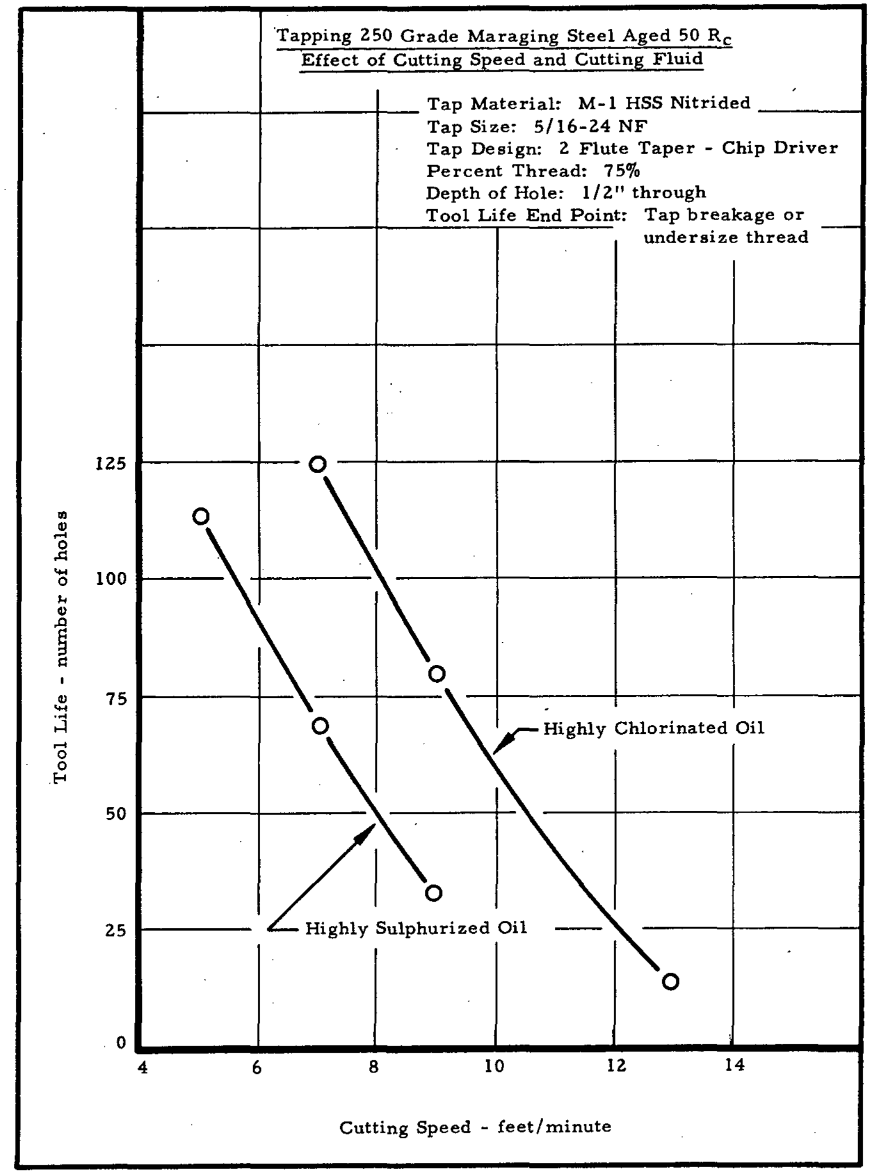

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Figure 101

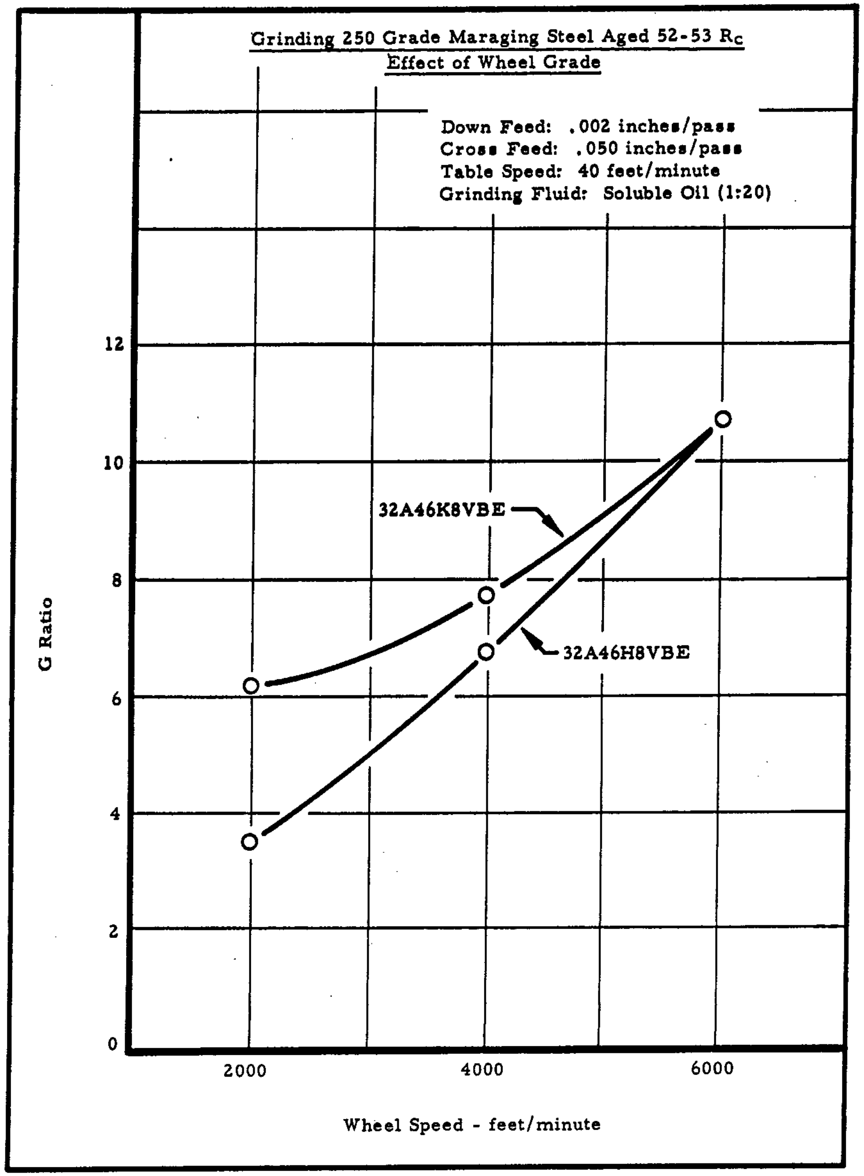

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Figure 102

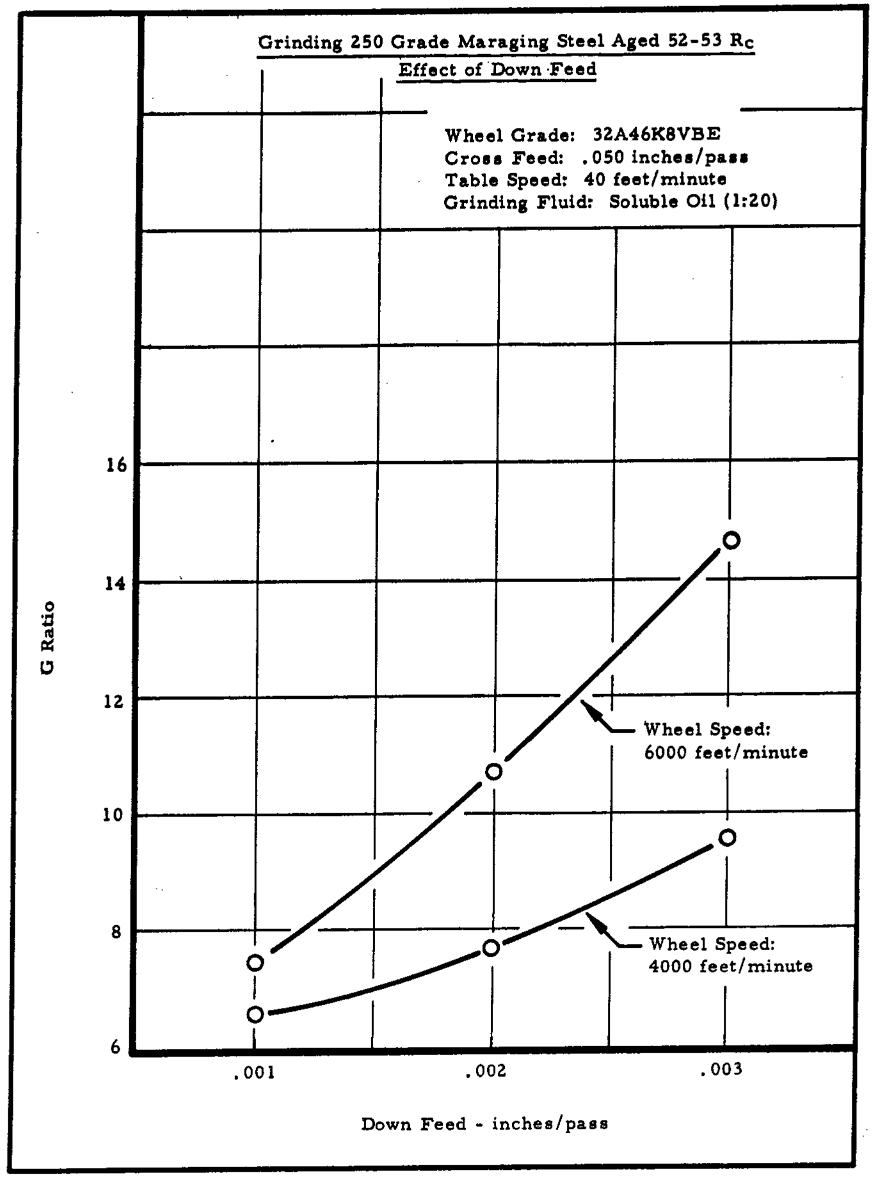

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Figure 103

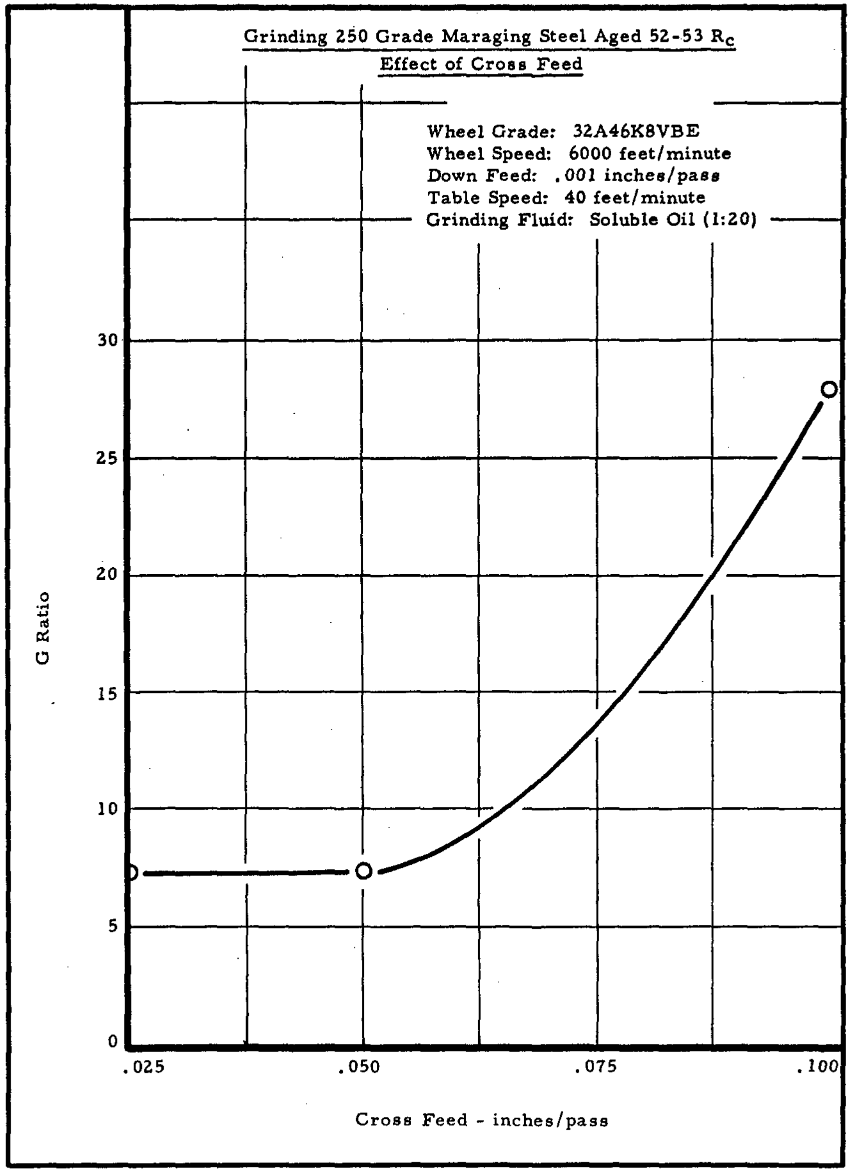

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Figure 104

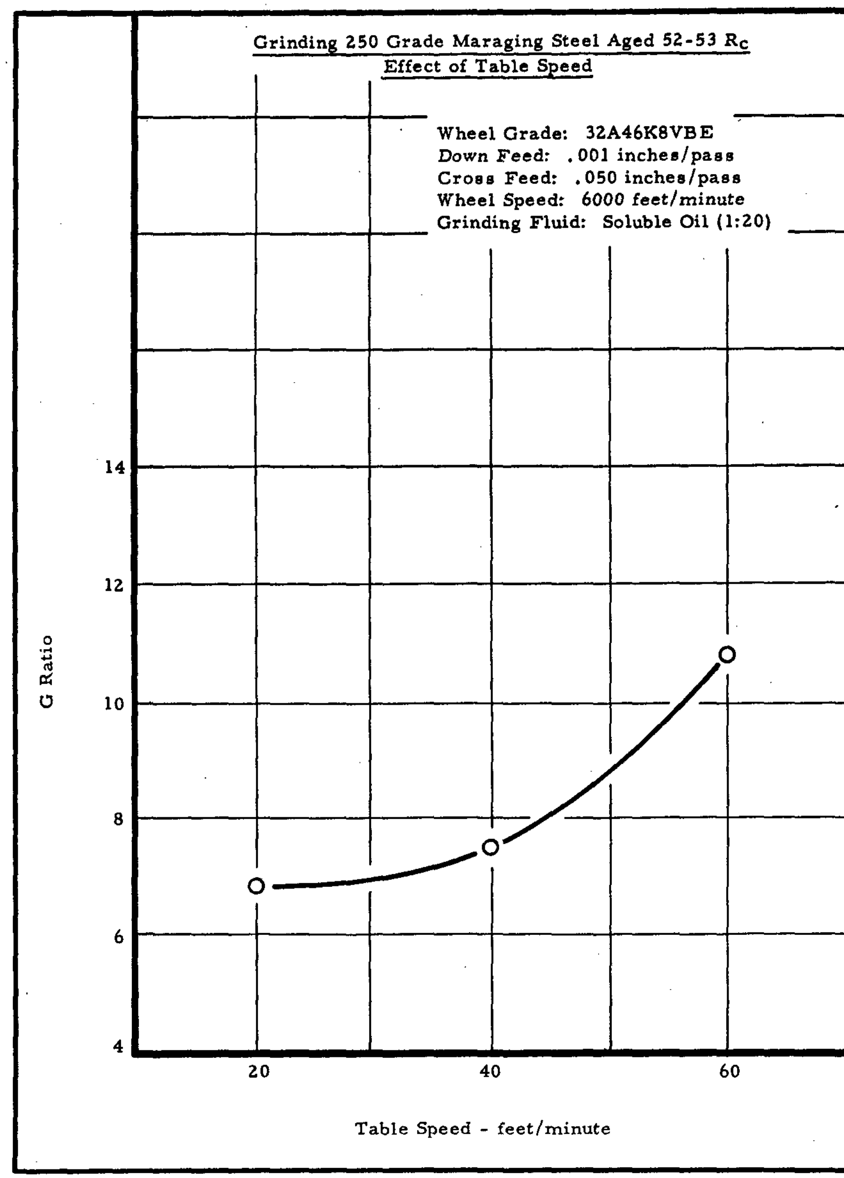

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Figure 105

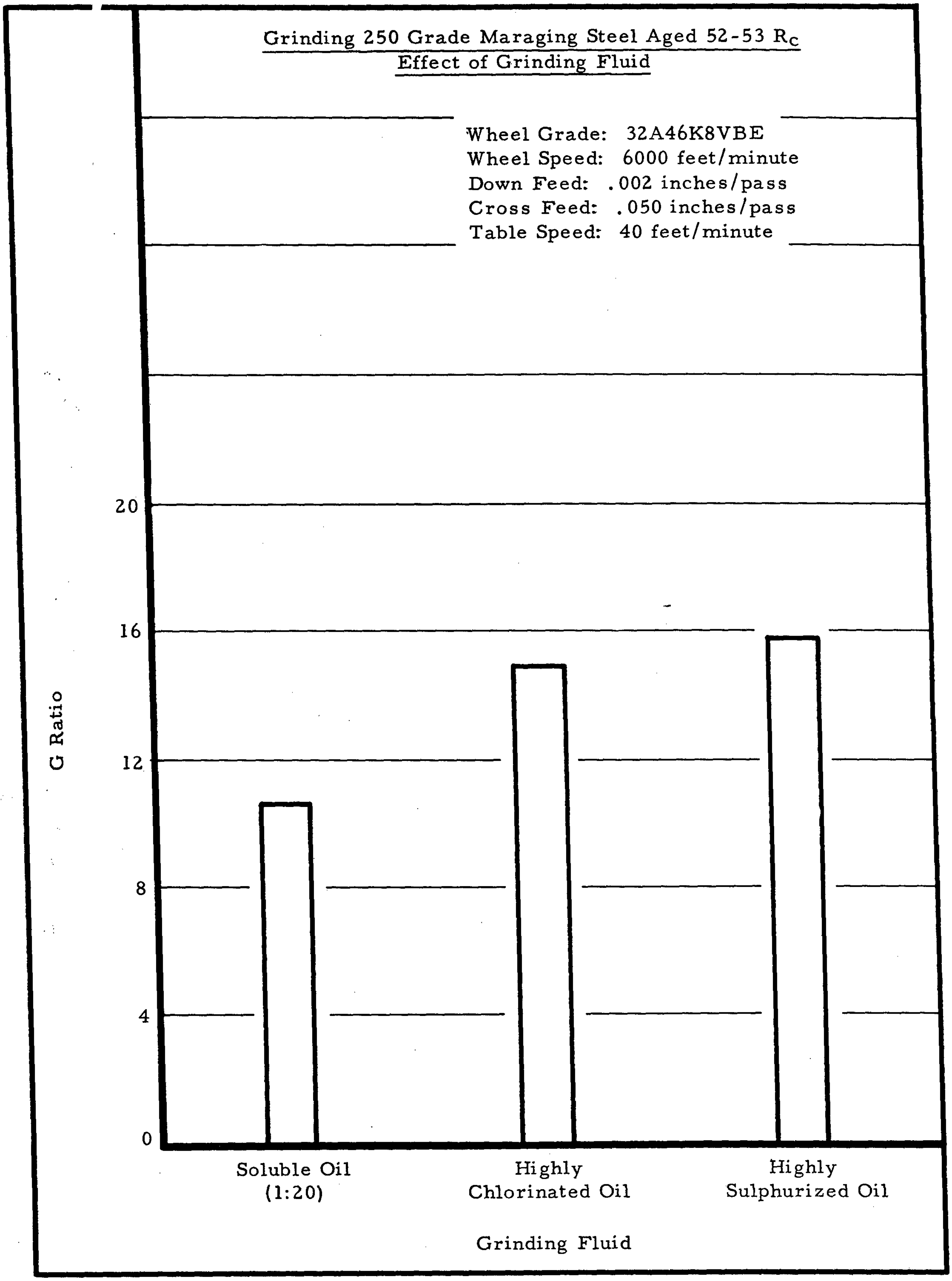

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Figure 106

3.4 18% Nickel 300 Grade Maraging Steel

Alloy Identification

The nominal analysis of 18% Nickel Grade 300 maraging steel is as follows:

Fe - 18.5 Ni - 9 Co - 4.9 Mo - .01 C - .7 Ti

The material for turning was procured as 4" diameter bar stock in the forged annealed condition. In this condition, it exhibited a hardness of 302 BHN. Rectangular bar stock 2" x 4" and 4" x 4" were also procured in the forged annealed condition. The hardness of these bars was 341-351 BHN.

The as-received microstructure, a roughly equiaxed or plate shaped martensite, is illustrated below.

18% Nickel 300 Grade Maraging Steel, Annealed

Etchant: Kalling's   Mag.: 500X

3.4 18% Nickel 300 Grade Maraging Steel (continued)

In order to compare the aged to the forged annealed condition, some previously annealed bars were aged as follows:

900° F/3 hours/air cool

The resulting hardness was 52-54 R_C for both the round and rectangular stock. The typical microstructure, illustrated below, consisted of a martensite matrix which has been strengthened by the precipitation of intermetallics and various carbides.

18% Nickel 300 Grade Maraging Steel, Aged

Etchant: $FeCl_3$ Mag.: 500X

Turning (Annealed 302 BHN)

A comparison of the tool life results obtained with two types of HSS tools is presented in Figure 107, page 97, in turning the 18% nickel 300 grade maraging steel annealed to 302 BHN. The cutting speed with the type T-15 tool was about 15% faster than with the type M-2 tool for a given tool life. Six different grades of carbide tools were also compared in Figure 108, page 97. Grades K-165 and TXL were superior to the other grades tested.

The relationship between tool life and cutting speed with a TXL grade of carbide in turning is shown in Figure 109, page 98. A cutting speed of about 450 ft. /min. would be satisfactory for turning the annealed 300 grade maraging steel under the conditions shown.

Drilling (Annealed 341-355 BHN)

Comparison of the results obtained with two different cutting oils in drilling the 300 grade maraging steel in the annealed condition is shown in Figure 110, page 98. Note that for a tool life of 200 holes the highly sulfurized oil permitted a 20% increase in cutting speed over that used with the highly chlorinated oil.

Figure 111, page 99, shows how rapidly the drill life decreases when the feed is increased from .005 in. /rev. to .009 in. /rev. at a cutting speed of 90 ft. /min. At a speed of 95 ft. /min. the feed of .005 in. /rev. produced the longest tool life.

Reaming (Annealed 341-355 BHN)

Figure 112, page 99, shows a comparison of results obtained with three cutting fluids in reaming. The straight cutting oils were far superior to the soluble oil, and the highly sulfurized oil was somewhat better than the highly chlorinated oil.

Tapping (Annealed 341-355 BHN)

The highly sulfurized oil was also more effective in tapping the annealed 300 grade maraging steel. As shown in Figure 113, page 100, the cutting speed for a given tool life with the highly sulfurized oil was 10% higher than with the highly chlorinated oil.

TABLE 6

RECOMMENDED CONDITIONS FOR MACHINING
18% NICKEL 300 GRADE MARAGING STEEL ANNEALED 302-355 BHN

Ni	Co	Mo	C	Ti	Fe
18.5	9	4.9	.01	.7	Bal.

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	T-15 HSS	BR: 0° SCEA: 15° SR: 10° ECEA: 15° Relief: 5° NR: .030"	5/8" square tool bit	.062	--	.009 in./rev.	95	45 min.	.060	Soluble Oil (1:20)
Turning	C-6 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square throwaway insert	.062	--	.009 in./rev.	450	30 min.	.008	Soluble Oil (1:20)
Drilling	M-1 HSS	118° plain point 7° clearance	1/4" diameter HSS drill 2-1/2" long	.500 thru	--	.005 in./rev.	90	200 holes	.015	Highly Sulphurized Oil
Reaming	M-1 HSS	Helix Angle: 0° CA: 45° Clearance: 7°	.272" diameter 6 Flute chucking reamer	.500 thru	--	.009 in./rev.	75	300 holes	.006	Highly Sulphurized Oil
Tapping	M-1 HSS	2 flute plug spiral point 75% thread	5/16-24 NF tap	.500 thru	--	--	110	115 holes	Under-size threads	Highly Sulphurized Oil

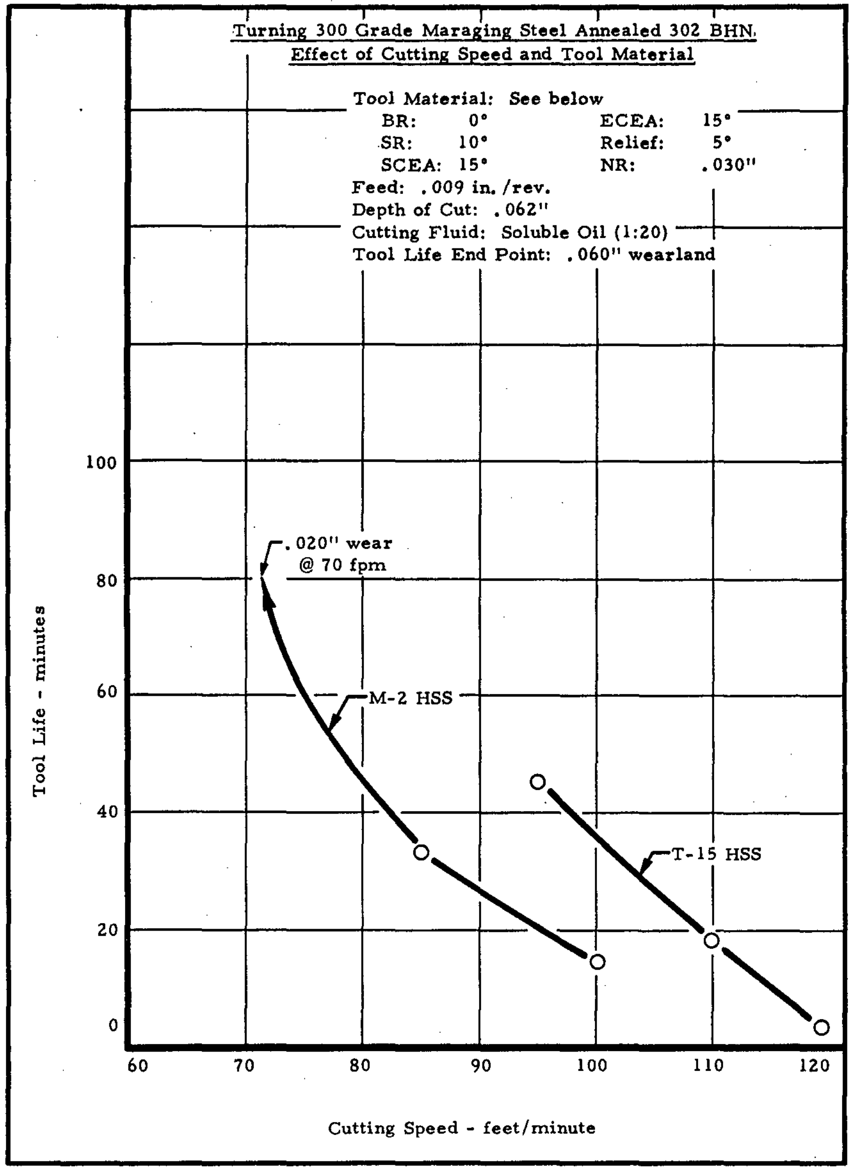

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Figure 107

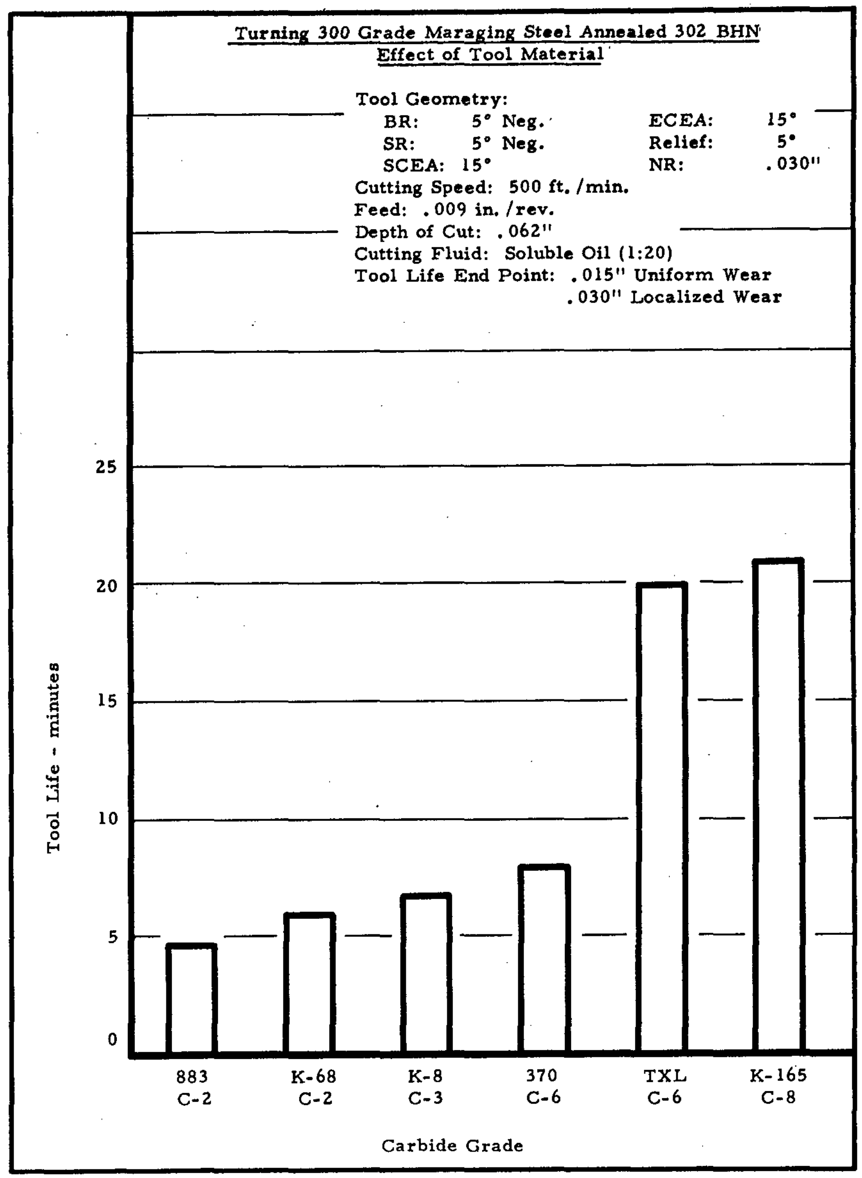

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Figure 108

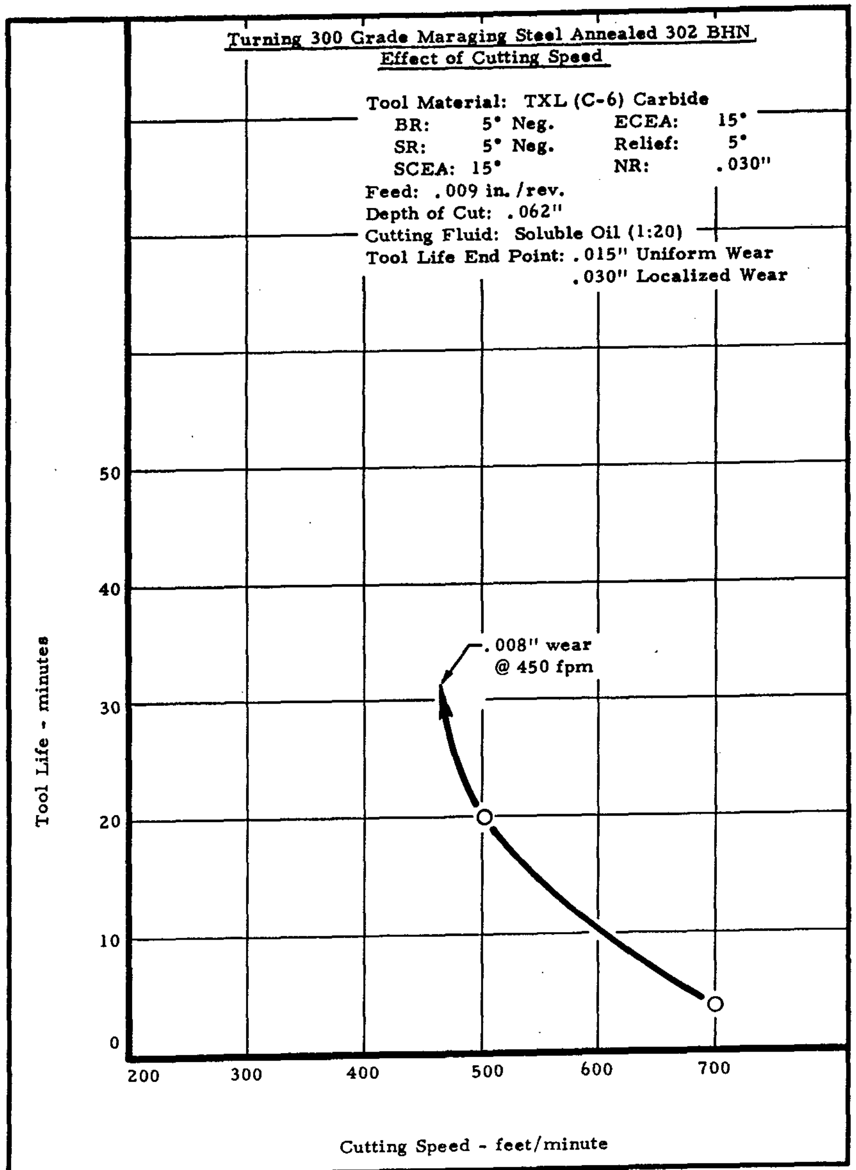

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Figure 109

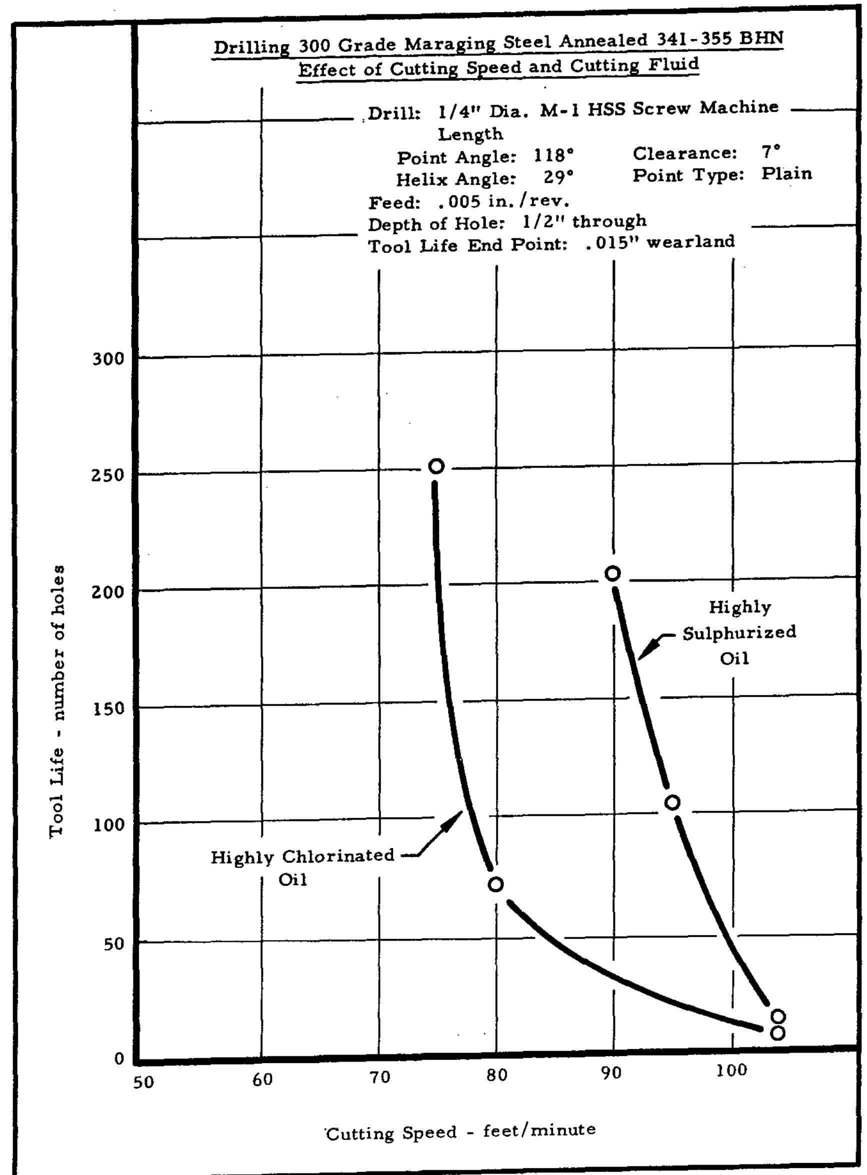

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Figure 110

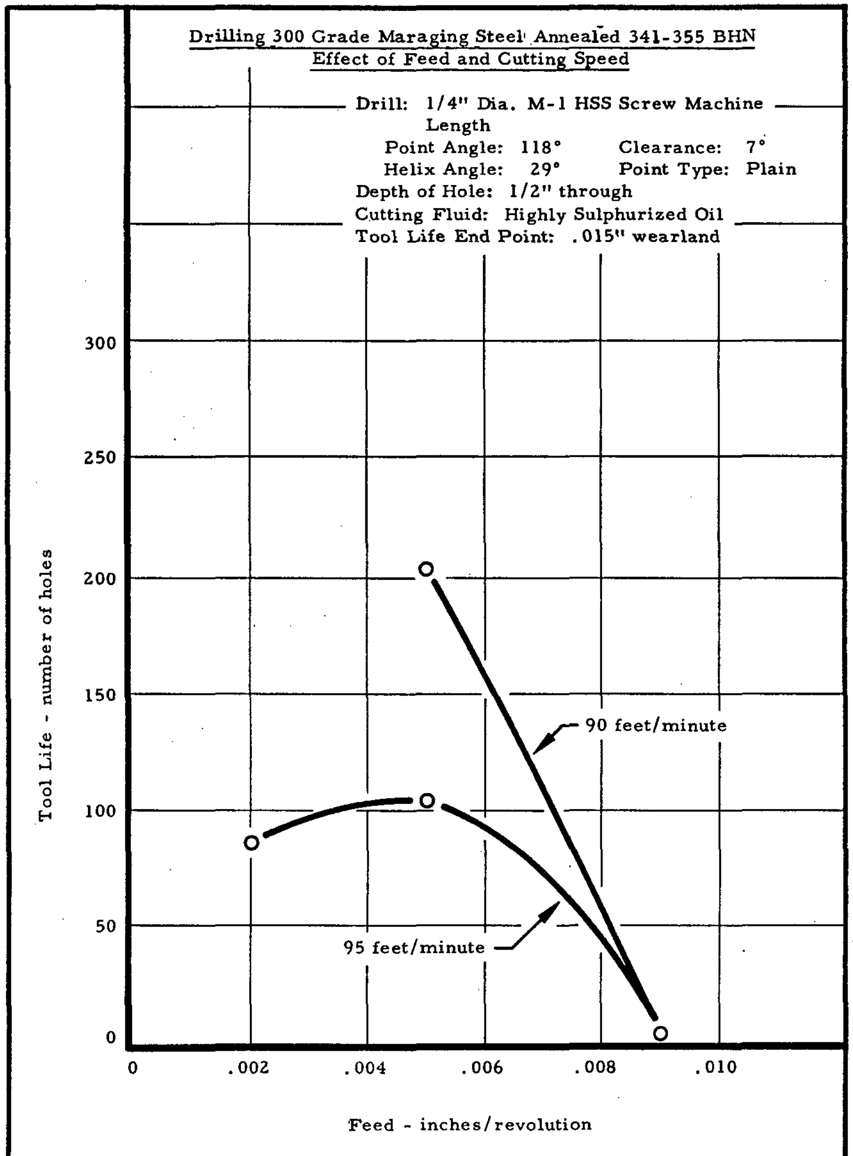

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Figure 111

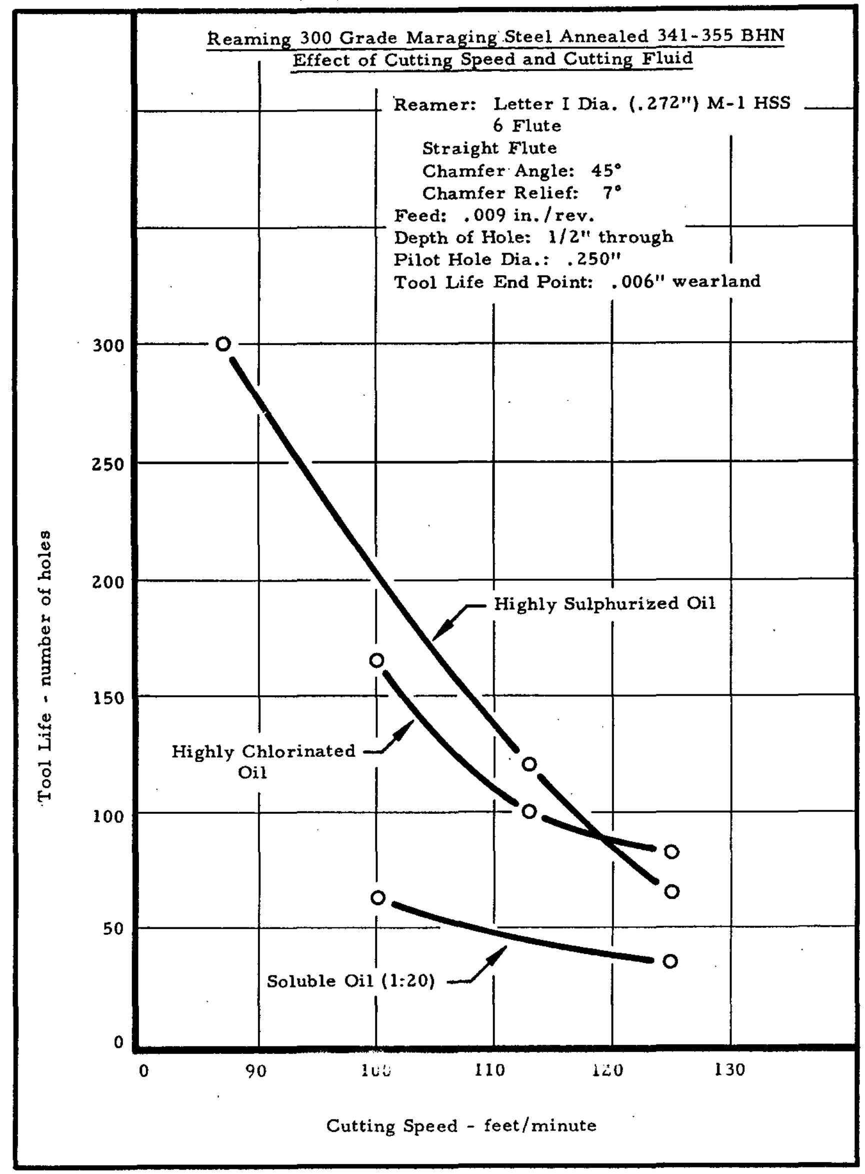

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Figure 112

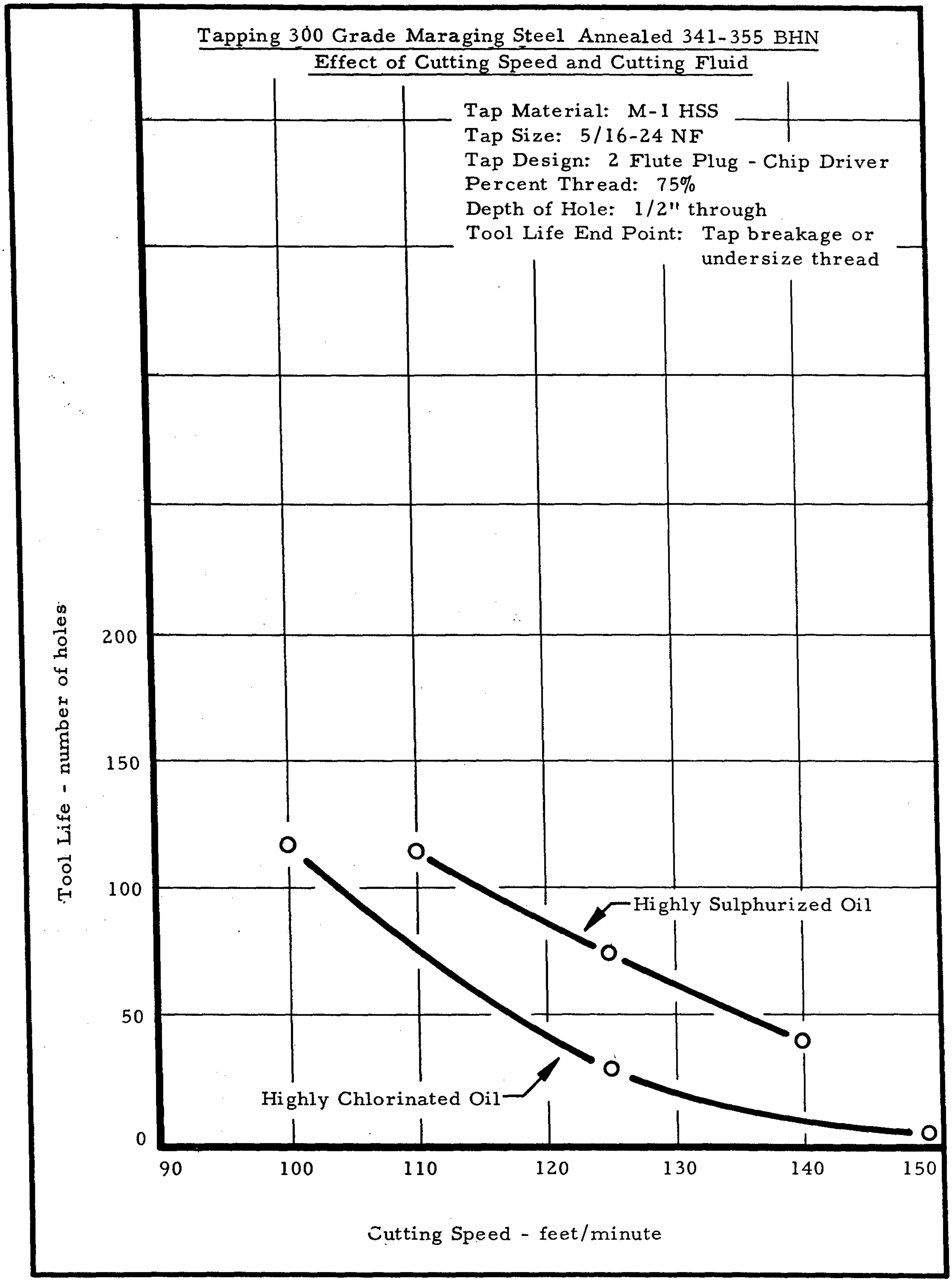

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Figure 113

Turning (Aged 54 R_c)

Tool life curves with three grades of carbide are shown in Figure 114, page 107, in turning the 300 grade of steel maraged to 54 R_c. The K-68 grade permitted a 35% higher cutting speed than either of the other two grades. The steepness of the curve indicates how critical the cutting speed is in turning steel having this high hardness level. From Figure 115, page 107, it is apparent that the feed is also critical. The tool life decreased from 45 minutes to 10 minutes when the feed was increased from .005 to .009 in./rev.

A comparison of the results obtained in turning the 300 grade steel in the annealed and the aged conditions with a T-15 HSS tool is shown in Figure 116, page 108. Note that the annealed steel can be machined 250% faster than the same steel in the aged condition.

Face Milling (Aged 52 R_c)

The tool life curve in Figure 117, page 108, shows the relationship between tool life and feed in face milling 300 grade maraging steel aged to 52 R_c with a HSS cutter. The cutter life decreased from 94 inches of work travel to 36 inches of work travel as the feed was increased from .0025 to .007 in./tooth. A comparison of three types of HSS cutters is shown in Figure 118, page 109. The M-44 HSS proved to be superior to both the T-15 and the M-2 HSS cutters. For example, at a cutting speed of 59 ft./min., cutter life with the M-2 tool was 48 inches; the T-15, 84 inches; and the M-44, 108 inches of work travel.

The results of face milling the 18% nickel 300 grade maraged steel with carbide cutters are shown in Figures 119 through 123, pages 109 through 111. Figure 119, page 109, illustrates the relatively low cutting speed range which must be used in face milling this hard steel even with carbide tools. Tool life was poor as a result of chipping at the cutting edge of the tool when using either the soluble oil or the highly chlorinated oil. Chipping was almost eliminated when the steel was face milled without a cutting fluid.

As on most hard metals, tool geometry was very important in face milling. This was demonstrated in face milling the 18% nickel 300 grade maraged steel with a hardness of 52 R_c (see Figure 120, page 110). Cutter life was increased more than 100% by changing the axial rake from -15° to -7°. Higher positive rake angles were less effective in increasing tool life.

3.4 18% Nickel 300 Grade Maraging Steel (continued)

Figure 121, page 110, shows the superiority of the grade 883 carbide over the other grades tested under the machining conditions cited. Note that the cutter life with the 883 (C-2) grade was double that obtained with the 370 (C-6) grade of carbide.

As shown in Figure 122, page 111, the feed was another critical factor in the face milling operation. Cutter life decreased rapidly as the feed per tooth was increased beyond .0035 at the cutting speed of 140 ft./min.

A tool life curve for a range of cutting speeds at a feed of .0035 in./tooth is given in Figure 123, page 111. Note that a reasonable tool life was obtained with this feed at a cutting speed of 140 ft./min. without the use of a cutting fluid.

Side Milling (Aged 52 R_c)

Figure 124, page 112, shows the relationship between tool life and cutting speed in side milling the 300 grade maraging steel aged to 52 R_c. At a cutting speed of 190 ft./min. cutter life was 76 inches of work travel per tooth.

Peripheral End Milling (Aged 52 R_c)

Figures 125 through 127, pages 112 through 113, present the results of the peripheral end milling tests conducted on the 18% nickel 300 grade steel maraged to 52 R_c.

As shown in Figure 125, page 112, an increase in cutting speed of more than 25% was obtained when using the highly chlorinated oil as compared to a soluble oil (1:20). At a tool life of 80 inches of work travel, the cutting speed with the soluble oil was 35 ft./min., while it was 45 ft./min. with the highly chlorinated oil. If the cutting speed of 45 ft./min. has been used with the soluble oil, the tool life would have been only about 40 inches. Note that a type M-2 high speed steel was used in these tests. A comparison of this tool with a type T-15 high speed steel tool is presented in Figure 126, page 113. There was a greater tendency for the T-15 HSS tool to chip and, as a result, it did not provide any longer tool life than the M-2 HSS cutter. The chipping was worst at the higher feeds. Figure 127, page 113, shows that the cutter life of the T-15 tool decreased more than 50% when the feed was increased from .0005 to .001 in./tooth.

End Mill Slotting (Aged 52 R_C)

The feed was very critical in end mill slotting the aged 300 grade steel with an M-2 HSS cutter. Note in Figure 128, page 114, that a cutter life of 130 inches was obtained at a feed of .0005 in./tooth and a cutting speed of 40 ft./min., while at a feed of .001 in./tooth and the same cutting speed the cutter life dropped to 25 inches of work travel. As a matter of fact, the cutter life was uniformly low when a feed of .001 in./tooth was used with the M-2 HSS cutter. However, as shown in Figure 129, page 114, the T-15 HSS cutter performed quite satisfactorily at a feed of .001 in./tooth. As a matter of fact, at a cutting speed of 43 ft./min. the tool life with the T-15 HSS at a feed of .001 in./tooth was equivalent to that obtained with an M-2 HSS cutter at a feed of .0005 in./tooth.

Drilling (Aged 52 R_C)

As shown in Figure 130, page 115, two cutting fluids; namely, highly chlorinated oil and highly sulfurized oil, performed similarly in the drilling of the 300 grade steel maraged to 52 R_C.

Figure 131, page 115, shows the relationship between tool life and feed for two different types of high speed steel drills. Unless light feeds are used in the drilling of this material having a hardness of 52 R_C, drill life is very poor. The results indicate that the feed should be in the vicinity of .001 in./rev. Both Figures 131 and 132, pages 115 and 116, indicate the superiority of the T-15 HSS drills over the M-1 HSS drills. For a given tool life, the cutting speed with the T-15 HSS drill was more than 70% faster than that used with the M-1 HSS drill. The difference in the tool lives obtained with the M-42 and the T-15 HSS drills was not significant, as shown in Figure 133, page 116.

Reaming (Aged 52 R_C)

Figure 134, page 117, shows the relationship between tool life and feed at two different cutting speeds in reaming. The reamer life was appreciably higher for the feed of .005 in./rev. as compared to .009 in./rev. However, from a production standpoint, the higher feed should be used with a lower cutting speed.

3.4 18% Nickel 300 Grade Maraging Steel (continued)

The results shown in Figure 135, page 117, indicate that a 30% increase in production, or cutting speed, was obtained by using M-33 HSS reamers as compared to M-2 HSS reamers for a given tool life. A further improvement in tool life was obtained by using a highly chlorinated oil as compared to a highly sulfurized oil, see Figure 136, page 118.

Tapping (Aged 52 R_c)

A comparison of the results obtained with several types of taps in tapping the aged 18% nickel steel is presented in Figure 137, page 118. Note the superiority of the 2 flute nitrided tap over the 4 flute tap. The 4 flute tapered nitrided tap produced a maximum of 11 holes as compared to 60 holes with the 2 flute plug nitrided tap having a spiral point.

As shown in Figure 138, page 119, the tool life was even greater, 75 holes, with the 2 flute tap at a cutting speed of 7 ft. /min. The tool life with this tap was negligible at a cutting speed of 12. 5 ft. /min.

By employing a 60% thread instead of a 75% thread, the tap life was reasonably good with the 4 flute chrome plated taper tap, see Figure 139, page 119.

TABLE 7

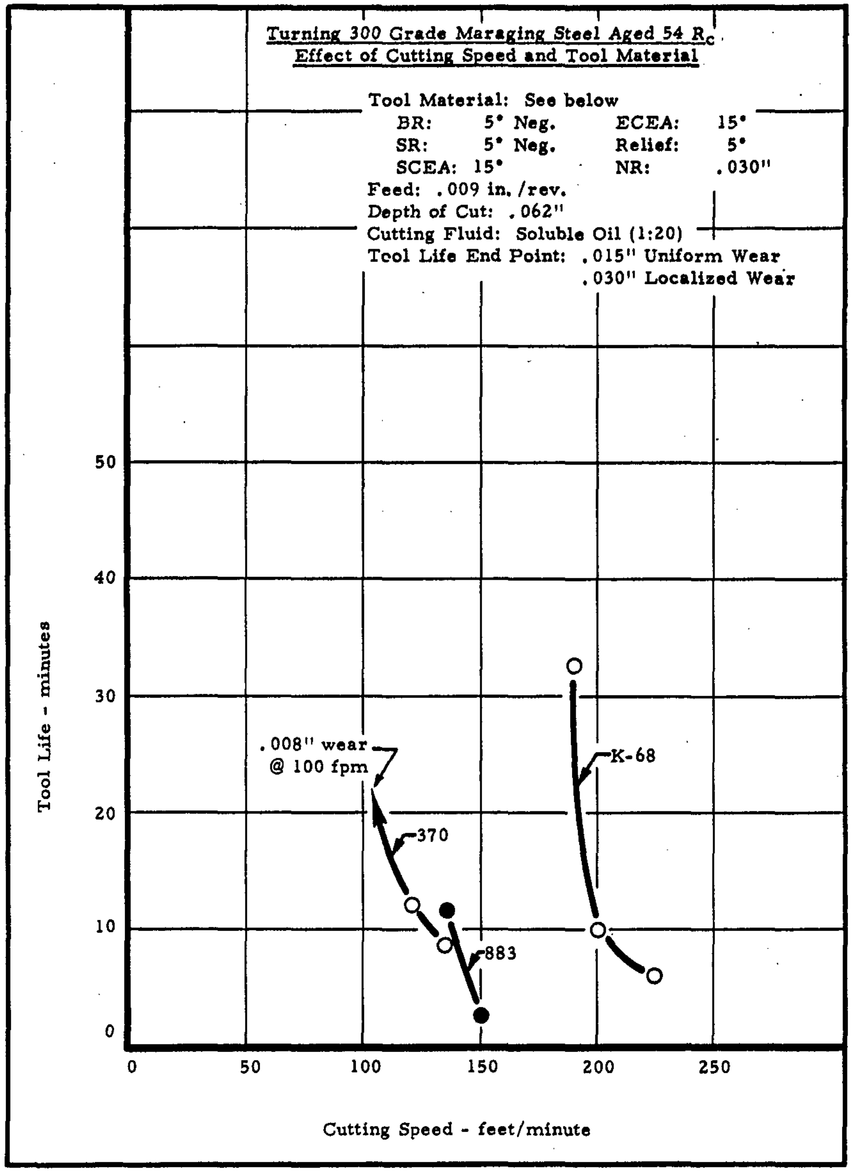
RECOMMENDED CONDITIONS FOR MACHINING
18% NICKEL 300 GRADE MARAGING STEEL - AGED 52-54 R_c

Ni	Co	Mo	C	Ti	Fe
18.5	9	4.9	.01	.7	Bal

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	T-15 HSS	BR: 0° SCEA: 15° SR: 10° ECEA: 5° Relief: 5° NR: .030"	5/8" square tool bit	.062	-	.009 in./rev.	35	80 min.	.026	Soluble Oil (1:20)
Turning	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square throwaway insert	.062	-	.009 in./rev.	175	30 min.	.015	Soluble Oil (1:20)
Face Milling	T-15 HSS	AR: 5° ECEA: 10° RR: 5° CA: 45° Clearance: 8°	4" diameter single tooth face mill	.060	2	.005 in./tooth	60	80" work travel	.060	Highly Chlorinated Oil
Face Milling	C-2 Carbide	AR: -7° ECEA: 5° RR: -7° CA: 45° Clearance: 6°	4" diameter single tooth face mill	.060	2	.004 in./tooth	140	200" work travel	.015	Dry
Side Milling	C-2 Carbide	AR: -7° ECEA: 45° RR: -7° CA: 45° Clearance: 6°	4" diameter single tooth face mill	.100	1.25	.004 in./tooth	175	75" work travel	.015	Dry
Peripheral End Milling	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.75	.001 in./tooth	40	100" work travel	.012	Highly Chlorinated Oil

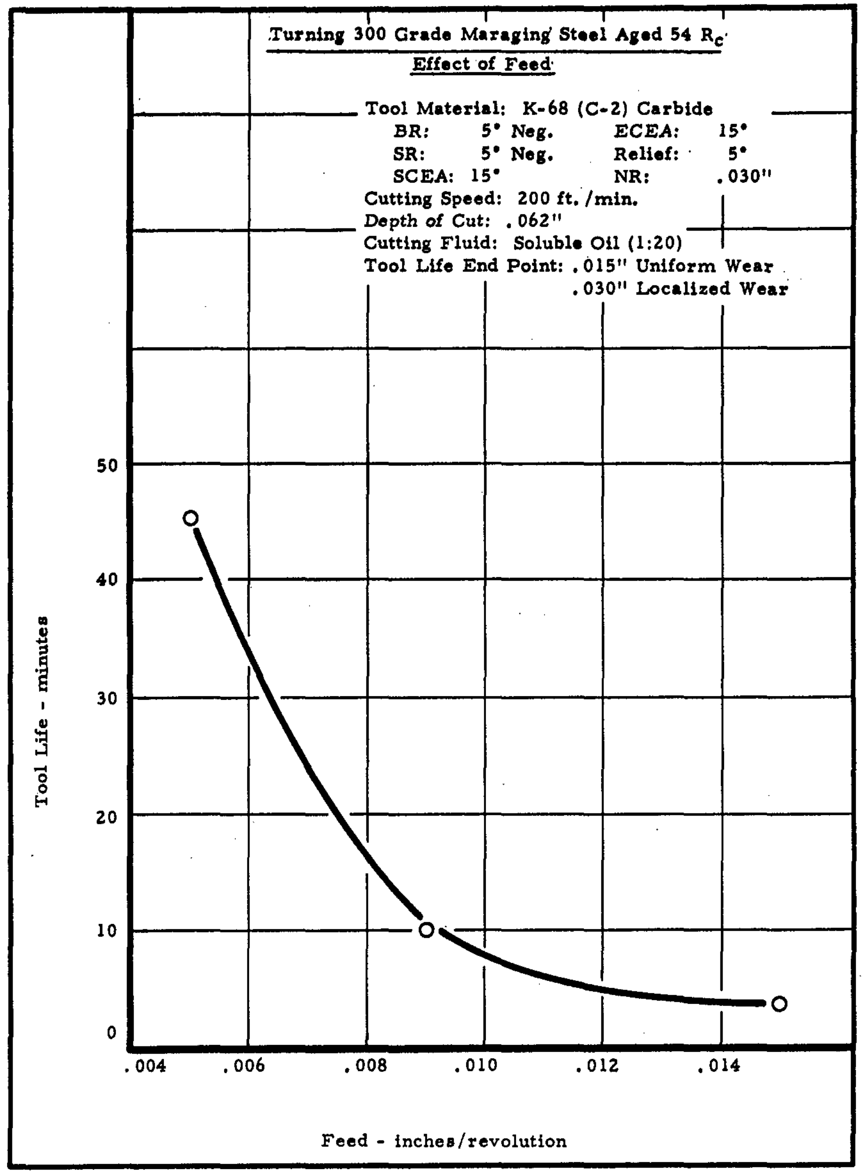
TABLE 7 (continued)
RECOMMENDED CONDITIONS FOR MACHINING
18% NICKEL 300 GRADE MARAGING STEEL - AGED 52-54 R_c

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	T-15 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.001 in/ tooth	43	140" work travel	.012	Highly Chlorinated Oil
Drilling	T-15 HSS	118° Plain Point Clearance: 7°	1/4" diameter HSS drill 2 1/2" long	.500 thru	-	.001 in/rev	25	250 holes	.015	Highly Sulphurized Oil
Reaming	M-2 HSS	Helix Angle: 0° CA: 45° Clearance: 7°	.272" diameter 6 flute chucking reamer	.500 thru	-	.005 in/rev	35	120 holes	.006	Highly Chlorinated Oil
Tapping	M-1 HSS Nitrided	2 Flute Plug Spiral Point 75% thread	5/16 - 24 NF tap	.500 thru	-	-	7	75 holes	Under-size threads	Highly Chlorinated Oil



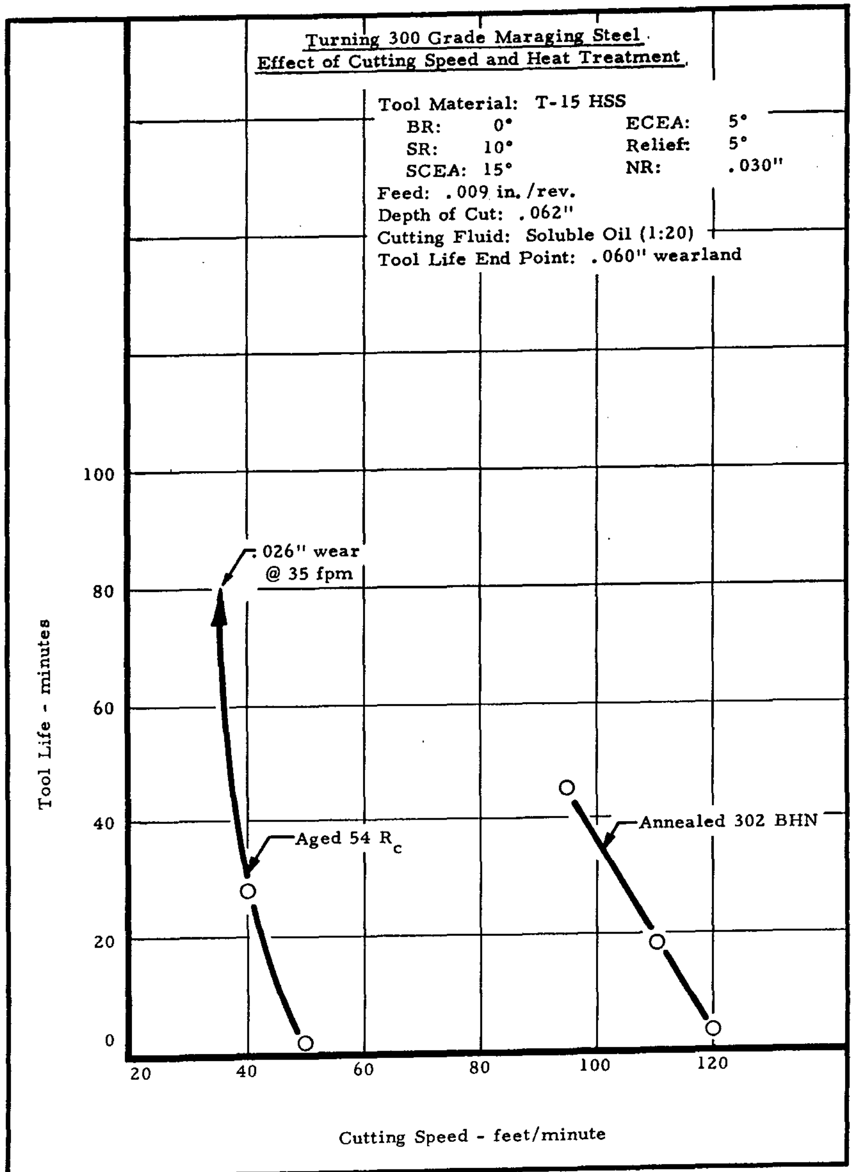
See text, page 101

Figure 114



See text, page 101

Figure 115



See text, page 101

Figure 116

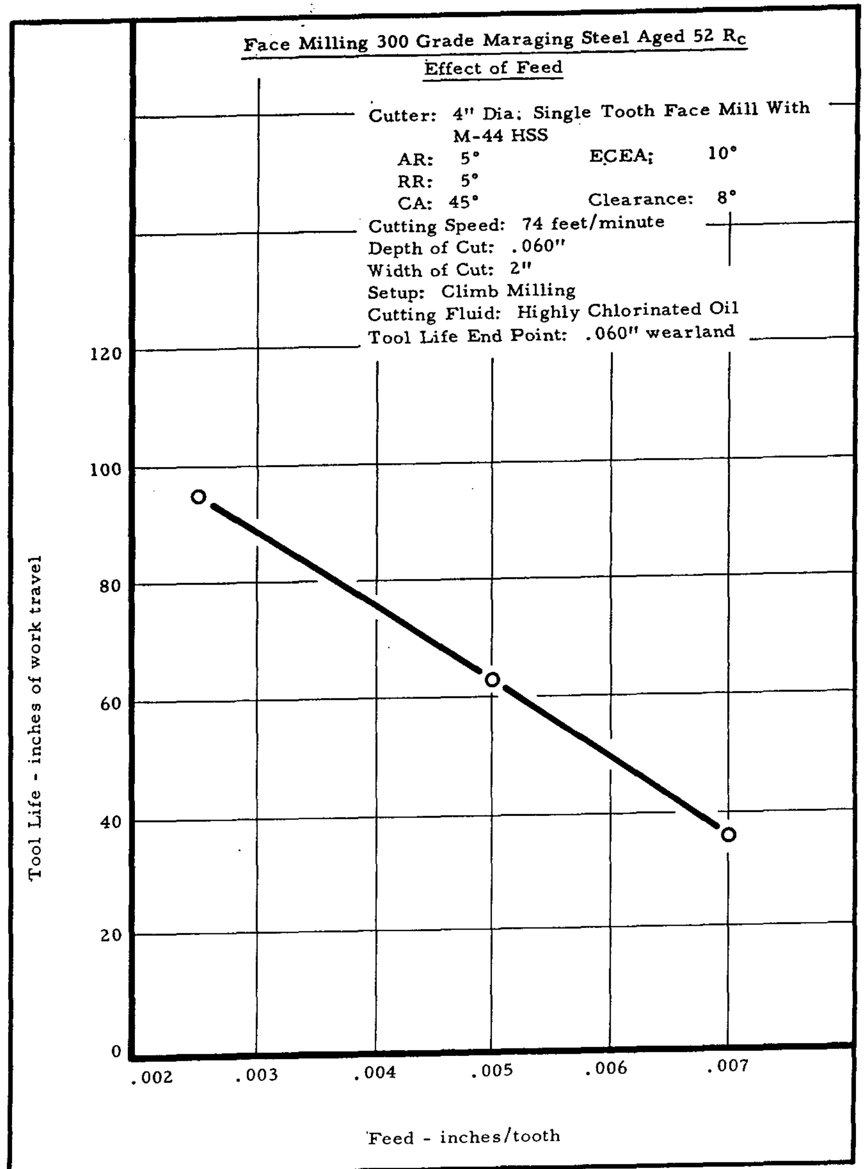


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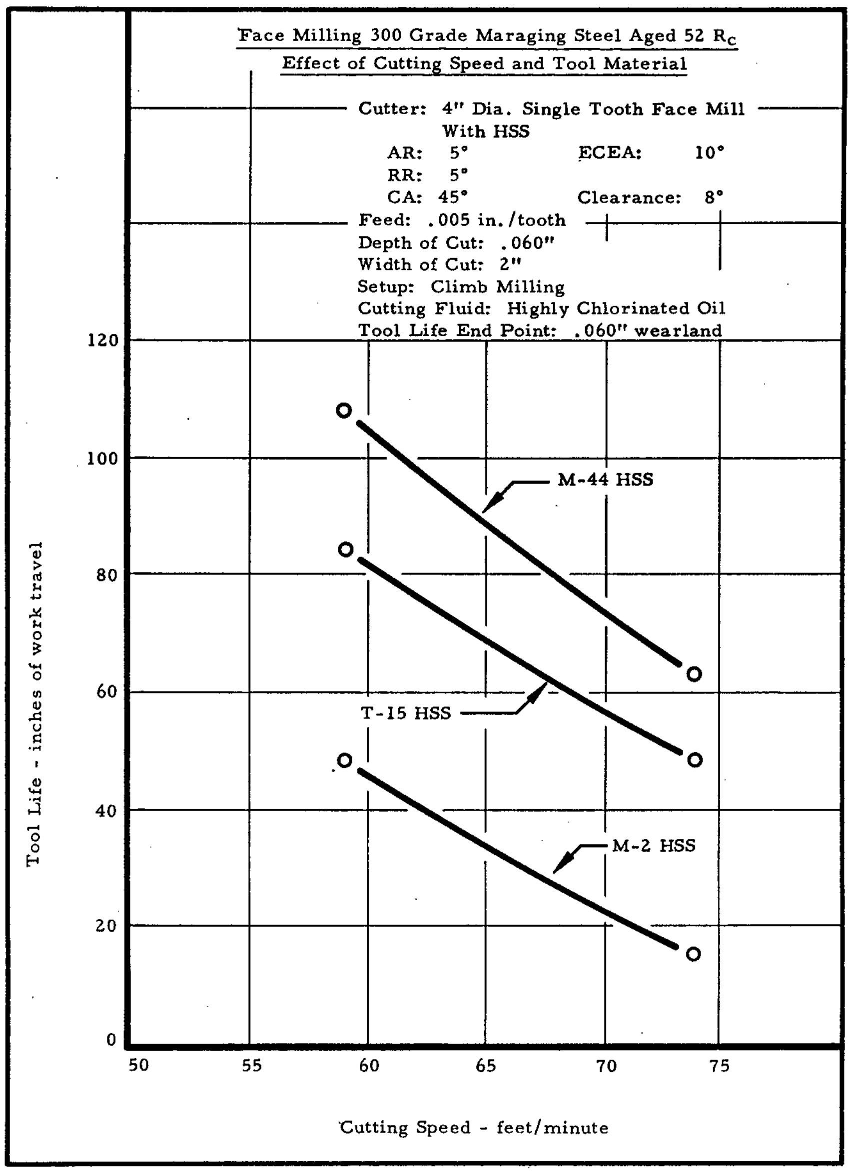
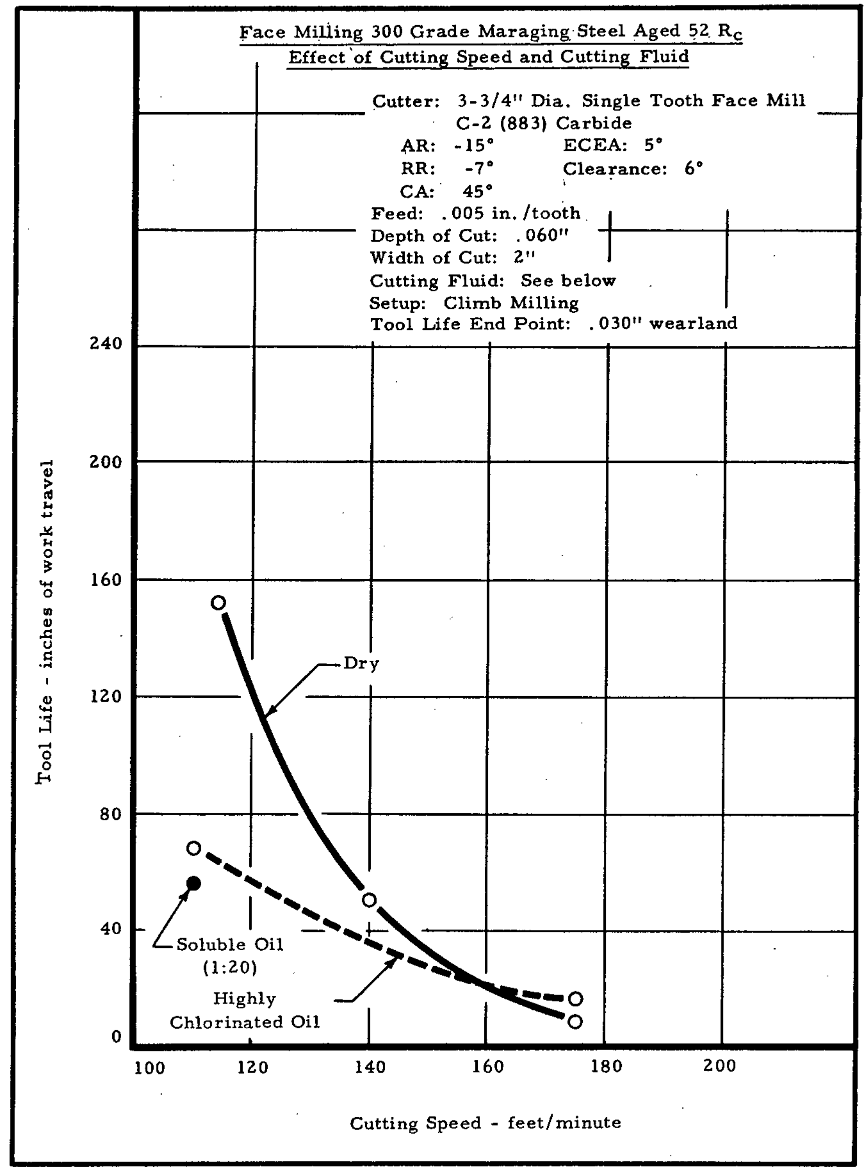
Figure 117



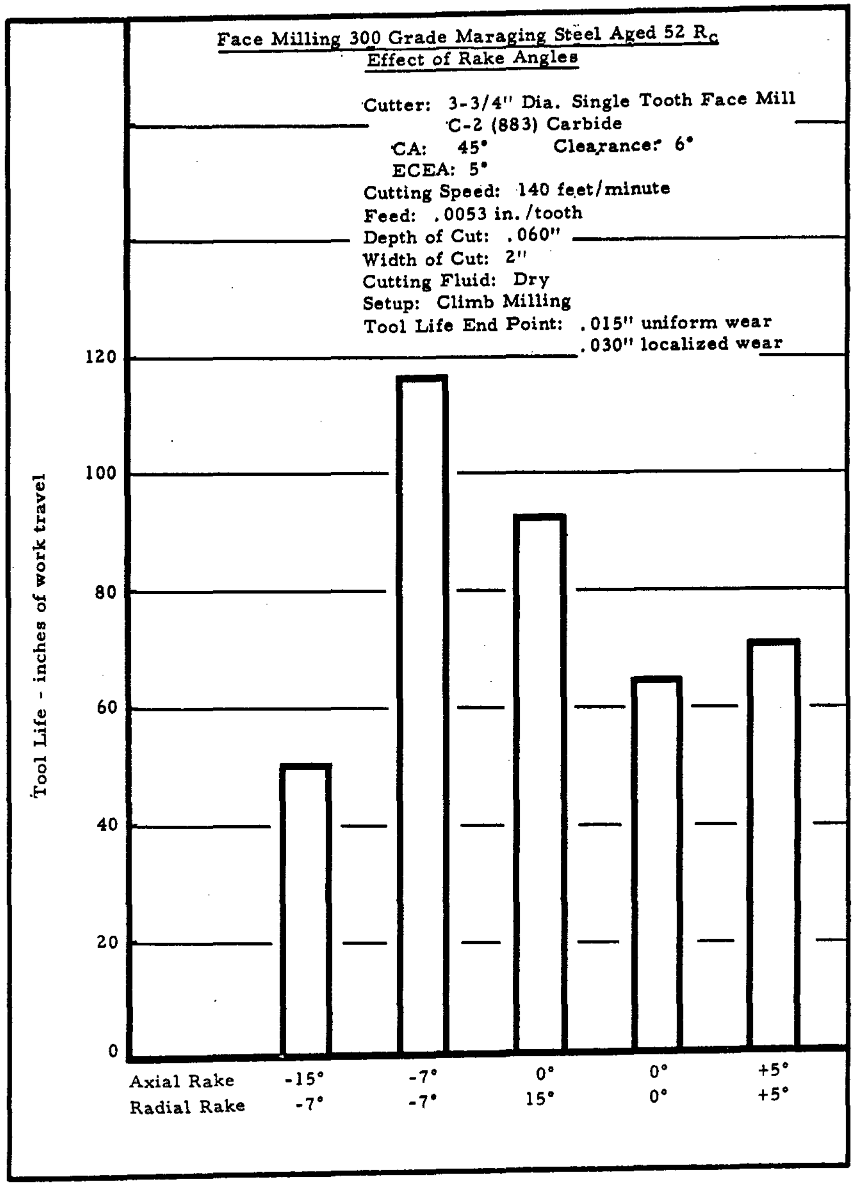
See text, page 101

Figure 118



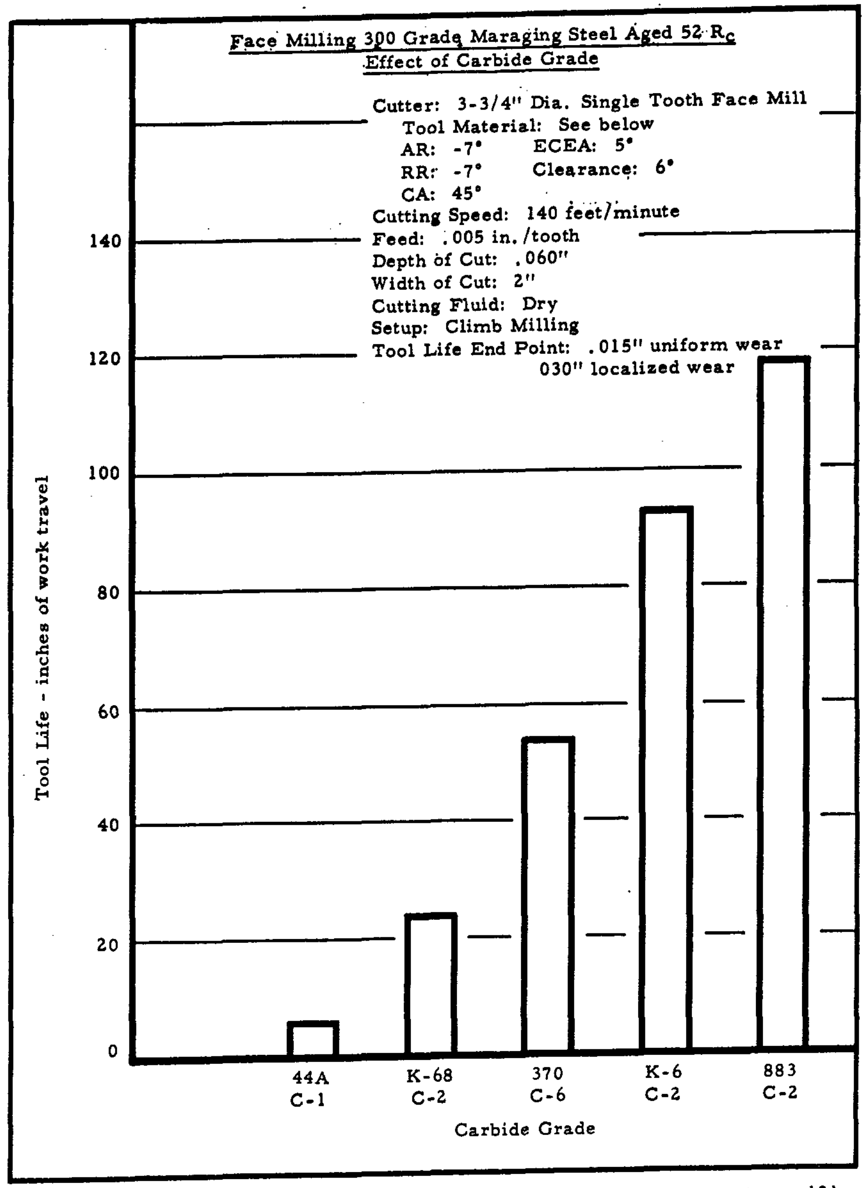
See Text, page 101

Figure 119



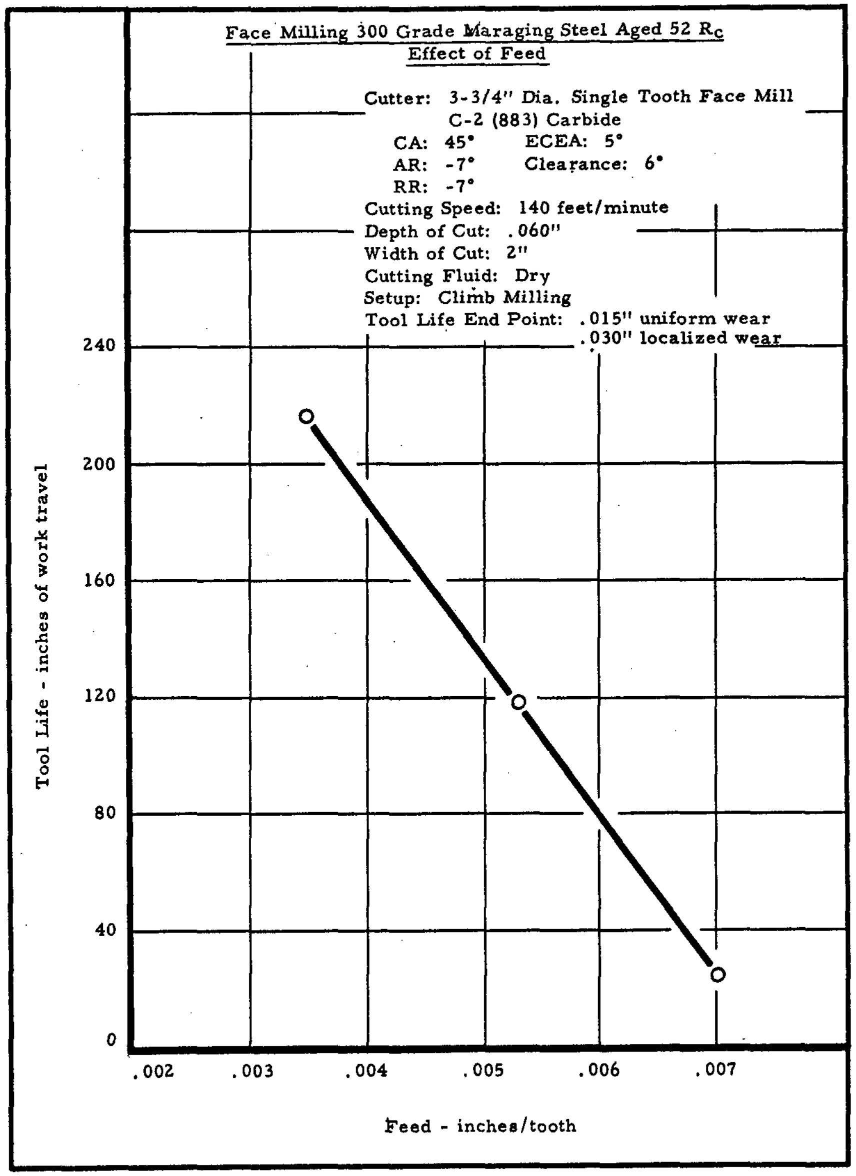
See Text, page 101

Figure 120



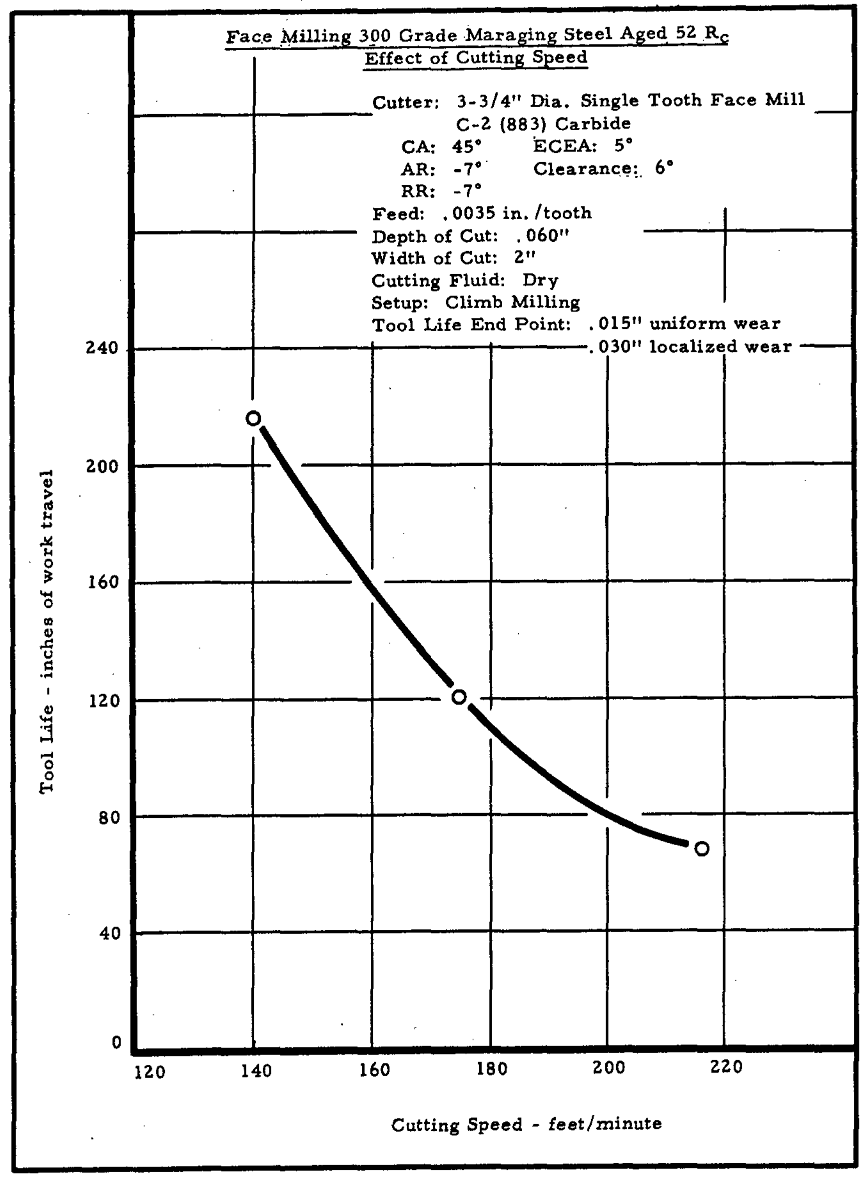
See Text, page 101

Figure 121



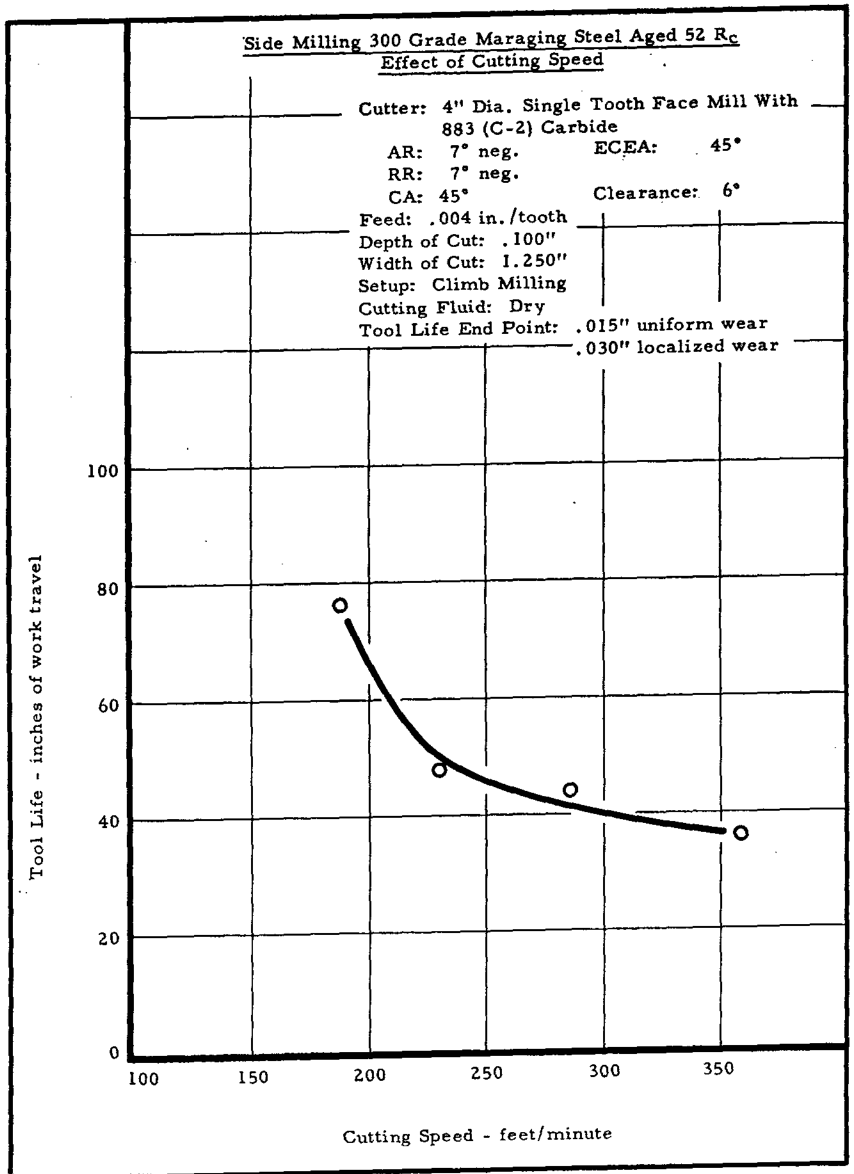
See Text, page 101

Figure 122



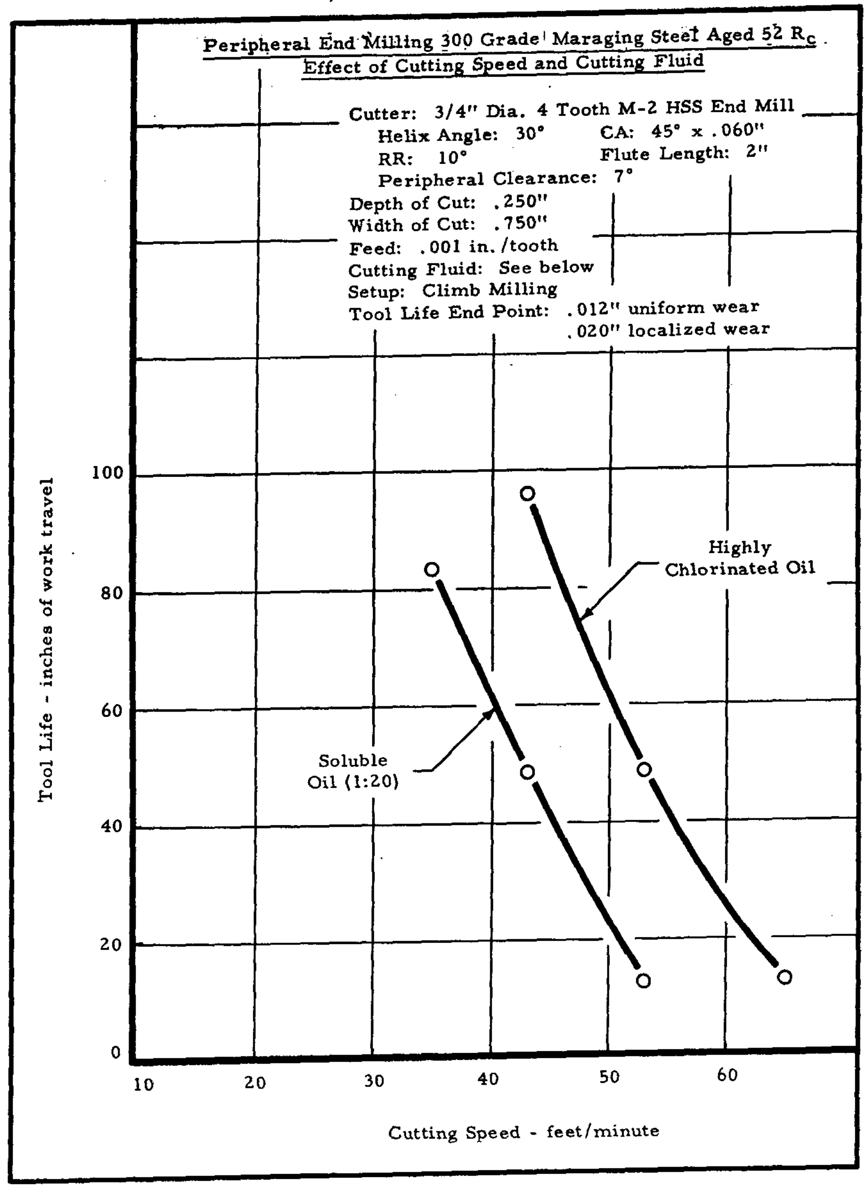
See Text, page 101

Figure 123



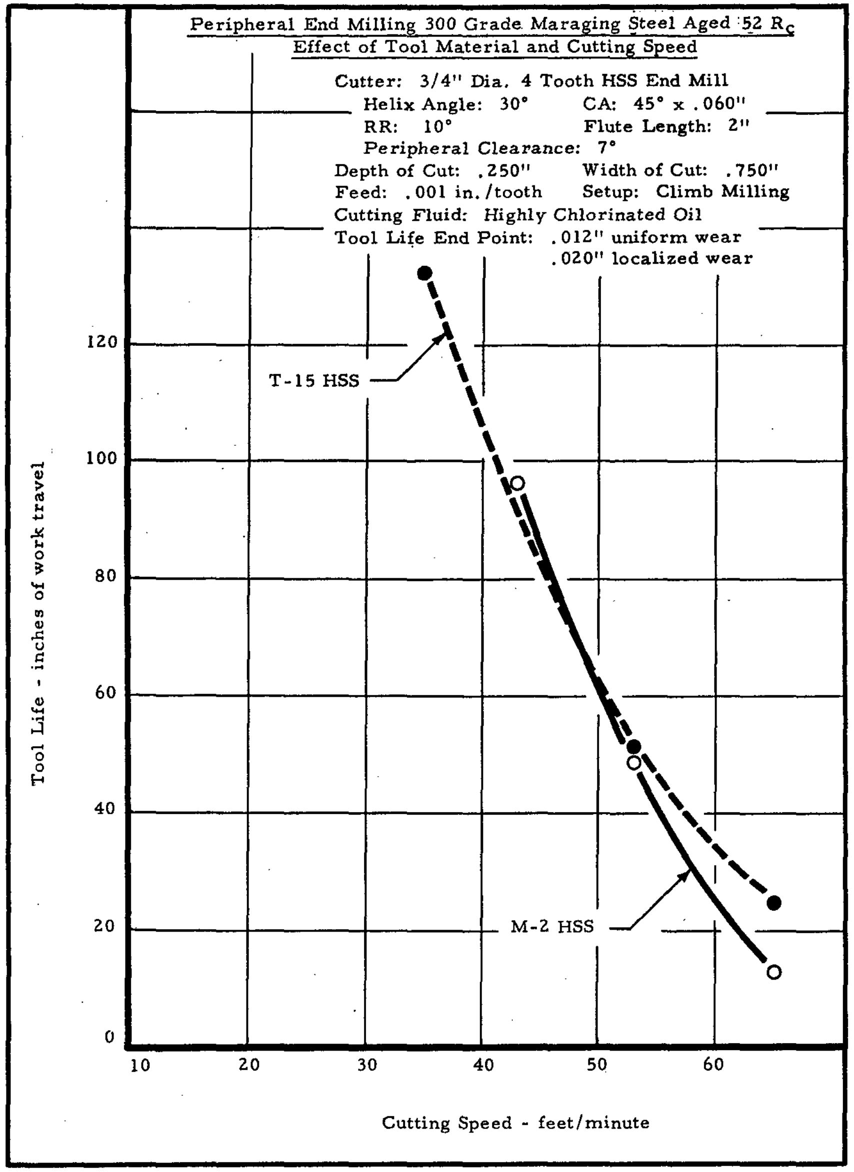
See text, page 102

Figure 124



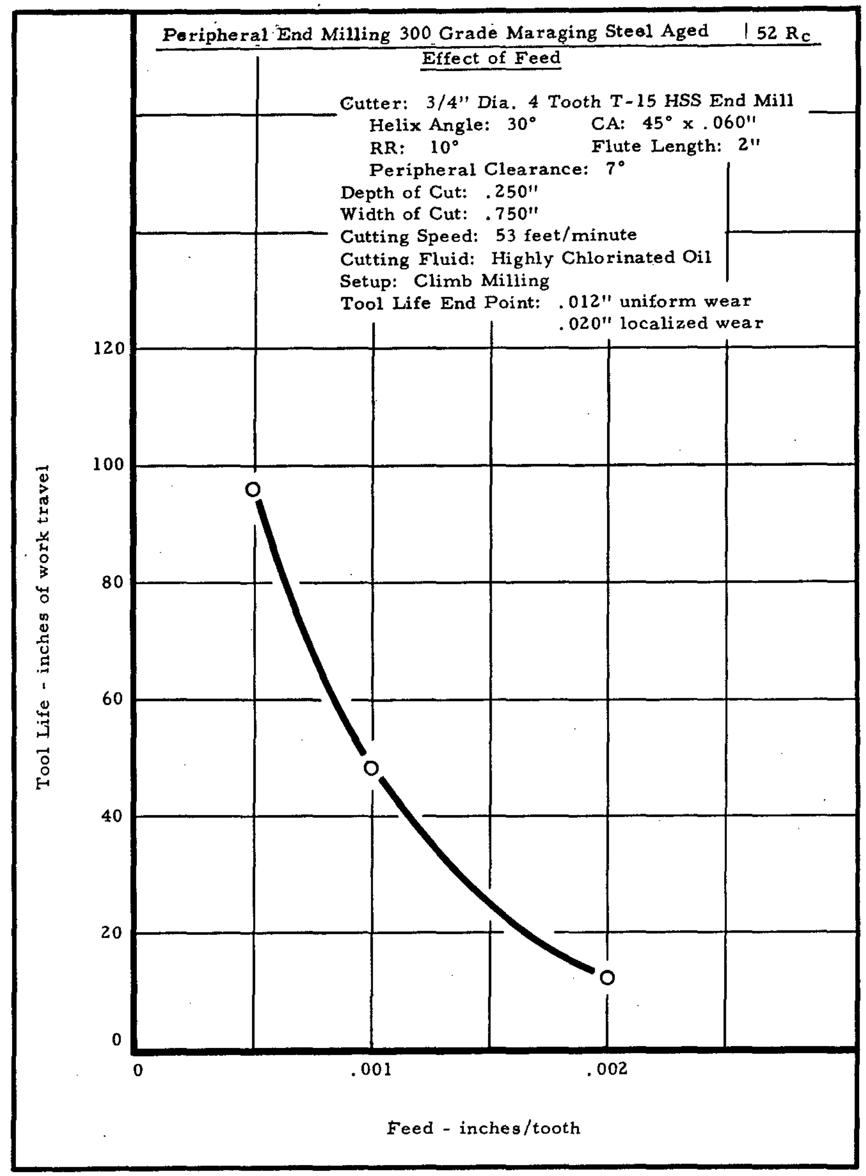
See Text, page 102

Figure 125



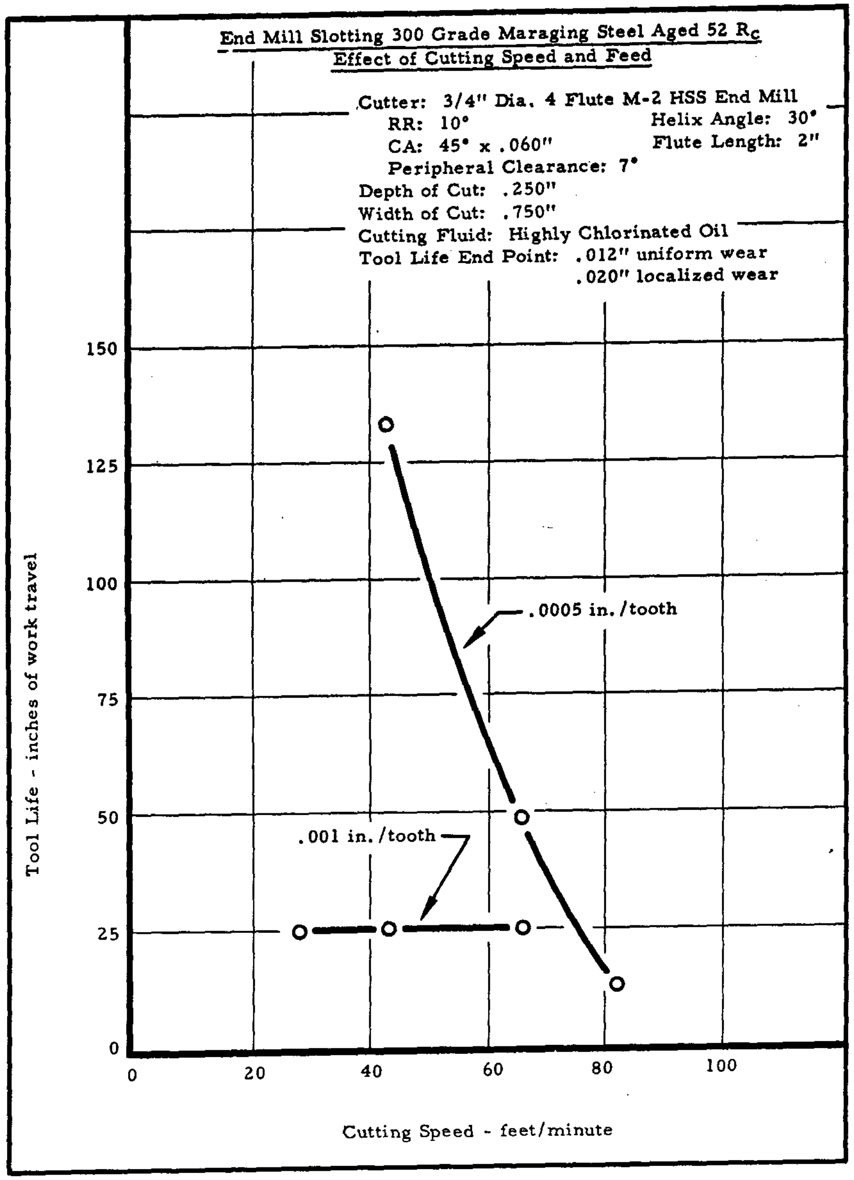
See Text, page 102

Figure 126



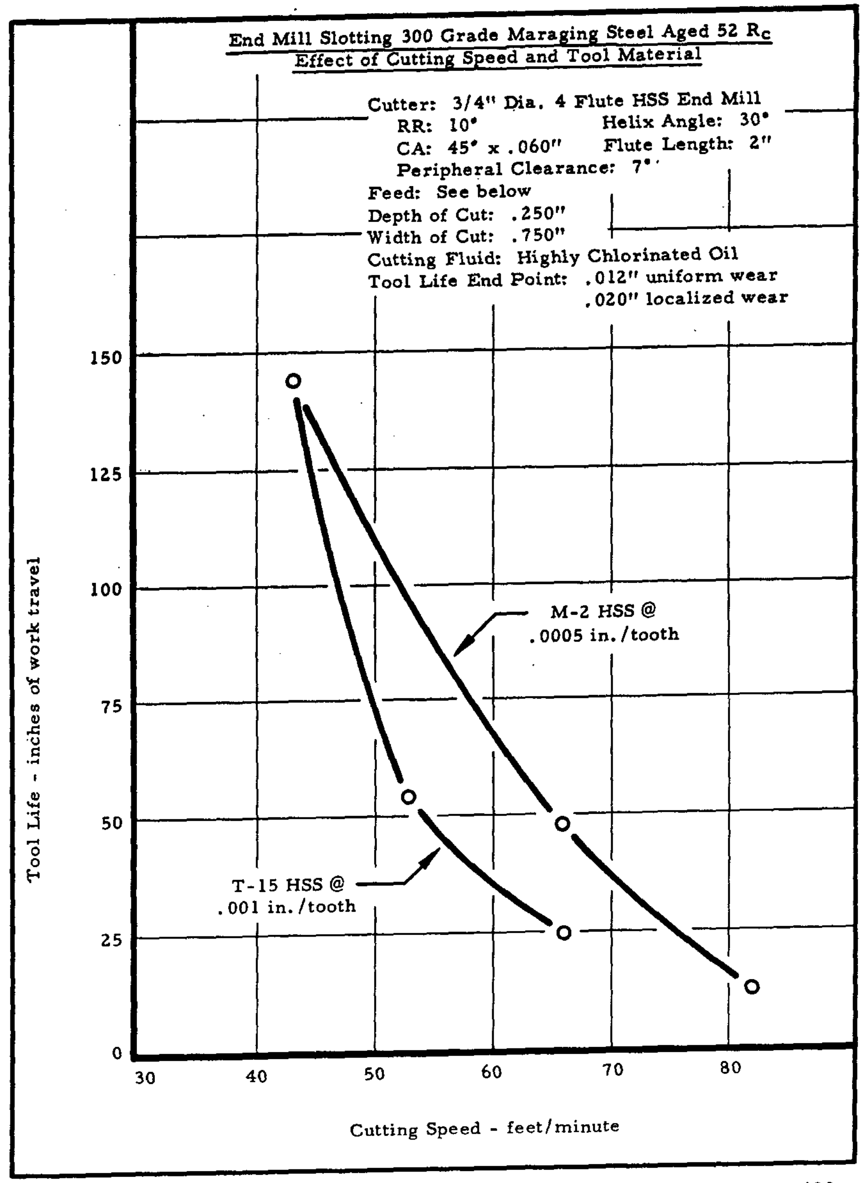
See Text, page 102

Figure 127



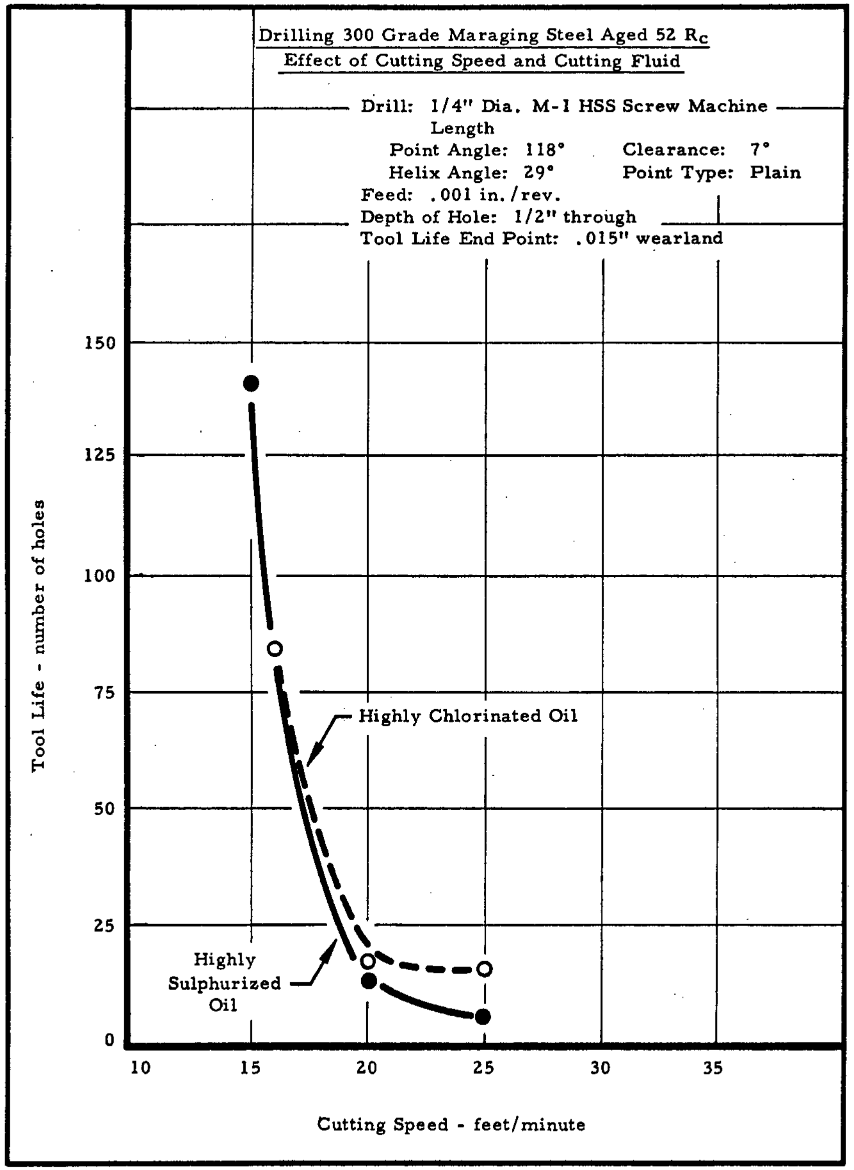
See text, page 103

Figure 128



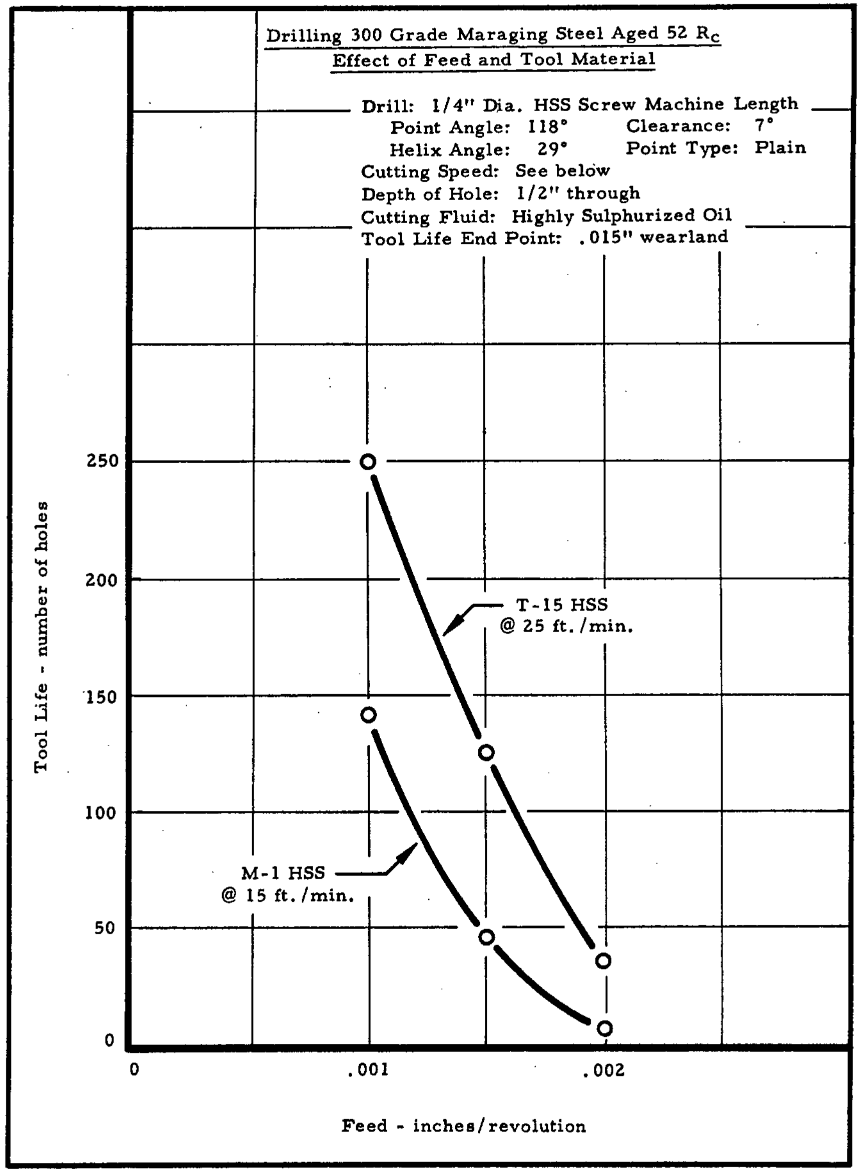
See text, page 103

Figure 129



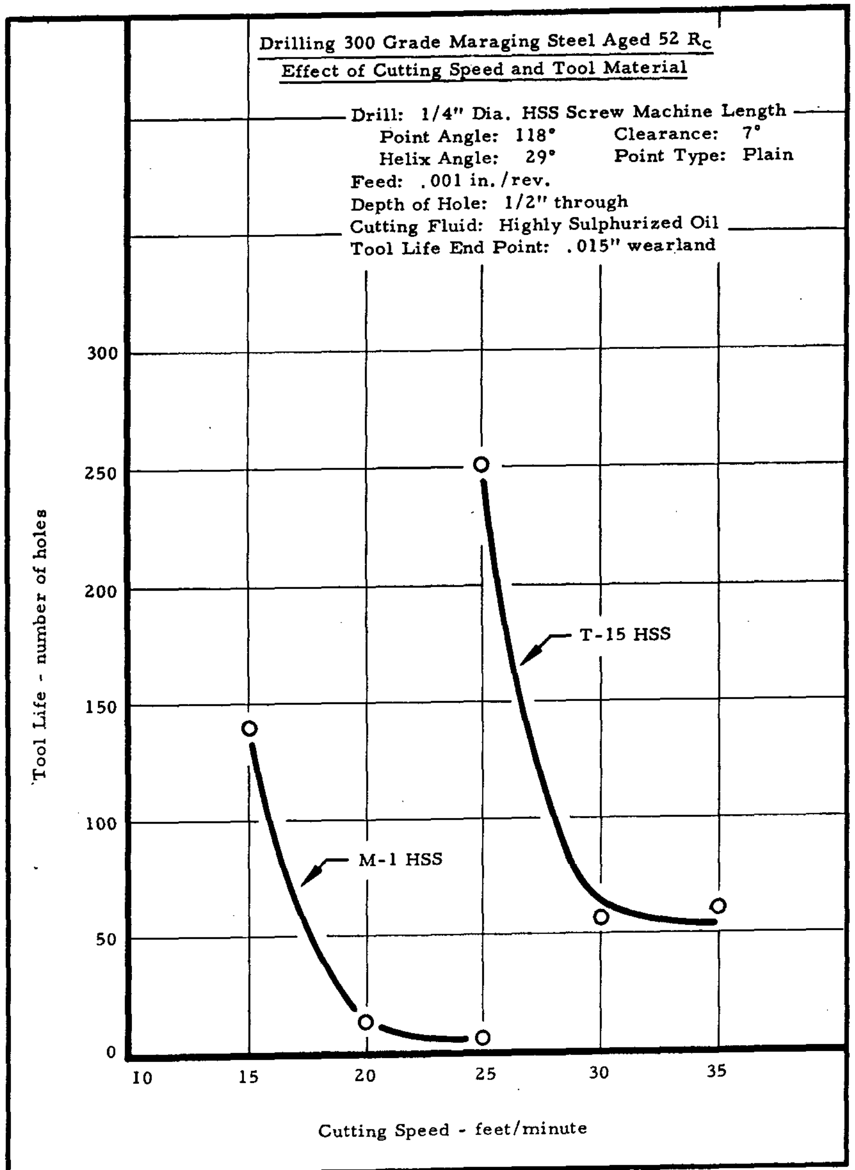
See text, page 103

Figure 130



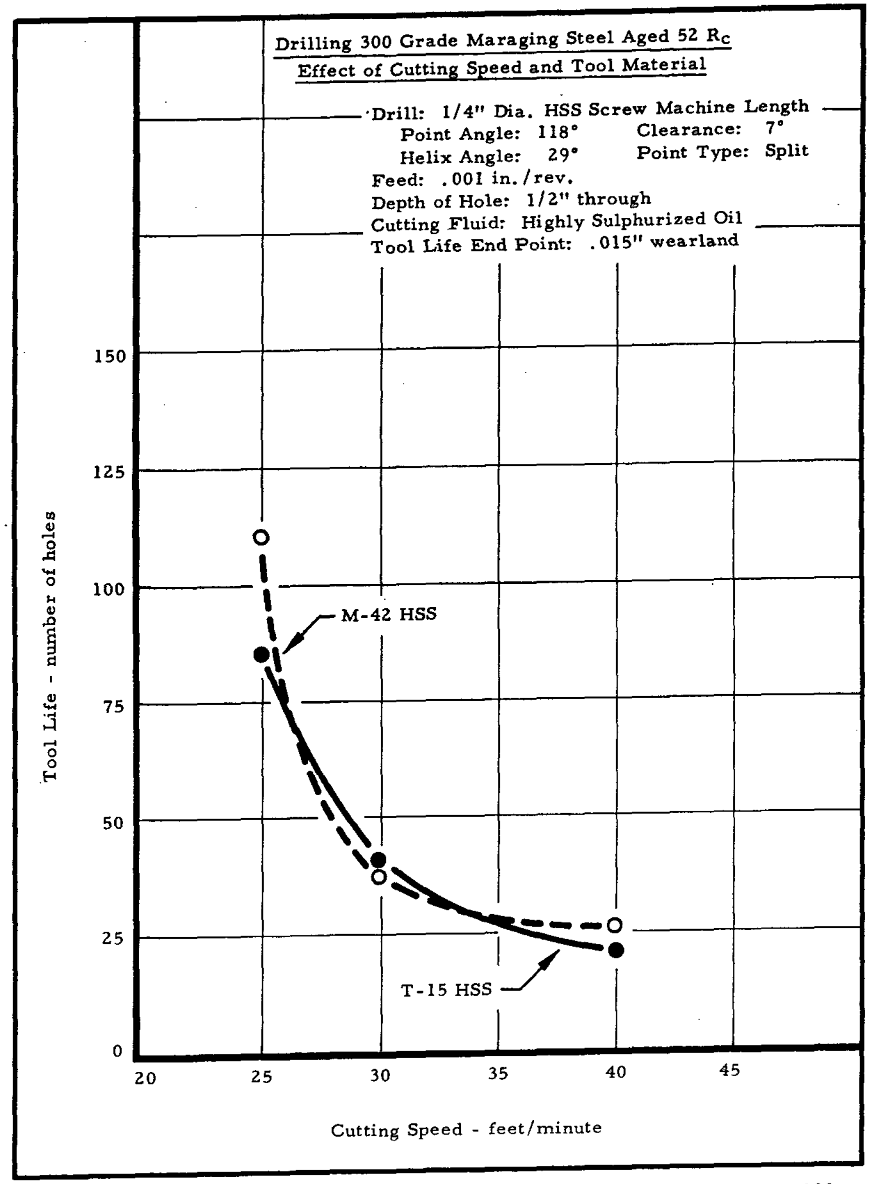
See text, page 103

Figure 131



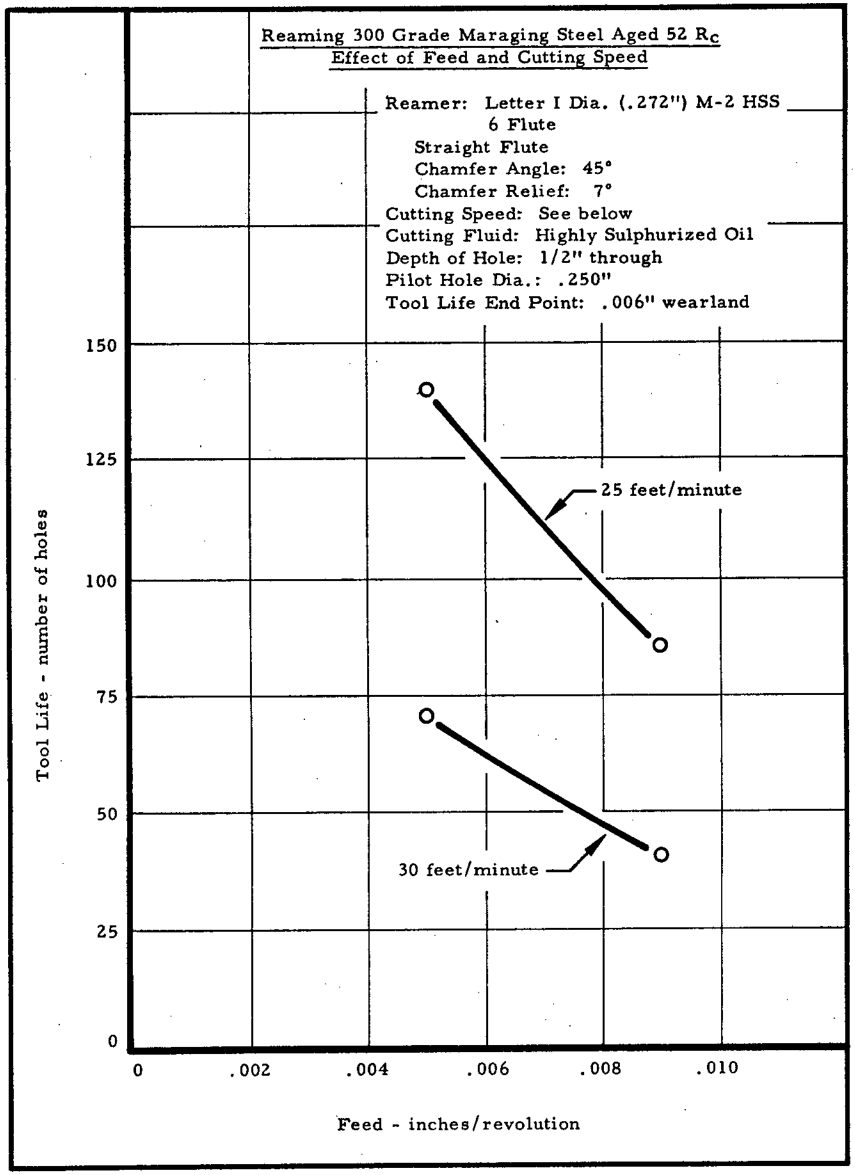
See text, page 103

Figure 132



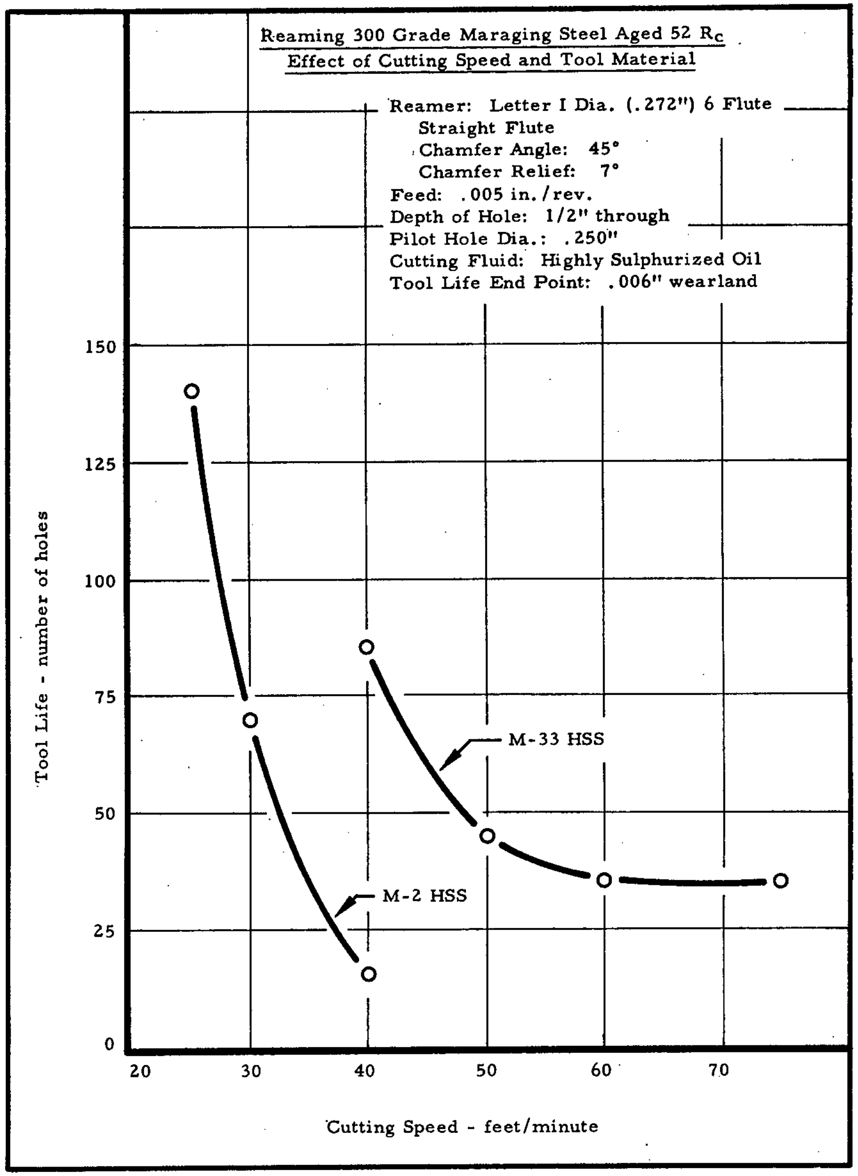
See text, page 103

Figure 133



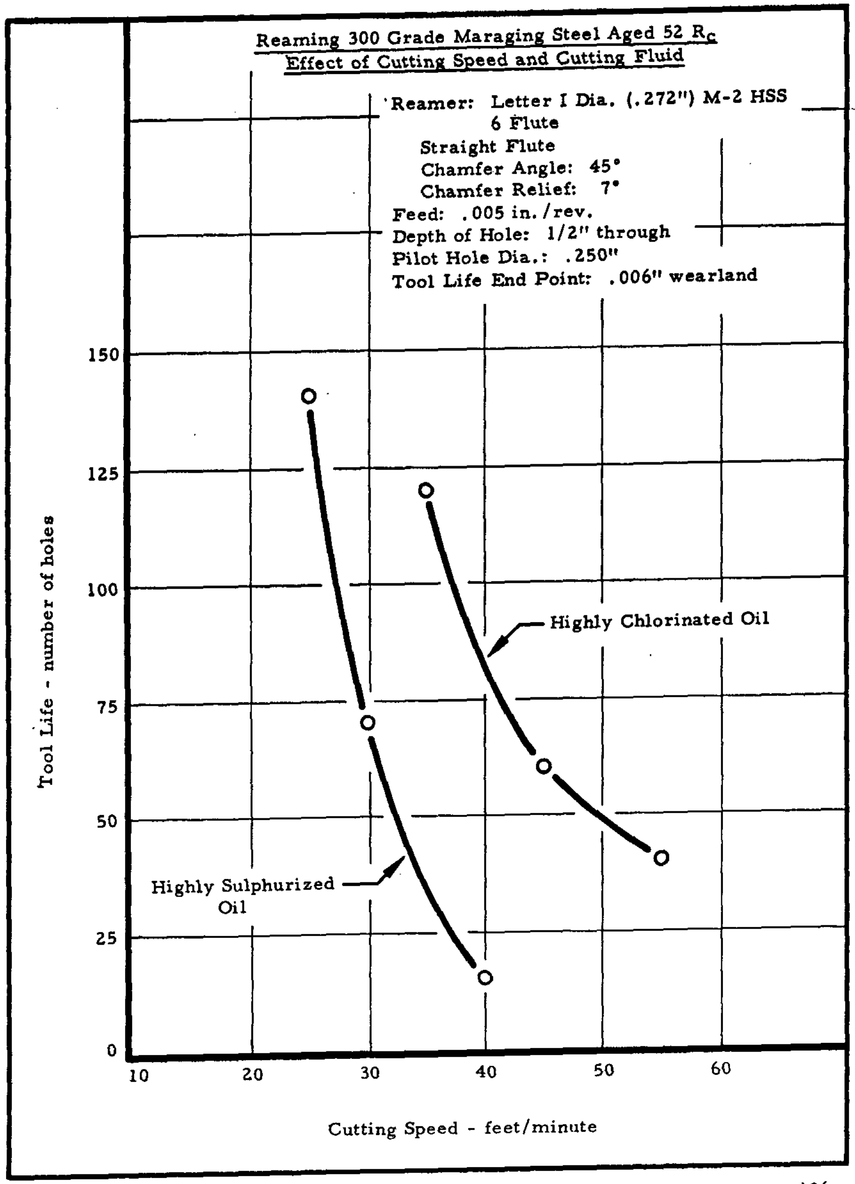
See text, page 103

Figure 134



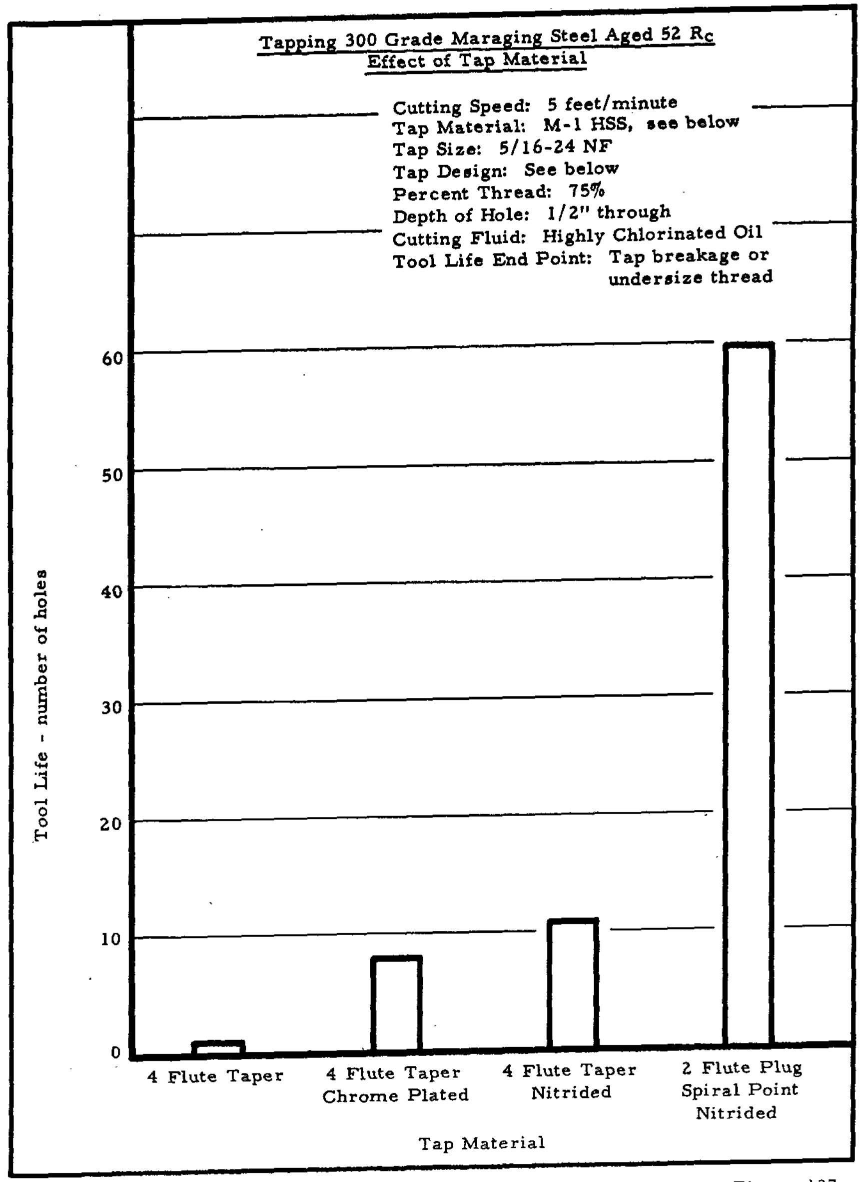
See text, page 104

Figure 135



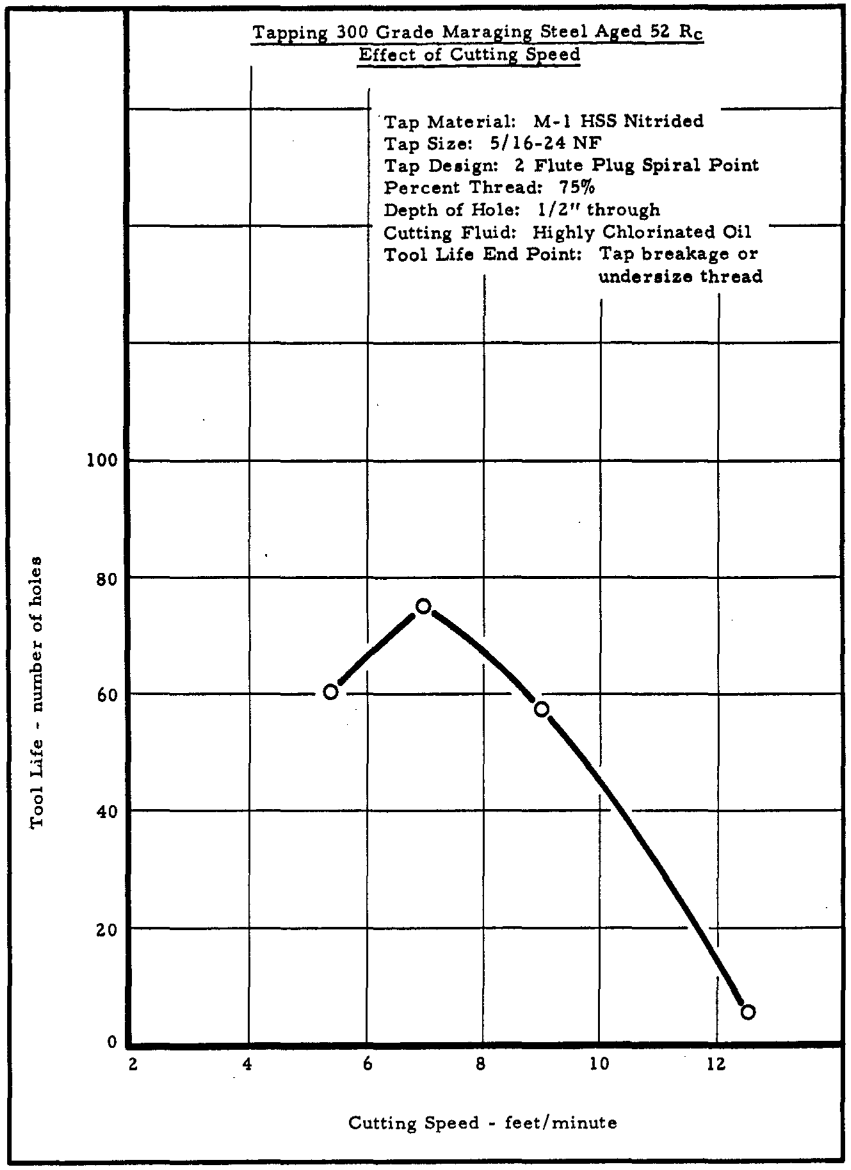
See text, page 104

Figure 136



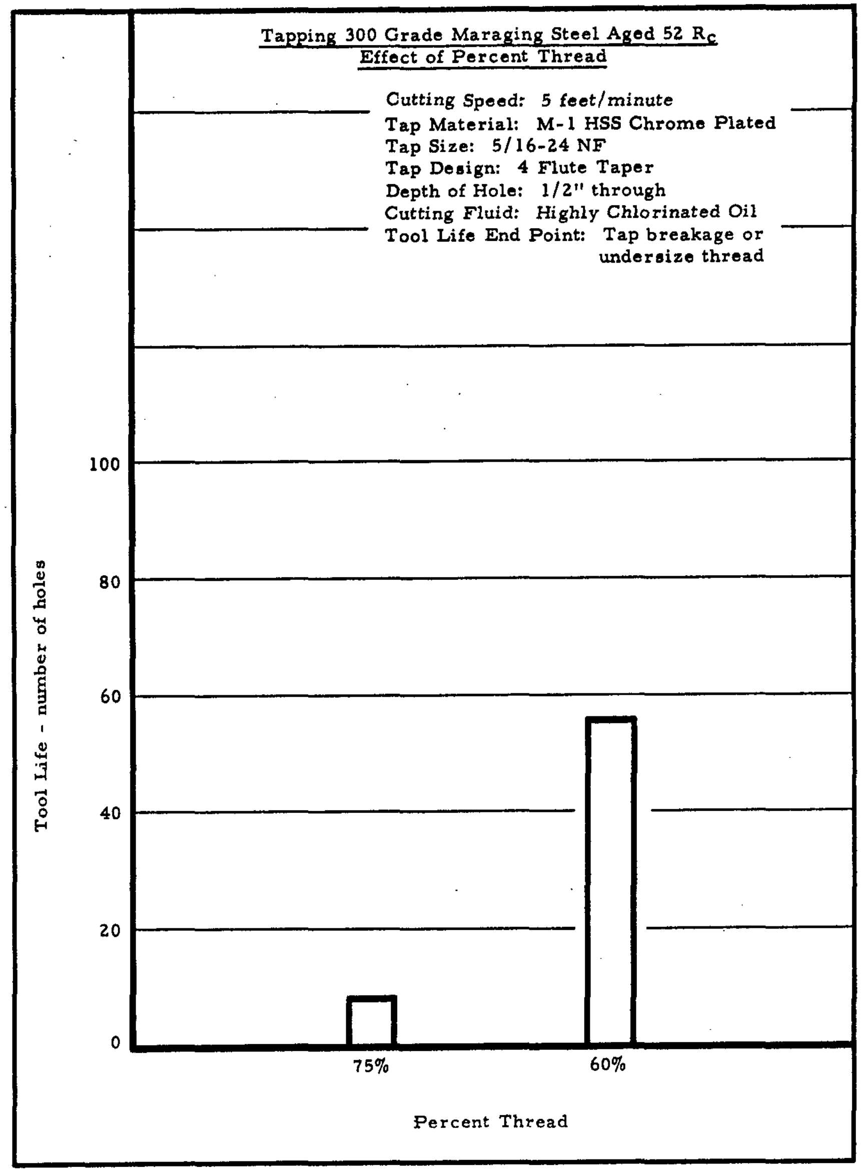
See text, page 104

Figure 137



See text, page 104

Figure 138



See text, page 104

Figure 139

3.5 HP 9-4-25 Steel

Alloy Identification

HP 9-4-25 is a high strength, high-alloy, hardenable steel. The nominal composition of this material is as follows:

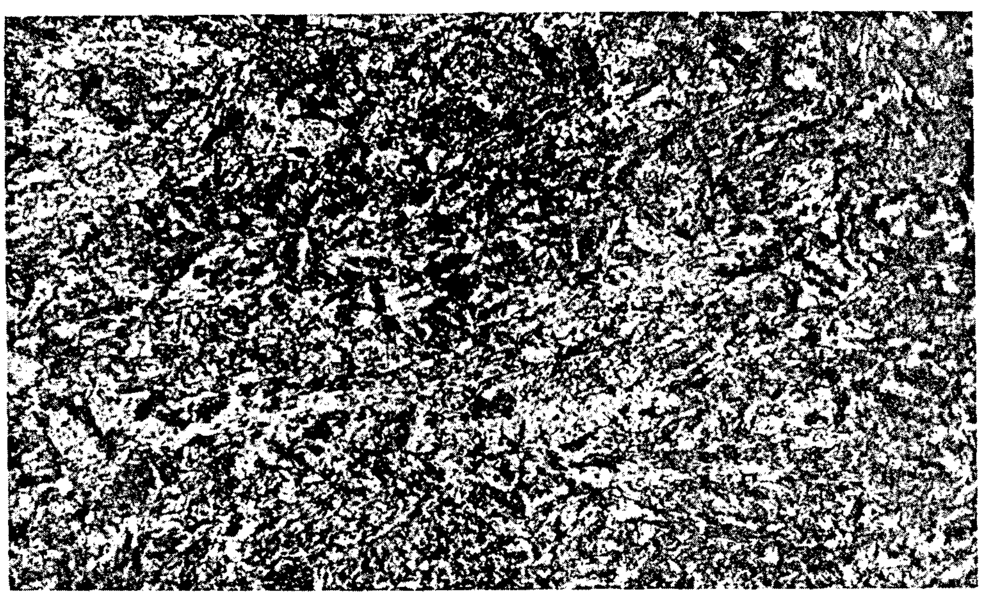
Fe - 9 Ni - 4 Co - 0.25 C - 0.5 Cr - 0.5 Mo

Forged, annealed bars 4" diameter were ordered for turning tests. The material for milling tests was procured as 2" x 4" bar stock in the forged, annealed condition. The material for the drilling tests was obtained by sectioning 1/2" thick plates from the 2" x 4" bar stock. The annealing treatment performed at the mill was as follows:

1159F/36 to 48 hours at temperature

The hardness of the material as received was 341-363 BHN.

This annealed material exhibits a microstructure which is essentially spheroidized. This condition is illustrated below:



HP 9-4-25, Annealed

Etchant: Kalling's   Mag: 1000X

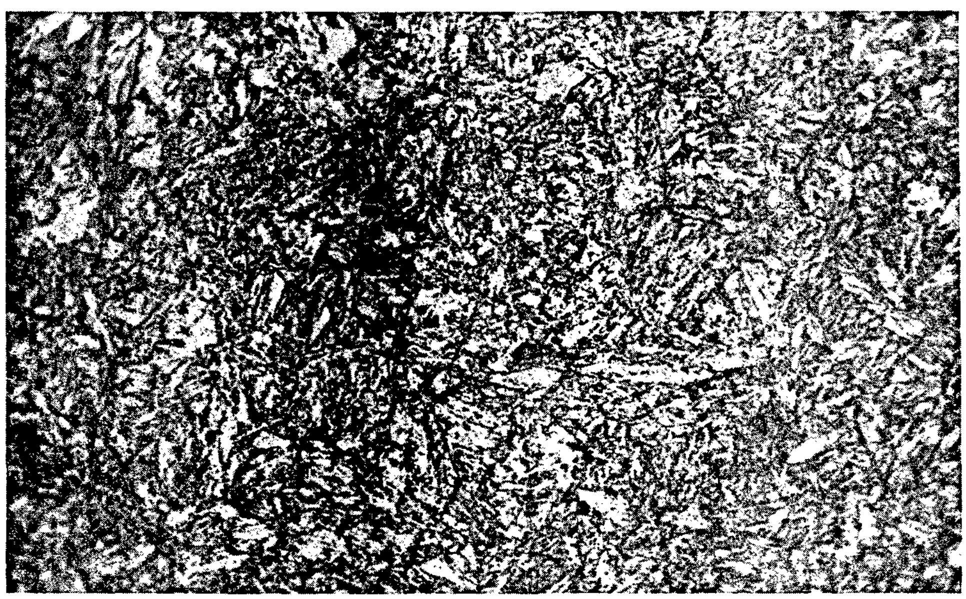
3.5 HP 9-4-25 Steel (continued)

In order to compare the hardened and double tempered to the annealed condition, previously annealed bars were hardened and tempered as follows:

> Normalize at 1600°F/1 hour/air cool. Austenitize at 1550°F/1 hour/oil quench. Double temper at 1000°F/2 hours for each temper.

This treatment yielded a hardness of 415-444 BHN.

The microstructure which is illustrated below consists of fine tempered martensite.



HP 9-4-25 Quenched and Double Tempered

Etchant: Kalling's Mag: 1000X

3.5 HP 9-4-25 Steel (continued)

Turning (Annealed 375 BHN)

Tool life data in turning HP 9-4-25 steel annealed 375 BHN with both high speed steel and carbide tools are presented in Figures 140 and 141, page 127. Tool life results obtained with three types of HSS tools; M-2, T-15 and M-44, are shown in Figure 140, page 127. Note that with the HP 9-4-25 steel in the annealed condition, the tool life with the harder HSS type M-44 was not as long as with the M-2 and the T-15 grades. Tool failure with the M-44 grade was usually the result of chipping. In the cutting speed range that would be normally used, the M-2 and T-15 HSS tools performed similarly.

In turning with carbide, the C-6 grade 370 carbide provided appreciably longer tool life than either the C-2 grade 883, the grades K-8 or K-68 as shown in Figure 141, page 127. The cutting speed with the 370 carbide was approximately double that used with the 883 carbide for an equivalent tool life.

Face Milling (Annealed 341-363 BHN)

The data obtained in face milling with high speed steel tools are presented in Figures 142 through 144, pages 128 and 129. As shown in Figure 142, page 128, the cutting speed with the type T-15 HSS tool was approximately 15% faster than that with a type M-2 HSS tool for an equivalent tool life. The relationship between cutter life and feed is shown in Figure 143, page 128. Tool life was almost constant over a range of feeds from .004 to .008 in./tooth for a type T-15 HSS tool. At a lower speed, 114 ft./min., and with the type M-2 HSS tool, the cutter life decreased from 98 inches of work travel at a feed of .0054 in./tooth to 66 inches at a feed of .0108 in./tooth, see Figure 144, page 129.

Face milling data with carbide tools on the HP 9-4-25 steel in the annealed condition (341-363 BHN) are presented in Figures 145 through 148, pages 129 through 131. Of the four grades of carbide tested, the grade 370 proved to be the best. As indicated in Figure 145, page 129, cutter life with the 370 (C-6) carbide was seven times longer than with the 883 (C-2) grade. This comparison was made cutting dry. The data shown in Figure 146, page 130, for a feed of .007 in./tooth indicate that the use of a soluble oil resulted in a marked decrease in cutter life when face milling with carbide tools the HP 9-4-25 steel in the annealed condition.

The feed used in face milling was somewhat critical with carbide cutters. Note in Figure 147, page 130, that at a cutting speed of 333 ft./min. chipping occurred at the cutting edge at feeds greater and less than .0065 in./tooth. Also at a lower speed, 220 ft./min., chipping also occurred at the lower feed. These results were obtained with cutters having negative rake angles. Using cutters with positive rake angles, the cutter life was fairly uniform over a range of feeds of .004 to .008 in./tooth as shown in Figure 148, page 131.

Side Milling (Annealed 363 BHN)

The relationship between cutting speed and tool life is presented in Figure 149, page 131, for side milling HP 9-4-25 steel in the annealed condition. The cutter life did not vary greatly over the range of cutting speeds of 225 to 360 ft./min.

Peripheral End Milling (Annealed 341-363 BHN)

The effect of cutting speed on tool life in peripheral end milling is shown in Figure 150, page 132. Under the conditions shown in the chart, a cutting speed of 75 to 90 ft./min. should be used in peripheral end milling HP 9-4-25 steel in the annealed condition.

End Mill Slotting (Annealed 341-363 BHN)

The curve in Figure 151, page 132, represents the relationship between cutting speed and tool life in end mill slotting the HP 9-4-25 steel in the annealed condition. Note that a 10% increase in cutting speed resulted in the tool life decreasing from 84 to 27 inches of work travel. A cutting speed of about 75 to 80 ft./min. would be recommended.

Drilling (Annealed 341 BHN)

The cutting speed in drilling was almost 19% faster with a soluble oil (1:20) as compared to a highly chlorinated oil, and the highly sulfurized oil was even poorer than the highly chlorinated oil. Note in Figure 152, page 133, that the cutting speed with the chlorinated oil was 74 ft./min. and 81 ft./min. with a soluble oil for a drill life of 120 holes.

The HP 9-4-25 steel in the annealed condition may have a fairly wide range of hardnesses. A comparison is made in Figure 153, page 133, of the drill life values obtained at two hardness levels; 341 BHN and 363 BHN. For a drill life of 120 holes, the steel having a hardness of

3.5 HP 9-4-25 Steel (continued)

341 BHN could be drilled at a cutting speed of 81 ft./min., while at the higher hardness the cutting speed had to be reduced about 20% to obtain the same number of holes.

Reaming (Annealed 341 BHN)

A comparison is made in Figure 154, page 134, between the tool life curve obtained with a highly sulfurized oil and one using soluble oil in reaming the HP 9-4-25 steel in the annealed condition. Note that the highly sulfurized oil was far more effective. For example, at a cutting speed of 110 ft./min. the tool life with the soluble oil was 62 holes as compared to 145 holes with the highly sulfurized oil.

Tapping (Annealed 341 BHN)

A tool life curve showing the relationship between cutting speed and number of holes tapped on the HP 9-4-25 steel in the annealed condition is shown in Figure 155, page 134. Note that as many as 200 holes were tapped at a cutting speed of 100 ft./min.

TABLE 8

RECOMMENDED CONDITIONS FOR MACHINING

HP 9-4-25 STEEL - ANNEALED 341 - 375 BHN

Ni	Co	C	Cr	Mo	Fe
9	4	.25	.5	.5	Bal

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	M-2 HSS	BR: 0° SCEA: 15° SR: 10° ECEA: 5° Relief: 5° NR: .030"	5/8" square Tool bit	.062	-	.009 in. / rev.	70	80 min.	.020	Soluble Oil (1:20)
Turning	C-6 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square throw-away inserts	.062	-	.009 in. / rev.	300	32 min.	.015	Soluble Oil (1:20)
Face Milling	T-15 HSS	AR: 5° ECEA: 10° RR: 5° CA 45° Clearance: 8°	4" diameter single tooth face mill	.062	2	.005 in. / tooth	117	170" work travel	.060	Soluble Oil (1:20)
Face Milling	C-6 Carbide	AR: -7° ECEA: 45° RR: -7° CA: 45° Clearance: 6°	4" diameter single tooth face mill	.062	2	.007 in. / tooth	220	90" work travel	.015	Dry
Side Milling	C-2 Carbide	AR: -7° ECEA: 10° RR: -7° CA: 45° Clearance: 8°	4" diameter single tooth face mill	.060	1.250	.006 in. / tooth	225	50" work travel	.015	Dry
Peripheral End Milling	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.004 in. / tooth	80	.260" work travel	.012	Soluble Oil (1:20)

TABLE 8 (continued)
RECOMMENDED CONDITIONS FOR MACHINING
HP 9-4-25 STEEL - ANNEALED 341 - 375 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
End Mill Slotting	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.002 in/ tooth	81	80" work travel	.012	Highly Chlorinated Oil
Drilling	M-1 HSS	118° plain point Clearance: 7°	1/4" diameter HSS drill 2 1/2" long	.500 thru	-	.005 in/rev	80	120 holes	.015	Soluble Oil (1:20)
Reaming	M-2 HSS	Helix Angle: 0° CA: 45° Clearance: 7°	.272" diameter 6 flute chucking reamer	.500 thru	-	.009 in/rev	110	145 holes	.006	Highly Sulphurized Oil
Tapping	M-1 HSS	2 Flute plug Spiral Point 75% thread	5/16 - 24 NF tap	.500 thru	-	-	100	200 holes	Under-size threads	Soluble Oil (1:20)

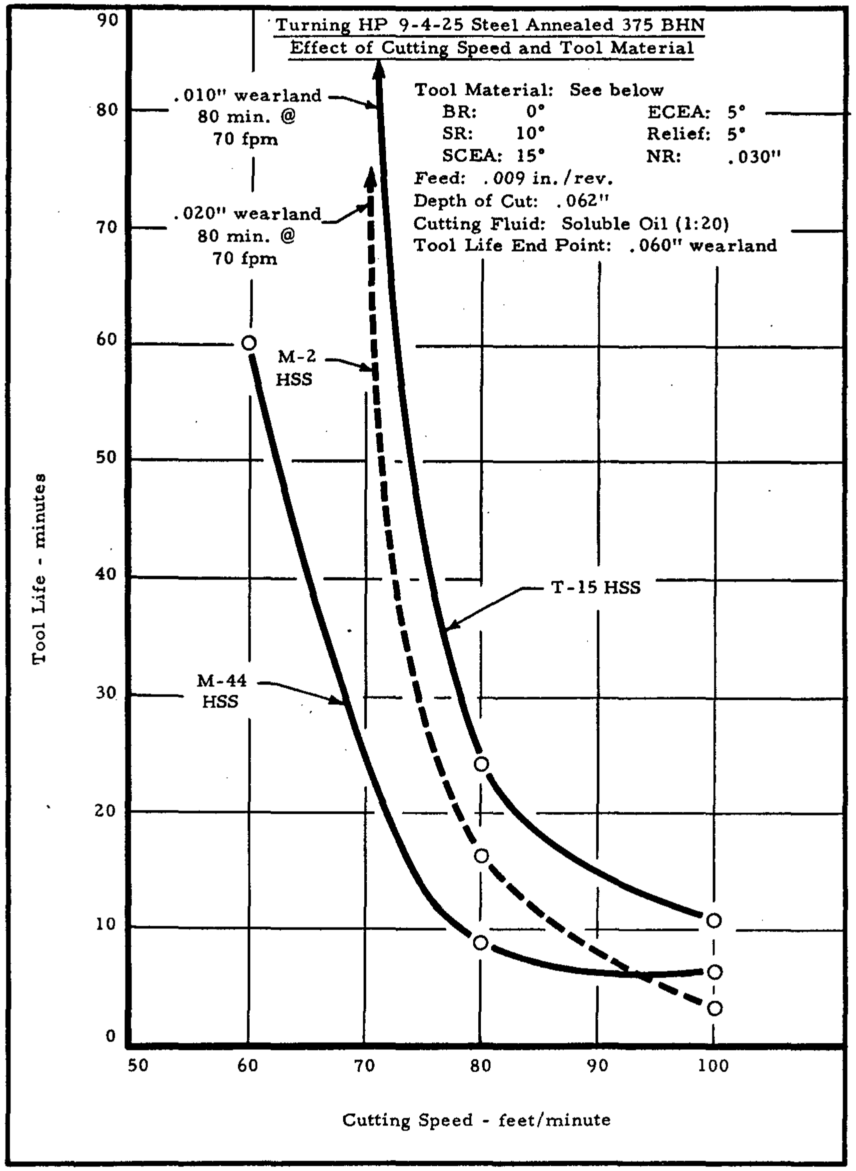


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Figure 140

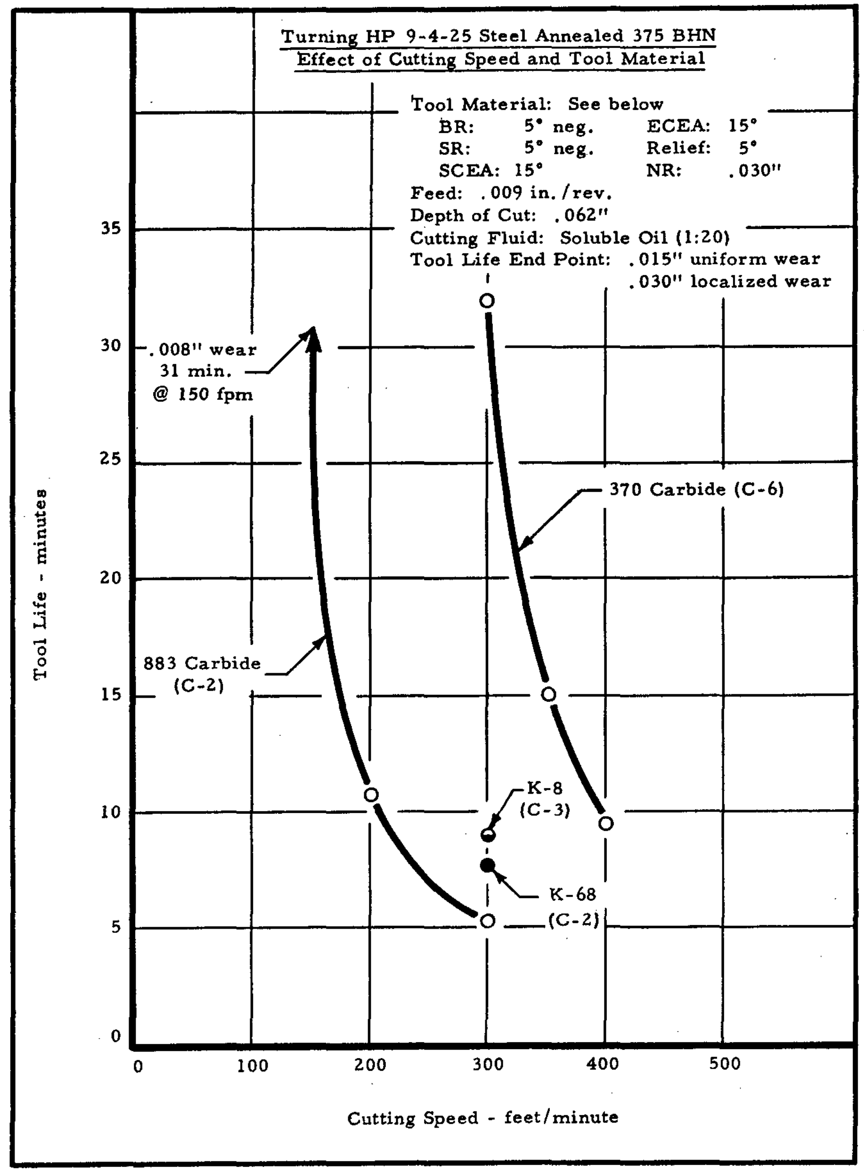

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Figure 141

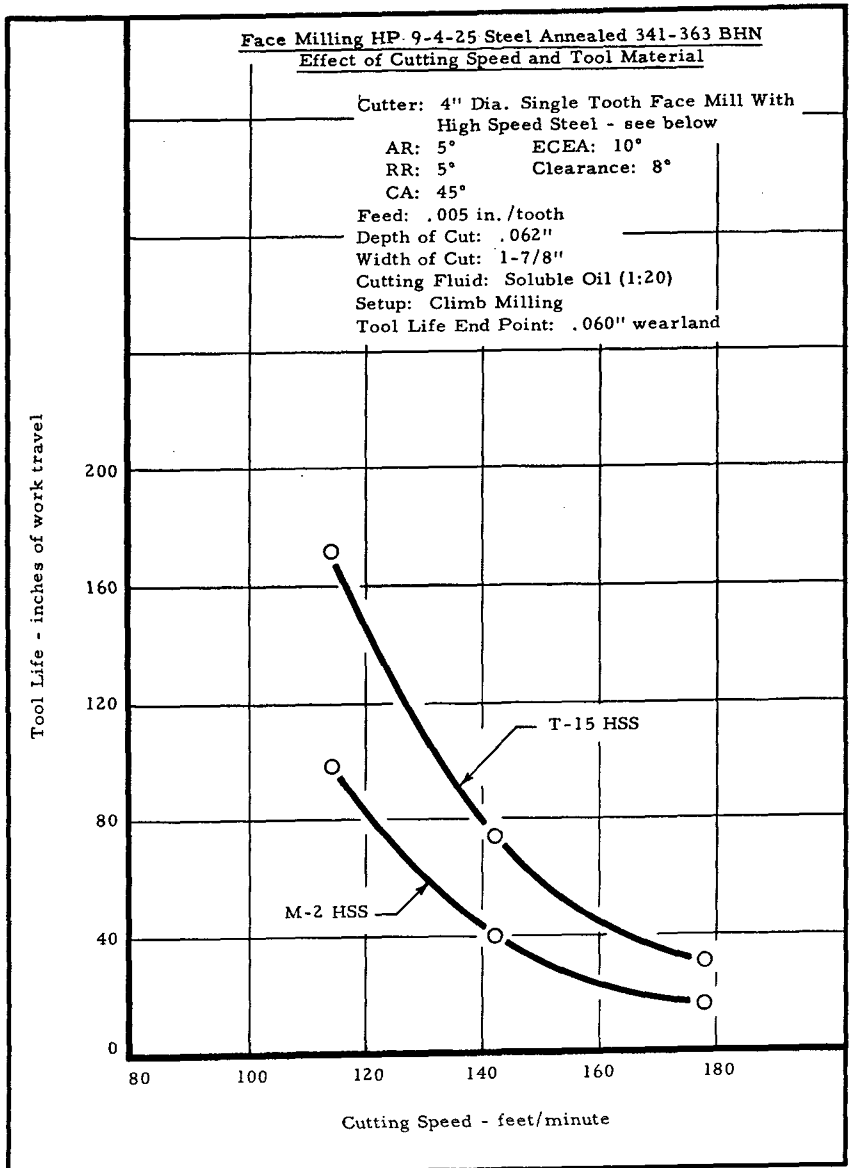

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Figure 142

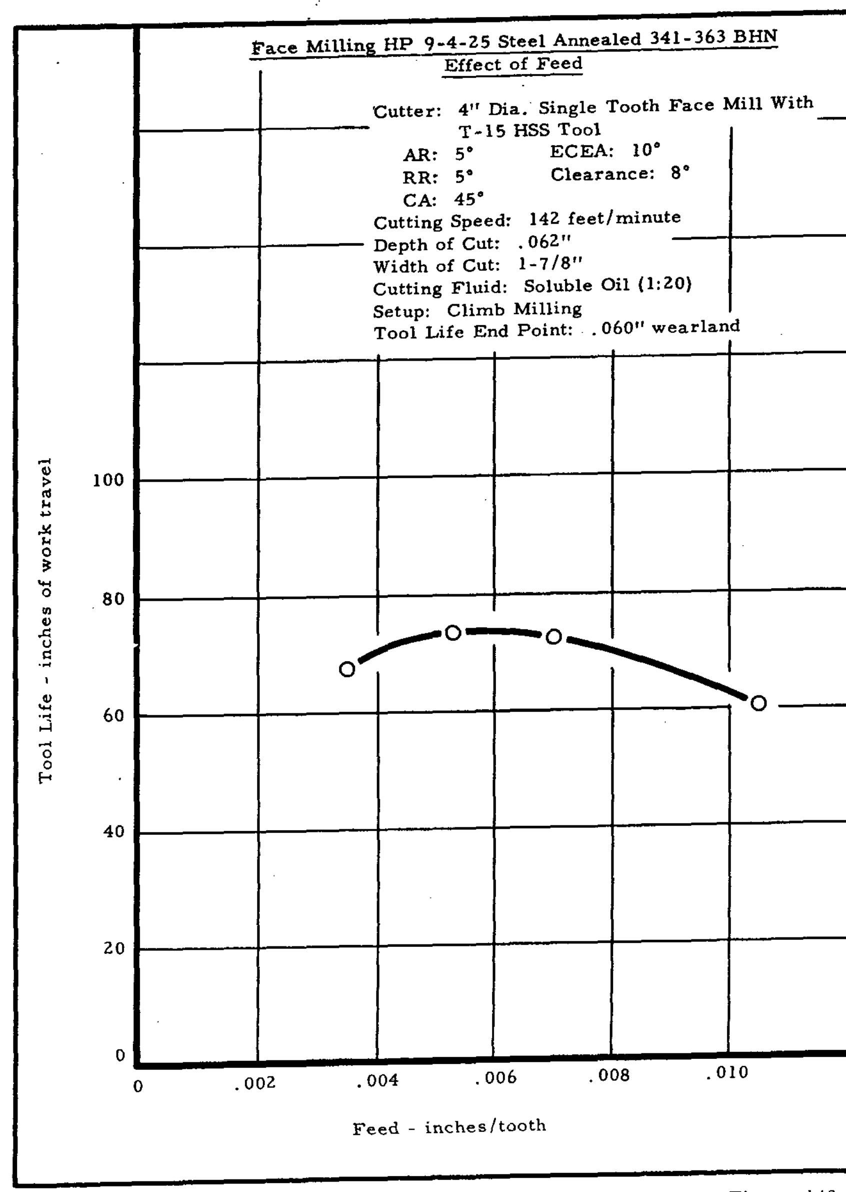

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Figure 143

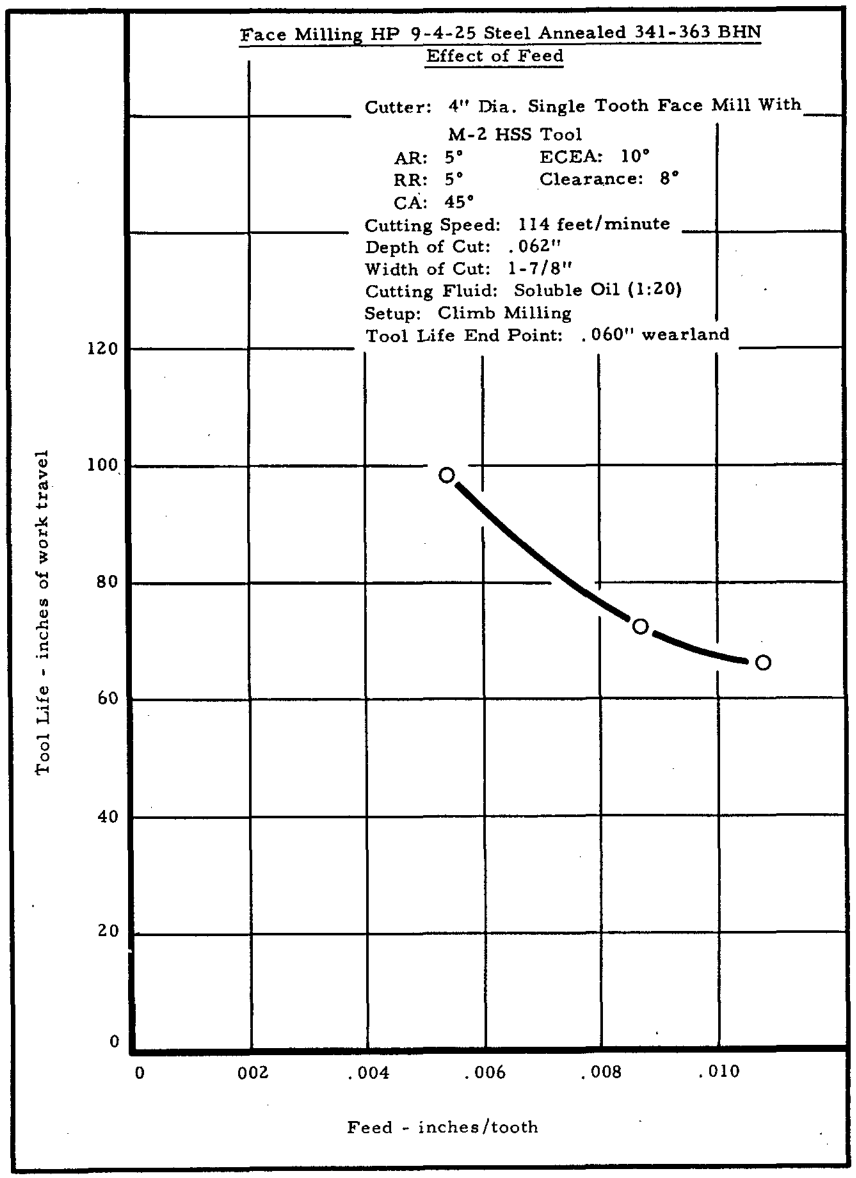

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Figure 144

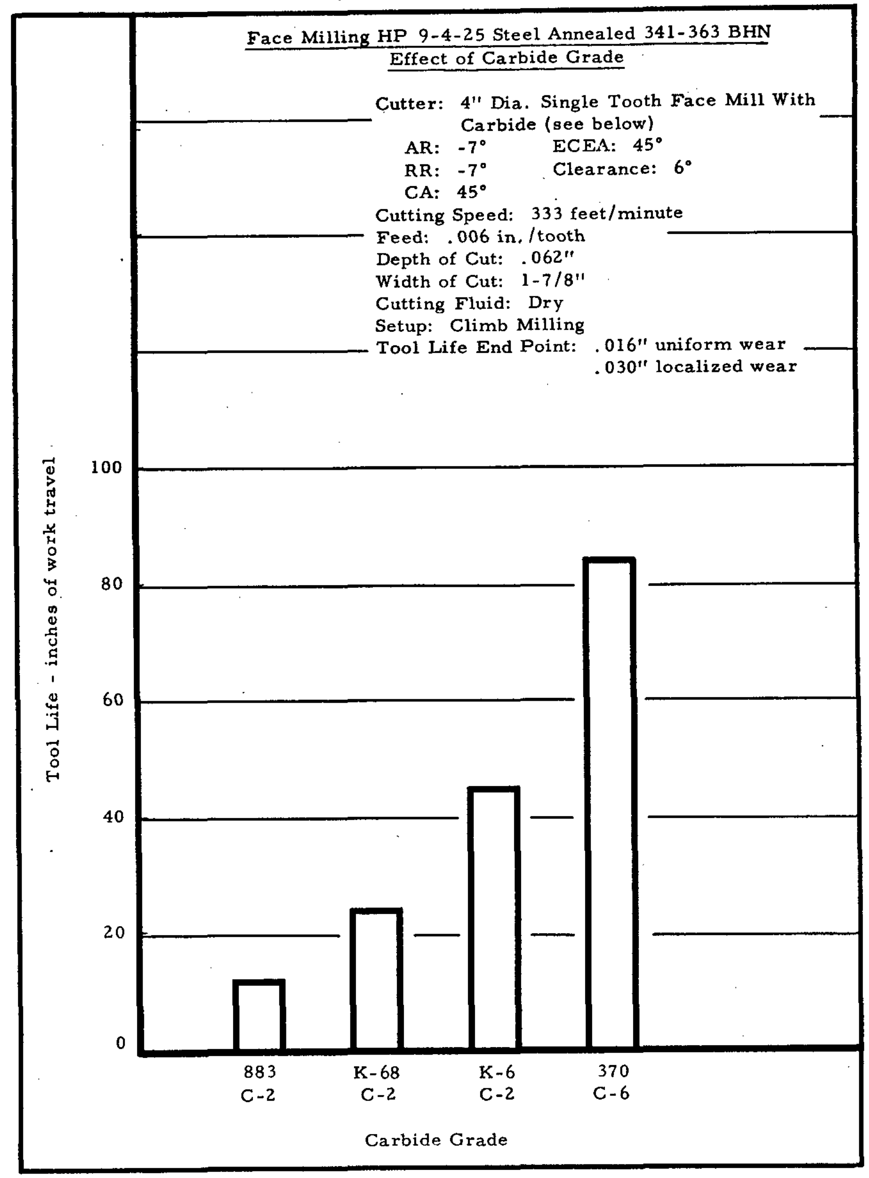

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Figure 145

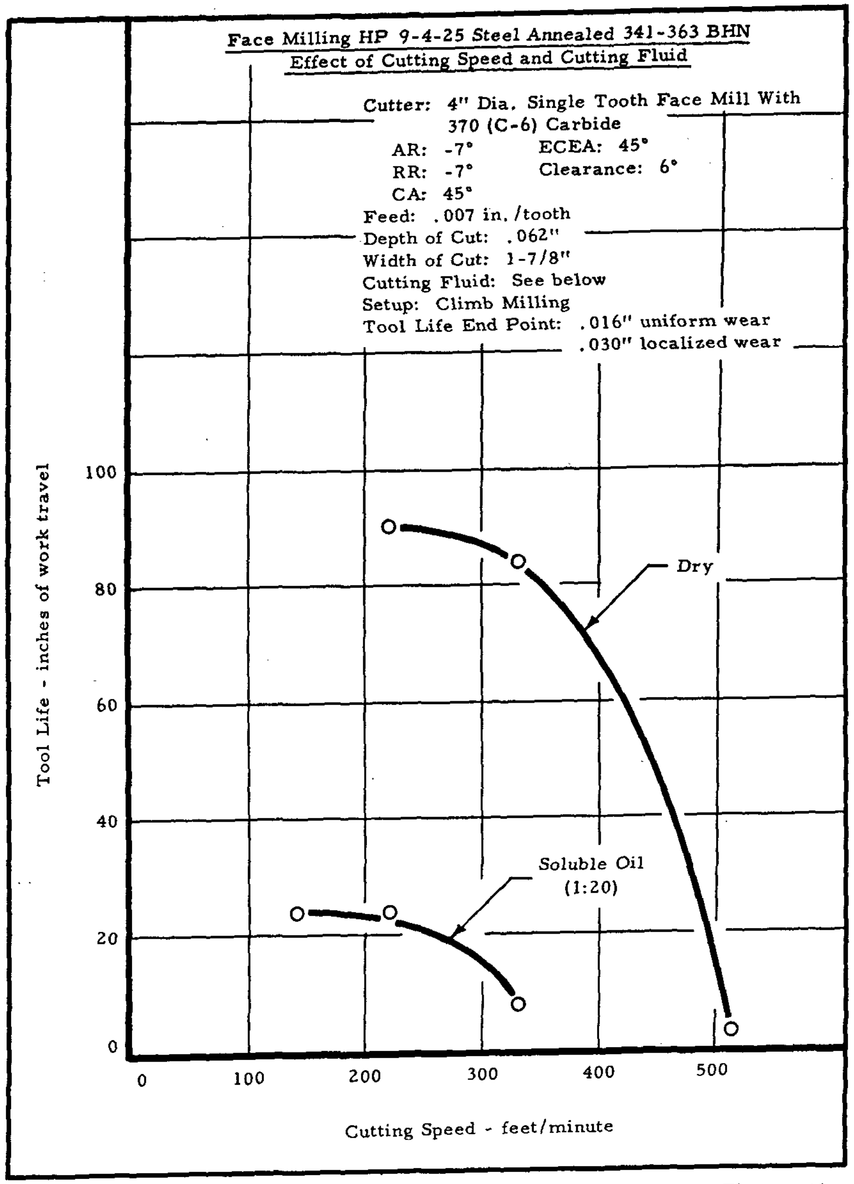

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Figure 146

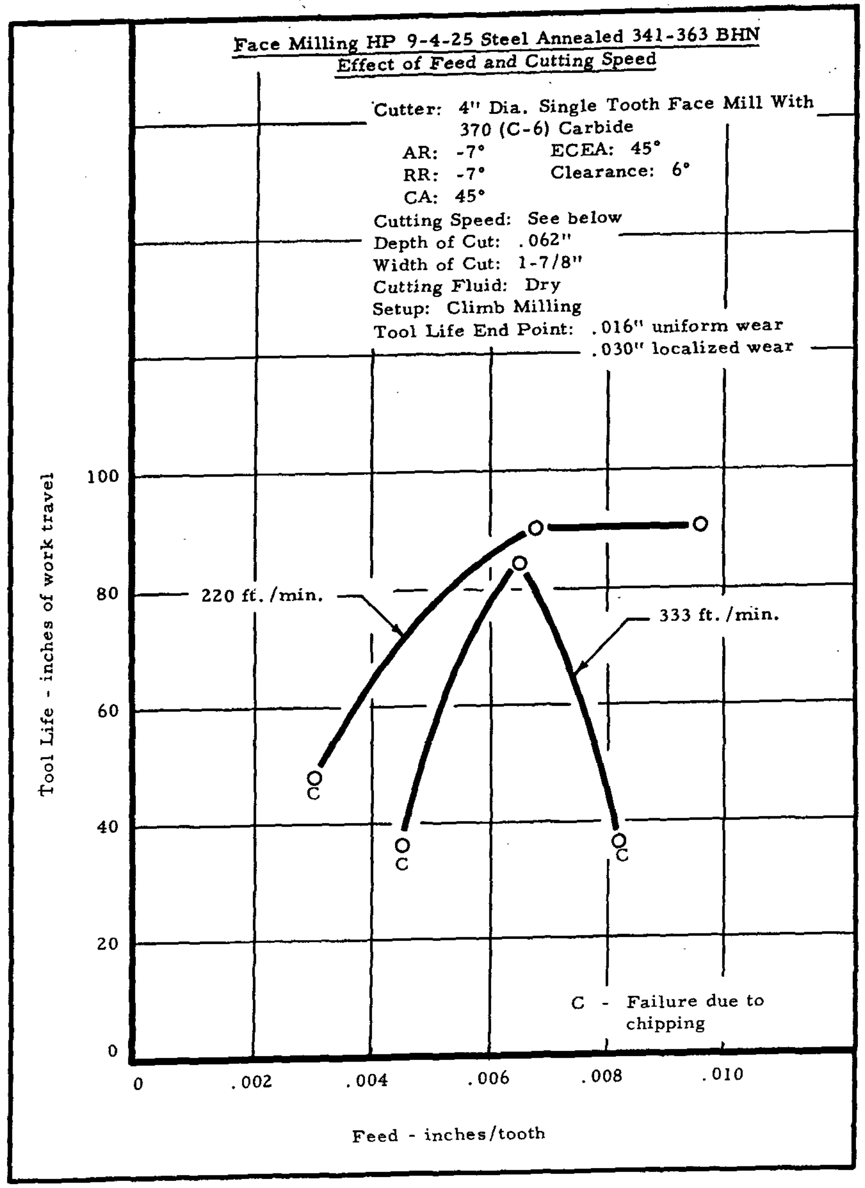

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Figure 147

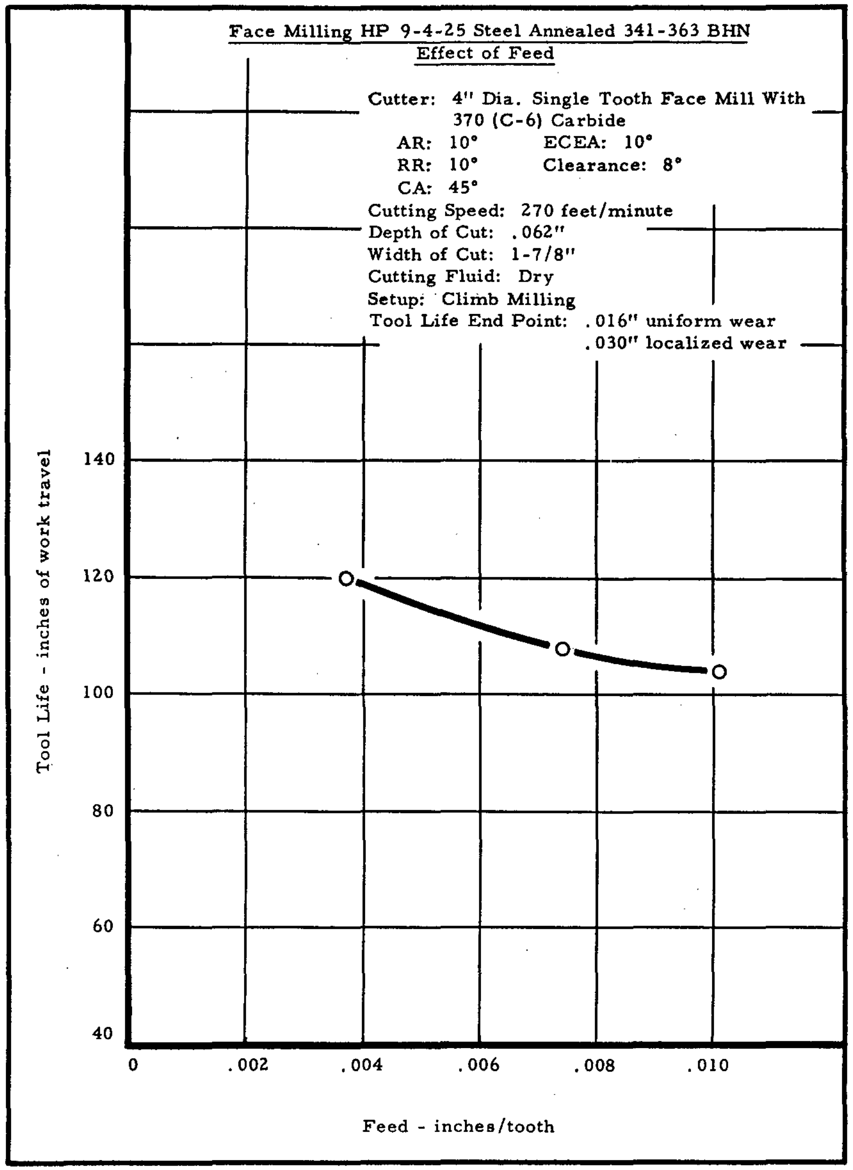

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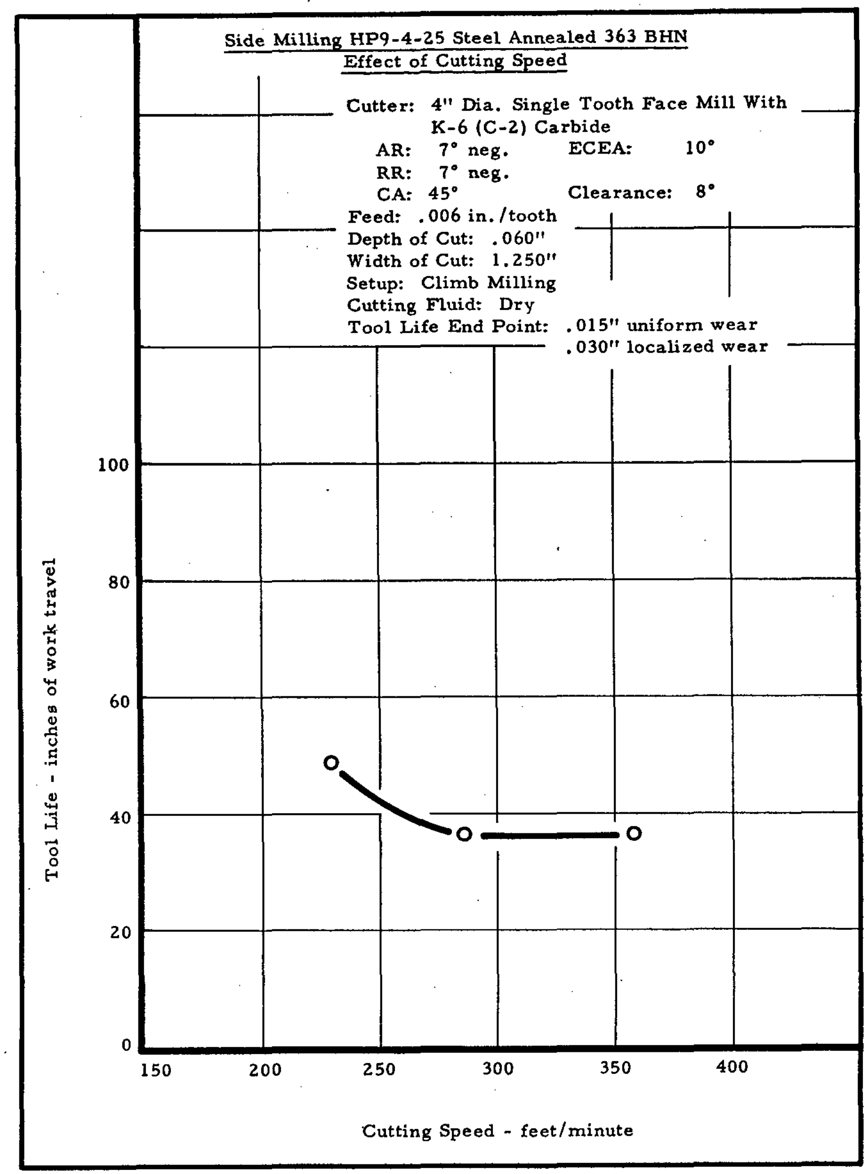
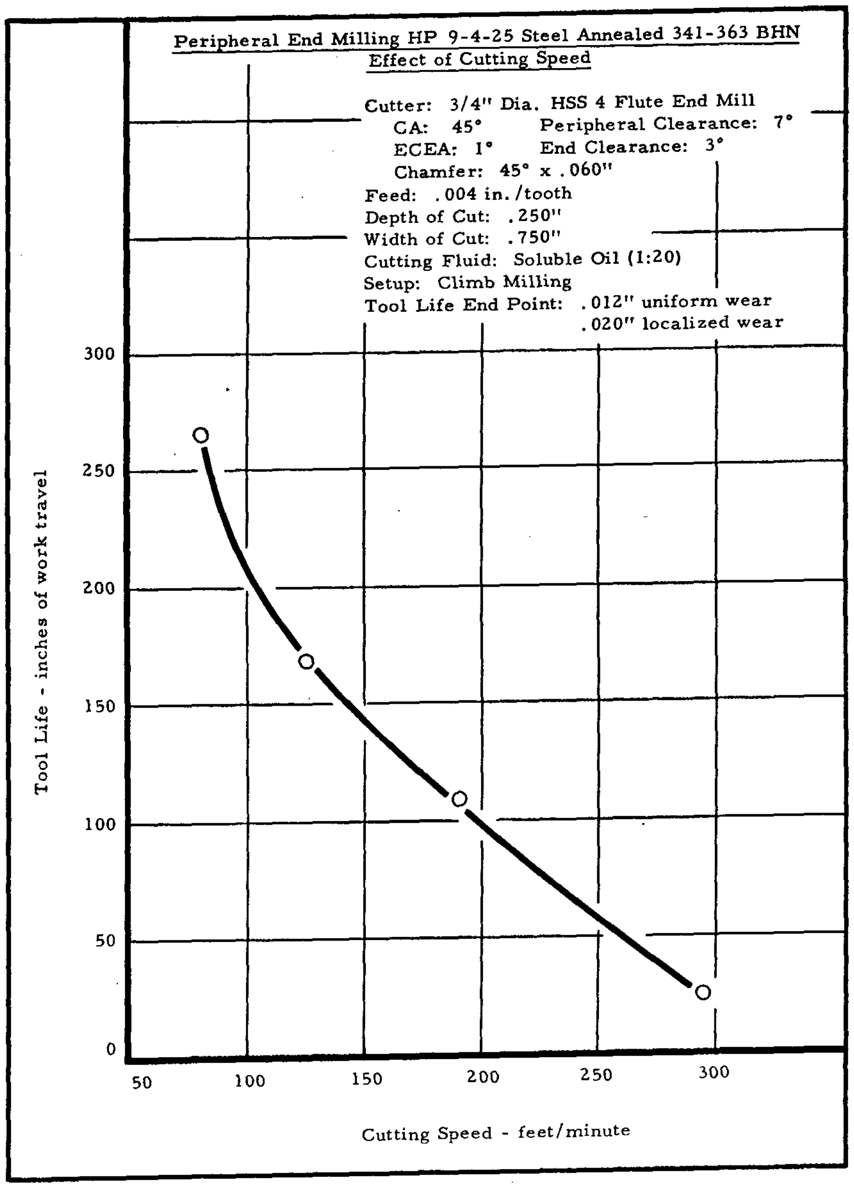
Figure 148



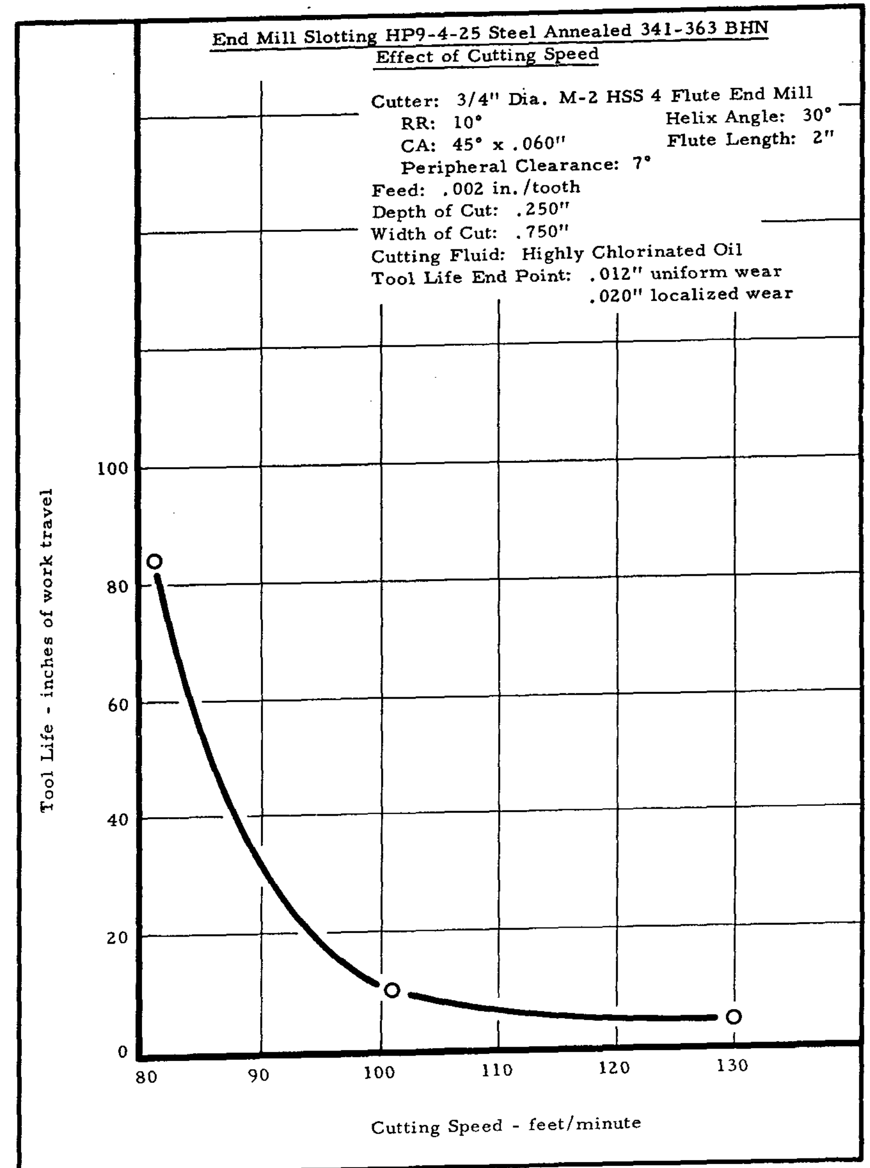
See text, page 123

Figure 149



See Text, page 123

Figure 150



See text, page 123

Figure 151

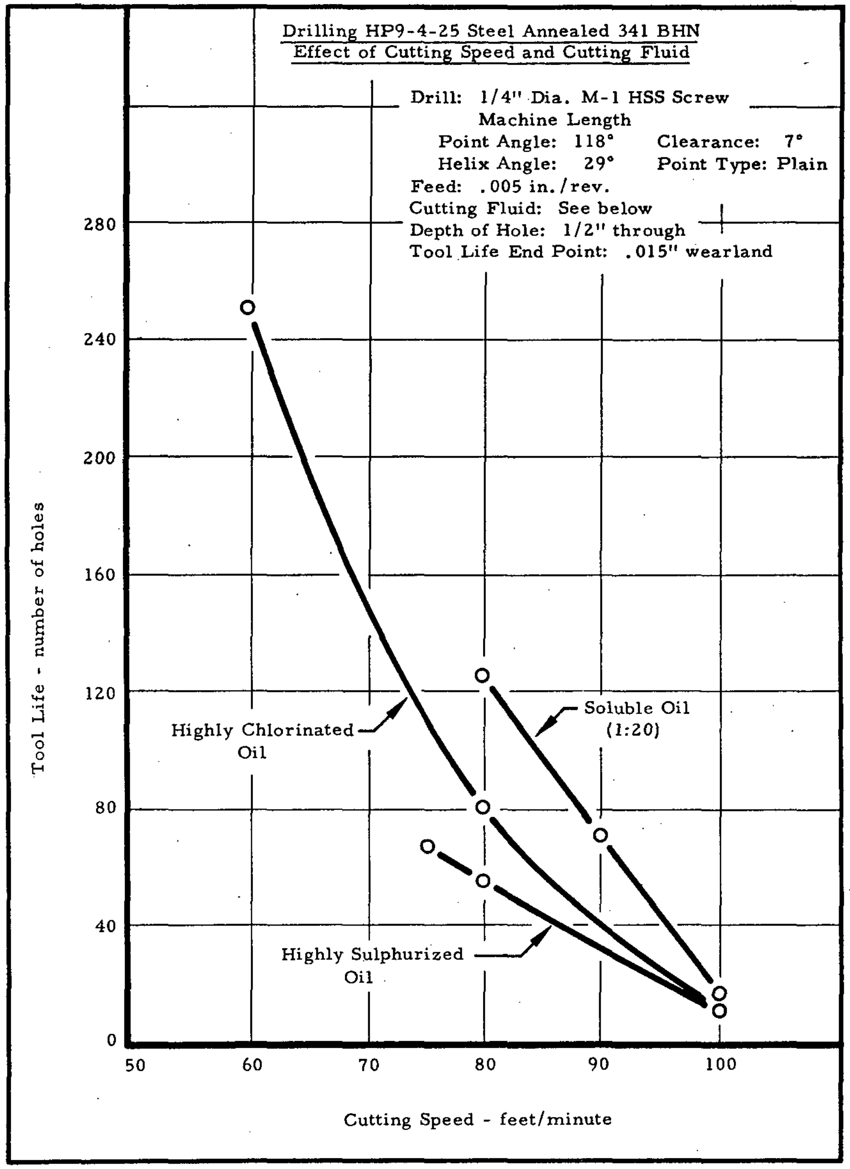


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Figure 152

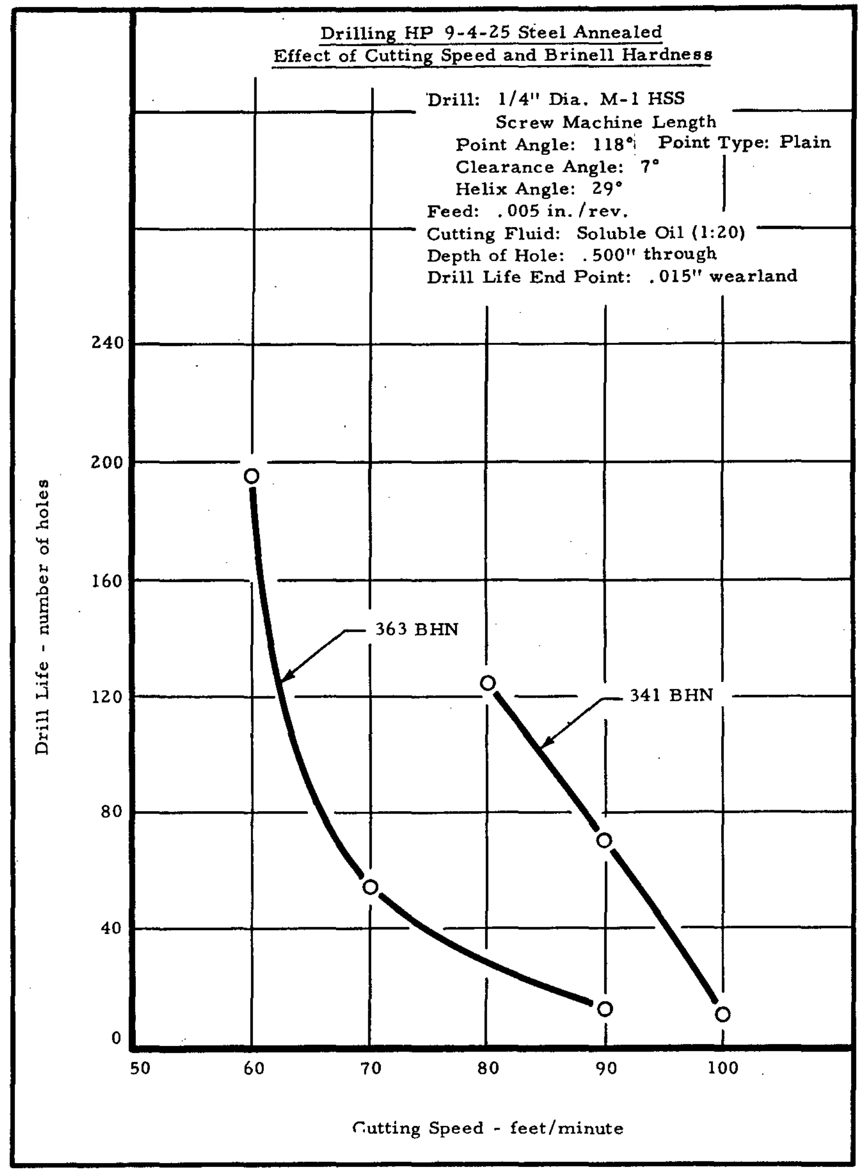

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Figure 153

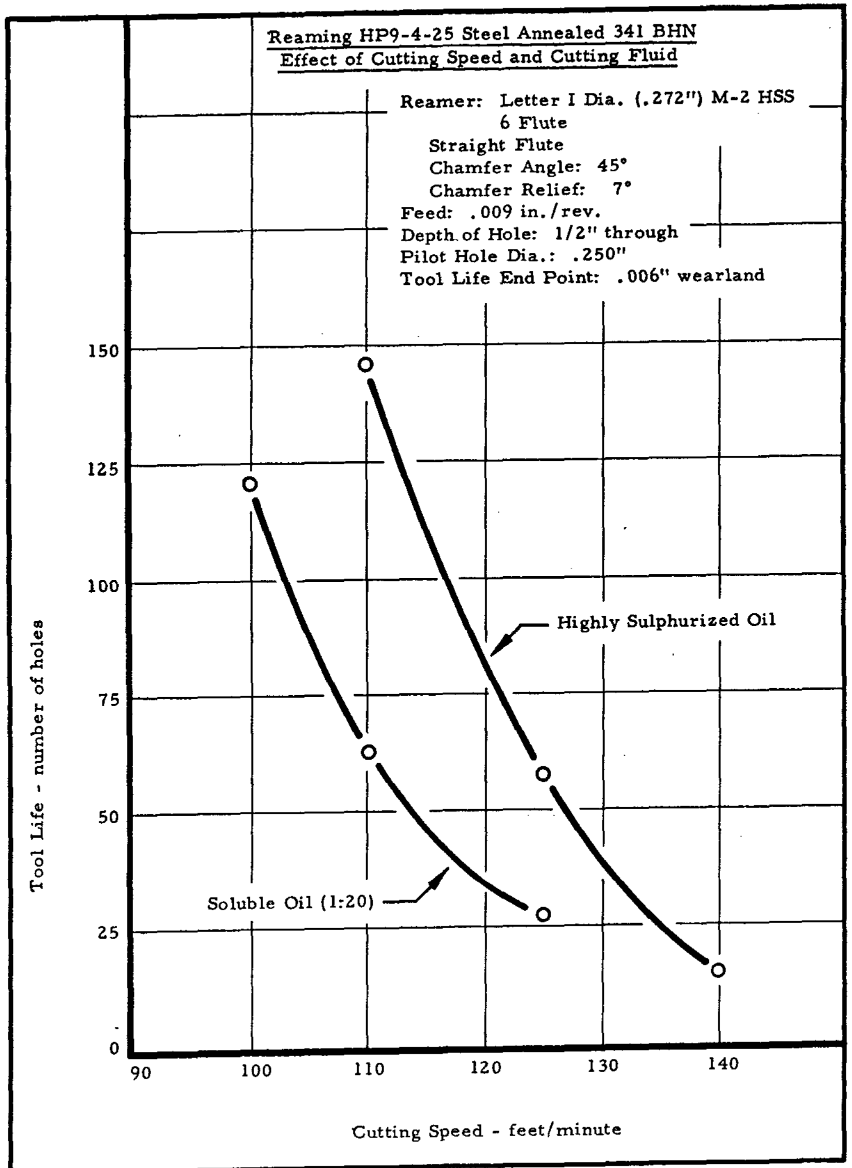

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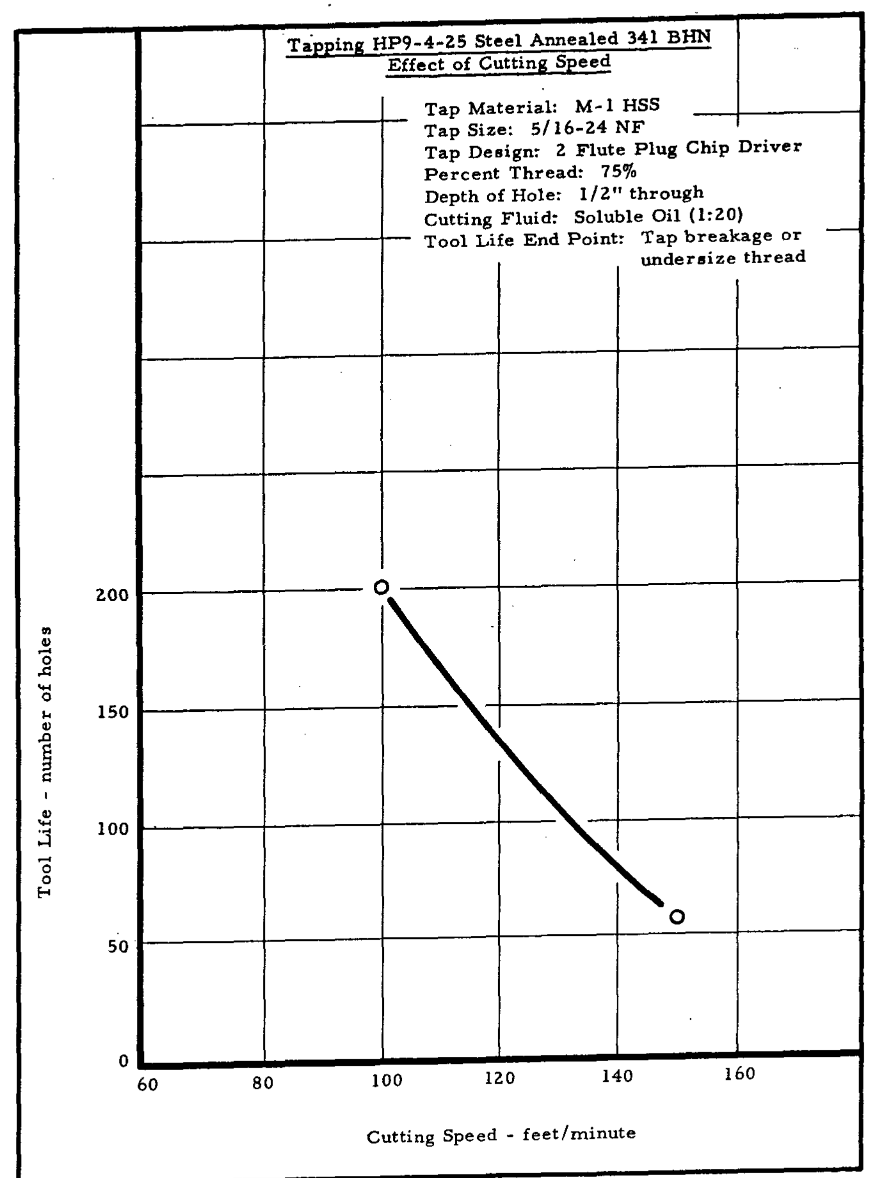
Figure 154



See text, page 124

Figure 155

Turning (Quenched and Tempered 415 BHN)

The results of turning HP 9-4-25 steel quenched and tempered to 415 BHN with both high speed steel and carbide tools are shown in Figures 156 through 158, pages 141 and 142. Note in Figure 156, page 141, that type T-15 HSS was superior to both the types M-2 and M-44 HSS. The cutting speed with the type T-15 was 76 ft./min. as compared to 69 ft./min. for the type M-2 HSS and 60 ft./min. for the M-44 HSS. Chipping of the cutting edge was the major factor in the poor tool life obtained with the type M-44 HSS tools.

The feed curve in Figure 157, page 141, indicates that the feed should not exceed about .005 in./tooth. Tool life decreased rapidly as the feed was increased.

As shown in Figure 158, page 142, the selection of the grade of carbide was very important in turning. Tool life was very short with both the 883 (C-2) and K165 (C-8) grades, while the 370 (C-6) grade was satisfactory.

Comparisons were made in Figures 159 and 160, pages 142 and 143, of the HP 9-4-25 steel in the annealed and the quenched and tempered conditions. Very small differences in the tool life values were obtained in turning these two heat treated forms with either high speed steel or carbide tools.

Face Milling (Quenched and Tempered 415 BHN)

A comparison of two tool life curves obtained in face milling with high speed steel cutters using soluble and chlorinated oils is shown in Figure 161, page 143. In the cutting speed range under 100 ft./min. the chlorinated oil proved to be somewhat more effective.

Feed curves using M-2 HSS and T-15 HSS cutters are shown in Figure 162, page 144. Note that when using the soluble oil the selection of feed with the T-15 HSS cutter should be made more carefully, since at feeds other than .008 in./tooth tool life decreased. However, with the M-2 HSS cutter tool life did not change significantly over a range of feeds from .002 to .008 in./tooth.

Using a chlorinated oil it was found that the M-2 HSS was much more effective than the T-15 HSS tool in face milling, see Figure 163, page 144. For a tool life of 125 inches of work travel the M-2 HSS cutter permitted a 20% higher cutting speed than the T-15 HSS cutter.

3.5 HP 9-4-25 Steel (continued)

A comparison of face milling the HP 9-4-25 steel with T-15 HSS in the annealed and quenched and tempered conditions is shown in Figure 164, page 145. Note the difference in the tool life results. For a tool life of 120 inches work travel, the cutting speed for the steel in the quenched and tempered condition was 92 ft./min. as compared to 127 ft./min. for the annealed condition.

The results of the face milling investigation on HP 9-4-25 steel in the quenched and tempered condition with carbide tools are presented in Figures 165 through 167, pages 145 and 146. As shown in Figure 165, C-5 grade K2S carbide was far superior to either of the C-2 grades 883 or K6. Also, the tool life with the K2S grade was almost 30% longer than with the C-6 grade 370 carbide.

Face milling HP 9-4-25 in either the annealed or the quenched and tempered condition with no cutting fluid was appreciably better than with a soluble oil. Note in Figure 166, page 146, that for a tool life of 100 inches of work travel, the cutting speed cutting dry was almost 50% greater than when a soluble oil (1:20) was used.

The feed was somewhat critical when face milling. As shown in Figure 167, page 146, the tool life decreased rapidly with feeds either less or greater than .008 in./tooth. A reduction of 20% or more in tool life occurred when a feed of either .006 or .010 in./tooth was used instead of .008 in./tooth feed.

Side Milling (Quenched and Tempered 444 BHN)

A comparison is shown in Figure 168, page 147, of the tool lives obtained with two grades of carbide in side milling HP 9-4-25 steel in a quenched and tempered condition over a range of cutting speeds. In the practical cutting speed range the tool life with the K2S carbide was more than double that obtained with the K6 grade.

Figure 169, page 147, presents a comparison of the same two grades of carbides over a range of feeds. Note that the K2S grade was far superior to the K6 grade at the higher feeds.

Drilling (Quenched and Tempered 421-429 BHN)

A comparison of the drilling results obtained with a soluble oil (1:20) and a highly chlorinated oil is presented in Figure 170, page 148. Note that the drill life values were almost the same for the two fluids at cutting speeds of 60 ft./min. and higher. However, the drill life decreased as the speed was reduced below 60 ft./min. with the soluble oil; while the drill life increased with the highly chlorinated oil.

As shown in Figure 171, page 148, the HP 9-4-25 steel in the annealed condition (341 BHN) could be drilled about 30% faster than the steel in the quenched and tempered condition (421 BHN). For a drill life of 100 holes, the cutting speed with the annealed steel was 67 ft./min. as compared to 51 ft./min. for the quenched and tempered steel.

Surface Grinding (Quenched and Tempered 421-429 BHN)

The effect of wheel speed on the G Ratio in grinding the HP 9-4-25 steel quenched and tempered to 421-429 BHN is shown in Figure 172, page 149, for both an H and a K hardness wheel. With both wheels the G Ratio increased with increasing wheel speed, with the K wheel providing a substantially higher G Ratio than the H wheel. The K wheel should be considered for roughing cuts and the H wheel for finishing cuts, where surface integrity has to be maintained. The tests in Figure 172, page 149, were run at a down feed of .002 in./pass, a cross feed of .050 in./pass, and a table speed of 40 ft./min., using a water soluble grinding fluid.

The effect of down feed on G Ratio is illustrated in Figure 173, page 149. The G Ratio increased with increasing down feed for both wheel speeds of 4000 and 6000 ft./min.

The G Ratio also increased with increasing cross feed, Figure 174, page 150. Here, while using a grinding wheel speed of 6000 ft./min. and a down feed of .001 in./pass, a G Ratio of 20 was obtained at a cross feed of .100 in./pass.

Increasing the table speed was also found to increase the G Ratio, Figure 175, page 150, where the G Ratio was found to increase from 2 to 10 as the table speed increased from 20 to 60 ft./min.

In grinding the HP 9-4-25 steel, the soluble oil was found to provide a higher G Ratio than either the sulfurized or the chlorinated oil, Figure 176, page 151.

The recommended conditions for grinding HP 9-4-25 steel are given in Table 9, page 139. The roughing conditions described are based

3.5 HP 9-4-25 Steel (continued)

upon getting higher G Ratio, and these conditions include:

Grinding Wheel:	32A46K8VBE
Wheel Speed:	6000 ft. /min.
Down Feed:	.002 in. /pass
Cross Feed:	.050 to .100 in. /pass
Table Speed:	60 ft. /min.
Cutting Fluid:	Soluble Oil or Highly Sulfurized Oil

However, there is a distinct danger of producing a hard white layer of untempered martensite if the wheel accidentally loads or if the grinding fluid were to be accidentally cut off. For finish grinding, therefore, the conditions should be adjusted to minimize the danger of surface damage. In finish grinding, Table 7, page 227, the "low stress" conditions should be used, consisting of:

Grinding Wheel:	32A46H8VBE
Wheel Speed:	3500 to 4000 ft. /min.
Down Feed:	.0005 in. /pass
Cross Feed:	.050 in. /pass
Table Speed:	60 ft. /min.
Cutting Fluid:	Highly Sulfurized Oil

Surface finish obtainable in grinding the HP 9-4-25 is 15 to 25 microinches, arithmetical average, in finishing; and 20 to 45 microinches, arithmetical average, in roughing.

TABLE 9

RECOMMENDED CONDITIONS FOR MACHINING

HP 9-4-25 STEEL - QUENCHED AND TEMPERED 415 - 444 BHN

Ni	Co	C	Cr	Mo	Fe
9	4	.25	.5	.5	Bal

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	T-15 HSS	BR: 0° SCEA: 15° SR: 10° ECEA: 5° Relief: 5° NR: .030"	5/8" square tool bit	.062	-	.009 in/rev	75	90 Min.	.060	Soluble Oil (1:20)
Turning	C-6 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square Throw-away Inserts	.062	-	.009 in/rev	300	32 Min.	.015	Soluble Oil (1:20)
Face Milling	M-2 HSS	AR: 5° ECEA: 10° RR: 5° CA: 45° Clearance: 8°	4" diameter Single Tooth Face Mill	.062	2	.005 in/ tooth	114	155" Work Travel	.060	Chlorinated Oil
Face Milling	C-5 Carbide	AR: -7° ECEA: 10° RR: -7° CA: 45° Clearance: 8°	4" diameter Single Tooth Face Mill	.062	2	.008 in/ tooth	175	180" Work Travel	.015	Dry
Side Milling	C-5 Carbide	AR: -7° ECEA: 10° RR: -7° CA: 45° Clearance: 8°	4" diameter Single Tooth Face Mill	.060	1.250	.008 in/ tooth	225	95" Work Travel	.015	Dry
Drilling	M-1 HSS	118° Plain Point 7° Clearance Angle	1/4" diameter HSS Drill 2 1/2" long	.500 thru	-	.005 in/rev	50	104" Work Travel	.015	Highly Chlorinated Oil

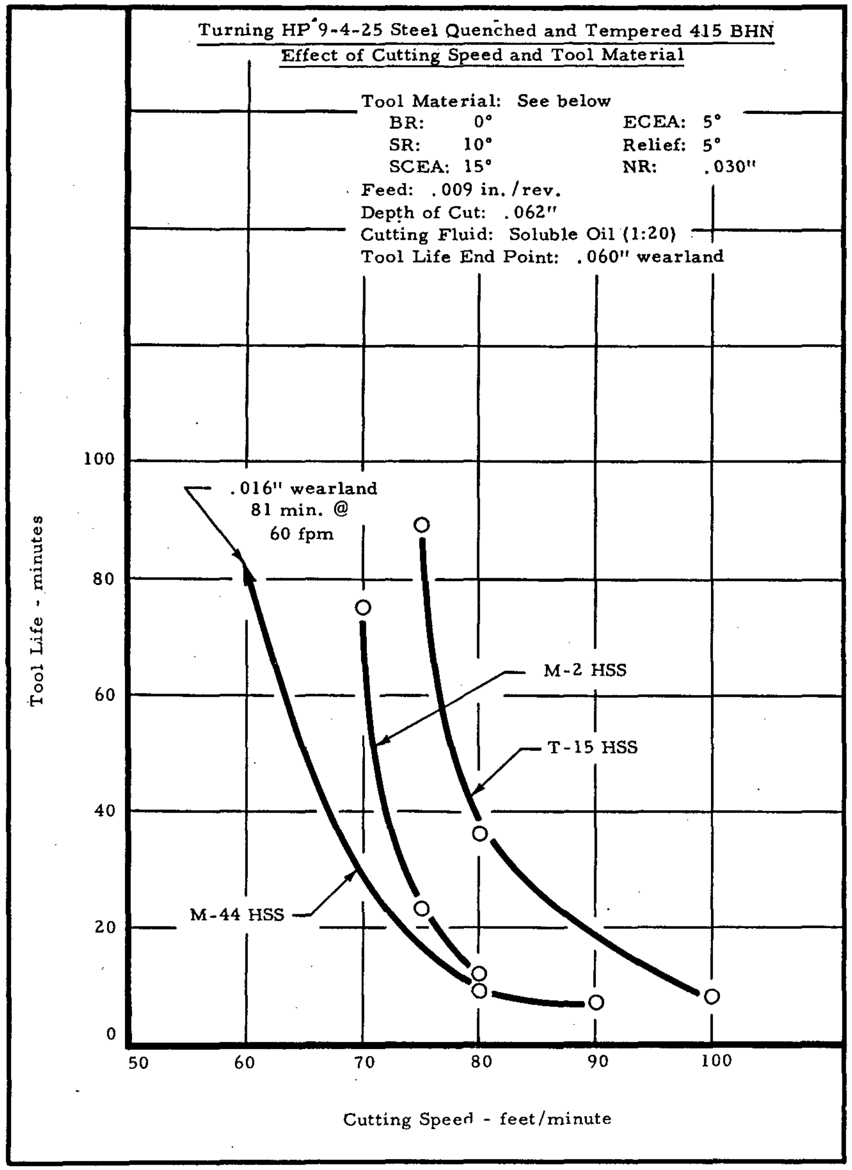
TABLE 9 (continued)

RECOMMENDED CONDITIONS FOR MACHINING

HP 9-4-25 STEEL - QUENCHED AND TEMPERED 415 - 444 BHN

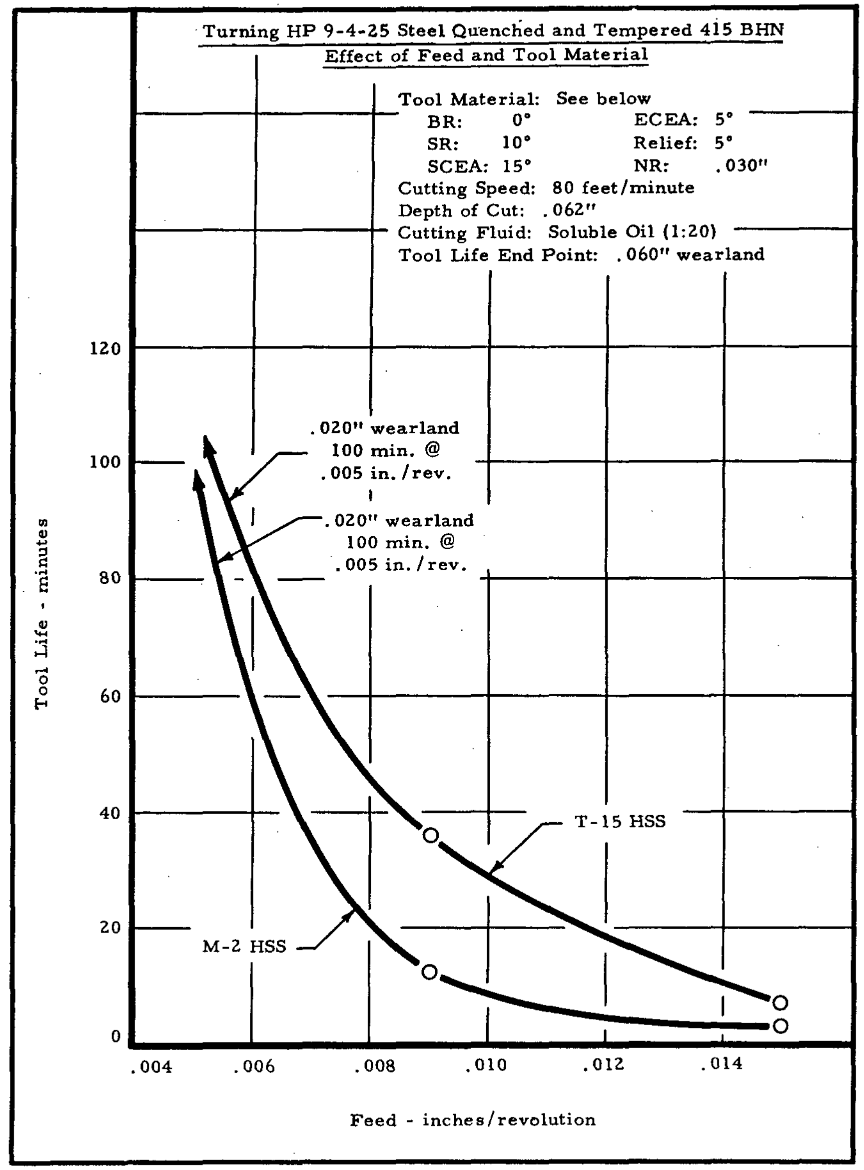
SURFACE GRINDING

Operation	Wheel Grade	Grinding Fluid	Wheel Speed Ft./Min.	Table Speed Ft./Min.	Down Feed In./Pass.	Cross Feed In./Pass.	G Ratio
Finishing	32A46H8VBE	Highly Sulphurized Oil	4000	60	.0005	.050	5
Roughing	32A46K8VBE	Highly Sulphurized Oil or Soluble Oil (1:20)	6000	60	.002	.050	15



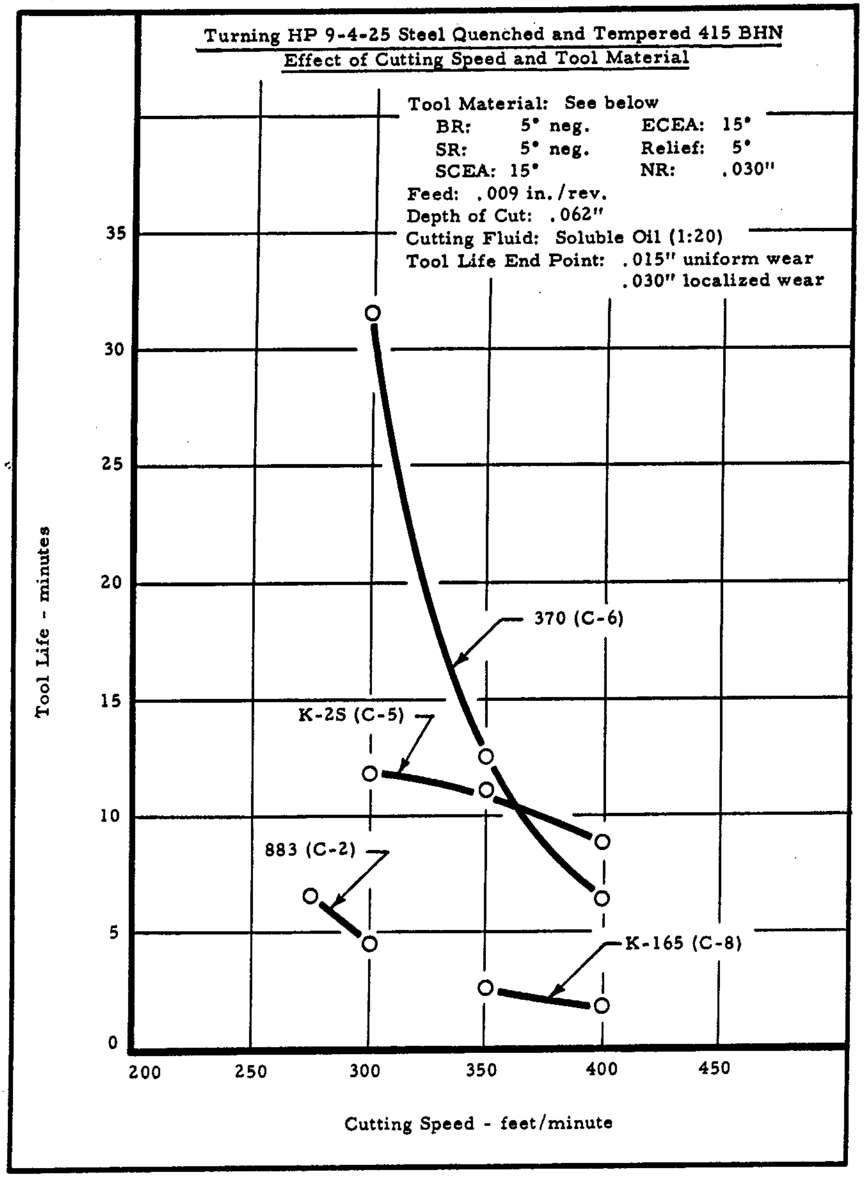
See Text, page 135

Figure 156



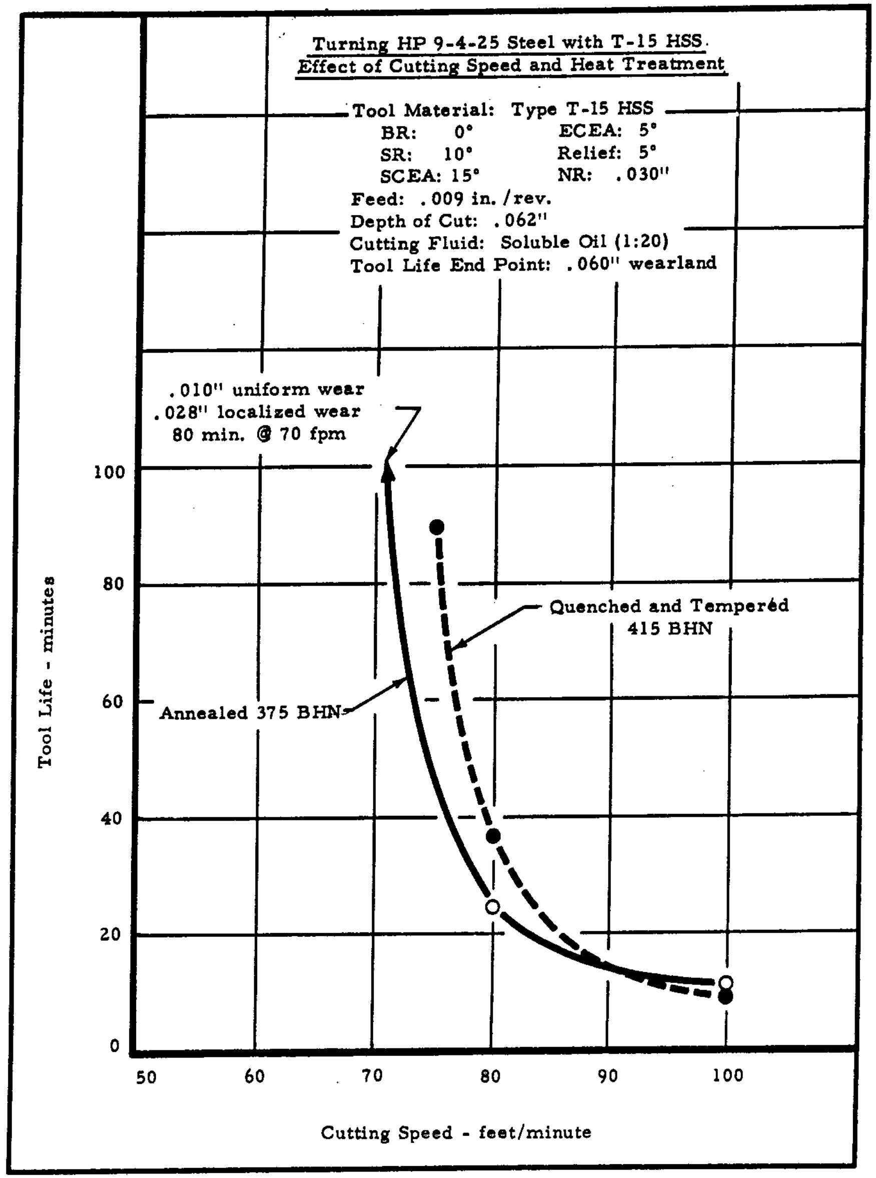
See Text, page 135

Figure 157



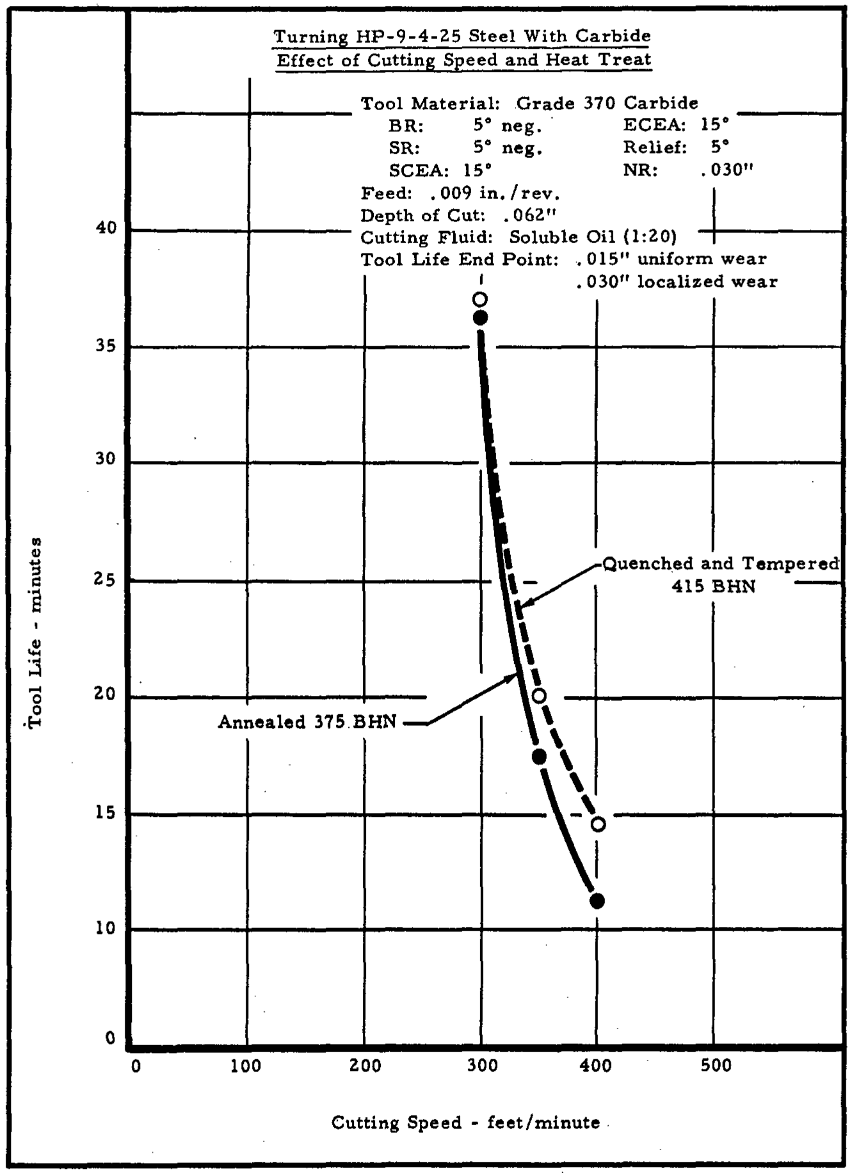
See Text, page 135

Figure 158



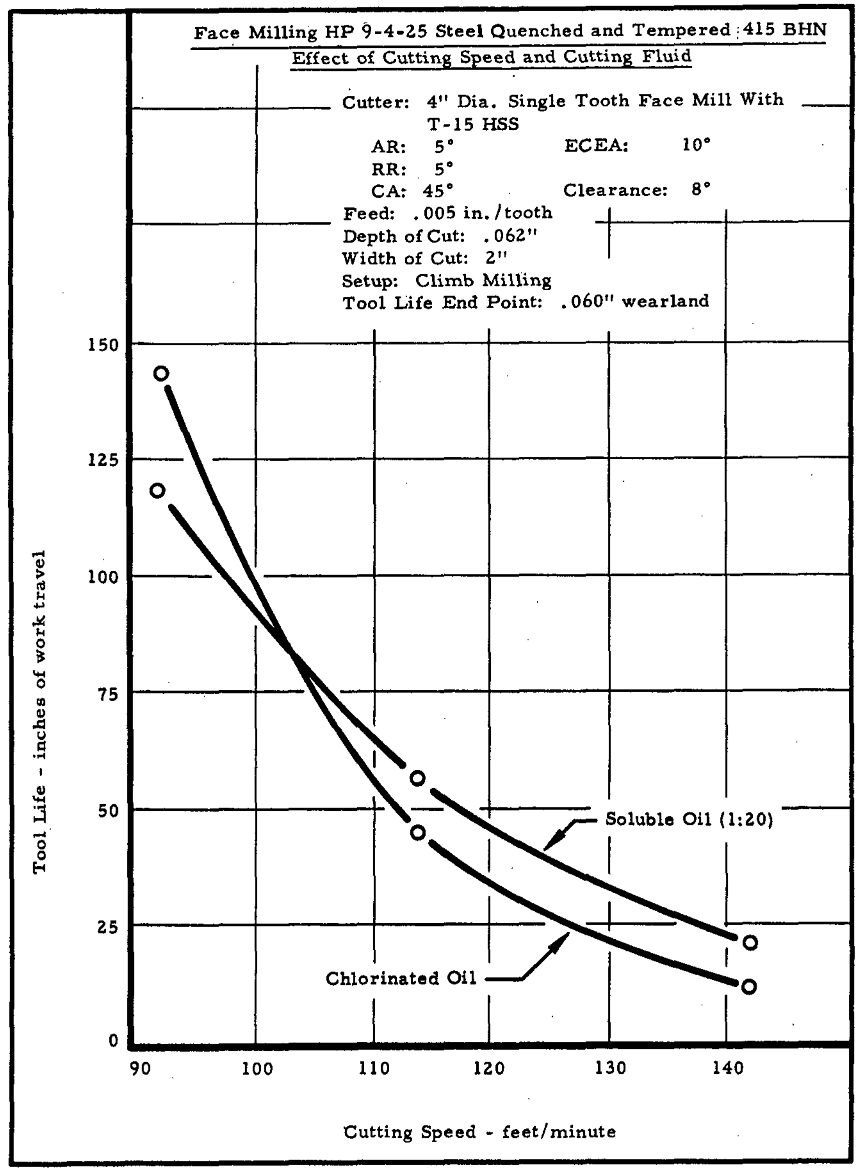
See Text, page 135

Figure 159



See Text, page 135

Figure 160



See text, page 135

Figure 161

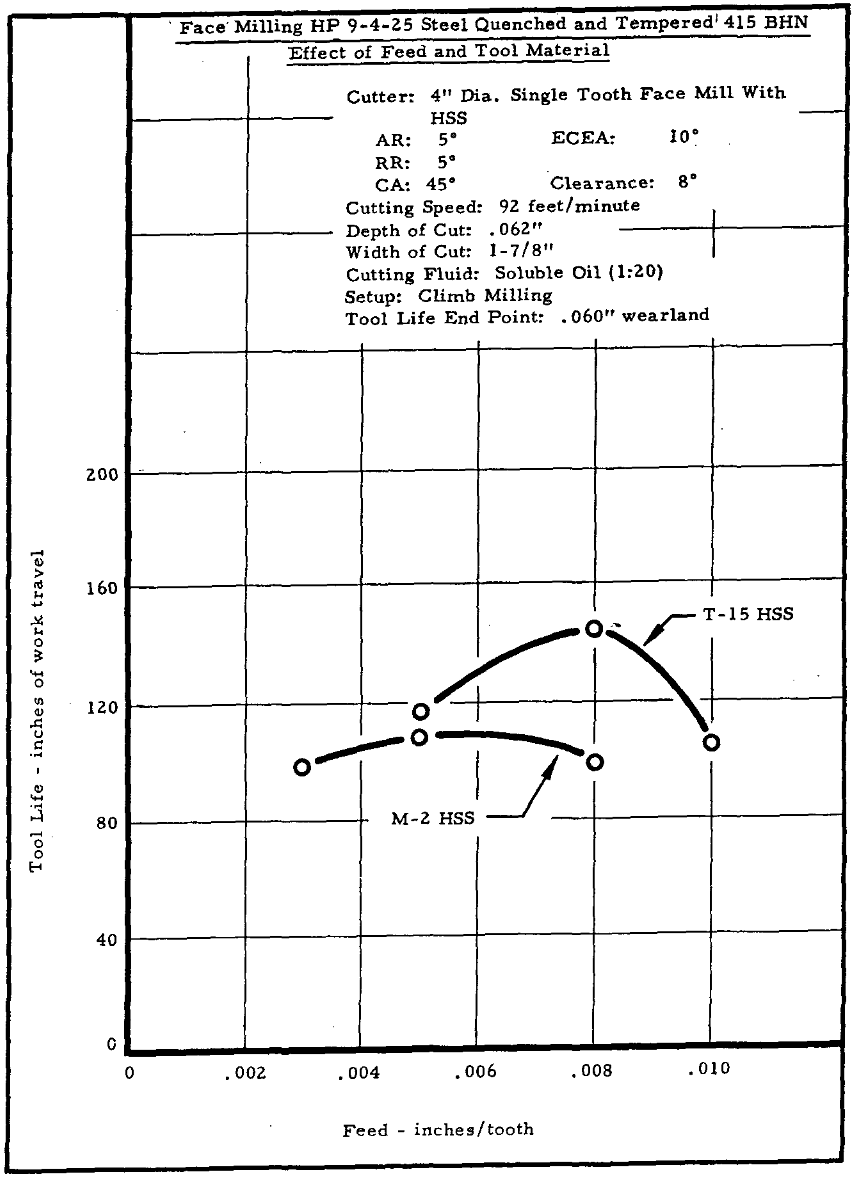


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Figure 162

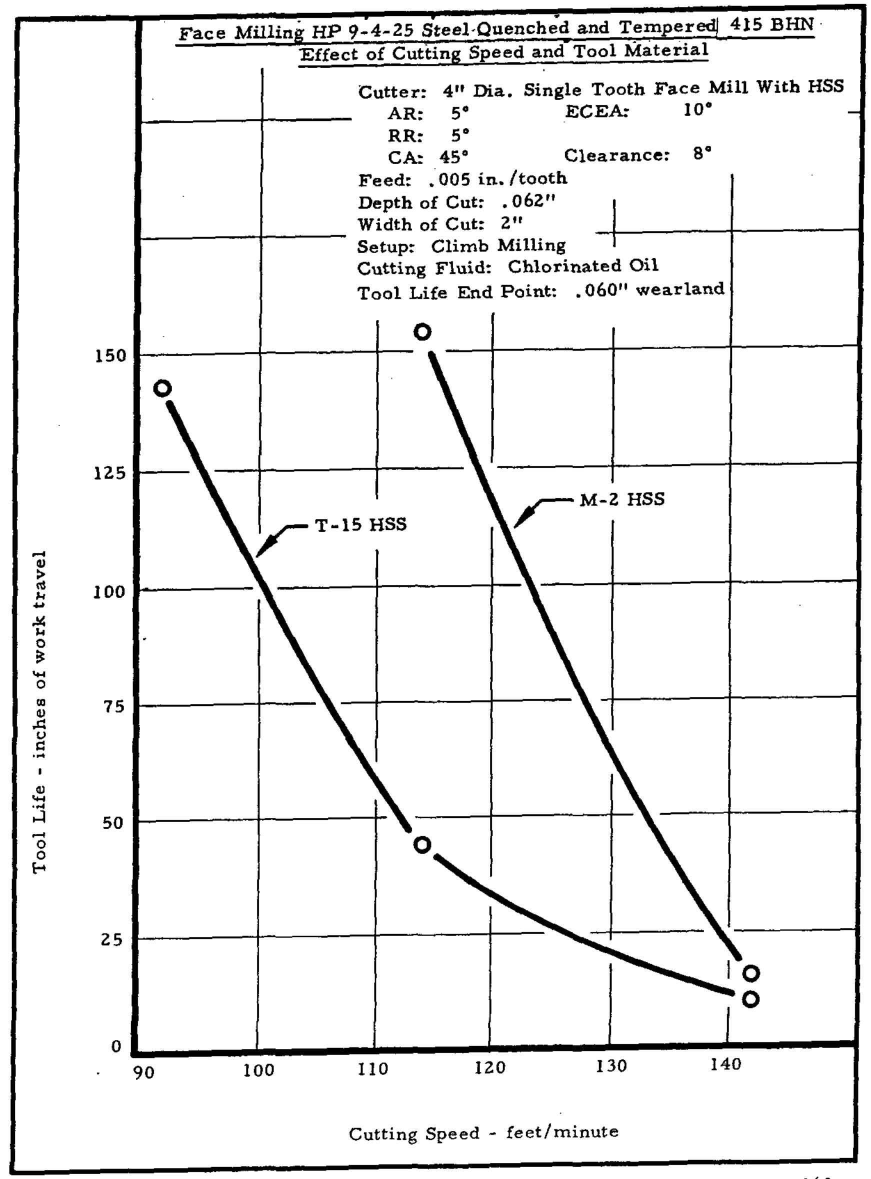

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Figure 163

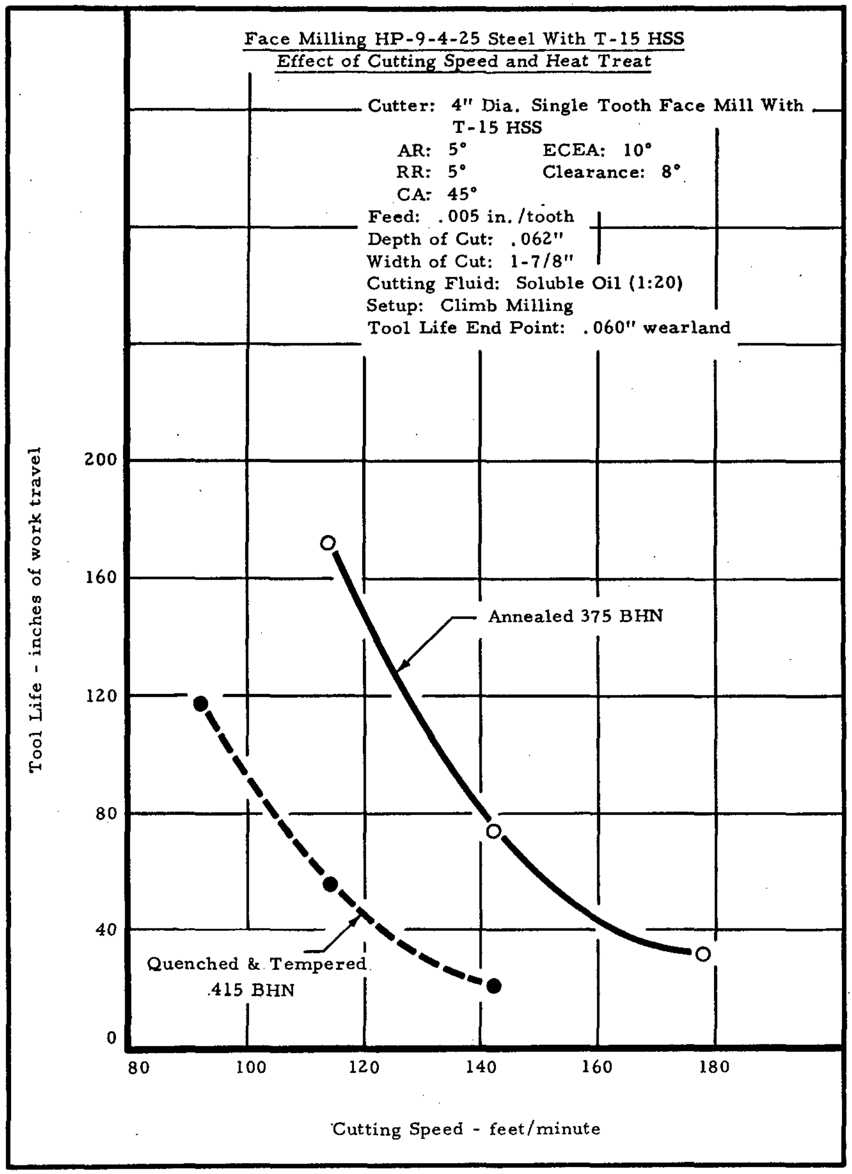

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Figure 164

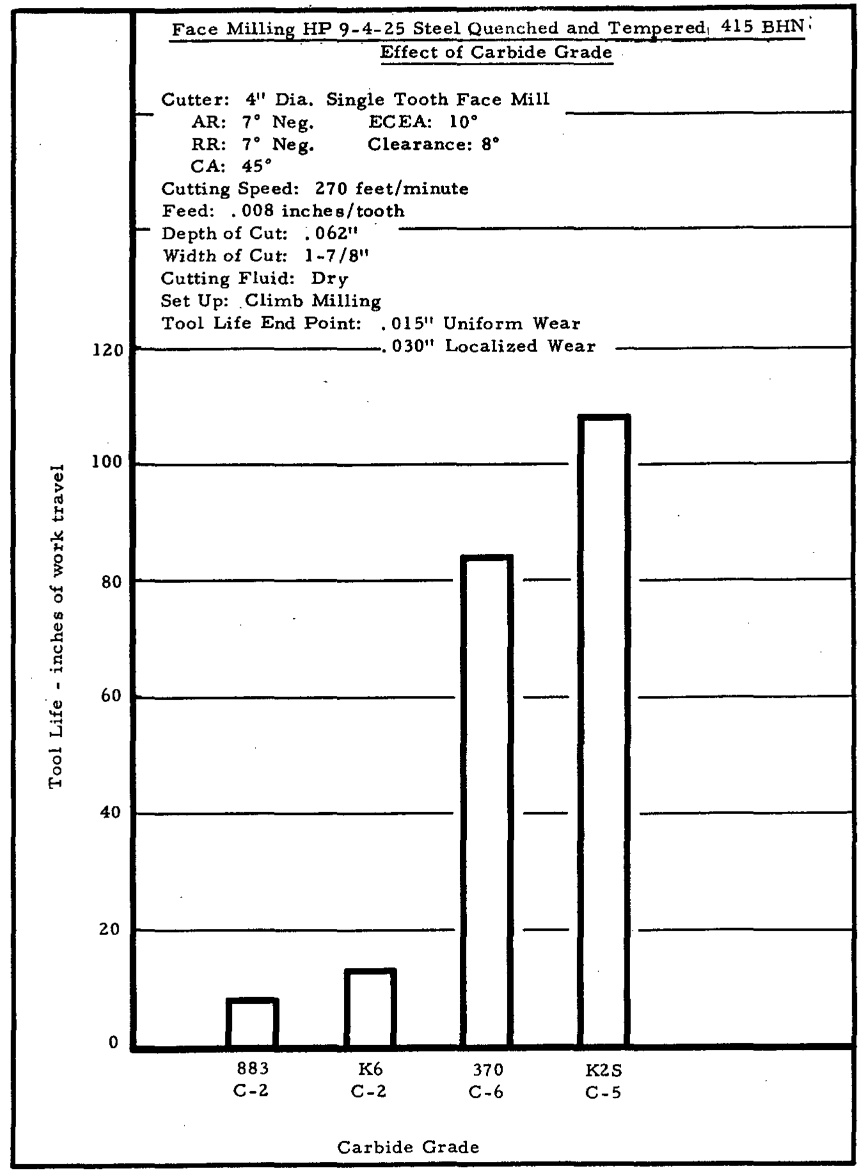

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Figure 165

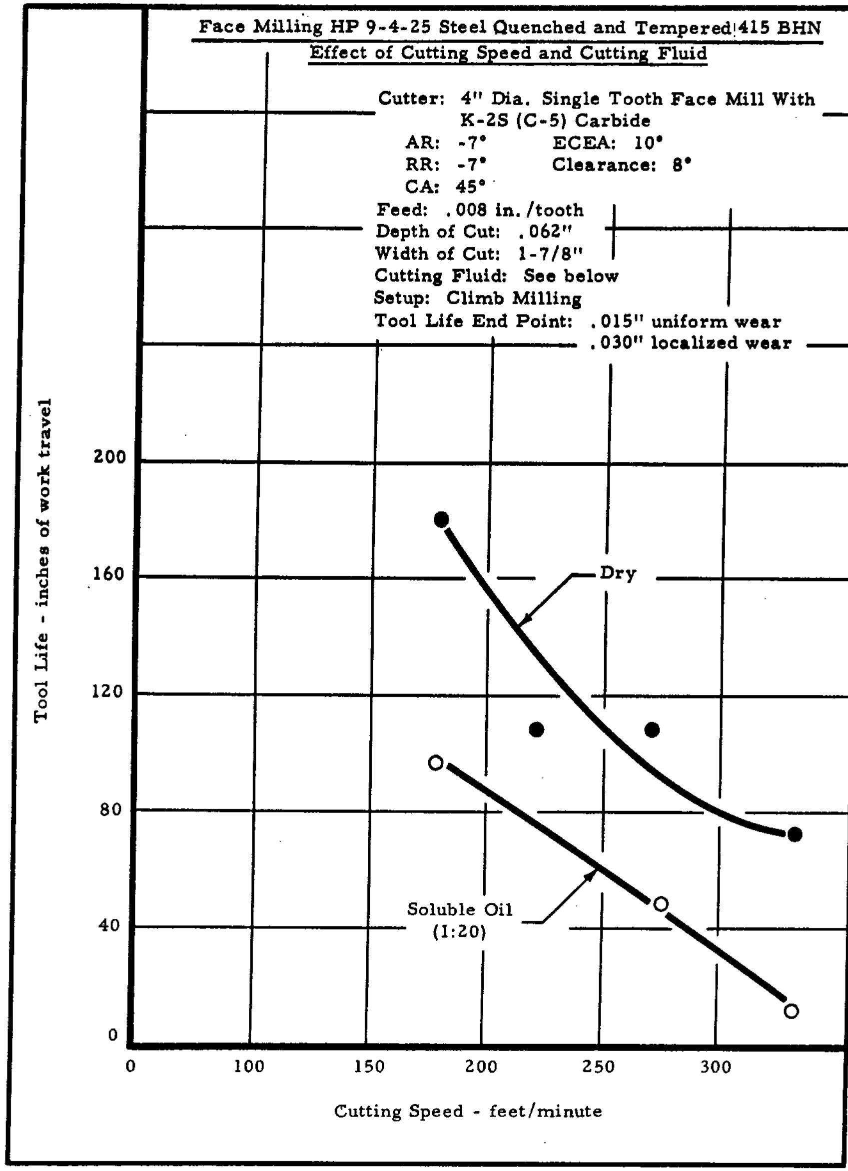

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Figure 166

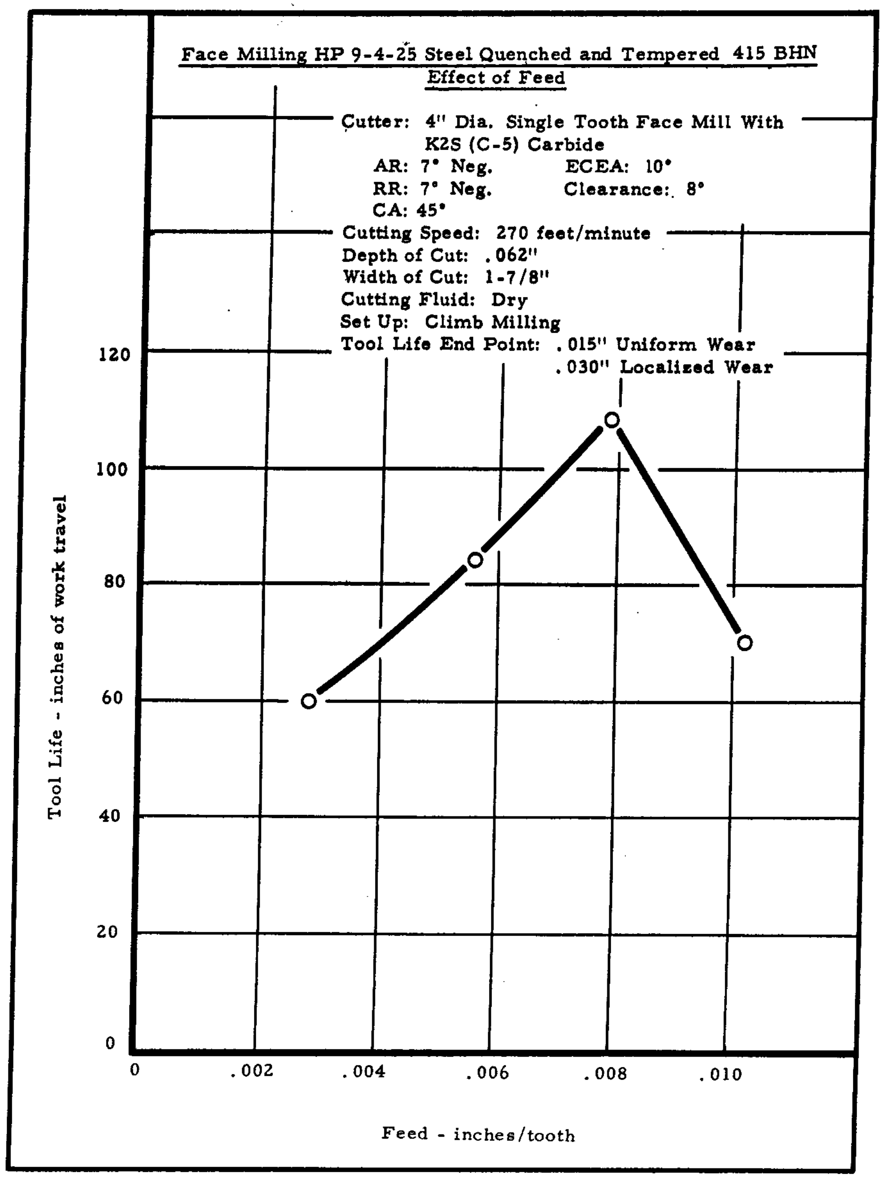

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Figure 167

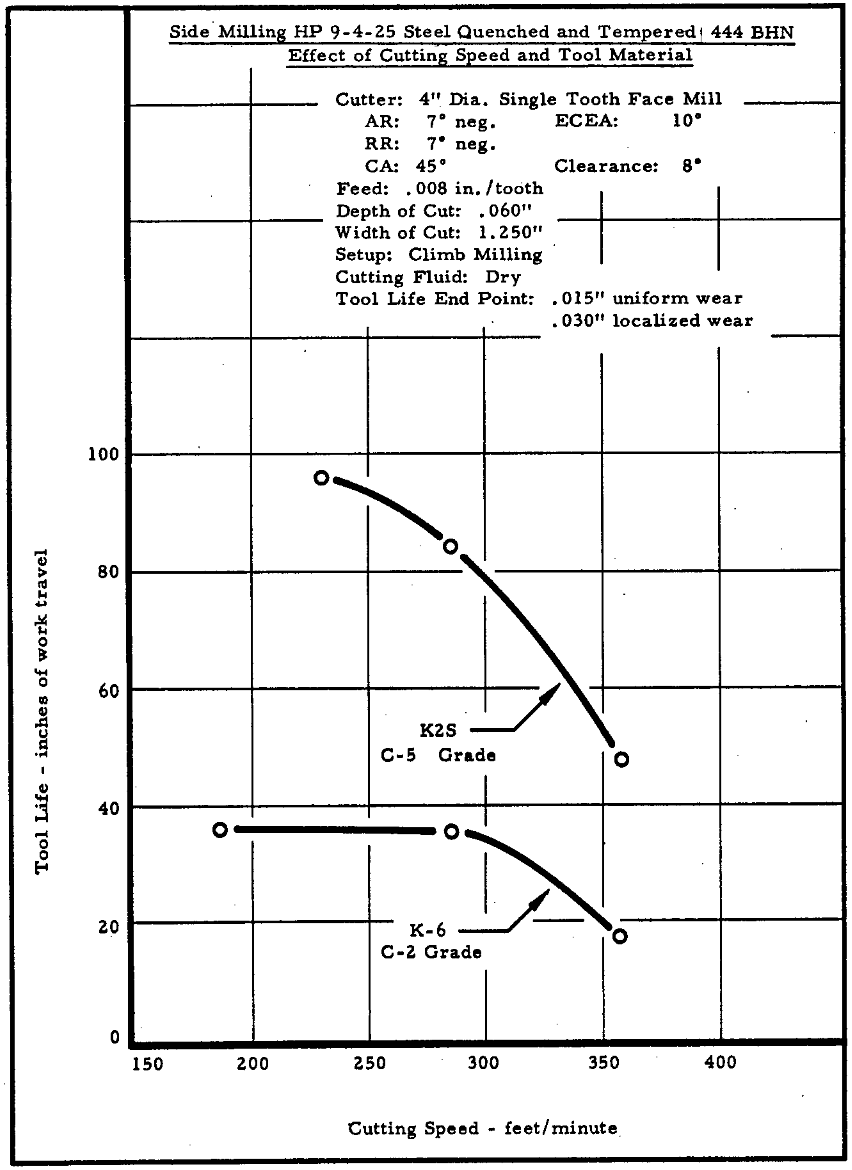

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Figure 168

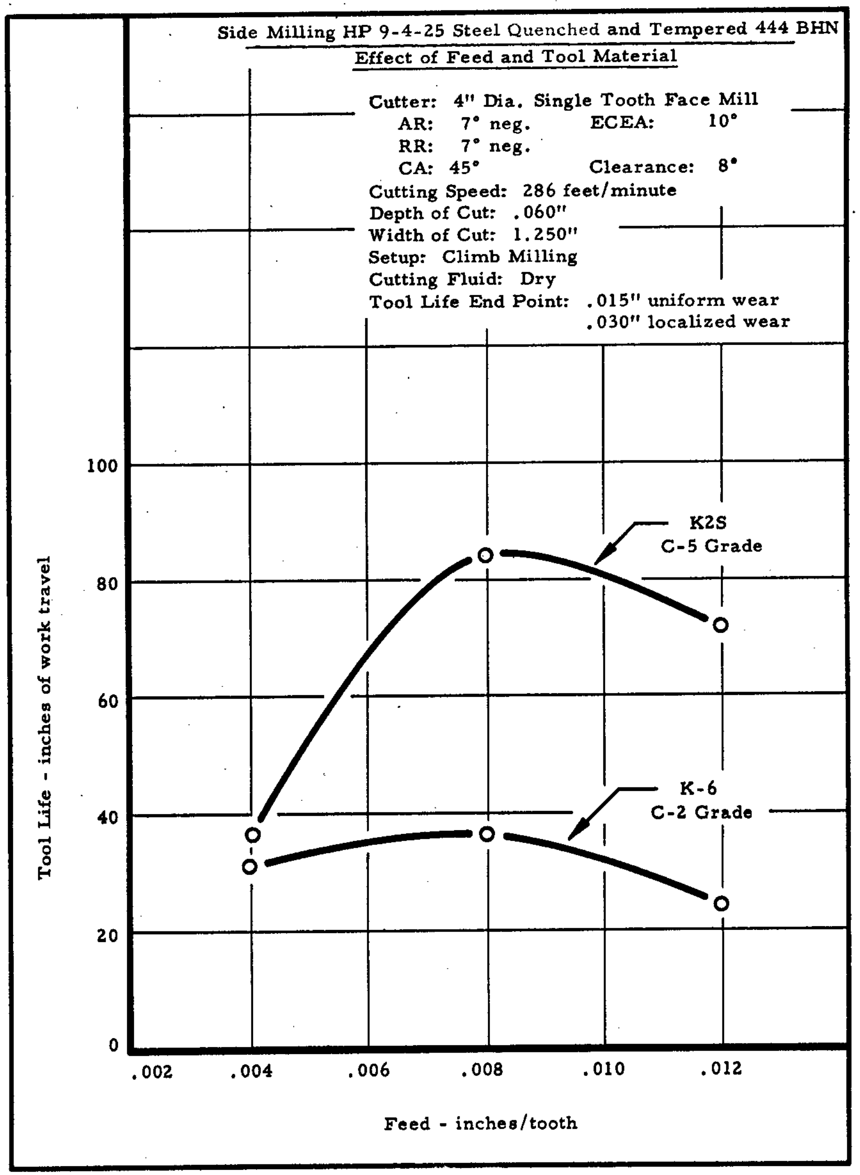

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Figure 169

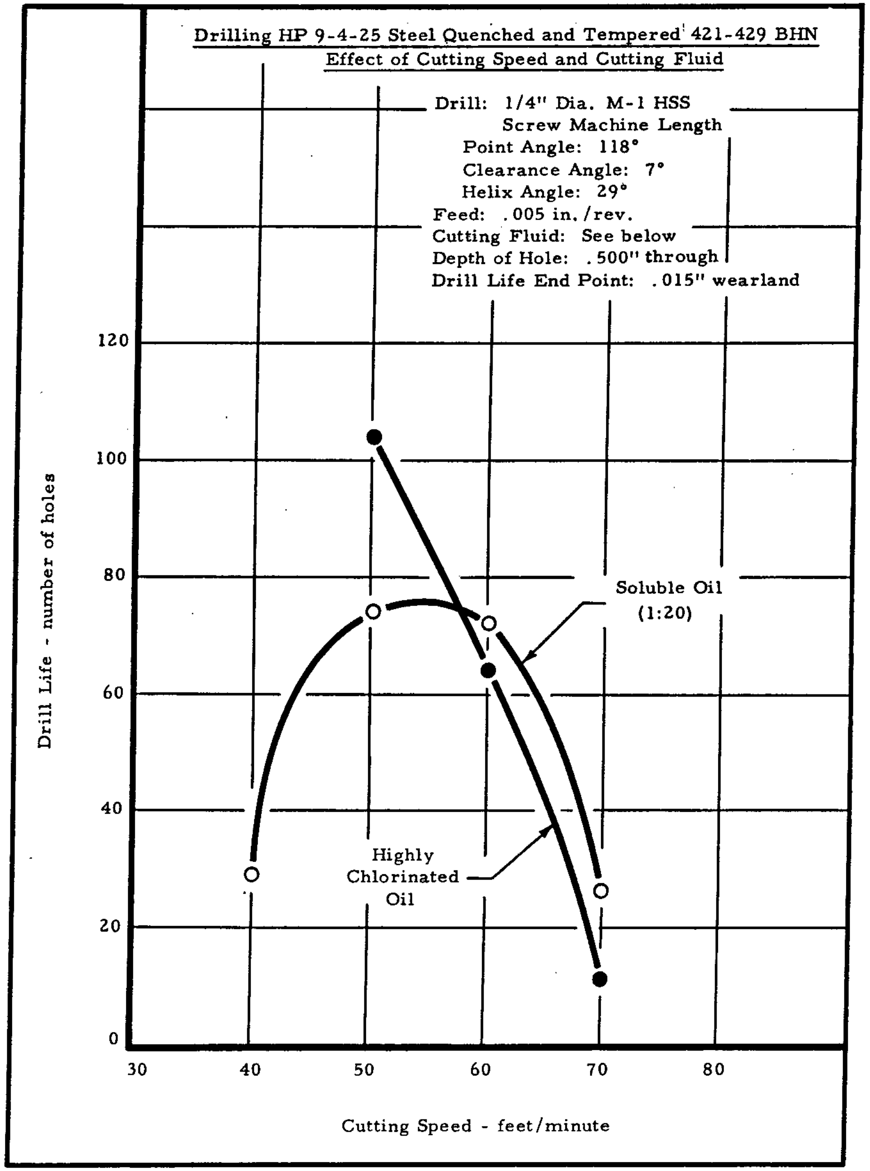

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Figure 170

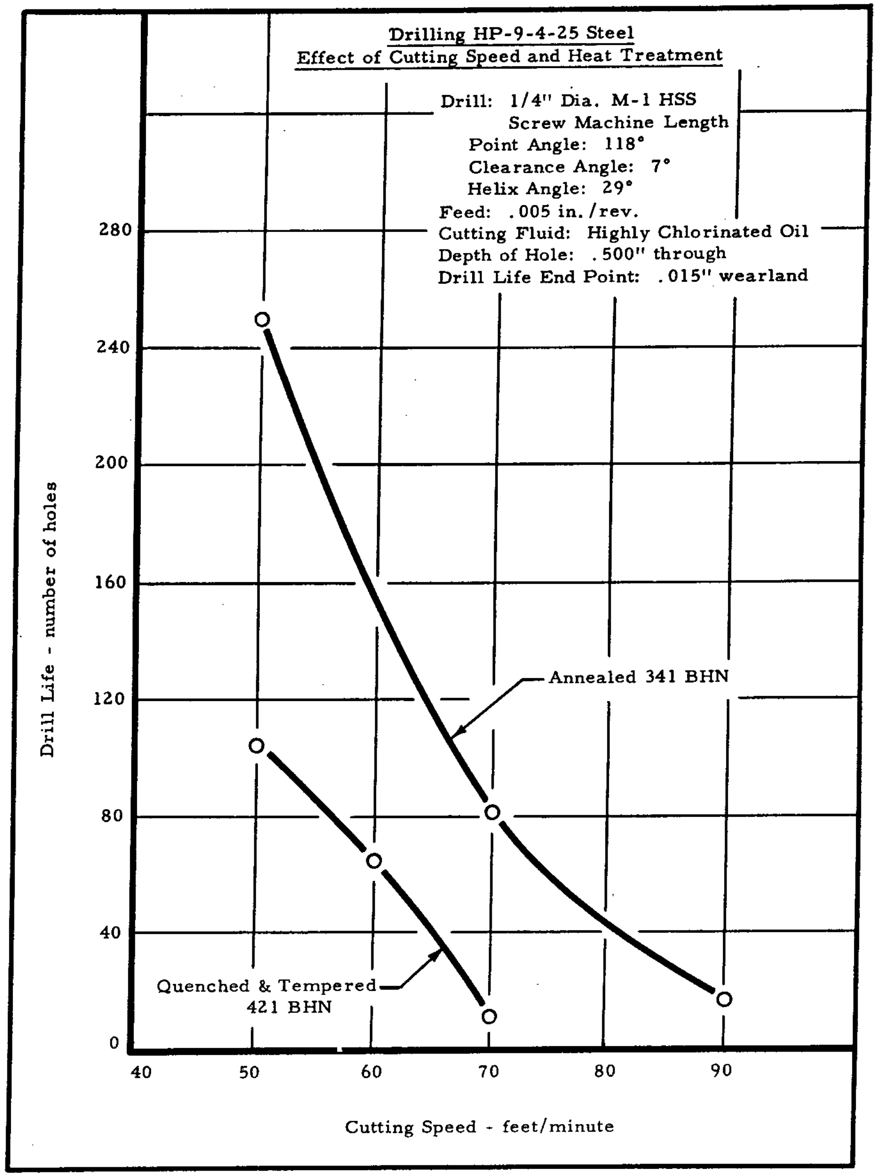

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Figure 171

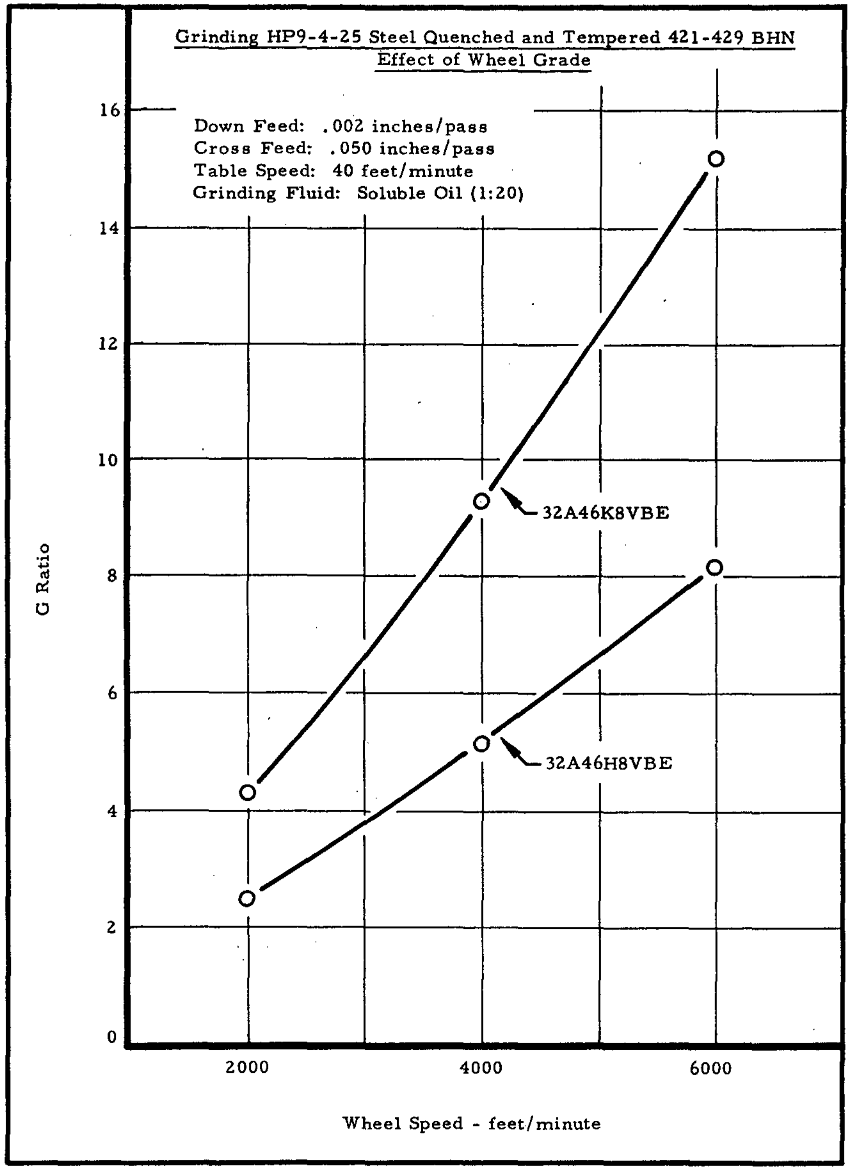

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Figure 172

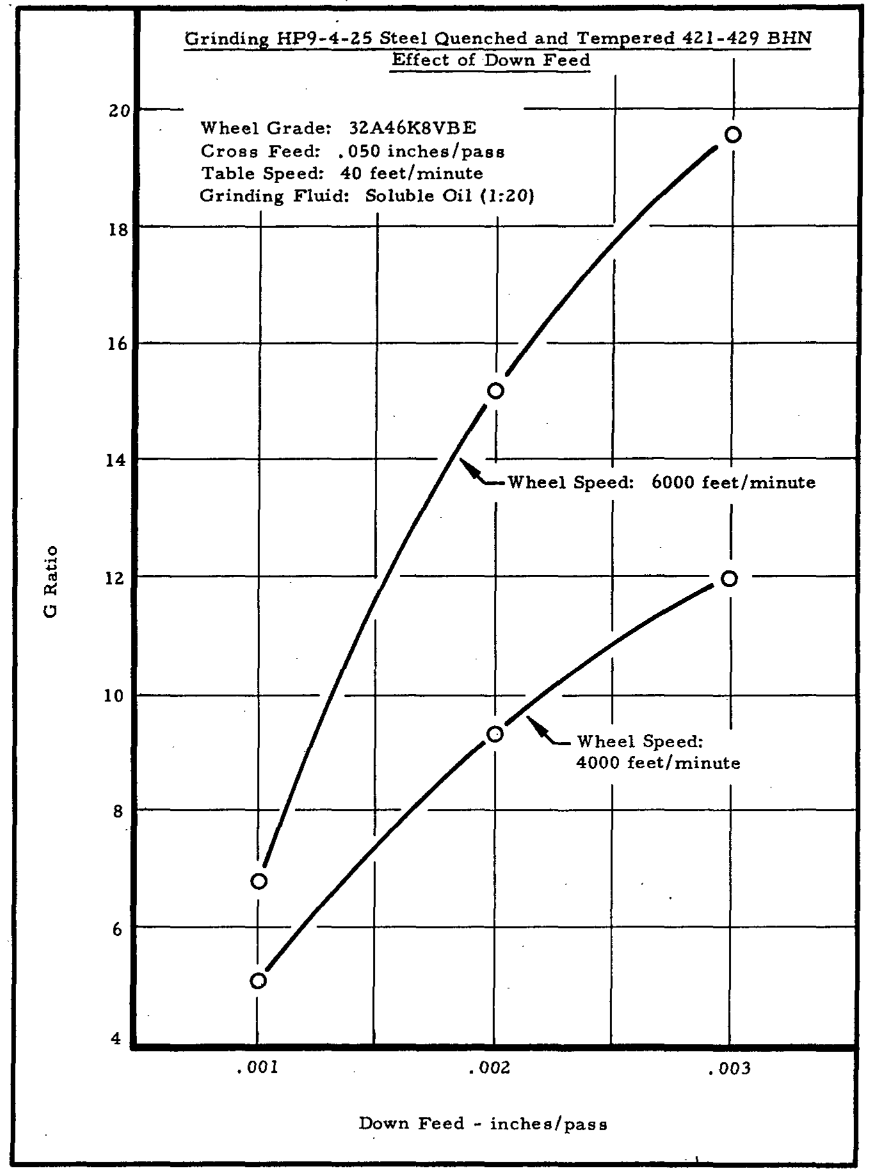

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Figure 173

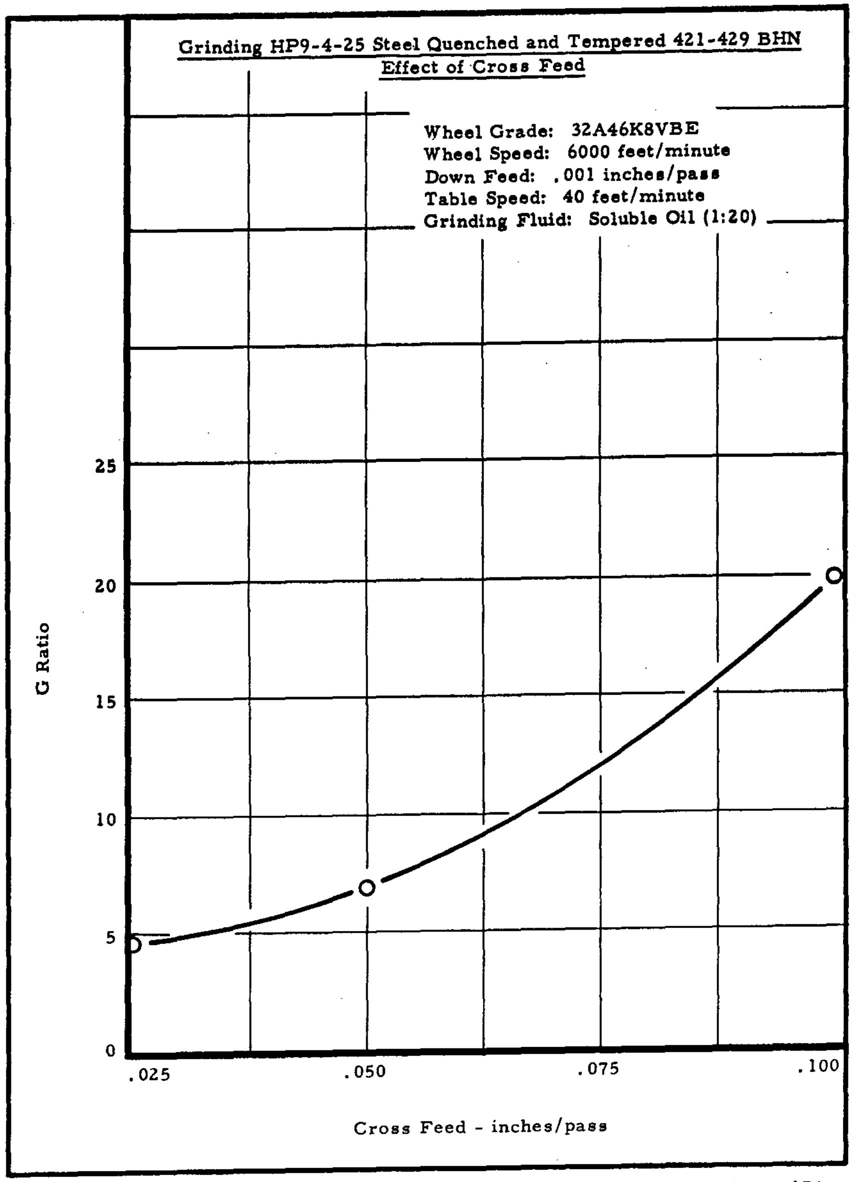

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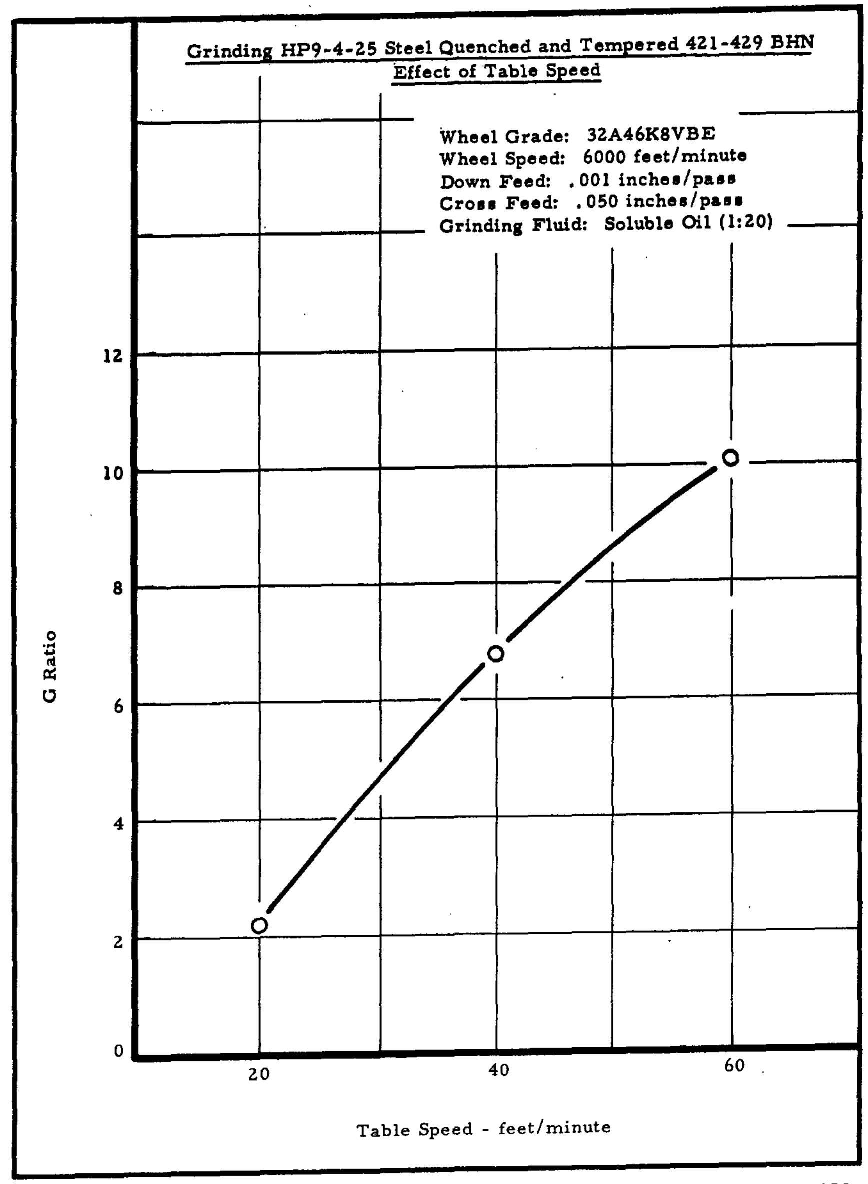
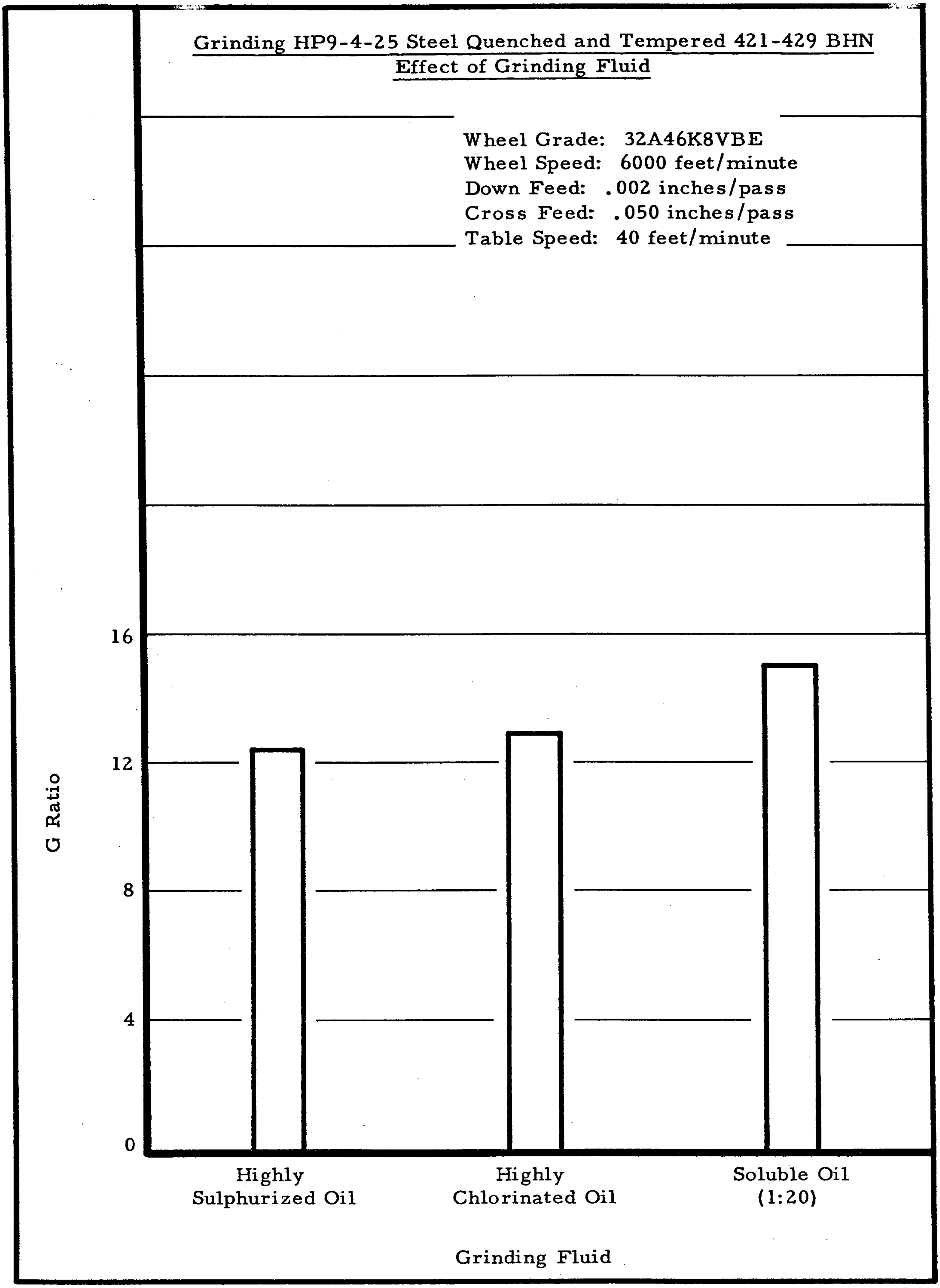
Figure 174



See text, page 137

Figure 175



See text, page 137 Figure 176

3.6 17-4 PH Stainless Steel

Alloy Identification

17-4 PH is a high strength precipitation-hardenable stainless steel having the following nominal composition:

Fe - 15.9 Cr - 4.3 Ni - 3.4 Cu - .69 Mn - .04 C - .2 Cb - .02 Ta

This alloy is normally martensitic and can be further strengthened by subjecting it to an age hardening treatment.

The material for milling tests was procured as 2" x 4" bar stock in the hot rolled, solution treated condition. The material for drilling tests was obtained by sectioning 1/2" thick plates from the 2" x 4" bar stock. The solution treatment performed at the mill was as follows:

1900° F/one-half hour/air cool

The material exhibited a hardness of 352 BHN in this condition. The microstructure, which is illustrated below, consists of coarse equiaxed martensite.

17-4 PH Stainless Steel, Solution Treated

Etchant: Kalling's | Mag: 500X

3.6 17-4 PH Stainless Steel (continued)

End Mill Slotting (Solution Treated 352 BHN)

The relationship between cutting speed and tool life for two different cutting fluids in end mill slotting 17-4 PH stainless steel in the solution treated condition is shown in Figure 177, page 155. The highly sulfurized oil proved to be much more effective than the soluble oil. For example, at a cutting speed of 81 ft./min. the tool life with the highly sulfurized oil was 310 inches of work travel as compared to 120 inches of work travel with the soluble oil.

While increasing the feed resulted in a decrease in tool life, the decrease was only moderate, as shown in Figure 178, page 155. Hence, it would be well to use a feed of .002 to .003 in./tooth at a cutting speed which would provide a satisfactory tool life. The principal concern at the higher feeds would be deflection of the cutter.

Drilling (Solution Treated 352 BHN)

The tool life curve in Figure 179, page 156, indicates that a cutting speed of about 75 ft./min. would be satisfactory for drilling the 17-4 PH stainless steel in the solution treated condition. At this speed over 200 holes were drilled with an M-1 HSS drill using a feed of .005 in./rev.

Note the curve in Figure 180, page 156, showing that at a cutting speed of 75 ft./min. the tool life decreased rapidly when the feed was increased from .005 to .009 in./rev. It should also be pointed out that at the higher cutting speed of 85 ft./min. a maximum was reached at a feed of .005 in./rev.

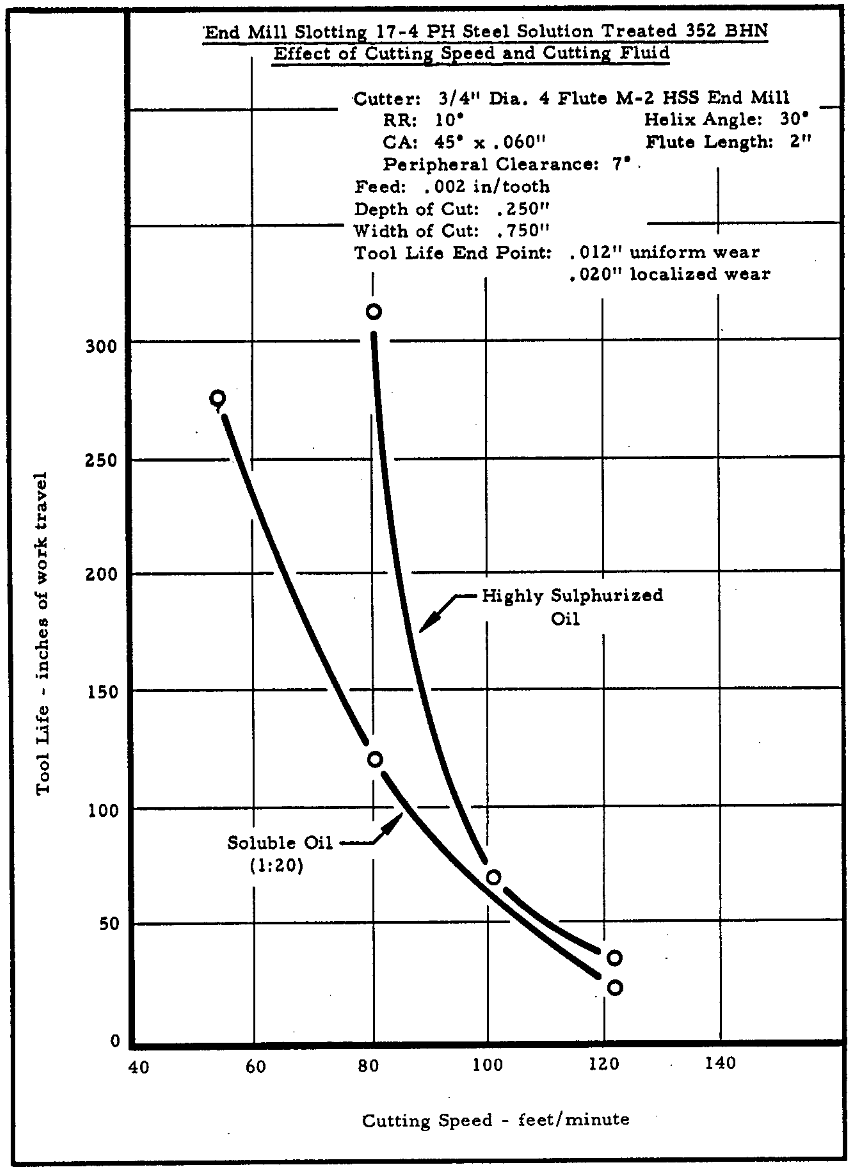
TABLE 10

RECOMMENDED CONDITIONS FOR MACHINING

17-4 PH STEEL - SOLUTION TREATED - 352 BHN

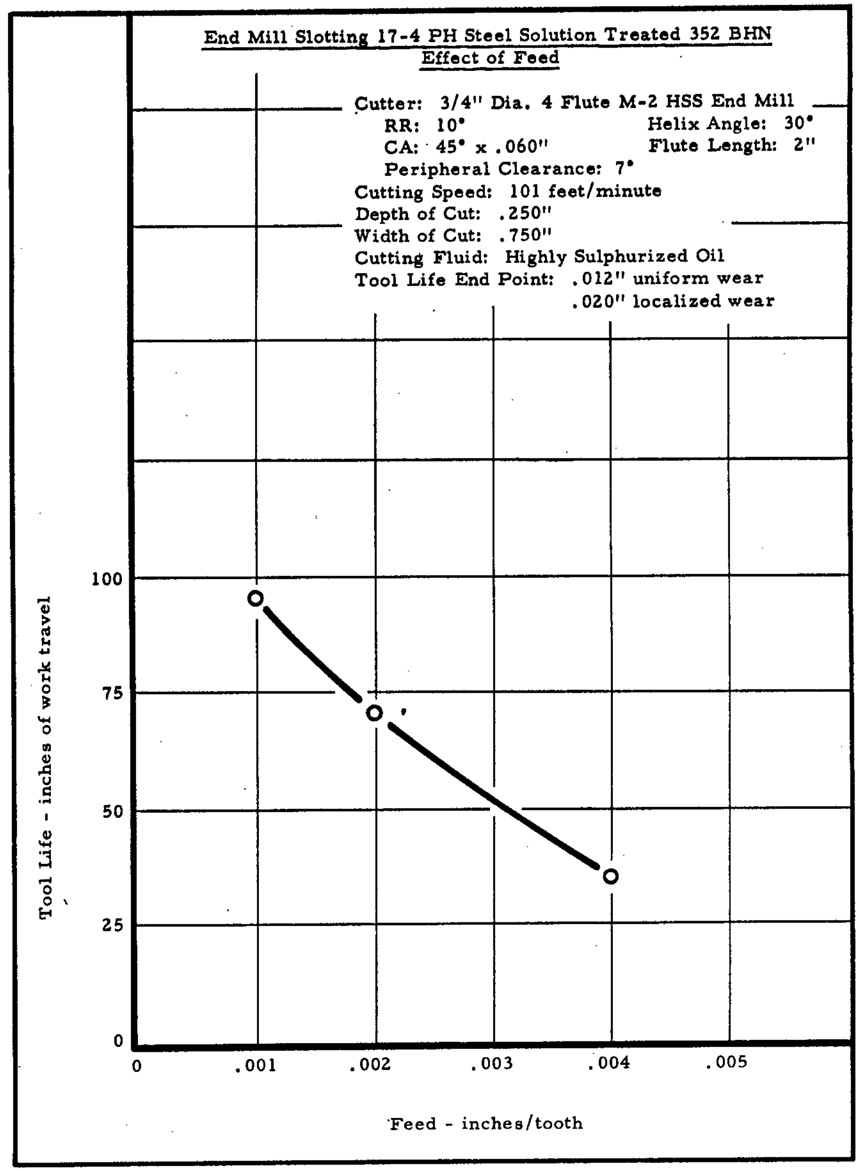
Cr	Ni	Cu	Mn	C	Cb	Ta	Fe
15.9	4.3	3.4	.69	.04	.2	.02	Bal

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	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.002 in/tooth	80	310" work travel	.012	Highly Sulphurized Oil
Drilling	M-1 HSS	118° plain point 7° clearance angle	1/4" diameter HSS drill 2 1/2" long	.500 thru	-	.005 in/rev	75	210 holes	.015	Highly Chlorinated Oil



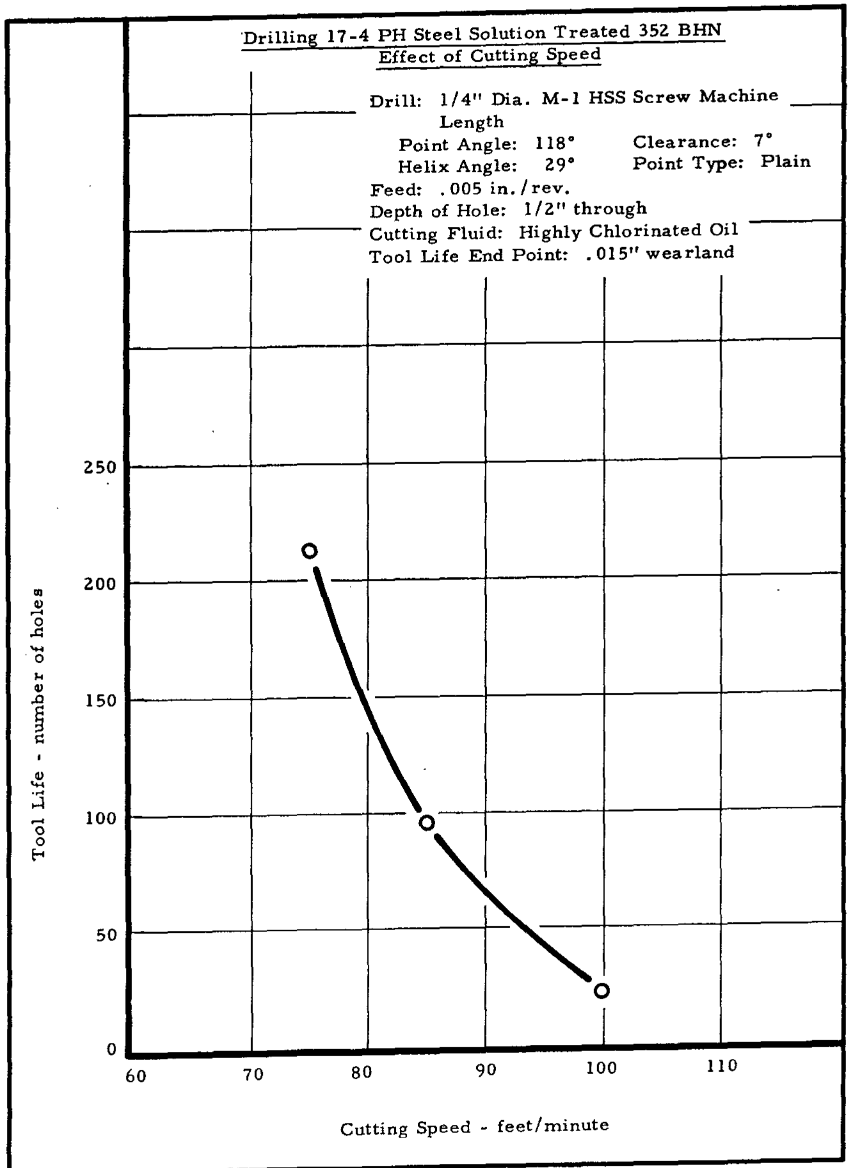
See text, page 153

Figure 177



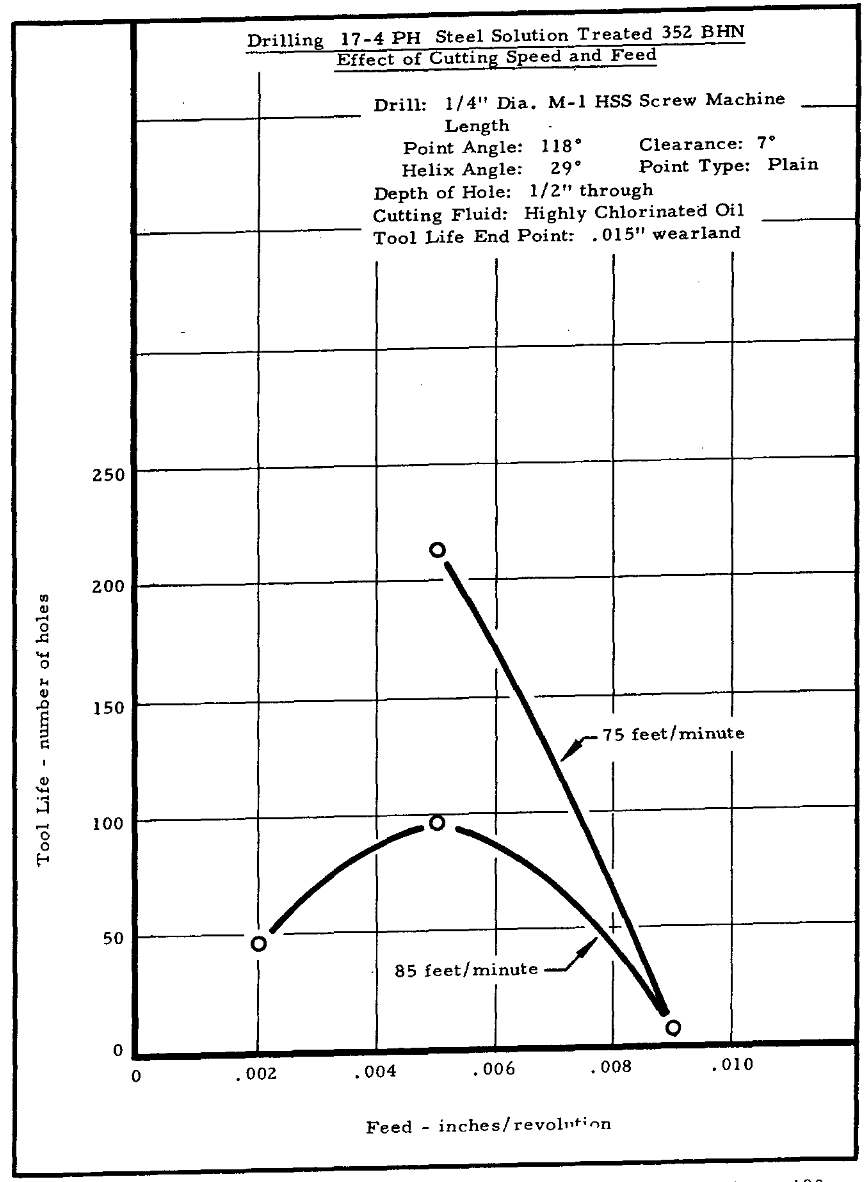
See text, page 153

Figure 178



See text, page 153

Figure 179



See text, page 153

Figure 180

4. MACHINING TITANIUM ALLOYS

4.1 Titanium 8Al-1Mo-1V

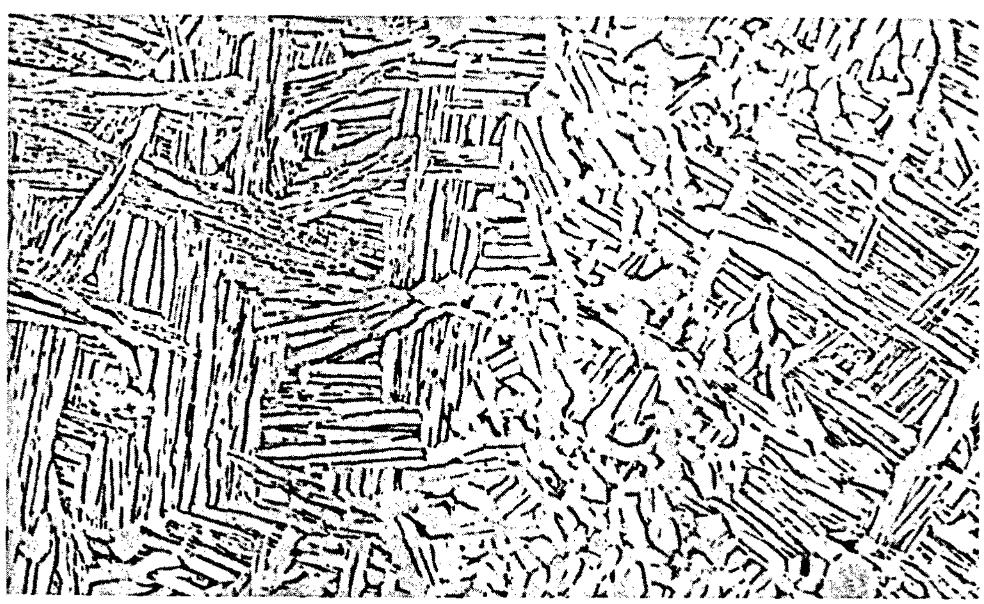
Alloy Identification

Ti-8Al-1Mo-1V is an alpha titanium base alloy which exhibits high strength at elevated temperatures. The nominal composition of this alloy is as follows:

Ti - 8 Al - 1 Mo - 1V - .024 C - .08 Fe

The material for turning tests was procured as forged, mill annealed 3" diameter bars. It exhibited a hardness of 311 BHN. The material for milling, drilling, etc. was procured as rectangular bars 2" x 4" x 12" at an annealed hardness of 302 BHN.

The microstructure of the alloy in the annealed condition is illustrated below. It consists of alpha platelets formed within beta grains resulting in a basket weave structure.



Ti-8Al-1Mo-1V, Annealed

Etchant: HF, 2% Mag: 500X

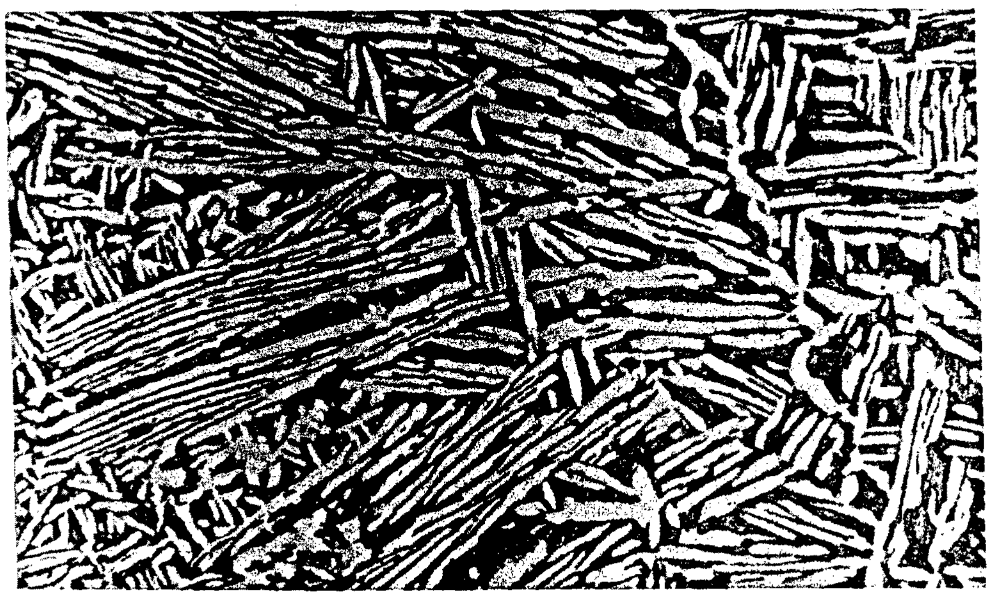
In order to compare the aged to the mill annealed condition, some previously annealed bars of both types were aged as follows:

1850F/1 hour/furnace cool to 1100F. Hold at 1100F until total aging time equals 8 hours/air cool.

4.1 Titanium 8Al-1Mo-1V (continued)

The aging treatment yielded a hardness of 341 BHN on the round bars used for turning tests. On aging the rectangular stock, the hardness remained unchanged at 302 BHN.

The microstructure of the aged material, apparently identical in both cases, is illustrated below. This treatment caused acicular alpha to precipitate from the beta phase.



Ti-8Al-1Mo-1V Aged

Etchant: HF, 2% Mag: 500X

Turning (Annealed 311 BHN)

The results of turning tests with both high speed steel and carbide tools on the titanium alloy 8Al-1Mo-1V in the annealed condition are shown in Figures 181 through 184, pages 164 and 165. While the tool life curves in Figure 181, page 164, show that the cutting speeds were appreciably higher with a feed of .005 in./rev. as compared with a feed of .009 in./rev. using high speed steel tools, the advantage of the higher feed still prevails. For example, for a tool life of 60 minutes and a feed of .009 in./rev., the cutting speed would be about 25% lower than that used with a feed of .005 in./rev.; however, the feed rate is 80% faster at the feed of .009 in./rev. Hence, the production rate which depends on both the cutting speed and feed is greater for the higher feed.

4.1 Titanium 8Al-1Mo-1V (continued)

The results obtained with high speed steel tools shown in Figure 182, page 164, indicate that a 15% increase in cutting speed was obtained by using soluble oil instead of the highly sulfurized oil. No difference was found between the two cutting fluids when using carbide tools, see Figure 183, page 165.

As shown in Figure 184, page 165, there was an even greater difference between the feeds of .005 and .009 in./rev. with carbide tools. The use of the heavier feed produced more chipping on the cutting edge of the tool and thus shorter tool life. As a result, the cutting speed with the lower feed (.005 in./rev.) was 200% faster than that used at the feed of .009 in./rev. for an equivalent tool life. Thus, this great difference in the cutting speeds more than offsets the advantage of the higher feed rate in turning with carbide tools.

Face Milling (Annealed 302 BHN)

The results shown in Figure 185, page 166, indicate that a highly chlorinated oil was no more effective than machining dry in face milling with carbide the surface or skin on the wrought bars of titanium 8Al-1Mo-1V in the annealed condition 302 BHN. However, the feed selection was important. As shown in Figure 186, page 166, at a cutting speed of 270 ft./min. with an 883 grade of carbide, the feed should be between .004 and .006 in./tooth.

Figure 187, page 167, shows a comparison of M-2 and T-15 HSS tools in face milling under the skin. At a cutting speed of 92 ft./min., cutter life was about 30% longer with the type T-15 HSS tool. Also at a cutting speed of 92 ft./min., the highly chlorinated oil provided a 30% longer tool life than the soluble oil using a T-15 HSS cutter, see Figure 188 page 167.

The selection of feed in face milling with high speed steel cutters is somewhat critical. Note in Figure 189, page 168, that with the T-15 cutter, increasing the feed from .005 to .008 in./tooth resulted in decreasing the tool life from 159 inches of work travel to 38 inches.

As shown in Figure 190, page 168, the 883 grade of carbide was the best of the group tested. Figure 191, page 169, presents the relationship between cutting speed and tool life with the 883 carbide in face milling titanium 8Al-1Mo-1V in the annealed condition. A cutting speed of about 400 ft./min. should be used with a carbide cutter in face milling. The tool life curve in Figure 192, page 169, illustrates that the feed is also critical with carbide cutters. Increasing the feed from .003 to .008 in./tooth resulted in the cutter life decreasing from 250 inches of work travel to less than 50 inches.

It is interesting to compare the cutter life obtained in face milling the skin with that obtained under the skin. In Figure 185, page 166, the cutter life on the skin at a feed of .005 in./tooth and a cutting speed of 414 ft./min. was 35 inches; while, with the same machining conditions under the skin, cutter life as shown in Figure 191, page 169, was 140 inches.

Peripheral End Milling (Annealed 302 BHN)

The advantage of climb milling over conventional milling in peripheral end milling titanium 8Al-1Mo-1V annealed 302 BHN is shown in Figure 193, page 170. At a cutting speed of 190 ft./min., the cutter life using climb milling was 110 inches of work travel as compared to only 20 inches with conventional milling.

Soluble oil (1:20) was appreciably better than a highly chlorinated oil in peripheral end milling the alloy. As shown in Figure 194, page 170, the cutter life with the soluble oil was almost twice that obtained with the active oil at a cutting speed of 153 ft./min.

While a comparison of two tool life curves at feeds of .002 in./tooth and .004 in./tooth presented in Figure 195, page 171, appears to indicate a distinct advantage for the lighter feed, this is not the case. For example, for a tool life of 100 inches of work travel, the cutting speed at a feed of .002 in./tooth was only about 20% faster, while the feed rate at .004 in./tooth was 100% greater. Thus, the production rate was appreciably higher at the feed of .004 in./tooth with equivalent tool life.

End Mill Slotting (Annealed 302 BHN)

Figure 196, page 171, illustrates the importance in selecting the proper cutting fluid in end mill slotting titanium 8Al-1Mo-1V in the annealed condition. At a cutting speed of 97 ft./min. with the three cutting fluids; 1) water base synthetic (1:15); 2) soluble oil (1:20); and 3) highly chlorinated oil; the corresponding tool life values were 205, 140 and 62 inches of work travel.

4.1 Titanium 8Al-1Mo-1V (continued)

Drilling (Annealed 302 BHN)

The tool life curve in Figure 197, page 172, shows the relationship between cutting speed and drill life using a type M-1 HSS screw machine drill with a plain point. A cutting speed of about 35 ft./min. should be used for a reasonable drill life with this type of drill. Under the same machining conditions, a type T-15 drill with a split point, a cutting speed of 45 ft./min. and a feed of .005 in./rev. could be used for a reasonable drill life, see Figure 198, page 172.

In this same Figure 198, page 172, a comparison was made of the tool life results obtained at two different feeds. Note that even though the cutting speed with the feed of .002 in/rev. was about 75% faster than with the feed of .005 in./rev. for a given tool life, the production rate was still greater with the .005 in./rev. feed because this feed rate was 250% higher.

Figure 199, page 173, indicates that the cutting speed with the Ti-Kut oil was about 10% faster than with the highly chlorinated oil using a type T-15 HSS drill with a split point.

Reaming (Annealed 302 BHN)

Three cutting fluids were compared in reaming titanium 8Al-1Mo-1V in the annealed condition. The results are shown in Figure 200, page 173. The highly chlorinated oil permitted a 15% increase in cutting speed for a given number of holes over the Ti-Kut oil and the soluble oil.

Tapping (Annealed 302 BHN)

Tool life curves showing the relationship between cutting speed and tap life for several cutting fluids are shown in Figure 201, page 174. The highly sulfurized oil proved to be more effective at the lower cutting speeds (less than 17.5 ft./min.). The Ti-Kut oil was least effective of the three fluids used.

TABLE 11

RECOMMENDED CONDITIONS FOR MACHINING

TITANIUM 8 Al - 1 Mo - 1 V - ANNEALED 302 - 311 BHN

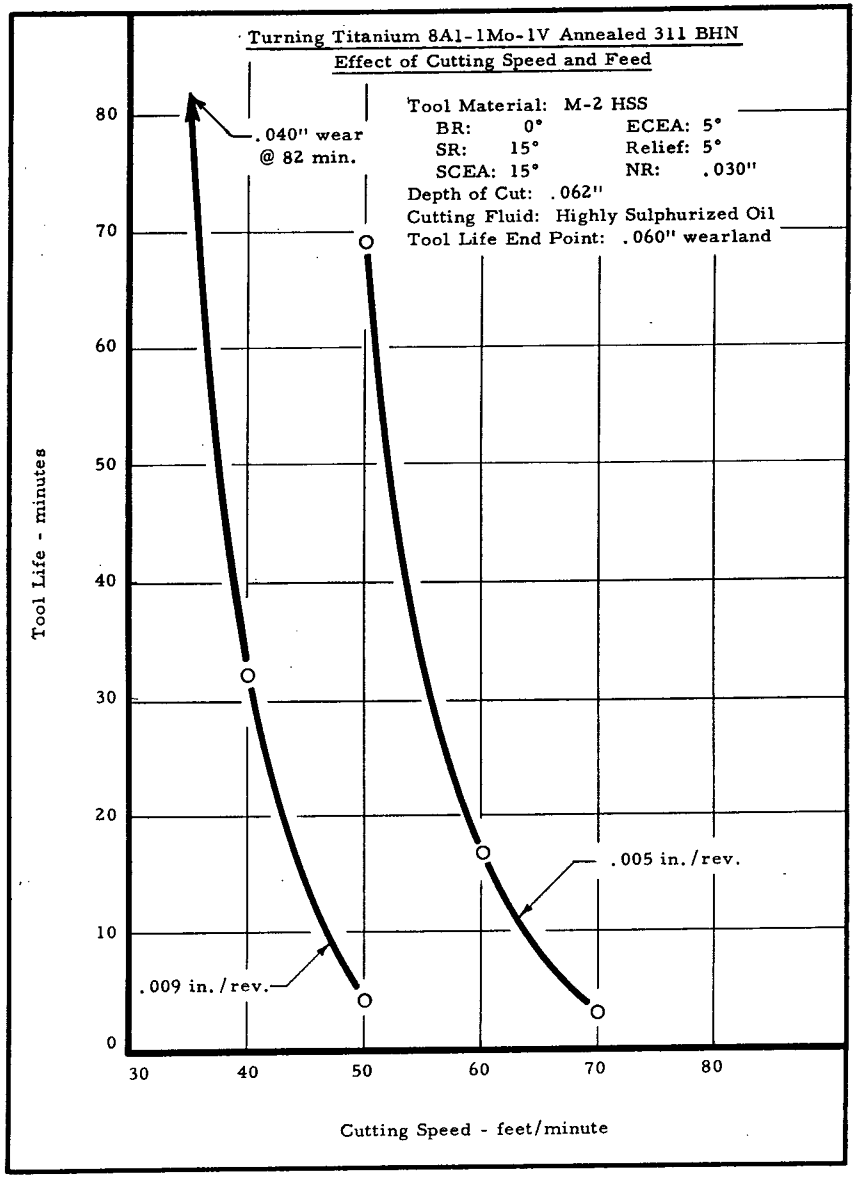
Al	Mo	V	C	Fe	Ti
8	1	1	.024	.08	Bal

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	M-2 HSS	BR: 0° SCEA: 15° SR: 15° ECEA: 5° Relief: 5° NR: .030"	5/8" square Tool Bit	.062	-	.005 in/rev	60	45 Min.	.060	Soluble Oil (1:20)
Turning	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square Throw-away Insert	.062	-	.005 in/rev	250	36 Min.	.015	Soluble Oil (1:20)
Face Milling	T-15 HSS	AR: 5° ECEA: 10° RR: 5° CA: 45° Clearance: 8°	4" diameter Single Tooth Face Mill	.060	2	.005 in/ tooth	90	160" Work Travel	.060	Highly Chlorinated Oil
Face Milling	C-2 Carbide	AR: 10° ECEA: 10° RR: 0° CA: 45° Clearance: 8°	4" diameter Single Tooth Face Mill	.060	2	.005 in/ tooth	410	140" Work Travel	.015	Dry
Peripheral End Milling	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS End Mill	.125	.750	.004 in/ tooth	150	250" Work Travel	.012	Soluble Oil (1:20)
End Mill Slotting	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS End Mill	.125	.750	.003 in/ tooth	97	210 Work Travel	.012	Water Base Synthetic (1:15)

TABLE 11 (continued)
RECOMMENDED CONDITIONS FOR MACHINING

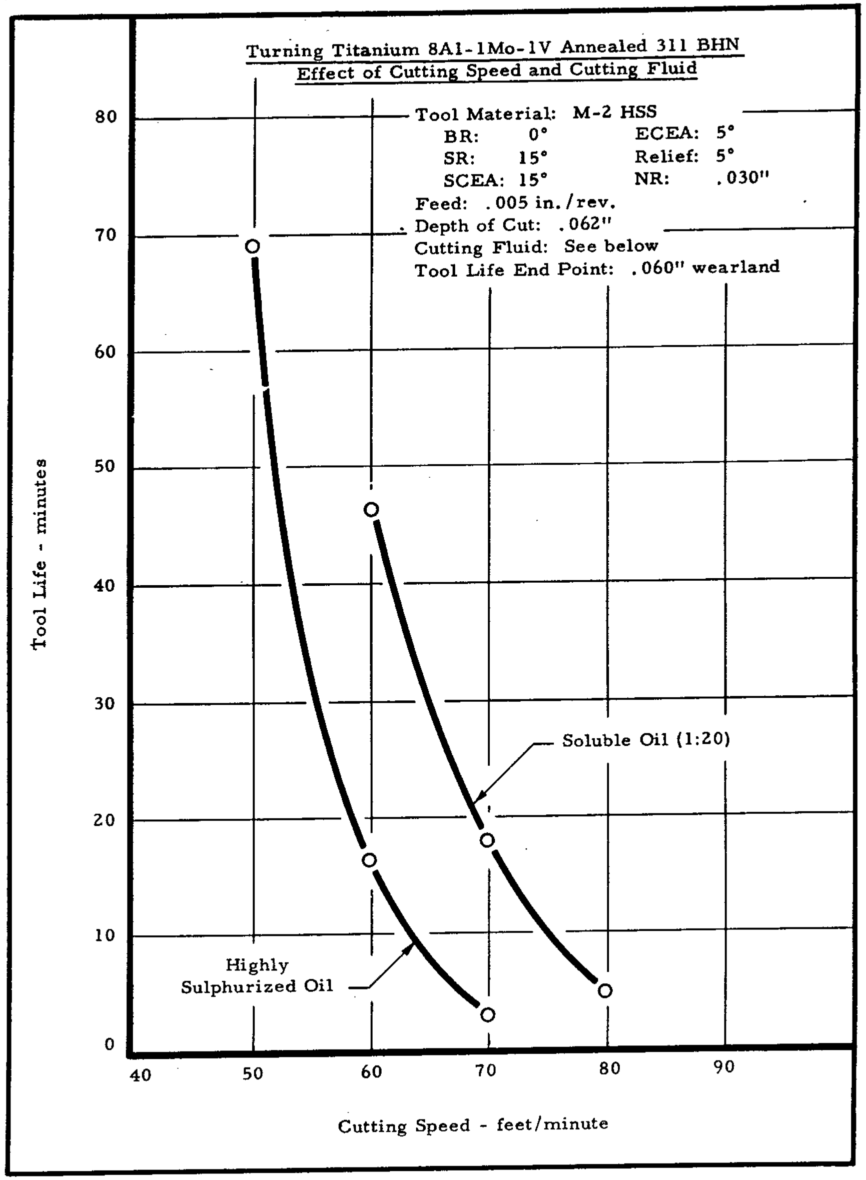
TITANIUM 8 Al - 1 Mo - 1 V - ANNEALED 302 - 311 BHN

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	T-15 HSS	118° Split Point 7° Clearance Angle	1/4" diameter HSS Drill 2 1/2" long	.500 thru	-	.005 in/rev	45	250 holes	.003	Highly Chlorinated Oil
Reaming	M-2 HSS	Helix Angle: 0° CA: 45° Clearance: 7°	.272" diameter 6 Flute Chucking Reamer	.500 thru	-	.009 in/rev	70	300 holes	.006	Highly Chlorinated Oil
Tapping	M-1 HSS	2 Flute Plug Spiral Point 75% Thread	5/16 - 24 NF tap	.500 thru	-	-	17	200 holes	Under size threads	Highly Sulphurized Oil



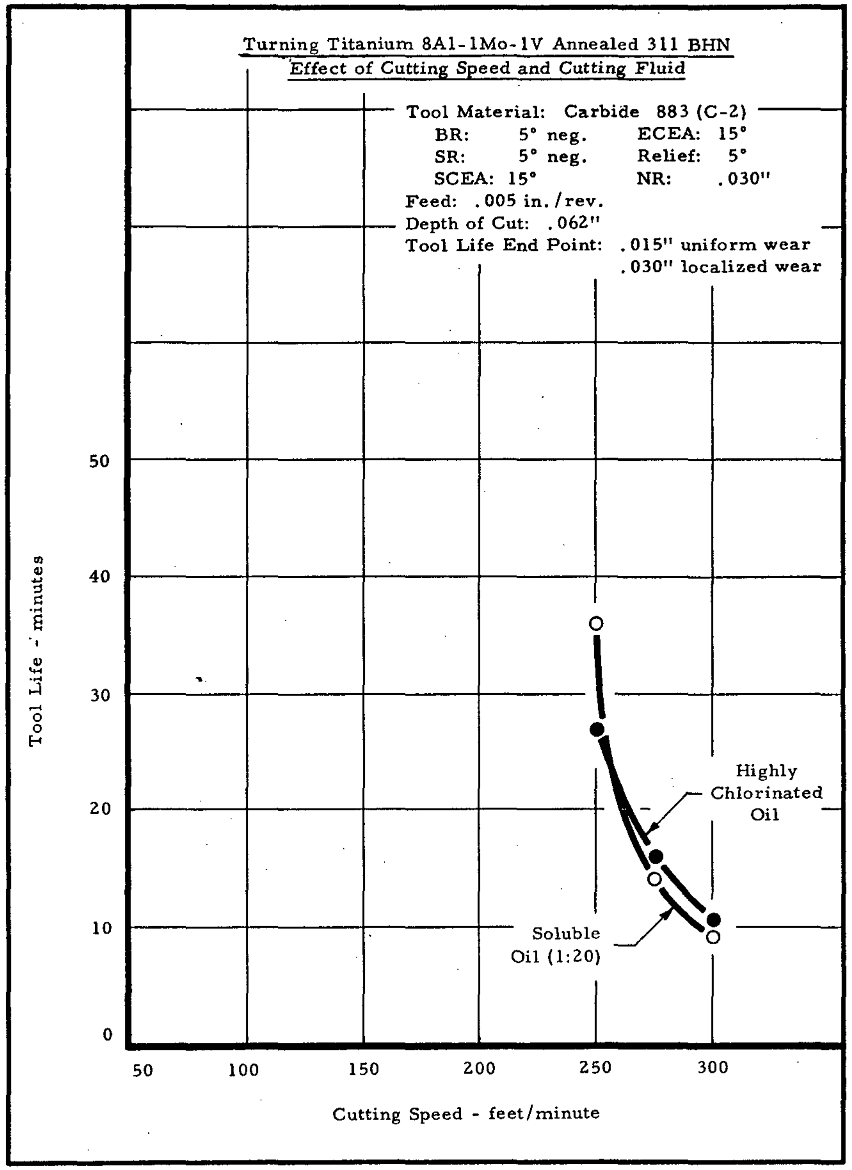
See Text, page 158

Figure 181



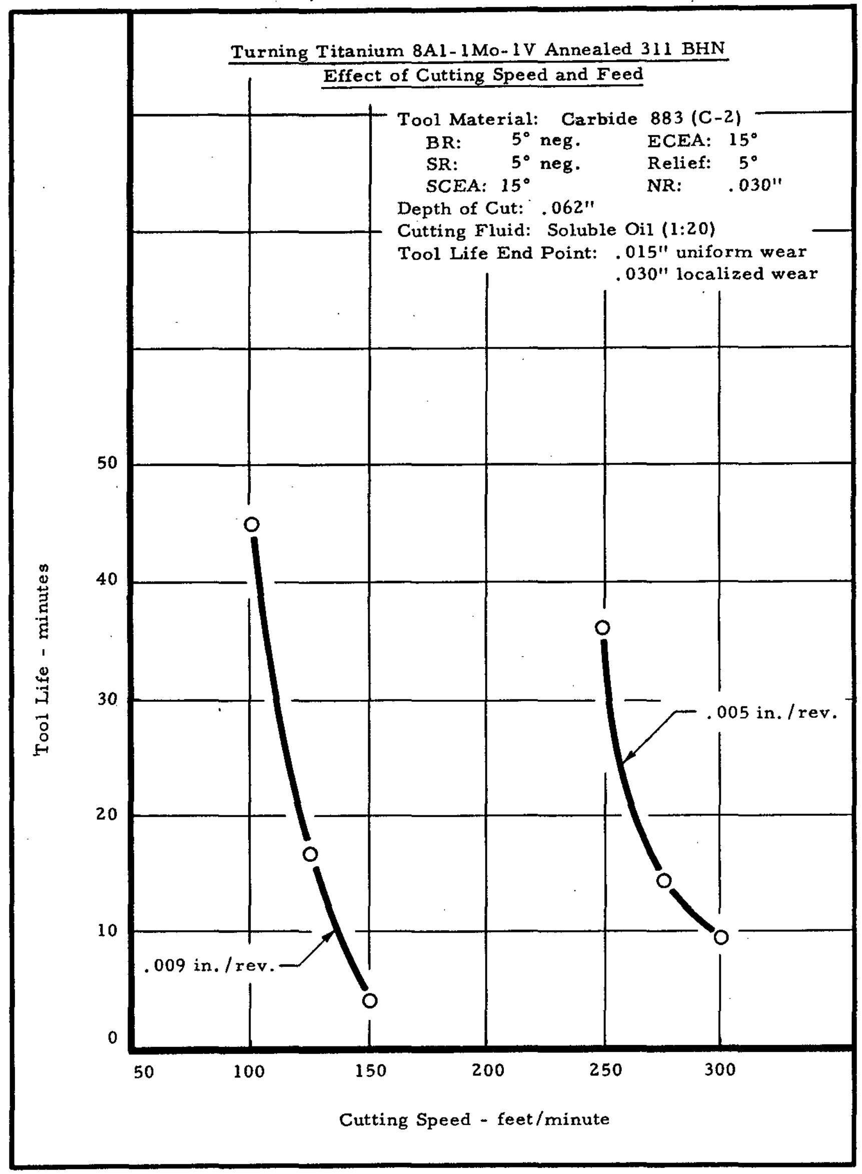
See Text, page 158

Figure 182



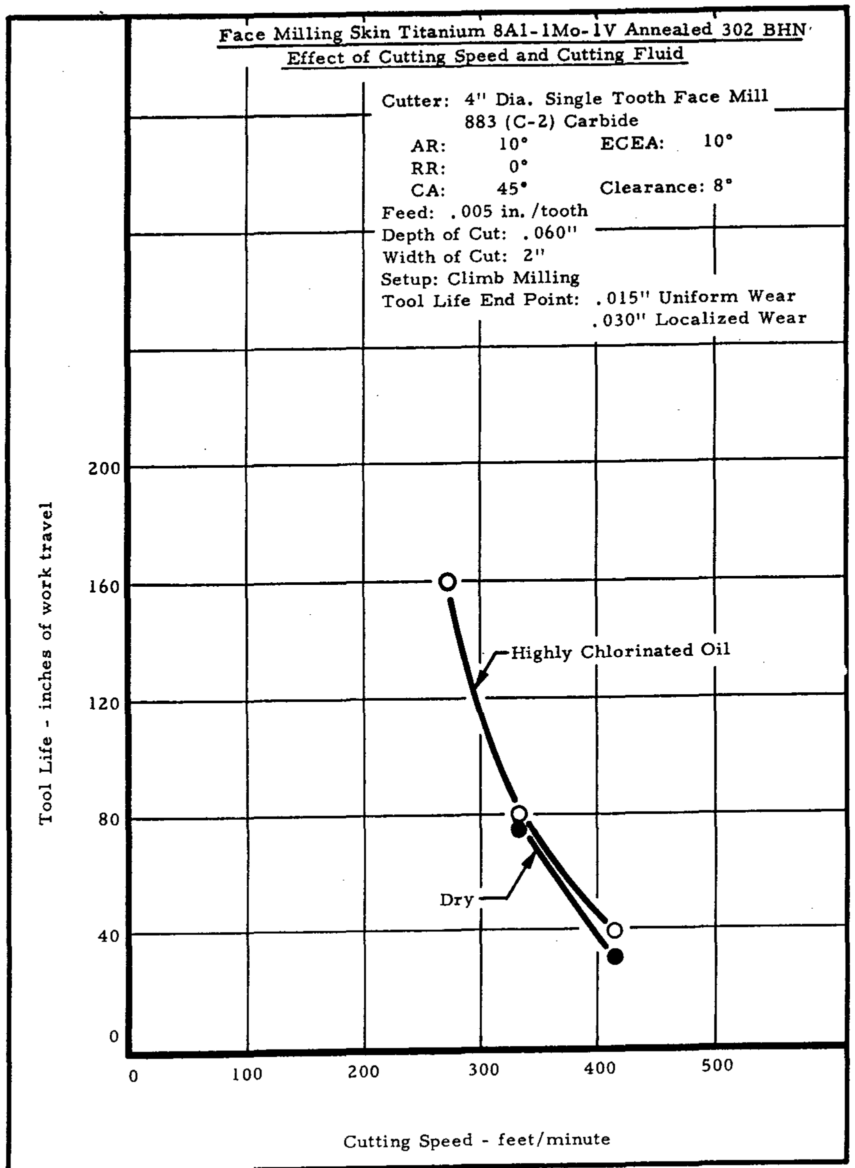
See Text, page 158

Figure 183



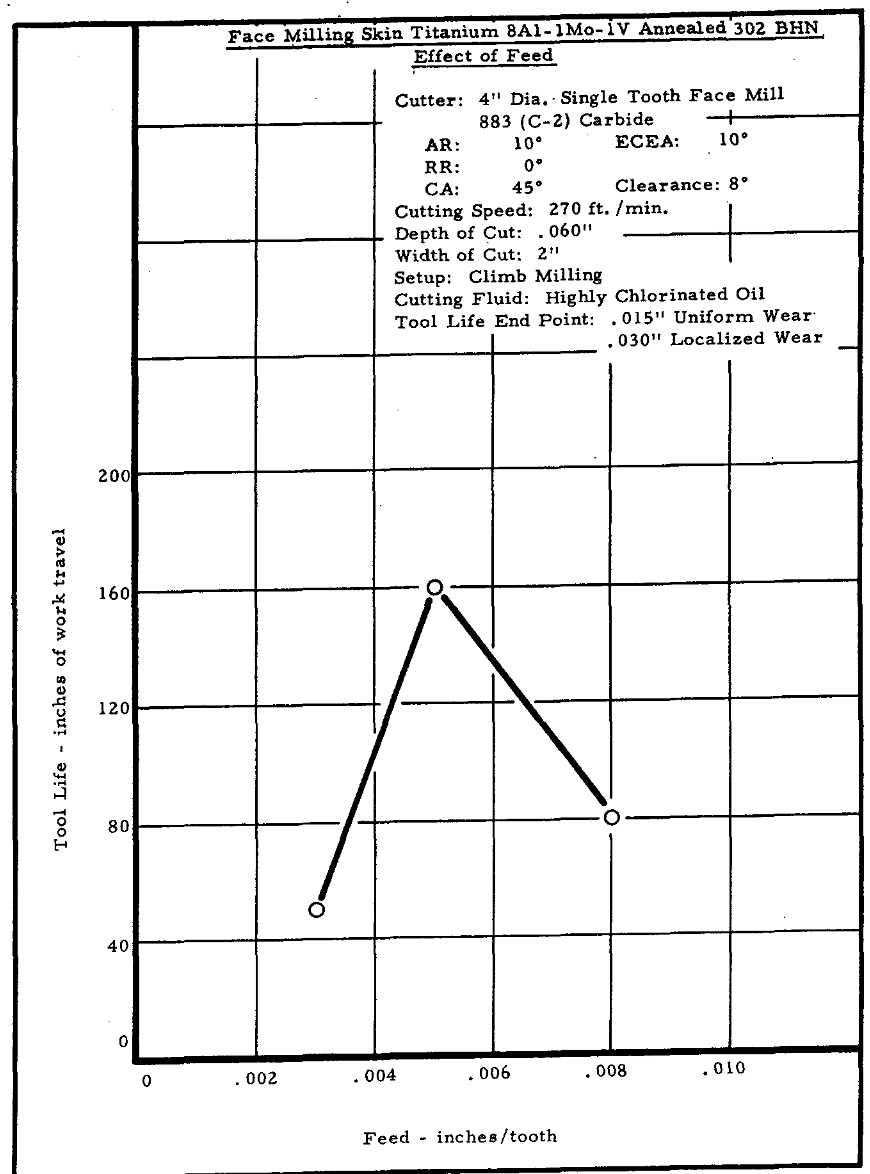
SeeText, page 158

Figure 184



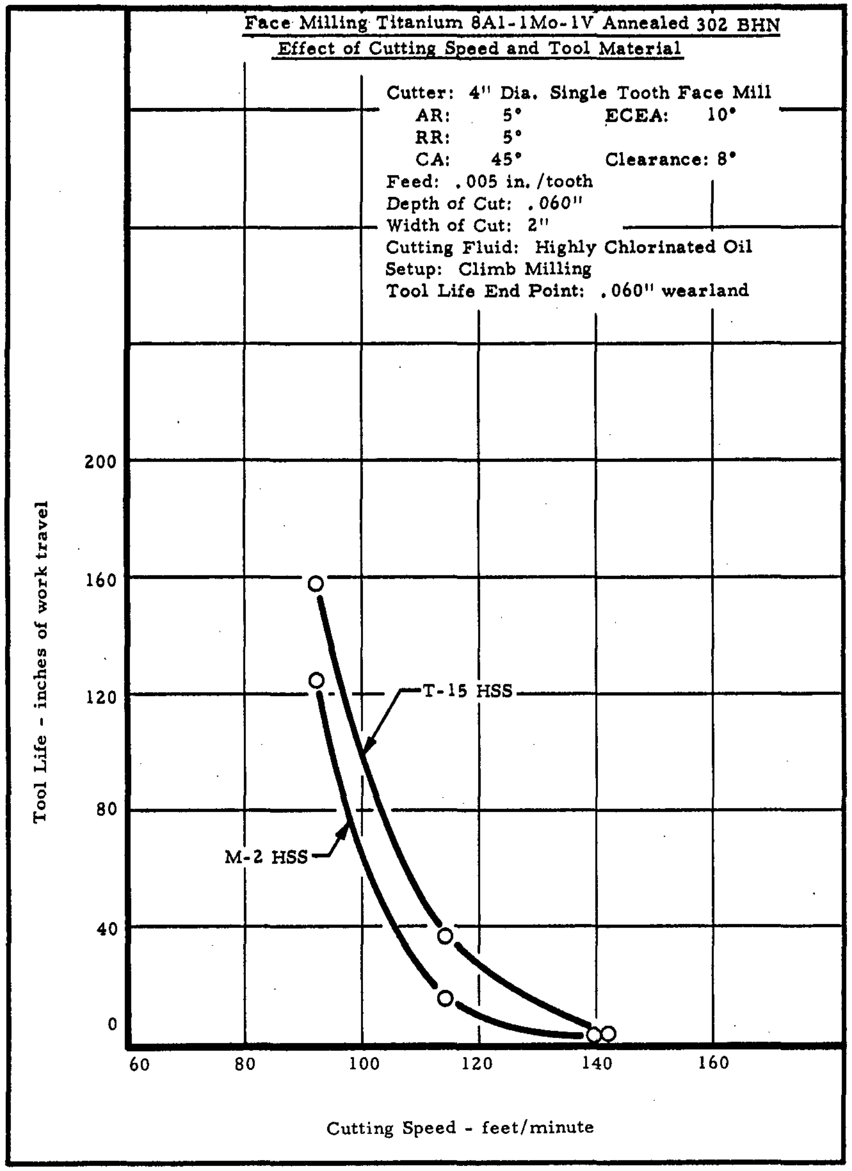
See text, page 159

Figure 185



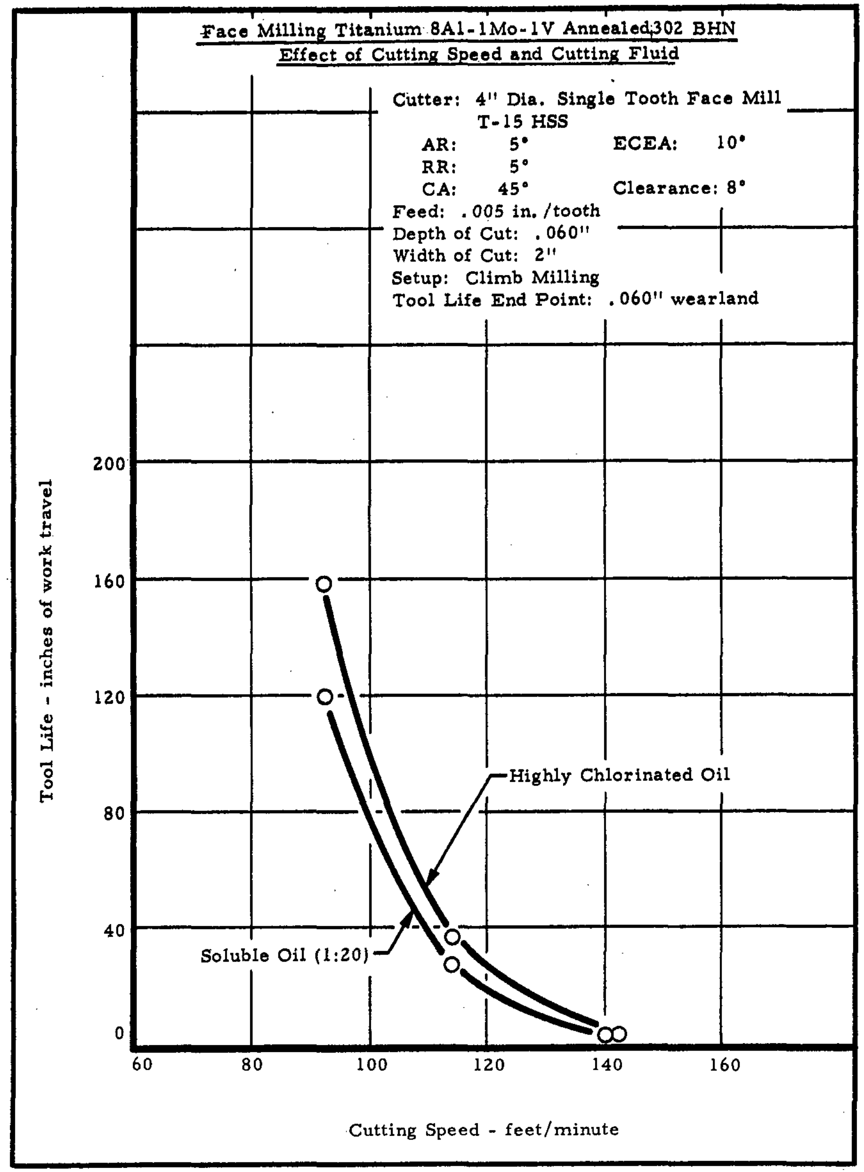
See text, page 159

Figure 186



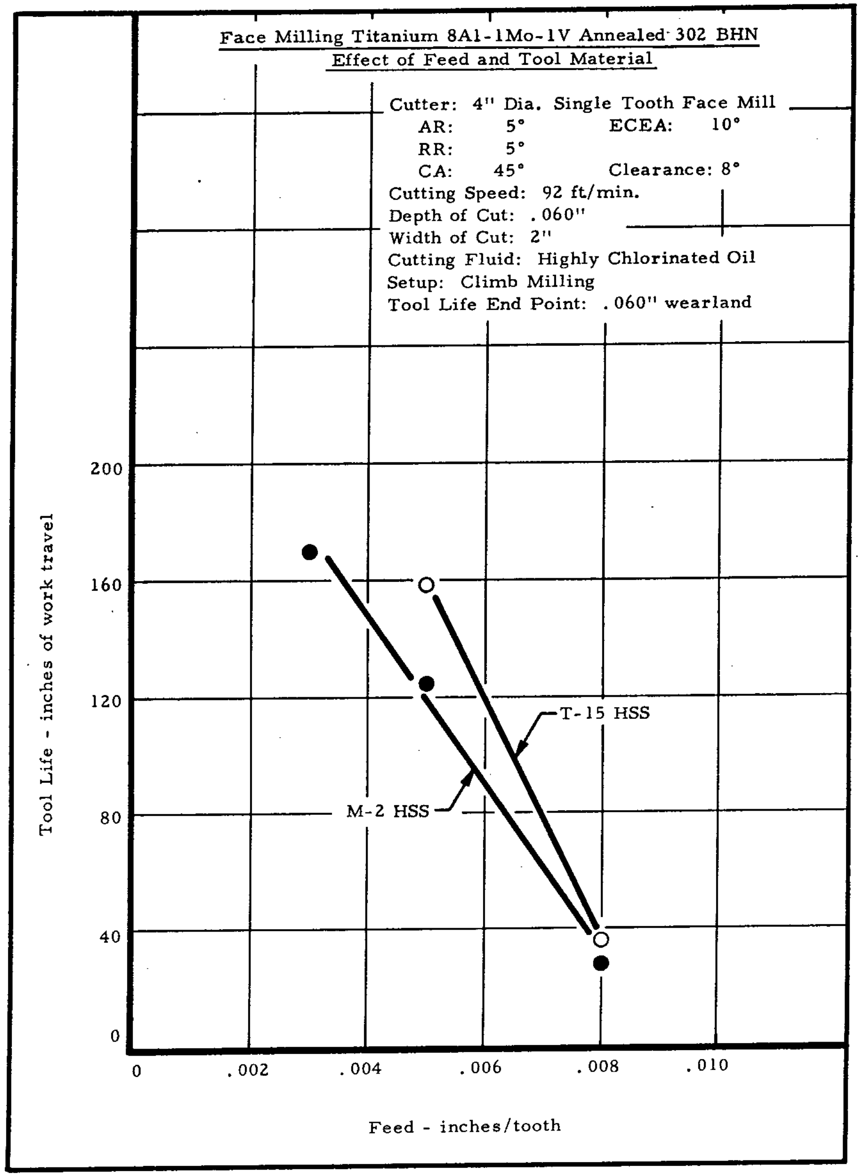
See text, page 159

Figure 187



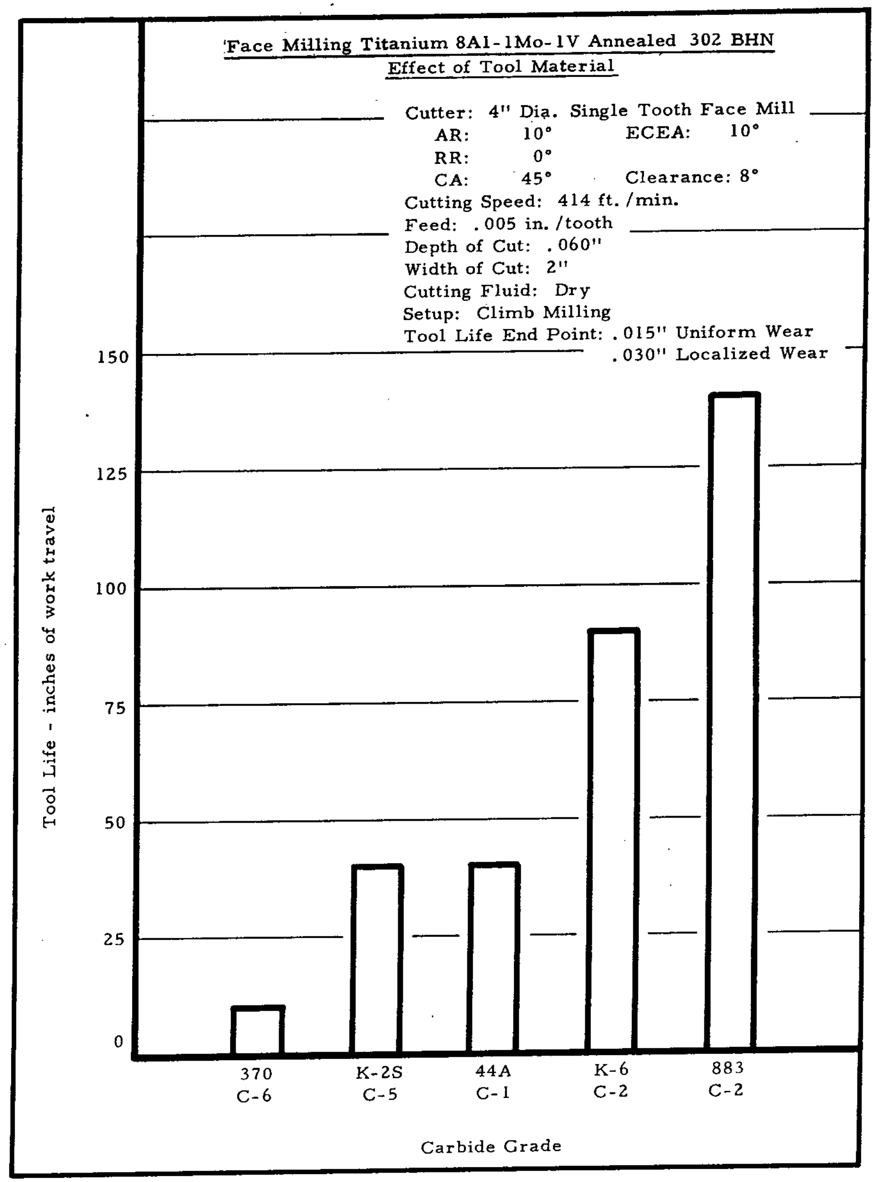
See text, page 159

Figure 188



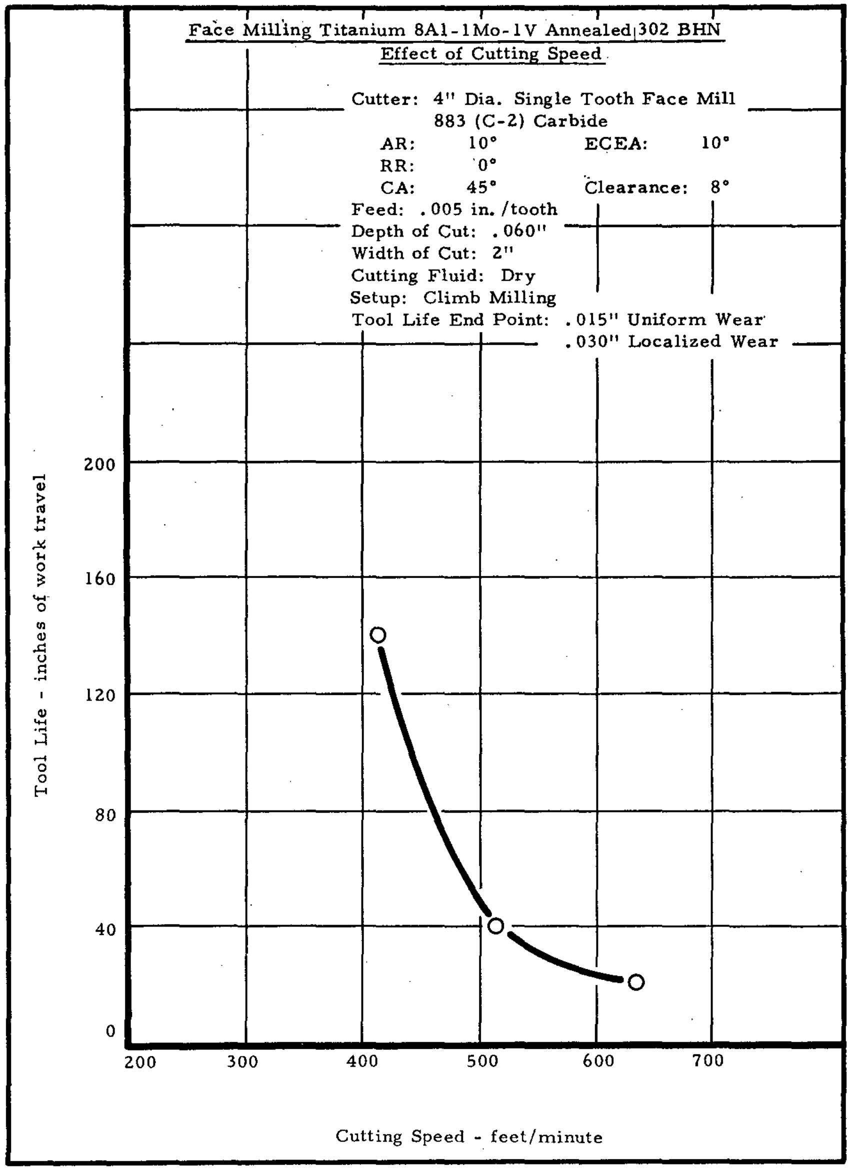
See text, page 159

Figure 189



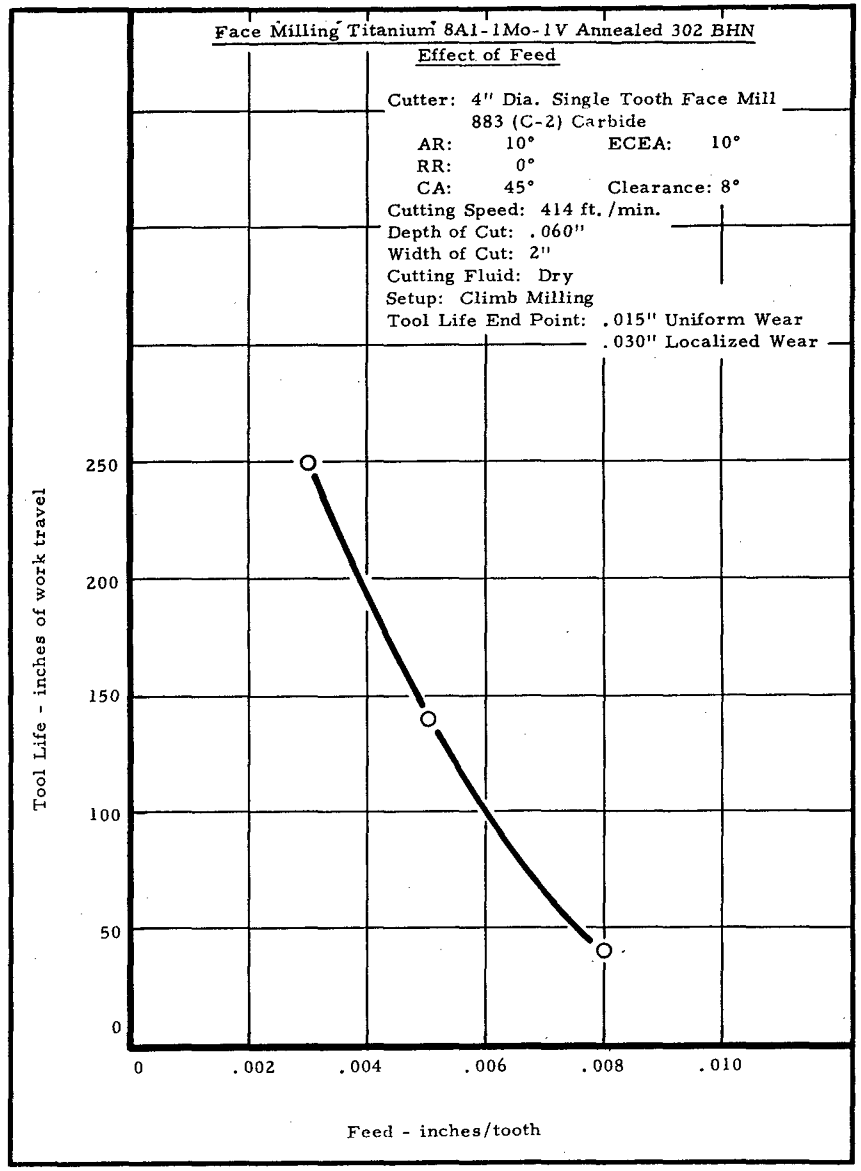
See text, page .59

Figure 190



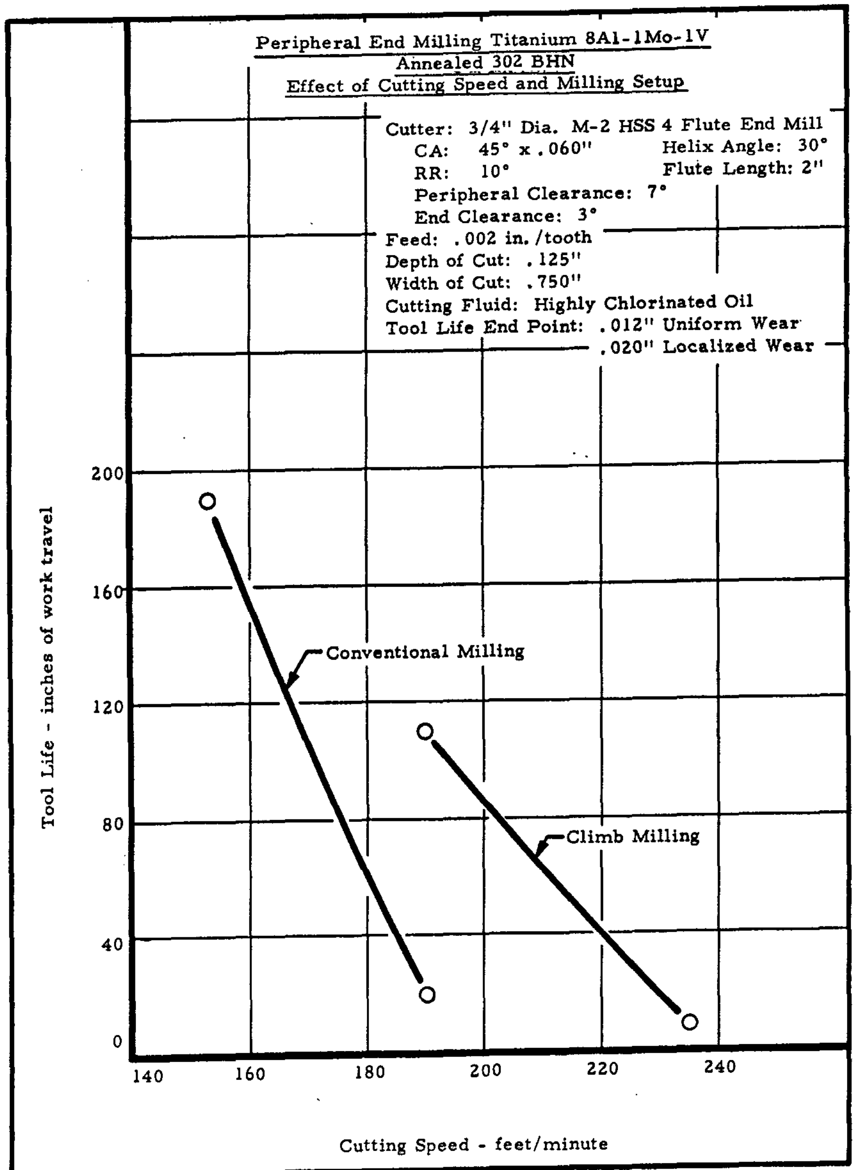
See text, page 159

Figure 191



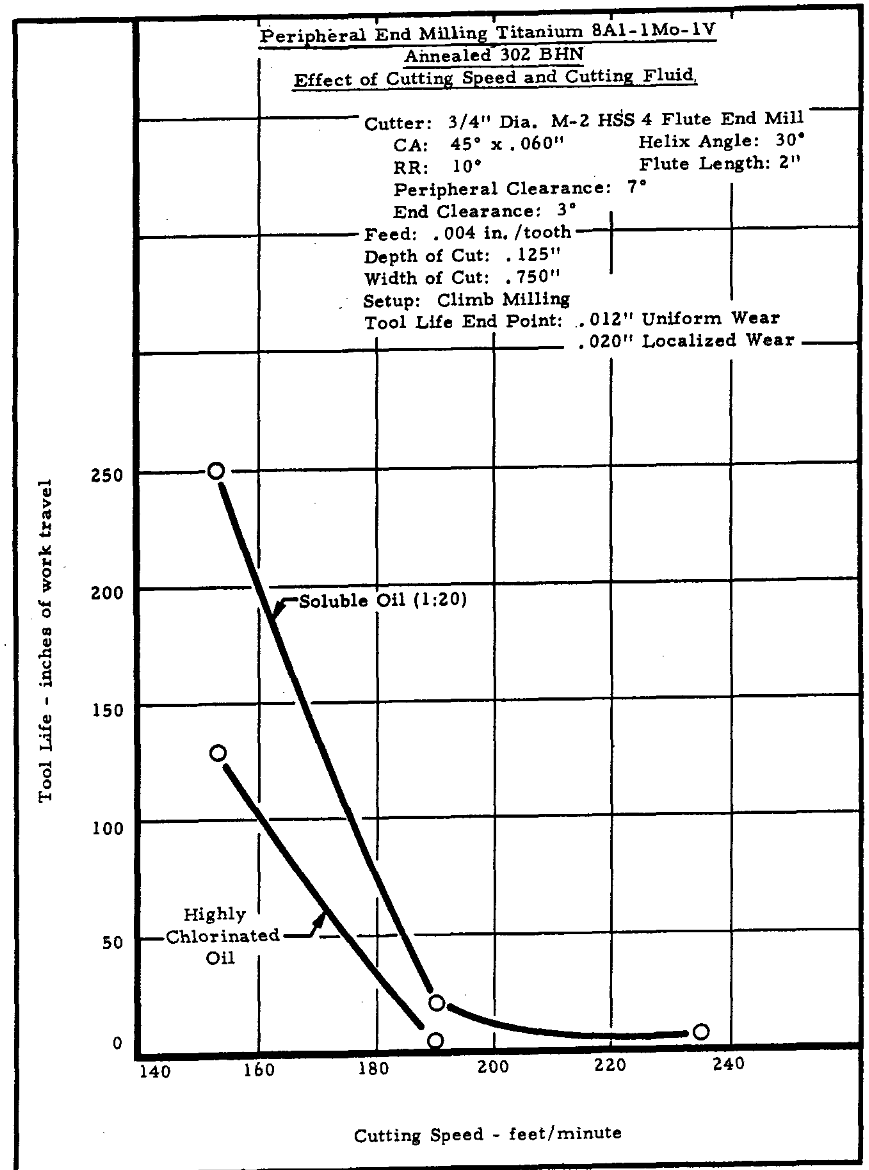
See text, page 159

Figure 192



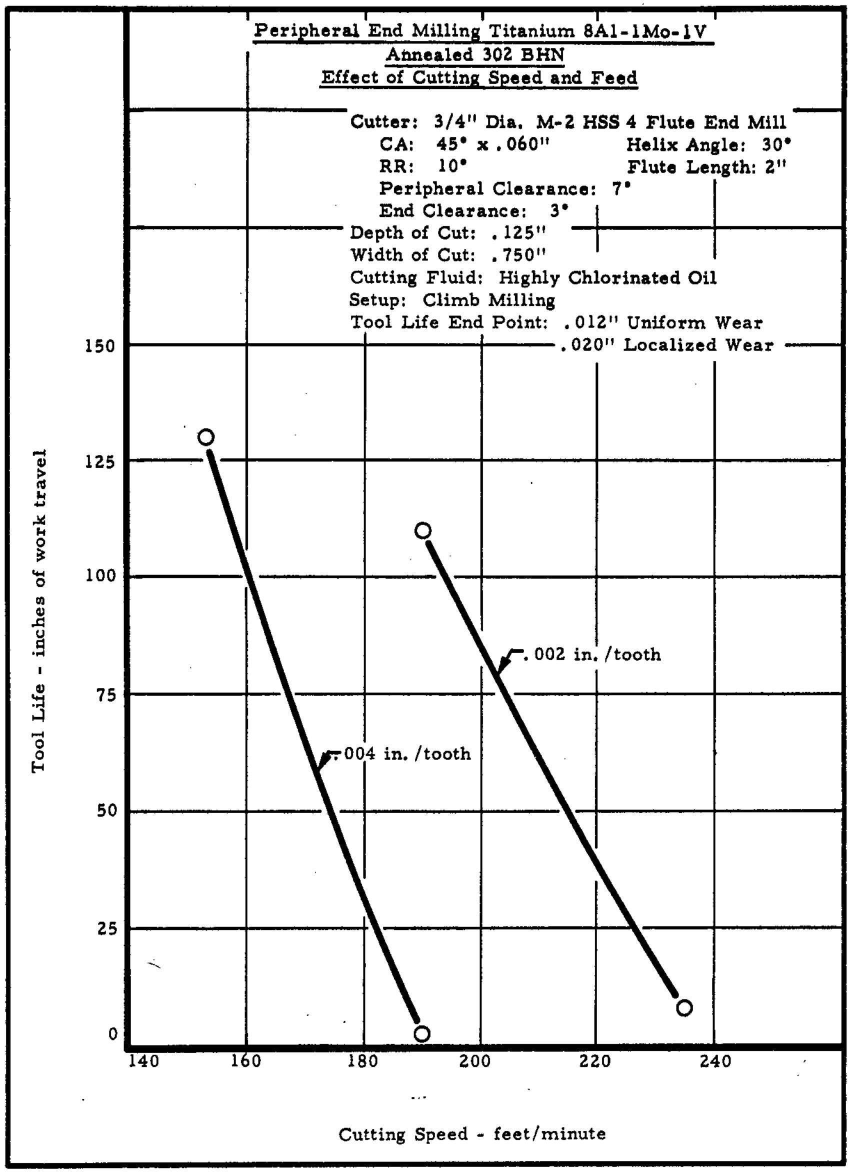
See text, page 160

Figure 193



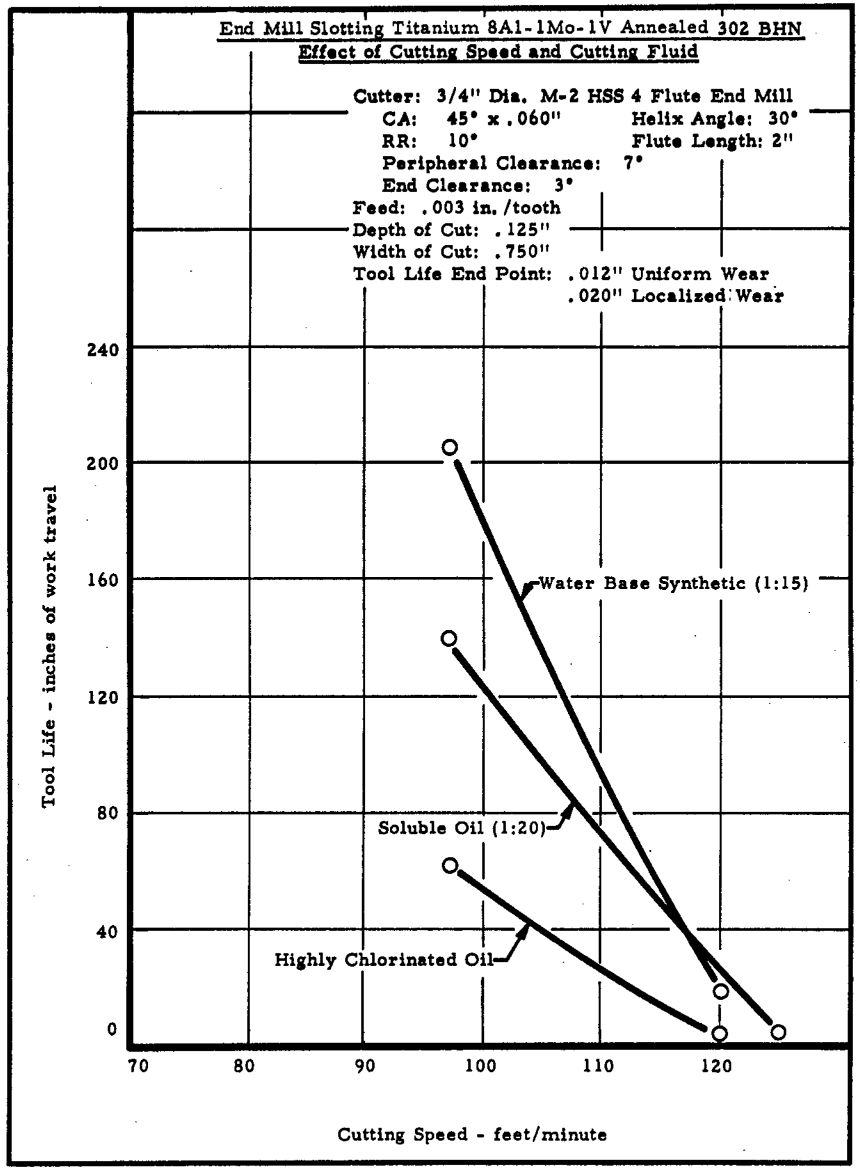
See text, page 160

Figure 194



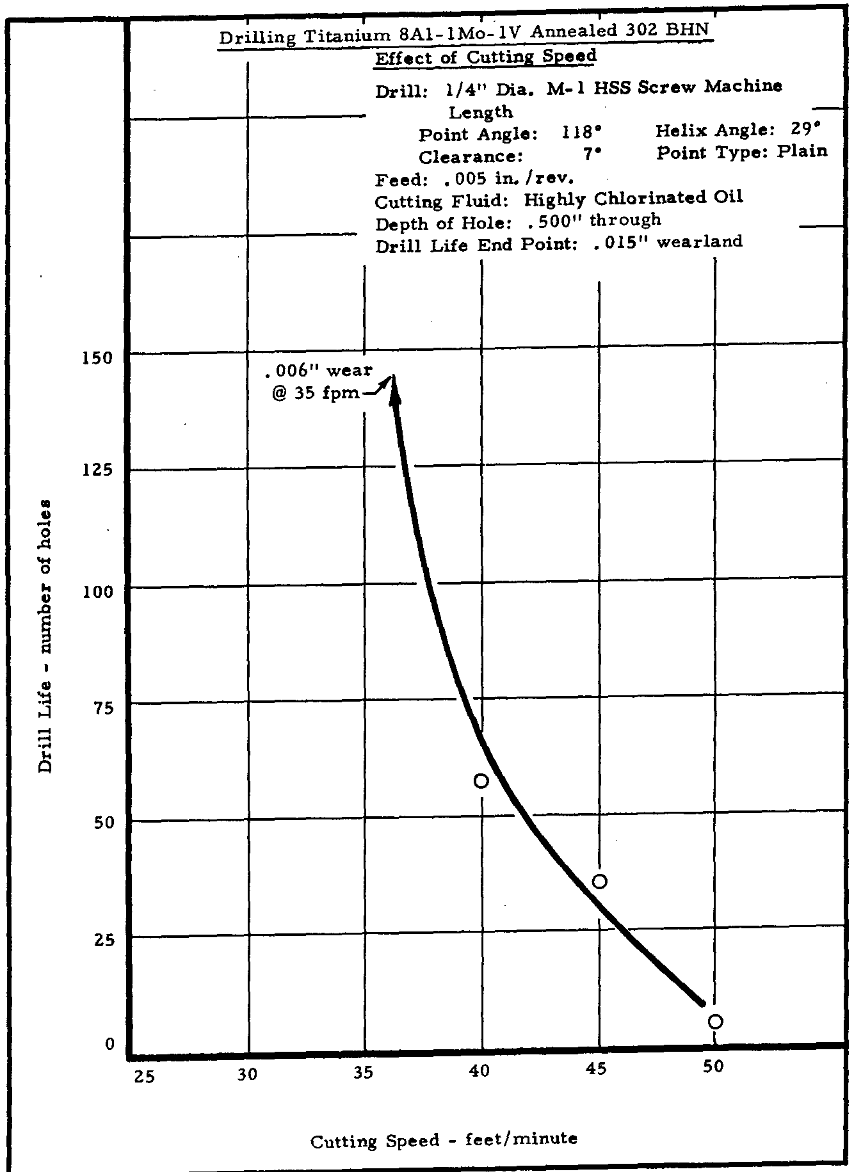
See text, page 160

Figure 195



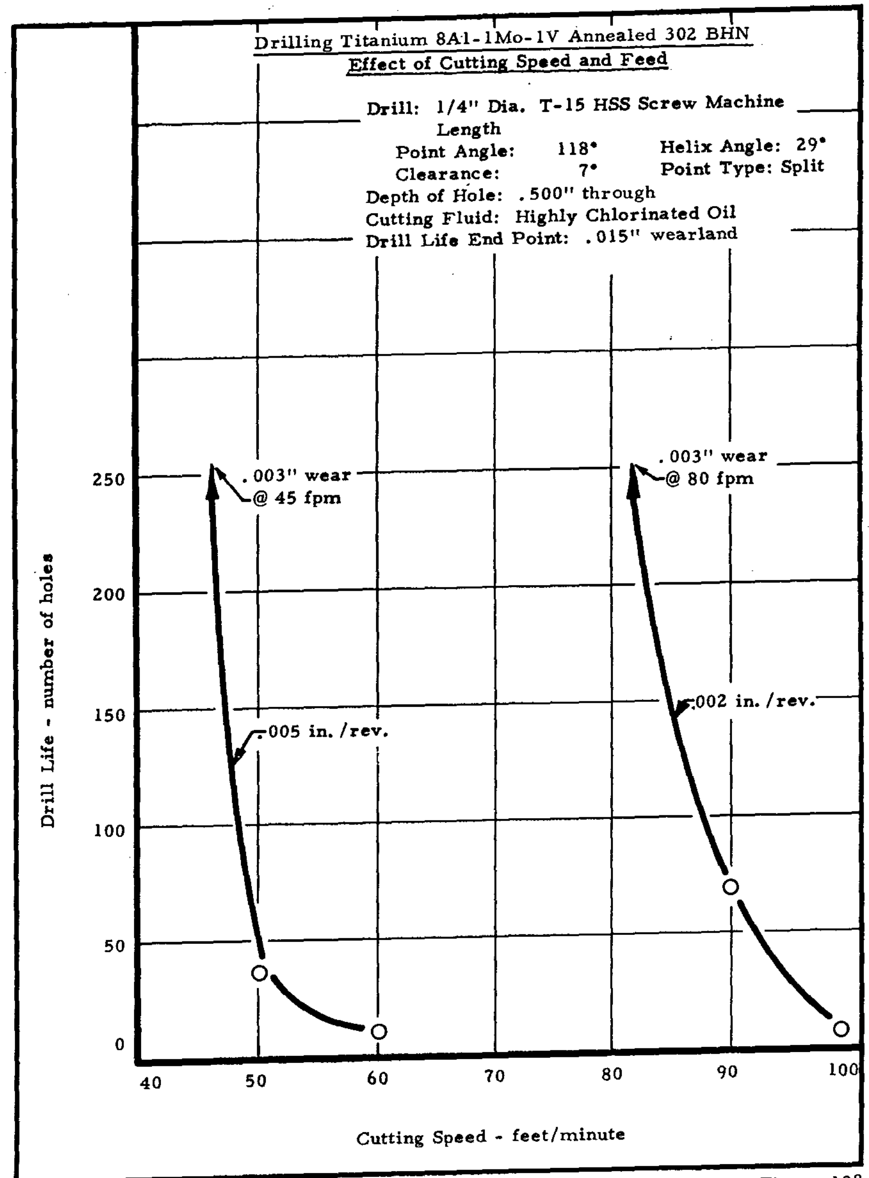
See text, page 160

Figure 196



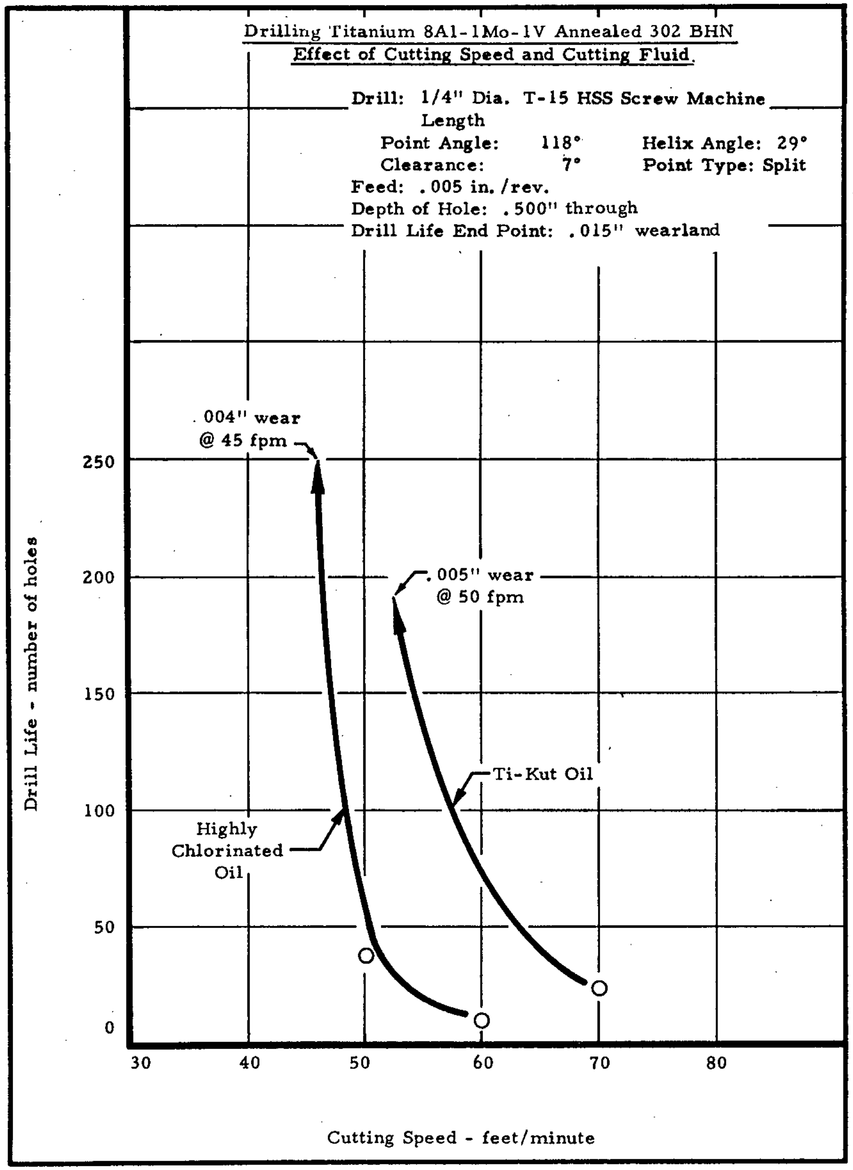
See text, page 161

Figure 197



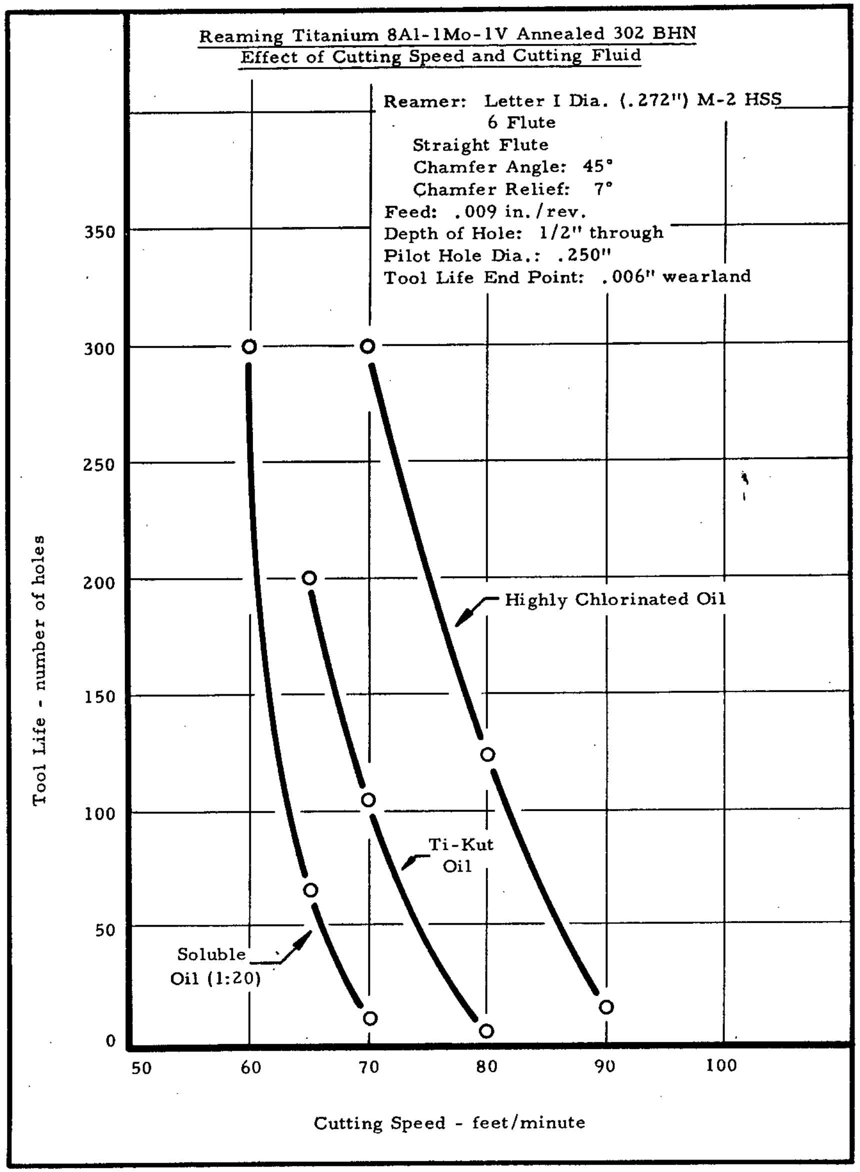
See text, page 161

Figure 198



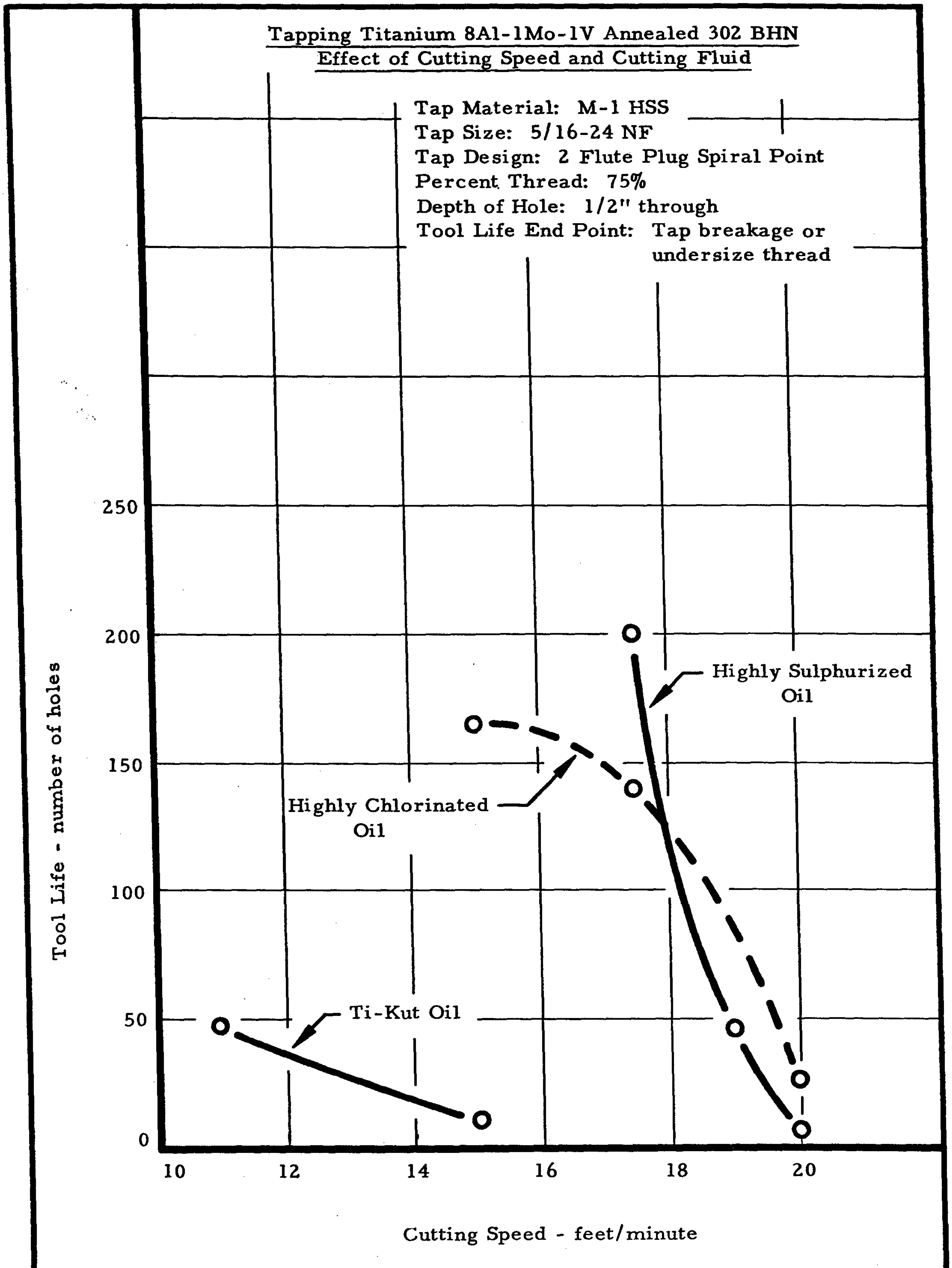
See text, page 161

Figure 199



See text, page 161

Figure 200



See text, page 161

Figure 201

4.1 Titanium 8Al-1Mo-1V (continued)

Turning (Solution Treated and Aged 341 BHN)

A 25% increase in cutting speed was obtained in turning titanium 8Al-1Mo-1V in the solution treated and aged condition with high speed steel tools by using a highly chlorinated oil instead of a soluble oil, see Figure 202, page 181. However, with carbide tools there was no difference in the tool life results with the two cutting fluids, as shown in Figure 203, page 181.

Comparisons between the annealed (311 BHN) and the solution treated and aged (341 BHN) conditions are presented in Figures 204 and 205, page 182, in turning with both HSS and carbide tools. The titanium 8Al-1Mo-1V could be turned at a 20% higher cutting speed with HSS tools when annealed, as compared to solution treated and aged. With carbide tools, the advantage was about 12%.

Face Milling (Solution Treated and Aged 302 BHN)

Figure 206, page 183, illustrates the advantage of using a type T-15 HSS as compared to a type M-2 in face milling titanium 8Al-1Mo-1V solution treated and aged 302 BHN. The cutter life was over 35% longer with the T-15 tool at a cutting speed of 92 ft. /min.

A comparison of two types of cutting oils is presented in Figure 207, page 183, for face milling titanium 8Al-1Mo-1V with a single tooth type T-15 HSS cutter. At a cutting speed of 92 ft. /min., the cutter life with the Ti-Kut oil was 270 inches of work travel and 220 inches with the highly chlorinated oil.

Several types of carbides were compared with positive and negative rake angles, see Figure 208, page 184. Positive rake angles were far superior on the 883 and K-6 grades, while negative rake was better on the K-68 grade. The 370 grade was not suitable for face milling the titanium.

The use of a highly chlorinated oil proved to be more effective in increasing cutter life than milling dry, see Figure 209, page 184. The cutting speed with the oil was almost 20% faster than dry for a cutter life of 160 inches of work travel.

Figure 210, page 185, demonstrates the results obtained with various cutting fluids and methods of application. Flooding the cutter with the highly chlorinated oil was appreciably better than using the Ti-Kut oil or no fluid at all. The Ti-Kut water soluble fluid in the form of a spray mist was ineffective.

4.1 Titanium 8Al-1Mo-1V (continued)

Peripheral End Milling (Solution Treated and Aged 302 BHN)

The cutter life with soluble oil (1:20) was considerably longer than with a highly chlorinated oil. The tool life, as shown in Figure 211, page 185, with the soluble oil (1:20) was about 75% longer than with the active cutting oil. A 12% higher cutting speed could be employed at a feed of .002 in./tooth as compared to a feed of .004 in./tooth, see Figure 212, page 186. Nevertheless, the production rate with the higher feed was considerably greater than that obtained at the lighter feed of .002 in./tooth.

A comparison of the titanium 8Al-1Mo-1V in the two heat treated conditions; 1) annealed, and 2) solution treated and aged, is presented in Figure 213, page 186. The difference in the tool life results was not significant.

End Mill Slotting (Solution Treated and Aged 302 BHN)

A comparison of two cutting fluids in end mill slotting is shown in Figure 214, page 187. The cutter life with the water base synthetic (1:15) was 137 inches of work travel as compared to 47 inches with the soluble oil at a feed of .002 in./tooth and a cutting speed of 116 ft./min.

As shown in Figure 215, page 187, a 20% reduction in cutting speed will permit doubling the feed in the range of .002 to .004 in./tooth. A further demonstration of this fact is illustrated in Figure 216, page 188. A feed of .004 in./tooth at a cutting speed of 97 ft./min. provided the same tool life as a feed of .002 in./tooth and a cutting speed of 118 ft./min.

The cutter life in end milling the solution treated and aged alloy was appreciably longer than on the annealed alloy. At a feed of .003 in./tooth and a cutting speed of 97 ft./min., a cutter life of 200 inches of work travel was obtained with the solution treated and aged alloy as compared to 140 inches for the annealed alloy, see Figure 217, page 188.

Surface Grinding (Solution Treated and Aged 302 BHN)

The effect of type of grinding wheel and grinding wheel speed on G Ratio is given in Figure 218, page 189. The aluminum oxide wheels provided very low G Ratios, under 1.5, at all wheel speeds between 2000 and 6000 ft./min. The silicon carbide grinding wheels, which are the ones preferred for grinding titanium, made possible G Ratios of 4 to 9. The harder J bond silicon carbide wheel produced a G Ratio of 4.8 to 9.2 as the wheel speed increased from 2000 to 6000 ft./min. The softer H grade of silicon carbide wheel was less sensitive to wheel speed, with the G Ratio varying between 4 and 5.8 as the wheel speed changed from 2000 to 6000 ft./min. Also shown in Figure 218, page 189, are the results when using potassium nitrite as a grinding fluid with the J hardness silicon carbide wheel. The G Ratio obtained using potassium nitrite was almost identical to that obtained in grinding with the highly chlorinated oil (see the upper two curves of Figure 218, page 189). All further investigations of grinding wheel variables were made using silicon carbide grinding wheels.

The effect of down feed on G Ratio for the J hardness silicon carbide wheel is shown in Figure 219, page 189, for a wheel speed of 4000 ft./min. with potassium nitrite grinding fluid. The G Ratio increased from 3.5 to 10.5 as the down feed increased from .0005 to .002 in./pass.

Both the cross feed and the table speed had significant effects on G Ratio. The grinding ratio increased with both cross feed and table speed, Figures 220 and 221, page 190.

The influence of grinding fluid on G Ratio is indicated in Figure 222, page 191. The sulfurized and the chlorinated oils produced only a small improvement in grinding ratio, compared to the potassium nitrite solution.

The titanium alloys are very susceptible to surface damage during grinding and, therefore, extreme care must be taken to maintain surface integrity. Care must be especially exercised when chlorinated compounds are employed on titanium alloys. The presence of chlorine on the titanium component may seriously affect the stress corrosion strength of titanium and its alloys when the titanium component is subjected to high temperatures and high stresses. If chlorinated compounds are used, the titanium component should be thoroughly cleaned to remove all chlorine residues prior to heat treating or prior to surface use of the component.

The recommended conditions for grinding titanium 8Al-1Mo-1V are given in Table 12, page 289. The conditions noted are those which provide satisfactory surface integrity. These conditions, which we call "low stress" grinding conditions, are:

4.1 Titanium 8Al-1Mo-1V (continued)

Grinding Wheel:	39C60J8VK
Wheel Speed:	3000 to 4000 ft./min.
Down Feed:	
Roughing:	.001 in./pass maximum
Finishing:	Last .010" removed taking progressively smaller down feeds of .0005 to .0002 in./pass
Cross Feed:	.050 in./pass
Table Speed:	40 to 60 ft./min.
Grinding Fluid:	KNO_2 (1:20)

The surface finish obtainable in grinding titanium 8Al-1Mo-1V is 20 to 40 microinches, arithmetical average, in finishing; and 30 to 70 microinches, arithmetical average, in roughing.

TABLE 12

RECOMMENDED CONDITIONS FOR MACHINING

TITANIUM 8 Al - 1 Mo - 1V - SOLUTION TREATED & AGED - 302 - 341 BHN

Al	Mo	V	C	Fe	Ti
8	1	1	.024	.08	Bal

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	M-2 HSS	BR: 0° SCEA: 15° SR: 15° ECEA: 5° Relief: 5° NR: .030"	5/8" square Tool Bit	.062	-	.005 in/rev	60	50 Min.	.060	Chlorinated
Turning	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square Throw-away Insert	.062	-	.005 in/rev	225	28 Min.	.015	Soluble Oil (1:20)
Face Milling	T-15 HSS	AR: 5° ECEA: 10° RR: 5° CA: 45° Clearance: 8°	4" diameter Single Tooth Face Mill	.060	2	.005 in/ tooth	90	220" Work Travel	.060	Highly Chlorinated Oil
Face Milling	C-2 Carbide	AR: 10° ECEA: 10° RR: 0° CA: 45° Clearance: 8°	4" diameter Single Tooth Face Mill	.060	2	.005 in/ tooth	400	250" Work Travel	.015	Highly Chlorinated Oil
Peripheral End Milling	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 Tooth HSS End Mill	.250	.750	.004 in/ tooth	150	275" Work Travel	.012	Soluble Oil (1:20)
End Mill Slotting	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 Tooth HSS End Mill	.125	.750	.004 in/ tooth	97	120" Work Travel	.012	Water Base Synthetic (1:15)

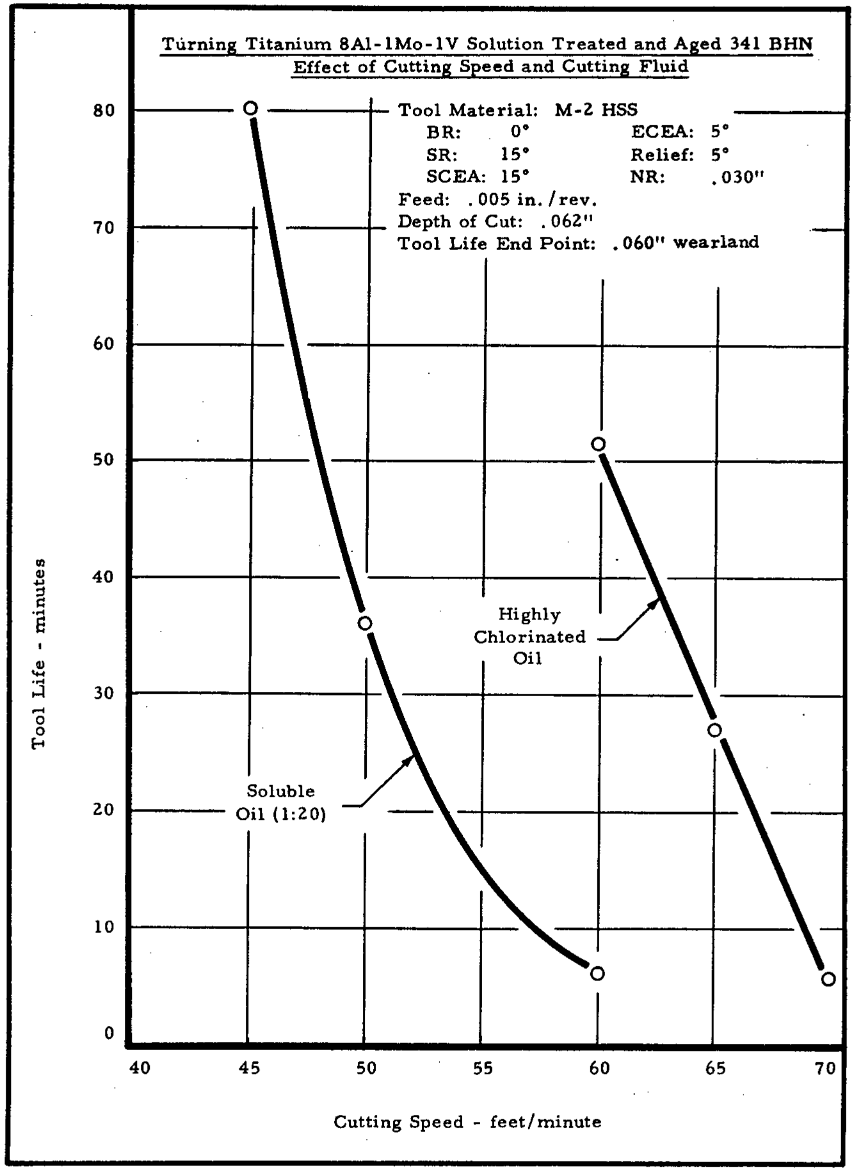
TABLE 12 (continued)

RECOMMENDED CONDITIONS FOR MACHINING

TITANIUM 8 Al - 1 Mo - 1V - SOLUTION TREATED & AGED - 302 - 341 BHN

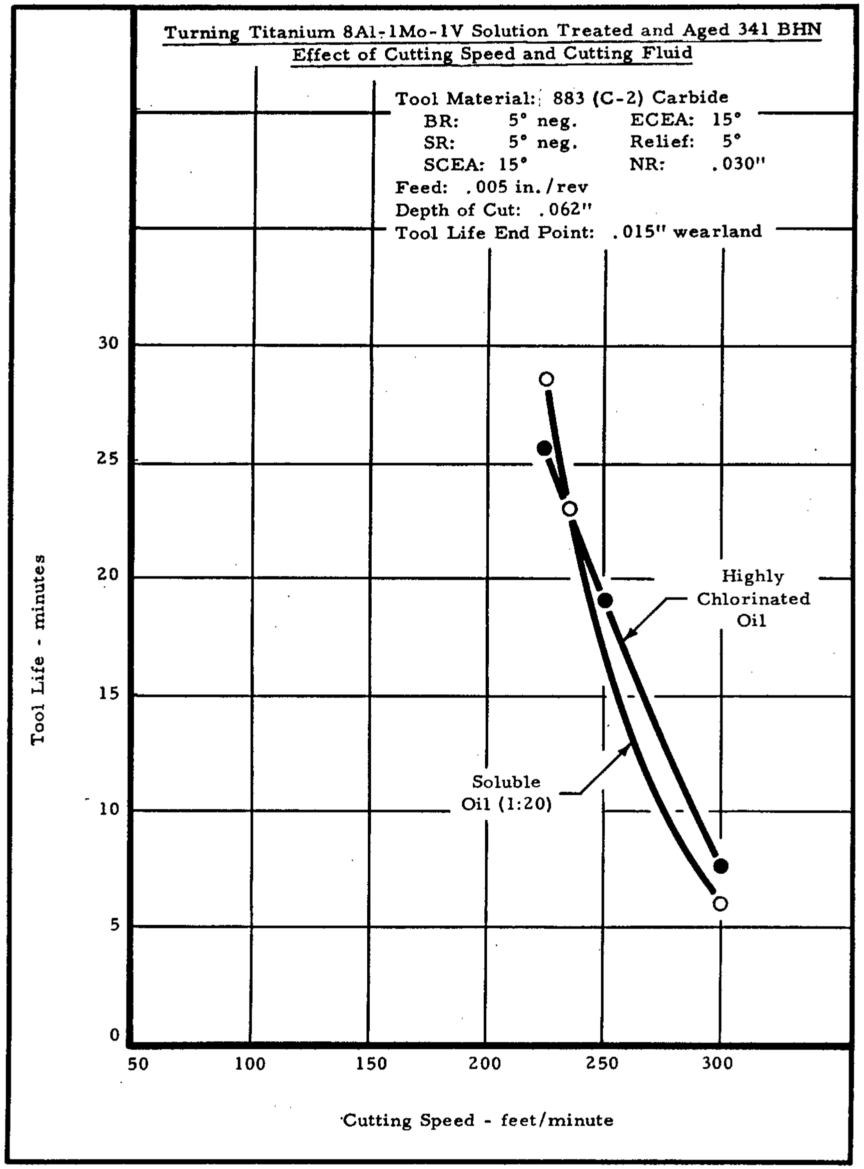
SURFACE GRINDING

Operation	Wheel Grade	Grinding Fluid	Wheel Speed Ft./Min.	Table Speed Ft./Min.	Down Feed In./Pass.	Cross Feed In./Pass.	G Ratio
Finishing	39C60J8VK	KNO_2 (1:20)	3000 - 4000	60	.0005	.050	4.0
Roughing	39C60J8VK	KNO_2 (1:20)	3000 - 4000	60	.001	.050	8.0



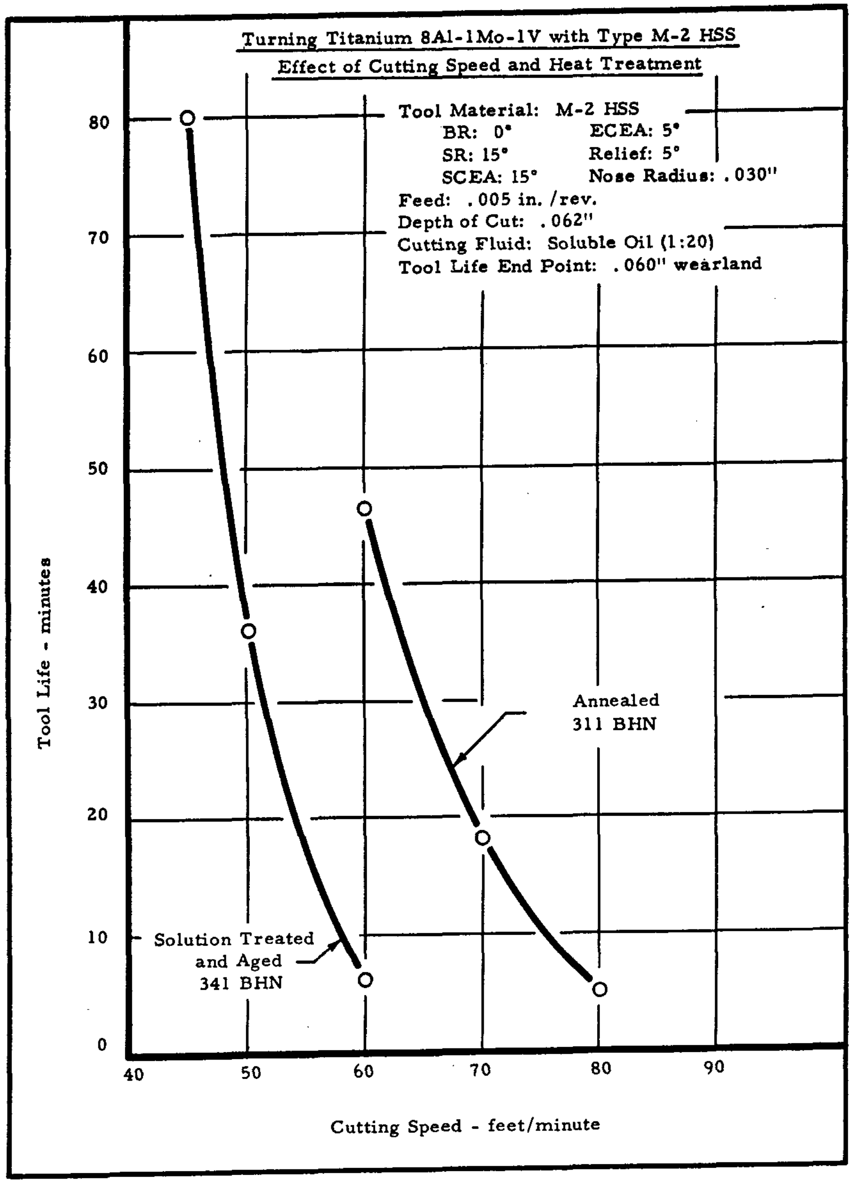
See text, page 175

Figure 202



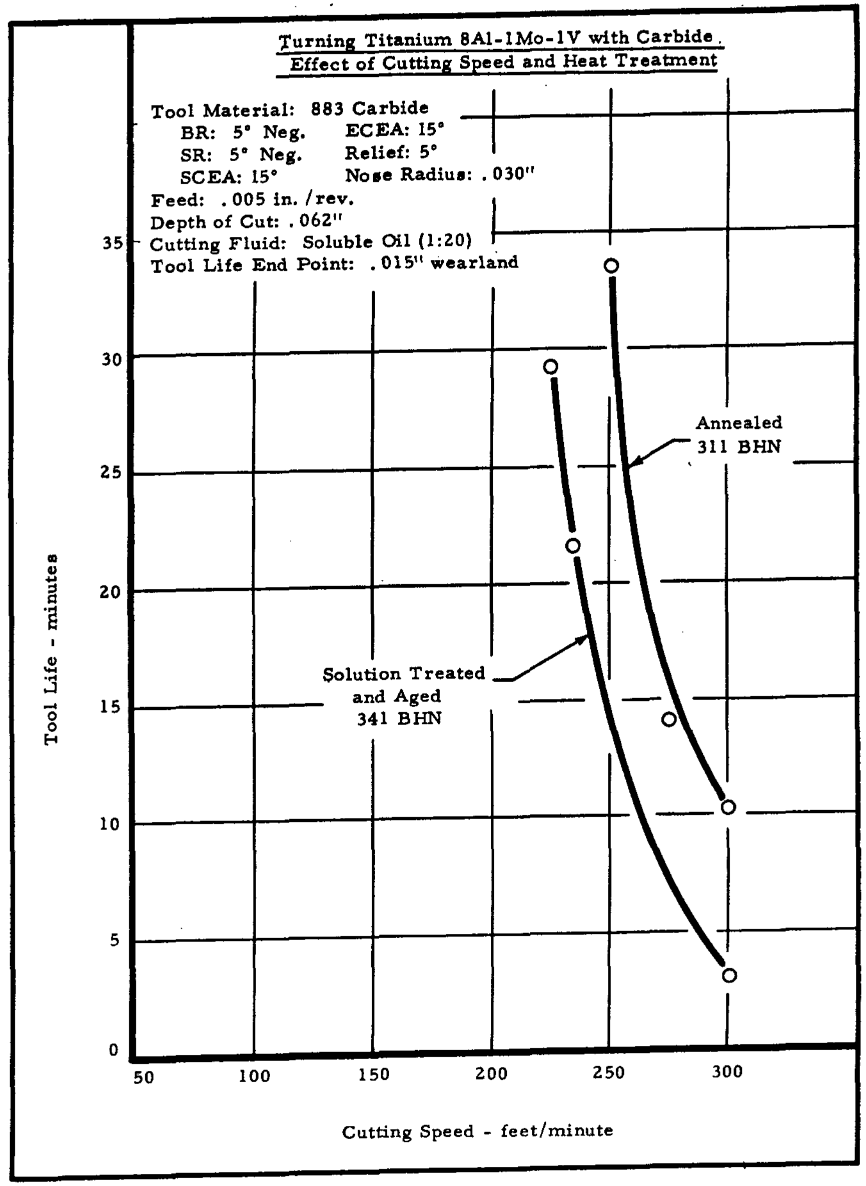
See Text, page 175

Figure 203



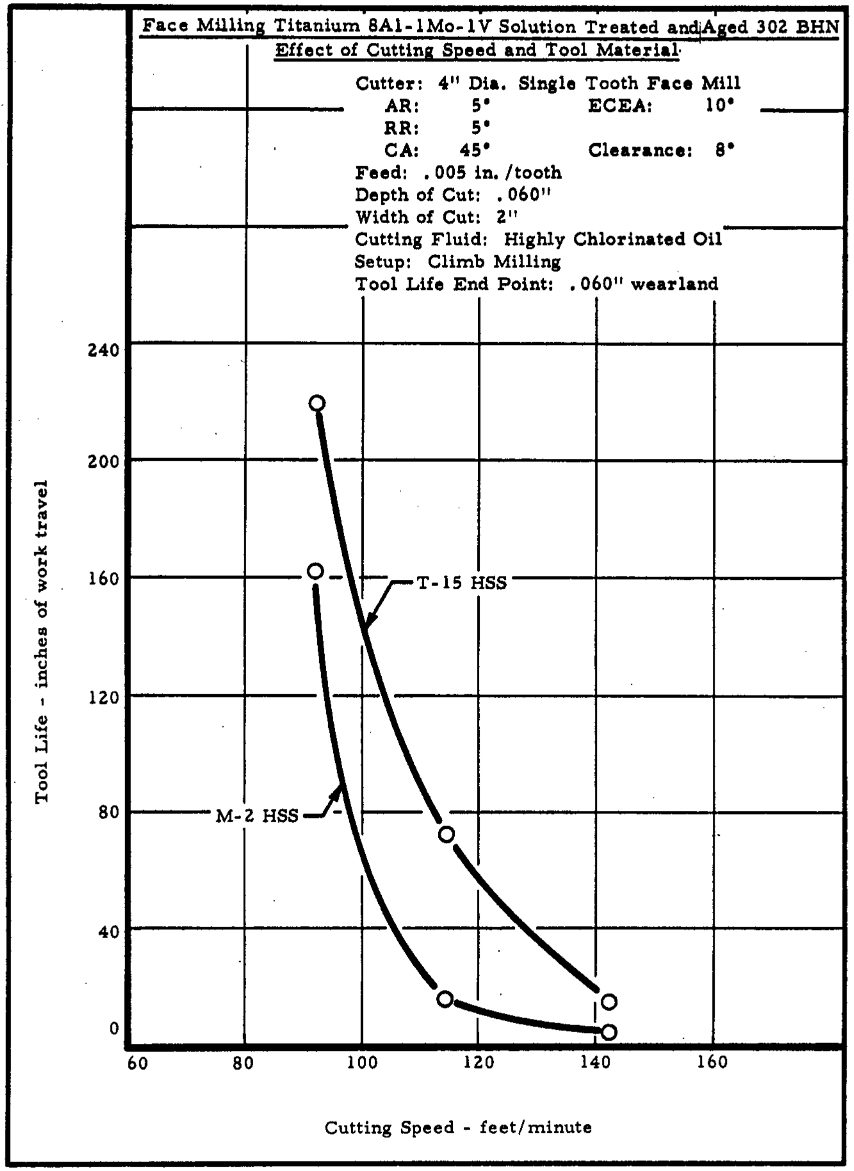
See text, page 175

Figure 204



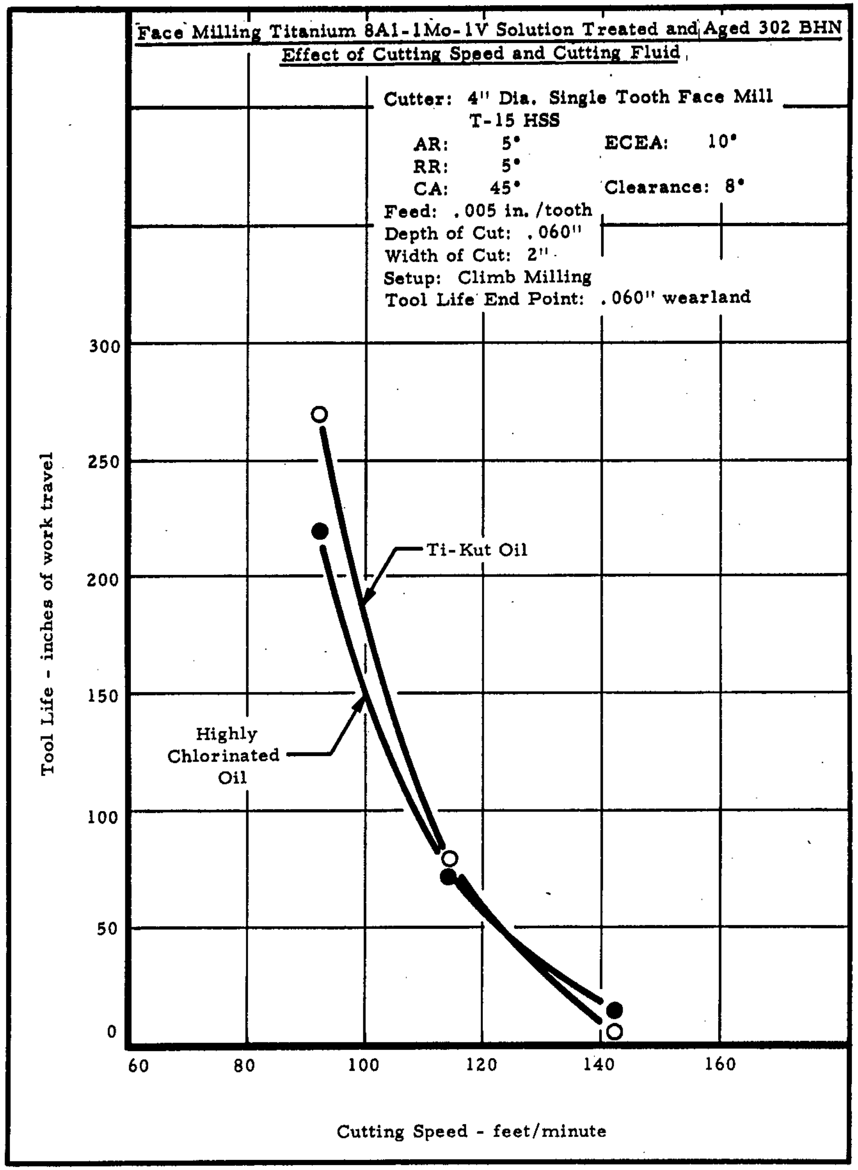
See text, page 175

Figure 205



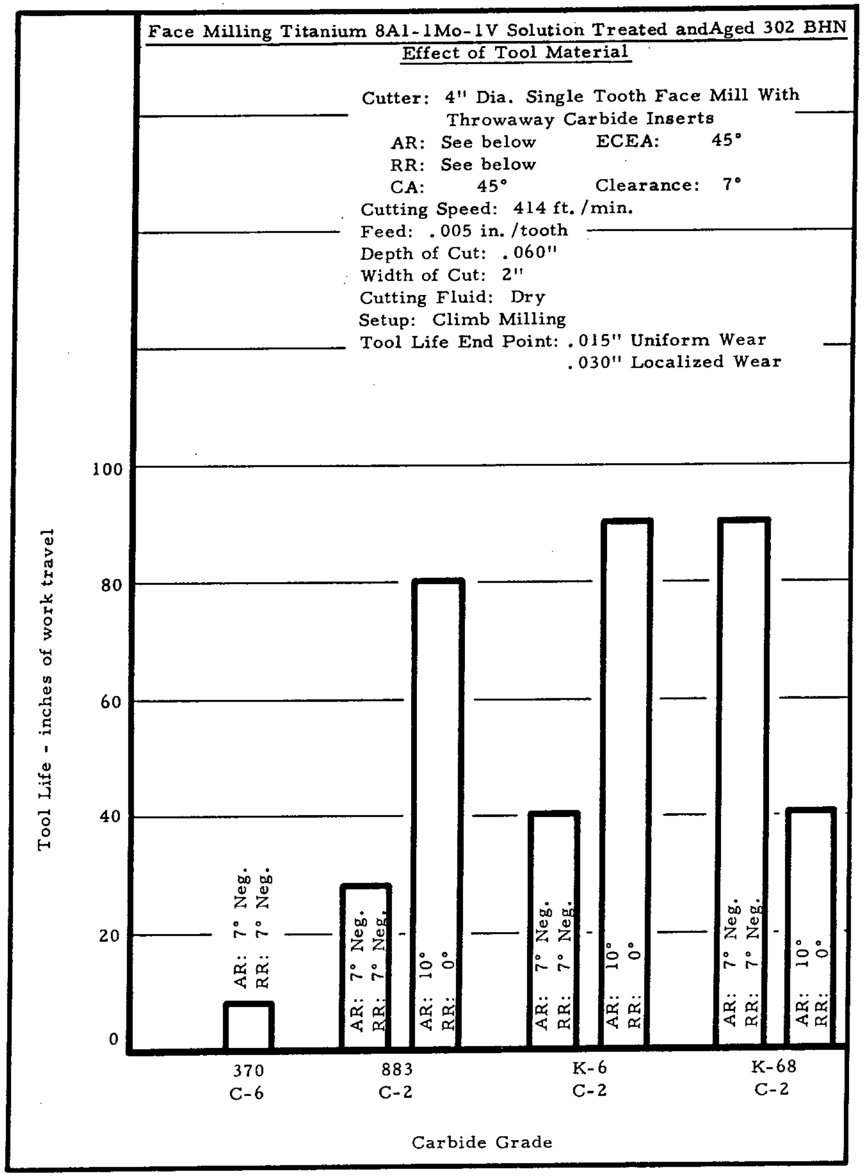
See text, page 175

Figure 206



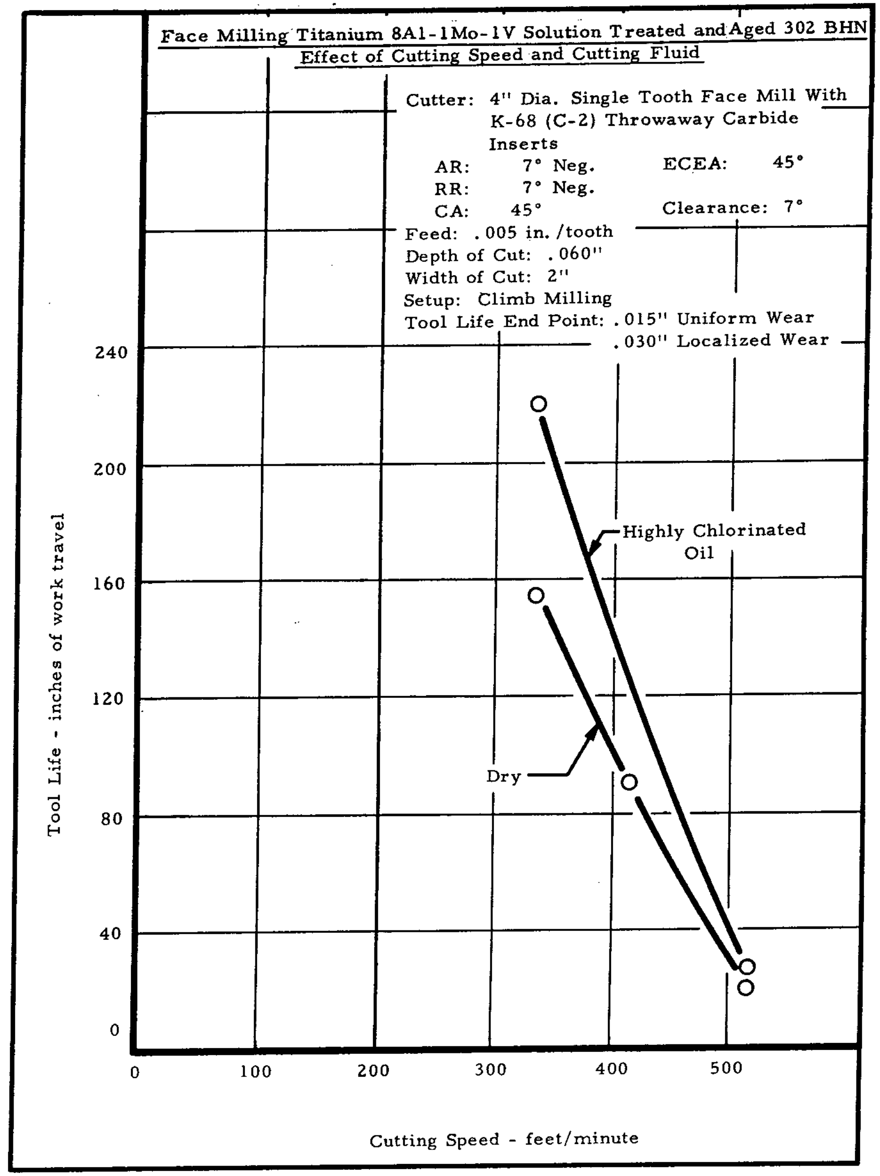
See text, page 175

Figure 207



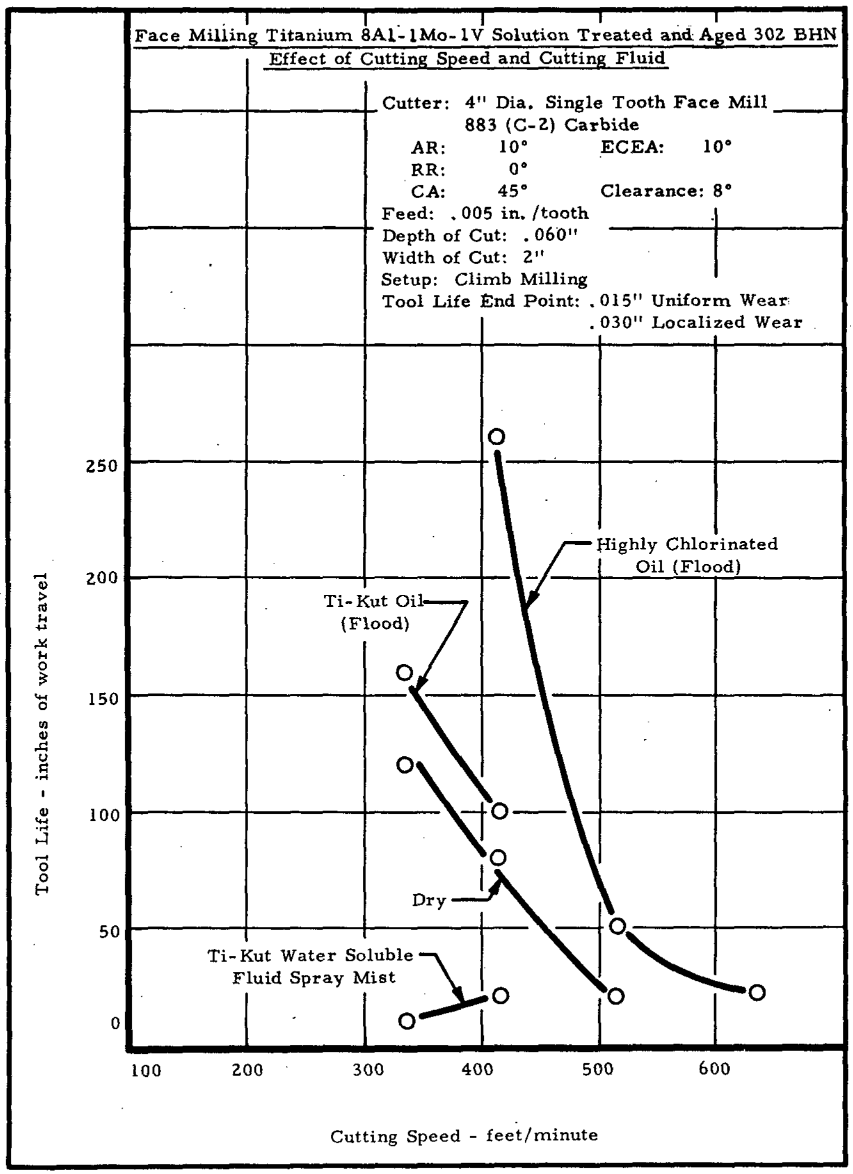
See text, page 175

Figure 208



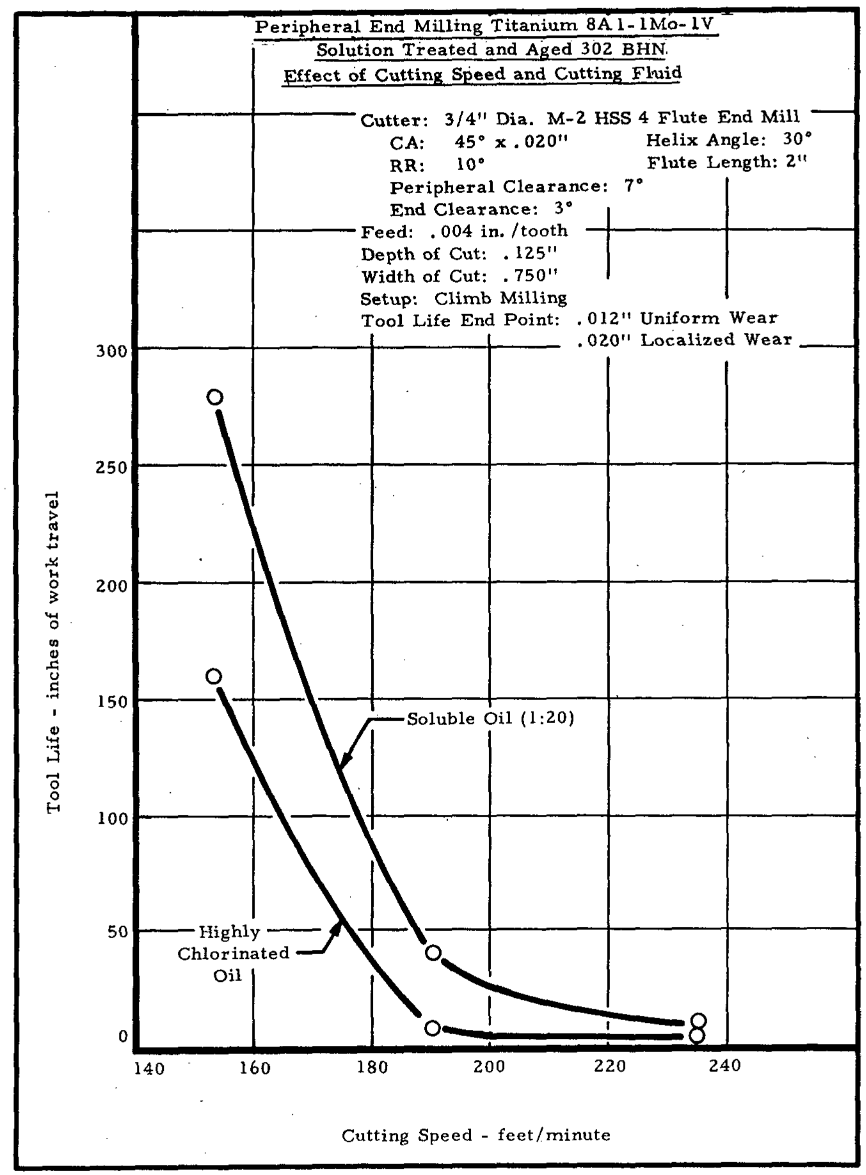
See text, page 175

Figure 209



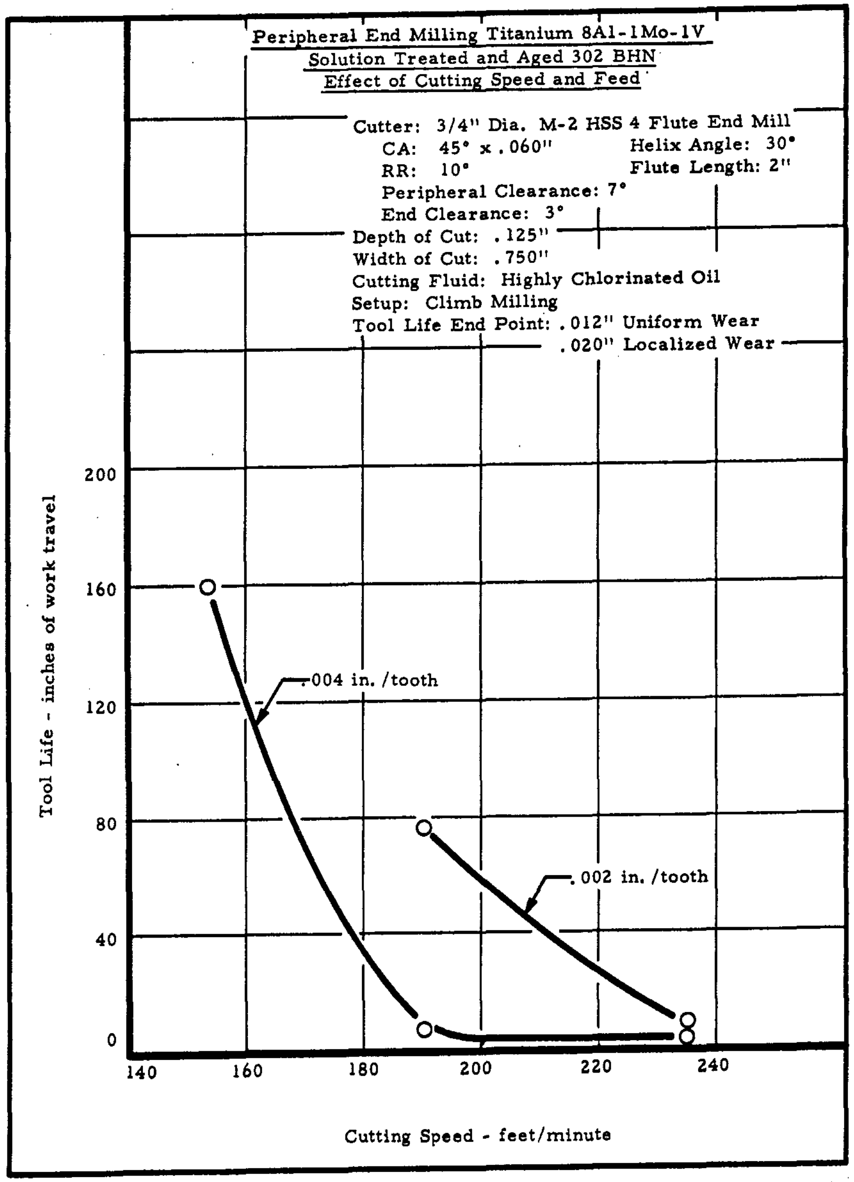
See text, page 175

Figure 210



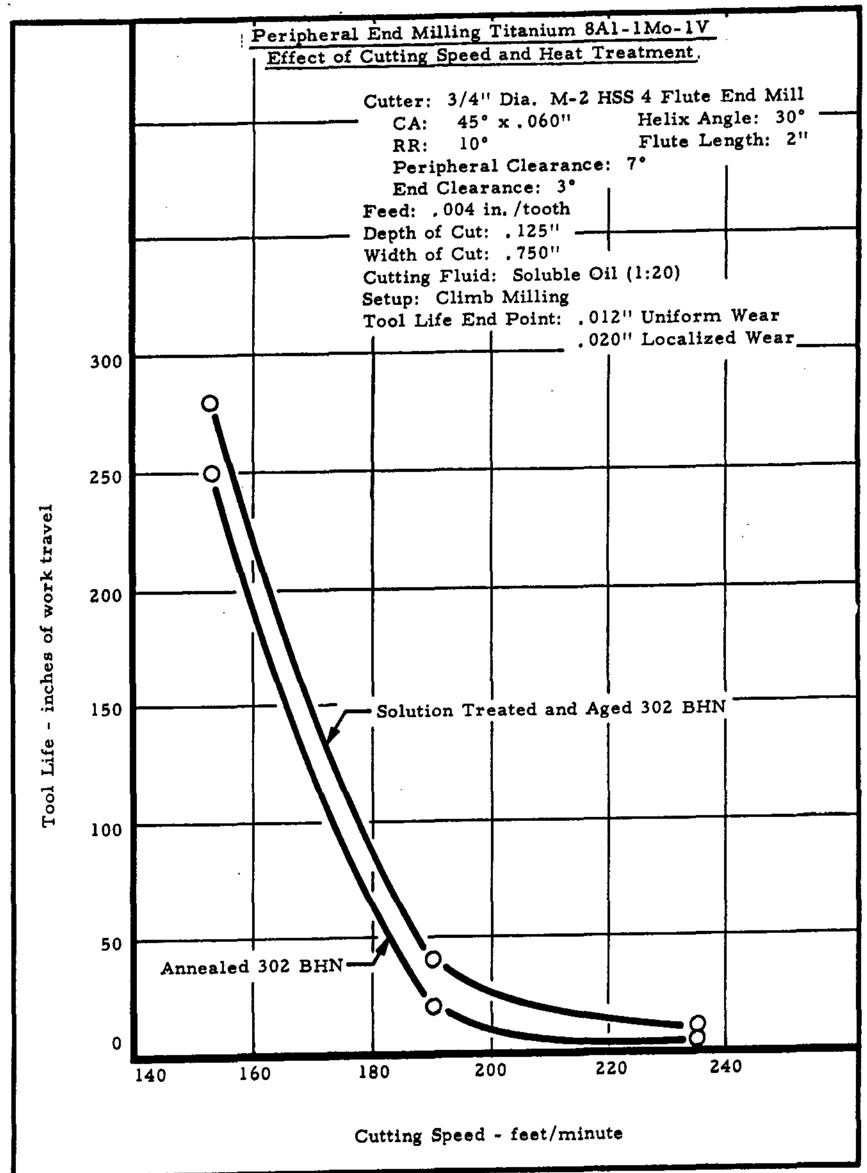
See text, page 176

Figure 211



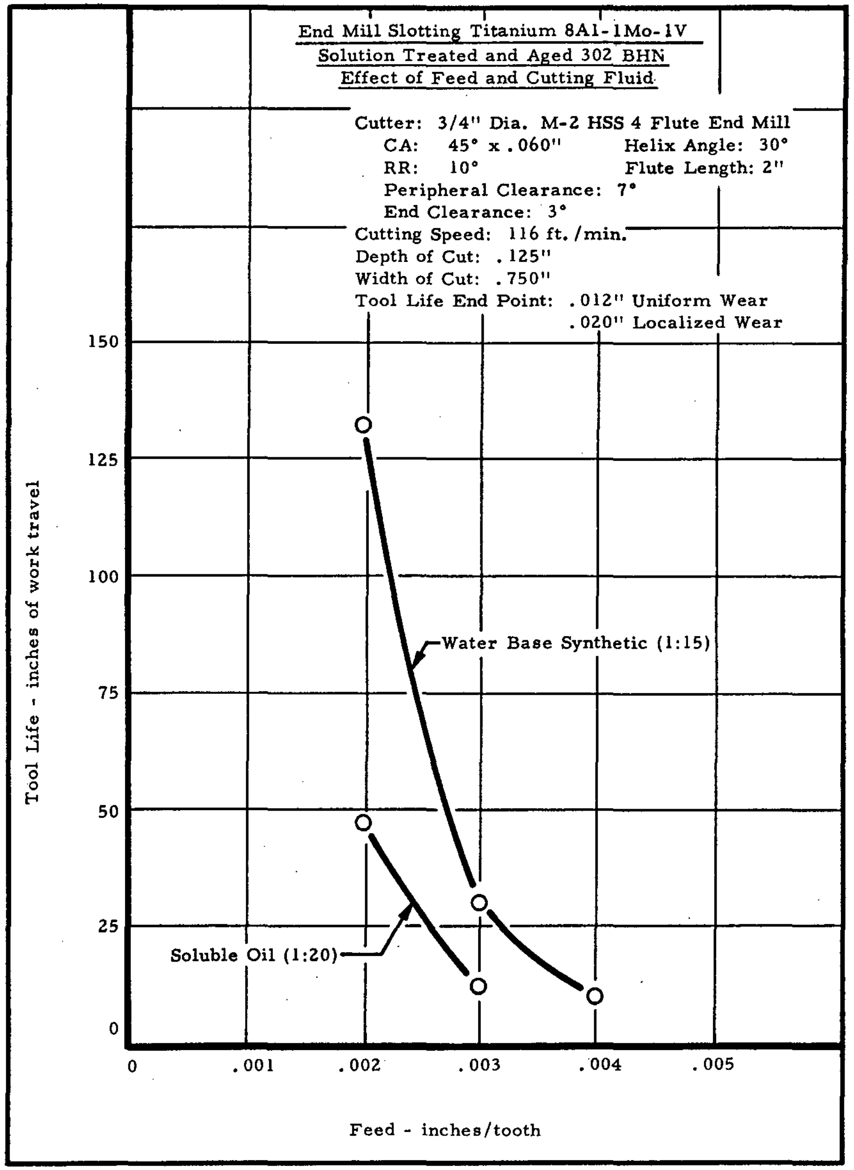
See text, page 176

Figure 212



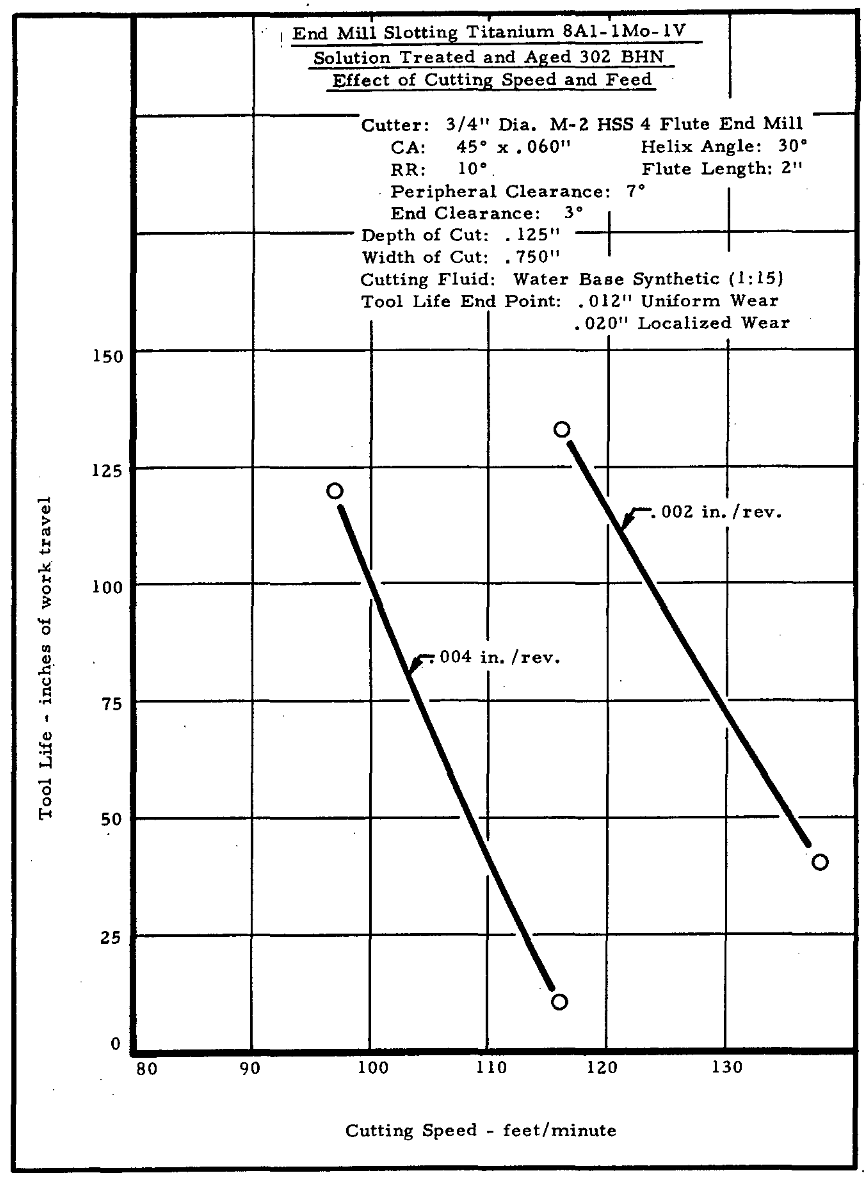
See text, page 176

Figure 213



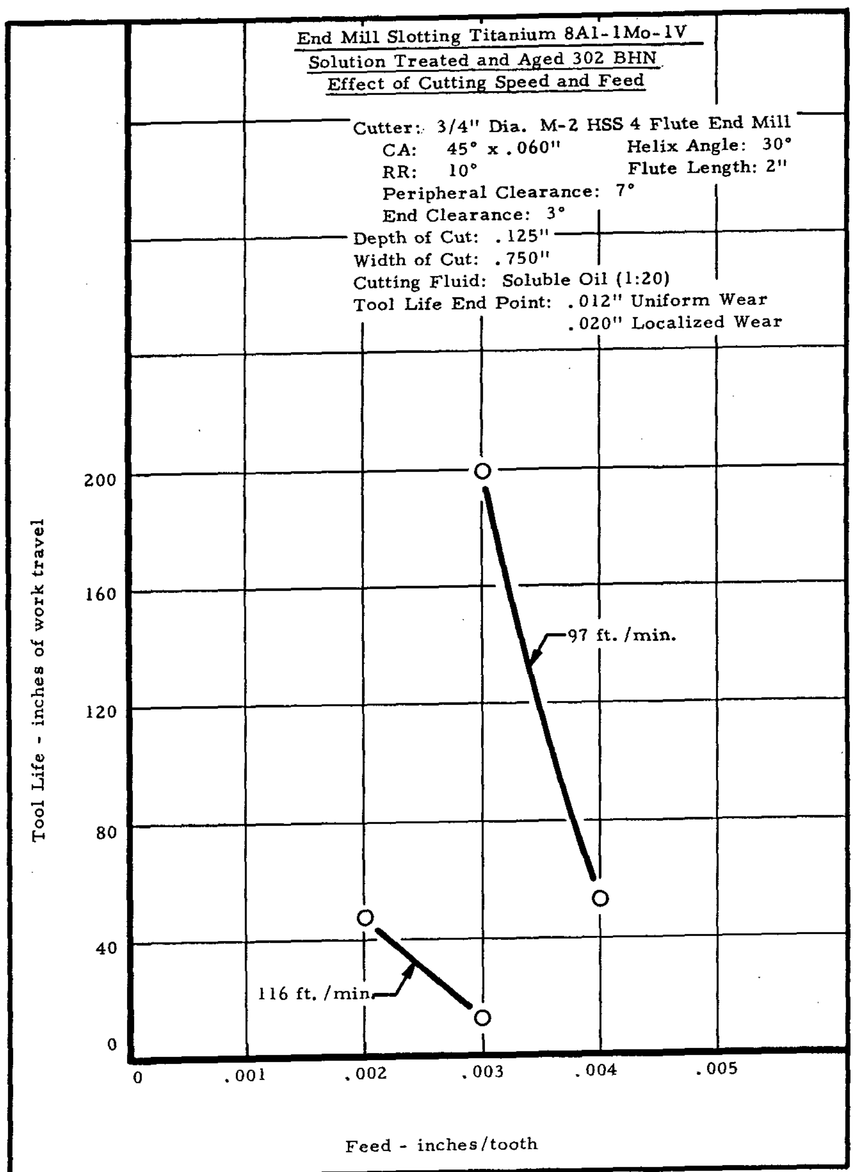
See text, page 176

Figure 214



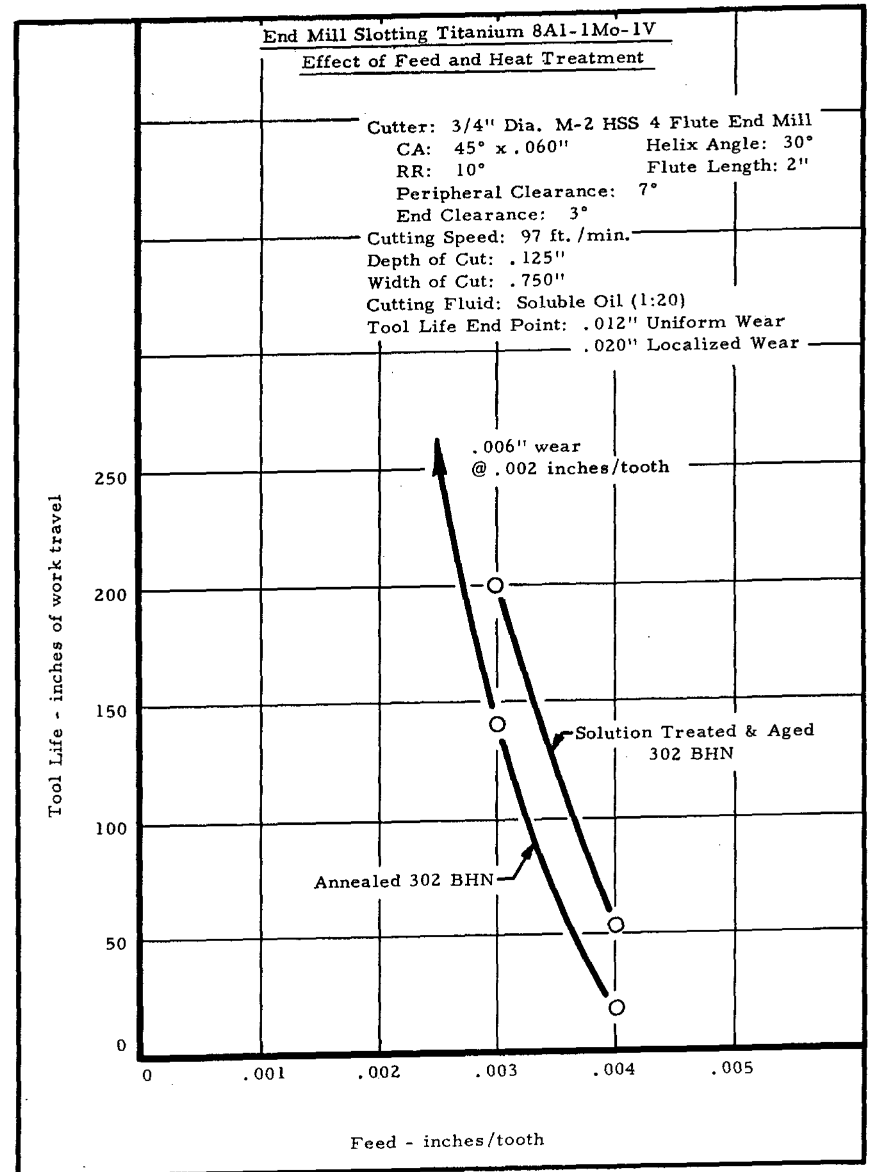
See text, page 176

Figure 215



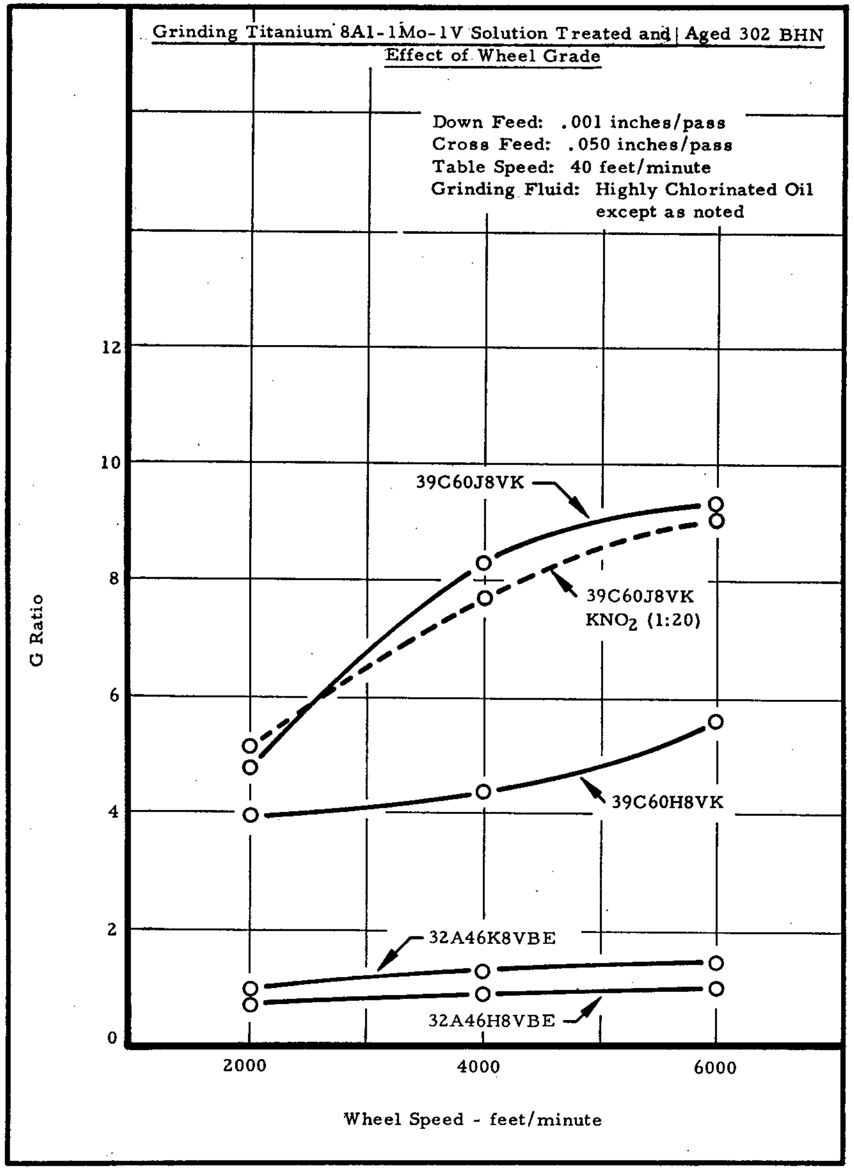
See text, page 176

Figure 216



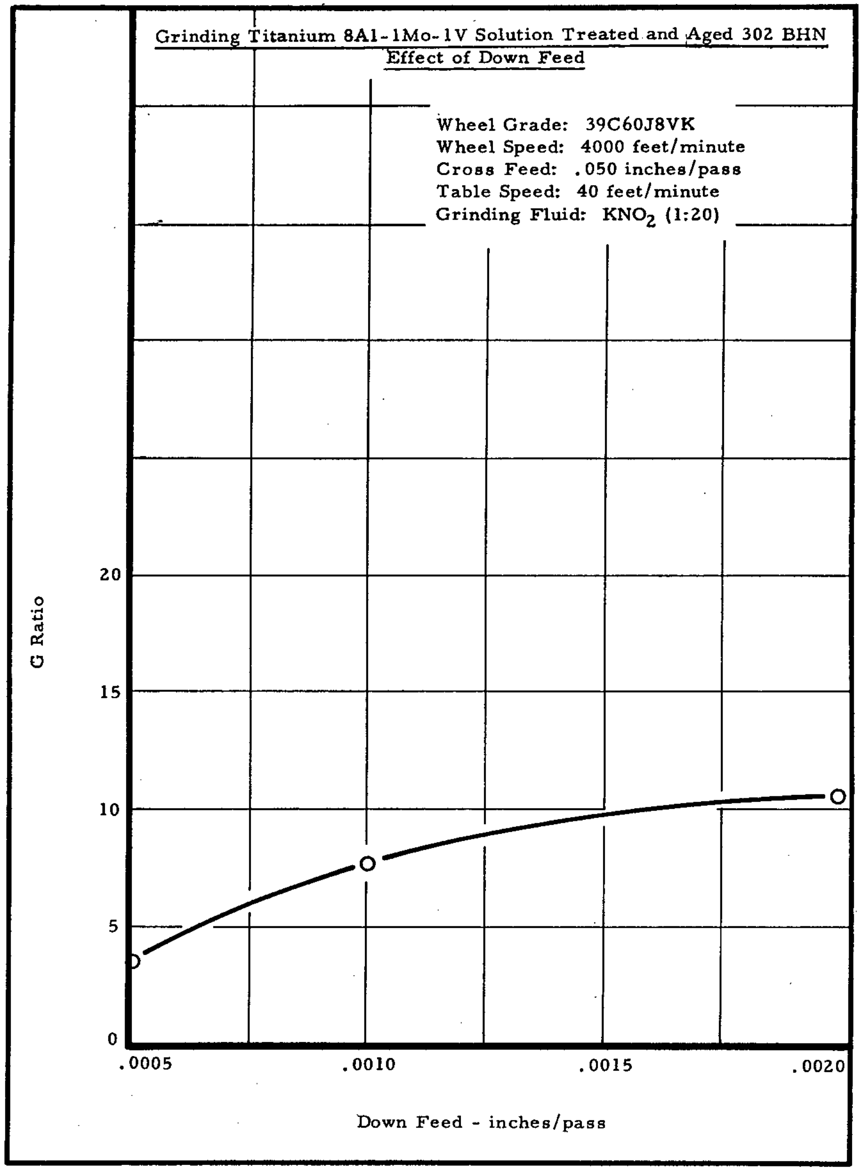
See text, page 176

Figure 217



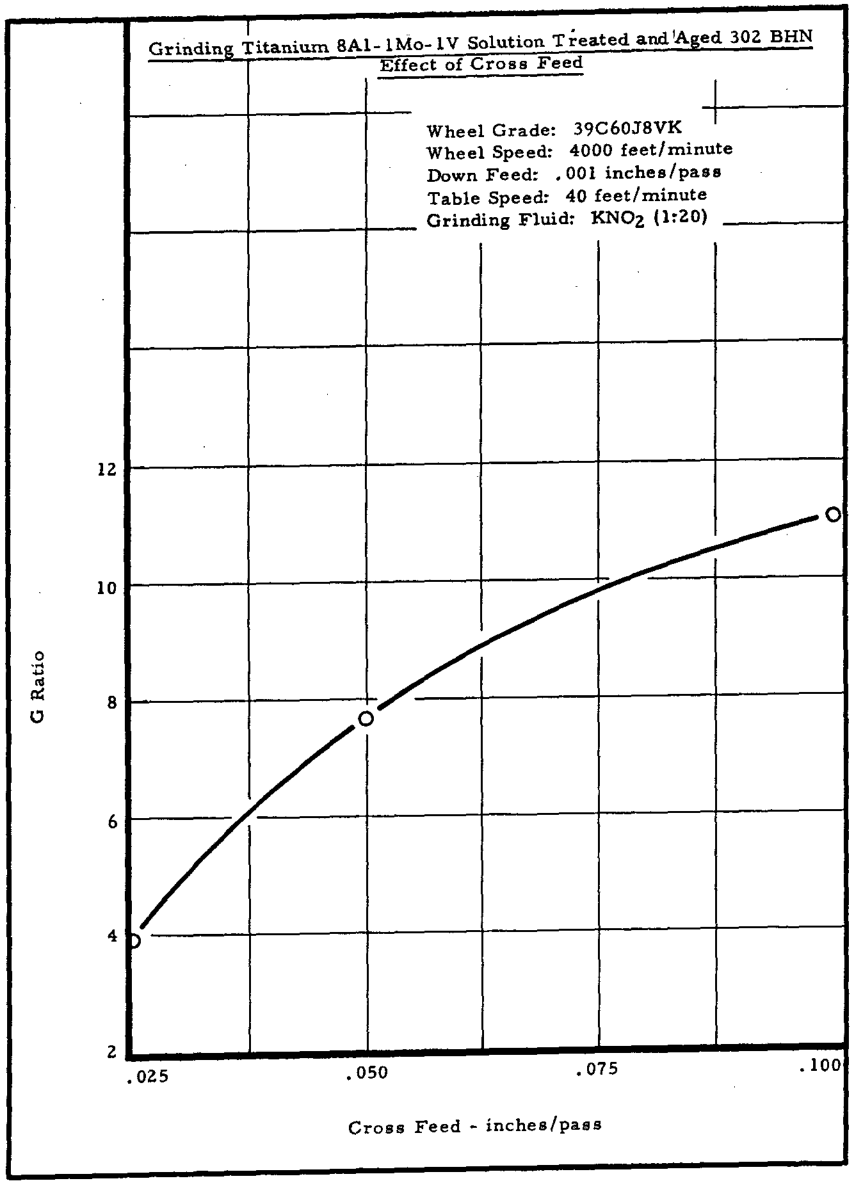
See text, page 176

Figure 218



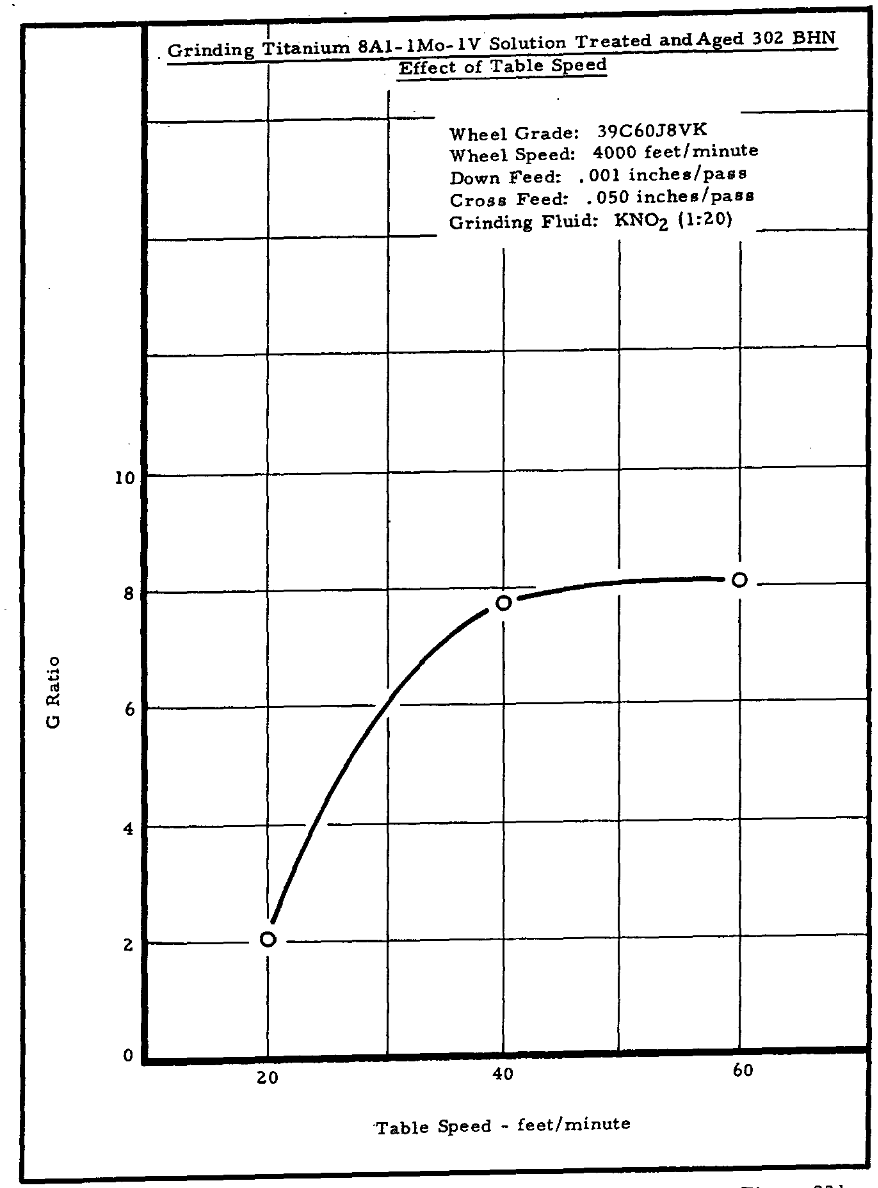
See text, page 177

Figure 219



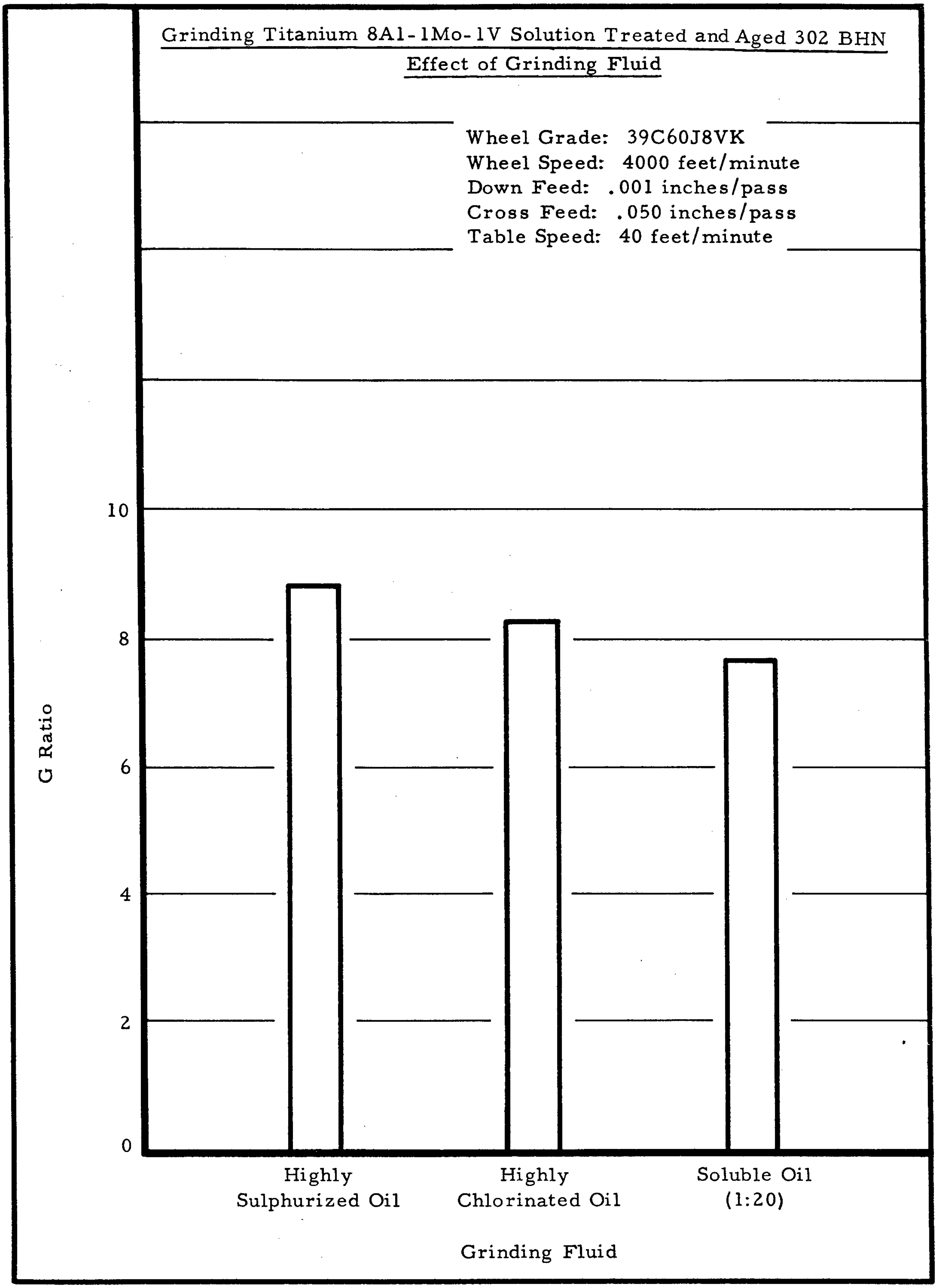
See text, page 177

Figure 220



See text, page 177

Figure 221



See text, page 177

Figure 222

4.2 Titanium 6Al-6V-2Sn

Alloy Identification

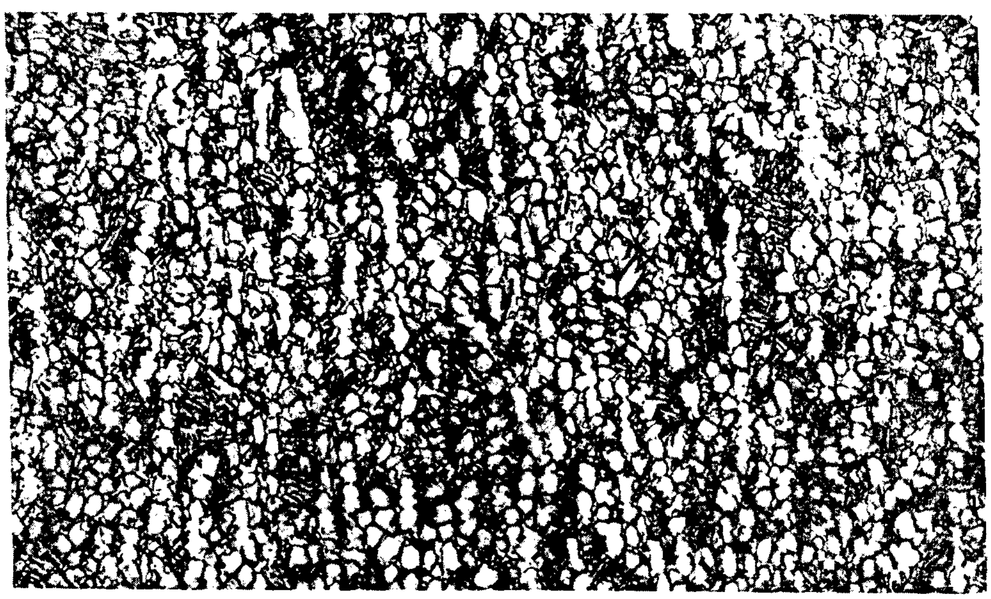
Titanium 6Al-6V-2Sn is an alpha beta titanium alloy which exhibits high strength at elevated temperatures. The nominal composition of this alloy is as follows:

Ti - 5.6 Al - 5.6 V - 2.0 Sn -.73 Fe - .71 Cu - .023 C

The material for turning tests was procured as 3" diameter bar stock in the forged, mill annealed condition. The material for drilling tests was obtained by sectioning 1/2" thick discs from the 3" diameter bar stock.

The hardness of the as received material was 331 BHN.

Exhibited below is the microstructure of this alloy, which consists primarily of alpha platelets precipitated from the beta phase.



Titanium 6Al-6V-2Sn, Annealed

Etchant: $HF-HNO_3$-Glycerol   Mag: 500X

4.2 Titanium 6Al-6V-2Sn (continued)

In order to compare the turning characteristics of the solution treated and aged to the forged annealed condition, some previously annealed bars were heat treated as follows:

Solution Treated:	1650°F/1 hour/water quench
Aged:	1000°F/6 hours/air cool

The resulting hardness was 429 BHN.

The solution treated and aged structure, illustrated below, is composed of primary alpha, retained beta, and a fine alpha precipitate (which is formed from the beta). This fine precipitate is the active constituent in the age hardening reaction that promotes strength.

Titanium 6Al-6V-2Sn Solution Treated and Aged

Etchant: HF-HNO_3-Glycerol Mag: 500X

Turning (Annealed 331 BHN)

Tool life curves for turning titanium 6Al-6V-2Sn in the annealed condition with T-15 and M-2 HSS tools are shown in Figure 223, page 196. There was an insignificant difference in the results obtained with these two types of HSS tools.

4.2 Titanium 6Al-6V-2Sn (continued)

The relationship between tool life and feed when using a carbide tool in turning the alloy is shown in Figure 224, page 196. A marked increase in tool life resulted as the feed was decreased from .015 to .005 in./rev. A comparison is made in Figure 225, page 197, of two different types of cutting fluids used in turning the titanium; one is a soluble oil diluted 1:20, while the other one was Ti-Kut oil. There was no appreciable difference between the two cutting fluids in this turning operation.

Drilling (Annealed 331 BHN)

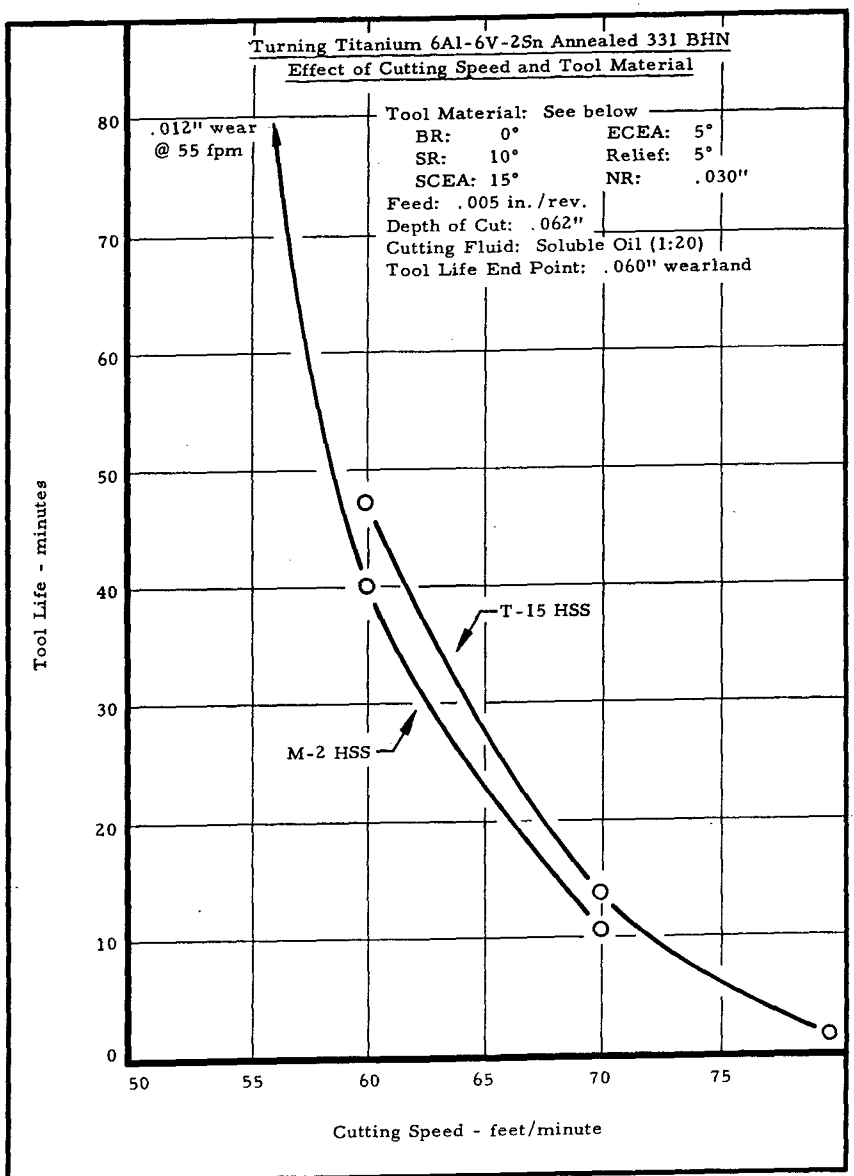
Note in Figure 226, page 197, the marked decrease in drill life with a 10% increase in cutting speed. Under the conditions shown, the drill life was 125 holes at a cutting speed of 40 ft./min. and only 11 holes at 45 ft./min.

TABLE 13

RECOMMENDED CONDITIONS FOR MACHINING
TITANIUM 6Al-6V-2Sn ANNEALED 331 BHN

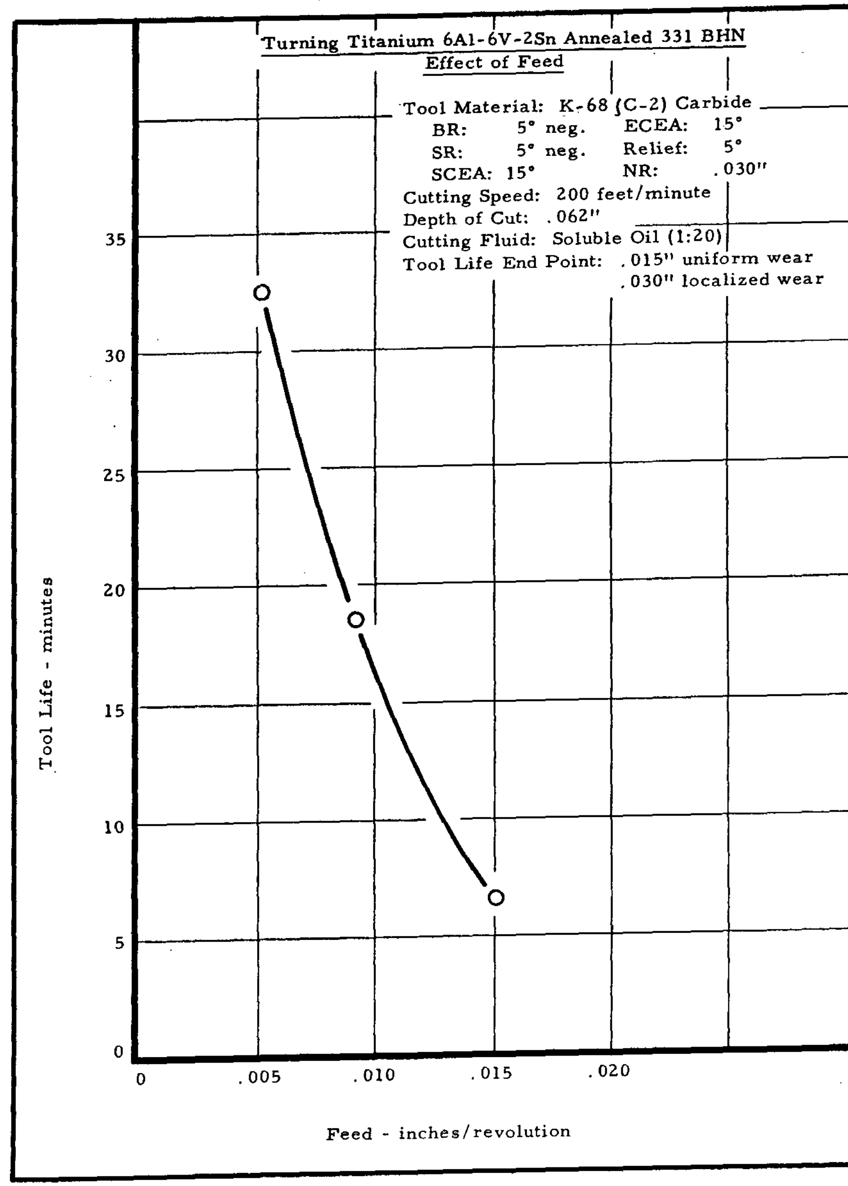
Al	V	Sn	Fe	Cu	C	Ti
5.6	5.6	2.0	.73	.71	.023	Bal.

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	M-2 HSS	BR: 0° SCEA: 15° SR: 10° ECEA: 5° Relief: 5° NR: .030"	5/8" square tool bit	.062	--	.005 in./ rev.	55	80 min.	.012	Soluble Oil (1:20)
Turning	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square throwaway insert	.062	--	.005 in./ rev.	200	33 min.	.015	Soluble Oil (1:20)
Drilling	M-1 HSS	118° plain point 7° clearance	1/4" diameter HSS drill 2-1/2" long	.500 thru	--	.005 in./ rev.	40	125 holes	.015	Highly Chlorinated Oil



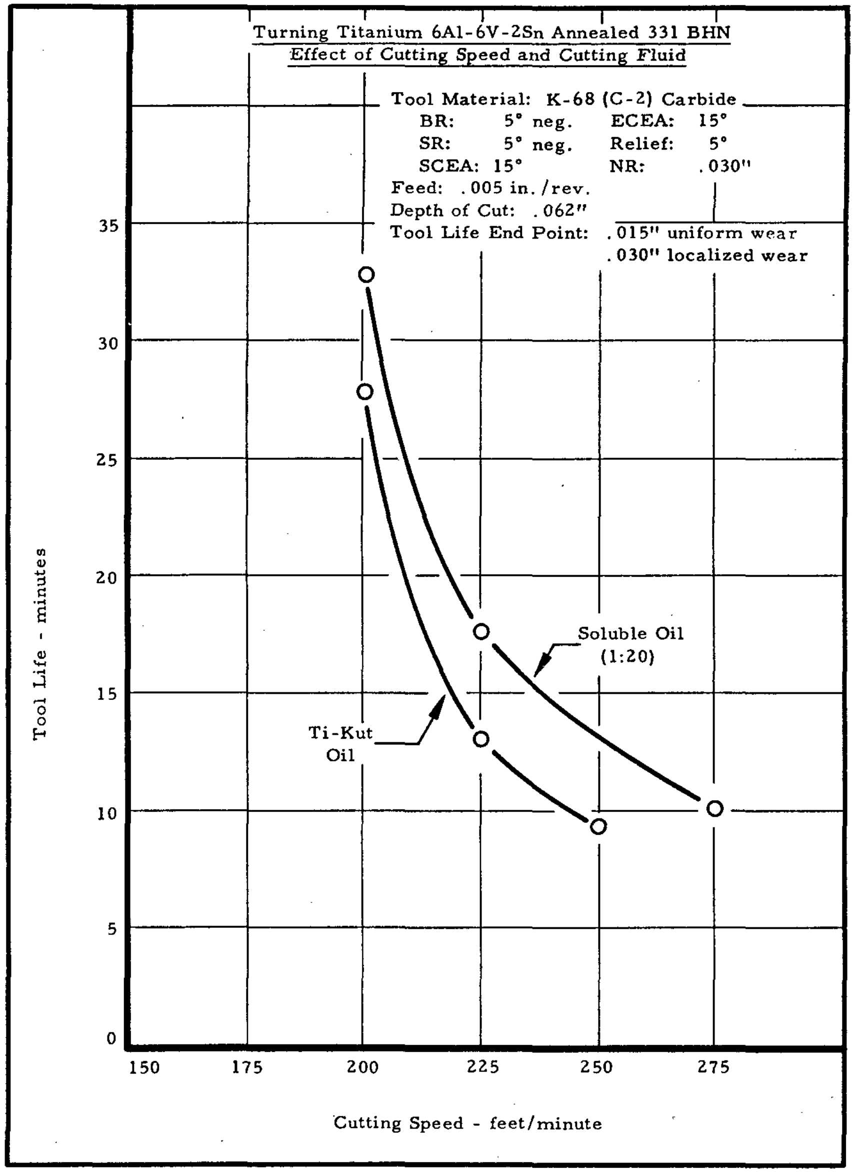
See text, page 193

Figure 223



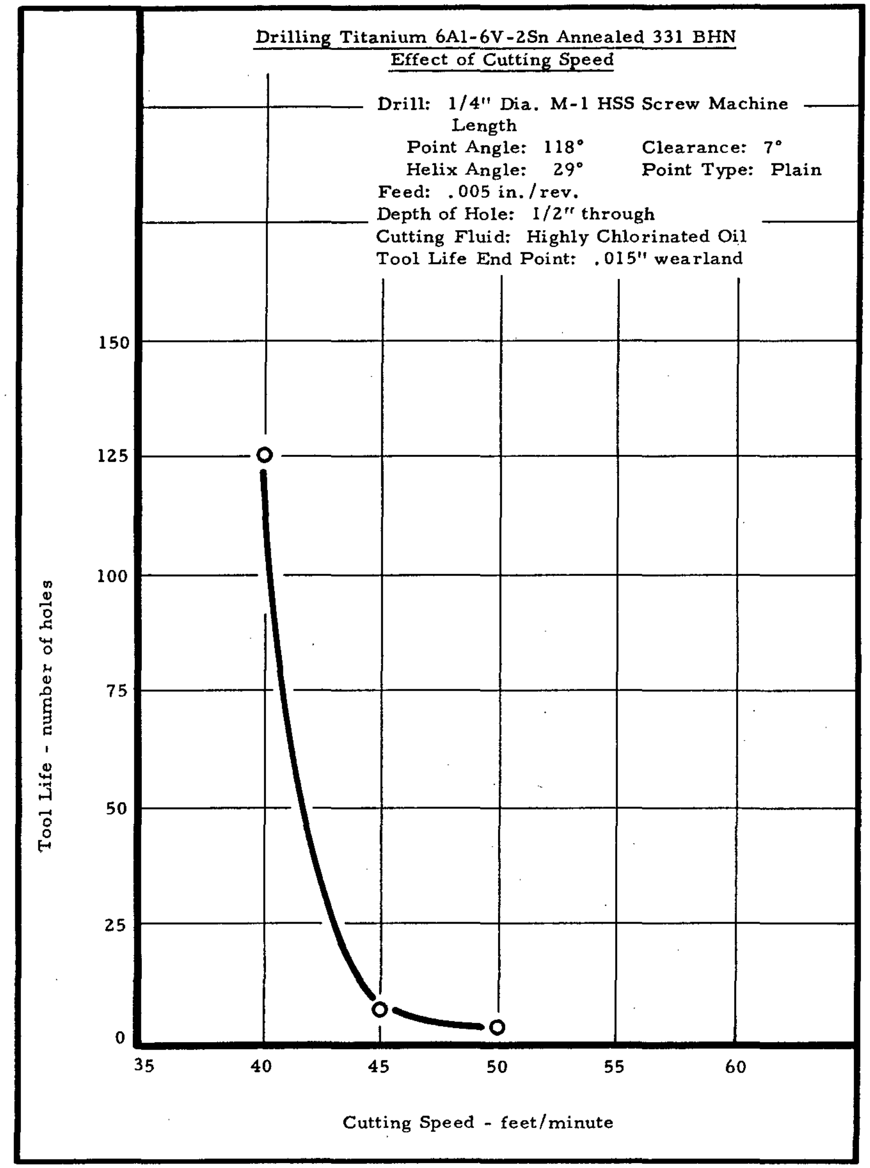
See text, page 194

Figure 224



See text, page 194

Figure 225



See text, page 194

Figure 226

4.2 Titanium 6Al-6V-2Sn (continued)

Turning (Solution Treated and Aged 429 BHN)

The importance of turning titanium 6Al-6V-2Sn in the solution treated and aged condition at low feeds is illustrated in Figure 227, page 200. The tool life dropped from 38 minutes at a feed of .005 in./rev. to 6 minutes at a feed of .009 in./rev. A comparison of two different grades of carbide in Figure 228, page 200, shows that grade 883 was appreciably better than grade K-68.

A comparison of the tool life curves obtained in turning the titanium alloy in the annealed (331 BHN) and the solution treated and aged (429 BHN) conditions is shown in Figure 229, page 201. Note that the alloy in the annealed condition can be turned at a 50% higher cutting speed than the alloy in the solution treated and aged condition.

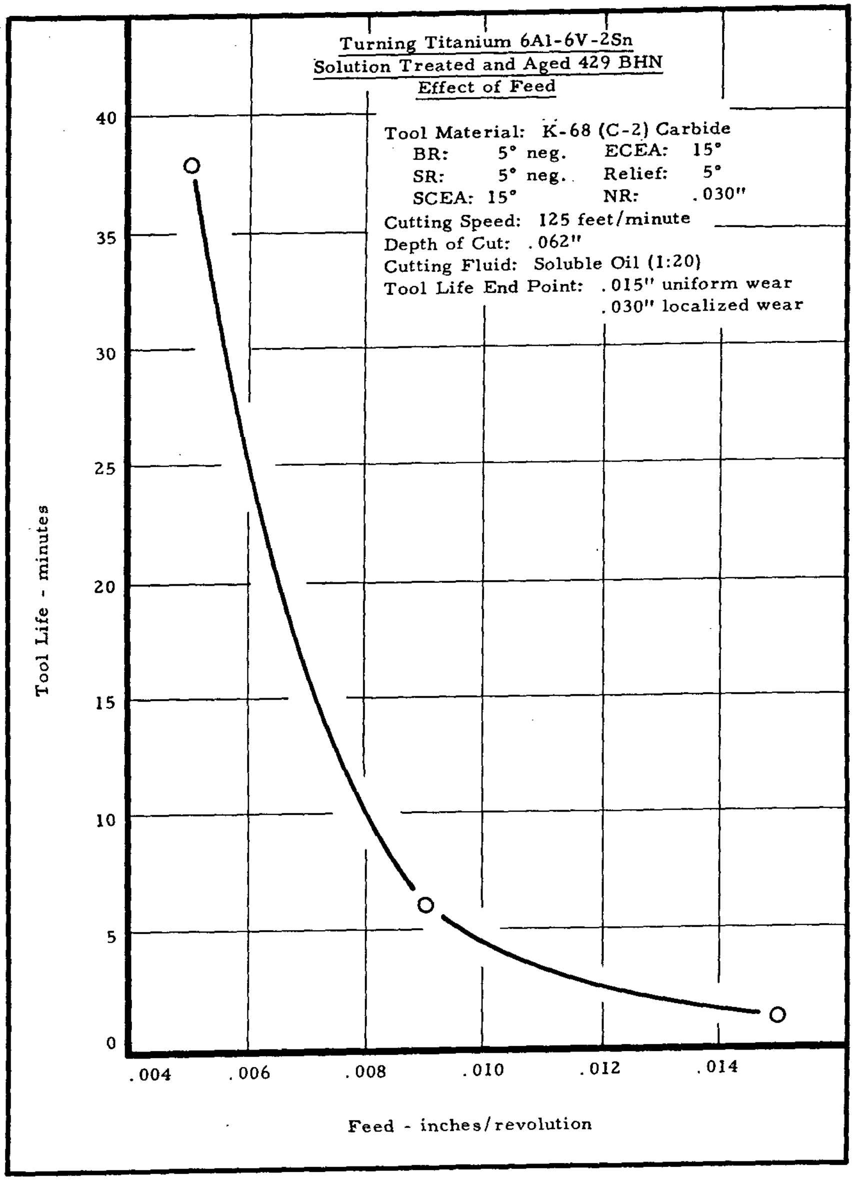
TABLE 14

RECOMMENDED CONDITIONS FOR MACHINING

TITANIUM 6 Al - 6V - 2 Sn - SOLUTION TREATED & AGED - 429 BHN

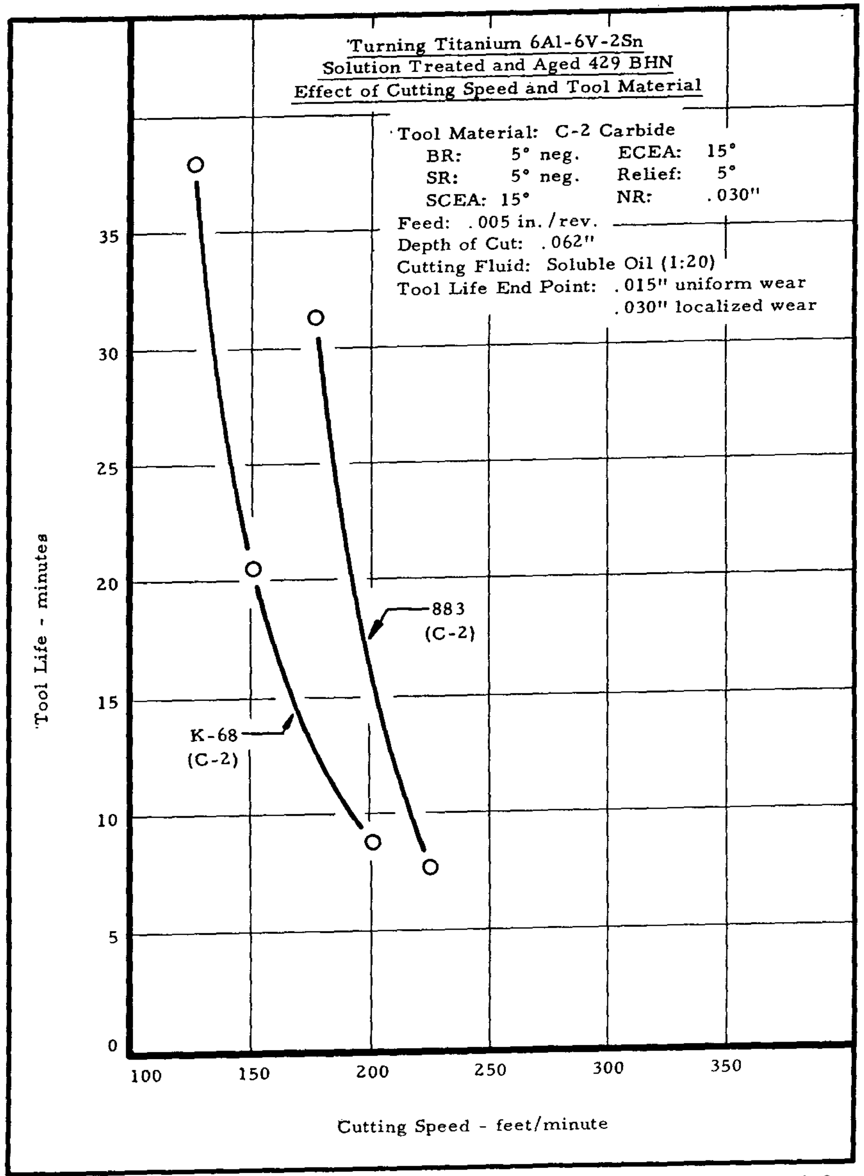
Al	V	Sn	Fe	Cu	C	Ti
5.6	5.6	2.0	.73	.71	.023	Bal

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	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square Throw-away insert	.062	-	.005 in./rev.	175	32 min.	.015	Soluble Oil (1:20)



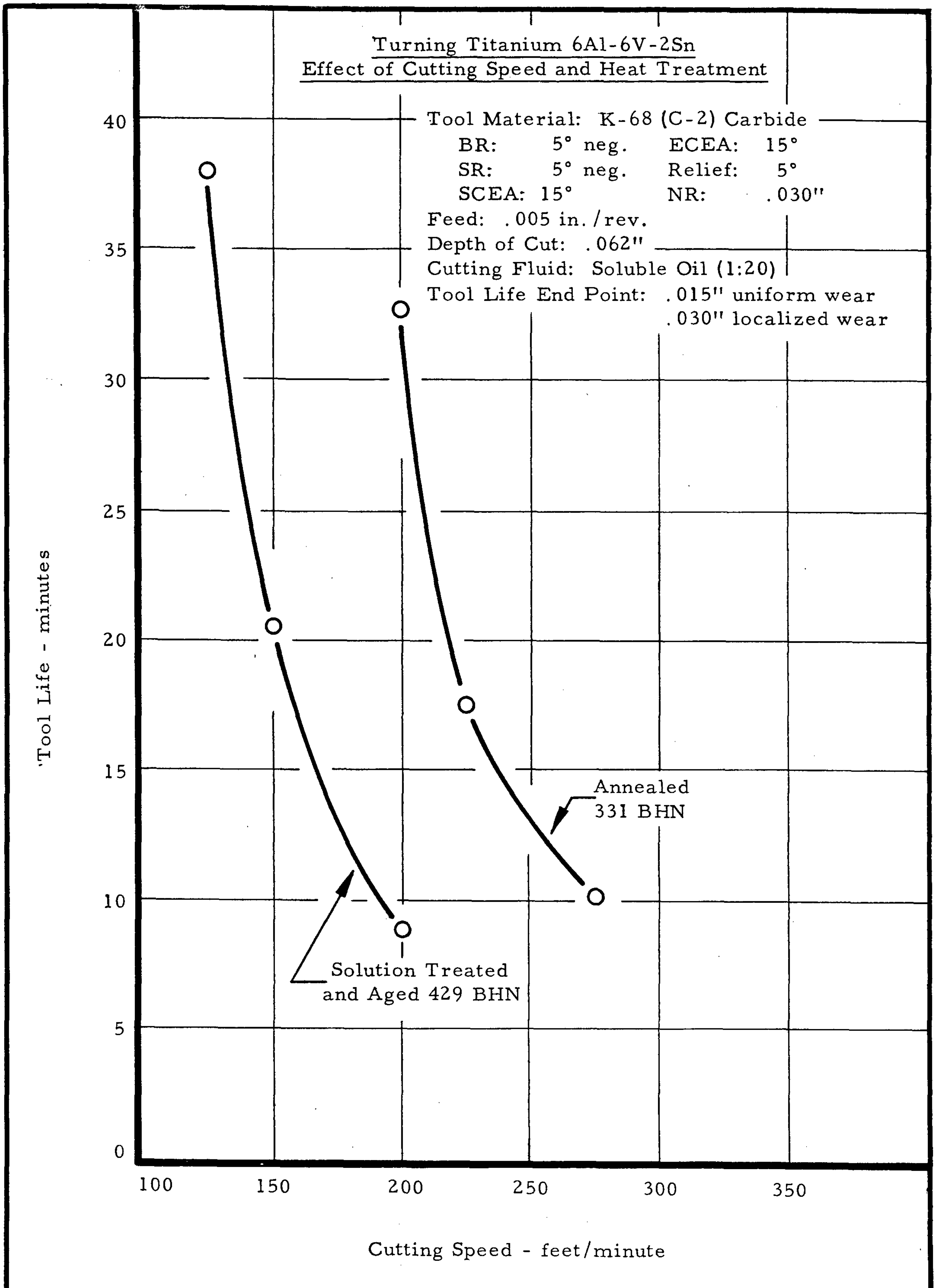
See text, page 198

Figure 227



See text, page 198

Figure 228



See text, page 198

Figure 229

4.3 Titanium 7Al-4Mo

Alloy Identification

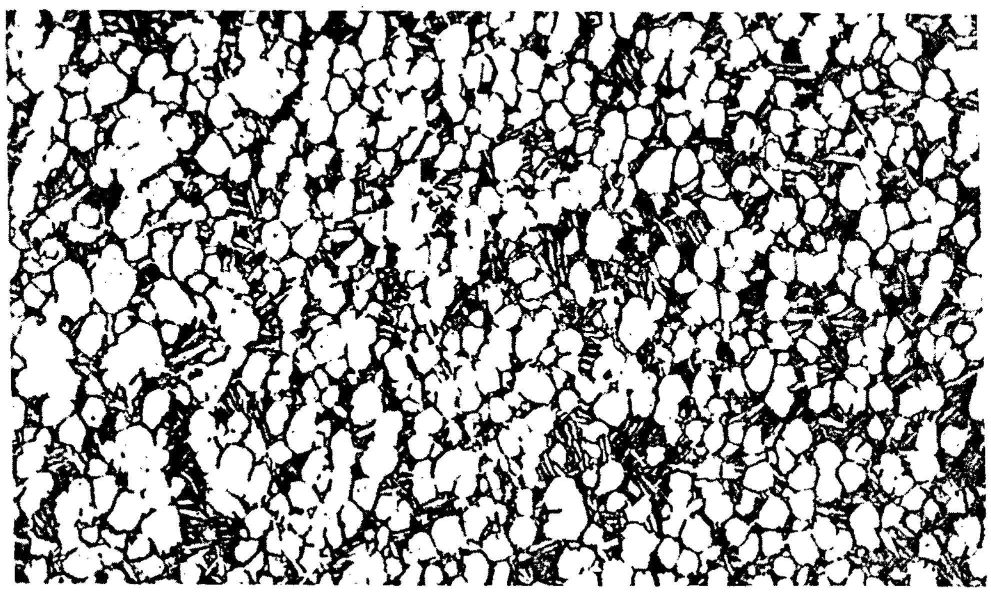
Titanium 7Al-4Mo is an alpha beta titanium alloy heat treatable to high strength levels. A significant advantage of the alloy is considerable high strength at elevated temperatures. Its nominal composition is as follows:

Ti - 6.8 Al - 4.2 Mo - .13 Fe - .024 C

The material for turning tests was procured as 3" diameter bar stock in the forged, mill annealed condition.

The as received hardness was 341 BHN.

The microstructure, illustrated below, consists of primary alpha platelets in a beta matrix.



Titanium 7Al-4Mo, Annealed

Etchant: HF, 2% Mag: 500X

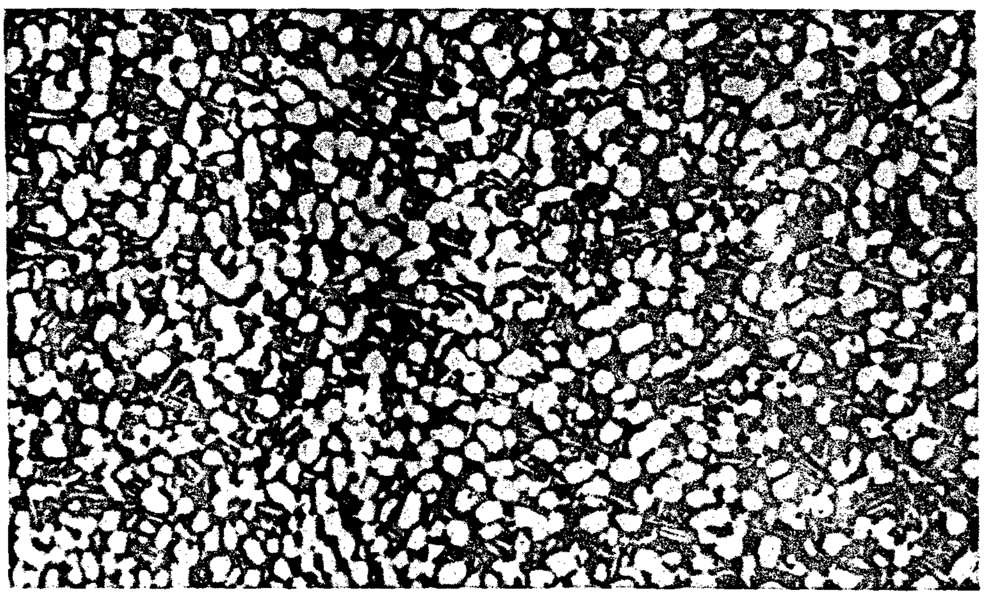
4.3 Titanium 7Al-4Mo (continued)

In order to compare the solution treated and aged condition to the forged, mill annealed condition, some previously mill annealed bars were solution treated and aged as follows:

Solution Treated:	1700°F/1 hour/water quench
Aged:	1100°F/8 hours/air cool

The resulting hardness was 388 BHN.

The resulting microstructure, which is illustrated below, consists of alpha platelets in a beta matrix with some alpha-prime precipitates.



Titanium 7Al-4Mo Solution Treated and Aged

Etchant: HF 2% Mag: 500X

Turning (Annealed 341 BHN)

The feed rate in turning titanium 7Al-4Mo annealed 341 BHN is very critical, as shown in Figure 230, page 206. Tool life dropped from 40 minutes to 9 minutes when the feed was increased from .005 in./rev. to .009 in./rev.

4.3 Titanium 7Al-4Mo (continued)

Several different types of C-2 grades of carbide were used in turning the titanium alloy. At a cutting speed of 250 ft./min., the tool life with the four grades tested ranged from 24 minutes to 40 minutes, see Figure 231, page 206. Grade K-6 carbide provided the longest tool life.

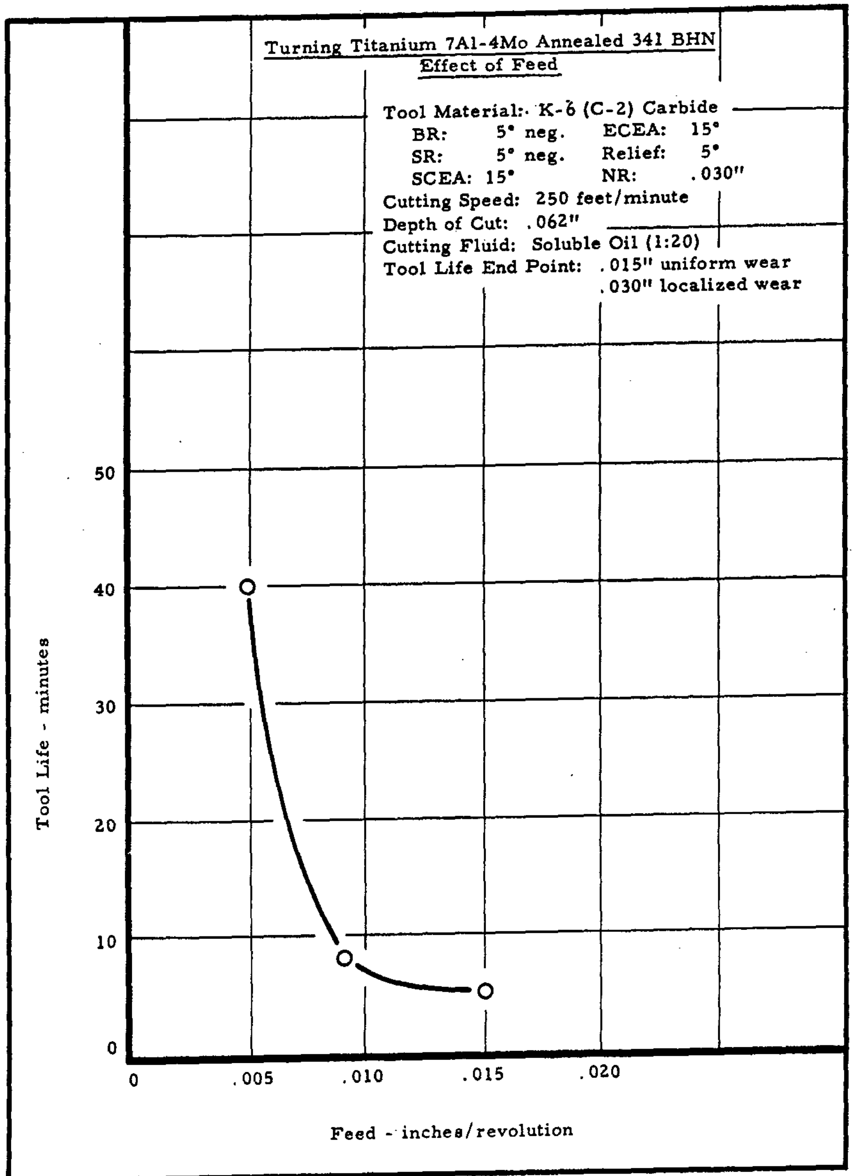
TABLE 15

RECOMMENDED CONDITIONS FOR MACHINING

TITANIUM 7 Al - 4 Mo - ANNEALED 341 BHN

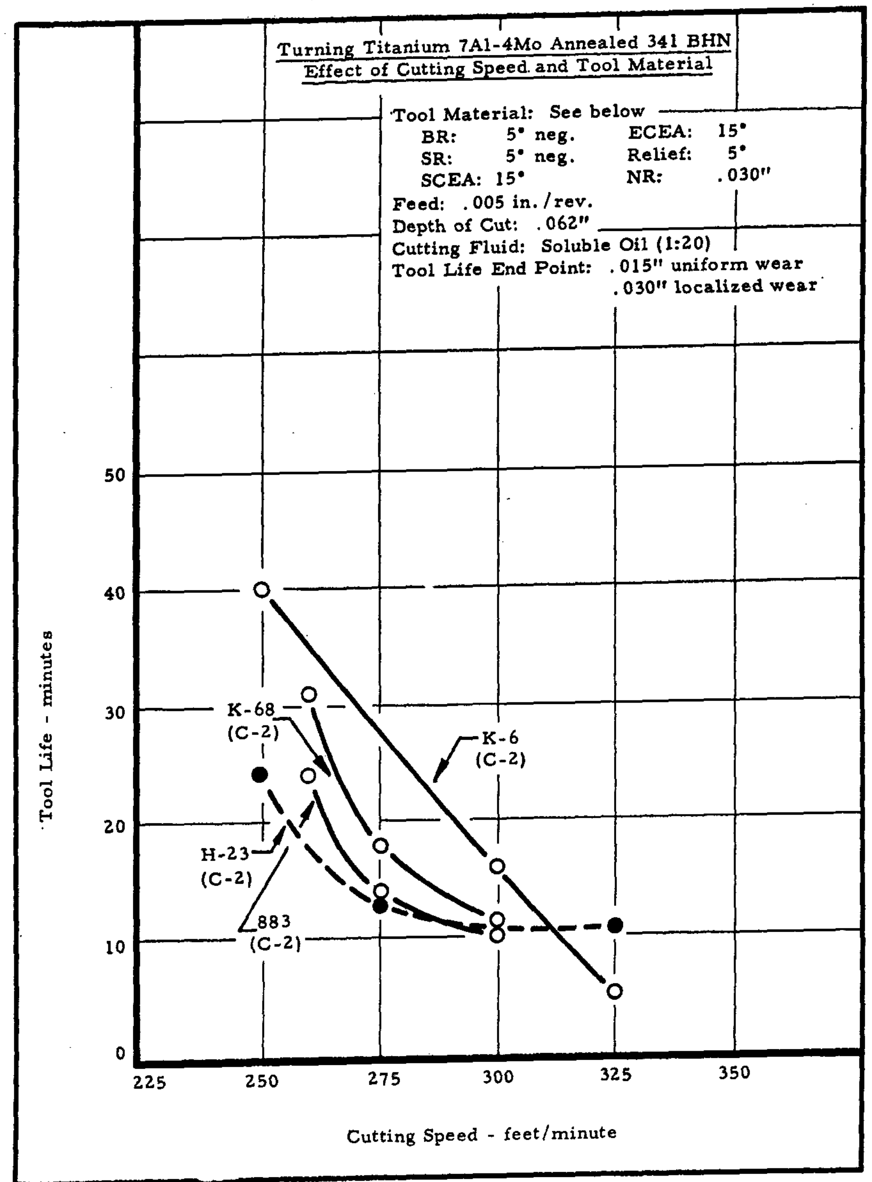
Al	Mo	Fe	C	Ti
6.8	4.2	.13	.024	Bal

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	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square Throw-away insert	.062	-	.005 in./rev.	250	40 min.	.015	Soluble Oil (1:20)



See text, page 203

Figure 230



See text, page 204

Figure 231

4.3 Titanium 7Al-4Mo (continued)

Turning (Solution Treated and Aged 388 BHN)

As has been found in turning other titanium alloys, the feed was very critical. Note in Figure 232, page 209, that the tool life dropped from 50 minutes to 13 minutes when the feed was increased from .005 to .009 in./rev. Figure 233, page 209, shows the performances of four types of C-2 grades of carbide in turning the titanium alloy. At a cutting speed of 200 ft./min., tool life ranged from 18 to 50 minutes, depending on which grade of carbide was used. The grade H-23 provided the longest tool life under the conditions cited in the figure.

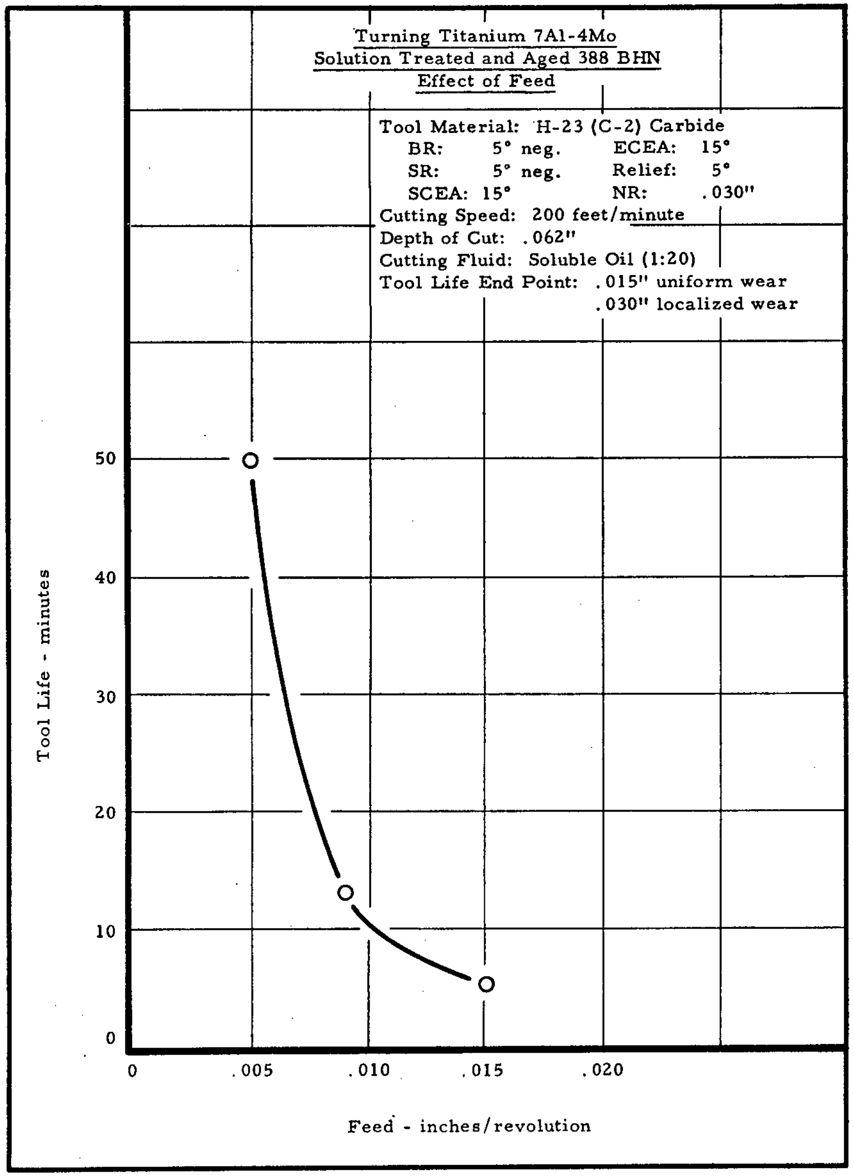
TABLE 16

RECOMMENDED CONDITIONS FOR MACHINING

TITANIUM 7 Al - 4 Mo - SOLUTION TREATED & AGED - 388 BHN

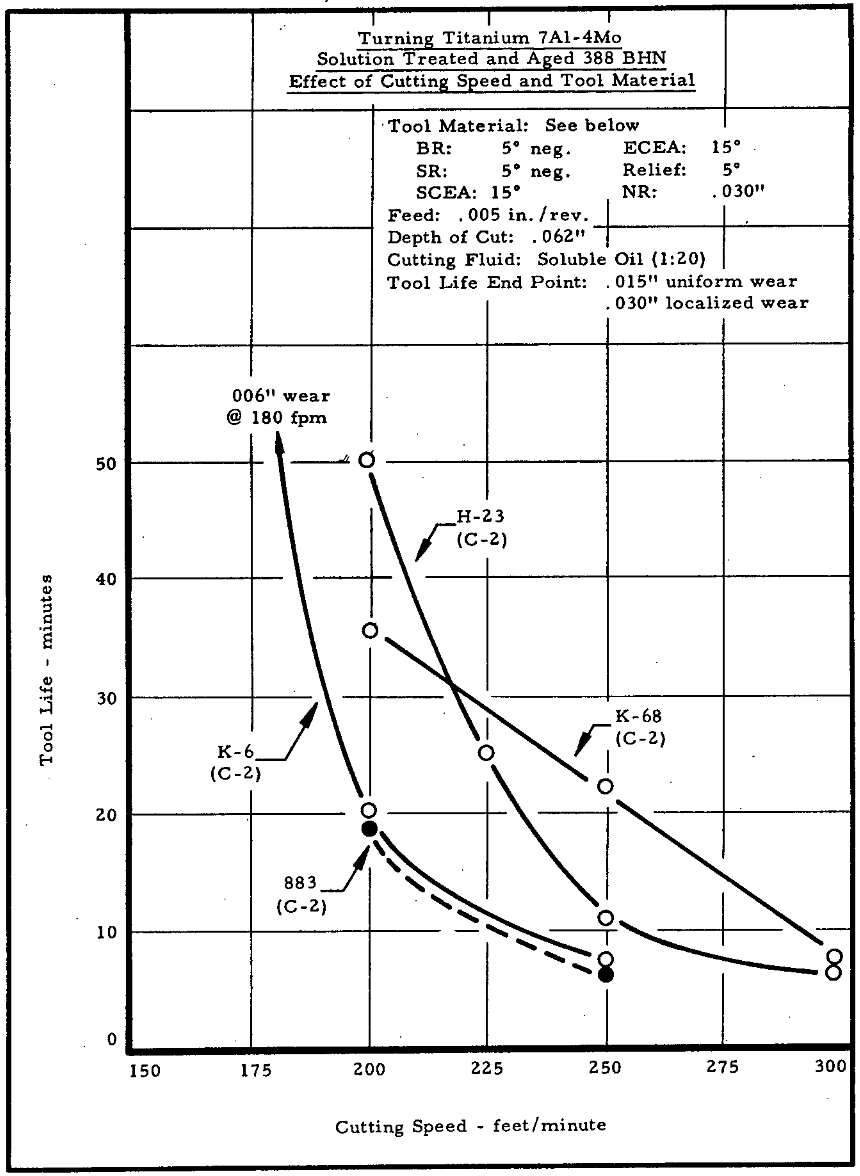
Al	Mo	Fe	C	Ti
6.8	4.2	.13	.024	Bal

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	C-2 Carbide	BR:-5° SCEA: 15° SR:-5° ECEA: 15° Relief: 5° NR: .030"	1/2" square Throw-away insert	.062	-	.005 in./rev.	200	50 min.	.015	Soluble Oil (1:20)



See text, page 207

Figure 232



See text, page 207

Figure 233

5. MACHINING NICKEL BASE ALLOYS

5.1 Inconel 718

Alloy Identification

Inconel 718 is a wrought high temperature alloy useful in the intermediate temperature range up to about 1500°F. The material has the following nominal composition:

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

Hot rolled, annealed bars 4" diameter were ordered for turning tests. These were solution annealed at the mill as follows:

1800°F/1 hour/air cool

This treatment resulted in an as-solutioned hardness of 277 BHN.

Rectangular bar stock 2" x 4" x 12" was ordered for the other machining operations. The milling tests were run on the as forged material having a hardness of 332 BHN. Drilling, reaming and tapping tests were performed on forgings which had been resolutioned at Metcut as follows:

1800°F/1 hour/air cool

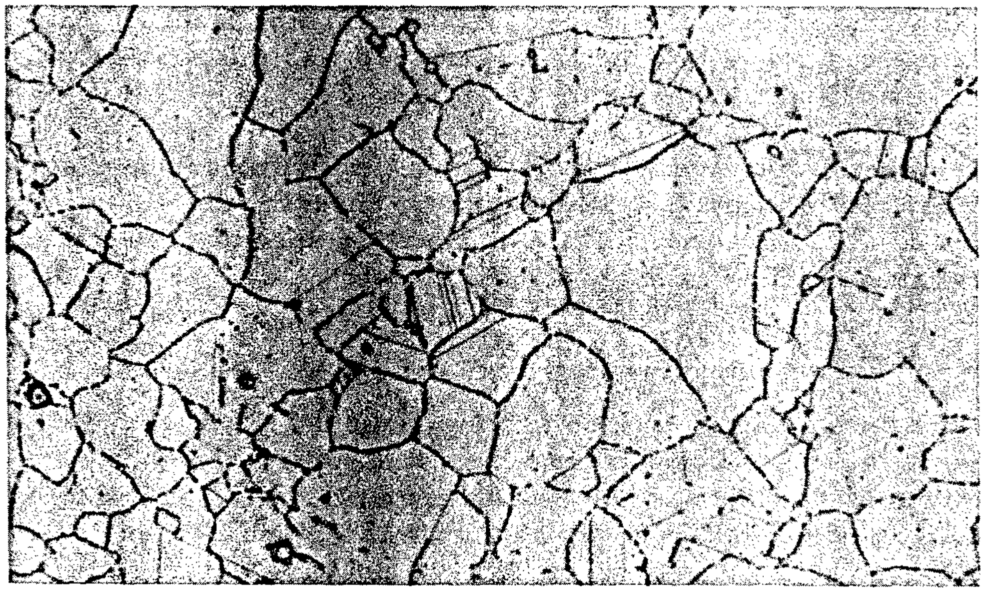
The hardness as a result of the resolutioning operation was 245 BHN.

In order to compare the aged to the solutioned condition, some previously solutioned bars were aged as follows:

1325°F/8 hours/furnace cool to 1150°F. Hold at 1150°F
until total aging time equals 18 hours/air cool

The aging treatment yielded a hardness of 41-45 R_c.

The microstructure of the alloy in both heat treated conditions consisted essentially of equiaxed single-phase grains plus random small particles, presumed to be carbides. The aging treatment caused the grain boundaries to be accentuated, as illustrated on page 211.



Inconel 718 Solution Treated and Aged

Etchant: Kalling's Mag: 500X

Turning (Solution Treated 277 BHN)

The results of the turning tests with high speed steel tools on Inconel 718 in the solution treated condition are presented in Figures 234 through 237, pages 217 and 218. A comparison of three feeds, .002, .005 and .007 in./rev. is shown in Figure 234, page 217, for a type M-2 HSS tool. The cutting speeds for the two feeds .005 and .007 in./rev. were the same, while the speeds at a feed of .002 in./rev. were 90% higher. However, since the feed rate at .007 in./rev. is 3-1/2 times faster than at .002 in./rev., the rate of production with the heavier feed would be much greater than with the lighter feed, even though the cutting speed would have to be reduced 50% to obtain equivalent tool life. The results of the tests presented in Figure 235, page 217, indicate that the tool life was the same for both the soluble oil (1:20) and the highly sulfurized oil.

As shown in Figure 236, page 218, the cutting speed with a type T-15 HSS tool was about 25% higher than with a type M-2 HSS tool for an equivalent tool life. The feed should not exceed .005 in./rev. with the T-15 HSS tool however, for as indicated in Figure 237, page 218, at a cutting speed of 25 ft./min. the tool life decreased more than 50% when the feed was increased from .005 to .006 in./rev.

5.1 Inconel 718 (continued)

Of the four grades of carbides tested in turning Inconel 718 in the solution treated condition, the C-6 grade 370 was the poorest. Grades K-68 and K-6 were the best, see Figure 238, page 219.

The effect of tool geometry on the tool life with carbides is presented in Figure 239, page 219. Note that by changing the side rake angle from $+15^{\circ}$ to $+5^{\circ}$, the tool life at a cutting speed of 110 ft. /min. increased from 15 minutes to 25 minutes.

Face Milling (As Forged 332 BHN)

The results obtained in face milling Inconel 718 as forged shown in Figure 240, page 220, indicate that at a cutting speed of 29 ft. /min the type M-44 HSS was somewhat superior to the T-15 HSS tool over a range of feeds. However, as shown in Figure 241, page 220, the difference in the two types of HSS was not as great at cutting speeds below 29 ft. /min.

Of the five different grades of carbide used in face milling Inconel 718, the C-2 grade 883 proved to be far superior to the other four, see Figure 242, page 221. It should be noted, however, that even with the best carbide the tool life was short (12 inches of work travel). Changing the tool geometry, see Figure 243, page 221, made a small difference in tool life.

The importance of selecting the optimum feed is indicated in Figure 244, page 222. Note that at a feed of .008 in. /tooth, the tool life was 36 inches of work travel, as compared to 12 inches at a feed of .007 in. /tooth and 17 inches of work travel at .010 in. /tooth feed.

In the curve presented in Figure 245, page 222, showing the relationship between tool life and cutting speed in face milling Inconel 718, the maximum tool life under the conditions shown was 36 inches of work travel at a cutting speed of 74 ft. /min. Speeds other than this produced shorter tool life. It should be noted that while the carbide cutter will permit cutting speeds that are two to three times faster than with HSS, the maximum tool life that could be obtained was still unsatisfactory. With HSS tools, particularly the M-44 and the T-15 grades, it was possible to obtain tool lives of as much as 175 to 200 inches of work travel by using a cutting speed of 22 ft. /min. and a feed of .010 in. /tooth.

5.1 Inconel 718 (continued)

Peripheral End Milling (As Forged 332 BHN)

A comparison is made in Figure 246, page 223, between T-15 and M-2 HSS tools over a range of cutting speeds. The T-15 permitted a cutting speed that was 50% higher than that with the M-2 HSS for a given tool life. At a tool life of 70 inches of work travel, the cutting speed with the M-2 was 74 ft./min. as compared to 107 ft./min. with the T-15 HSS. The effect of feed on tool life when using a T-15 HSS end mill is shown in Figure 247, page 223. It is interesting to note that at a lower speed of 92 ft./min., tool life went up as the feed was increased from .001 to .002 in./tooth. However, when the cutting speed was increased to 142 ft./min. the tool life decreased at the higher feeds.

End Mill Slotting (As Forged 332 BHN)

The T-15 HSS cutter was also superior to the M-2 HSS cutter in end mill slotting Inconel 718. As shown in Figure 248, page 224, the cutter life at a given cutting speed was about 50% higher with the T-15 HSS end mill. Also, as shown in Figure 249, page 224, tool life increased as the feed was increased from .001 to .003 in./tooth. Over this range of feeds the cutter life was 2-1/2 times higher at .003 in./tooth than at .001 in./tooth.

Drilling (Solution Treated 245 BHN)

The feed was very critical in the drilling of Inconel 718 in the solution treated condition. Figure 250, page 225, shows that at a feed of .005 in./rev. a tool life of 100 holes was obtained with a T-15 HSS drill. However, a drill life of less than 25 holes resulted when the feed was either .002 or .009 in./rev. A comparison of the drill lives obtained with two different types of HSS drills is shown in Figure 251, page 225, over a range of cutting speeds. The results with the T-15 HSS were far superior to those obtained with the M-42 HSS drill. For example, for a tool life of 50 holes, the cutting speed with the M-42 HSS drill was 15 ft./min. as compared to 28 ft./min. with the T-15 HSS drill.

Reaming (Solution Treated 245 BHN)

A C-2 carbide grade of reamer should be used in reaming Inconel 718 in the solution treated condition. Note in Figure 252 page 226, that 75 holes were reamed with a C-2 grade carbide reamer having four flutes at a cutting speed of 70 ft./min. A maximum of less than 10 holes was obtained with an M-2 HSS six flute reamer even at a speed as low as 20 ft./min.

5.1 Inconel 718 (continued)

Tapping (Solution Treated 245 BHN)

In order to get a reasonable tool life in the tapping of Inconel 718 in the solution treated condition, a 2 flute spiral point tap should be used. A comparison of this type of tap with a 4 flute plug tap, in Figure 253, page 226, shows the advantage of the 2 flute spiral point tap. Also, the cutting speed should be carefully selected. For example, also as shown in Figure 253, page 226, at a cutting speed of 20 ft. /min., 125 holes were tapped; while at speeds lower and greater than 20 ft. /min. tool life was considerably less.

TABLE 17

RECOMMENDED CONDITIONS FOR MACHINING
INCONEL 718 - 245-332 BHN

Cr	Mo	Cb	Ti	Al	Fe	Ni
19	3	5.2	.8	.6	18	Bal.

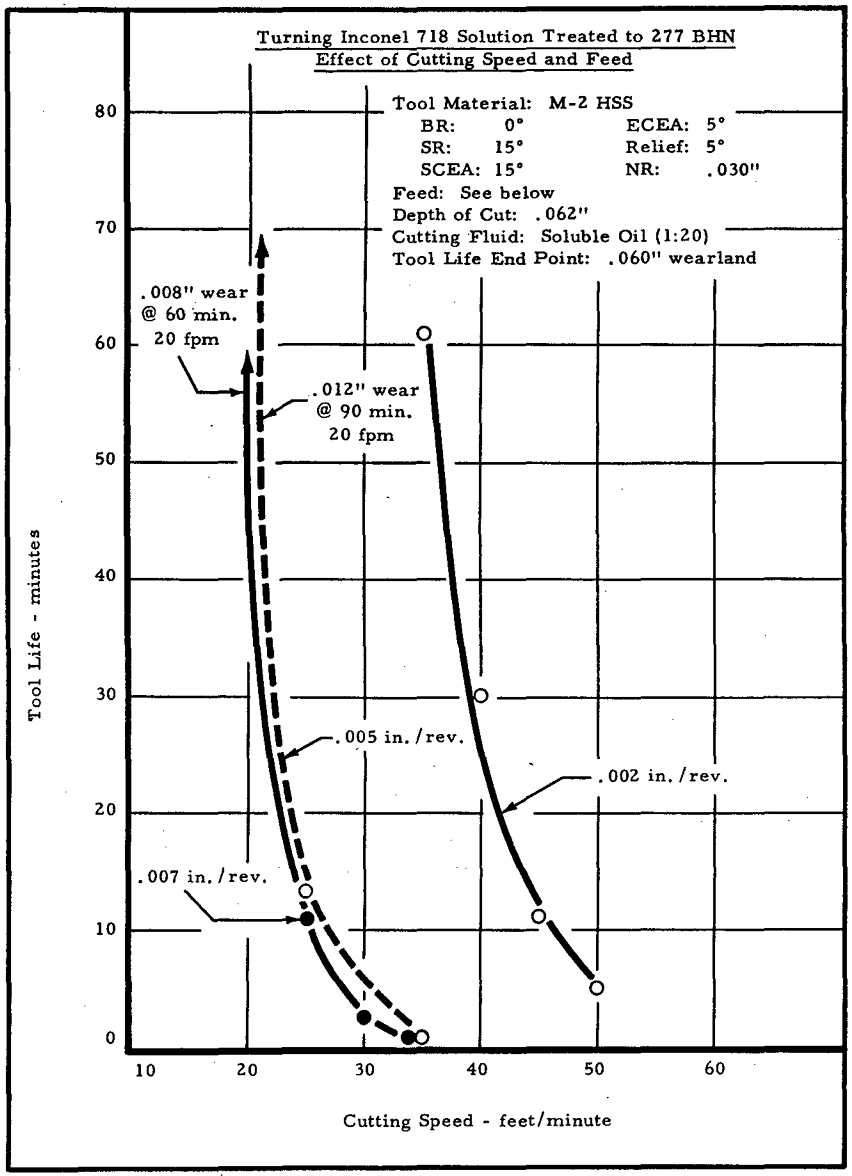
Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool Life	Wear-land inches	Cutting Fluid
Turning (Sol. Treat 277 BHN)	T-15 HSS	BR: 0° SCEA: 15° SR: 15° ECEA: 5° Relief: 5° NR: .030"	5/8" square tool bit	.062	--	.005 in./rev.	25	47 min.	.060	Soluble Oil (1:20)
Turning (Sol. Treat 277 BHN)	C-2 Carbide	BR: 0° SCEA: 15° SR: 5° ECEA: 15° Relief: 5° NR: .030"	1/2" square throwaway insert	.062	--	.009 in./rev.	90	42 min.	.015	Soluble Oil (1:20)
Face Milling (As Forged 332 BHN)	T-15 HSS	AR: 0° ECEA: 10° RR: 30° CA: 45° Clearance: 10°	4" diameter single tooth face mill	.060	2	.010 in./tooth	25	120" work travel	.060	Highly Chlorinated Oil
Peripheral End Milling (As Forged 332 BHN)	T-15 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.002 in./tooth	17 ~~25~~	120" work travel	.012	Highly Chlorinated Oil
End Mill Slotting (As Forged 332 BHN)	T-15 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.003 in./tooth	11	95" work travel	.012	Highly Chlorinated Oil
Drilling (Sol. Treat 245 BHN)	T-15 HSS	118° split point 7° clearance	1/4" diameter HSS end mill 2-1/2" long	.500 thru	--	.005 in./rev.	25	100 holes	.015	Highly Chlorinated Oil

see errata inside front cover

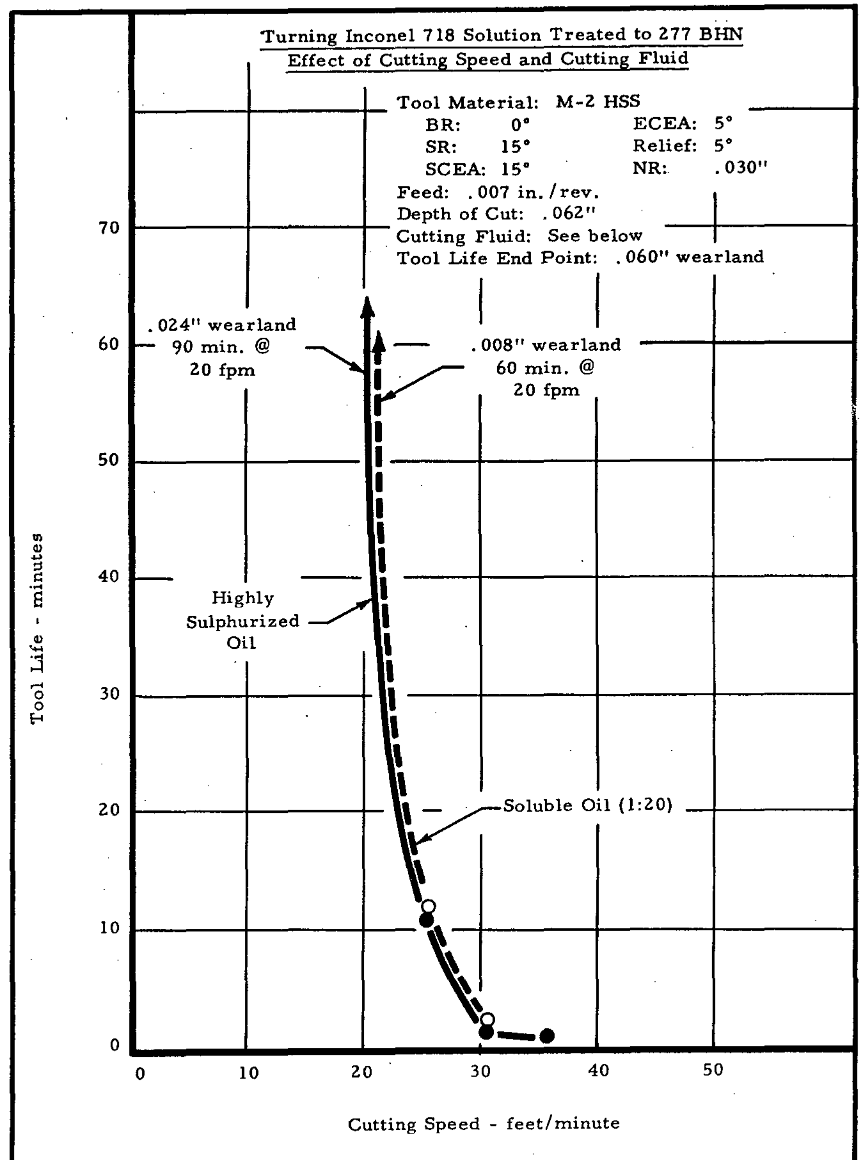
TABLE 17 (continued)

RECOMMENDED CONDITIONS FOR MACHINING
INCONEL 718 - 245-332 BHN

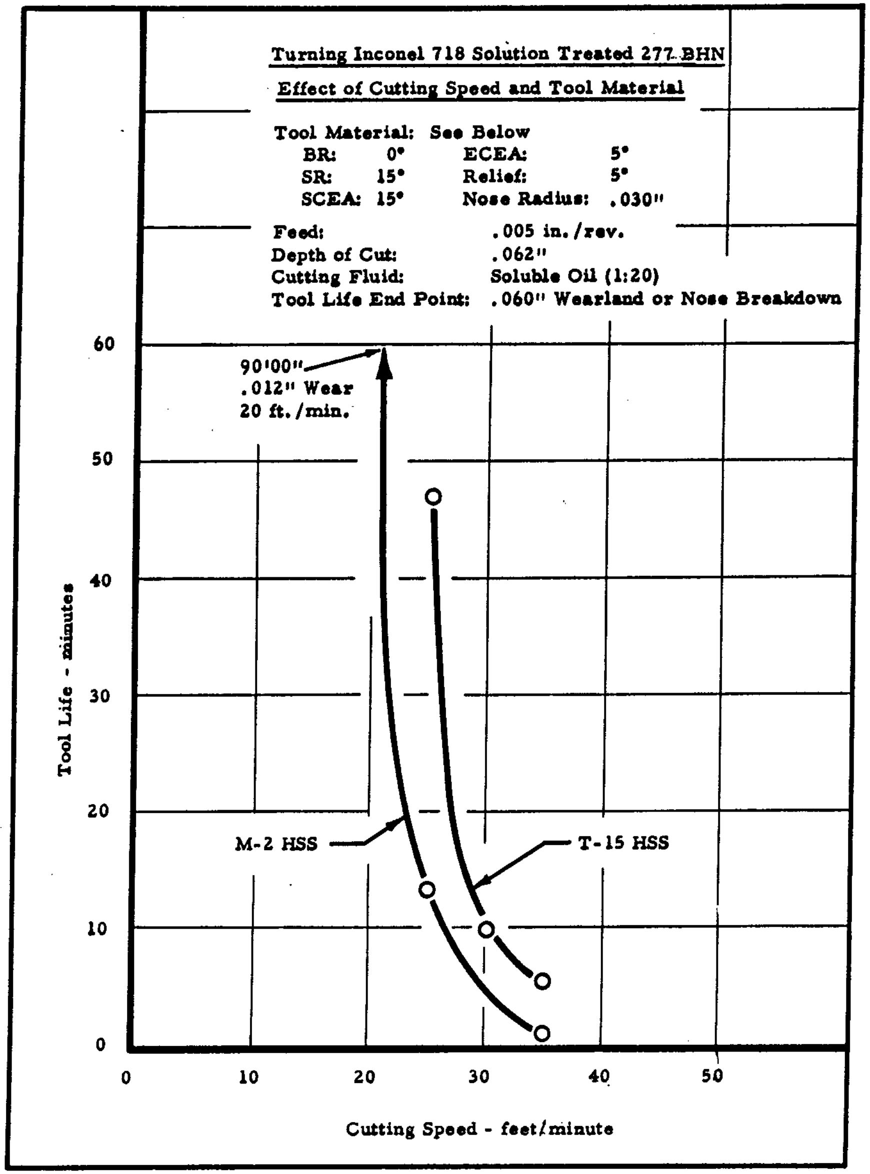
Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool Life	Wear-land inches	Cutting Fluid
Reaming (Sol. Treat 245 BHN)	C-2 Carbide	Helix Angle: 0° CA: 45° Clearance: 7°	.272" diameter 4 flute chucking reamer	.500 thru	--	.009 in./rev.	70	75 holes	.006	Highly Sulphurized Oil
Tapping (Sol. Treat 245 BHN)	M-1 HSS	2 flute plug spiral point 75% thread	5/16-24 NF tap	.500 thru	--	--	20	125 holes	Tap Breakage	Highly Chlorinated Oil



See Text, page 211 Figure 234



See Text, page 211 Figure 235



See Text, page 211

Figure 236

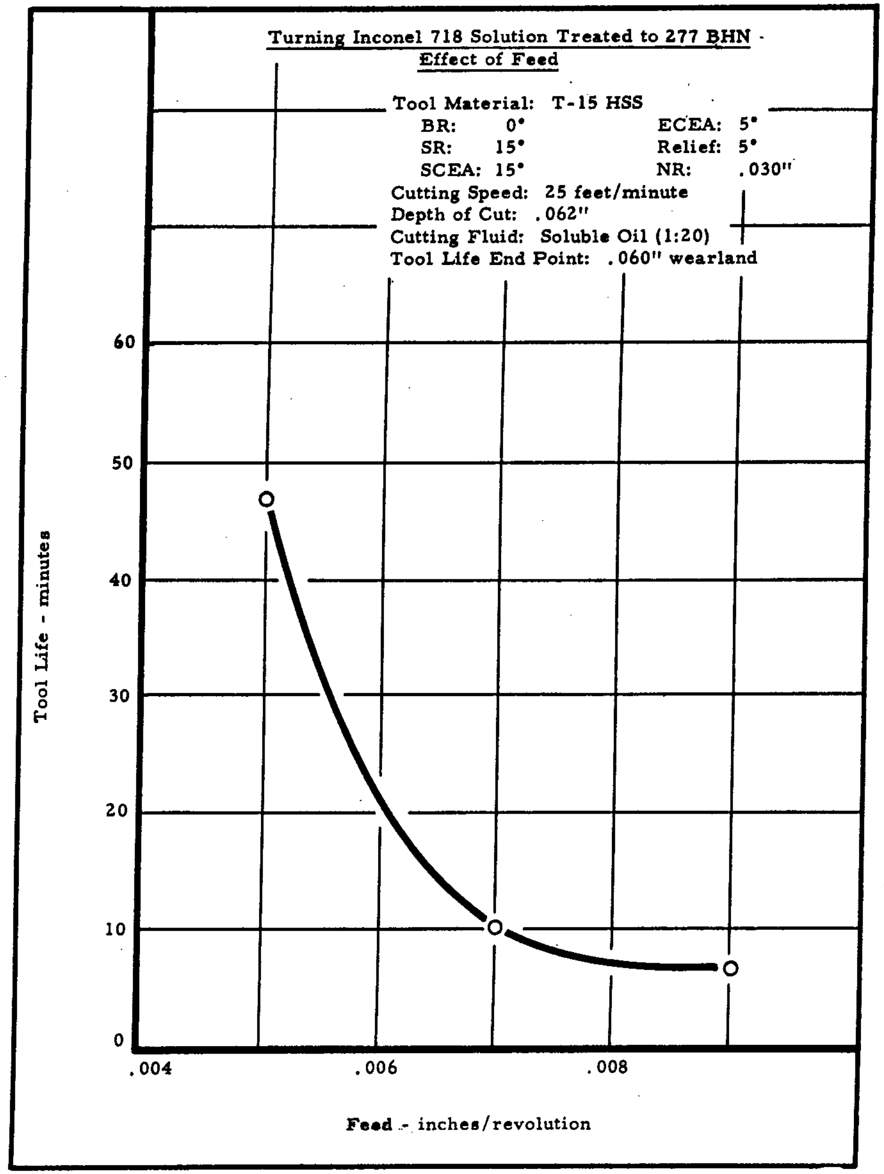


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Figure 237

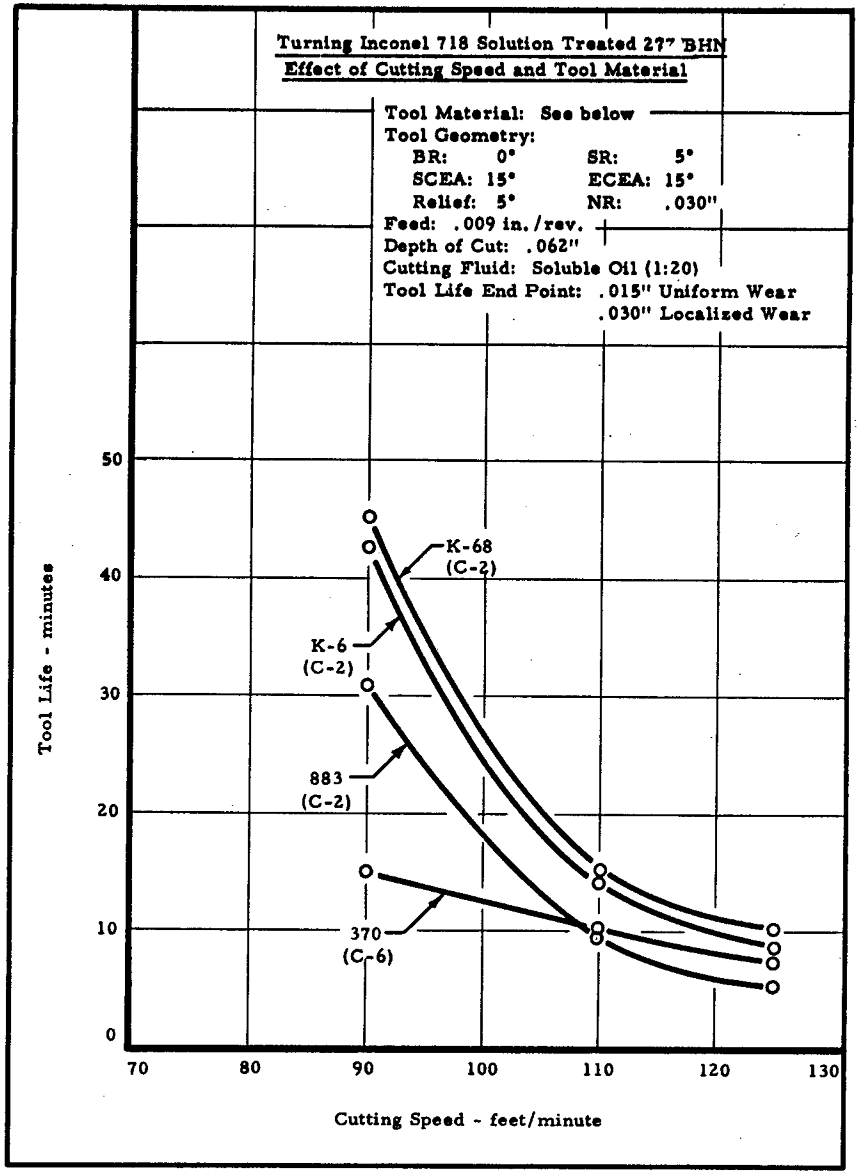

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Figure 238

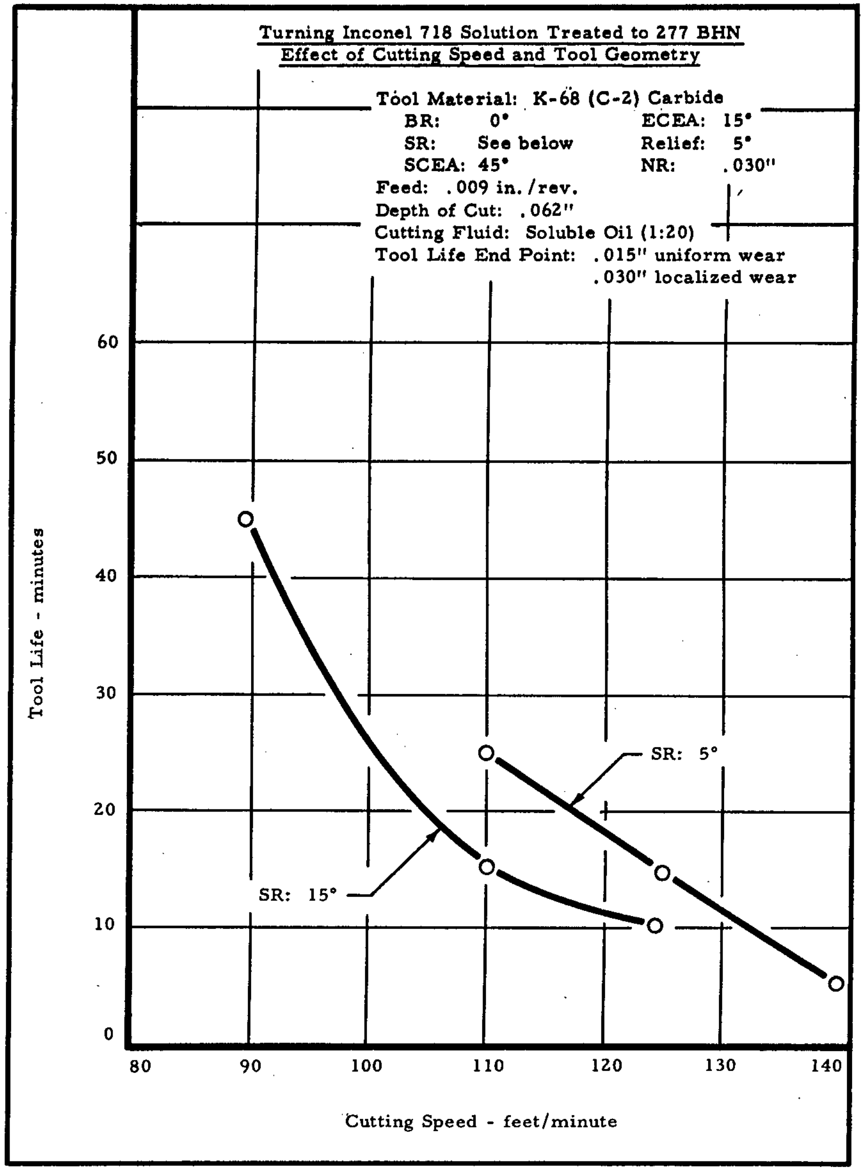

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Figure 239

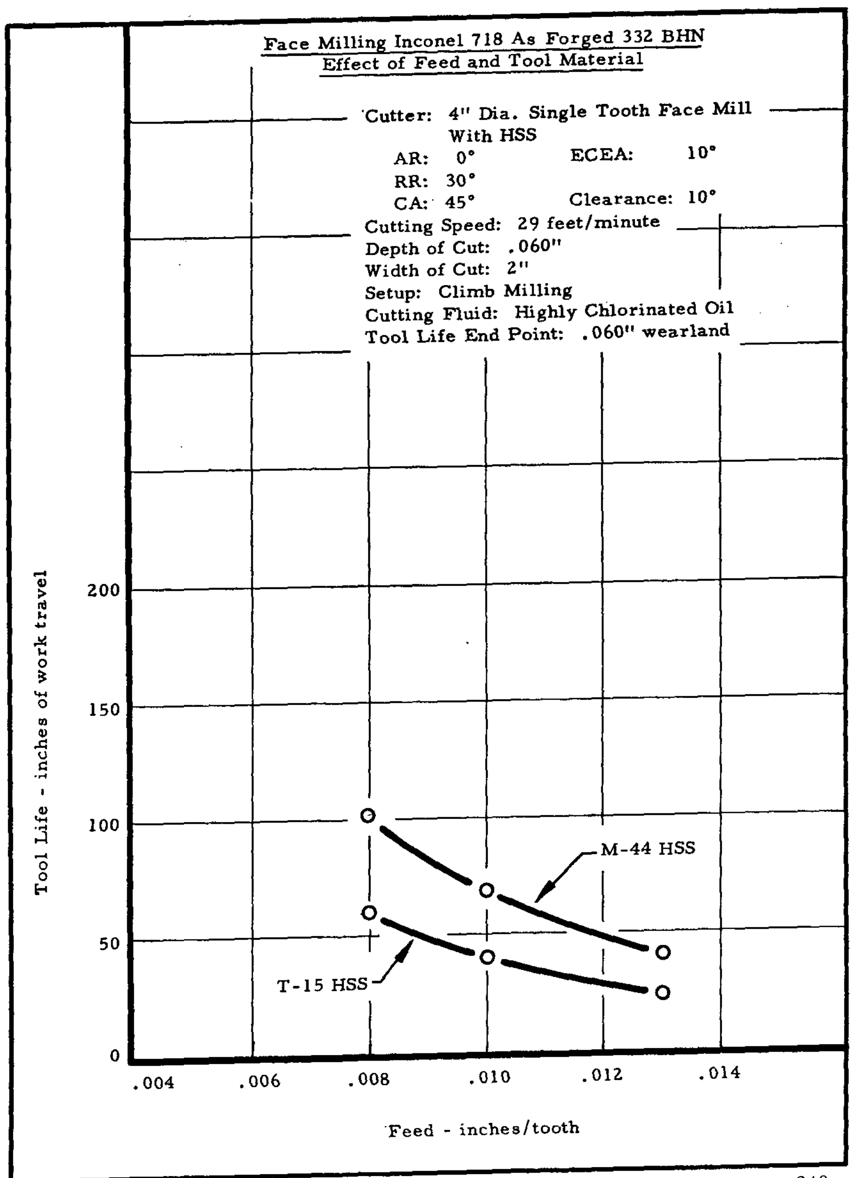

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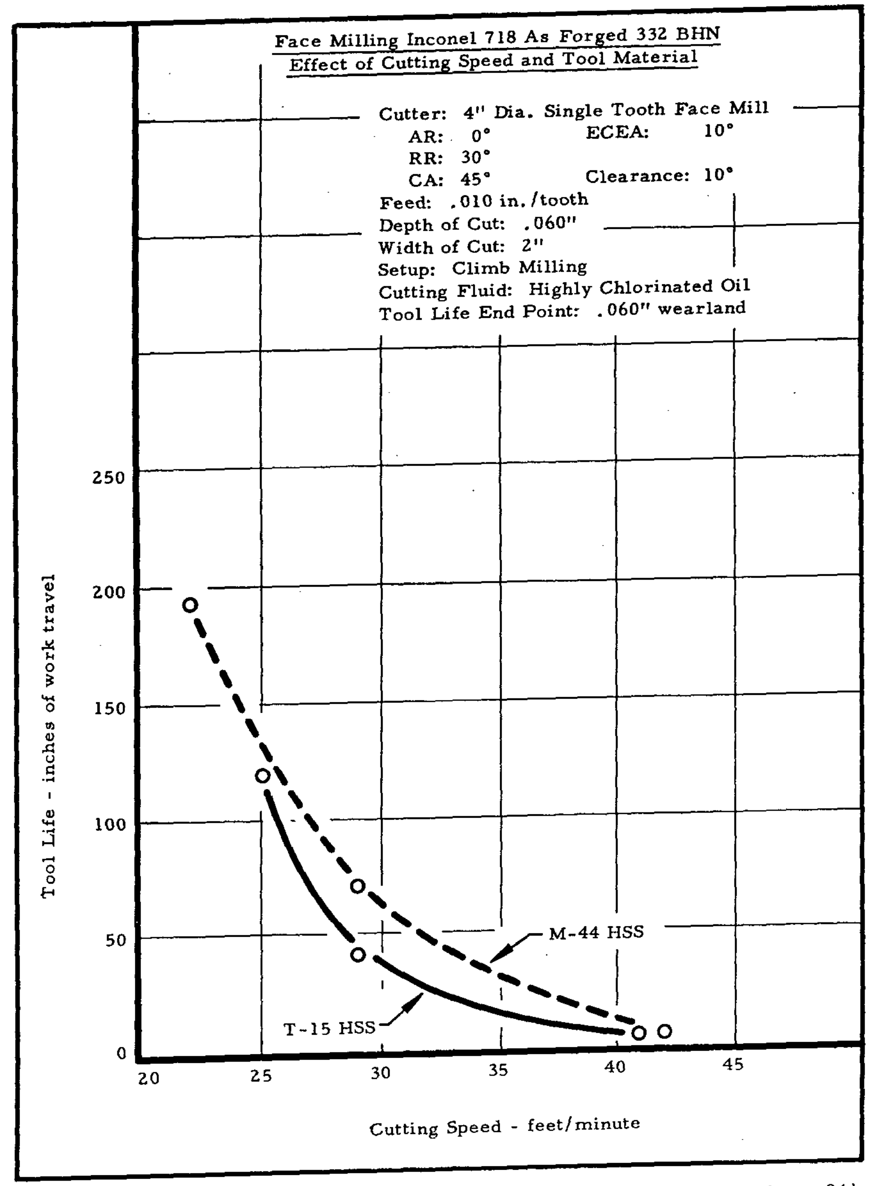
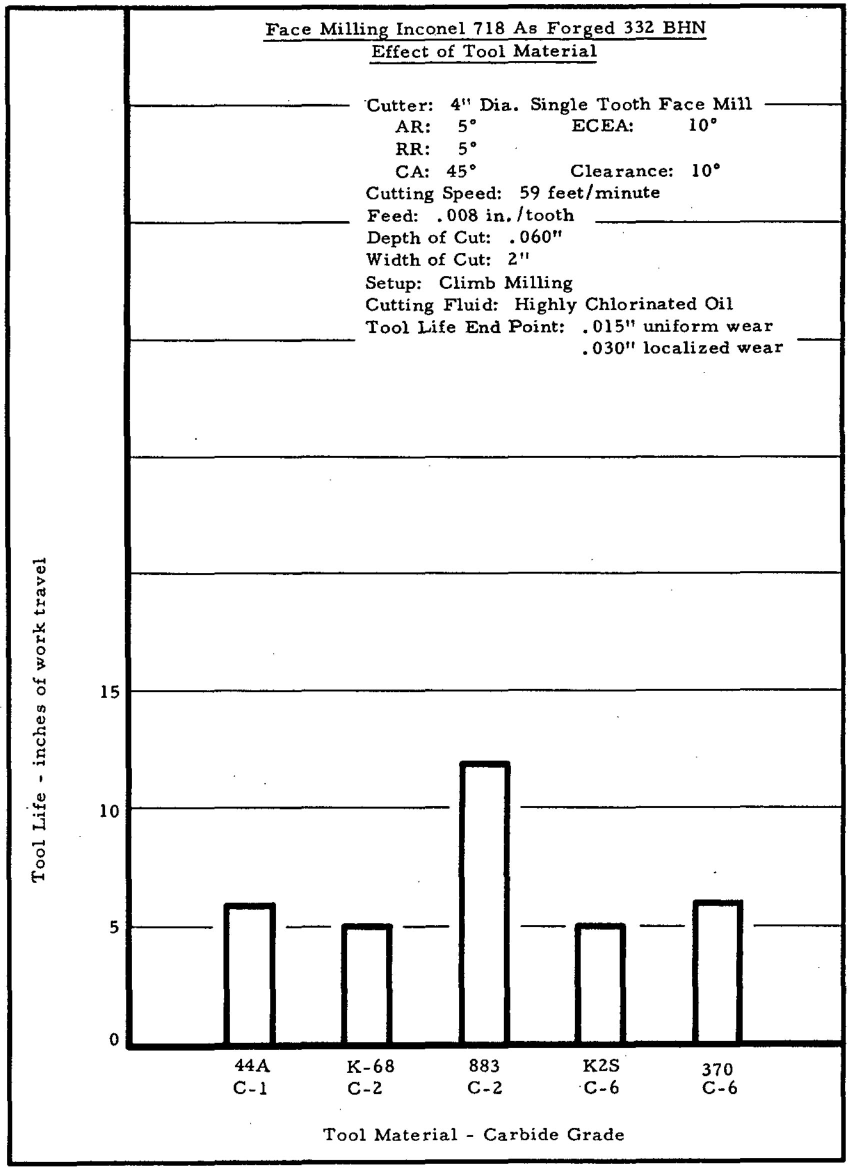
Figure 240



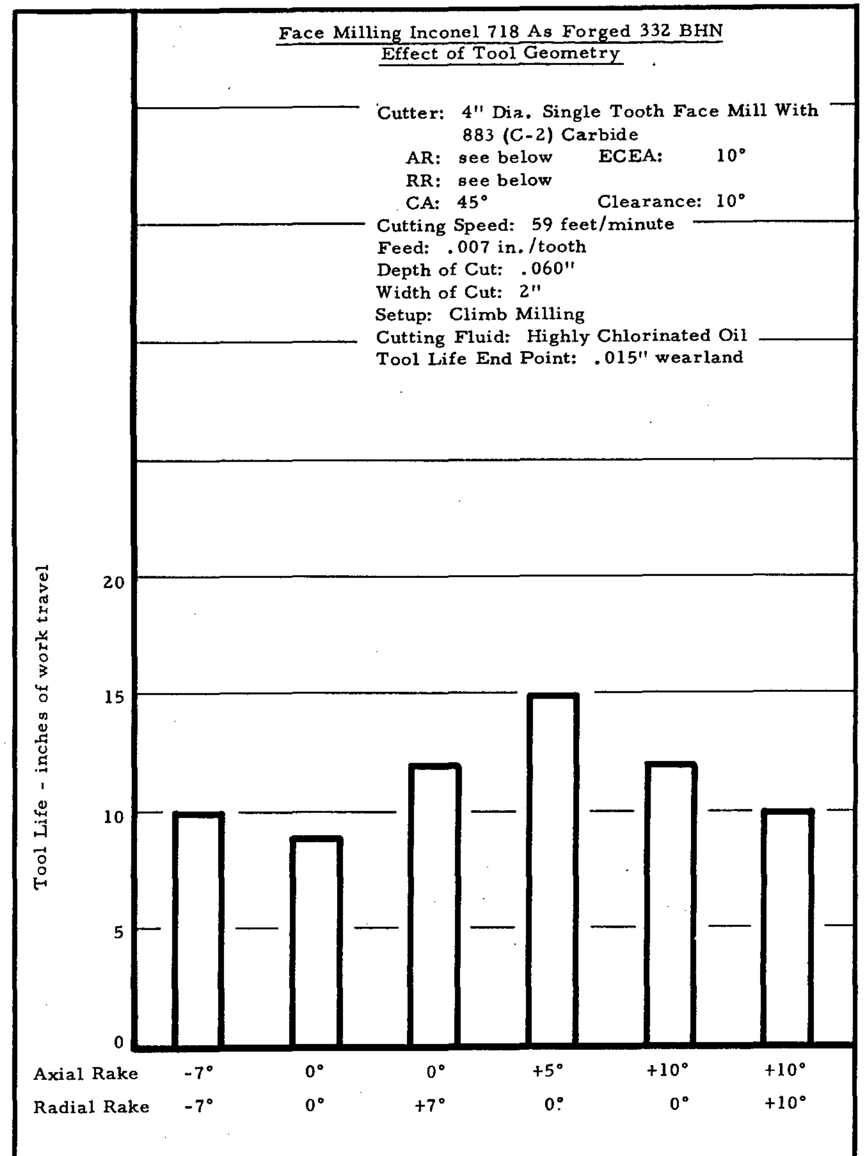
See text, page 212

Figure 241



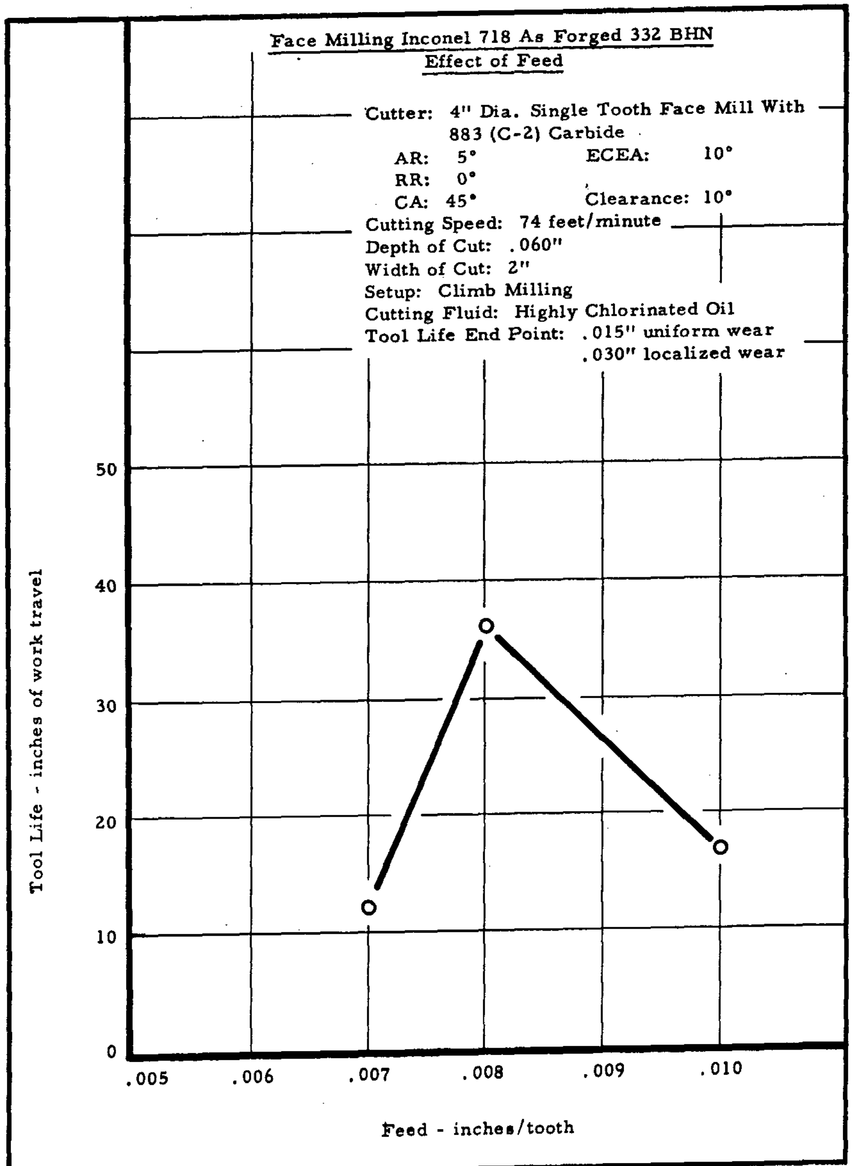
See text, page 212

Figure 242



See text, page 212

Figure 243



See text, page 212

Figure 244

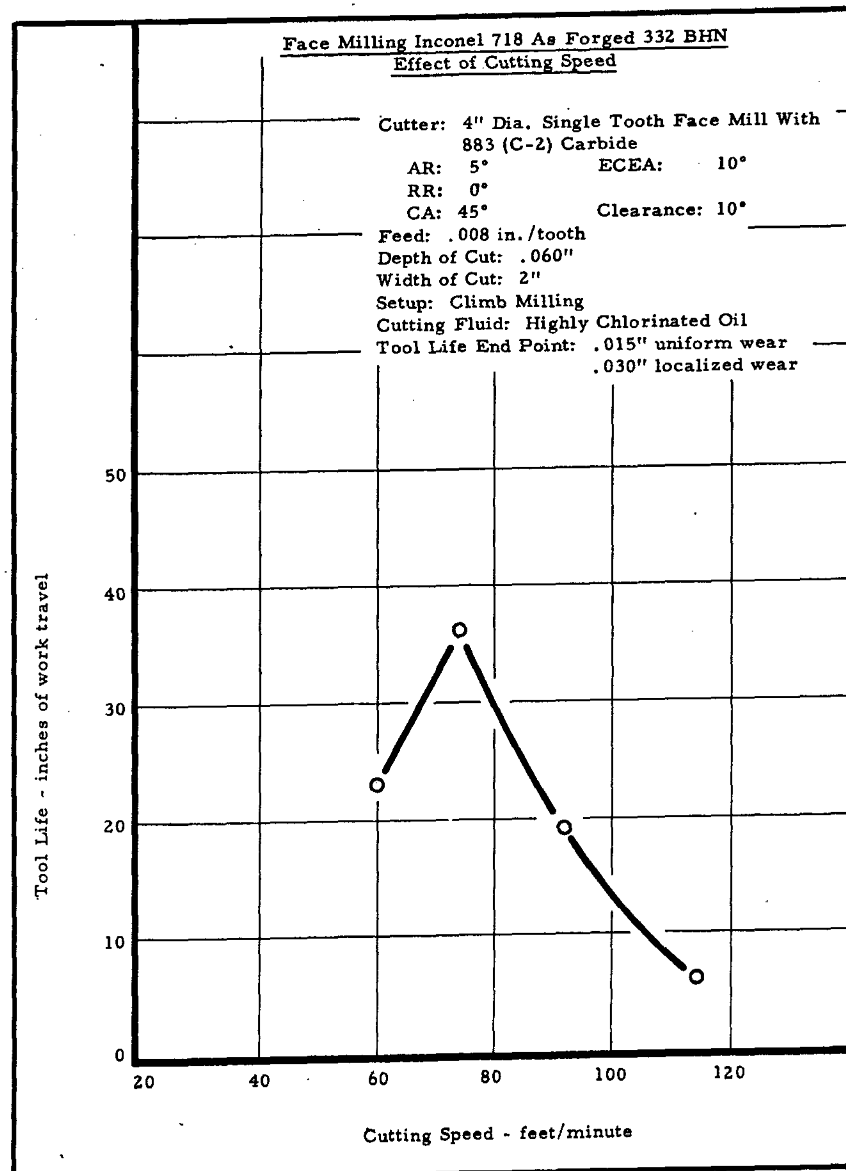


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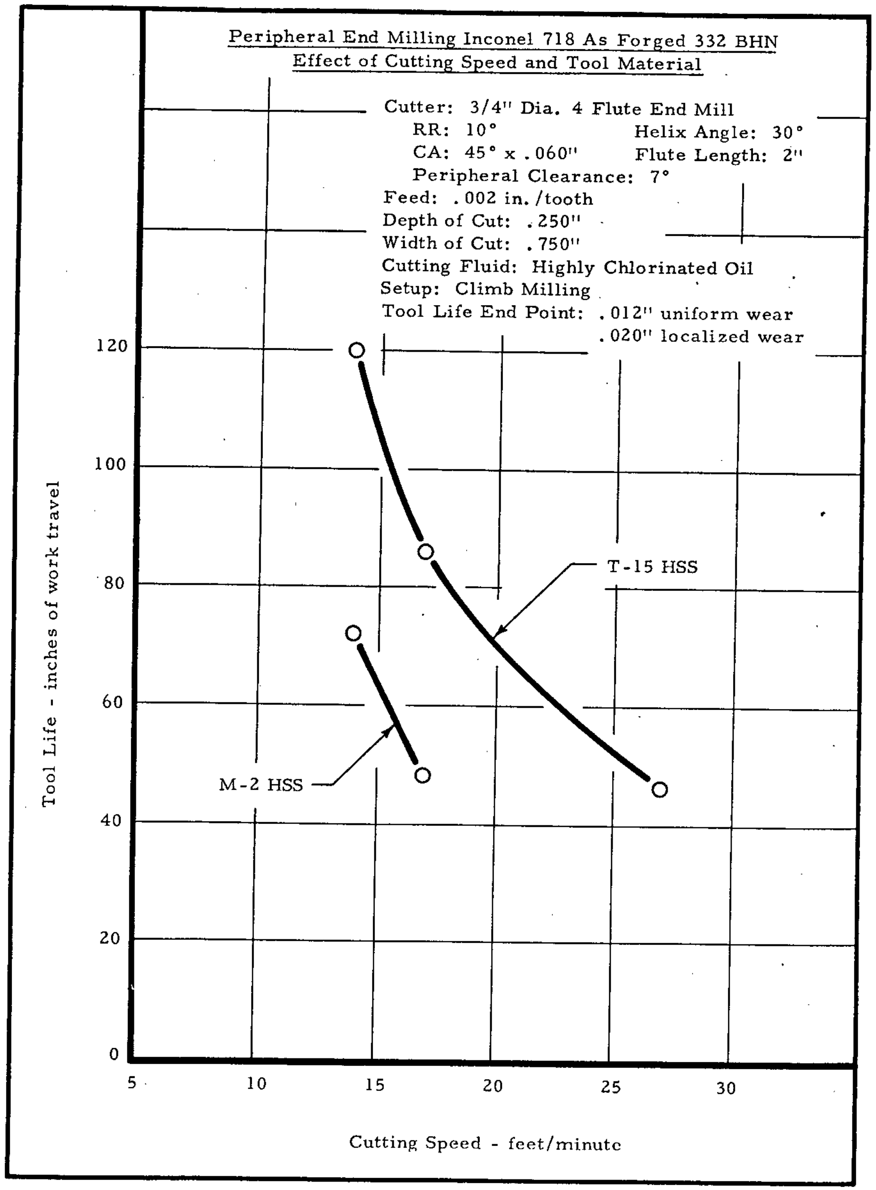
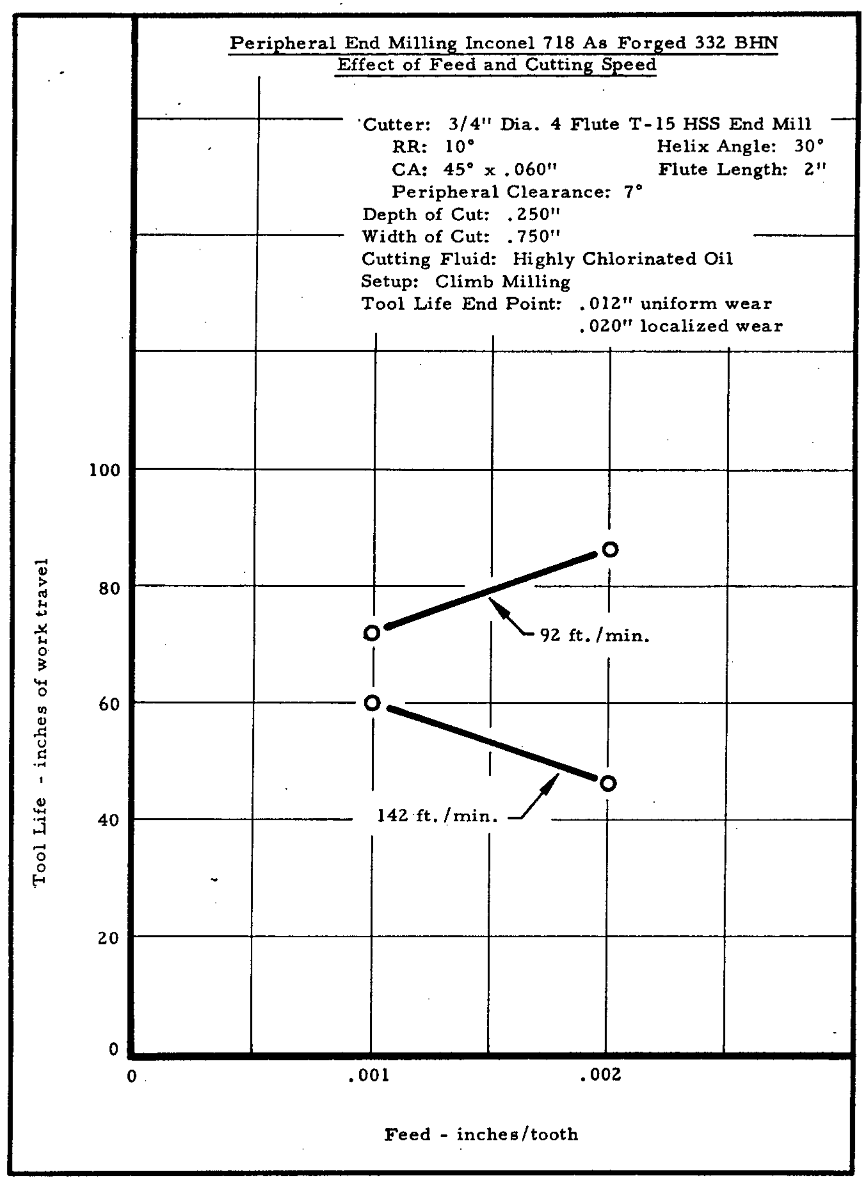
Figure 245



See text, page 213

Figure 246



See text, page 213

Figure 247

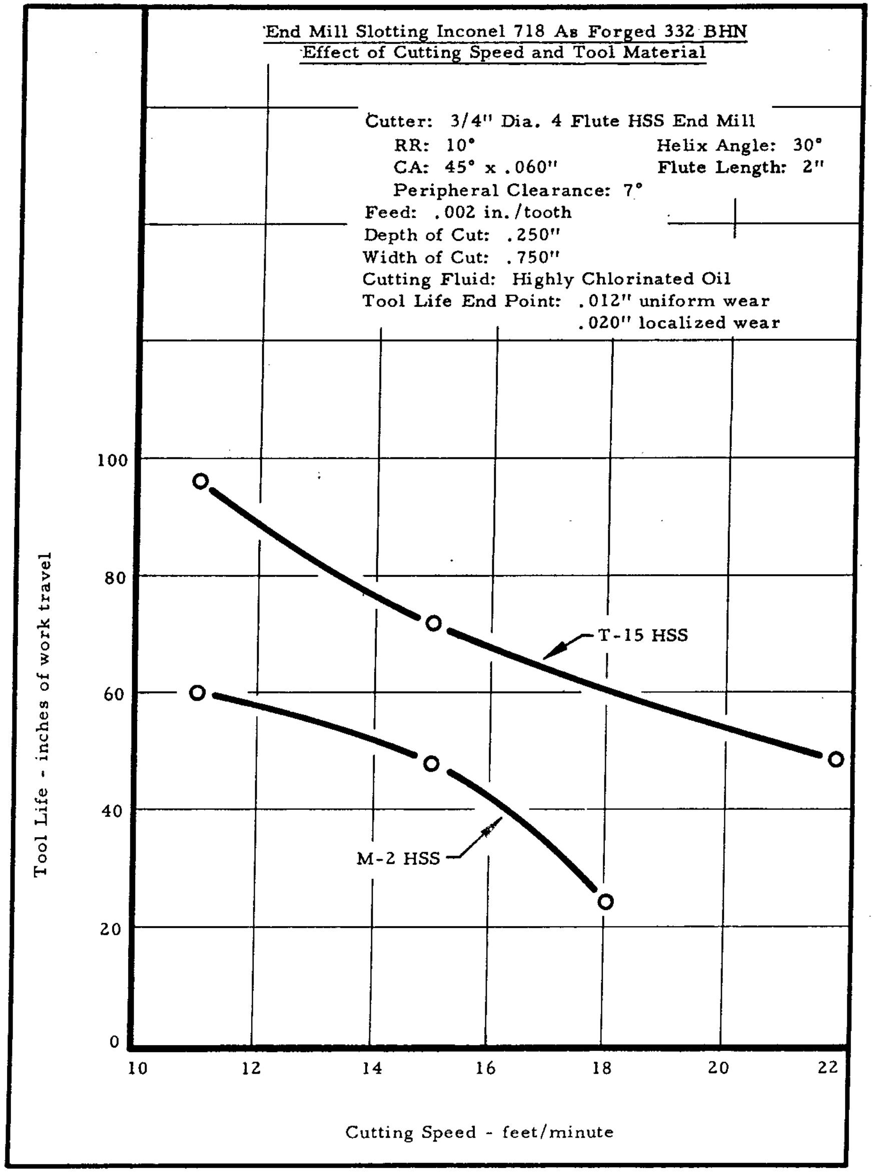


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Figure 248

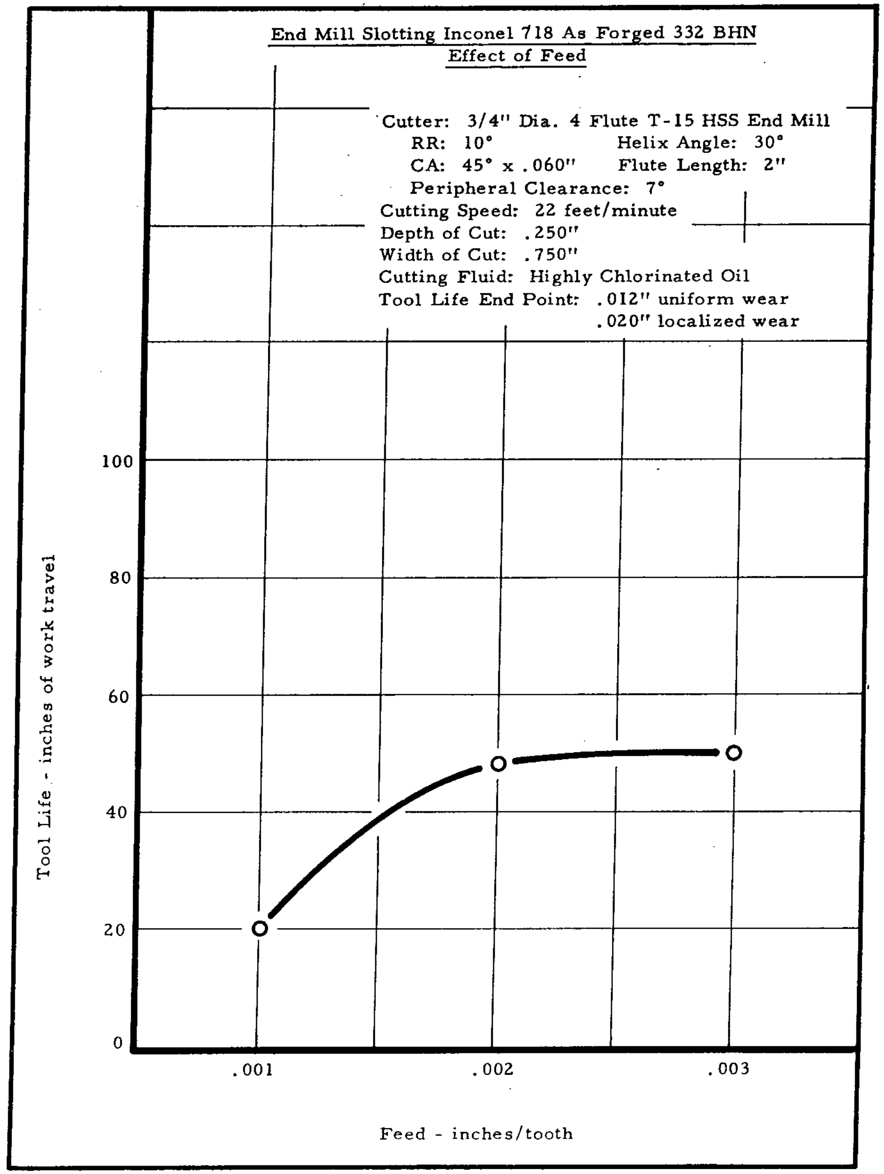

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Figure 249

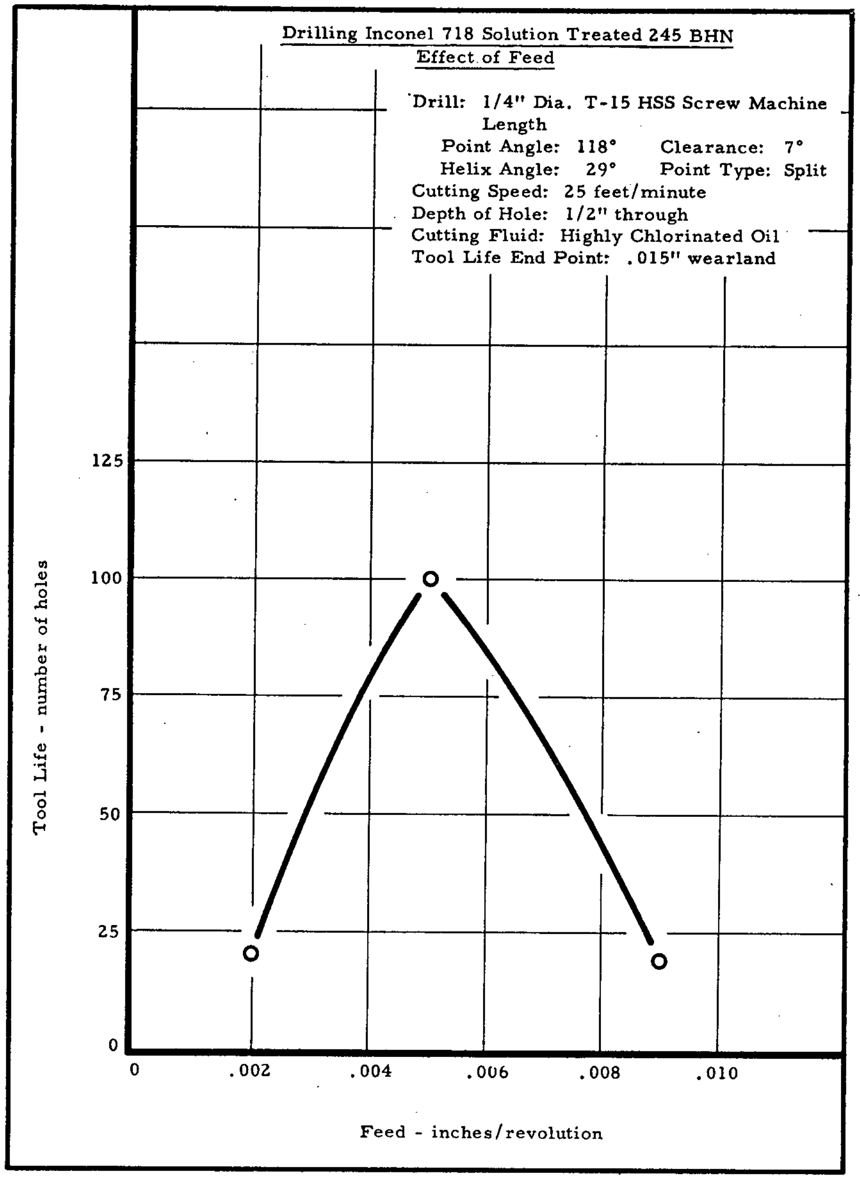

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Figure 250

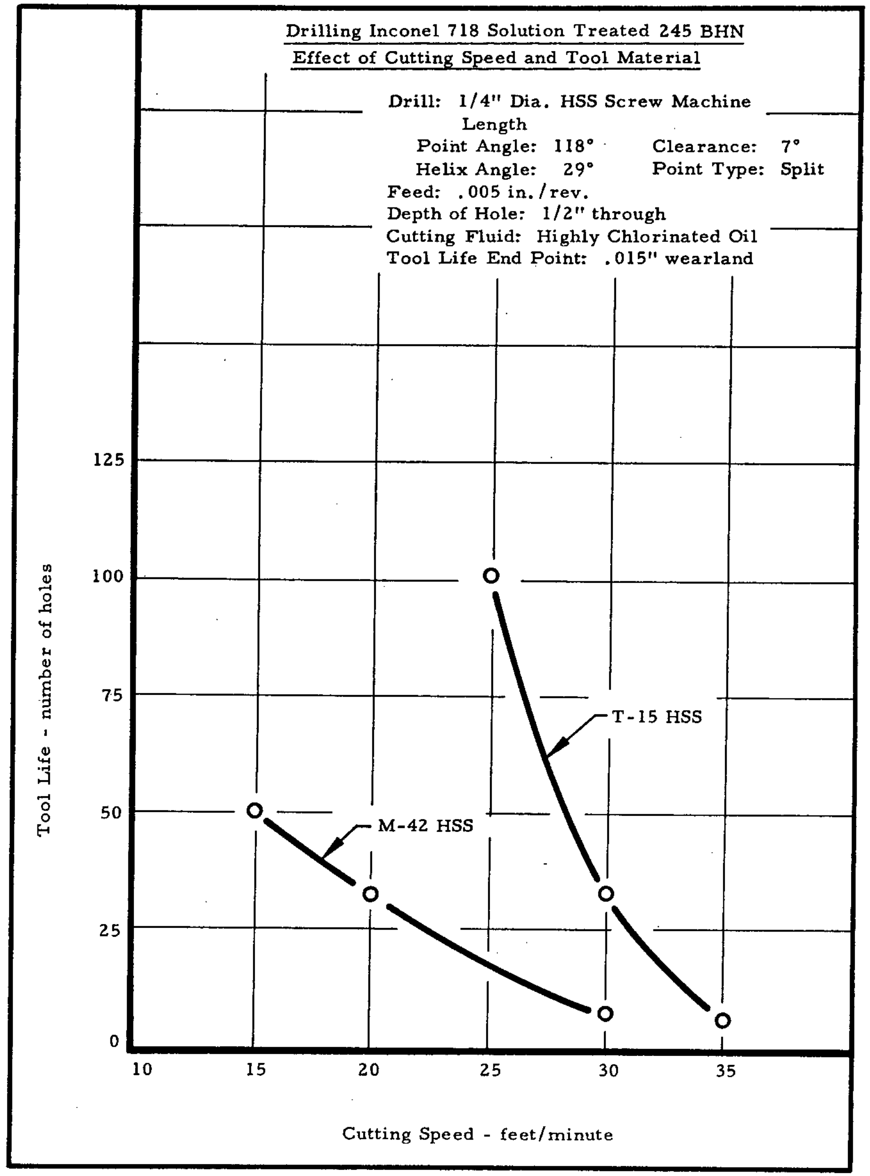

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Figure 251

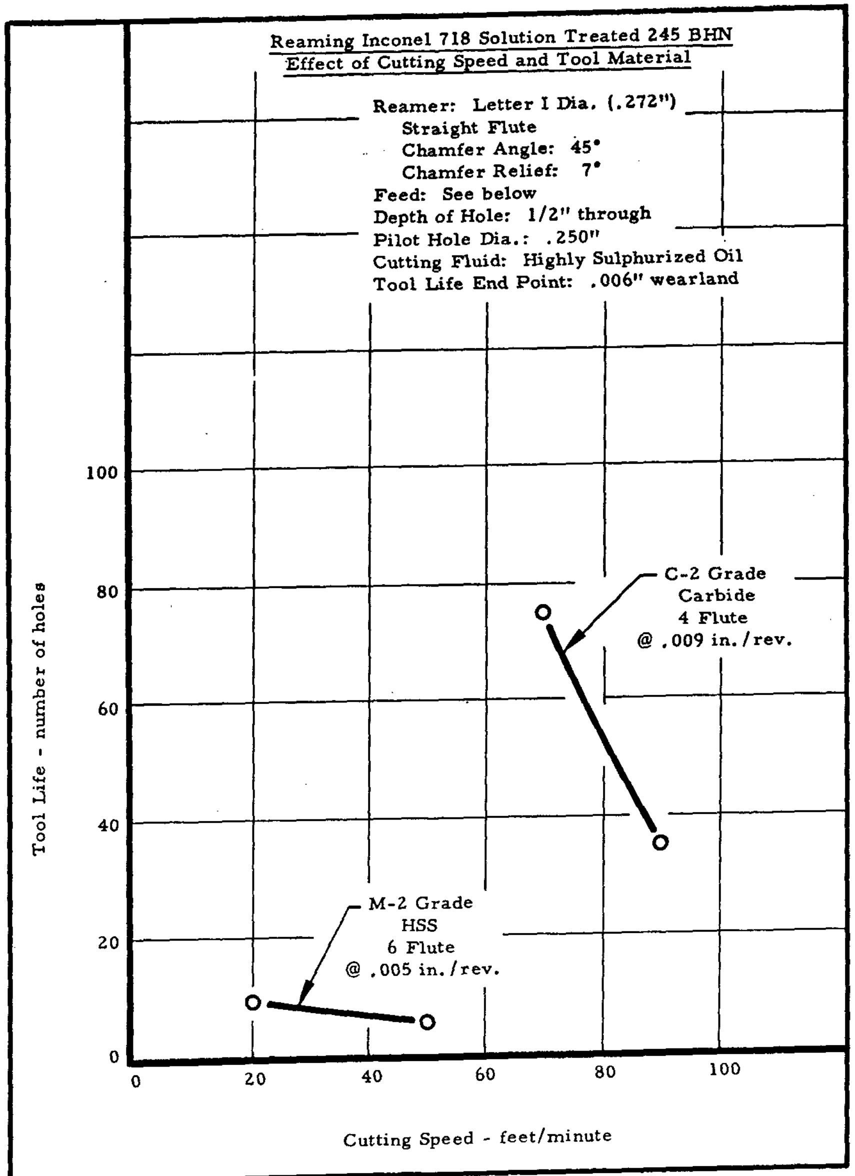

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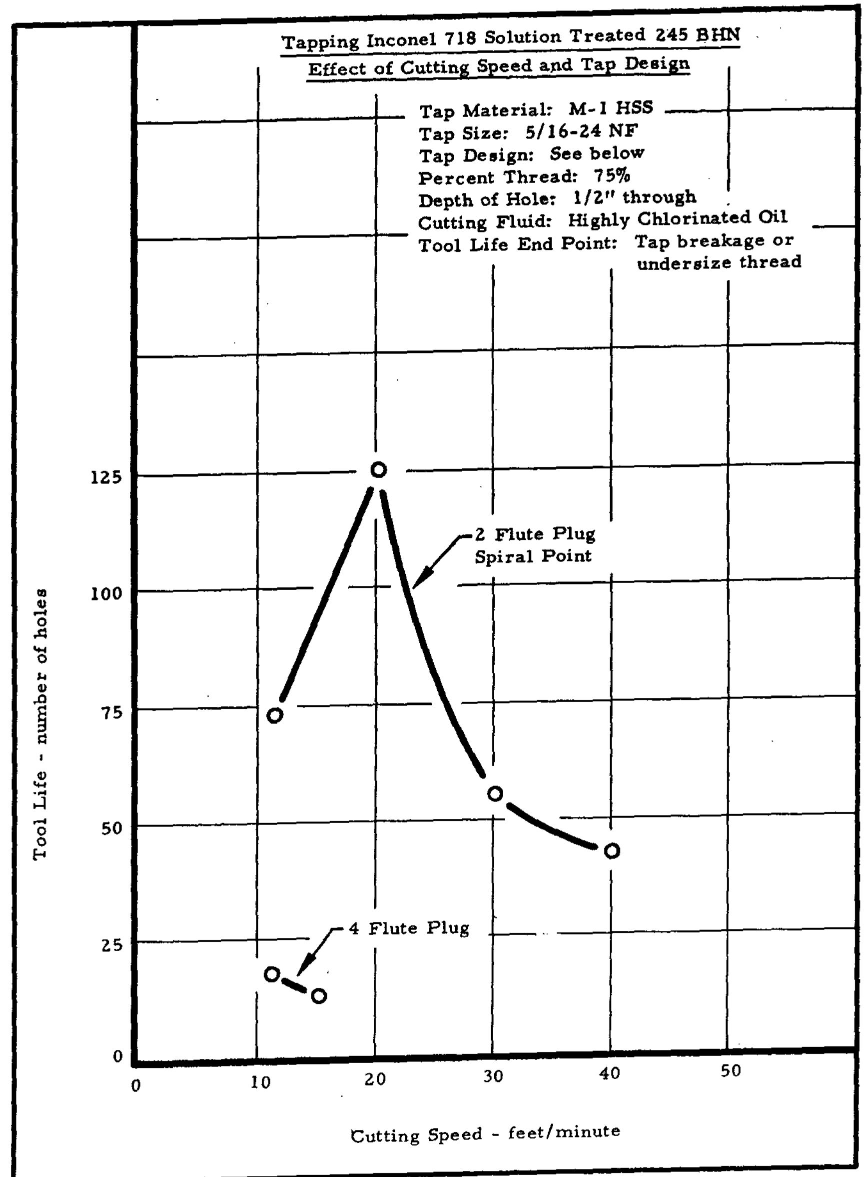
Figure 252



See text, page 214

Figure 253

5.1 Inconel 718 (continued)

Turning (Solution Treated and Aged 45 R_C)

A comparison of the T-15 and the M-2 HSS shown in Figure 254, page 232, in turning Inconel 718 solution treated and aged, shows that appreciable improvement can be obtained in the tool life with the T-15 HSS cutter. At a cutting speed of 35 ft./min. tool life of 9 minutes was obtained with the M-2 HSS, as compared to 38 minutes with the T-15 HSS. Using the T-15 HSS tool at a cutting speed of 40 ft./min., it was found that cutter life decreased rapidly when the feed was increased from .002 to .005 in./rev. As shown in Figure 255, page 232, cutter life dropped from 80 minutes to 12 minutes over this range of feeds. However, as shown in Figure 256, page 233, a cutter life of 40 minutes was obtained at the .005 in./rev. feed at a speed of 35 ft./min. Also, the highly sulfurized oil was the most effective cutting fluid when turning Inconel 718 in the solution treated and aged condition.

Tool life data in turning Inconel 718 in the solution treated and aged condition with carbide is shown in Figures 257 and 258, pages 233 and 234. Figure 257 shows the marked improvement obtained by using a tool with positive rake angles rather than a tool having negative rake angles. The advantage was 100% increase in tool life.

The selection of the optimum grade of carbide is somewhat critical. Note in Figure 258 the vast difference between the various grades of carbide tested. Grade 883 (C-2) was far superior to the 370 (C-6) carbide.

Face Milling (Solution Treated and Aged 42 R_C)

A comparison of several different types of high speed steel cutters in face milling Inconel 718 solution treated and aged 42 R_C is shown in Figure 259, page 234. At a given cutting speed, tool life with the T-15 was appreciably greater than that obtained with either M-44 or M-2 HSS. It appears from the results shown in Figure 260, page 235, that the feed was not very critical in the face milling operation. As the feed was increased from .007 to .014 in./rev., cutter life decreased from 80 inches of work travel to 40 inches of work travel.

Of the six grades of carbide used in face milling Inconel 718, the C-2 grades were the best. As shown in Figure 261, page 235, K-6 and 883 were appreciably better than the other grades. However, it should be noted that the tool life was very short for all of the grades used under the conditions shown. At the cutting speed of 59 ft./min.

shown in Figure 262, page 236, tool life was 24 inches at a feed of .010 in./tooth. Either increasing or decreasing the feed from this value resulted in a lower tool life. It appears from the results shown in Figure 263, page 236, that the cutting speed of 59 ft./min. was optimum with carbide tools. It should be pointed out that if the cutting speed is reduced to 20 ft./min., HSS cutters such as the T-15 will provide tool life values of over 110 inches of work travel, see Figure 259, page 234, as compared to a maximum of under 25 inches of work travel with carbide tools at a cutting speed of 59 ft./min.

Peripheral End Milling (Solution Treated and Aged 42 R_C)

The relationship between tool life and cutting speed in peripheral end milling of Inconel 718 solution treated and aged is shown in Figure 264, page 237, for two different depths of cut. Note the wide difference in tool life for these two depths. For example, at a speed of 11 ft./min. the cutter life with the 1/4" depth of cut was 7 inches of work travel, as compared to 36 inches of work travel at 1/8" depth of cut. It was found, as shown in Figure 265, page 237, that by changing from climb milling to conventional milling at the depth of cut of 1/8", the tool life could be increased from 36 inches of work travel to 84 inches of work travel.

A comparison of tool life curves using two types of HSS; namely, T-15 and M-2, is shown in Figure 266, page 238. The M-2 HSS appeared to be better at the lower cutting speeds. At these lower speeds the T-15 HSS tended to chip and tool life was short. The tool life curve in Figure 267, page 238, shows how critical the feed was in peripheral end milling Inconel 718 in the solution treated and aged condition. The cutter life decreased rapidly when a feed other than .002 in./tooth was used.

End Mill Slotting (Solution Treated and Aged 42 R_C)

The effect of feed on tool life in end mill slotting with two types of HSS is shown in Figure 268, page 239. Note that the cutting speed is different for each of the two high speed steels. In general, T-15 HSS was appreciably better and produced longer tool life, even at a speed of 15 ft./min. as compared to 12 ft./min. for the M-2 HSS over the range of feeds employed. A similar comparison is made over a range of cutting speeds in Figure 269, page 239. Again, the T-15 HSS cutter proved to be far superior to the M-2 cutter.

5.1 Inconel 718 (continued)

Surface Grinding (Solution Treated and Aged 41 R_C)

The effect of wheel speed on G Ratio in grinding Inconel 718 solution treated and aged to 41 R_C is shown in Figure 270, page 240. Here the G Ratio increased from 4.5 to 9.4 as the wheel speed increased from 2000 to 6000 ft./min. These results are with an aluminum oxide J hardness wheel, with a down feed of .001 in./pass, a cross feed of .050 in./pass, using highly sulfurized oil. The G Ratio was found to increase with increasing down feed, Figure 271, page 240. Higher G Ratios were obtained at the 6000 than at the 4000 ft./min. wheel speed. However, the 4000 ft./min. wheel speed is recommended as the top limit in grinding Inconel 718 in order to maintain surface integrity.

The grinding ratio increased with increasing cross feed, Figure 272, page 241. At 4000 ft./min. the G Ratio increased from 5 to 10.4 with increasing cross feed of .025 to 0.1 in./pass. Increasing table speed was found to provide higher G Ratio, Figure 273, page 241. A G Ratio of as high as 16.5 was obtained at a table speed of 60 ft./min. and at a wheel speed of 4000 ft./min. using highly sulfurized oil.

The recommended conditions for grinding Inconel 718 are given in Table 18, page 231. These conditions have been stipulated in accordance with the need for maintaining high integrity of the ground surface. The conditions given are those corresponding to "low stress" grinding, which provide a minimum of surface alterations as well as low residual stresses (Chapter 7, pages 317-378). These conditions consist of:

Grinding Wheel:	32A46J8VBE
Wheel Speed:	3000 to 4000 ft./min.
Down Feed:	
Roughing:	.001 in./pass
Finishing:	.0005 in./pass
Cross Feed:	.050 in./pass
Table Speed:	40 to 60 ft./min.
Grinding Fluid:	Highly Sulfurized Oil

The surface finish obtained in grinding Inconel 718 was 10 to 20 microinches, arithmetical average, in finishing; and 15 to 40 microinches, arithmetical average, in roughing.

TABLE 18

RECOMMENDED CONDITIONS FOR MACHINING
INCONEL 718 SOLUTION TREATED AND AGED 41-45 R_c

Cr	Mo	Cb	Ti	Al	Fe	Ni
19	3	5.2	.8	.6	18	Bal.

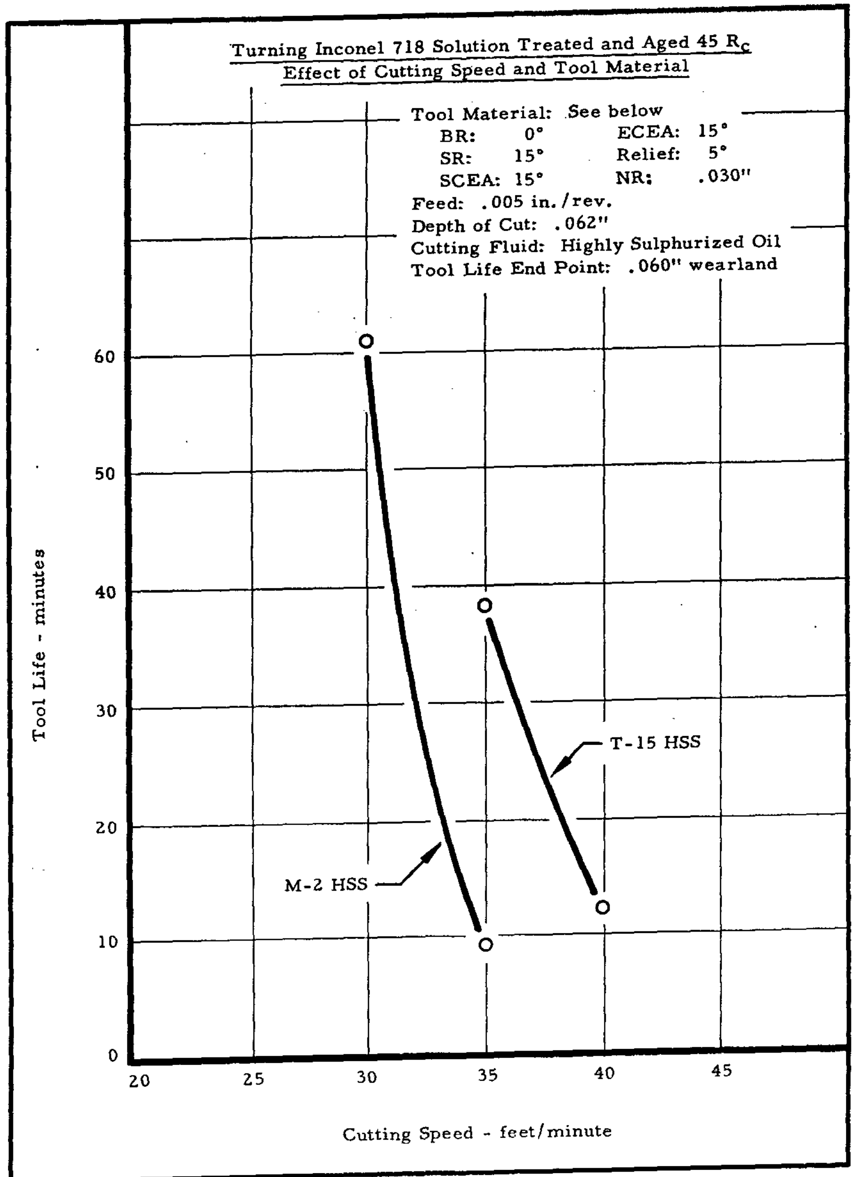
Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool Life	Wear-land inches	Cutting Fluid
Turning	T-15 HSS	BR: 0° SCEA: 15° SR: 15° ECEA: 15° Relief: 5° NR: .030"	5/8" square tool bit	.062	--	.005 in./ rev.	35	38 min.	.060	Highly Sulphurized Oil
Turning	C-2 Carbide	BR: 0° SCEA: 15° SR: 5° ECEA: 15° Relief: 5° NR: .030"	1/2" square throwaway insert	.062	--	.009 in./ rev.	90	50 min.	.015	Soluble Oil (1:20)
Face Milling	T-15 HSS	AR: 0° ECEA: 10° RR: 30° CA: 45° Clearance: 10°	4" diameter single tooth face mill	.060	2	.010 in./ tooth	20	120" work travel	.060	Highly Chlorinated Oil
Peripheral End Milling	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.125	.750	.002 in./ tooth	11	82" work travel	.012	Highly Sulphurized Oil
End Mill Slotting	T-15 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.002 in./ tooth	15	60" work travel	.012	Highly Sulphurized Oil

TABLE 18 (continued)

RECOMMENDED CONDITIONS FOR MACHINING
INCONEL 718 SOLUTION TREATED AND AGED 41-45 R_c

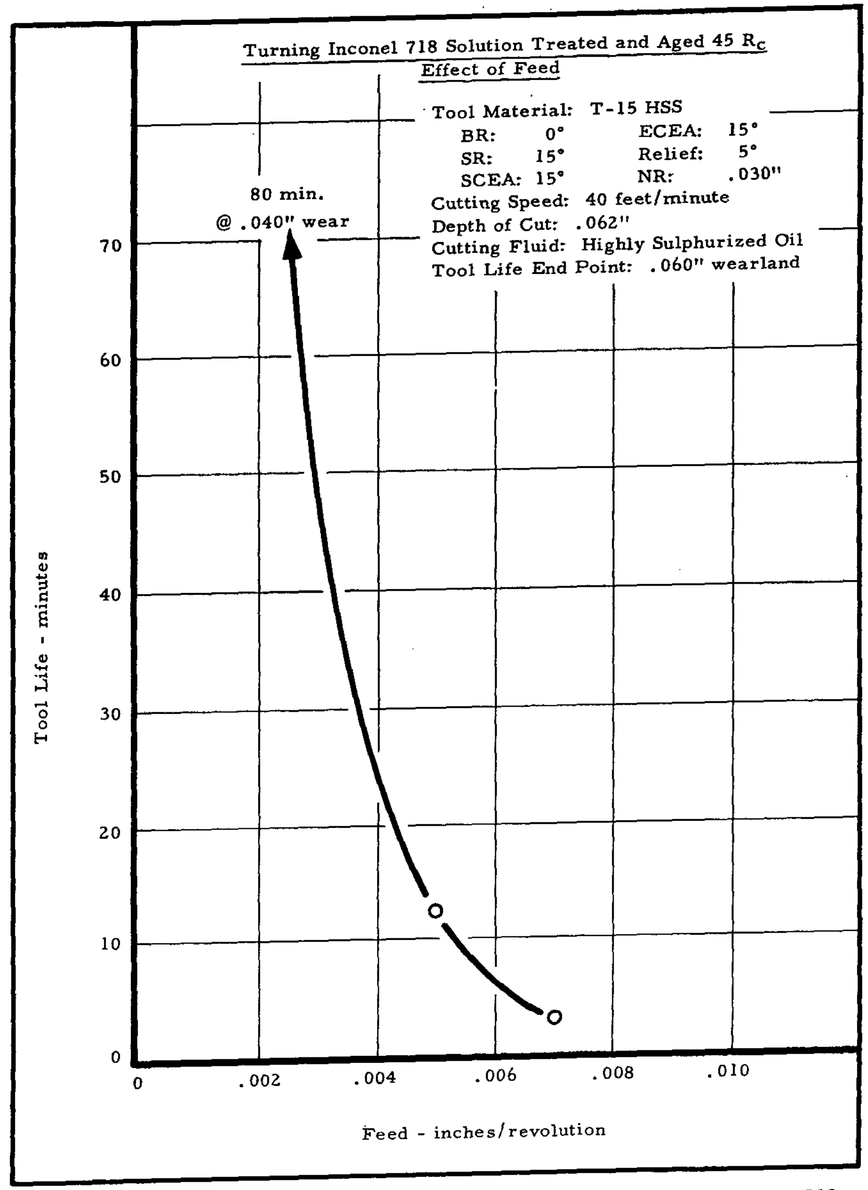
SURFACE GRINDING

Operation	Wheel Grade	Grinding Fluid	Wheel Speed Ft./Min.	Table Speed Ft./Min.	Down Feed In./Pass.	Cross Feed In./Pass.	G Ratio
Finishing	32A46J8VBE	Highly Sulphurized Oil	3000-4000	60	.0005	.050	4
Roughing	32A46J8VBE	Highly Sulphurized Oil	3000-4000	60	.001	.050	17



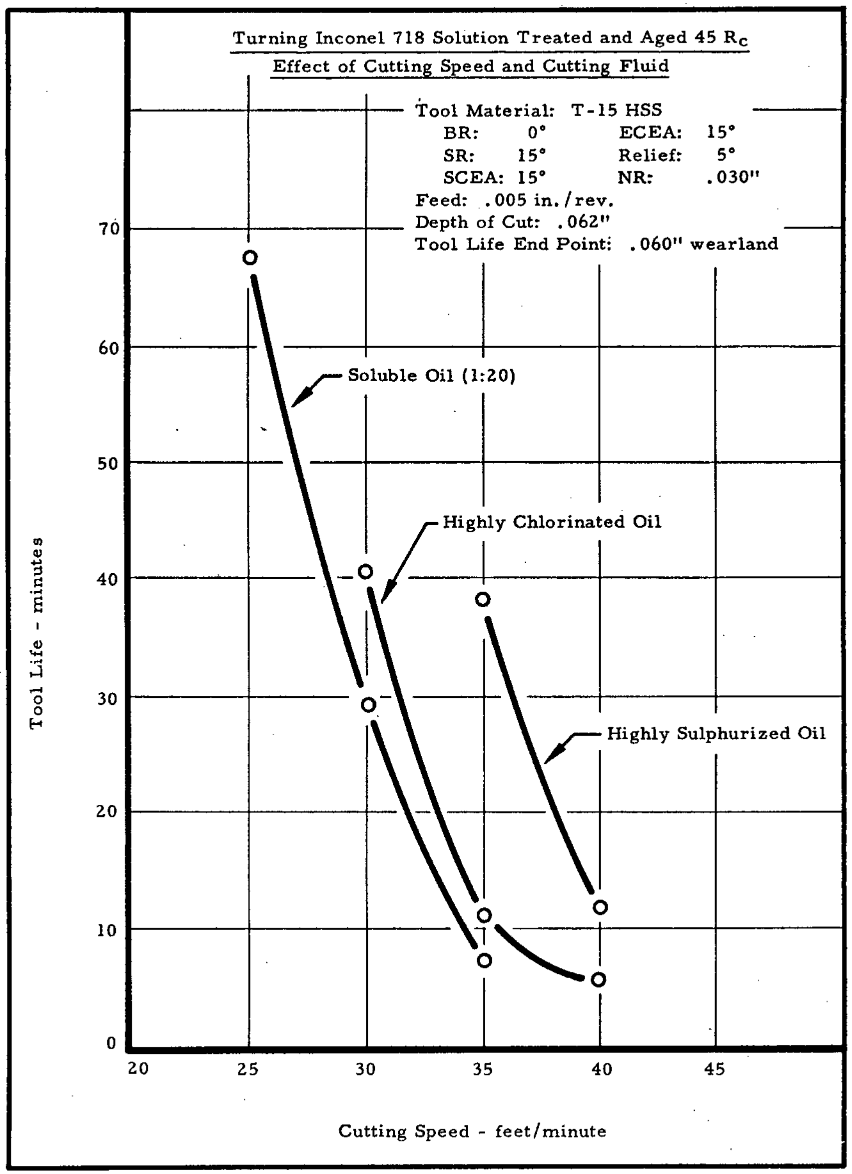
See text, page 227

Figure 254



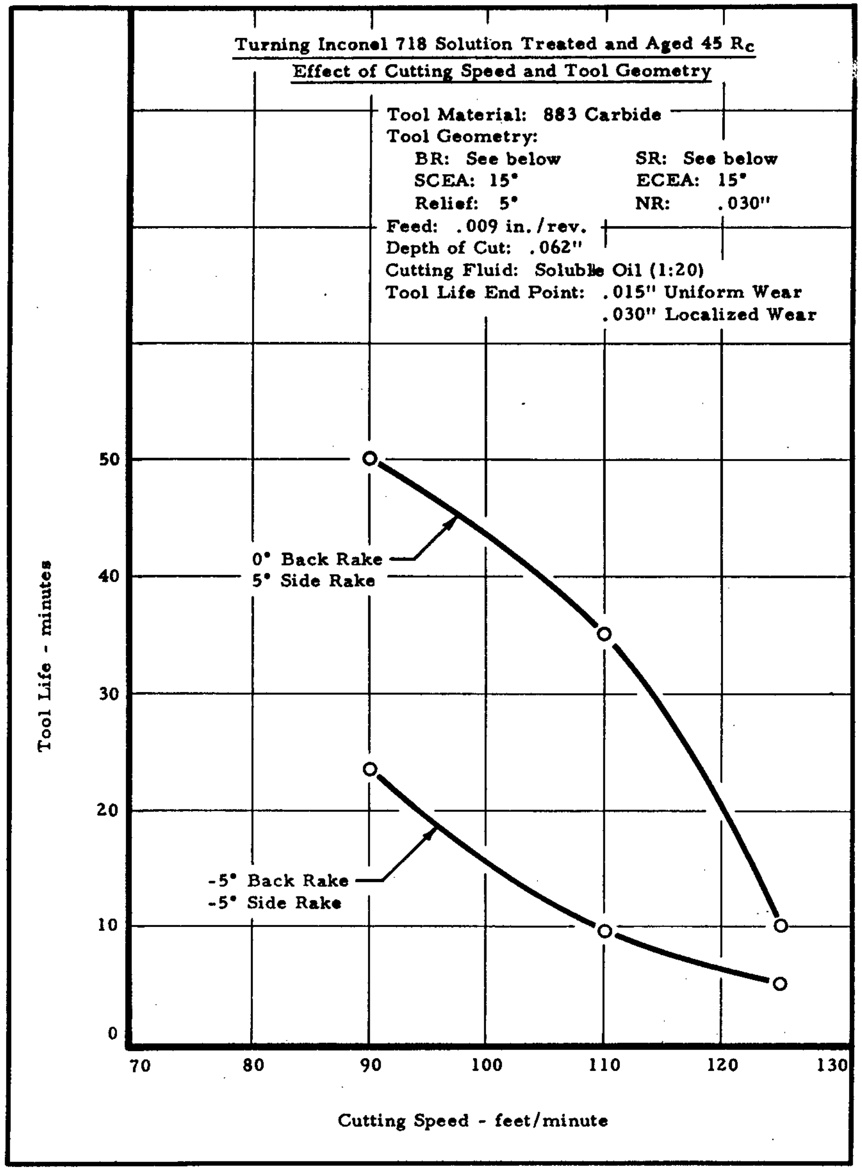
See text, page 227

Figure 255



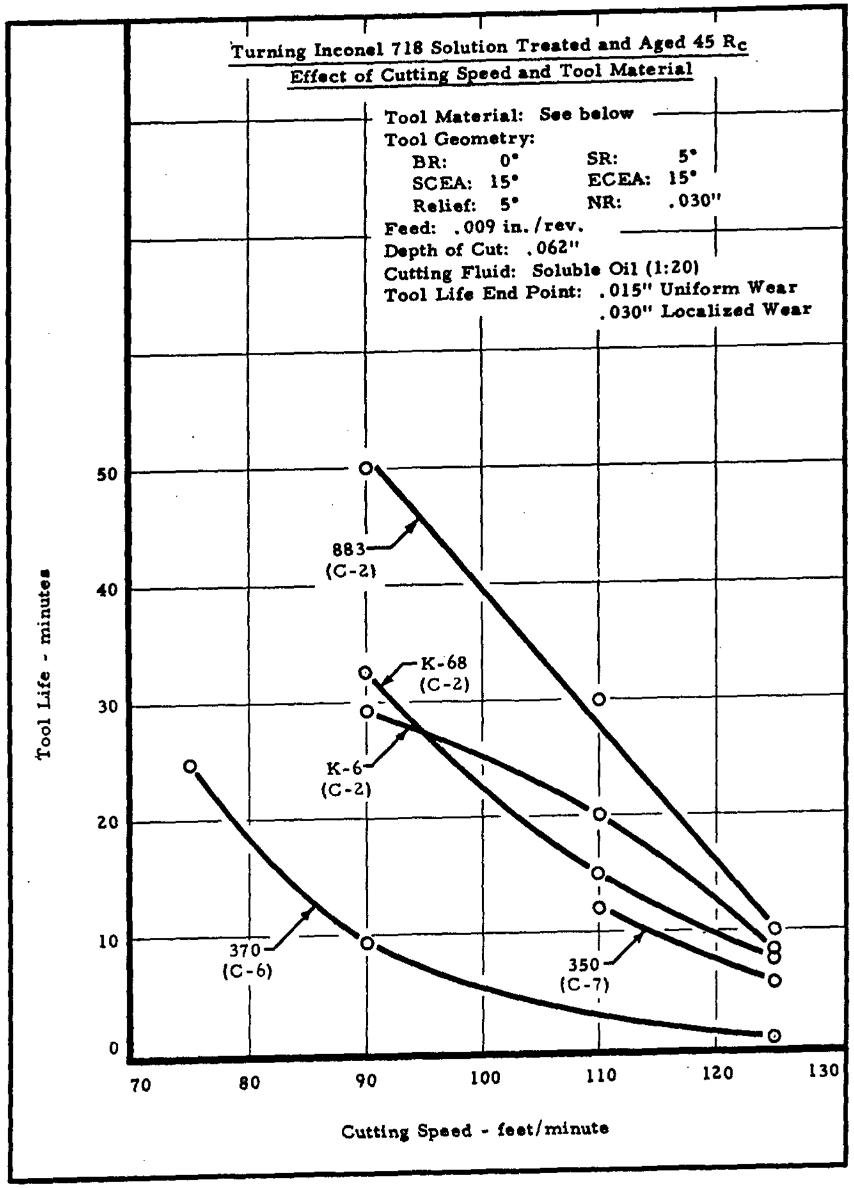
See text, page 227

Figure 256



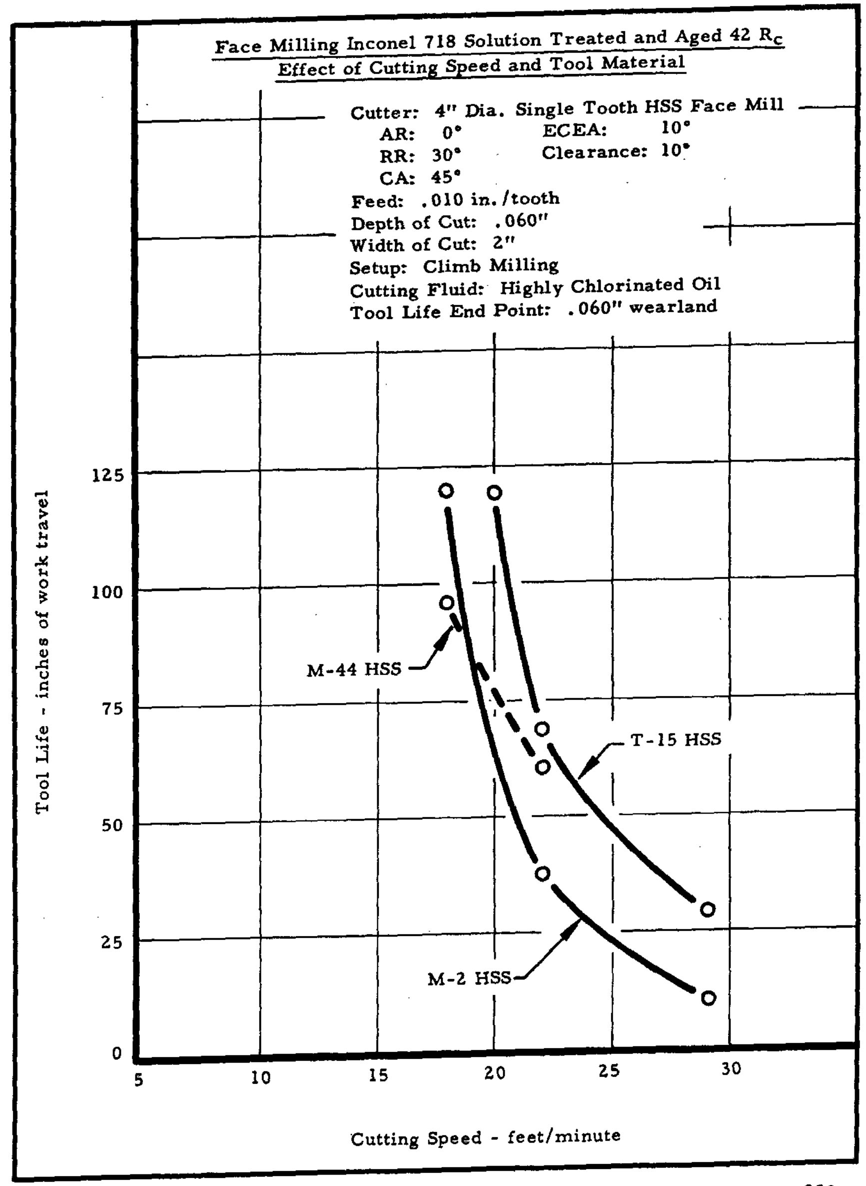
See Text, page 227

Figure 257



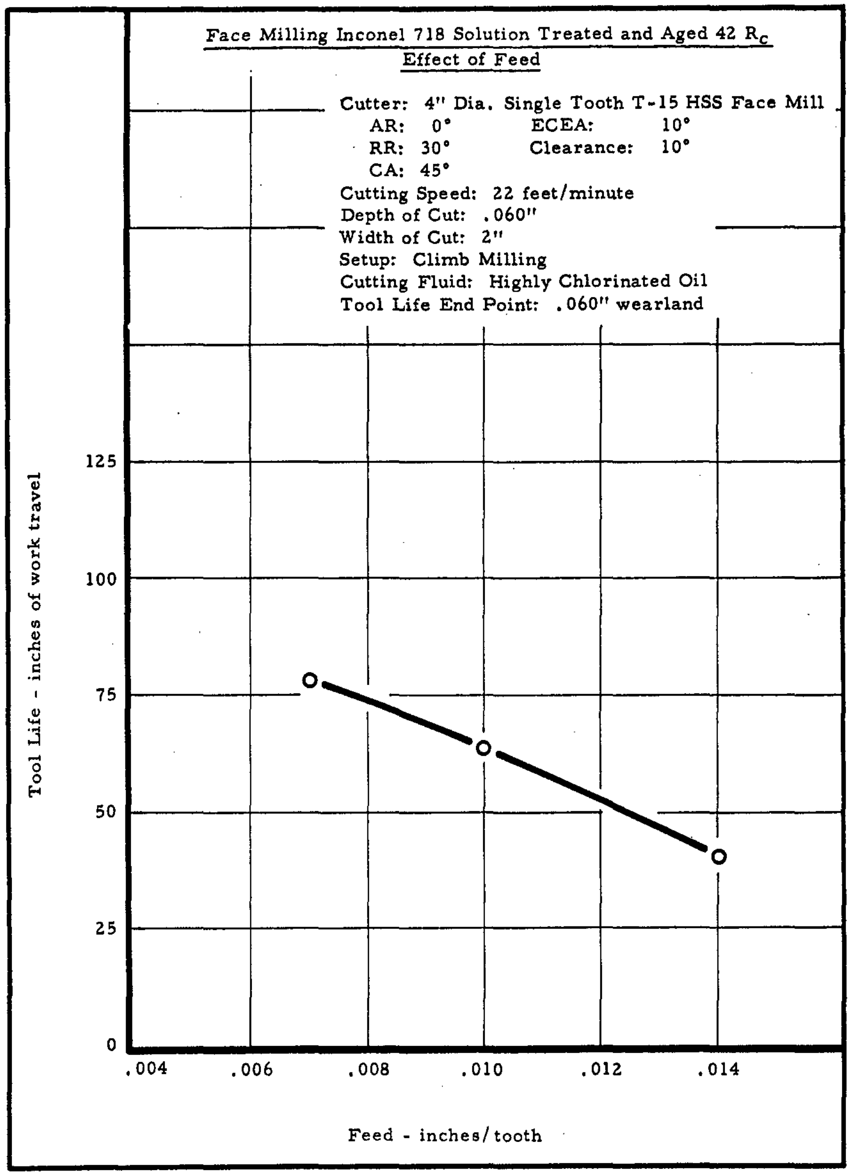
See Text, page 227

Figure 258



See text, page 227

Figure 259



See text, page 227

Figure 260

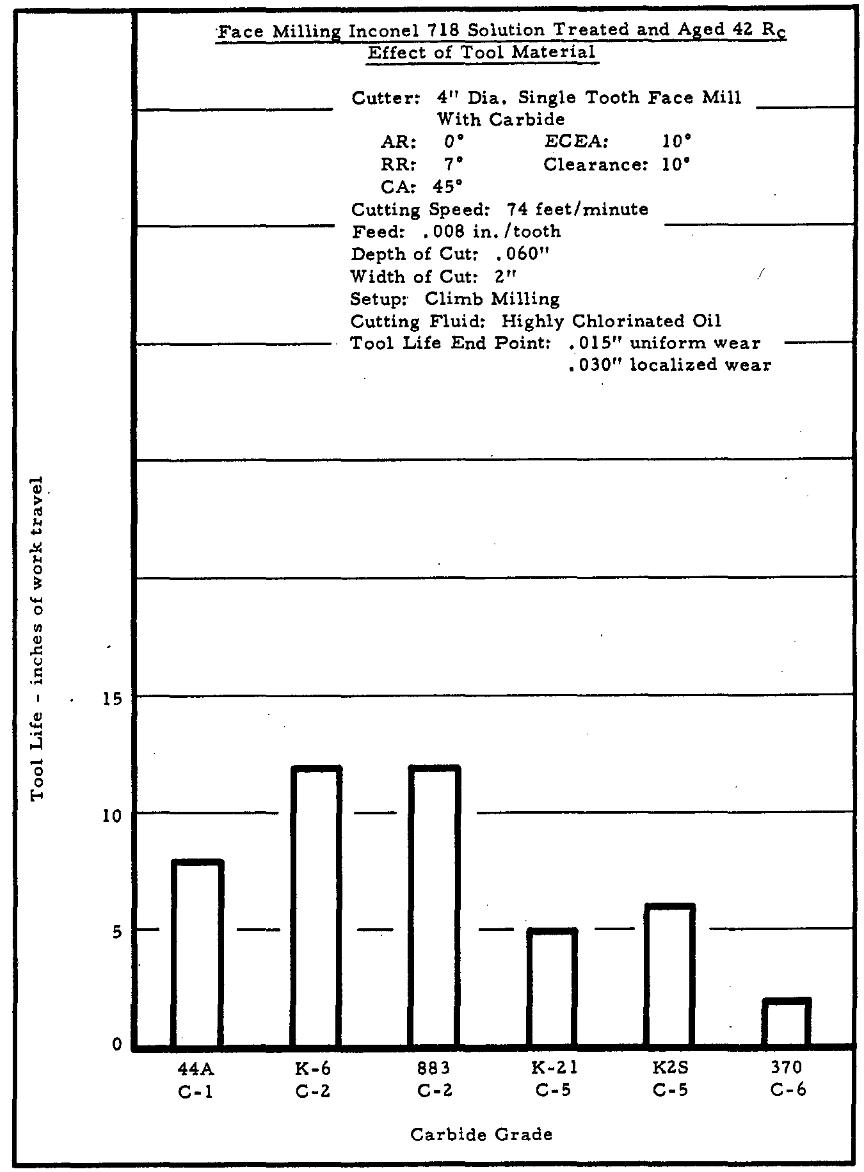


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Figure 261

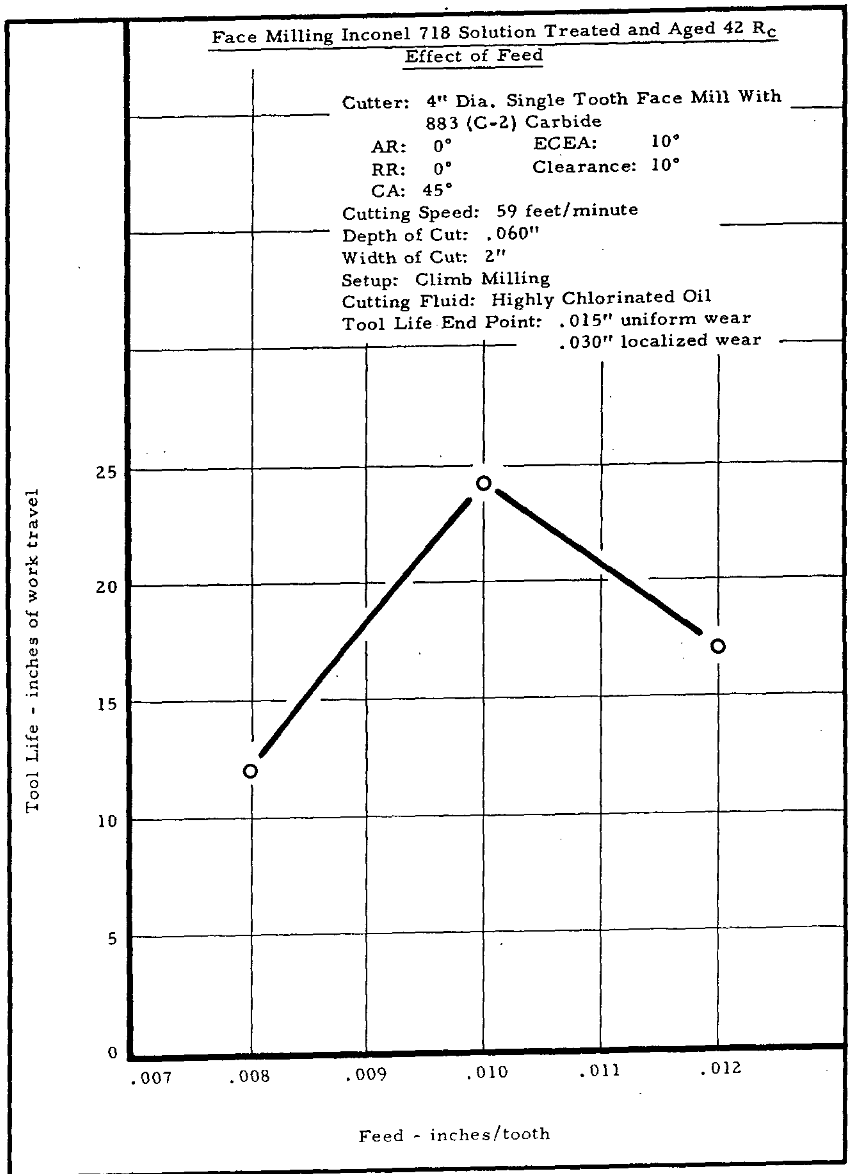

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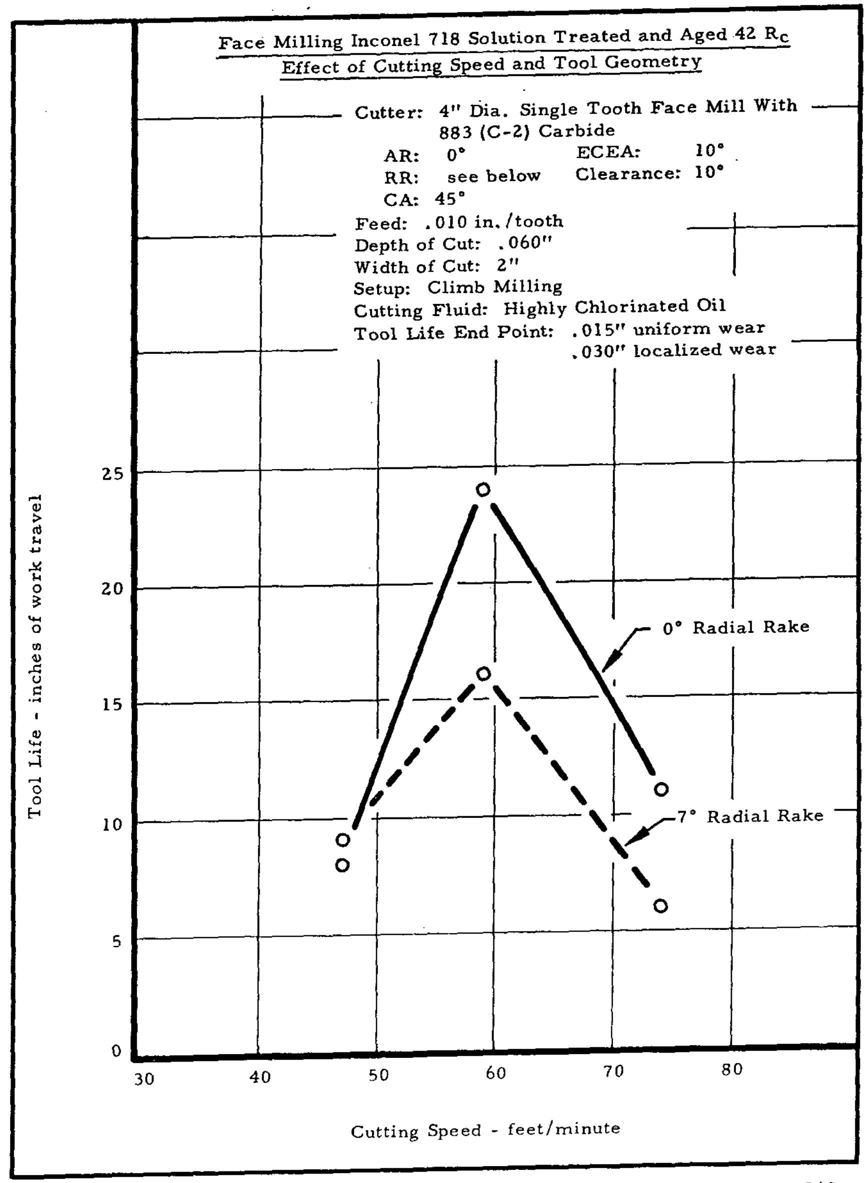
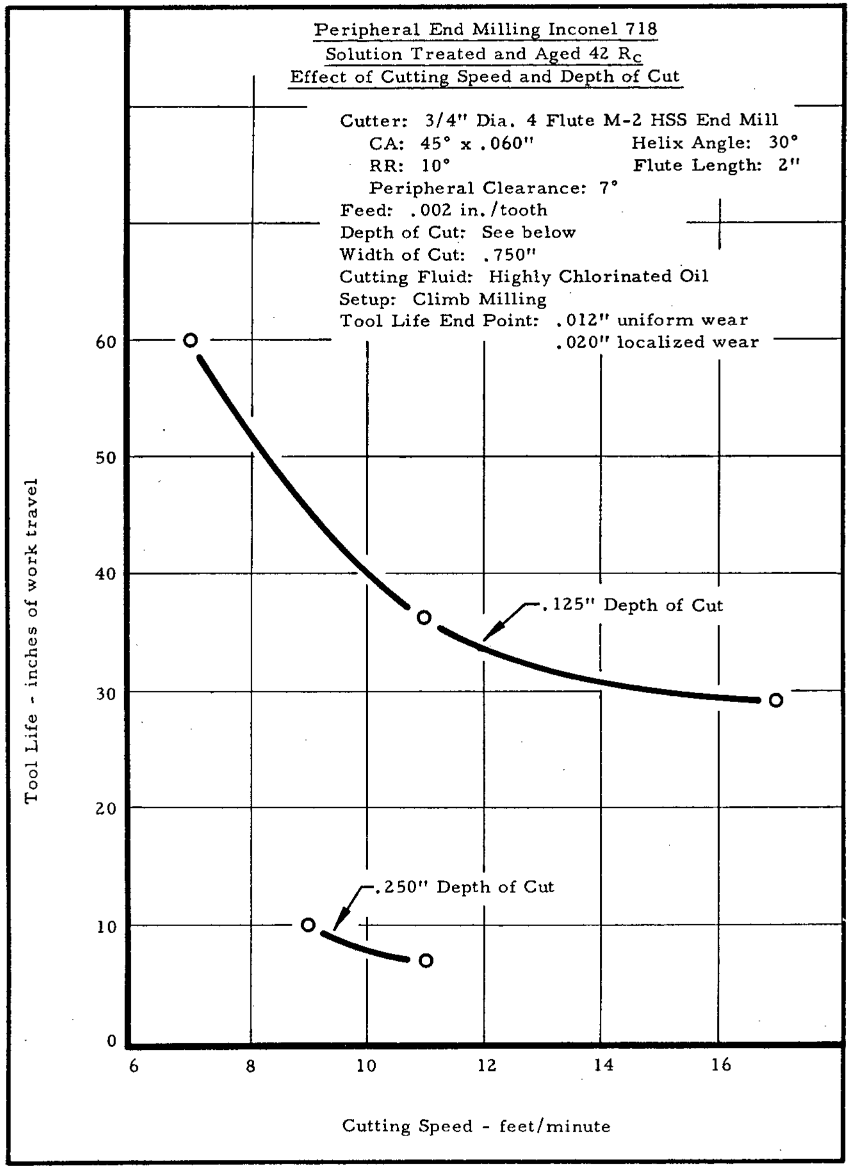
Figure 262



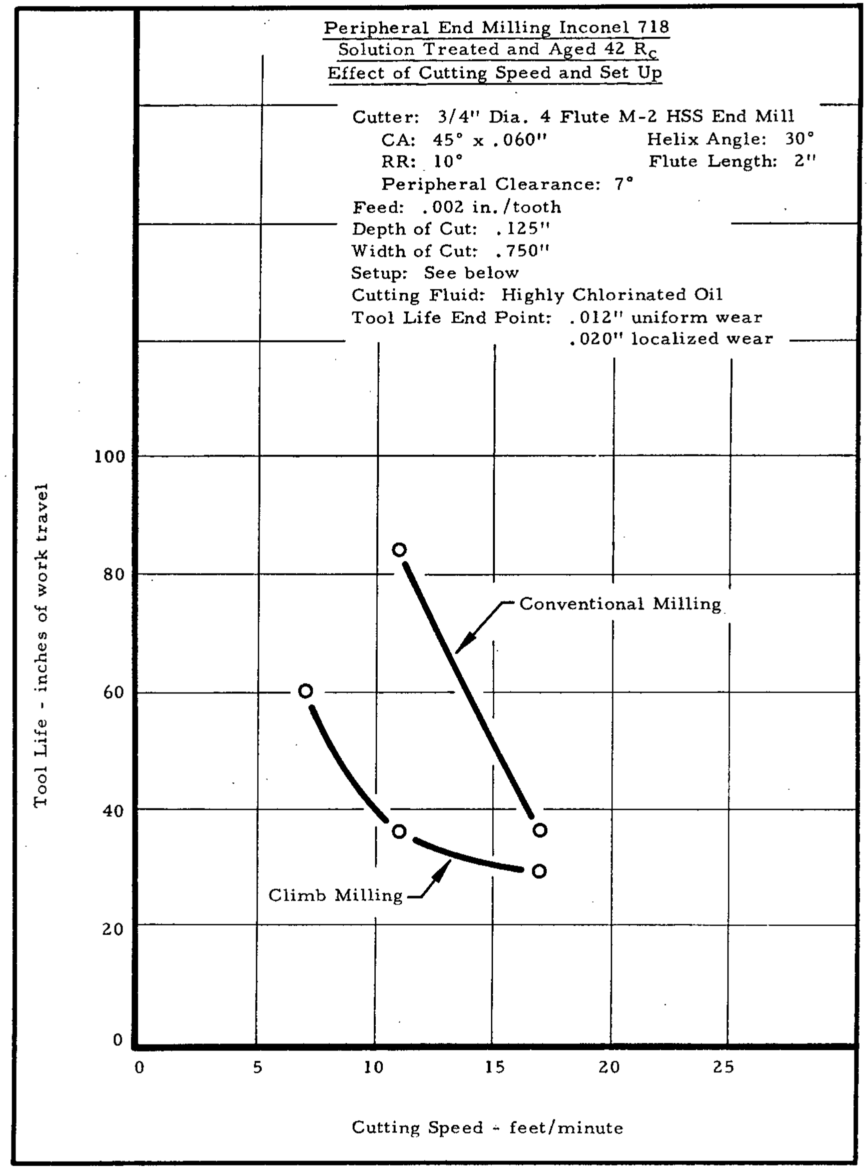
See text, page 228

Figure 263



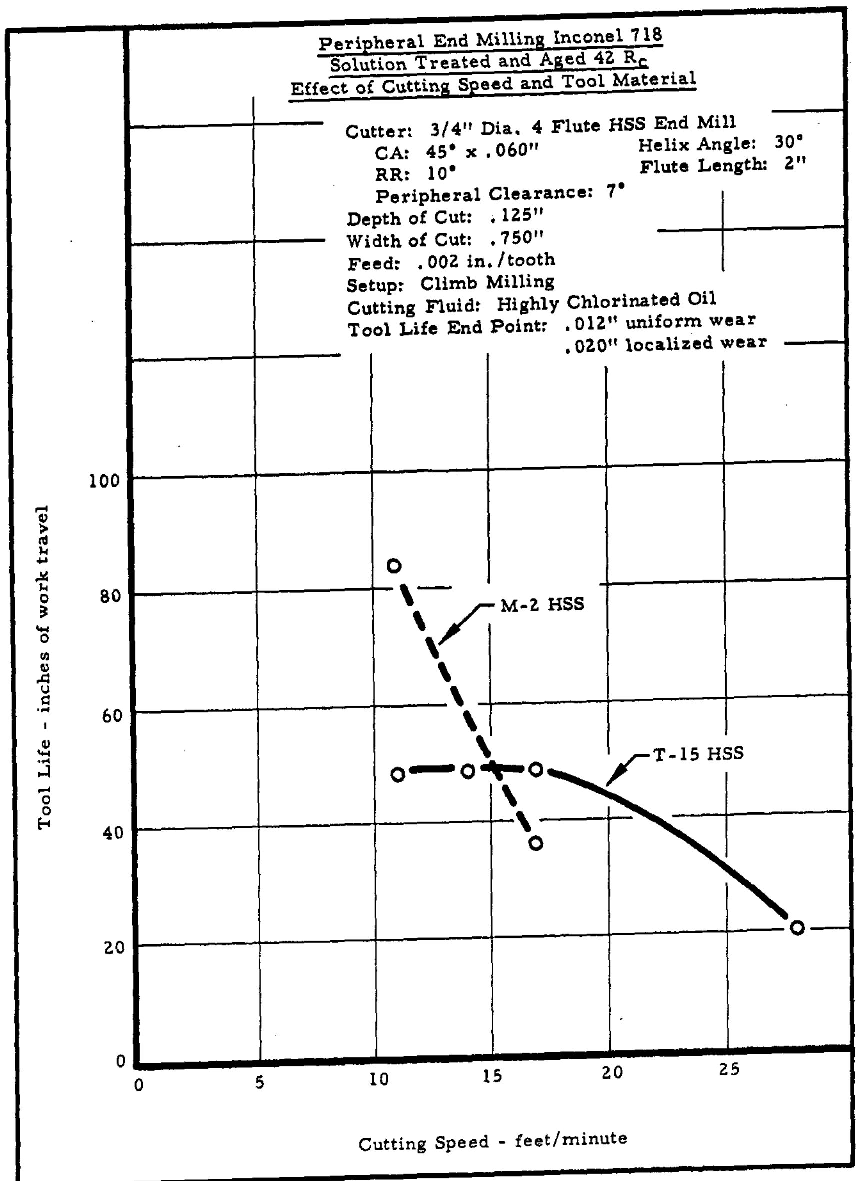
See text, page 228

Figure 264



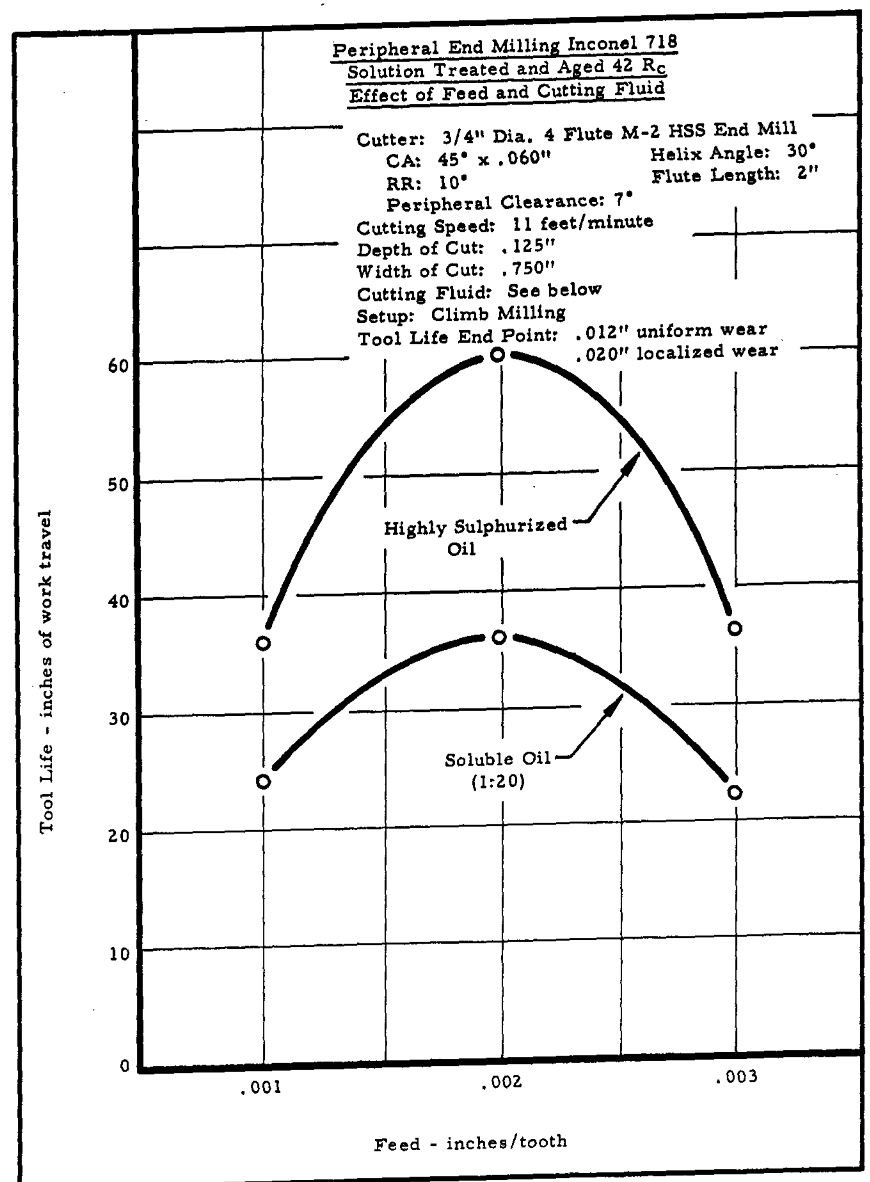
See text, page 228

Figure 265



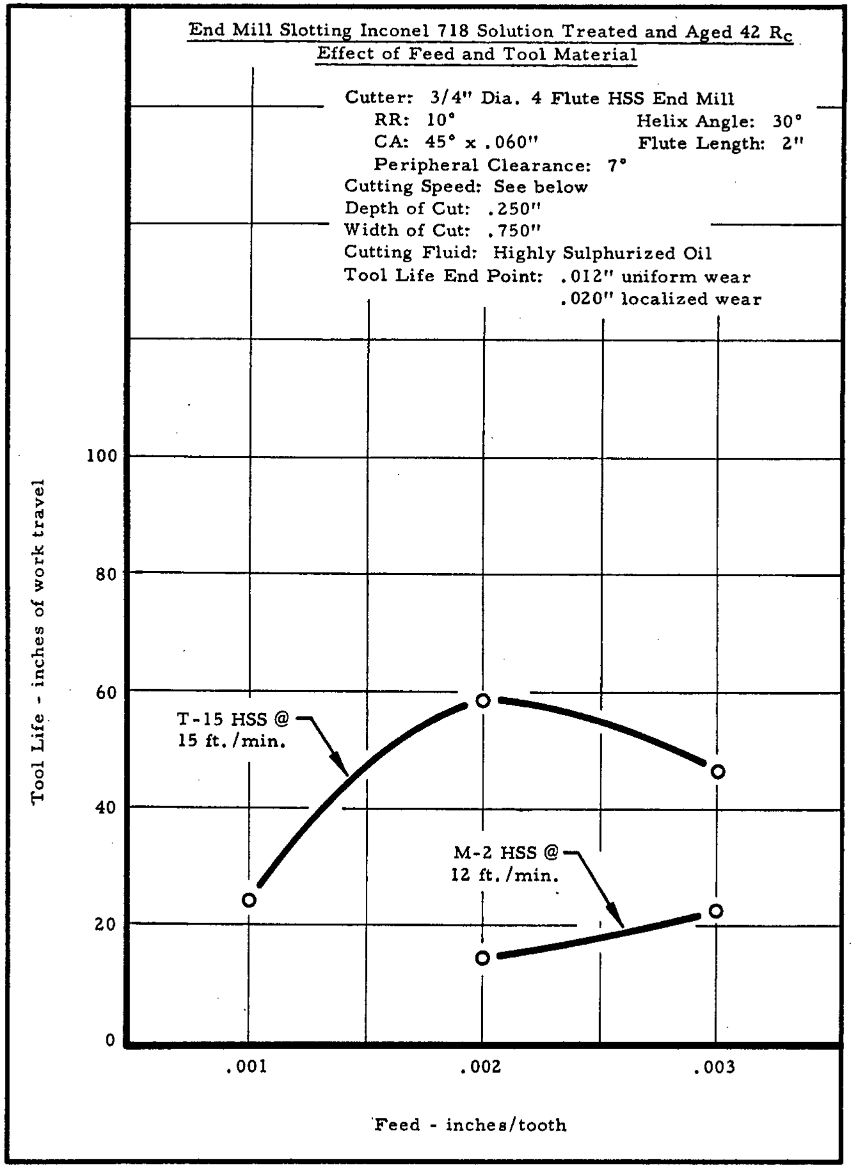
See text, page 228

Figure 266



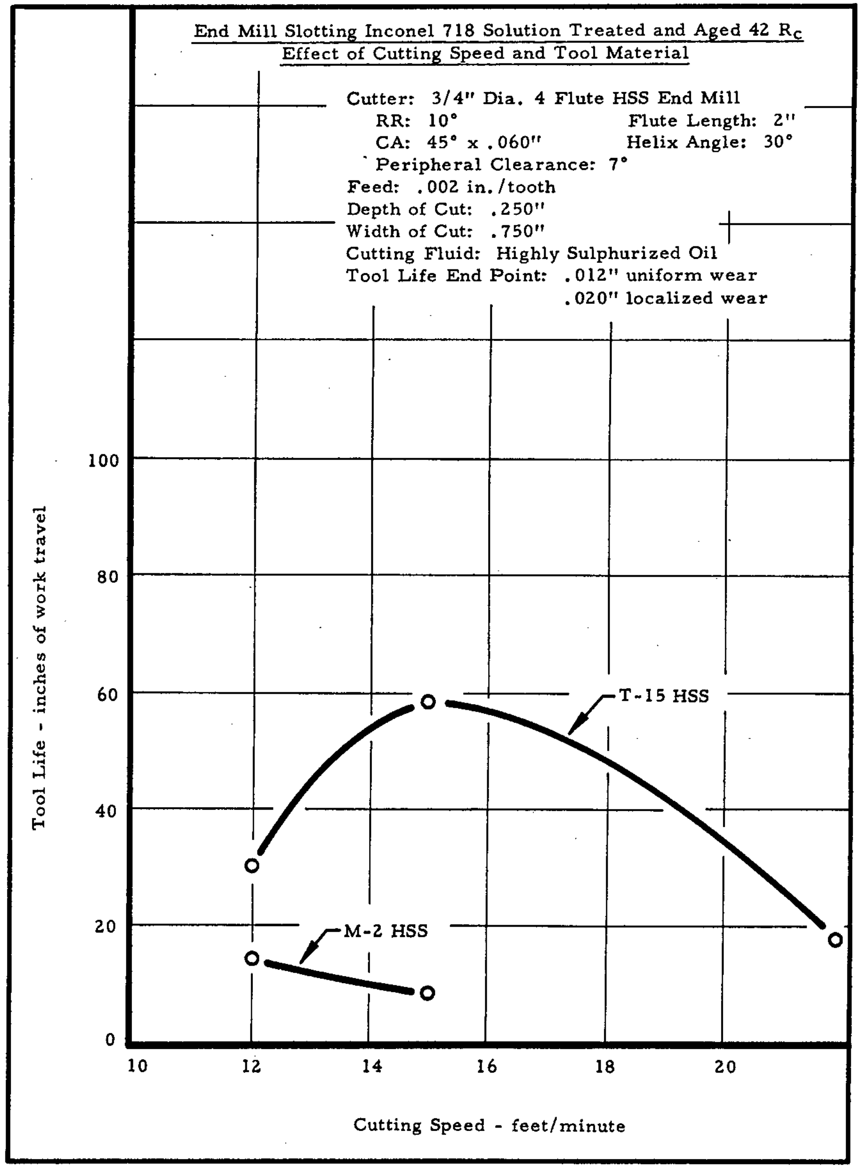
See text, page 228

Figure 267



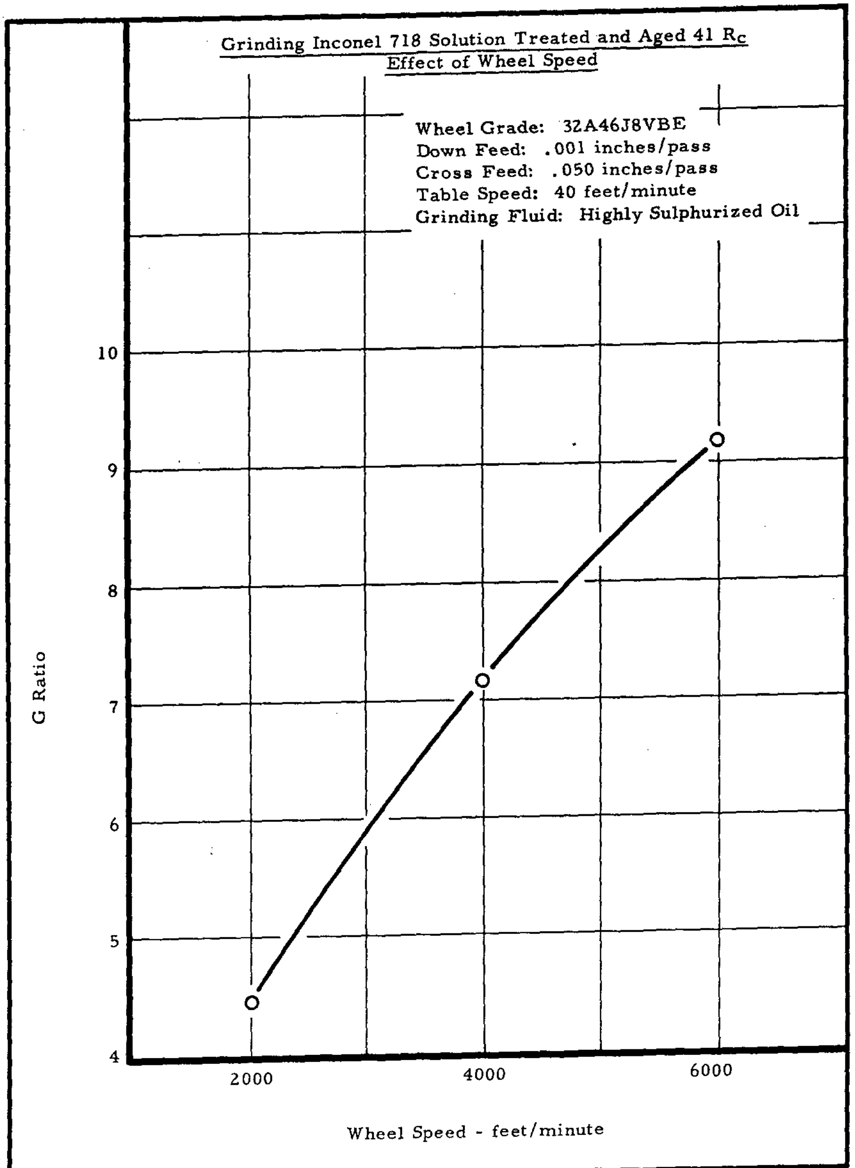
See text, page 228

Figure 268



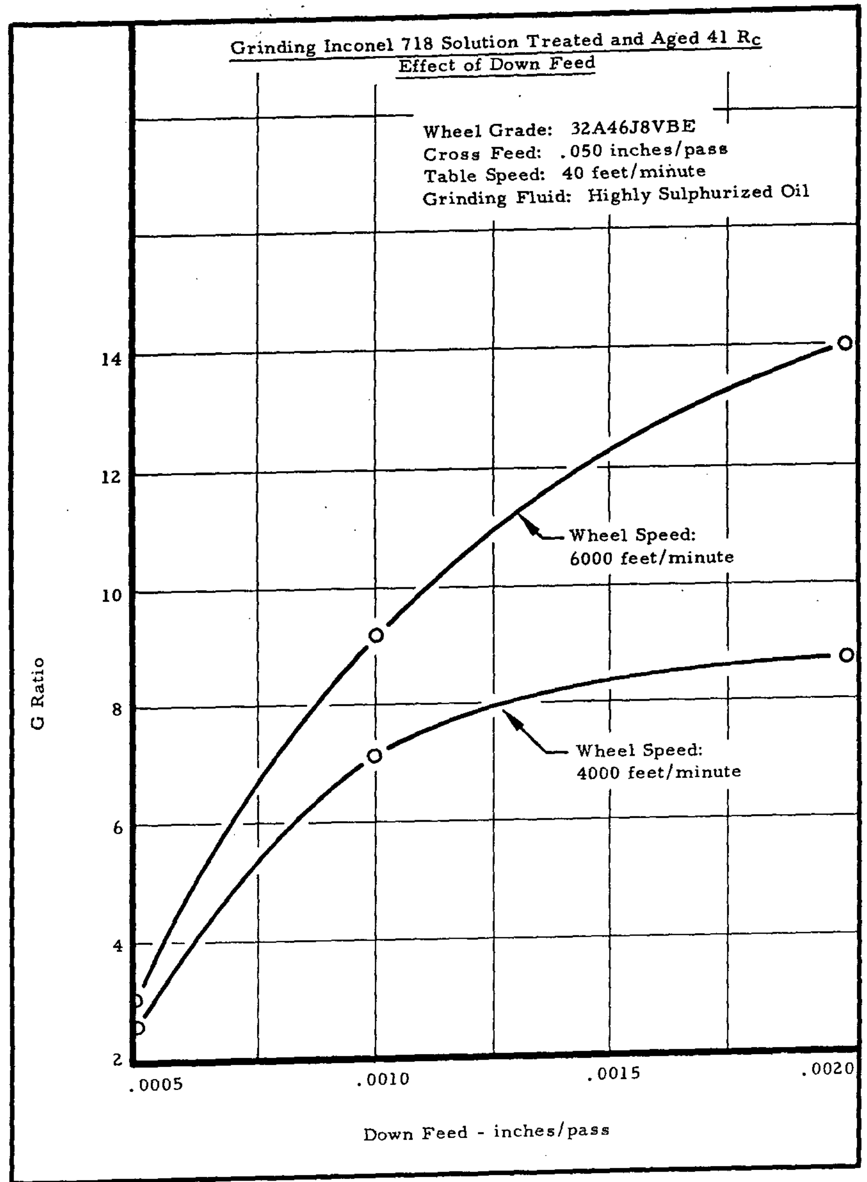
See text, page 228

Figure 269



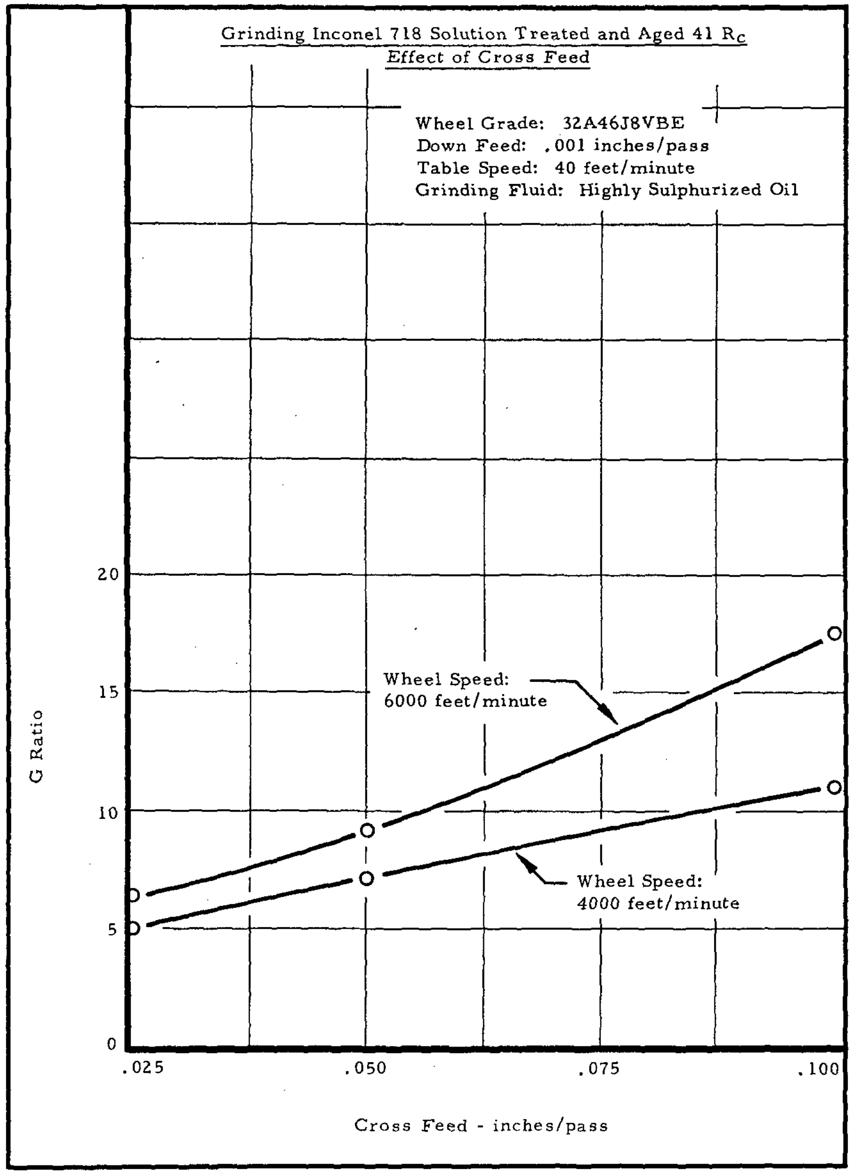
See text, page 229

Figure 270



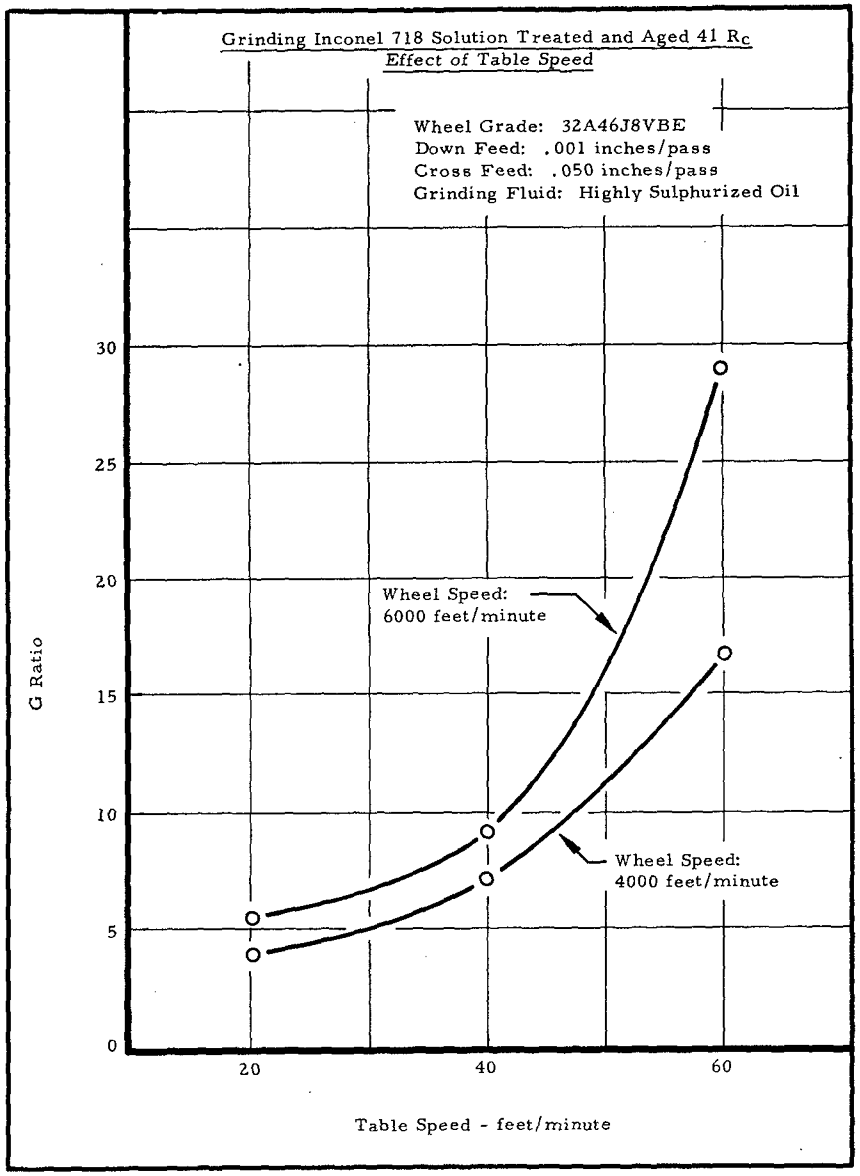
See text, page 229

Figure 271



See text, page 229

Figure 272



See text, page 229

Figure 273

5.2 Waspaloy

Waspaloy is a precipitation age-hardenable (vacuum melted) nickel base alloy for high temperature service up to 1800F. The nominal composition of this alloy is as follows:

Ni - 19.5 Cr - 13.5 Co - 4.0 Mo - 3.0 Ti - 1.3 Al - .05 C

Forged, solution treated bars 4" in diameter were procured for turning tests. These were solution treated at the mill as follows:

1850F/4 hours/oil quench

Hardness of these bars as received was 341 BHN. In addition, material for the milling operations, etc. was procured as 2" x 4" bar stock. This material, also ordered in the solution treated condition, had a hardness of 293-302 BHN.

In order to compare the aged to the solution treated and mill annealed conditions, appropriate samples were aged as follows:

1550F/4 hours/air cool to 1400F. Hold at 1400F until
total aging time equals 16 hours/air cool

The aging treatment yielded a hardness of 388 BHN.

The microstructure of the alloy in both heat treated conditions consists basically of small randomly distributed carbides in an equiaxed single-phase grained matrix. Accentuation of the grains as a result of carbide precipitation occurs from the aging cycle. The predominant grain size was in the range of ASTM 3-4.

Waspaloy, Solution Treated and Aged

Etchant: Kalling's Mag: 500X

5.2 Waspaloy (continued)

Turning (Solution Treated 341 BHN)

Three types of HSS tools are compared in Figure 274, page 249, in turning Waspaloy in the solution treated condition. Appreciable differences in tool life values were obtained for a given cutting speed. For example, at a cutting speed of 25 ft./min., tool life values of 24, 31 and 44 minutes resulted with the corresponding types of tools M-2, T-15 and M-44. Note also that with all three types of tools cutting speed was critical. An increase in cutting speed of only 5 ft./min. resulted in a 50% reduction in tool life.

As shown in Figure 275, page 249, the use of a highly chlorinated oil provided less tool life than the soluble oil (1:20). For a given tool life with the T-15 tools, the cutting speeds were 15 to 20% lower with the chlorinated oil than with the soluble oil.

The relationships of tool life with feed for two cutting speeds are illustrated in Figure 276, page 250, with a T-15 HSS tool. At a cutting speed of 25 ft./min., the tool life at a feed of .005 in./rev. was 80 minutes as compared to 31 minutes at a feed of .009 in./rev. Again, it should be pointed out that at the higher feed, the production rate was 80% faster.

A comparison is made in Figure 277, page 250, of two different tool geometries with carbide tools. A considerable improvement in tool life was obtained when the tool geometry with the 45° side cutting edge angle was used. At a cutting speed of 125 ft./min. the tool life increased from 5 minutes to 33 minutes. It was later shown in tests on the Waspaloy in the aged condition that increasing the side cutting edge angle resulted in minimizing the rapid wear or gouging at the point on the cutting edge which cuts the previously machined surface.

As shown in Figure 278, page 251, the tool life with K-68 carbide was appreciably longer than with an 883 carbide. For a 30 minute life, the cutting speed with the K-68 carbide was 126 ft./min. as compared to 90 ft./min. with the 883 carbide.

Earlier it was pointed out that the soluble oil was superior to the highly chlorinated oil in turning with HSS tools. Figure 279, page 251, indicates that the same situation exists with carbide tools.

The feed with carbide tools appears to be just as critical as with HSS tools, see Figure 280, page 252. The tool life at a feed of .005 in./rev. was more than 3 times that obtained at a feed of .009 in./rev.

5.2 Waspaloy (continued)

Face Milling (Solution Treated 302 BHN)

The chart in Figure 281, page 252, shows results obtained with five different grades of carbide in face milling the skin of Waspaloy solution treated to 302 BHN. The 883 carbide provided the longest cutter life in this operation. However, the tool life was less than 25 inches of work travel. The tool life curve in Figure 282, page 253, shows the relationship between cutting speed and tool life in face milling the skin. Note that care should be exercised in selecting the proper cutting speed, in that a maximum was reached at a cutting speed of 92 ft./min. for the alloy involved.

The results presented in Figure 283, page 253, indicate the need to use feeds of less than .011 in./tooth in face milling under the skin with HSS tools. At a cutting speed of 32 ft./min. with an M-44 HSS tool, it was found that when the feed per tooth was increased beyond .011 in./tooth the cutter life dropped from 125 inches of work travel to 10 inches of work travel at a feed of .013 in./tooth. Also note that the cutter life was about the same at a feed of .008 in./tooth as at .011 in./tooth. A comparison of three types of high speed steels used in a cutter for face milling Waspaloy solution treated is shown in Figure 284, page 254. The M-44 HSS cutter proved to be superior to both the T-15 and the M-2 HSS. For example, at a cutting speed of 34 ft./min. and a feed of .011 in./tooth, the cutter lives for the M-2, T-15 and M-44 HSS tools were 20, 55 and 120 inches of work travel, respectively.

The selection of the cutting fluid to be used in face milling Waspaloy in the solution treated condition was also somewhat critical. Note in Figure 285, page 254, that the cutter life at a cutting speed of 34 ft./min. increased from 20 inches of work travel with the highly sulfurized oil to 120 inches of work travel with the highly chlorinated oil.

As has been the case on many of the nickel base alloys, face milling with carbide was not satisfactory. For example, as shown in Figure 286, page 255, the maximum cutter life obtained with a C-2 grade of carbide was 18 inches of work travel. The cutting speeds used ranged from 59 ft./min. to 114 ft./min. A comparison of these results with those shown in Figure 285 indicates that while with a HSS tool the cutting speed must be reduced to 34 ft./min., a cutter life of over 100 inches of work travel was obtained with a single tooth cutter.

5.2 Waspaloy (continued)

Peripheral End Milling (Solution Treated 302 BHN)

Climb milling in peripheral end milling of Waspaloy in the solution treated condition is preferred over conventional milling, see Figure 287, page 255. For a given tool life the cutting speed was 30% higher with the climb milling as compared to conventional milling. As shown in Figure 288, page 256, using climb milling it was found that a feed of .002 in./tooth produced the longest tool life at a cutting speed of 28 ft./min. While at a feed of .004 in./tooth the tool life was not drastically lower, chipping occurred at the corners of the cutter. Thus, even with the higher production rate at the .004 in./tooth feed, this feed is not recommended.

A comparison of the T-15 and the M-2 HSS cutters is given in Figure 289, page 256. For a tool life of 125 inches of work travel, the cutting speed with the T-15 HSS tool was 50% greater than with the M-2 HSS cutter. However, note in Figure 290, page 257, that with the T-15 HSS end mill the feed is far more critical than it was with the M-2 HSS cutter. In climb milling the cutter life dropped very rapidly when the feed was increased from .002 to .003 in./tooth. At the higher feed, chipping was the major reason for tool failure.

With an M-2 HSS end mill it was found, as shown in Figure 291, page 257, that a highly sulfurized oil was much more effective than a highly chlorinated oil. For example, at a cutting speed of 35 ft./min. the cutter life was 115 inches of work travel with the highly sulfurized oil as compared to only 55 inches of work travel with the highly chlorinated oil.

End Mill Slotting (Solution Treated 302 BHN)

The T-15 HSS did not prove to be any more effective than the M-2 HSS in end mill slotting Waspaloy solution treated to 302 BHN at the lower cutting speeds. As shown in Figure 292, page 258, the difference was insignificant between the two types of high speed steel at a cutting speed of 12 ft./min. However, at a cutting speed of 18 ft./min., the cutter life with the T-15 HSS was 80 inches of work travel as compared to 55 inches of work travel with the M-2 HSS. Note in Figure 293, page 258, that the feed with the T-15 HSS was somewhat more critical than with the M-2 as the feed was increased beyond .003 in./tooth.

5.2 Waspaloy (continued)

A comparison of two active cutting oils is shown in Figure 294, page 259. The highly chlorinated oil provided considerably longer tool life than the highly sulfurized oil. For example, at 12 ft./min. the cutter life with the highly chlorinated oil was 120 inches of work travel as compared to 70 inches of work travel with the highly sulfurized oil.

Drilling (Solution Treated 293 BHN)

The effect of both feed and cutting speed on drill life when drilling Waspaloy solution treated is shown in Figure 295, page 259. Note that the feeds of .002 and .005 in./rev. produced the most holes at the low cutting speed of 13 ft./min. Also, at the heavier feeds the drill life decreased rapidly with increases in cutting speed. It is suggested that a combination of feed and speed be selected so as to produce satisfactory tool life at maximum production. For example, a feed of .005 in./rev. and a cutting speed of 13 ft./min. produced over 150 holes. At a feed of .002 in./rev. and a cutting speed of 25 ft./min. over 100 holes were drilled. From the data presented, it appears that the recommended conditions should be .005 in./rev. feed at a cutting speed of 13 ft./min.

The results obtained in drilling with several types of high speed steel drills are shown in Figure 296, page 260. Both the M-42 and the T-15 HSS were far superior to the M-1 HSS drills.

Reaming (Solution Treated 293 BHN)

It is indicated in Figure 297, page 260, that the higher the cutting speed the more critical the feed selection. At a cutting speed of 45 ft./min. maximum tool life was obtained in the feed range of .005 to .009 in./rev. However, at a cutting speed of 50 ft./min., a drastic reduction in tool life occurred when the feed was increased from .005 to .009 in./rev.

Tapping (Solution Treated 293 BHN)

The tool life relationship between cutting speed and tap life is shown in Figure 298, page 261. A cutting speed of 20 ft./min. produced 200 holes on this material, while at 30 ft./min. less than 10 holes were tapped.

TABLE 19

RECOMMENDED CONDITIONS FOR MACHINING
WASPALOY SOLUTION TREATED 293-341 BHN

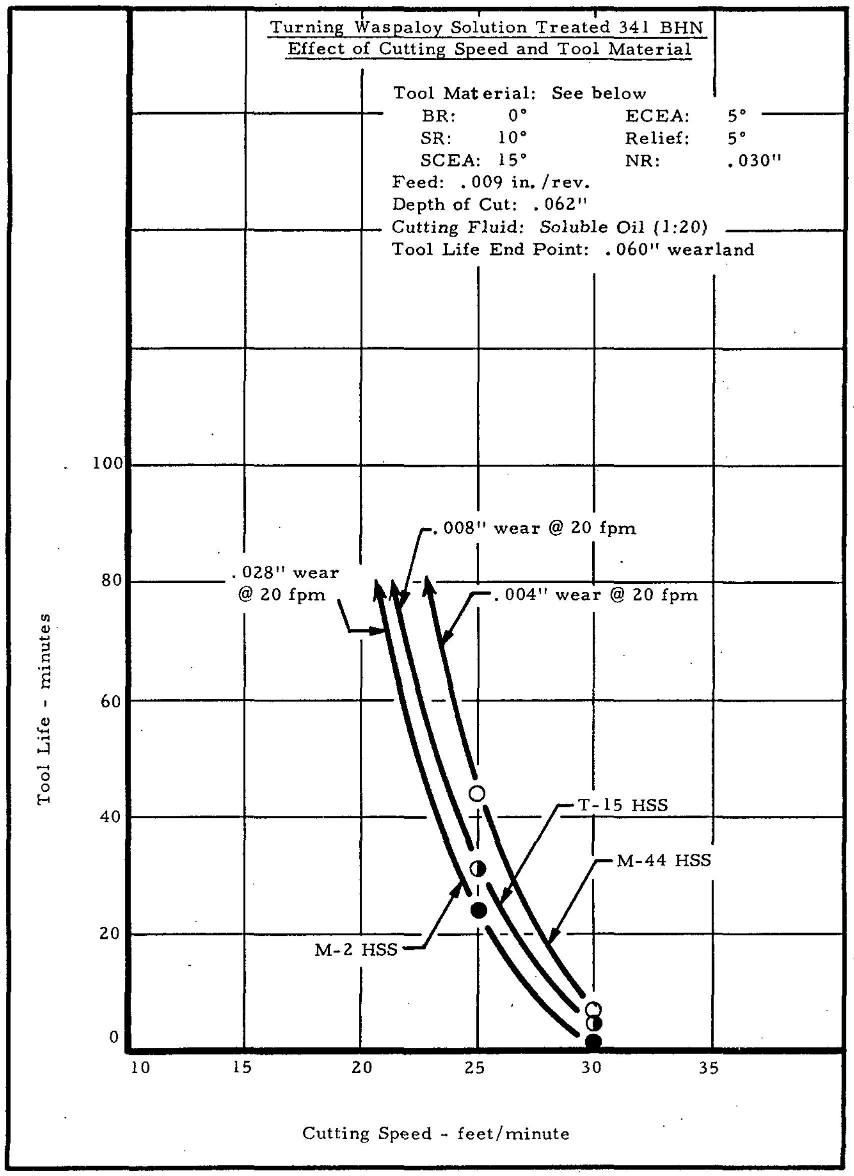
Cr	Co	Mo	Ti	Al	C	Ni
19.5	13.5	4.0	3.0	1.3	.05	Bal.

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	T-15 HSS	BR: 0° SCEA: 15° SR: 10° ECEA: 5° Relief: 5° NR: .030"	5/8" square tool bit	.062	--	.009 in./rev.	20	80 min.	.008	Soluble Oil (1:20)
Turning	C-2 Carbide	BR: 5° SCEA: 45° SR: 0° ECEA: 45° Relief: 7° NR: .030"	1/2" square throwaway insert	.062	--	.009 in./rev.	122	33 min.	.015	Soluble Oil (1:20)
Face Milling	M-44 HSS	AR: 0° ECEA: 10° RR: 30° CA: 45° Clearance: 10°	4" diameter single tooth face mill	.060	2	.011 in./tooth	32	120" work travel	.060	Highly Chlorinated Oil
Peripheral End Milling	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.125	.750	.002 in./tooth	35	115" work travel	.012	Highly Sulphurized Oil
End Mill Slotting	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 7° CA: 45° x .060"	3/4" diameter 4 tooth HSS end mill	.250	.750	.003 in./tooth	12	120" work travel	.012	Highly Chlorinated Oil
Drilling	T-15 HSS	118° plain point 7° clearance	1/4" diameter HSS drill 2-1/2" long	.500 thru	--	.005 in./rev.	13	150 holes	.015	Highly Chlorinated Oil

TABLE 19 (continued)

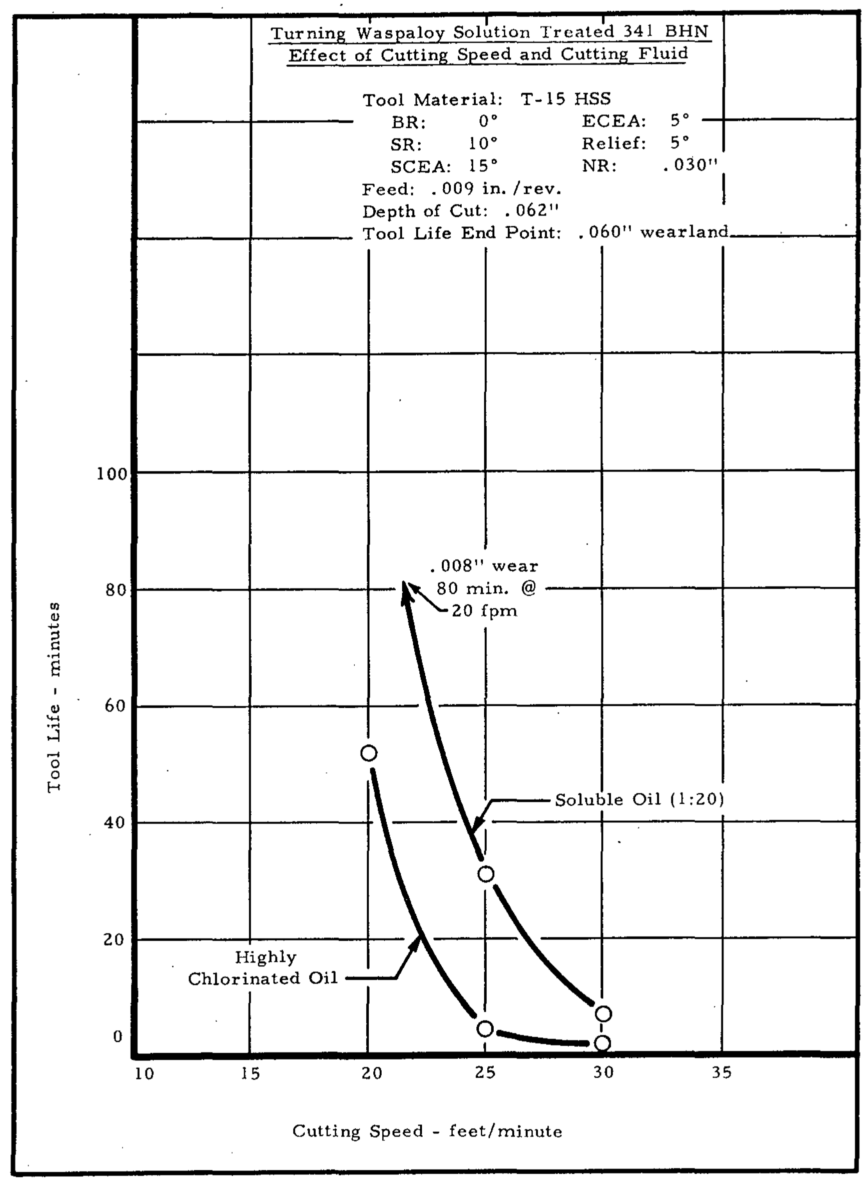
RECOMMENDED CONDITIONS FOR MACHINING
WASPALOY SOLUTION TREATED 293-341 BHN

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
Reaming	M-2 HSS	Helix Angle: 0° CA: 45° Clearance: 7°	.272" diameter 6 flute chucking reamer	.500 thru	--	.009 in./rev.	45	80 holes	.006	Highly Sulphurized Oil
Tapping	M-1 HSS	2 flute plug spiral point 75% thread	5/16-24 NF tap	.500 thru	--	--	20	200 holes	Tap Breakage	Highly Chlorinated Oil



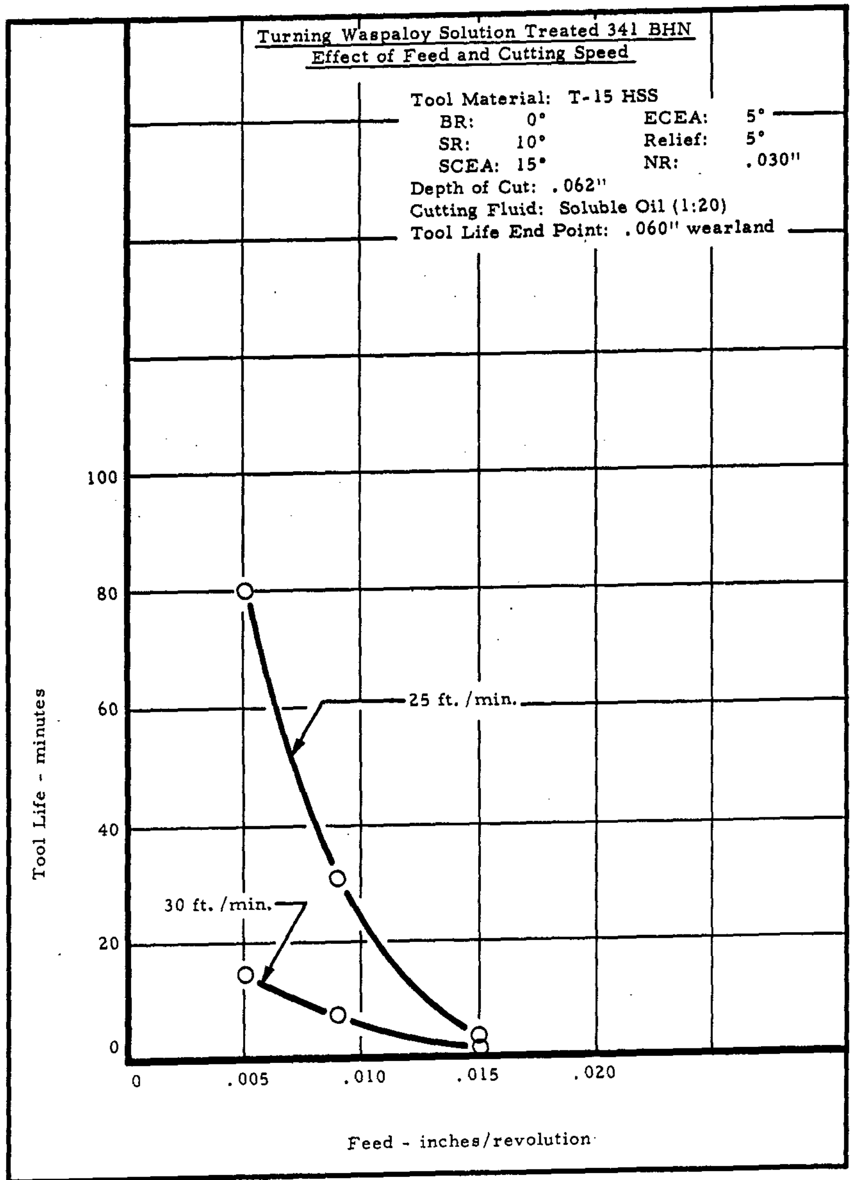
See text, page 243

Figure 274



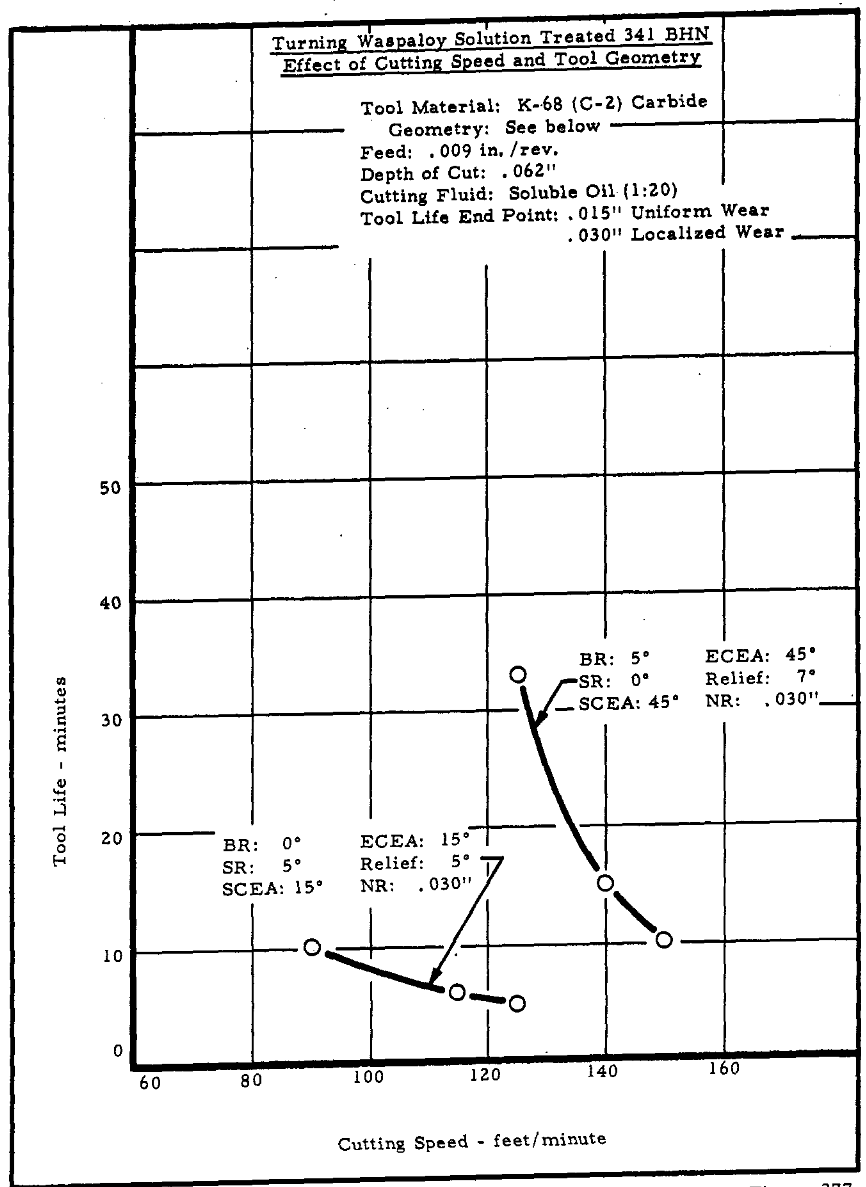
See text, page 243

Figure 275



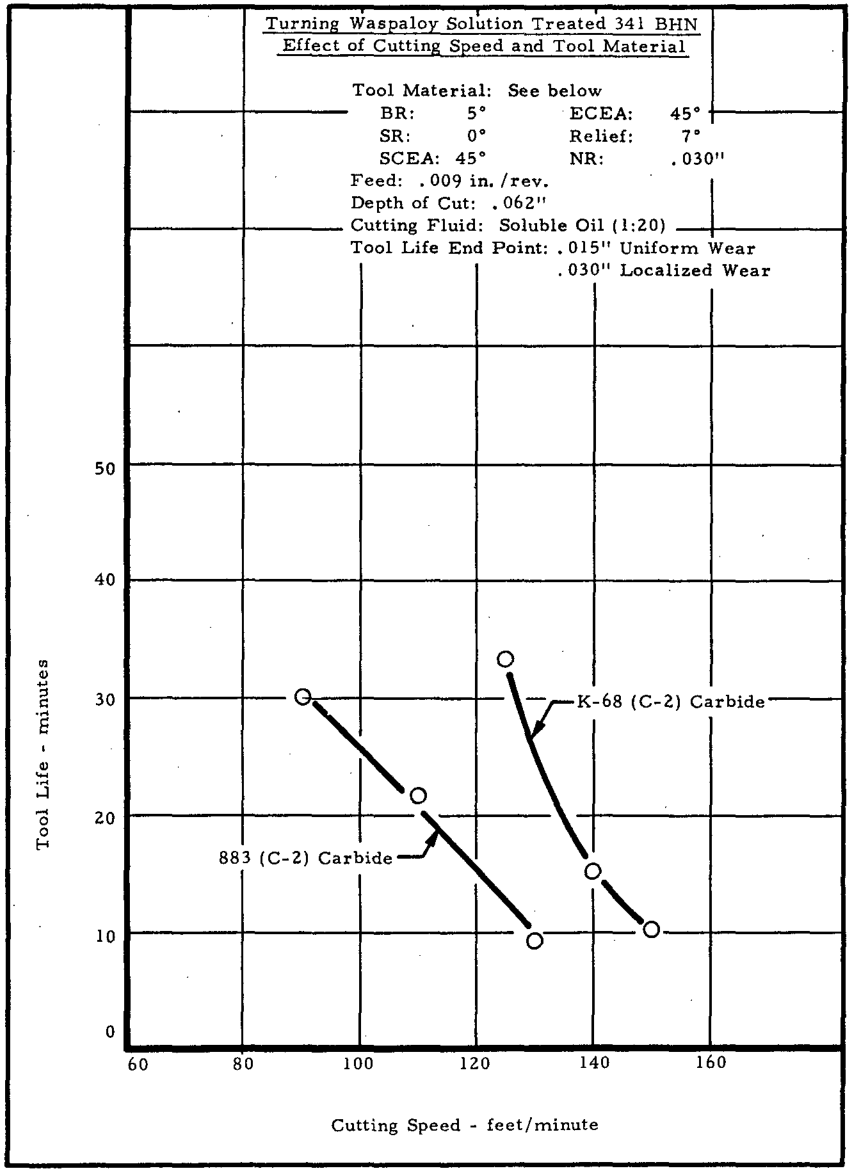
See text, page 243

Figure 276



See text, page 243

Figure 277



See text, page 243

Figure 278

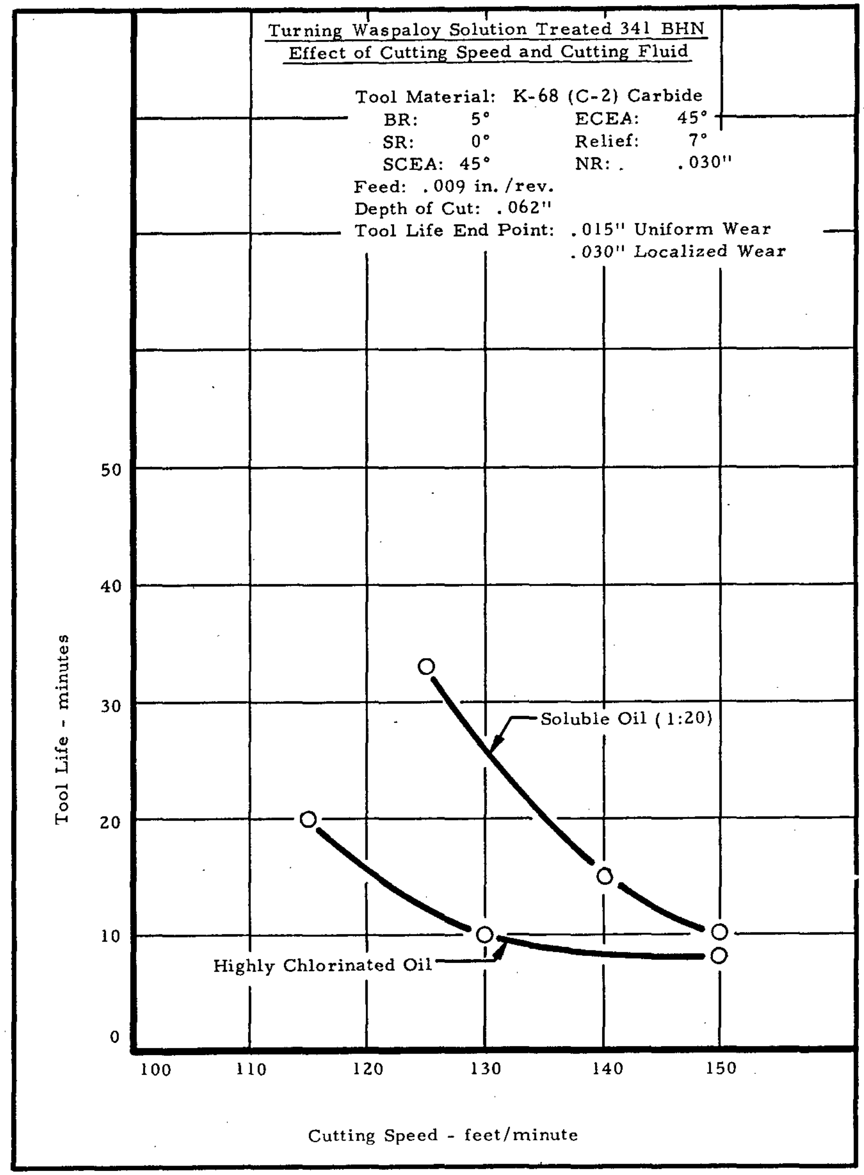


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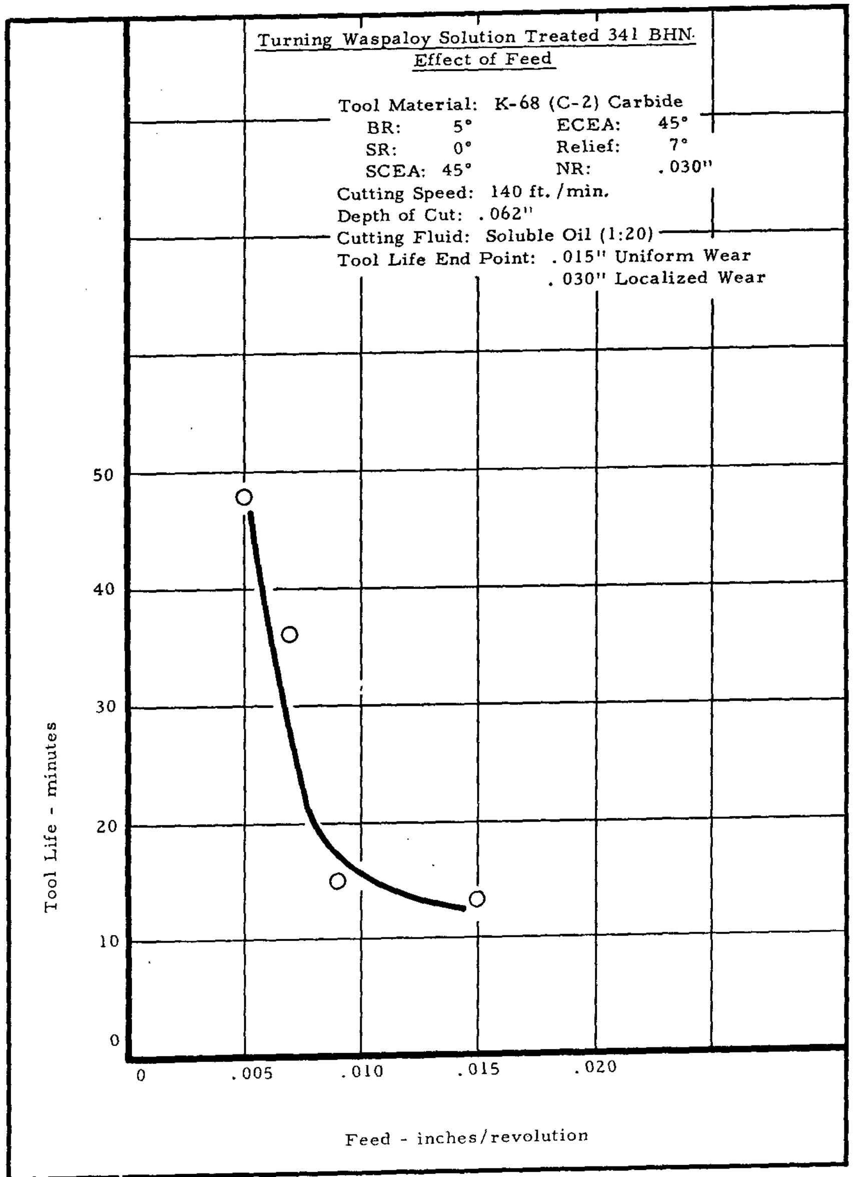
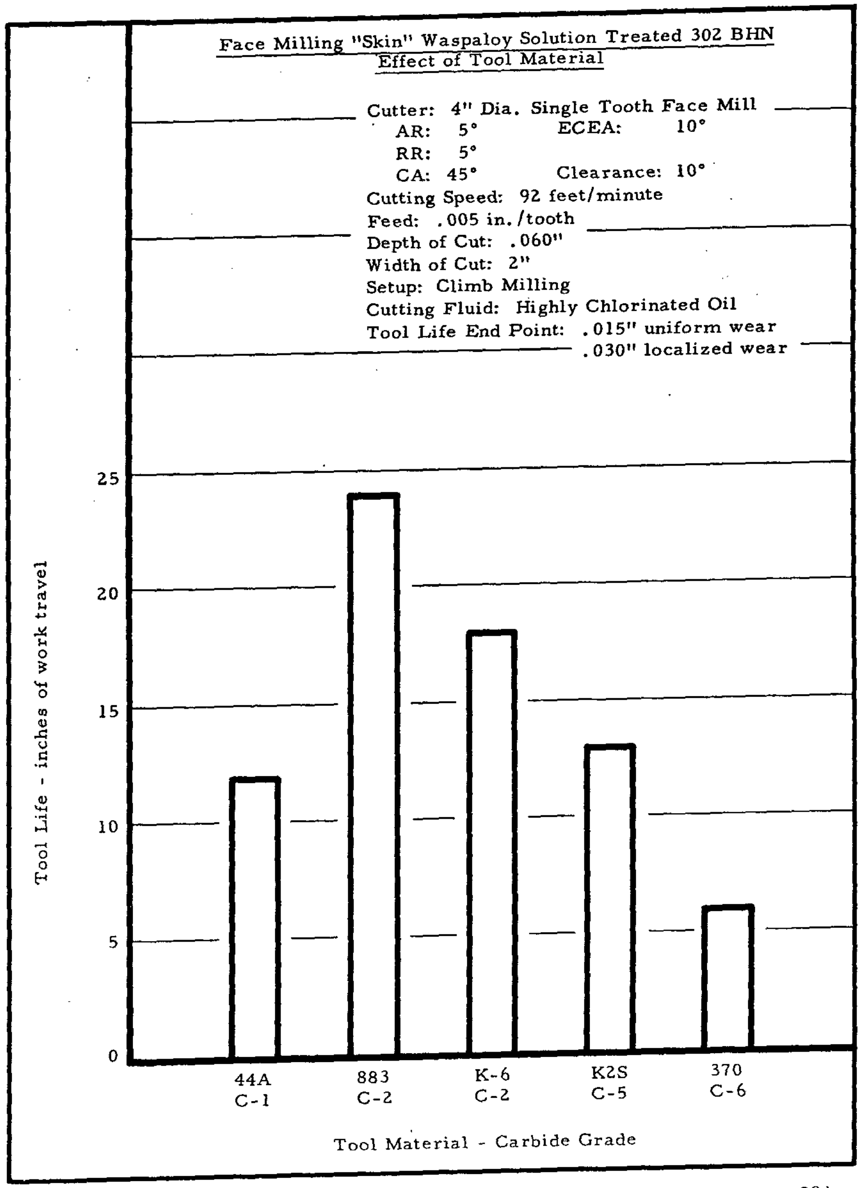
Figure 279



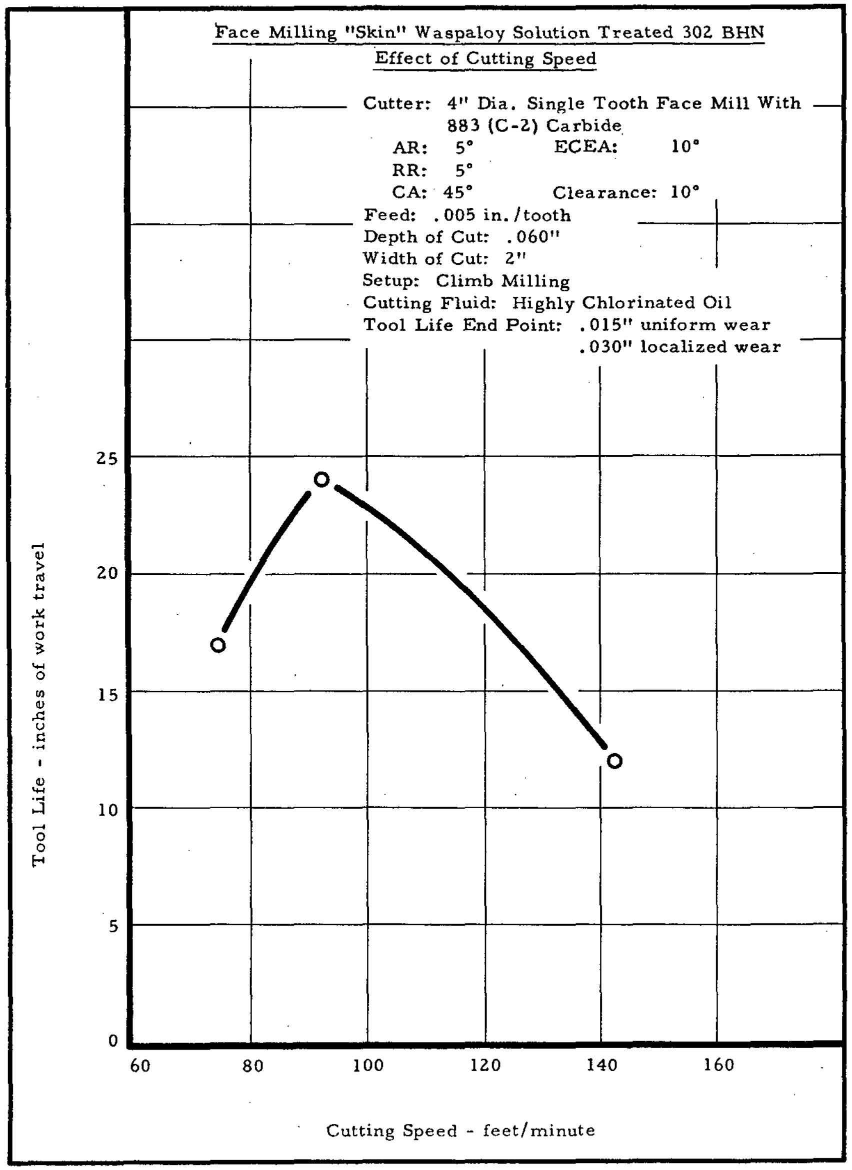
See text, page 243

Figure 280



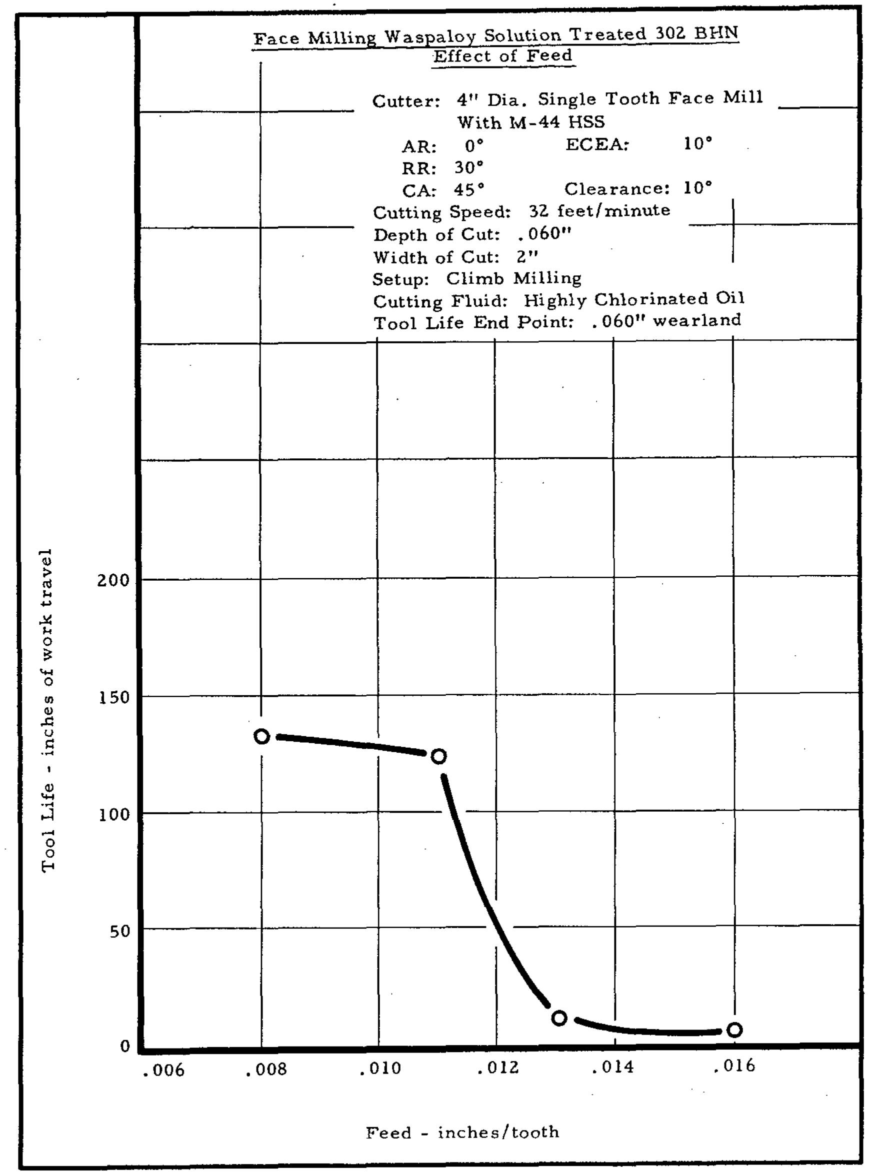
See text, page 244

Figure 281



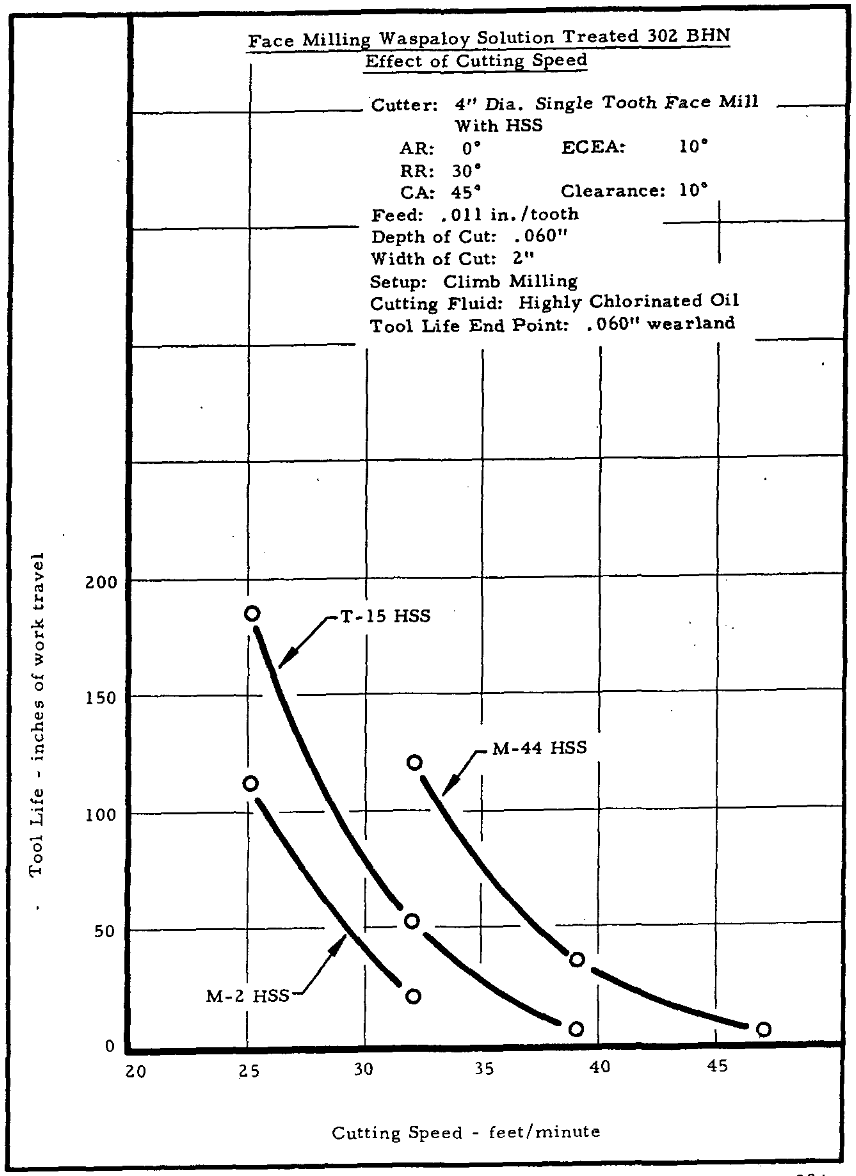
See text, page 244

Figure 282



See text, page 244

Figure 283



See text, page 244

Figure 284

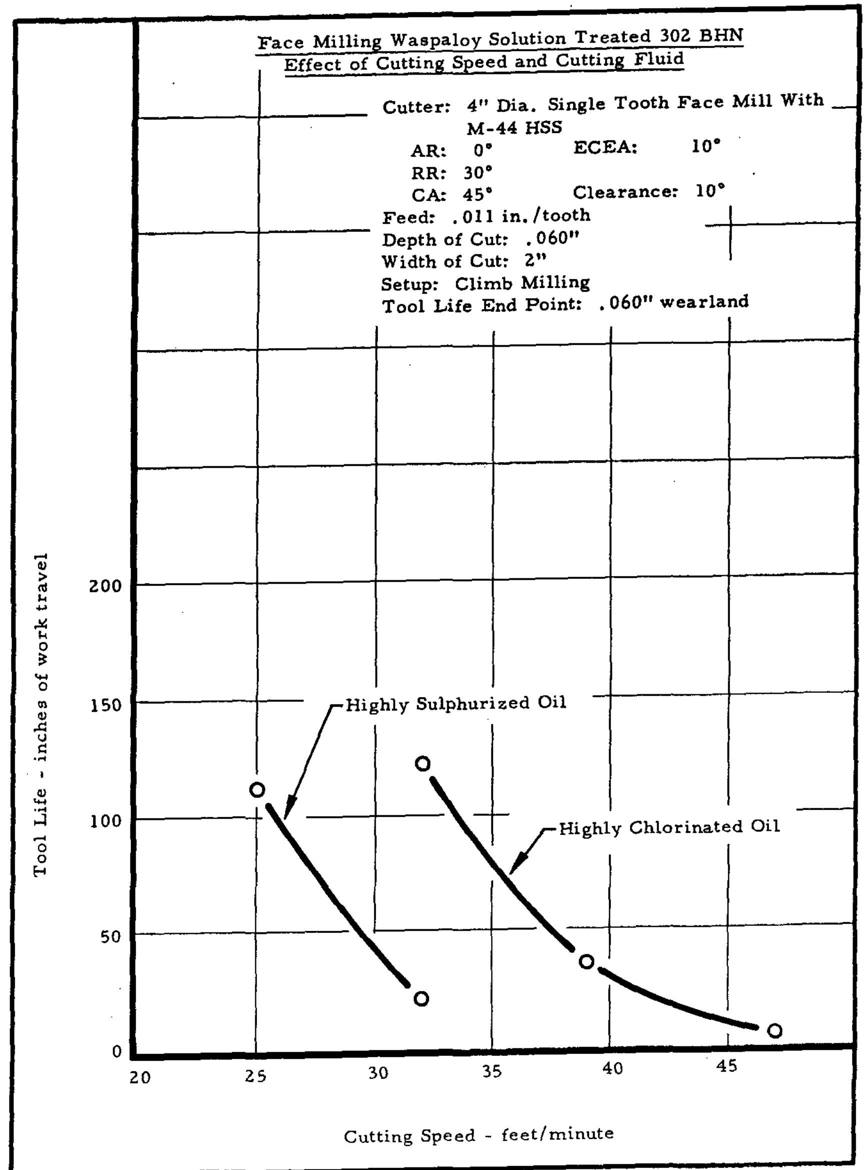


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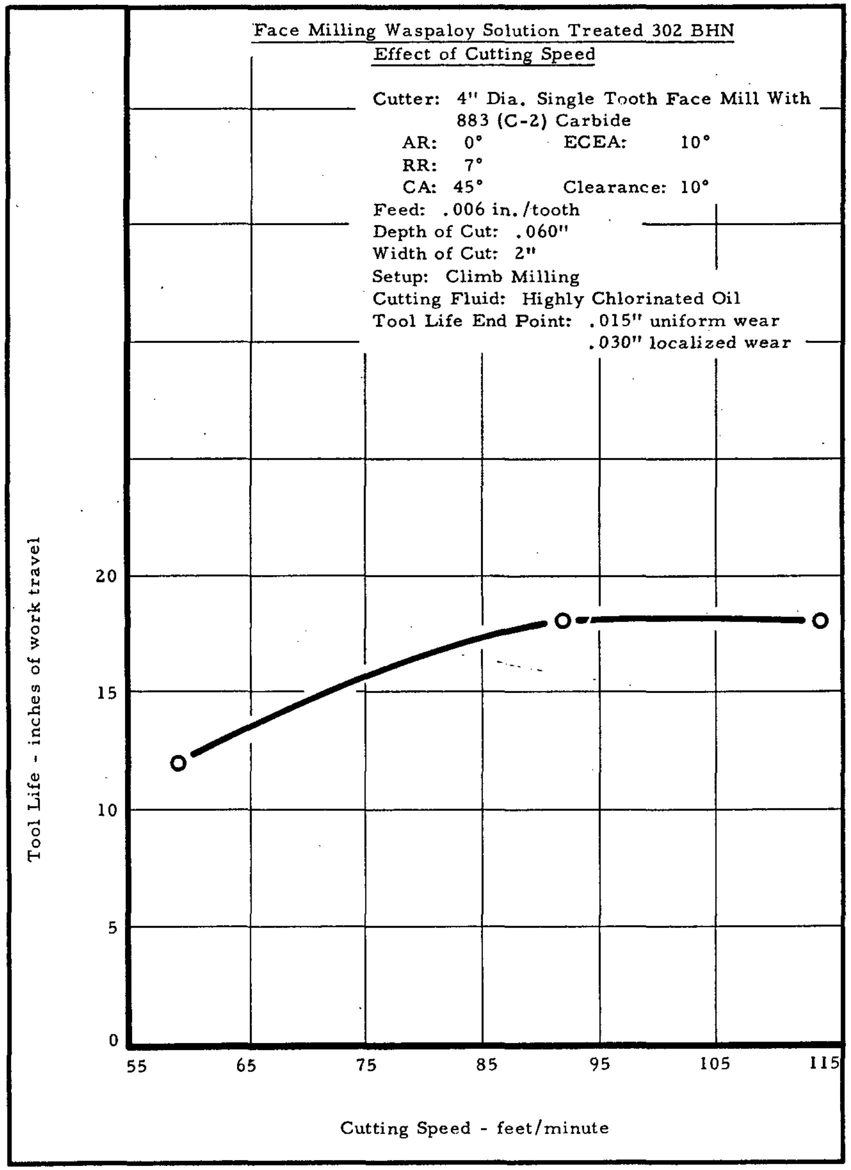
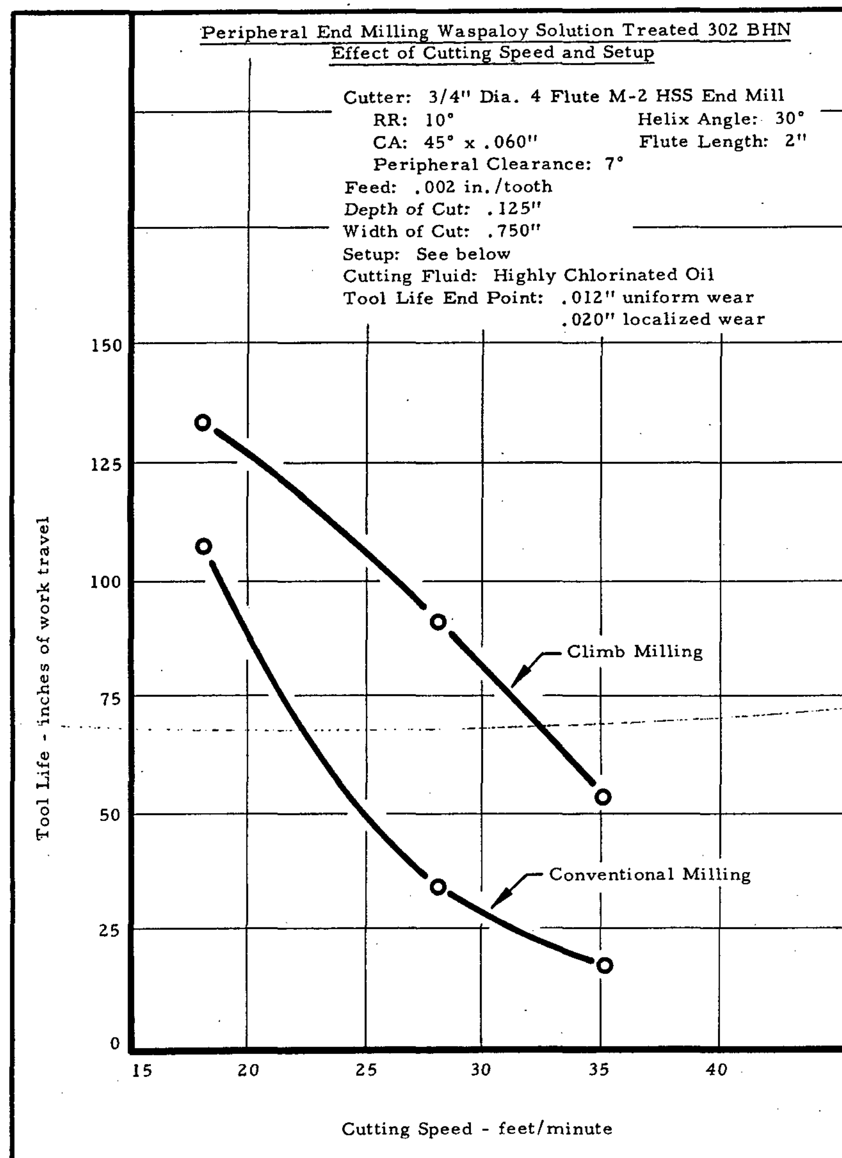
Figure 285



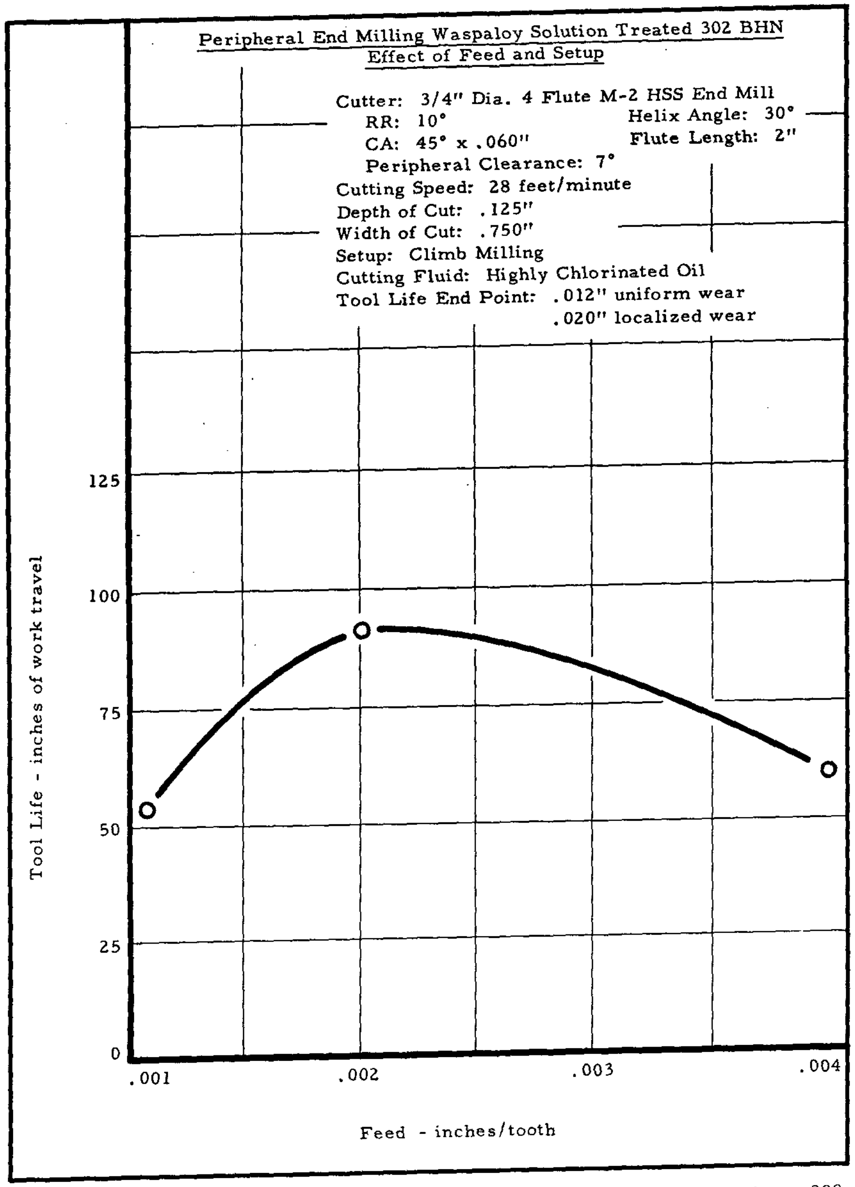
See text, page 244

Figure 286



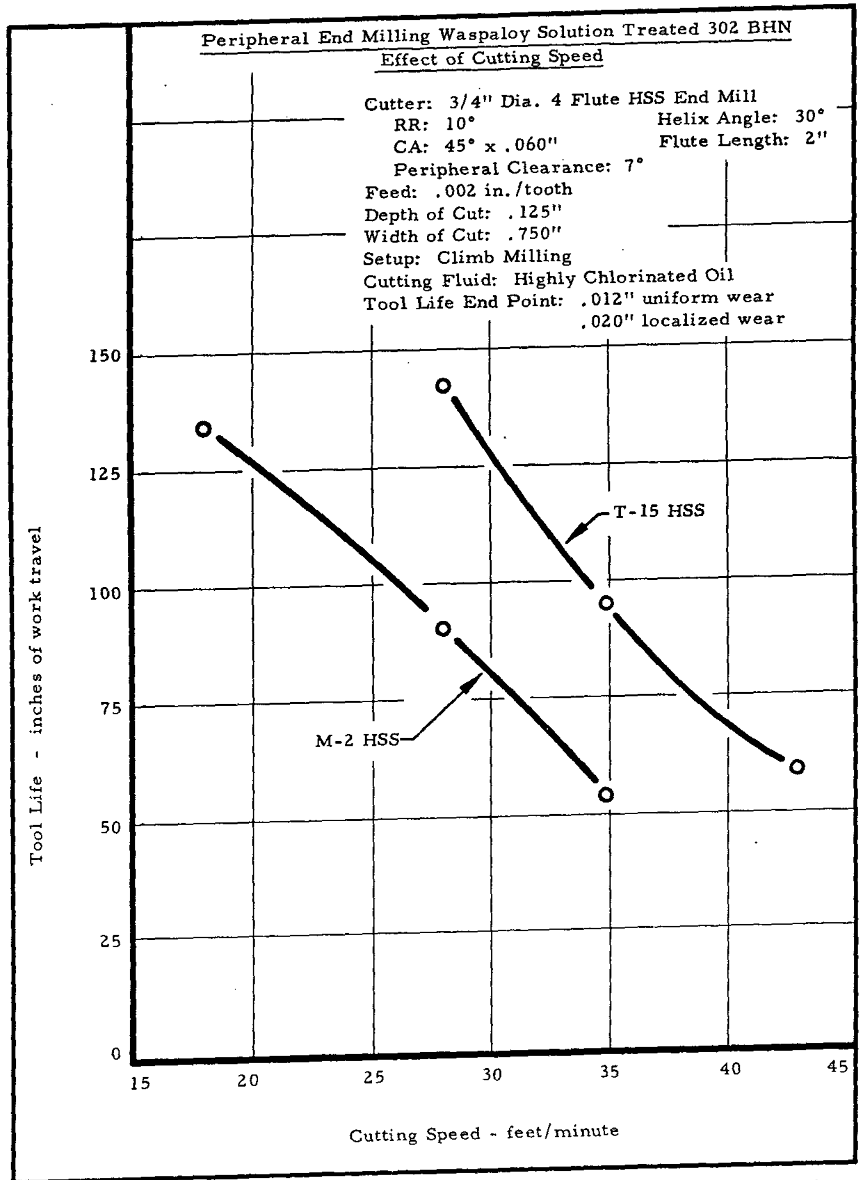
See text, page 245

Figure 287



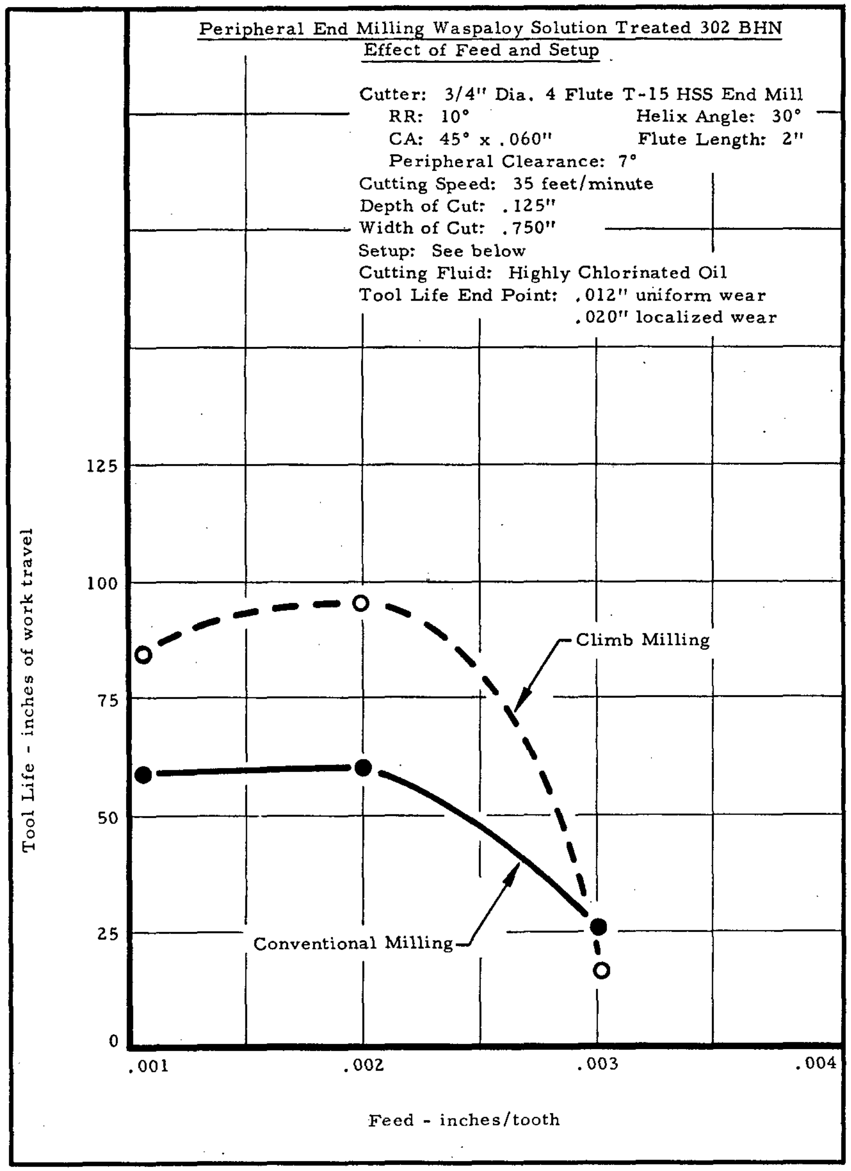
See text, page 245

Figure 288



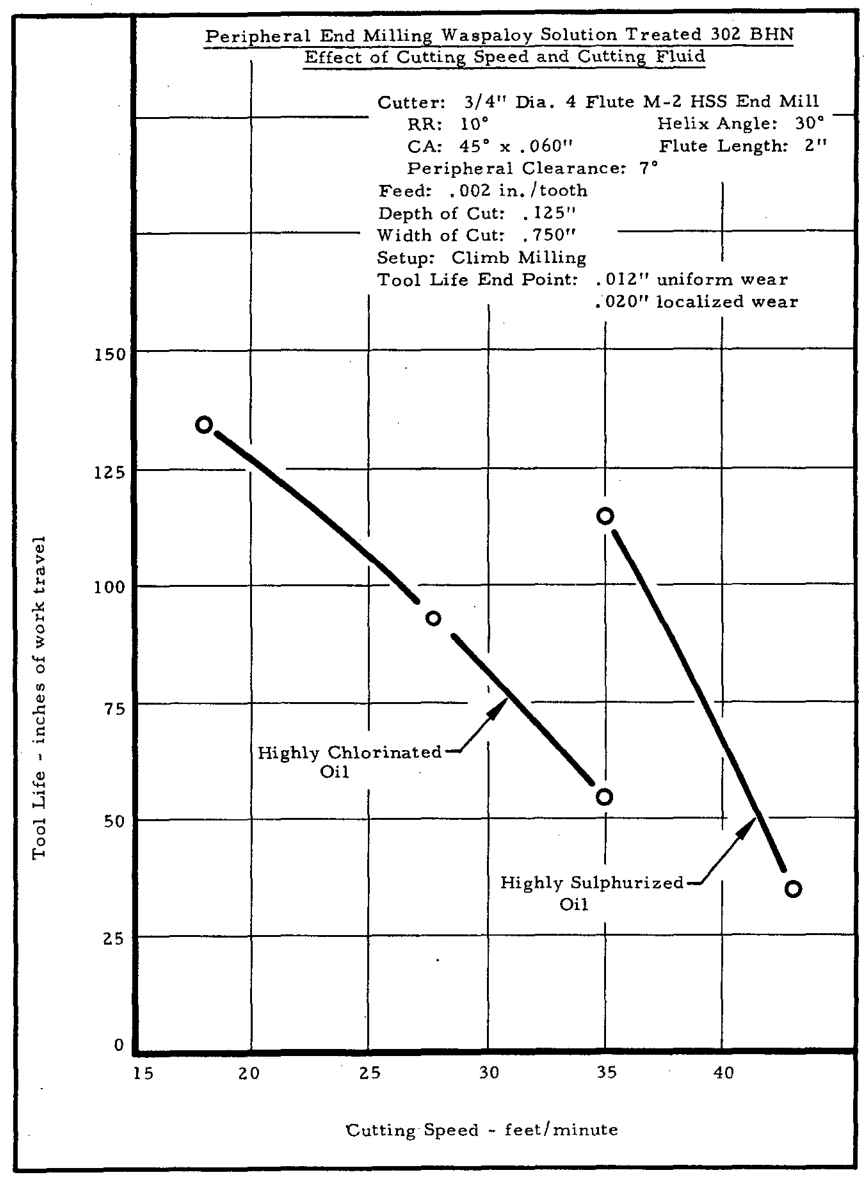
See text, page 245

Figure 289



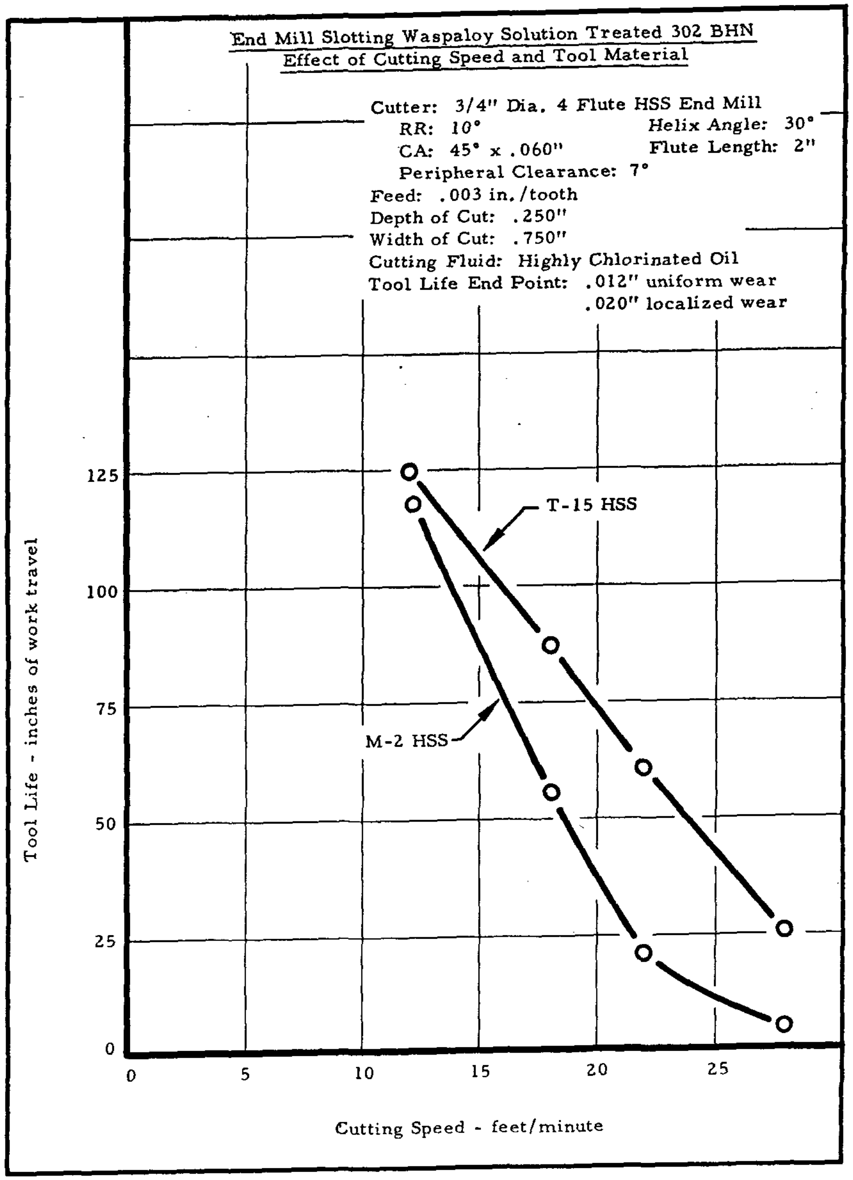
See text, page 245

Figure 290



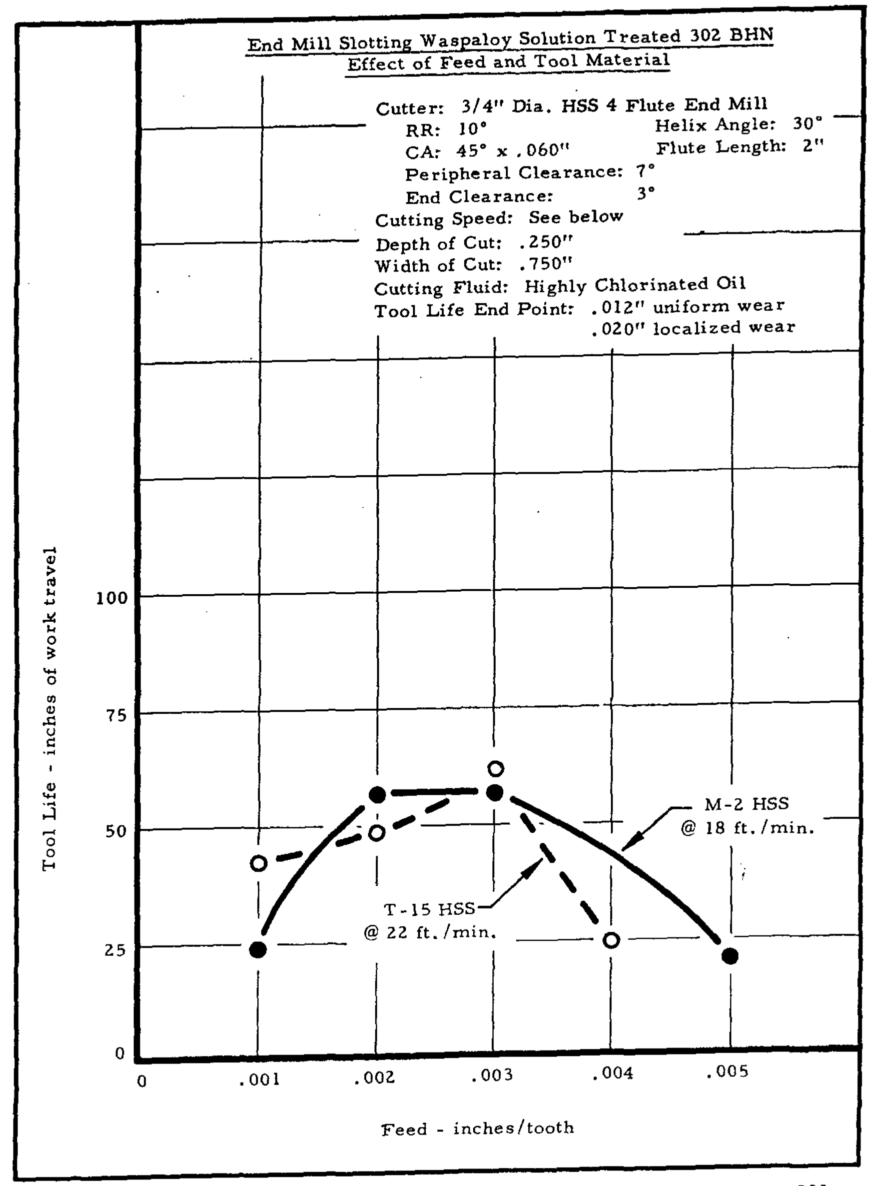
See text, page 245

Figure 291



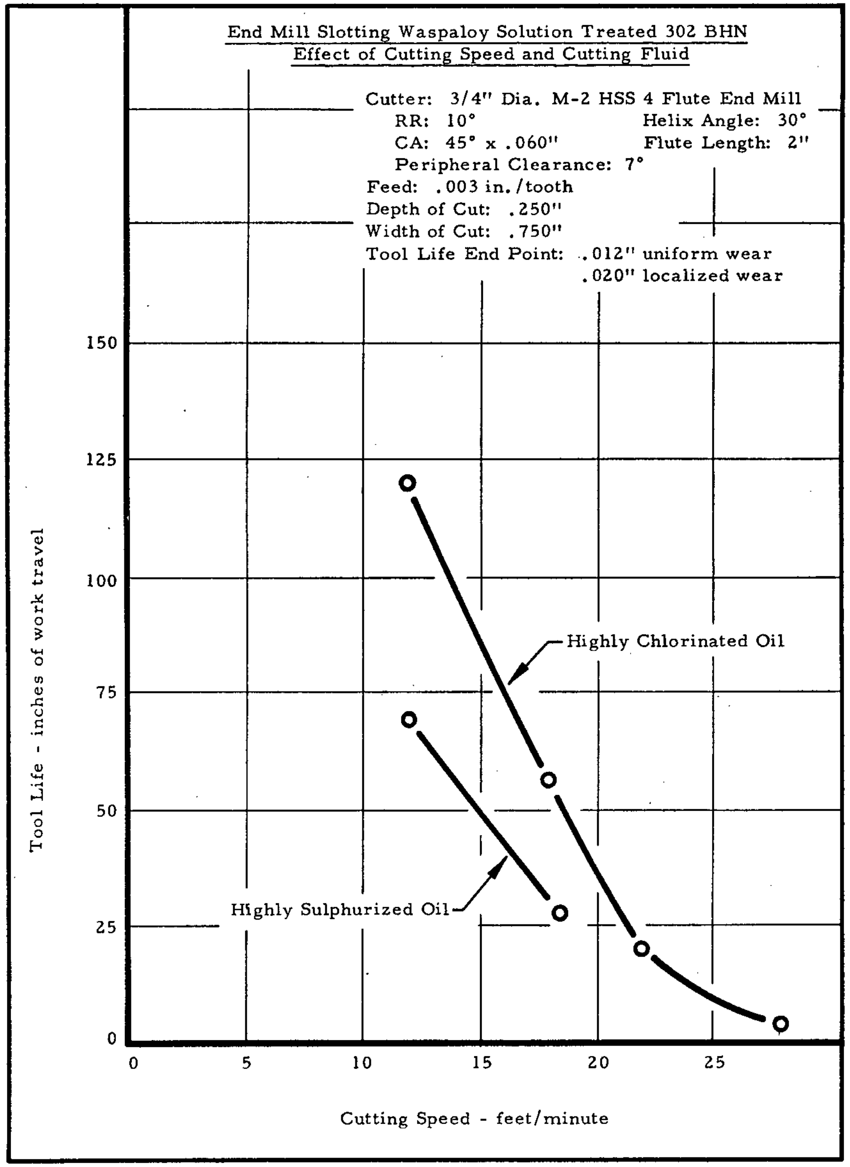
See text, page 245

Figure 292



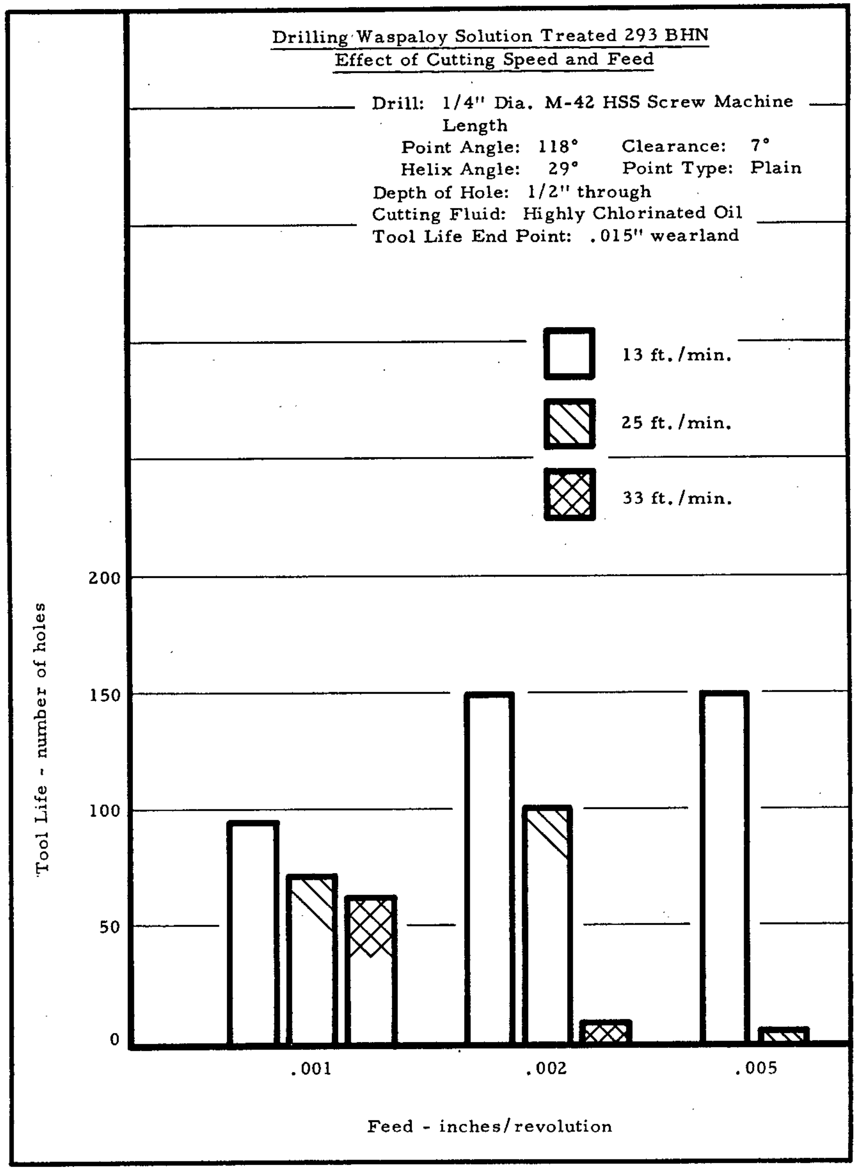
See text, page 245

Figure 293



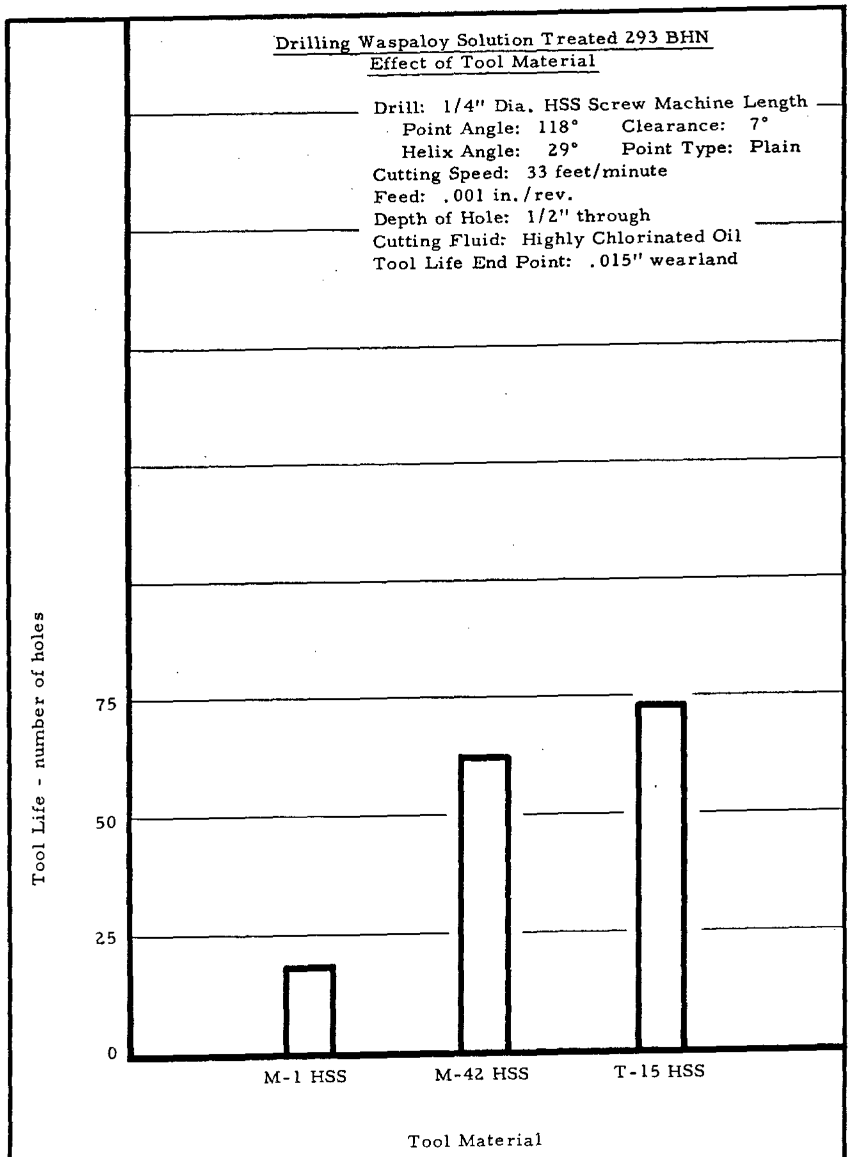
See text, page 246

Figure 294



See text, page 246

Figure 295



See text, page 246

Figure 296

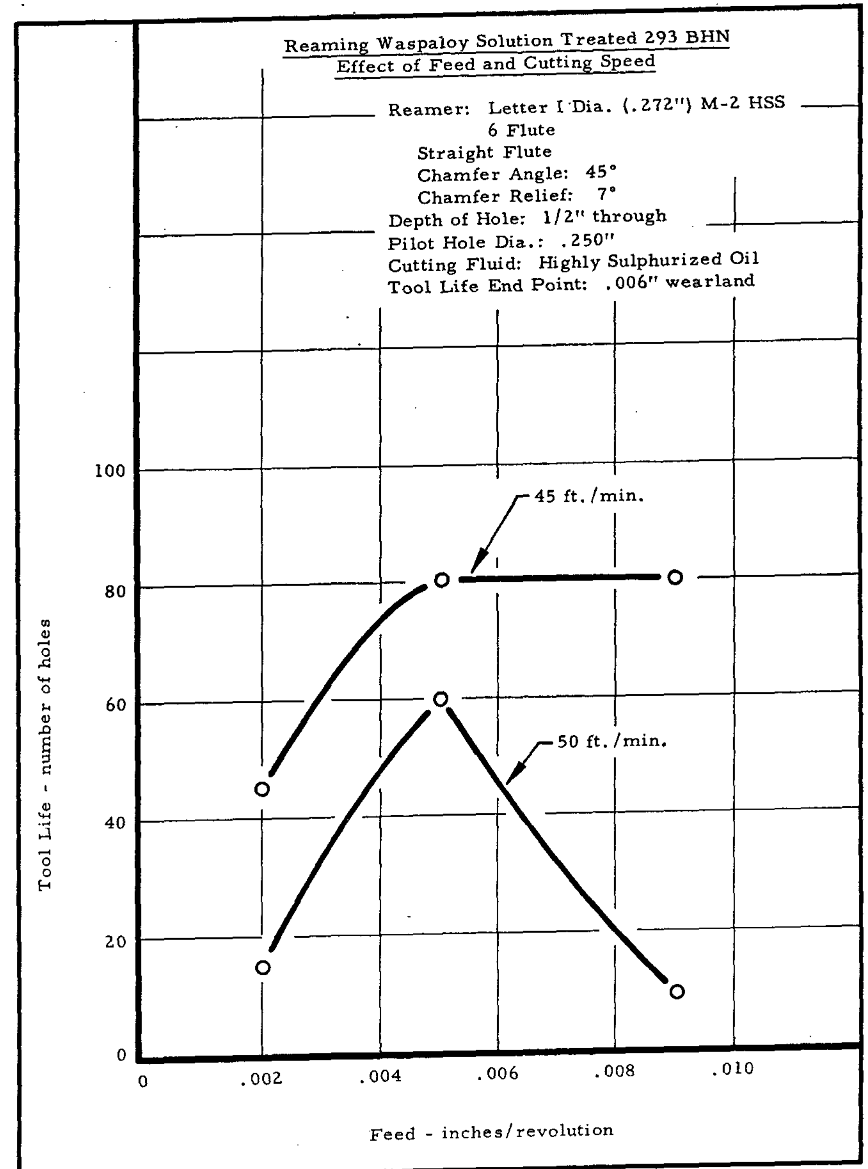


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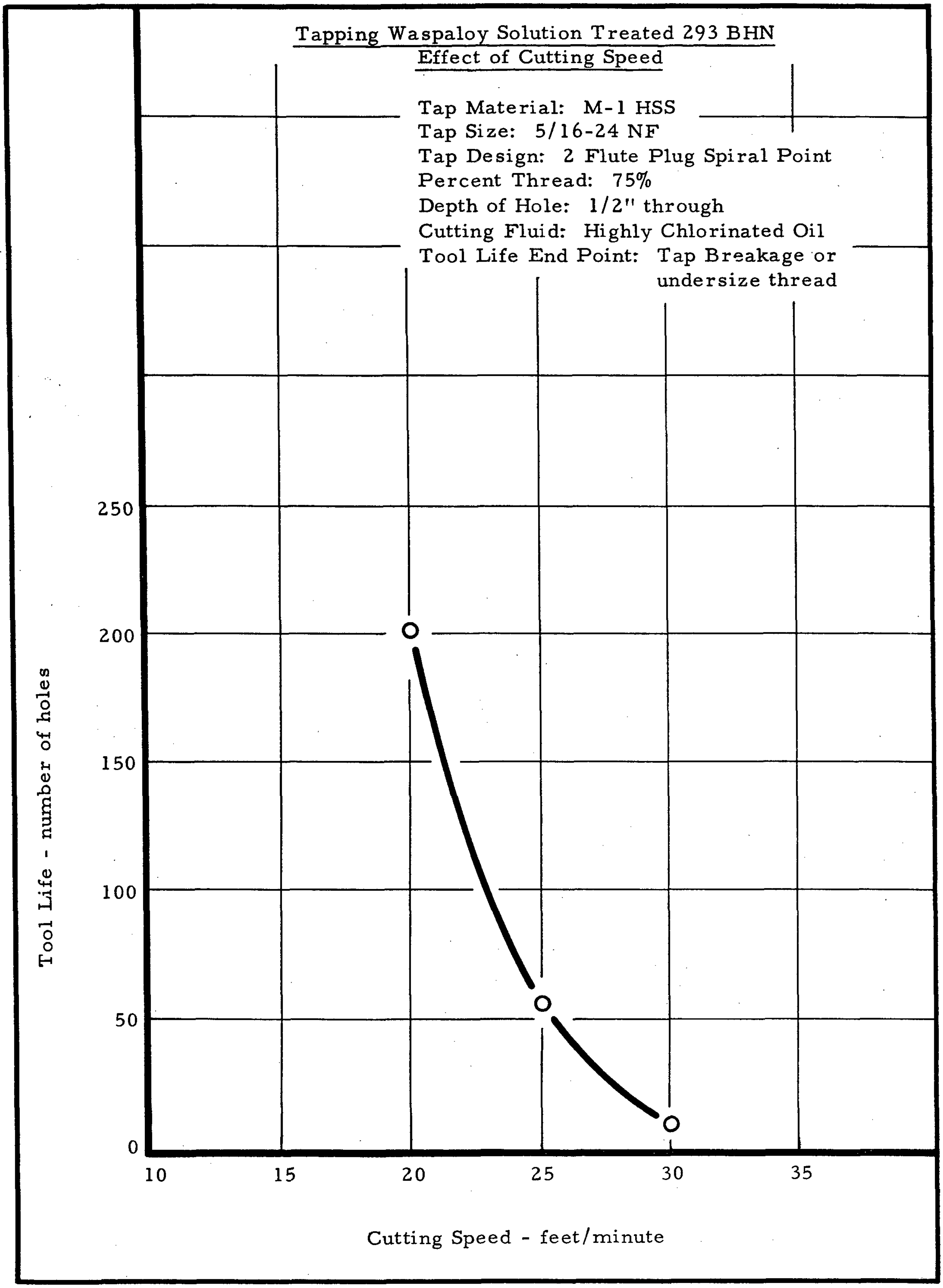
Figure 297



See text, page 246

Figure 298

5.2 Waspaloy (continued)

Turning (Solution Treated and Aged 388 BHN)

A comparison of types M-44, T-15 and M-2 HSS tools is presented in Figure 299, page 266, in turning Waspaloy solution treated and aged 388 BHN. Types M-44 and T-15 were appreciably better than the M-2 HSS tools. Also at a cutting speed of 20 ft./min. the tool life with the M-44 tool was double that with the T-15 tool. Again, as with the Waspaloy in the solution treated condition, the cutting speed was critical. Increasing the cutting speed from 20 to 25 ft./min. reduced the tool life more than 75%.

As shown in Figure 300, page 266, the active cutting oils were less effective than soluble oil in prolonging tool life using a T-15 tool.

The effect of feed on tool life is demonstrated in Figure 301, page 267. Increasing the feed from .005 to .009 in./rev. resulted in about a 45% reduction in tool life.

Figure 302, page 267, presents the difference between the 883 and the K-68 carbides in turning Waspaloy solution treated and aged. The K-68 carbide provided a 50% longer tool life than the 883 carbide at a cutting speed of 110 ft./min. It is further confirmed in Figure 303, page 268, that a soluble oil (1:20) is superior to an active oil such as a highly chlorinated or sulfurized oil in turning Waspaloy. This conclusion was reached with both HSS and carbide tools on Waspaloy in both the solution treated and the solution treated and aged conditions.

The shape of the tool life feed curves shown in Figure 304, page 268, is normal for turning an alloy such as Waspaloy that work hardens readily. The optimum feed was in the range of .007 to .010 in./rev.

Figure 305, page 269, shows the relationship between side cutting edge angle on the tool and tool life. Note how rapidly tool life increases for a given set of machining conditions as the side cutting edge angle is increased from 30° to 75°. It should be pointed out, however, that at the higher side cutting edge angles the cutting force perpendicular to the axis of the work material increases rapidly as tool wear progresses. Hence, if a side cutting edge angle of 60° or more is used, the tool wear should be limited to .010". A tool life curve showing the relationship between cutting speed and tool life using a 75° side cutting edge angle is shown in Figure 306, page 269. A comparison between Figures 306, page 269, and 303, page 268, shows the advantage of the higher side cutting edge angle.

A comparison is made in Figure 307, page 270, in turning Waspaloy in two heat treated conditions; 1) solution treated 341 BHN, and 2) solution treated and aged 388 BHN, with M-44 HSS tools. The tool life on the solution treated Waspaloy was appreciably longer than on the alloy in the solution treated and aged condition.

Figure 308, page 270, shows a comparison of the tool life curves obtained on the Waspaloy in the two heat treated conditions with carbide grade K-68 (C-2). At a cutting speed of 125 ft./min., the tool life on the solution treated alloy was more than double that obtained on the solution treated and aged alloy, or 32 minutes compared to 15 minutes.

Surface Grinding (Solution Treated and Aged 388 BHN)

The effect of wheel speed on G Ratio for grinding solution treated and aged Waspaloy is shown in Figure 309, page 271, when grinding with an aluminum oxide J hardness wheel at a down feed of .001 in./pass, a cross feed of .050 in./pass, using highly sulfurized oil. The G Ratio increased from 2.8 to 9.5 as the wheel speed increased from 2000 to 6000 ft./min. The effect of down feed on the grinding ratio is shown in Figure 310, page 271, for both 4000 and 6000 ft./min. wheel speeds. The higher wheel speed provided a higher G Ratio; however, a wheel speed of 4000 ft./min. is the speed recommended when grinding Waspaloy in order to maintain satisfactory surface integrity. The G Ratio increased with down feed from 4.0 to 9.5 as the down feed increased from .0005 to .002 in./pass.

Increasing the cross feed also increased the G Ratio, Figure 311, page 272. It was likewise found, as shown in Figure 312, page 272, that increasing the table speed improved the G Ratio, with the higher table speed of 60 ft./min. providing a G Ratio of 7.4 compared with a G Ratio of 3.8 at a table speed of 20 ft./min. while grinding at a wheel speed of 4000 ft./min. The conditions recommended for grinding Waspaloy are given in Table 20, page 265. These conditions are specified so as to minimize the danger of surface damage to the ground component, and also to minimize the residual stress in grinding (see Chapter 7, pages 317-378).

The conditions recommended for grinding Waspaloy are those corresponding to "low stress" grinding techniques, and consist of:

5.2 Waspaloy (continued)

Grinding Wheel:	32A46J8VBE
Wheel Speed:	3000 to 4000 ft. /min.
Down Feed:	
Roughing:	.0001 in. /pass
Finishing:	.0005 in. /pass
Cross Feed:	.050 in. /pass
Table Speed:	60 ft. /min.
Grinding Fluid:	Highly Sulfurized Oil

The surface finish obtainable in grinding Waspaloy is 10 to 20 microinches, arithmetical average, in finishing; and 15 to 40 microinches, arithmetical average, in roughing.

TABLE 20

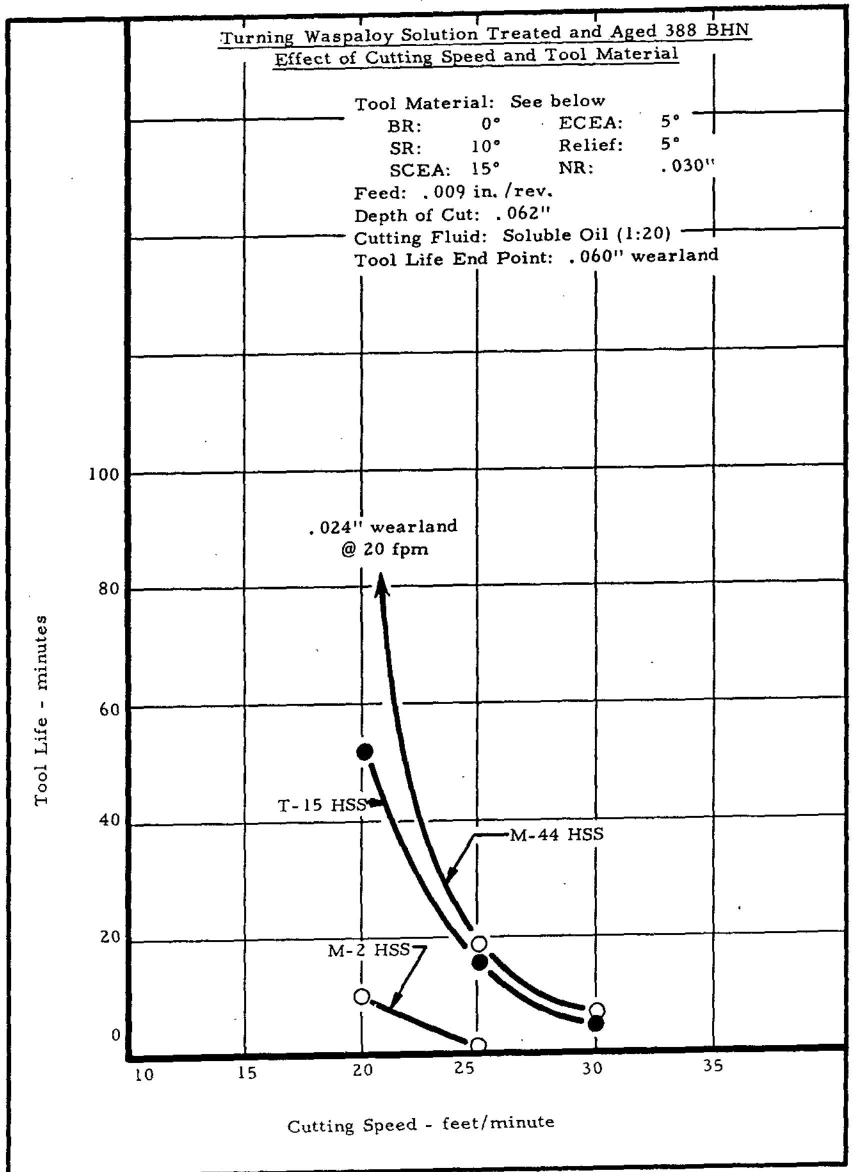
RECOMMENDED CONDITIONS FOR MACHINING
WASPALOY SOLUTION TREATED AND AGED 388 BHN

Cr	Co	Mo	Ti	Al	C	Ni
19.5	13.5	4.0	3.0	1.3	.05	Bal.

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	M-44 HSS	BR: 0° SCEA: 15° SR: 10° ECEA: 5° Relief: 5° NR: .030"	5/8" square tool bit	.062	--	.009 in./rev.	20	80 min.	.024	Soluble Oil (1:20)
Turning	C-2 Carbide	BR: 5° SCEA: 45° SR: 0° ECEA: 45° Relief: 7° NR: .030"	1/2" square throwaway insert	.062	--	.009 in./rev.	110	60 min.	.015	Soluble Oil (1:20)

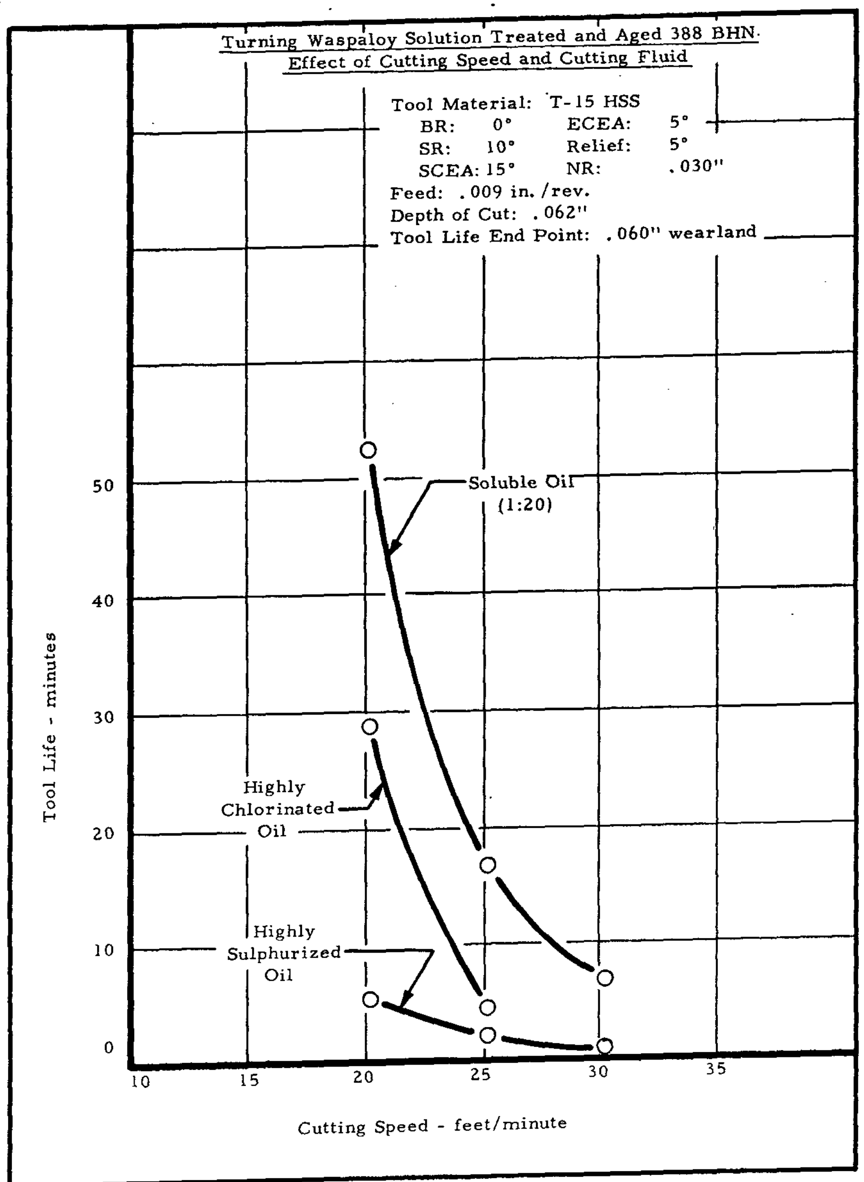
SURFACE GRINDING

Operation	Wheel Grade	Grinding Fluid	Wheel Speed Ft./Min.	Table Speed Ft./Min.	Down Feed In./Pass	Cross Feed In./Pass	G Ratio
Finishing	32A46J8VBE	Highly Sulphurized Oil	3000-4000	60	.0005	.050	5.0
Roughing	32A46J8VBE	Highly Sulphurized Oil	3000-4000	60	.001	.050	7.4



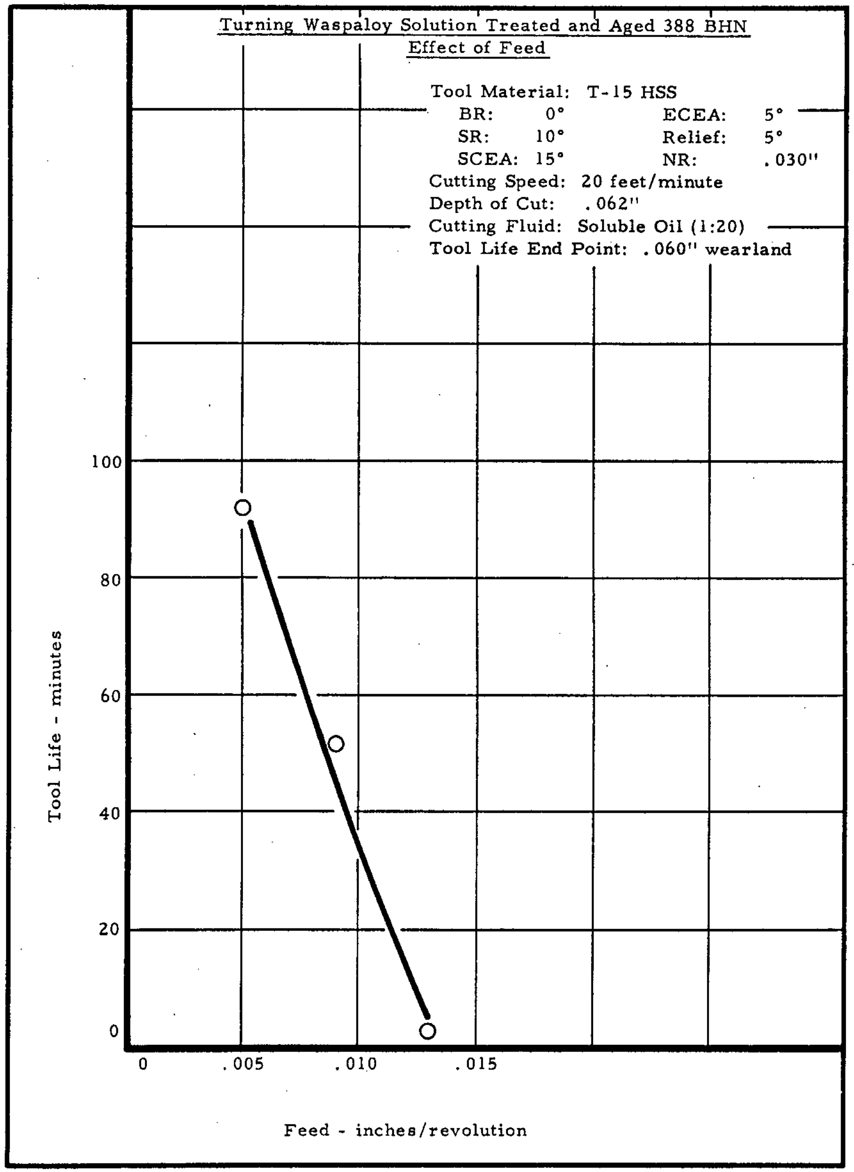
See text, page 262

Figure 299



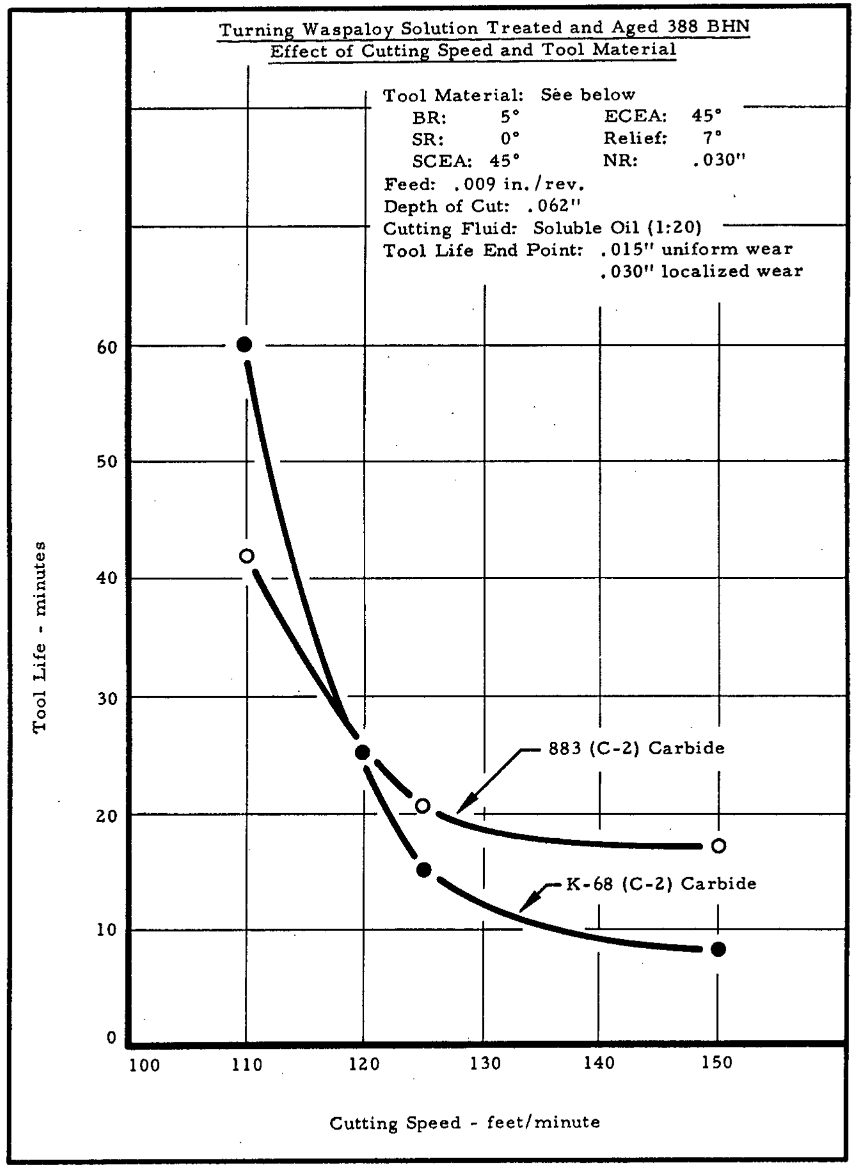
See text, page 262

Figure 300



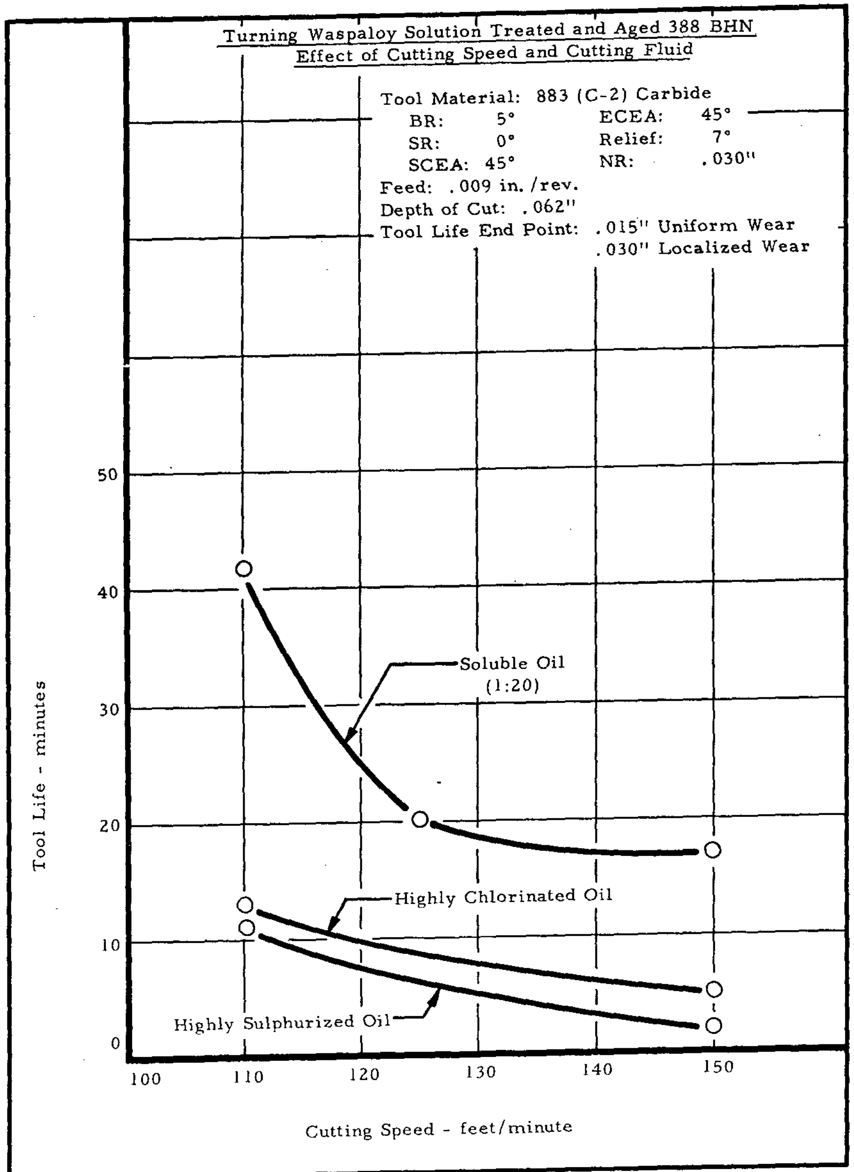
See text, page 262

Figure 301



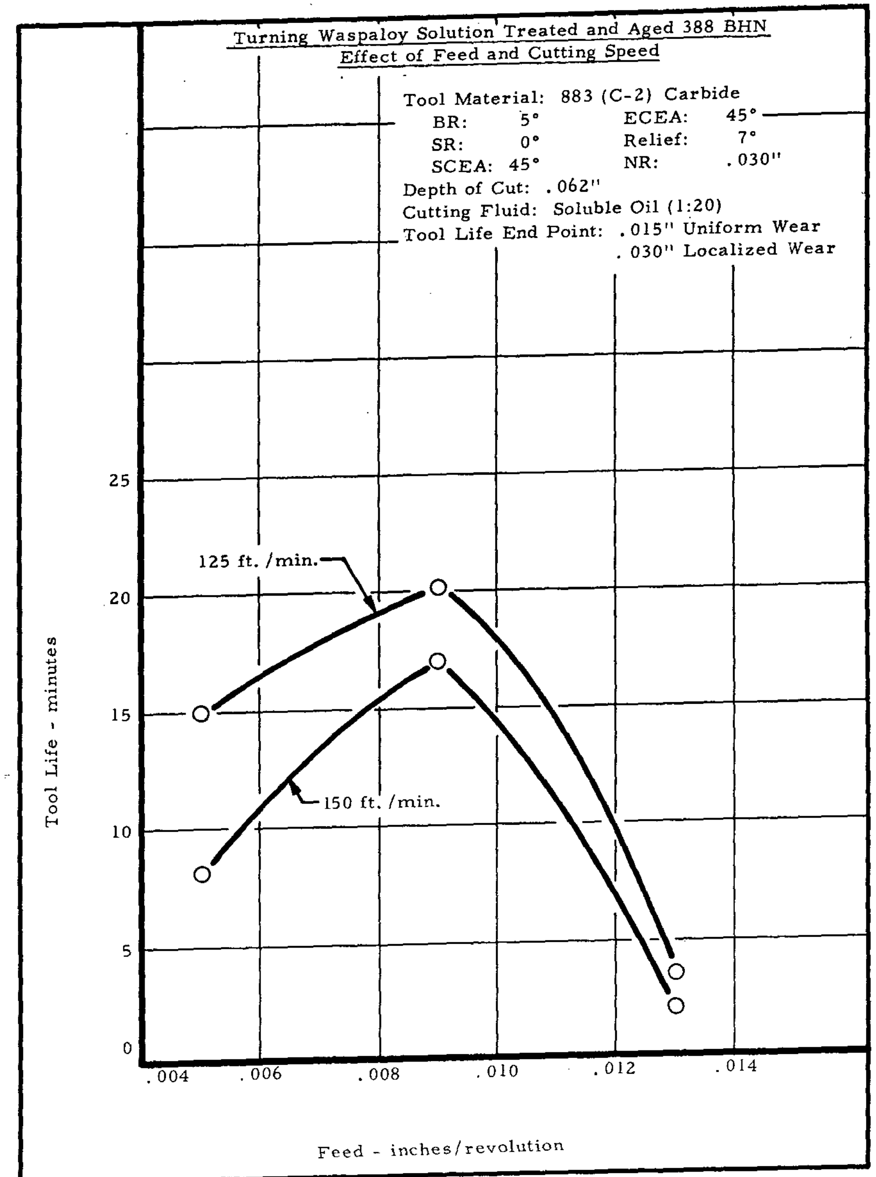
See text, page 262

Figure 302



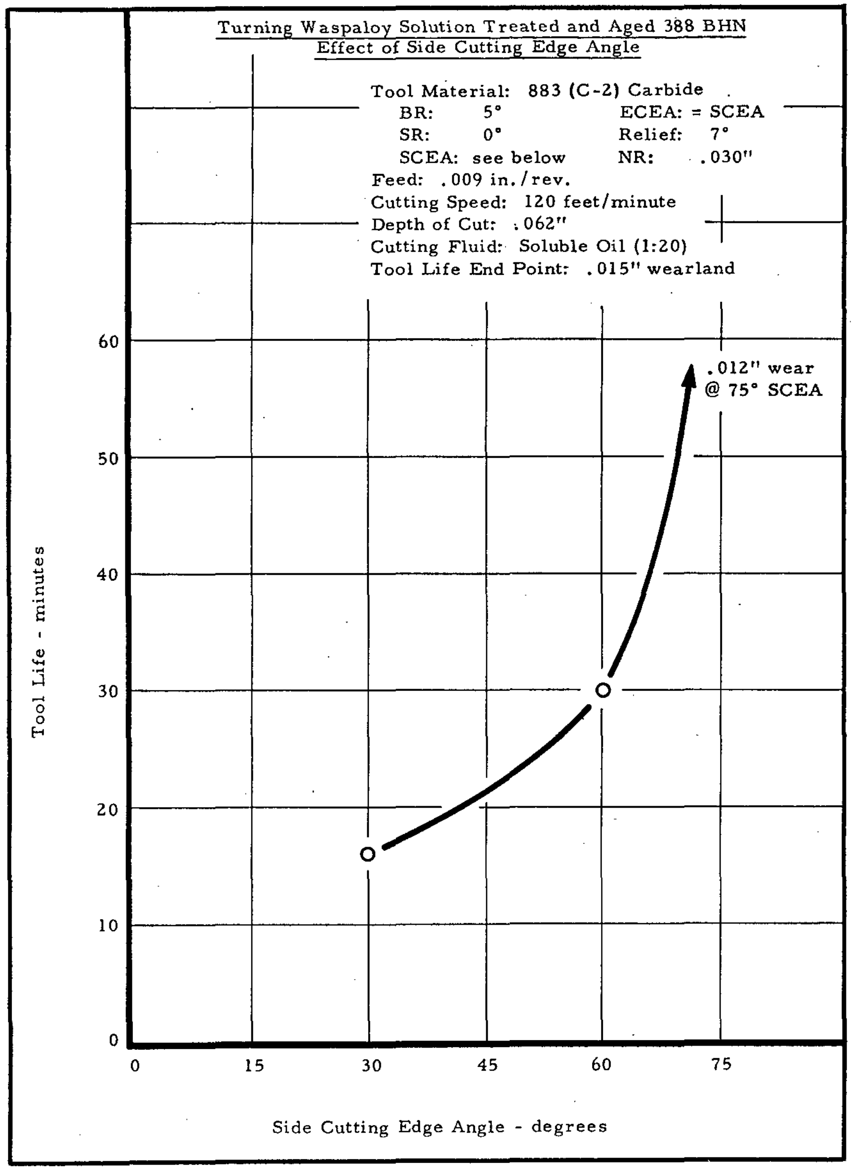
See text, page 262

Figure 303



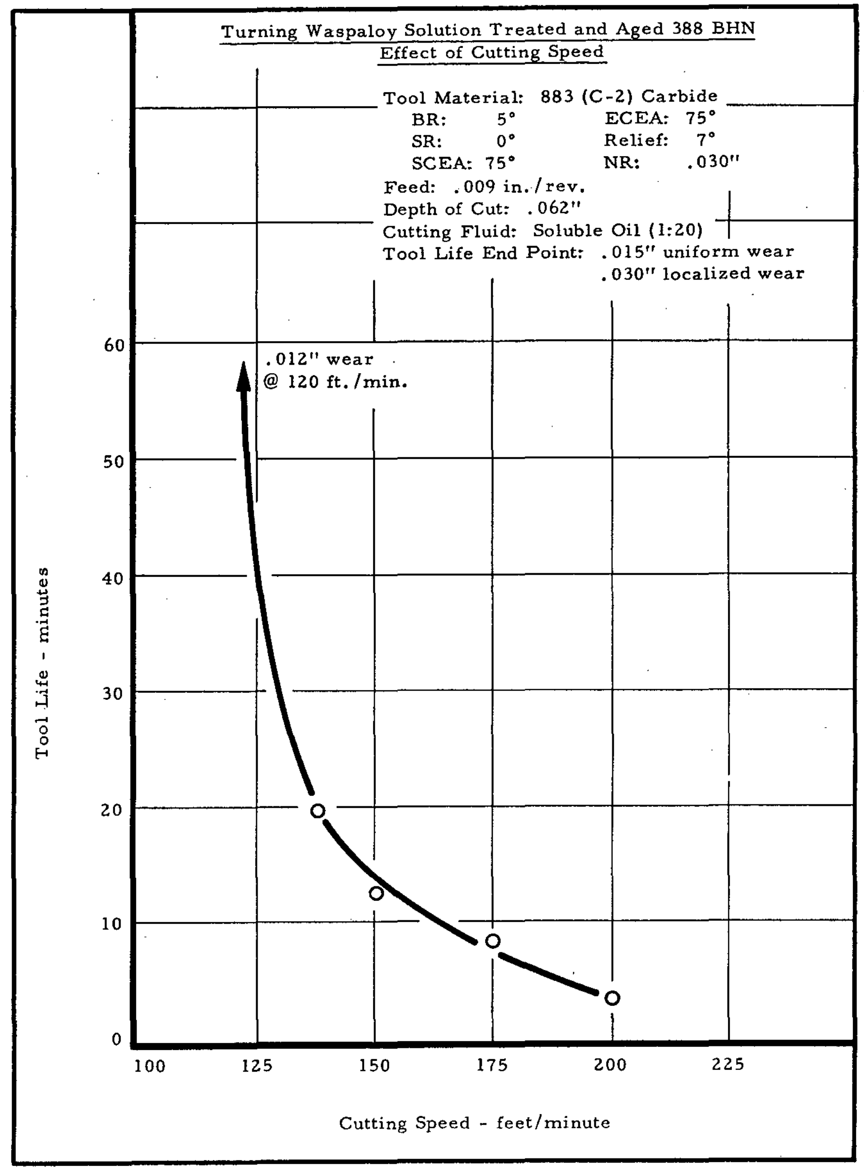
See text, page 262

Figure 304



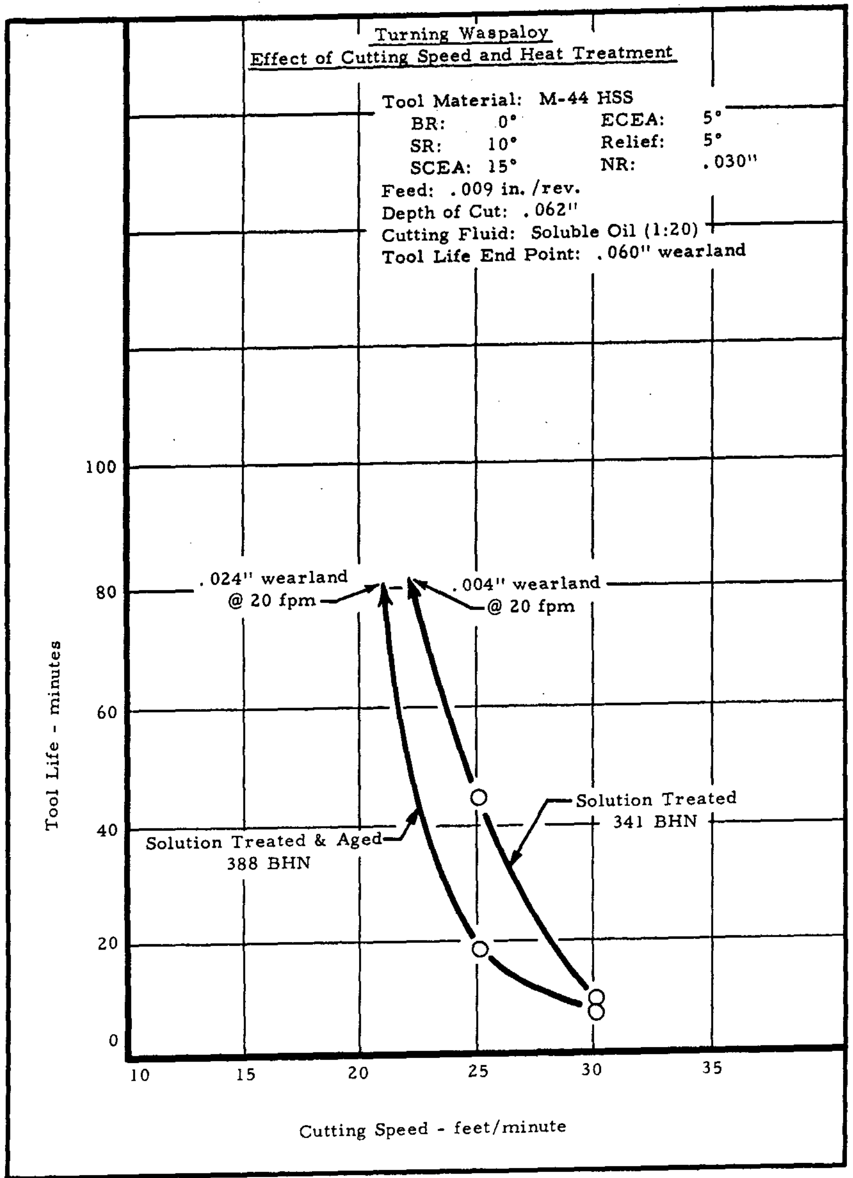
See text, page 262

Figure 305



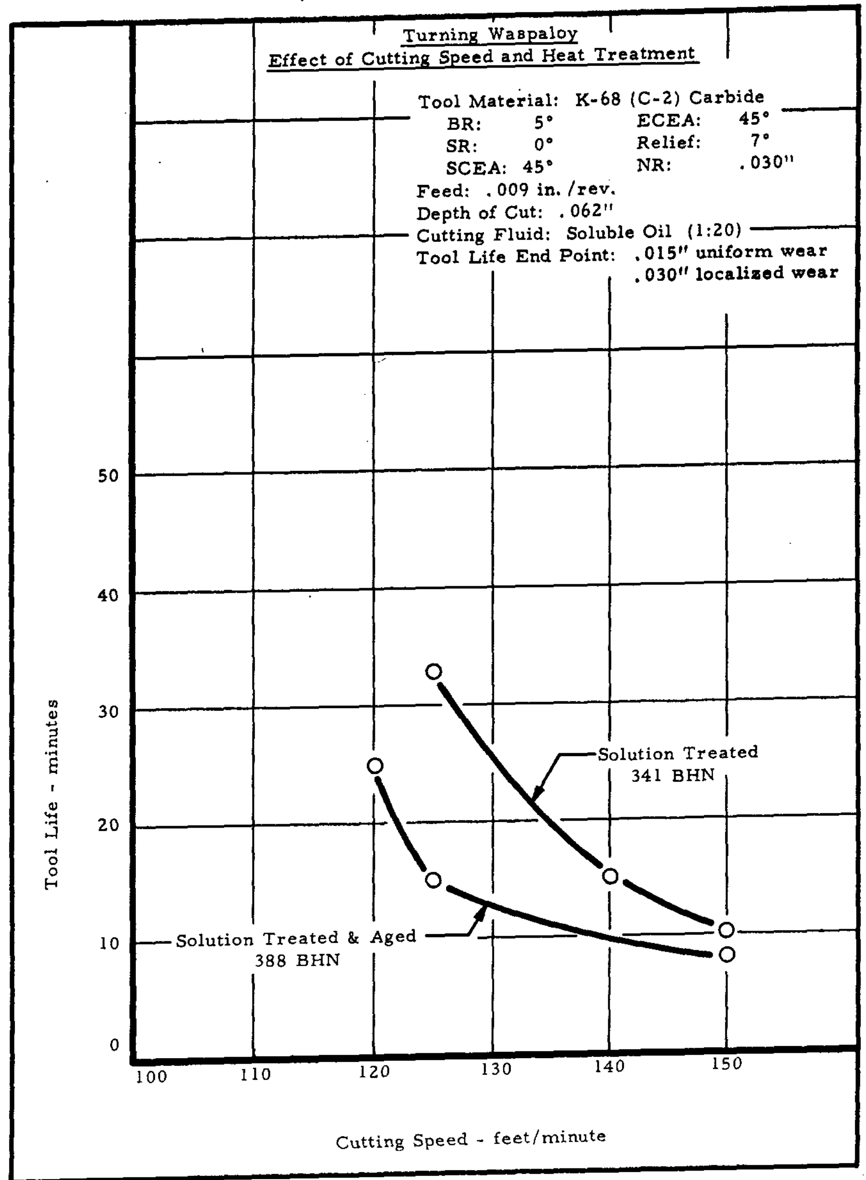
See text, page 262

Figure 306



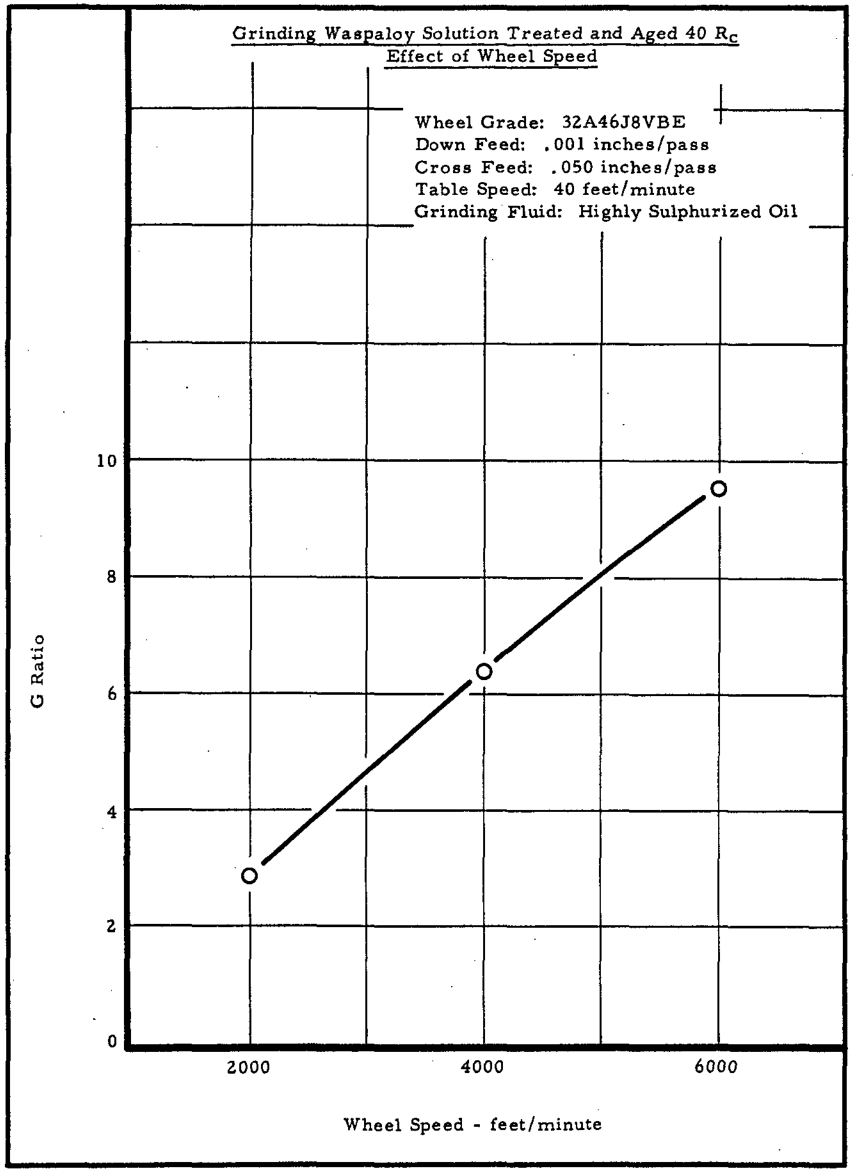
See text, pages 263

Figure 307



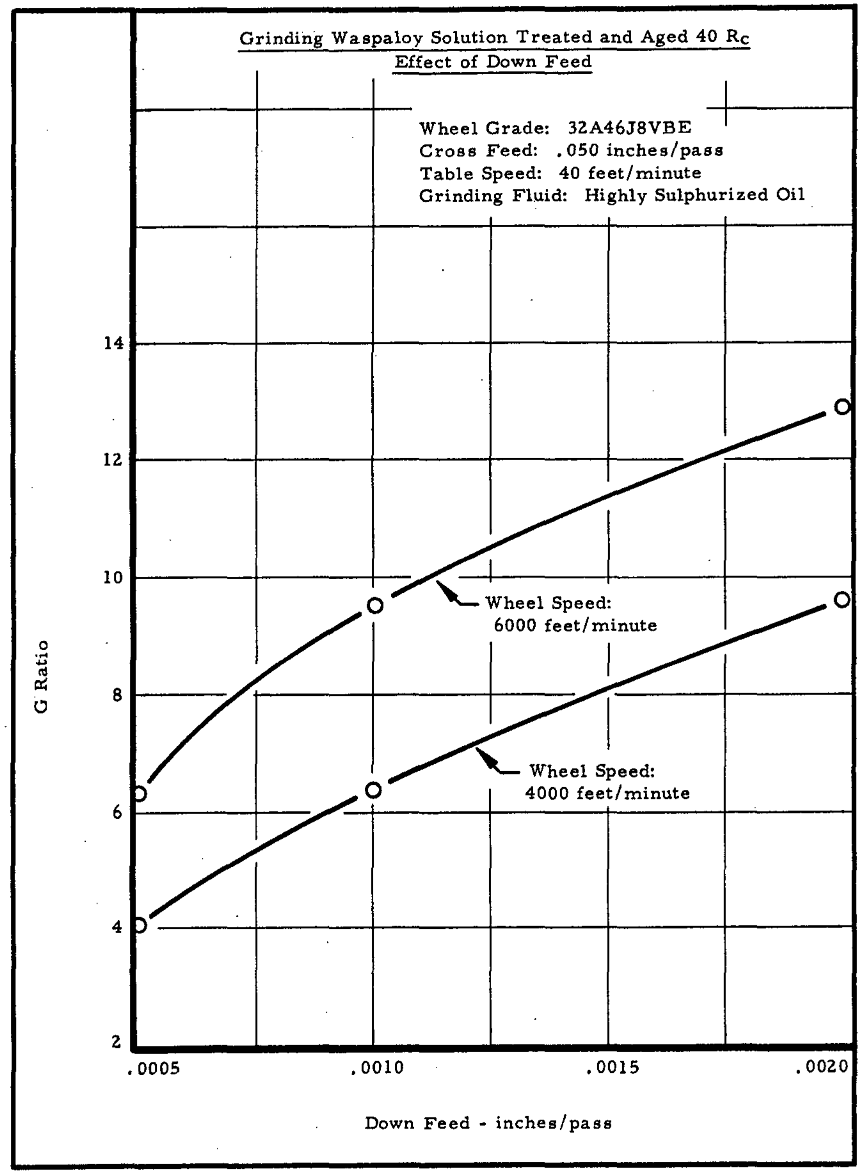
See text, page 263

Figure 308



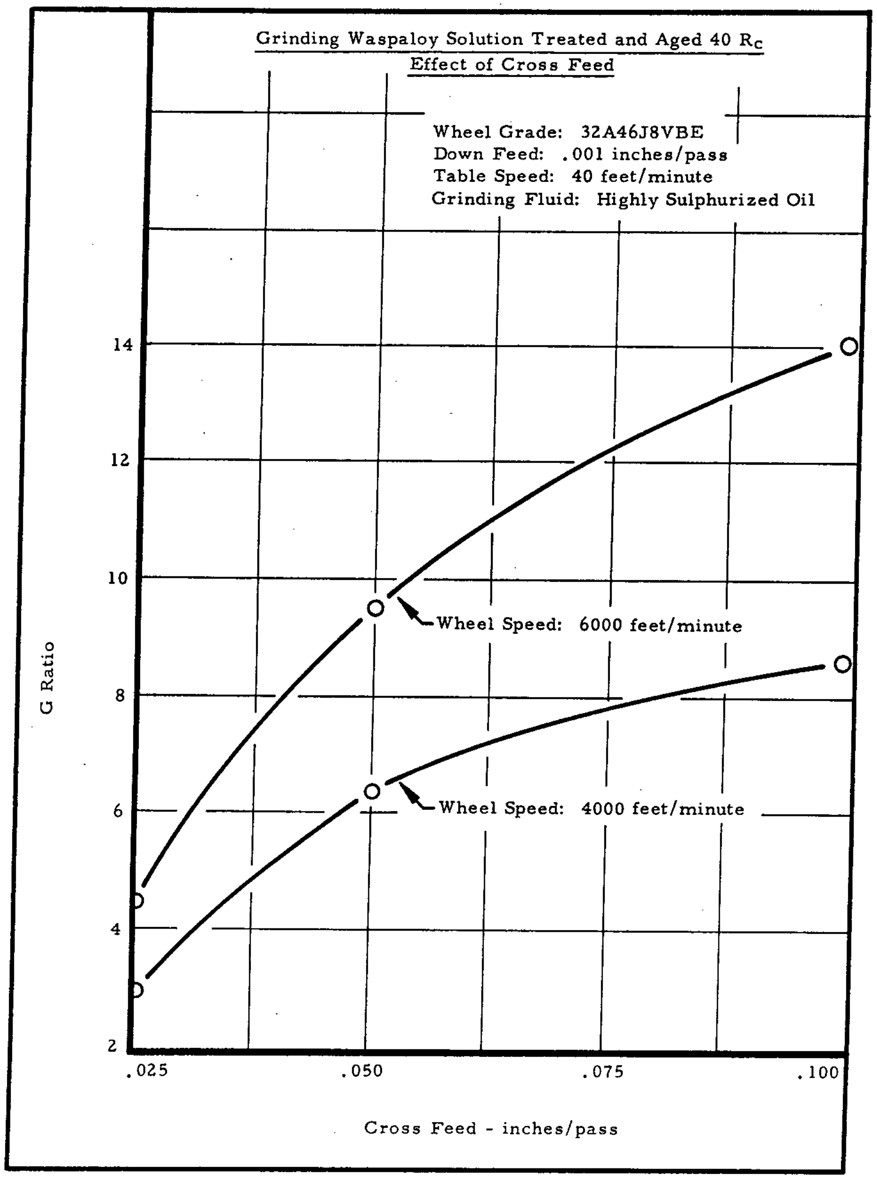
See text, page 263

Figure 309



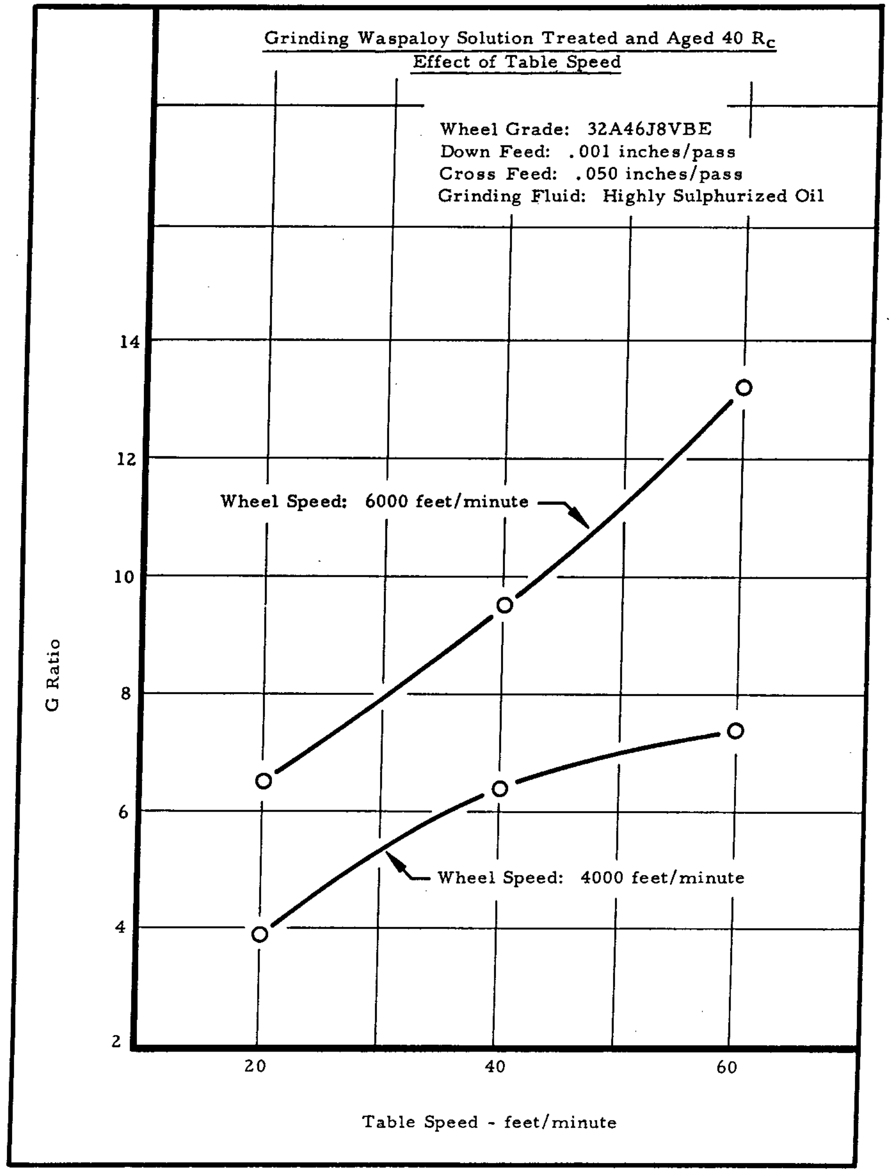
See text, page 263

Figure 310



See text, page 263

Figure 311



See text, page 263

Figure 312

5.3 IN-100

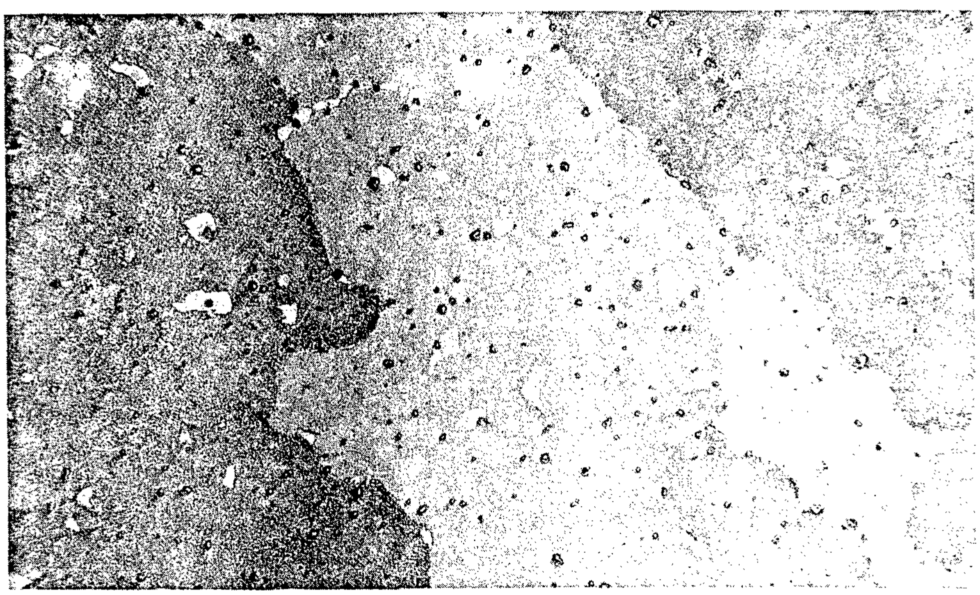
Alloy Identification

IN-100 is a cast, nickel base high temperature alloy having the following nominal composition:

Ni-15.0Co-9.5Cr-5.5Al-5.0Ti-3.0Mo-.17C

The material for turning tests was procured as 3" diameter x 10" long castings. Plates for drilling tests were obtained as 4" x 4" x 1/4" castings, and coupons for grinding ratio tests were 1" x 2" x 6" castings. No heat treatment was performed on these samples prior to use. Hardness was measured as 352-375 BHN.

Exhibited below is the microstructure of this alloy, which consists of dispersed islands of Ni_3 (Al, Ti) formed by liquid phase reaction and small equiaxed particles of Ti (C, N) in a large grained nickel-rich matrix.



IN-100, As Cast

Etchant: Kalling's   Mag: 100X

5.3 IN-100 (continued)

Turning (As Cast 331 BHN)

The effect of increased cutting speed upon tool life is shown in Figure 313, page 278. Increasing the cutting speed 20% resulted in a 50% reduction in tool life; 12 minutes to 6 minutes.

A comparison of four grades of carbide is presented in Figure 314, page 278, in turning IN-100 as cast, at a hardness of 331 BHN. The tool life with the C-3 grade K-8 carbide was slightly higher than the C-2 grade 883.carbide, 12 minutes compared to 10 minutes. Both of these grades were better than the C-6 and C-8 grades, which produced tool life values of only 5-1/2 and 1-1/2 minutes respectively.

The tool life curve in Figure 315, page 279, indicates that feeds up to .009 in./rev. are suitable for turning this material with carbide tools. Increasing the feed from .0045 to .009 in./rev. reduced the tool life approximately 30%, but doubled the production rate. Note also if the depth of cut is increased from .050" to .075" the tool life drops 20% but again the production rate is 50% greater.

Drilling (As Cast 331 BHN)

The as cast IN-100 alloy was particularly difficult to drill. As shown in Figure 316, page 279, the maximum drill life was 25 holes. Tool life decreased rapidly as the feed was decreased below .002 in./rev. or increased beyond .003 in./rev. with HSS drills. Also, as shown in Figure 317, page 280, the cutting speed was very critical. For example, at 5.5 ft./min. 25 holes were drilled with an M-42 HSS drill, while at 4 ft./min. only 16 holes were drilled, and at 7 ft./min. the drill life was less than 10 holes.

Also, as shown in Figure 317, page 280, the maximum drill life with a C-2 carbide tipped drill was only 21 holes; however, the cutting speed was 14 ft./min. as compared to 5.5 ft./min. with HSS tools. Nevertheless, it is questionable whether the higher cutting speed justifies the use of the carbide tipped drill. Note also that the drill life decreased rapidly when the speed was changed. At a cutting speed of 8 ft./min. tool life was about the same as with the HSS drills. Also, the drill life was only 10 holes at a cutting speed of 18 ft./min.

Surface Grinding (As Cast 331 BHN)

The effect of wheel speed on G Ratio in grinding as cast IN-100 is given in Figure 318, page 280. This grinding was done with an aluminum oxide J hardness wheel with a down feed of .001 in./pass, a cross feed of .005 in./pass, a table speed of 40 ft./min. and with a highly sulfurized oil. A G Ratio of 3.5 was obtained at a wheel speed of 2000 ft./min. and 5.4 at a wheel speed of 6000 ft./min.

The effect of down feed on the G Ratio is shown in Figure 319, page 281, for both 4000 and 6000 ft./min. A maximum wheel speed of 4000 ft./min. is recommended in grinding the cast IN-100 to insure surface integrity of the finished component. At 4000 ft./min., the G Ratio increased from 3 to 6 as the down feed increased from .0005 to .002 in./pass. At the wheel speed of 4000 ft./min., the grinding ratio was found to be essentially constant at cross feeds from .025 to .100 in./pass, see Figure 320, page 281. However, increasing table speed increased the G Ratio, see Figure 321, page 282. The G Ratio increased from 3.6 to 4.6 as the table speed increased from 20 to 60 ft./min.

The conditions recommended for surface grinding as cast IN-100 are given in Table 21, page 277. These conditions are specified to obtain adequate surface integrity and to minimize residual stress, and consist of:

Grinding Wheel:	32A46J8VBE
Wheel Speed:	3000 to 4000 ft./min.
Down Feed:	
Roughing:	.001 in./pass
Finishing:	.0005 in./pass
Cross Feed:	.050 in./pass
Table Speed:	60 ft./min.
Grinding Fluid:	Highly Sulfurized Oil

5.3 IN-100 (continued)

The surface finish obtainable in grinding as cast IN-100 was 10 to 30 microinches, arithmetical average, in finishing; and 20 to 45 microinches, arithmetical average, in roughing.

TABLE 21

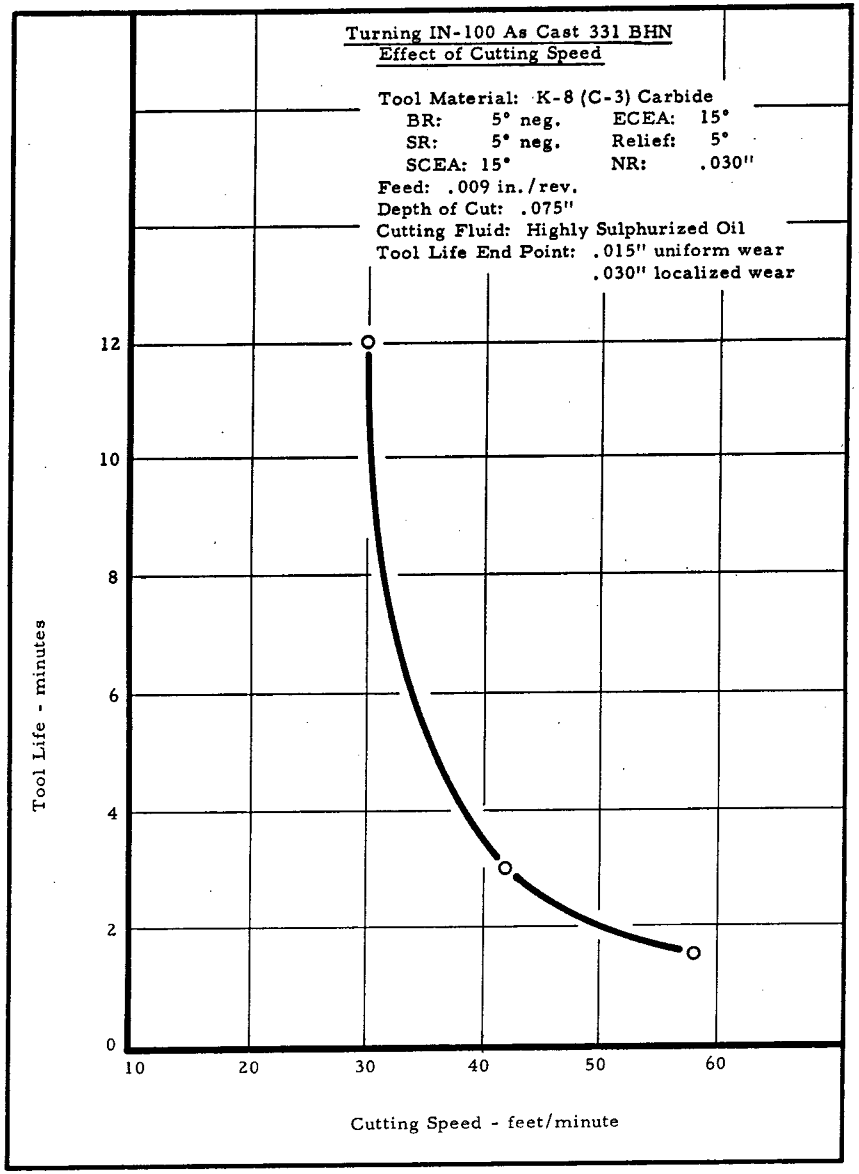
RECOMMENDED CONDITIONS FOR MACHINING
IN-100 AS CAST 331 BHN

Co	Cr	Al	Ti	Mo	C	Ni
15.0	9.5	5.5	5.0	3.0	.17	Bal.

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	C-3 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square throw-away insert	.075	--	.009 in./rev.	30	12 min.	.015	Highly Sulphurized Oil
Drilling	M-42 HSS	118° plain point 7° clearance angle	1/4" diameter drill 2-1/2" long	.250 thru	--	.003 in./rev.	5	25 holes	.015	Highly Chlorinated Oil
Drilling	C-2 Carbide	118° plain point 7° clearance angle	1/4" diameter drill 2" long	.250 thru	--	.003 in./rev.	14	21 holes	.015	Highly Chlorinated Oil

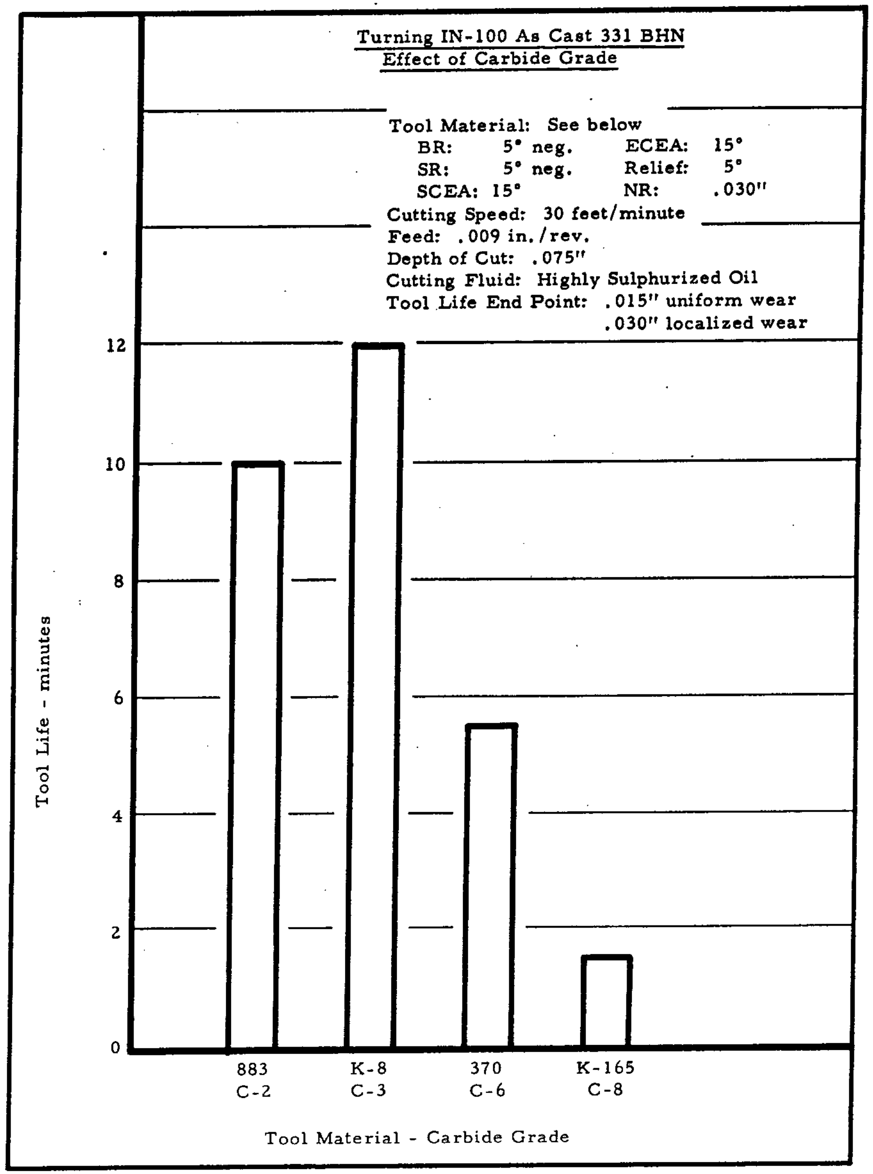
SURFACE GRINDING

Operation	Wheel Grade	Grinding Fluid	Wheel Speed Ft./Min.	Table Speed Ft./Min.	Down Feed In./Pass	Cross Feed In./Pass	G Ratio
Finishing	32A46J8VBE	Highly Sulphurized Oil	3000-4000	60	.0005	.050	3.5
Roughing	32A46J8VBE	Highly Sulphurized Oil	3000-4000	60	.001	.050	4.5



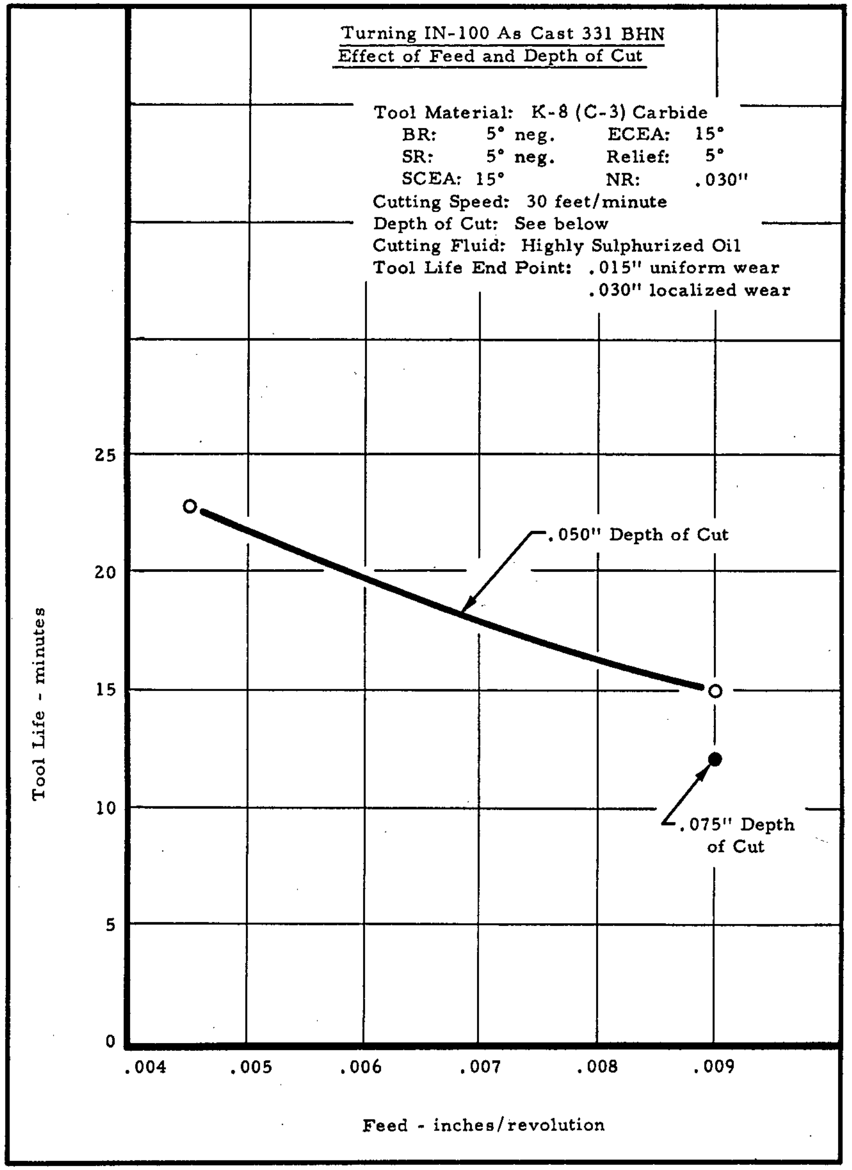
See text, page 274

Figure 313



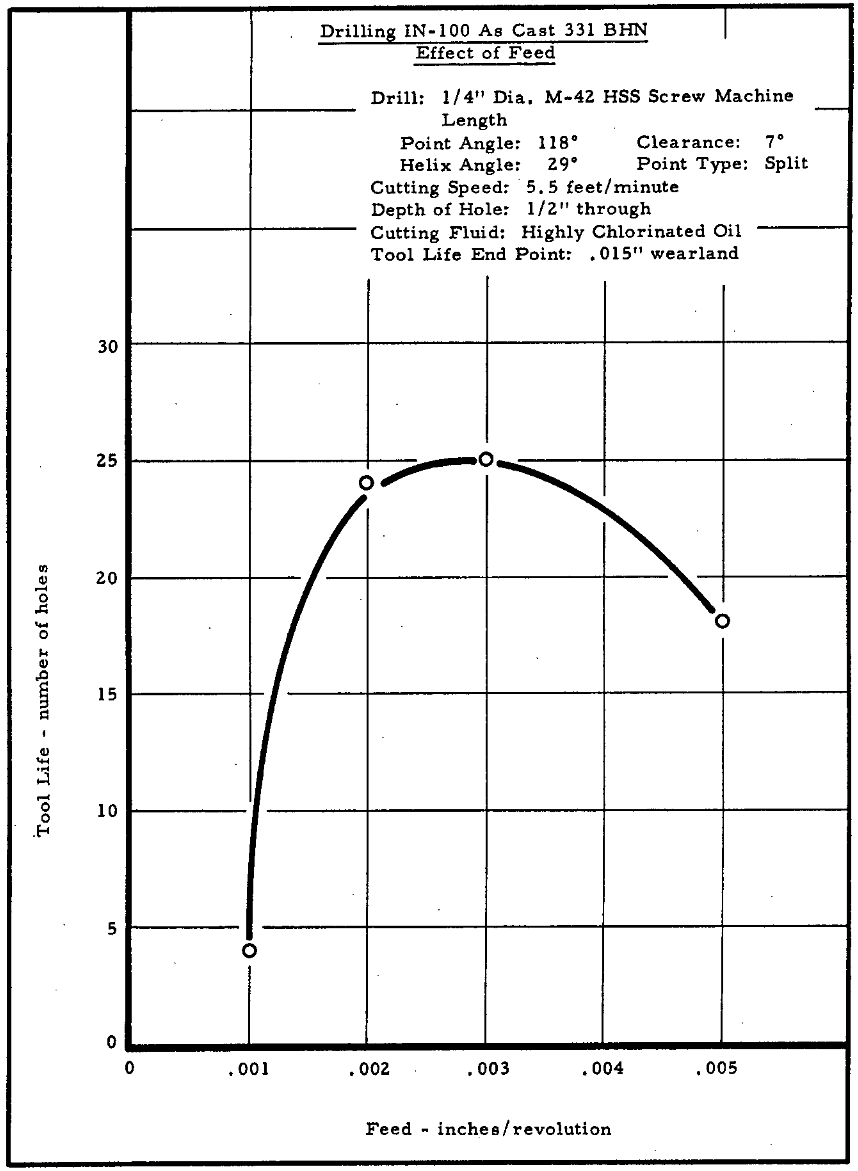
See text, page 274

Figure 314



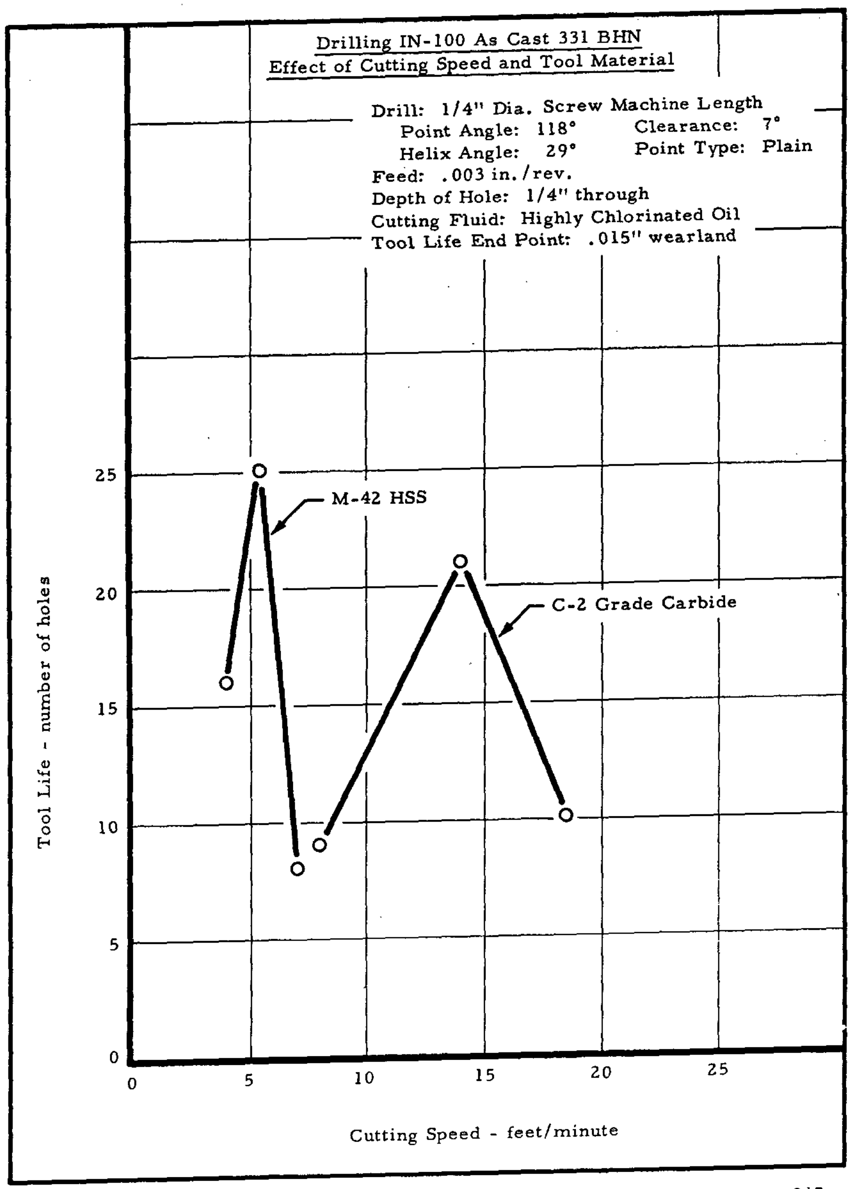
See text, page 274

Figure 315



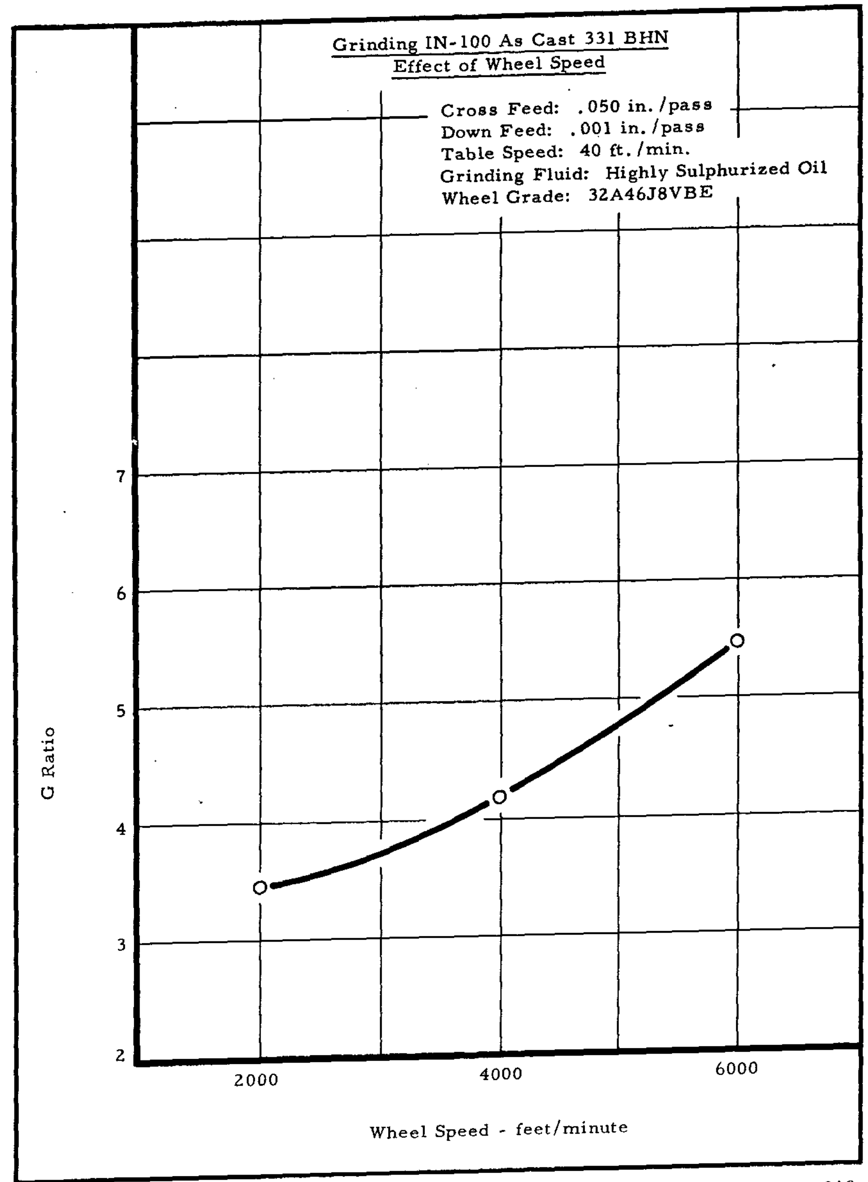
See text, page 274

Figure 316



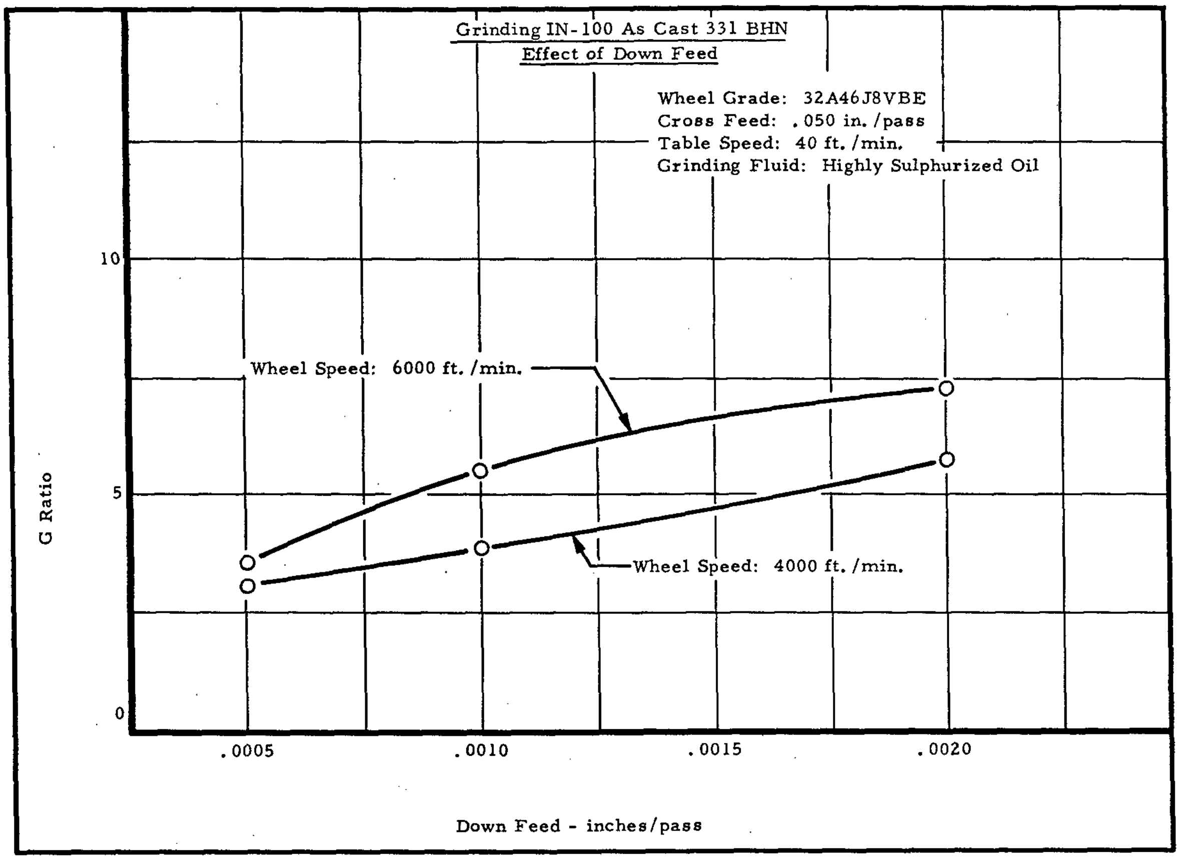
See text, page 274

Figure 317



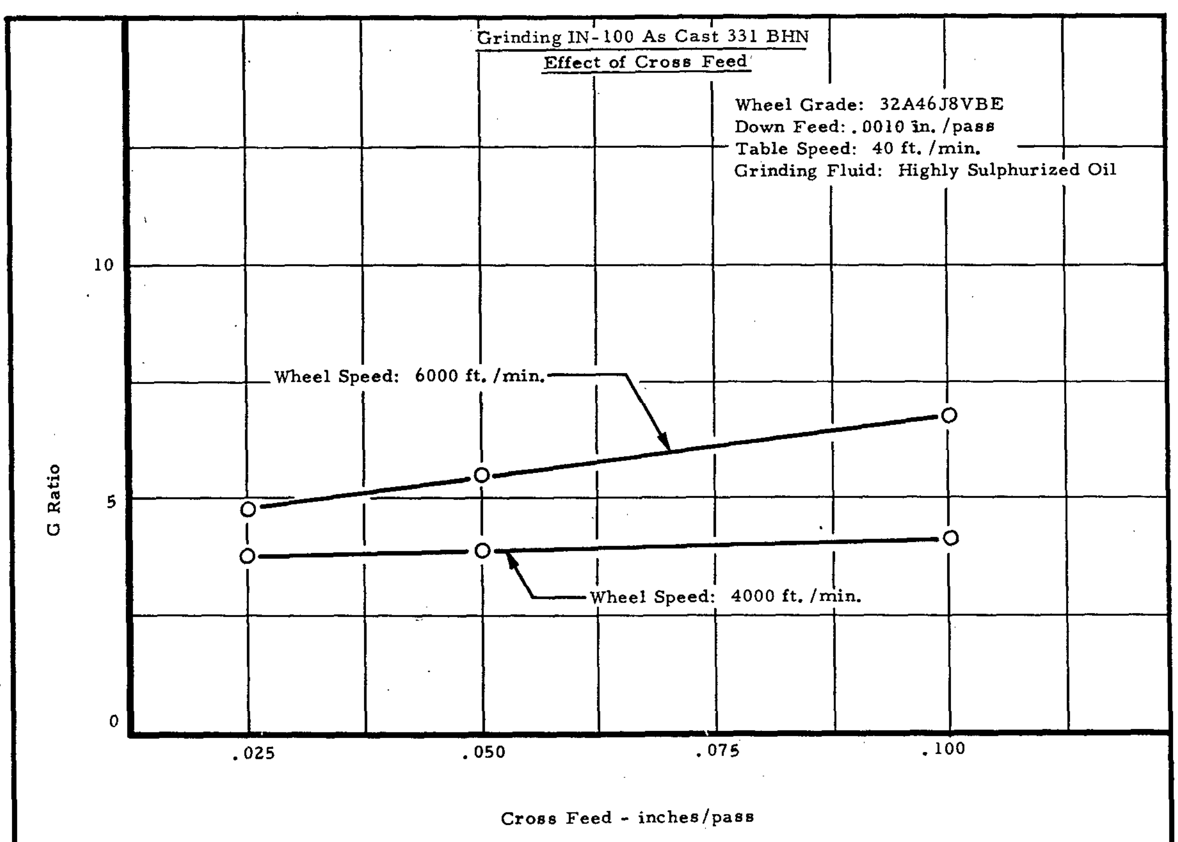
See text, page 275

Figure 318



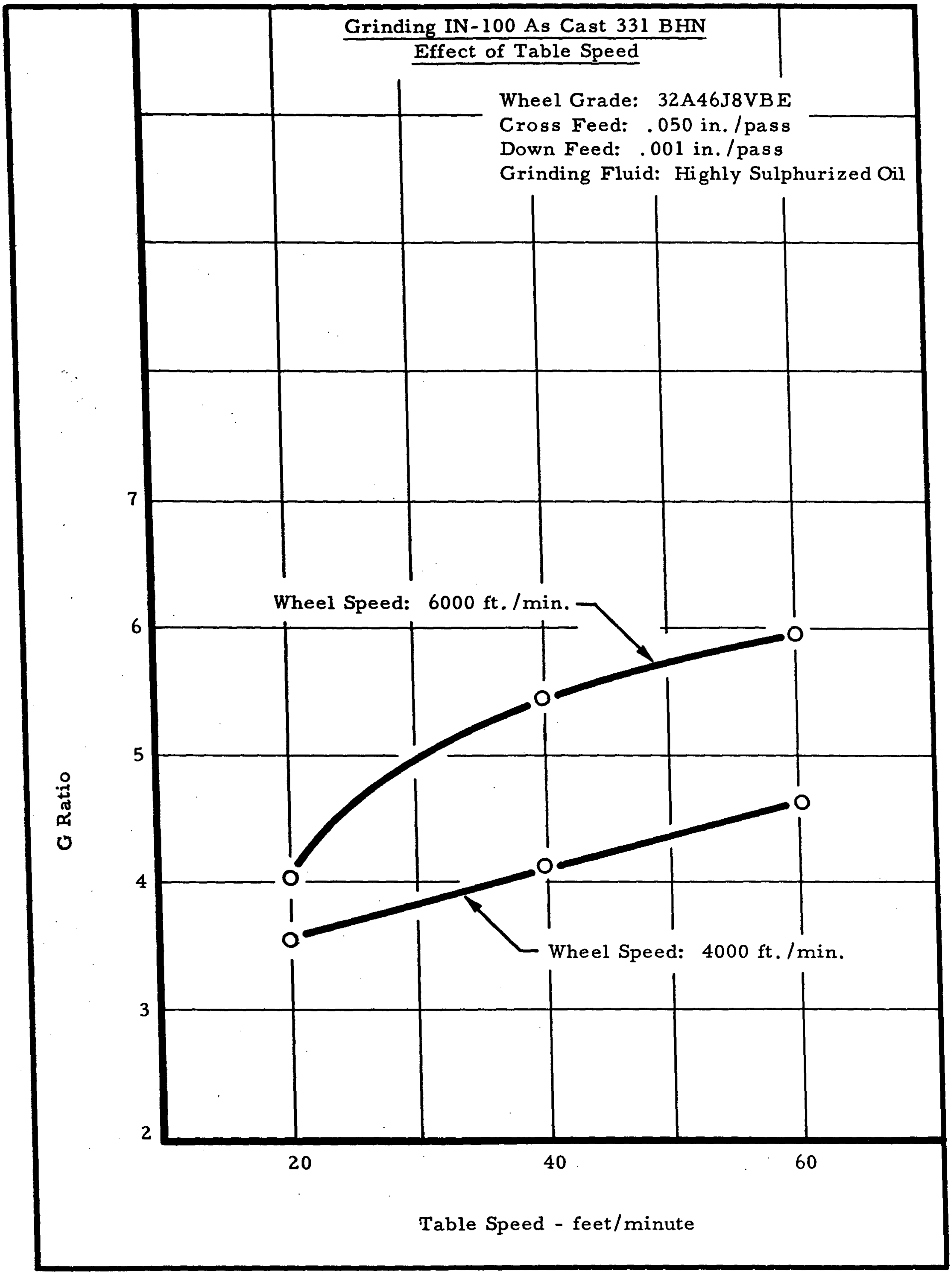
See text, page 275

Figure 319



See text, page 275

Figure 320



See text, page 275

Figure 321

5.4 SM-200

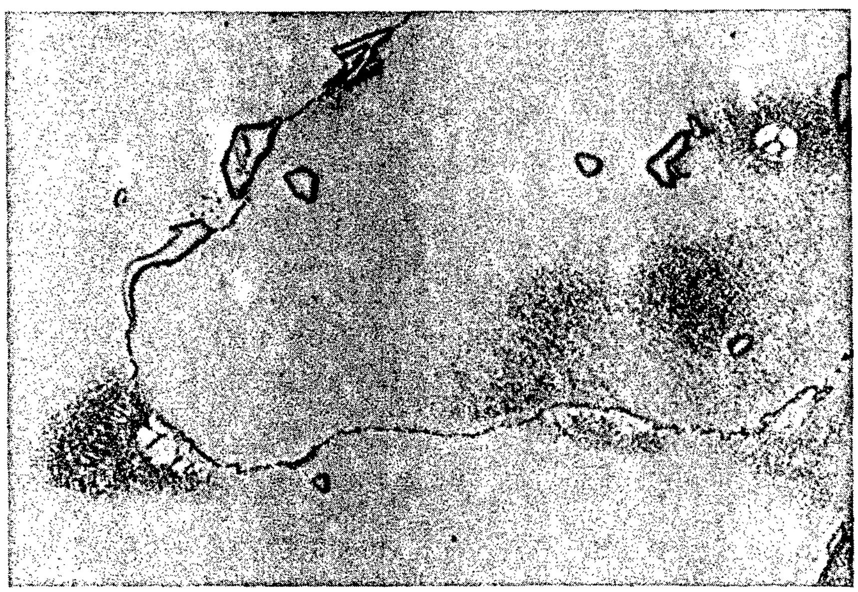
Alloy Identification

SM-200 is a cast, nickel-base high temperature alloy. The nominal composition of this material is as follows:

Ni-9Cr-12.5W-10Co-1Cb-5Al-2Ti

Plates for drilling tests were obtained as 4" x 4" x 1/4" castings, and coupons for grinding ratio tests were procured as castings 1" x 2" x 6". As is typical with cast high temperature nickel base alloys, these samples were not heat treated prior to use. The hardness of the material as received was 345-363 BHN.

The microstructure of this material, exhibiting random carbides in a large-grained matrix, is illustrated below.



SM-200 As Cast

Etchant: Kalling's | Mag: 1000X

5.4 SM-200 (continued)

Drilling (As Cast 363 BHN)

The SM-200 as cast was one of the most difficult alloys of the group to be machined. A wide range of cutting speeds and feeds was used, together with types M-1, T-15 and M-42 HSS drills, in an attempt to obtain a reasonable drill life. As shown in Figure 322, page 287, even with the most active cutting fluids, a drill life of 10 holes was the maximum that could be achieved under the conditions listed.

Surface Grinding (As Cast 345 BHN)

The effect of the various grinding variables on the relative wheel wear, or G Ratio, is illustrated in Figures 323 through 329, pages 289 and 290.

In Figure 323, the effect of grinding wheel speed and grit size on the G Ratio is shown. All the wheels were aluminum oxide, J hardness, vitrified bond. The grit size varied from 46 to 80. There was a small improvement in the G Ratio as the grit size became finer. It was observed that for all three wheels the G Ratio increased with increasing speed. Thus, for the 32A46J8VBE wheel, the G Ratio was 4 at 2000 ft./min., 7.5 at 4000 ft./min., and 10 at 6000 ft./min.

The comparative wheel wear of aluminum oxide with silicon carbide abrasive is shown in Figure 324, page 288. The silicon carbide wheel (39C60J8VK) is seen to wear excessively. The maximum G Ratio achieved was only about 0.25 at all speeds between 2000 and 6000 ft./min., compared with G Ratios of 5 to 10 for the aluminum oxide wheel (32A60J8VBE).

Increasing the down feed per pass improved the G Ratio at both 4000 and 6000 ft./min., Figure 325, page 288. Thus, at 4000 ft./min., the G Ratio was approximately 7.5 at .0005 and .001 in./pass, whereas the G Ratio increased to 10 at a down feed of .002 in./pass.

Varying the cross feed produced a minimum G Ratio at .050 in./pass, Figure 326, page 289. It will be noted that the G Ratio was highest for the highest cross feed of 0.1 in./pass at both 4000 and 6000 ft./min. Thus, at 0.1 in./pass, a G Ratio of 12 was achieved at 4000 ft./min. and 14 at 6000 ft./min.

5.4 SM-200 (continued)

As shown in Figure 327, page 289 at a wheel speed of 4000 ft./min., the G Ratio was 7.5 at table speeds of 20 and 40 ft./min., with the G Ratio increasing to 12 at a table speed of 50 ft./min. At a wheel speed of 6000 ft./min., a maximum G Ratio of 22 was obtained at 20 ft./min. The G Ratio dropped rapidly to a minimum of 10 at 40 ft./min. and then increased to a value of 13 at 50 ft./min.

The effect of wheel hardness on G Ratio is depicted in Figure 328, page 290, for a wheel speed of 4000 ft./min. Under the conditions shown, it is observed that the lowest G Ratio of 5.2 was obtained with the softest wheel (H hardness). The G Ratio increased to 7.2 with the J hardness wheel, and the highest G Ratio of 15 was obtained with the L hardness wheel.

All of the previous tests, as depicted in Figures 323, page 287 through 328, page 290, were run with highly sulfurized oil. The effect of three grinding fluids on wheel wear is given in Figure 329, page 290. Both the highly sulfurized and chlorinated oils produced considerably higher G Ratios than the soluble oil.

The surface finishes achieved in these grinding tests vary between 12 and 40 microinches, arithmetical average, with all the test conditions illustrated in Figures 323, page 287, through 329, page 290. There was no particular correlation between any of the grinding variables and the surface finish values obtained in these tests within the range of surface values indicated.

The recommended conditions for grinding as cast SM-200 are given in Table 22, page 286. These conditions have been stipulated in accordance with the need for maintaining high integrity of the ground surface. The conditions are those corresponding to "low stress" grinding, which provide a minimum of surface alterations as well as low residual stresses (Chapter 7, pages 317-378). These conditions consist of:

Grinding Wheel:	32A46J8VBE
Wheel Speed:	4000 ft./min. maximum
Down Feed:	
Roughing:	.001 in./pass
Finishing:	.0005 in./pass
Cross Feed:	.050 in./pass
Table Speed:	60 ft./min.
Grinding Fluid:	Highly Sulfurized Oil

TABLE 22

RECOMMENDED CONDITIONS FOR MACHINING

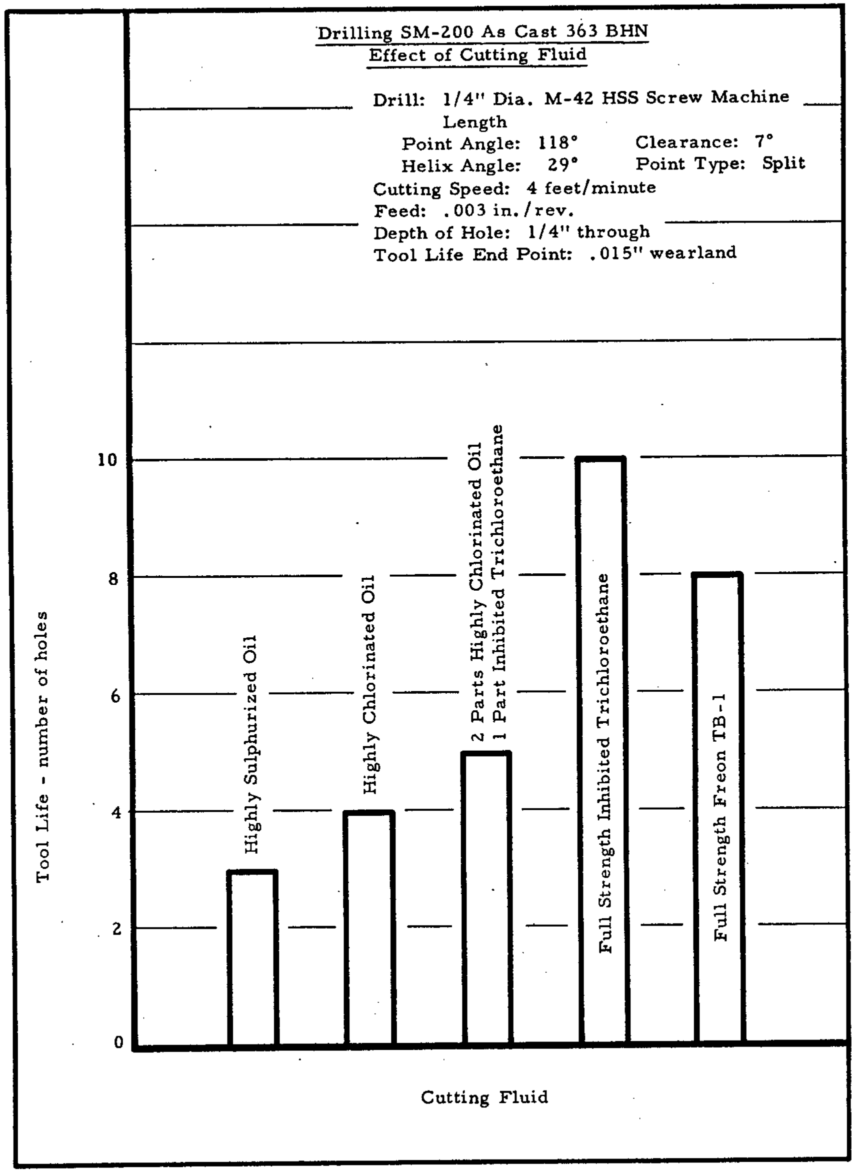
SM-200 AS CAST 345 - 363 BHN

Cr	W	Co	Cb	Al	Ti	Ni
9	12.5	10	1	5	2	Bal

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	M-42 HSS	118° Split Point 7° clearance angle	1/4" diameter drill 2 1/2" long	.250 thru	-	.003 in/rev	4	10 holes	.015	Inhibited Trichloro-ethane

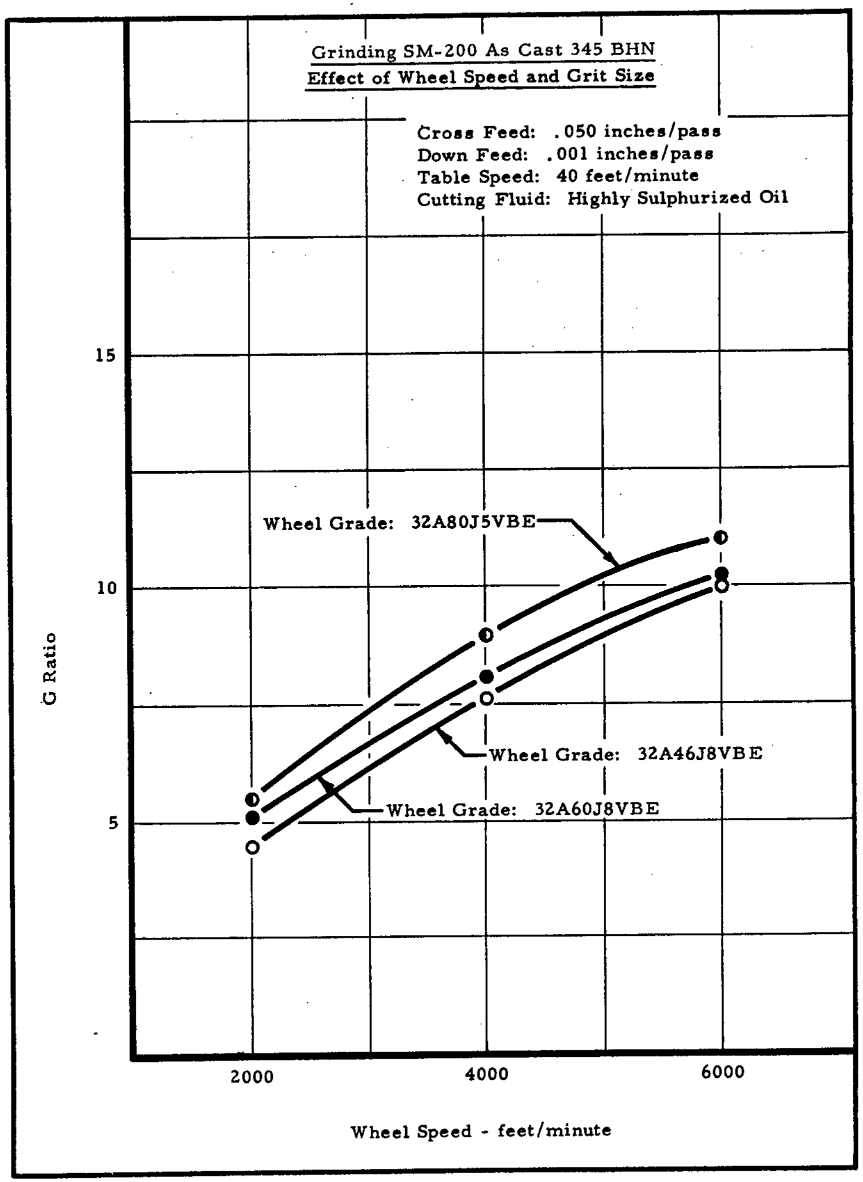
SURFACE GRINDING

Operation	Wheel Grade	Grinding Fluid	Wheel Speed Ft./Min.	Table Speed Ft./Min.	Down Feed In./Pass.	Cross Feed In./Pass.	G Ratio
Finishing	32A46J8VBE	Highly Sulphurized Oil	4000 Max.	60	.0005	.050	8
Roughing	32A46J8VBE	Highly Sulphurized Oil	4000 Max.	60	.001	.050	12



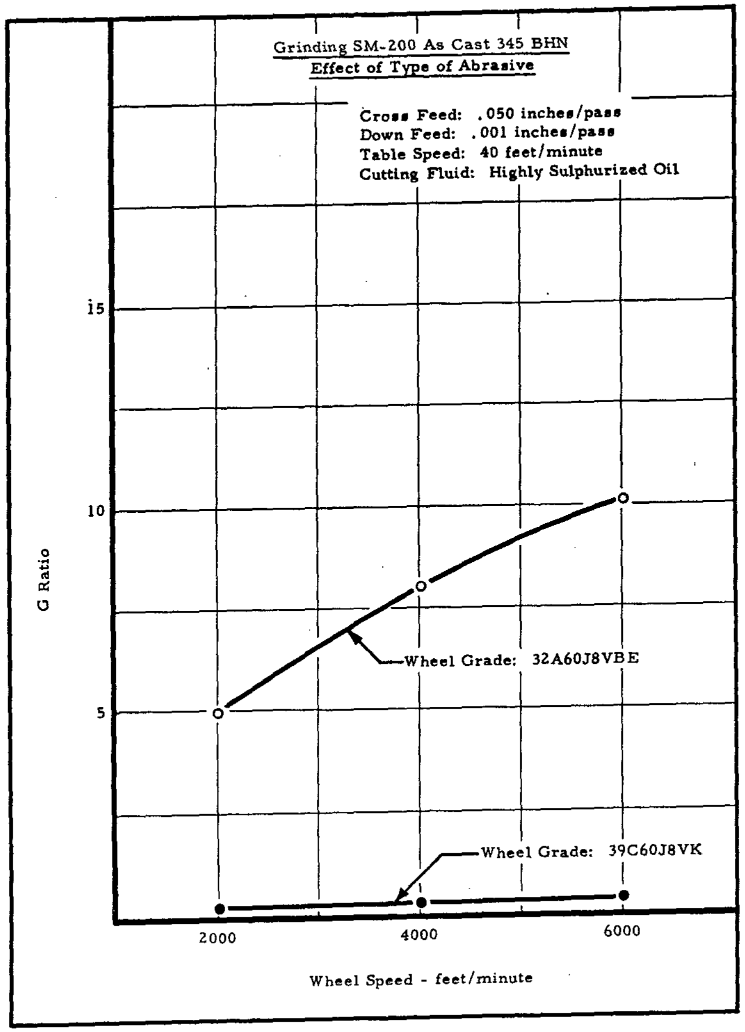
See text, page 284

Figure 322



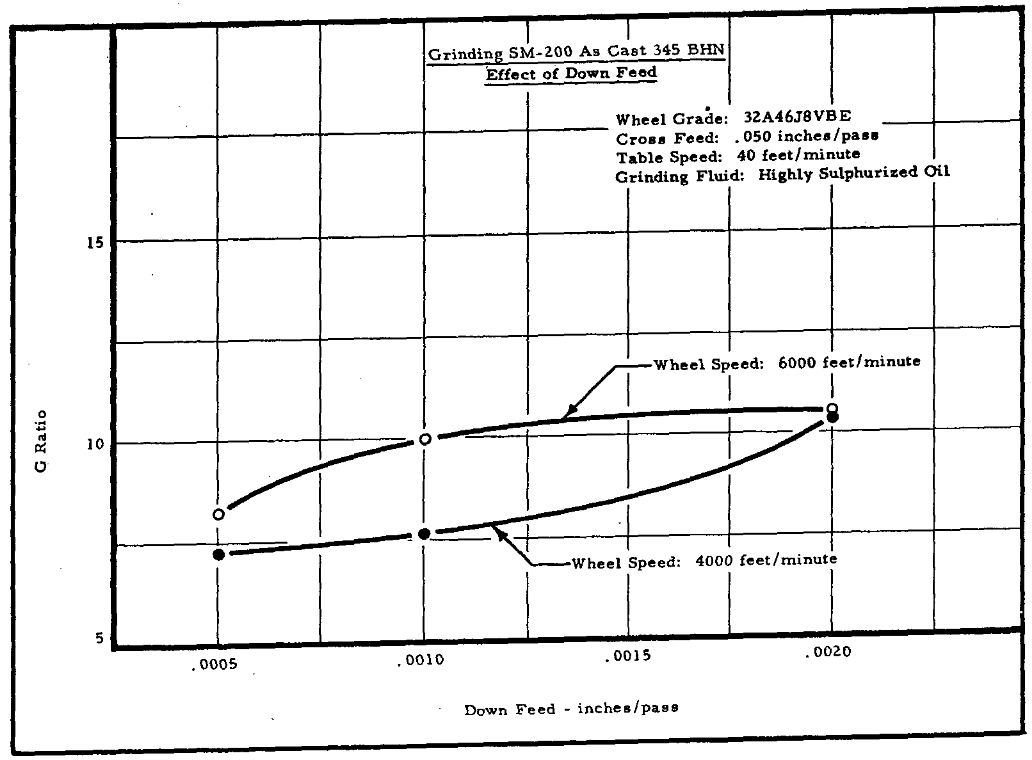
See Text, page 284

Figure 323



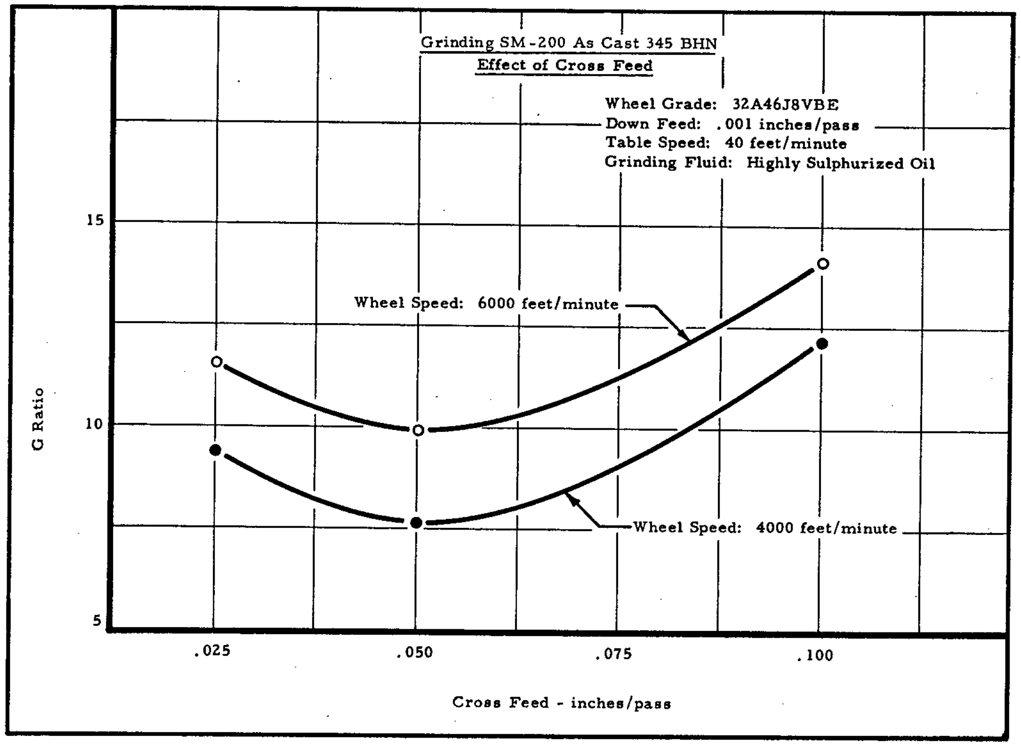
See Text, page 284

Figure 324



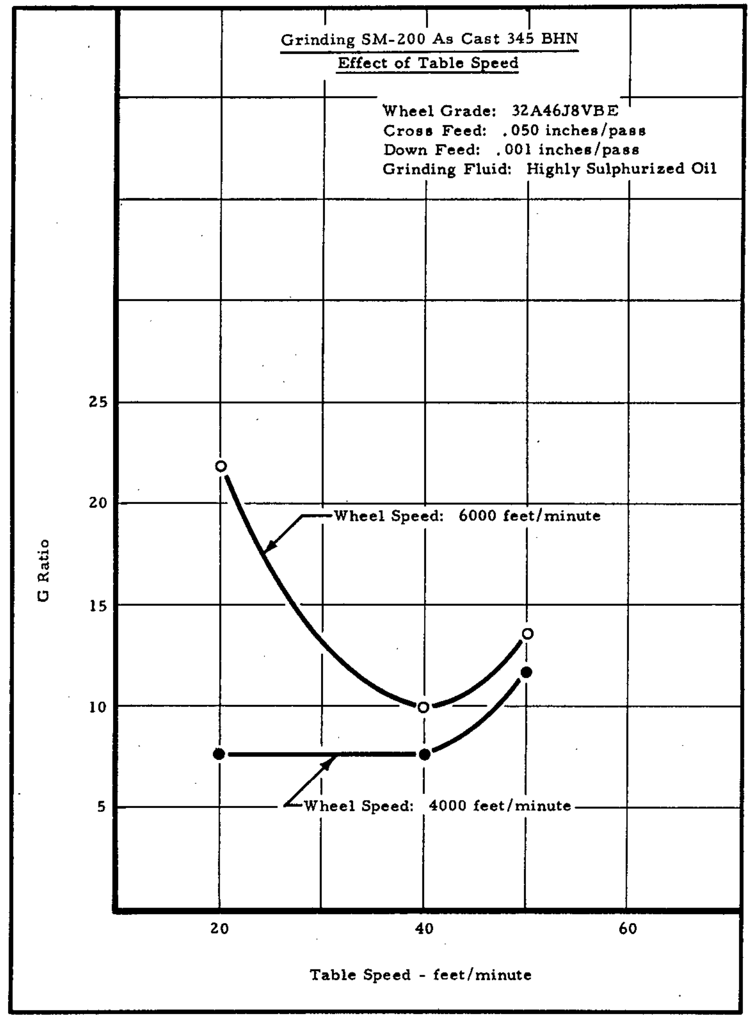
See text, page 284

Figure 325



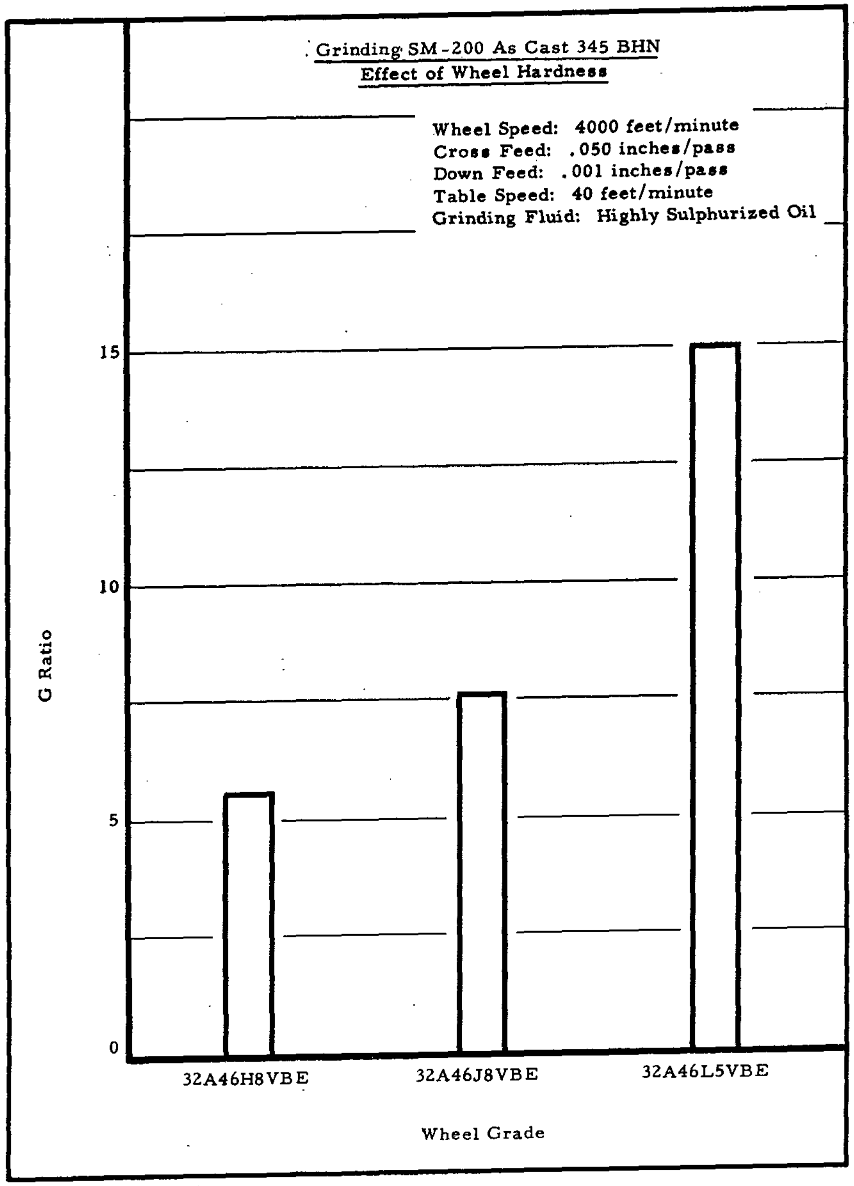
See text, page 284

Figure 326



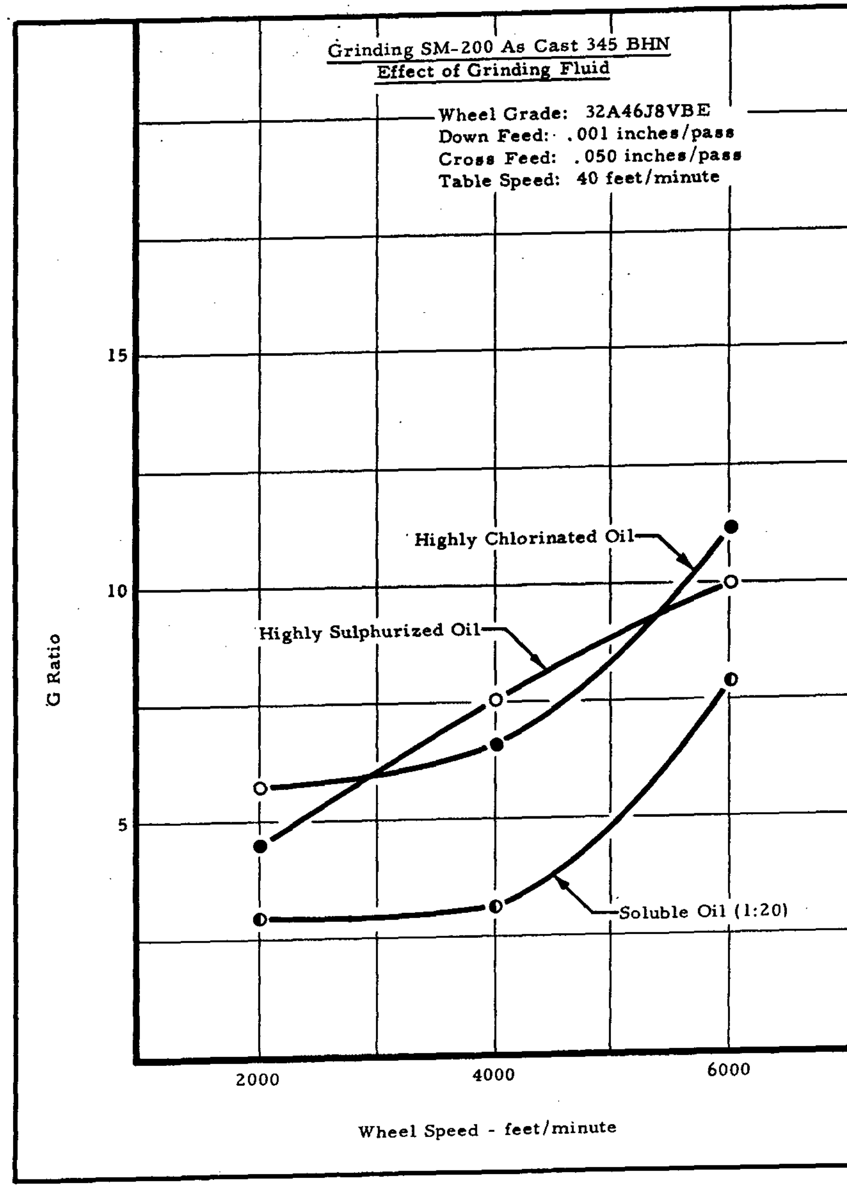
See Text, page 284

Figure 327



See Text, page 284

Figure 328



See Text, page 284

Figure 329

5.5 Inconel 713C

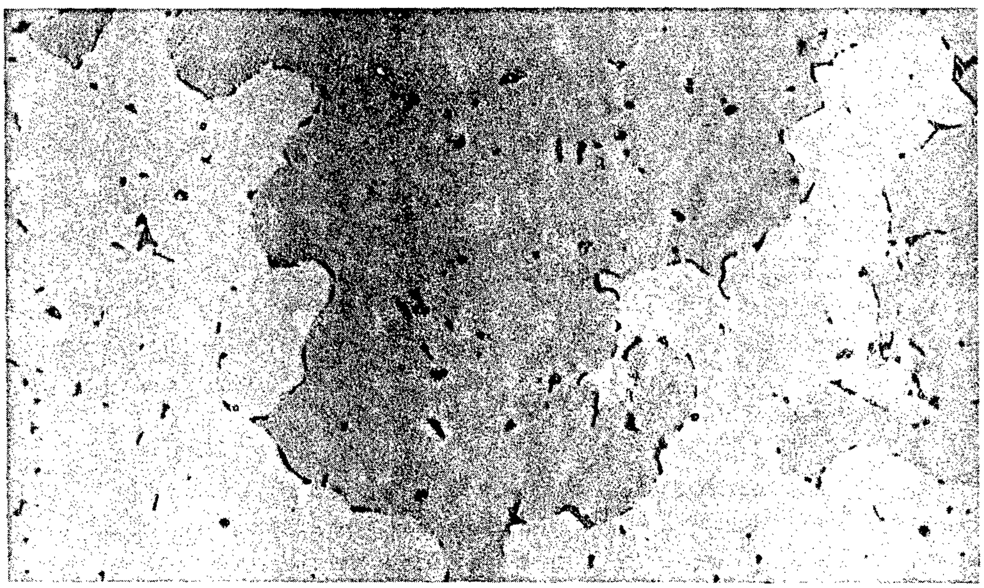
Alloy Identification

Inconel 713C is a nickel-chromium high temperature alloy having the following nominal composition:

Ni-4Fe-6Al-4.5Mo-12.5Cr

Plates for drilling tests were procured as 4" x 4" x 1/4" castings, and coupons for grinding ratio tests were procured as castings 1" x 2" x 6". No heat treatment was performed on these samples prior to use. The hardness of the material as received was 311-321 BHN.

The microstructure of this material, exhibiting random carbide distribution in a large grained matrix, is illustrated below:



Inconel 713C As Cast

Etchant: Kalling's Mag: 100X

Drilling (As Cast 321 BHN)

100 holes were drilled in the Inconel 713C as cast alloy with an M-42 HSS drill by using a drilling speed of 5.5 ft./min. and a feed of .005 in./rev. with a highly chlorinated oil; see Figure 330, page 294. However, when the feed was increased to .009 in./rev., all other conditions remaining the same, the drill life dropped to 13 holes.

5.5 Inconel 713C (continued)

The relationship between cutting speed and drill life on the Inconel 713C is shown in Figure 331, page 294. Note that when the speed was increased from 5 to 10 ft./min. the drill life decreased 50%.

Surface Grinding (As Cast 311 BHN)

The effect of wheel speed on the wheel wear or G Ratio of the as cast Inconel 713C is shown in Figure 332, page 295. The G Ratio increased as the wheel speed increased from 2000 to 6000 ft./min. At 6000 ft./min., a G Ratio of 12 was obtained. These tests were run with a 32A46J8VBE grinding wheel using a cross feed of .050 in./pass, .001 in./pass down feed, 40 ft./min. table speed and a highly sulfurized cutting oil.

The G Ratio was observed to increase with down feed, Figure 333, page 295. Here are shown the results at two wheel speeds, 4000 and 6000 ft./min. The 4000 ft./min. wheel speed is more significant since this is the top limit of wheel speed recommended to minimize surface alterations as a result of grinding.

The effect of cross feed on the wheel wear is shown in Figure 334, page 296 for both 4000 and 6000 ft./min. The G Ratio is seen to remain essentially constant at cross feeds of .050 to .100 in./pass. The G Ratio was likewise found to increase as the table speed increased, Figure 335, page 296. Thus, at a wheel speed of 4000 ft./min. a value of 9 was obtained at a table speed of 60 ft./min. compared to 4 at a table speed of 20 ft./min.

The conditions recommended for surface grinding of Inconel 713C are given in Table 23, page 293. These conditions are specified to obtain adequate surface integrity and to minimize residual stress (see Chapter 7, pages 317-378) and consist of:

Grinding Wheel:	32A46J8VBE
Wheel Speed:	3000 to 4000 ft./min.
Down Feed:	
Roughing:	.001 in./pass
Finishing:	.0005 in./pass
Cross Feed:	.050 in./pass
Table Speed:	60 ft./min.
Grinding Fluid:	Highly Sulfurized Oil

The surface finish obtainable in grinding Inconel 713C is 20 to 40 microinches, arithmetical average, in finishing; and 35 to 50 microinches, arithmetical average, in roughing.

TABLE 23

RECOMMENDED CONDITIONS FOR MACHINING

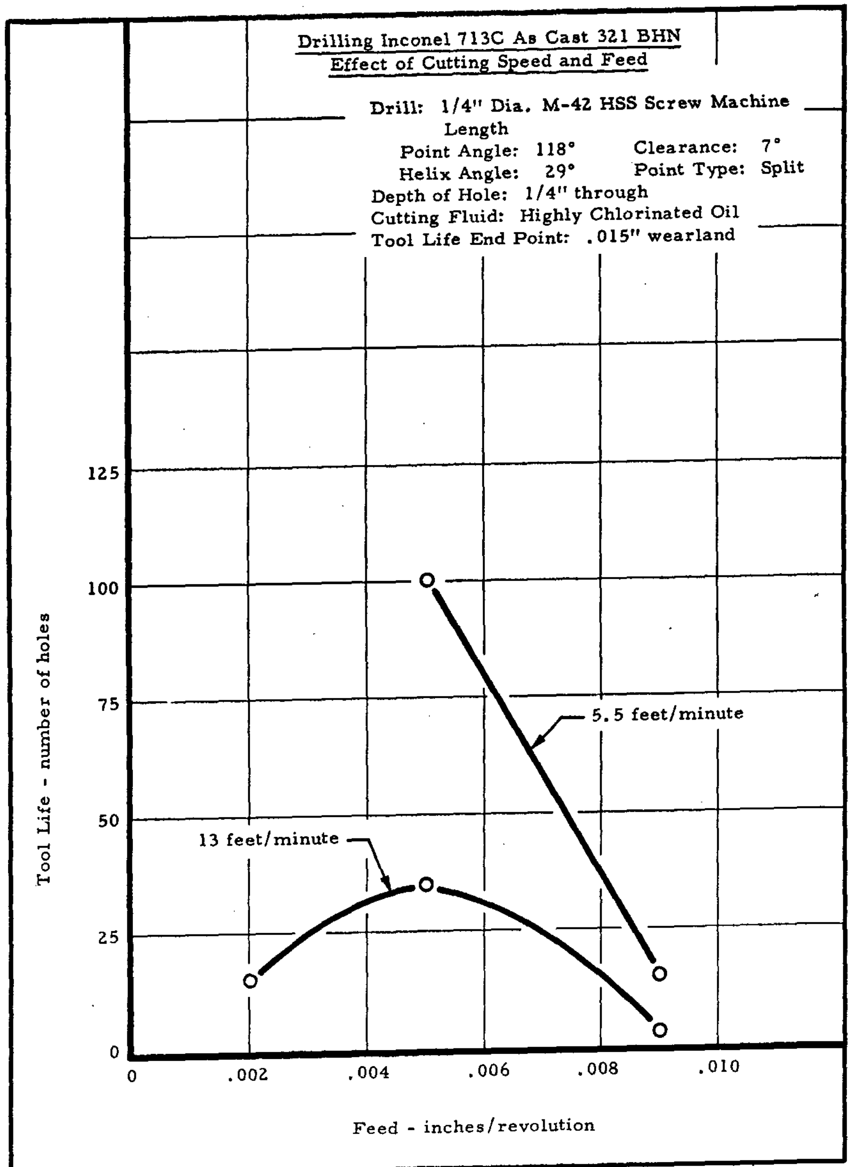
INCONEL 713-C AS CAST 311 - 321 BHN

Fe	Al	Mo	Cr	Ni
4	6	4.5	12.5	Bal

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	M-42 HSS	118° split point 7° clearance angle	1/4" diameter drill 2 1/2" long	.250 thru	-	.005 in/rev	5	100 holes	.015	Highly Chlorinated Oil

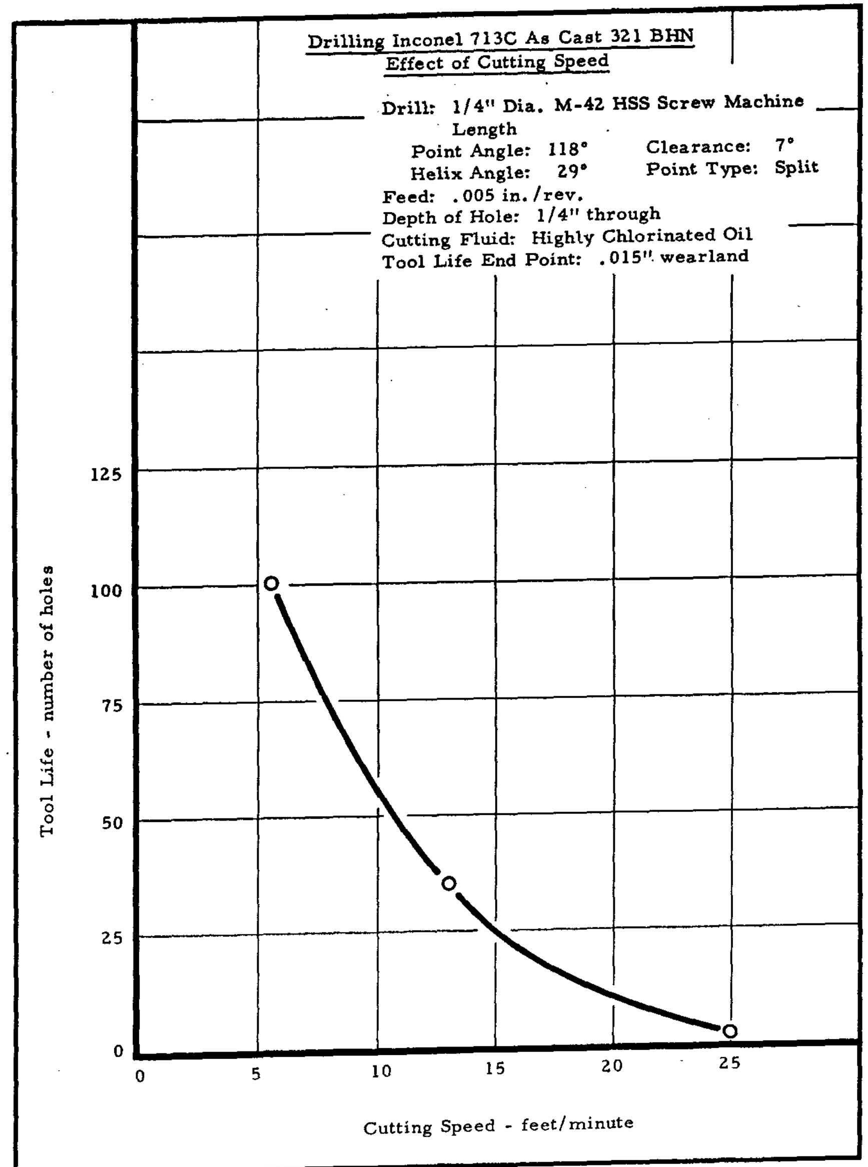
SURFACE GRINDING

Operation	Wheel Grade	Grinding Fluid	Wheel Speed Ft./Min.	Table Speed Ft./Min.	Down Feed In./Pass.	Cross Feed In./Pass.	G Ratio
Finishing	32A46J8VBE	Highly Sulphurized Oil	4000 max.	60	.0005	.050	4
Roughing	32A46J8VBE	Highly Sulphurized Oil	4000 max.	60	.001	.050	9



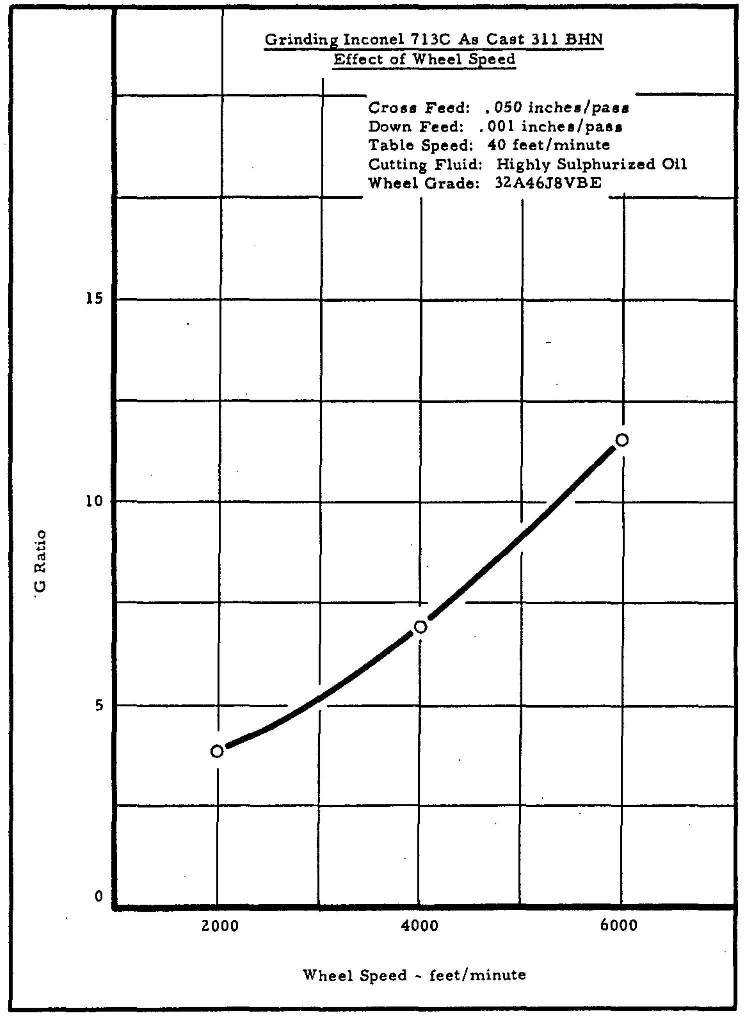
See text, page 291

Figure 330



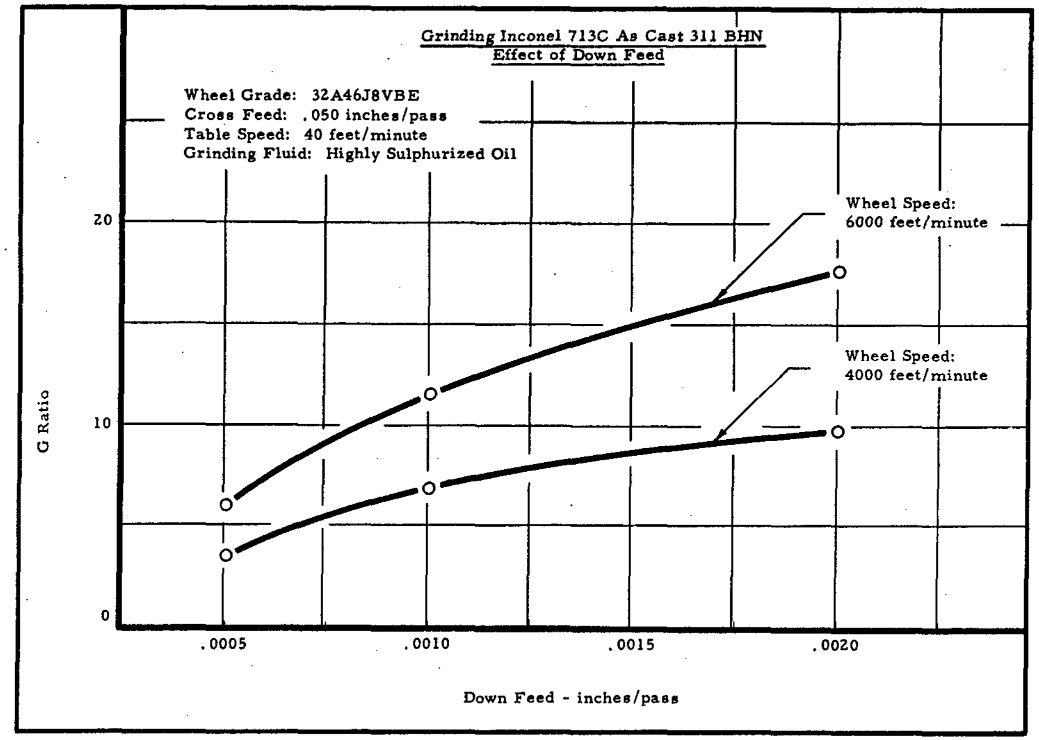
See text, page 292

Figure 331



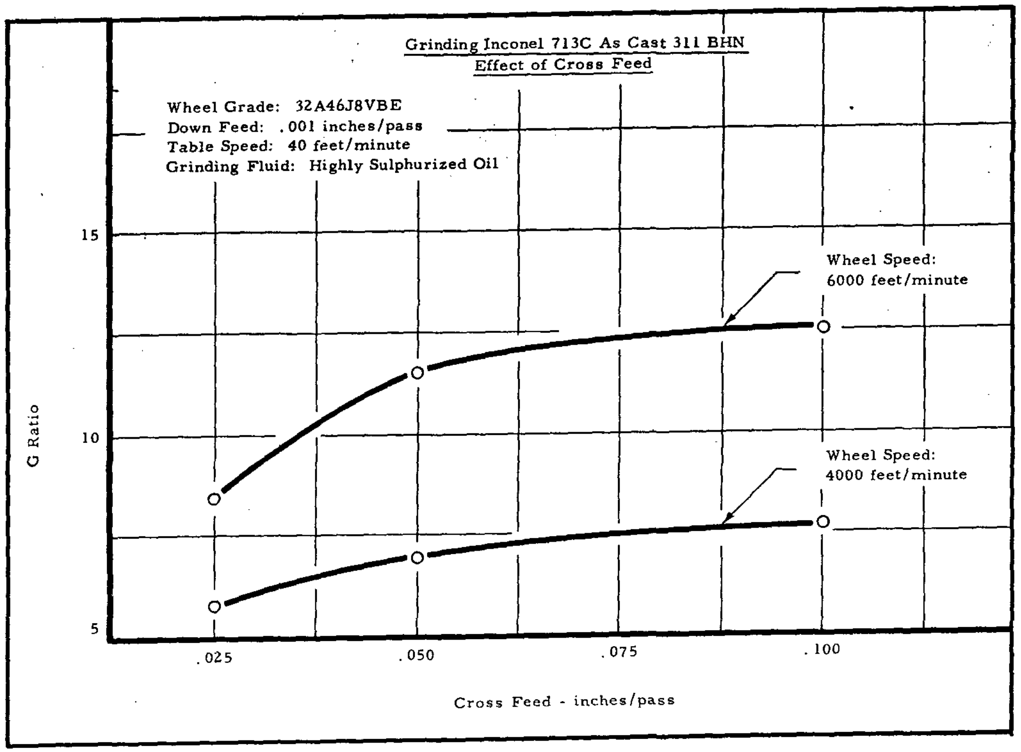
See Text, page 292

Figure 332



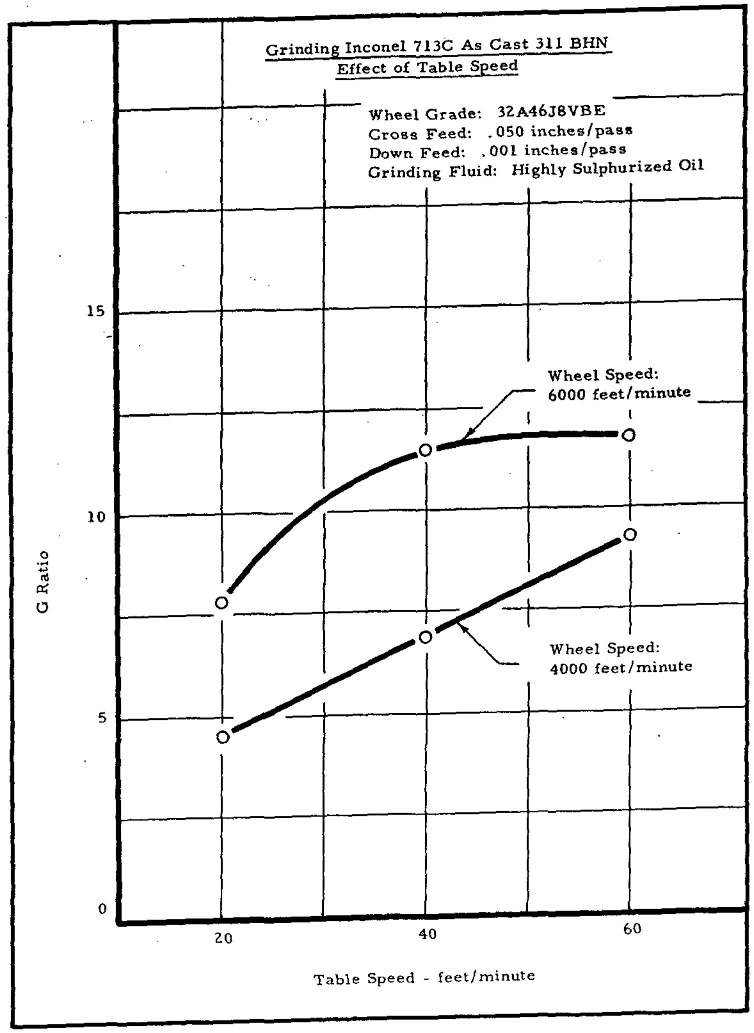
See text, page 292

Figure 333



See text, page 292

Figure 334



See Text, page 31

Figure 335

5.6 B1900

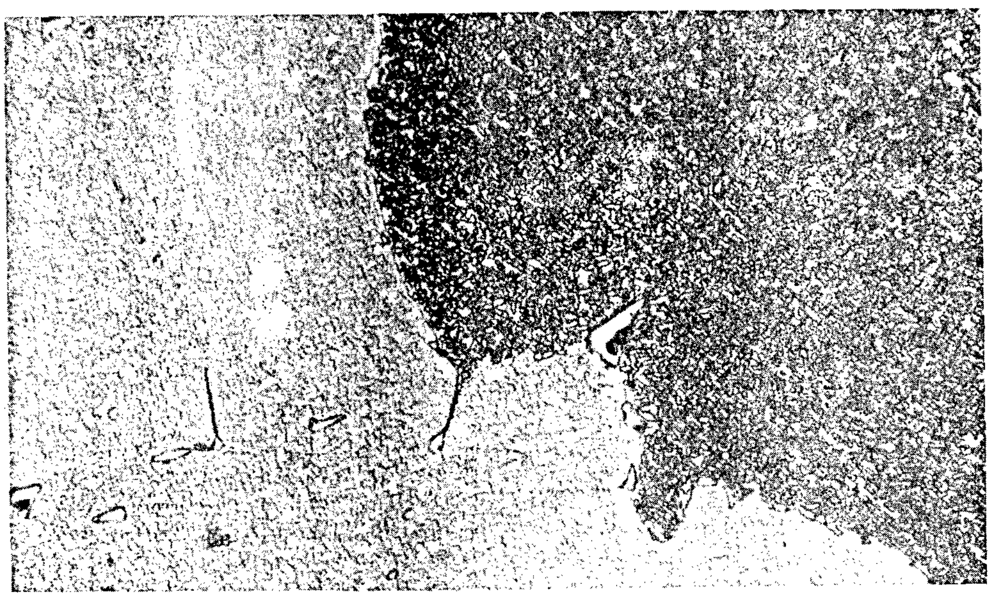
Alloy Identification

B1900 is a cast complex nickel base super alloy which exhibits good strength and structural stability at elevated temperatures promoted by solution strengtheners and precipitation hardening elements. The nominal composition of the alloy is as follows:

Ni-8Cr-10Co-6Mo-4.2Ta-6Al-1Ti-.10C-.015B

Material for drilling tests was obtained as castings 4" x 4" x 1/4", and coupons for grinding tests were procured as castings 1" x 2" x 6". Hardness of the as received material ranged from 285-332 BHN.

The microstructure below reveals precipitation of gamma-prime (Ni_3 (Al, Ti)), MC grain boundary carbides and borides which strengthen the gamma matrix.



B1900 As Cast

Etchant: Kalling's Mag: 500X

Drilling (As Cast 285 BHN)

M-42 HSS drills were compared with the T-15 HSS drills in drilling B1900 in the as cast condition. As shown in Figure 336, page 300, the M-42 drills were far superior to the T-15 drills under the conditions listed.

A drill life of 65 holes was obtained at a feed of .003 in./rev. and a cutting speed of 4 ft./min., see Figure 337, page 300. Note that the drill life was far less at the same cutting speed for a feed of .002 in./rev.

Surface Grinding (As Cast 332 BHN)

The effect of wheel speed on the G Ratio in grinding B1900 as cast is given in Figure 338, page 301. This grinding was done with an aluminum oxide J hardness wheel with a down feed of .001 in./pass, a cross feed of .050 in./pass, a table speed of 40 ft./min., and with a highly sulfurized cutting oil. A G Ratio of 3.5 to 7.8 was obtained at wheel speeds of 2000 to 6000 ft./min. The effect of down feed on G Ratio is given in Figure 339, page 301, for both 4000 and 6000 ft./min. The wheel speed of 4000 ft./min. maximum is recommended in grinding the B1900 to insure surface integrity of the finished component. At the 4000 ft./min. wheel speed the G Ratio increased from 2.7 to 7.2 as the down feed increased from .0005 to .002 in./pass.

Increasing the cross feed from .050 to .100 in./pass had only a small effect on G Ratio at the 4000 ft./min. wheel speed, Figure 340, page 302. It was possible at a wheel speed of 4000 ft./min. to increase the G Ratio from 4 to 7.6 as the table speed was increased from 20 to 60 ft./min., Figure 341, page 302.

The conditions recommended for surface grinding B1900 are given in Table 24, page 299. These conditions are specified to obtain adequate surface integrity and to minimize residual stress (see Chapter 7, pages 317-378) and consist of:

Grinding Wheel:	32A46J8VBE
Wheel Speed:	3000 to 4000 ft./min.
Down Feed:	
Roughing:	.001 in./pass
Finishing:	.0005 in./pass
Cross Feed:	.050 in./pass
Table Speed:	60 ft./min.
Grinding Fluid:	Highly Sulfurized Oil

The surface finish obtainable in grinding B1900 is 6 to 20 microinches, arithmetical average, in finishing; and 20 to 50 microinches, arithmetical average, in roughing.

TABLE 24

RECOMMENDED CONDITIONS FOR MACHINING

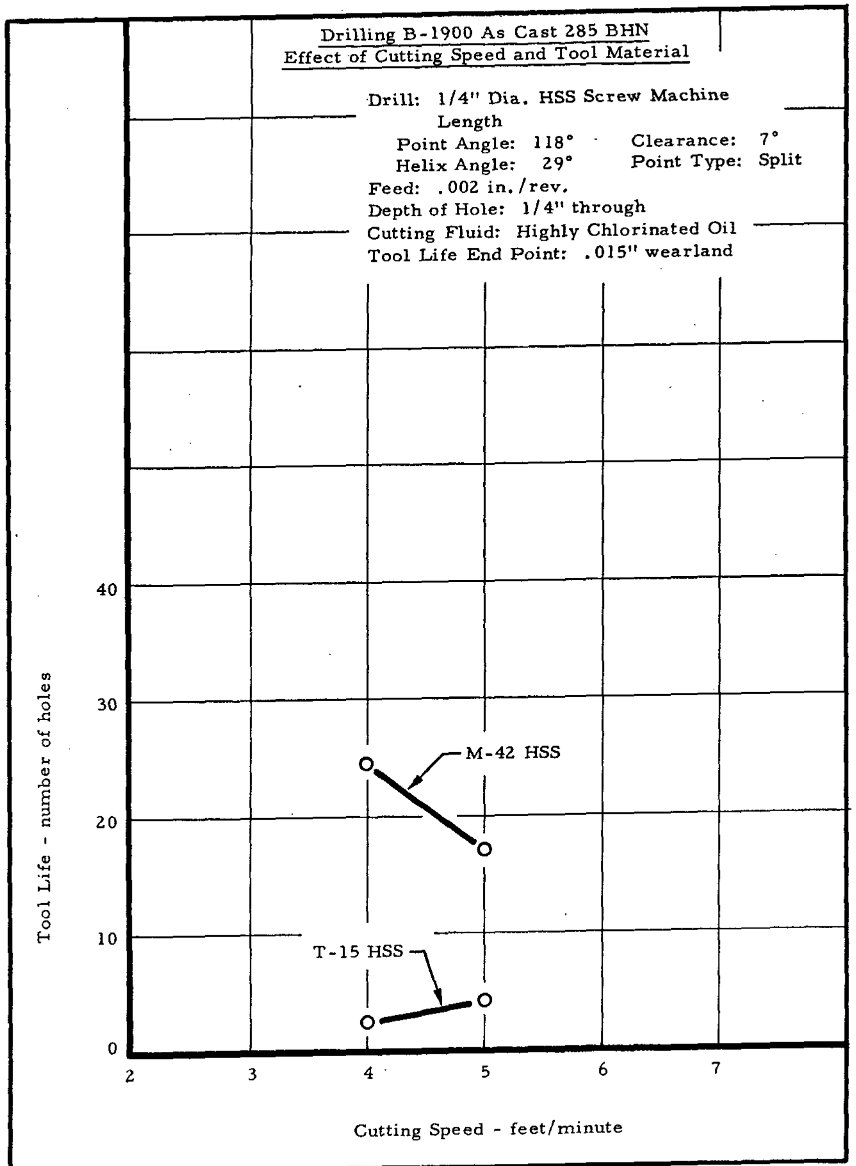
B 1900 AS CAST 285 - 332 BHN

Cr	Co	Mo	Ta	Al	Ti	B	C
8	10	6	4.25	6	1	.015	.10

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	M-42 HSS	118° split point 7° clearance angle	1/4" diameter drill 2 1/2" long	.250 thru	-	.005 in/rev	5	100 holes	.015	Highly Chlorinated Oil

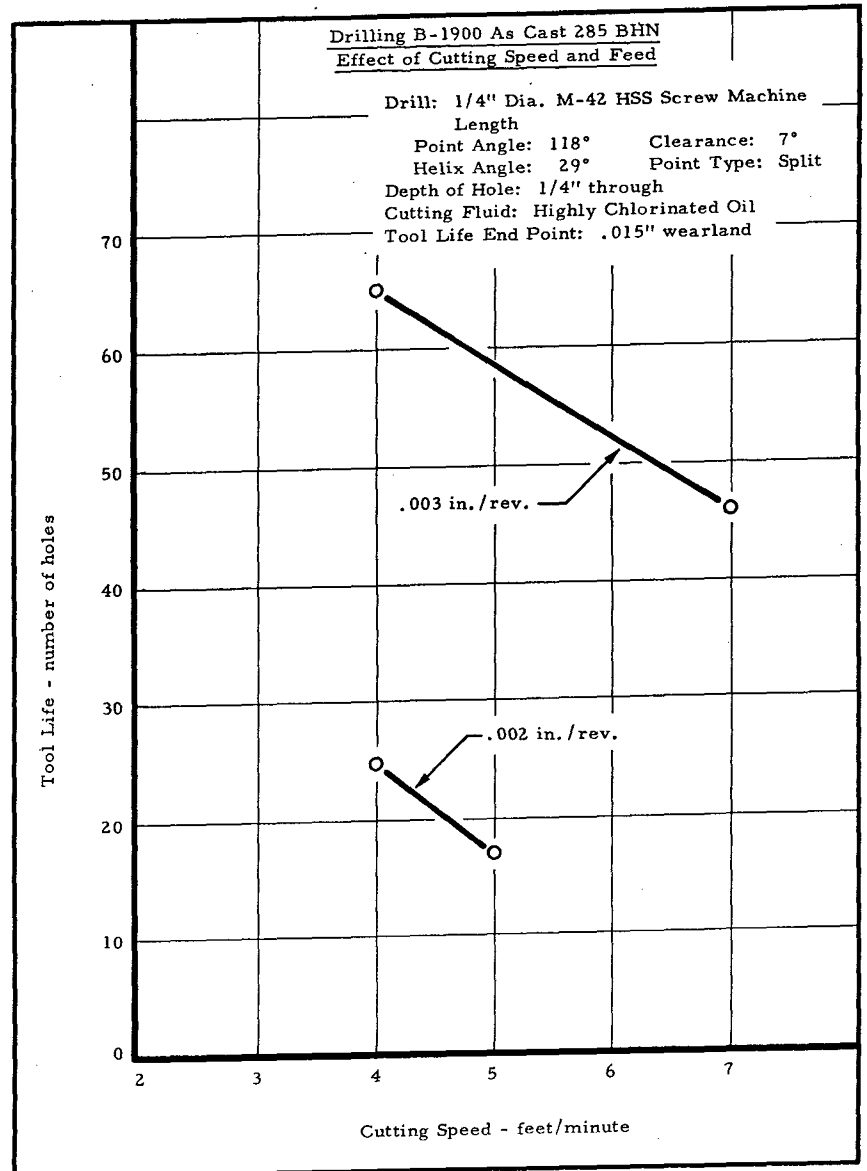
SURFACE GRINDING

Operation	Wheel Grade	Grinding Fluid	Wheel Speed Ft./Min.	Table Speed Ft./Min.	Down Feed In./Pass.	Cross Feed In./Pass.	G Ratio
Finishing	32A46J8VBE	Highly Sulphurized Oil	3000 - 4000	60	.0005	.050	3.4
Roughing	32A46J8VBE	Highly Sulphurized Oil	3000 - 4000	60	.001	.050	5.6



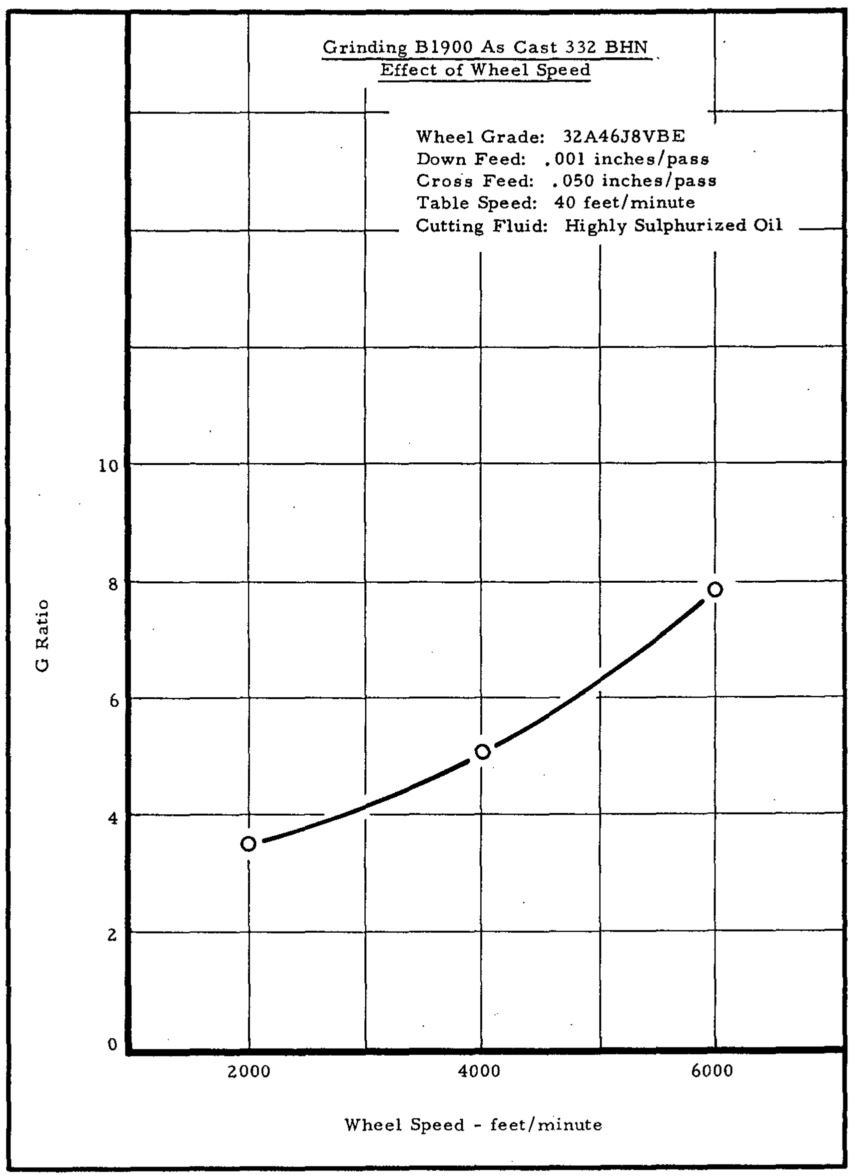
See text, page 297

Figure 336



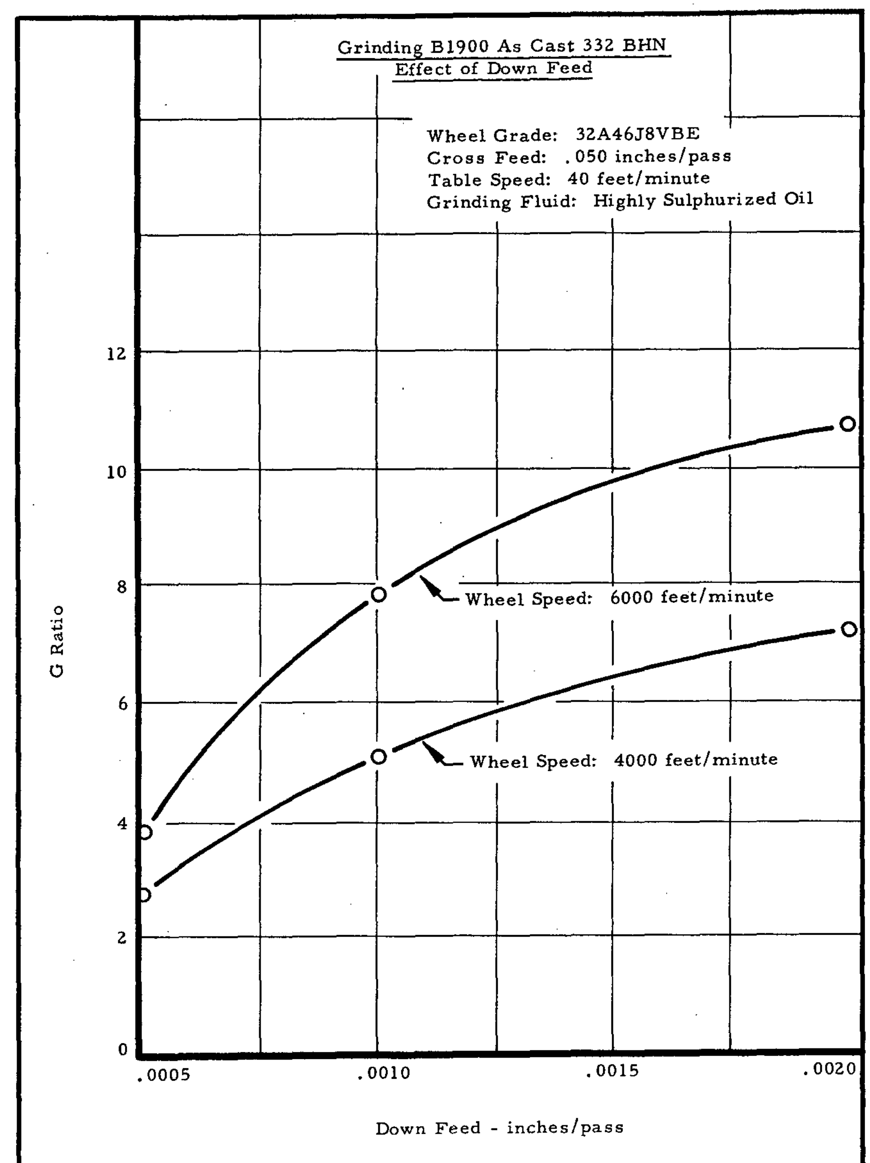
See text, page 298

Figure 337



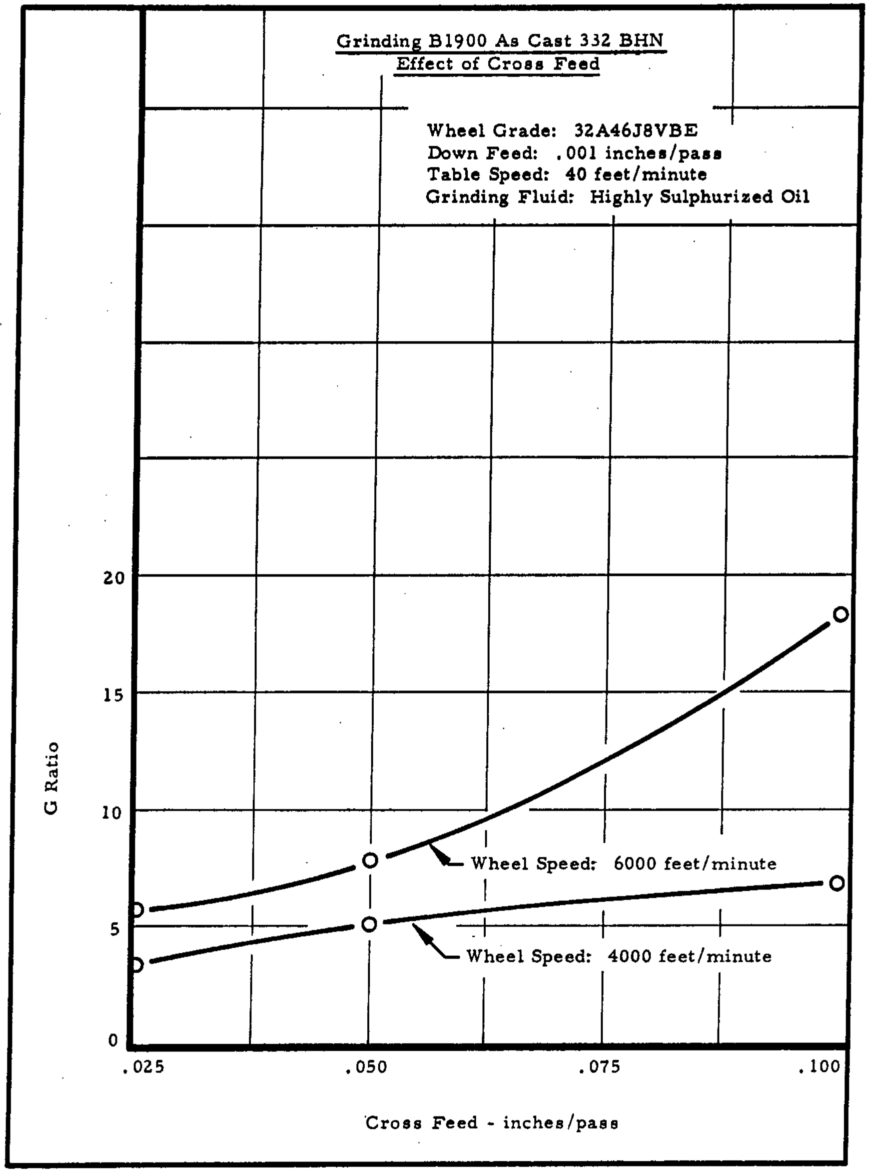
See text, page 298

Figure 338



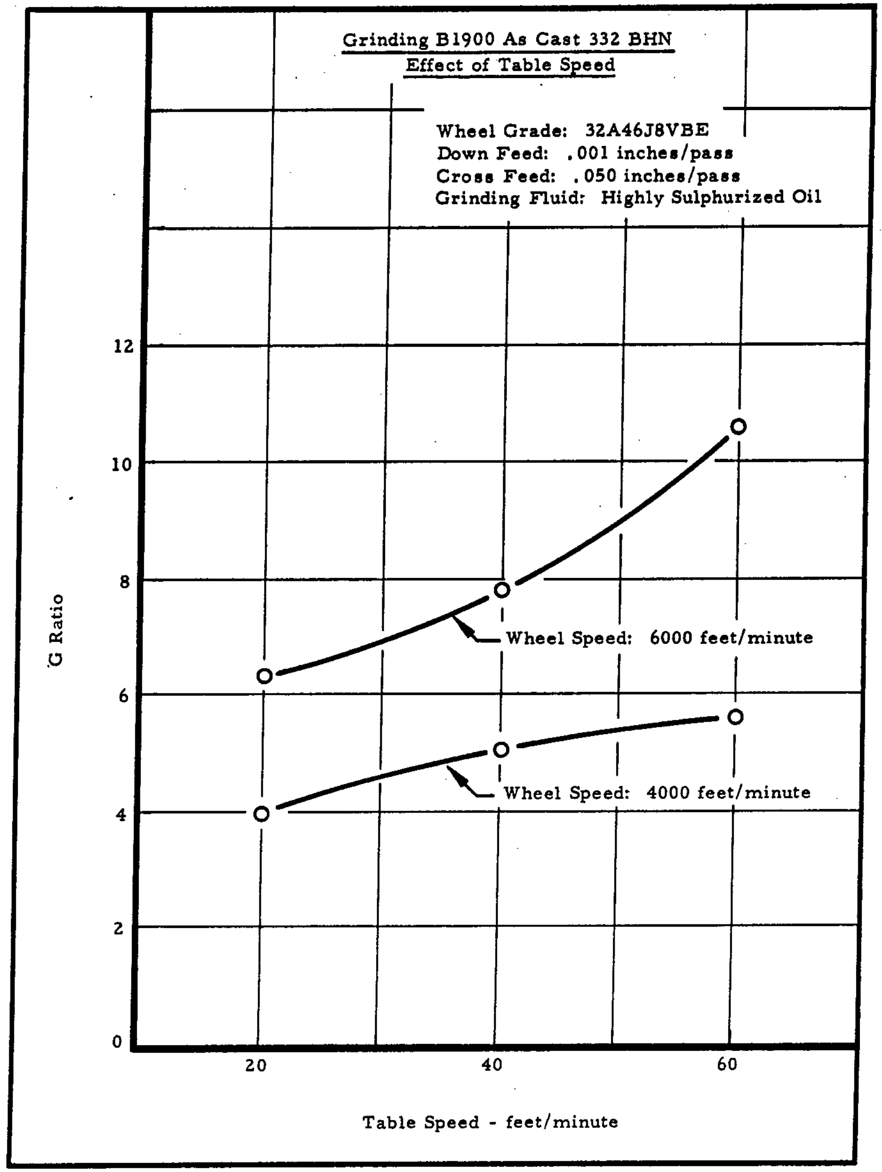
See text, page 298

Figure 339



See text, page 298

Figure 340



See text, page 298

Figure 341

5.7 U-700

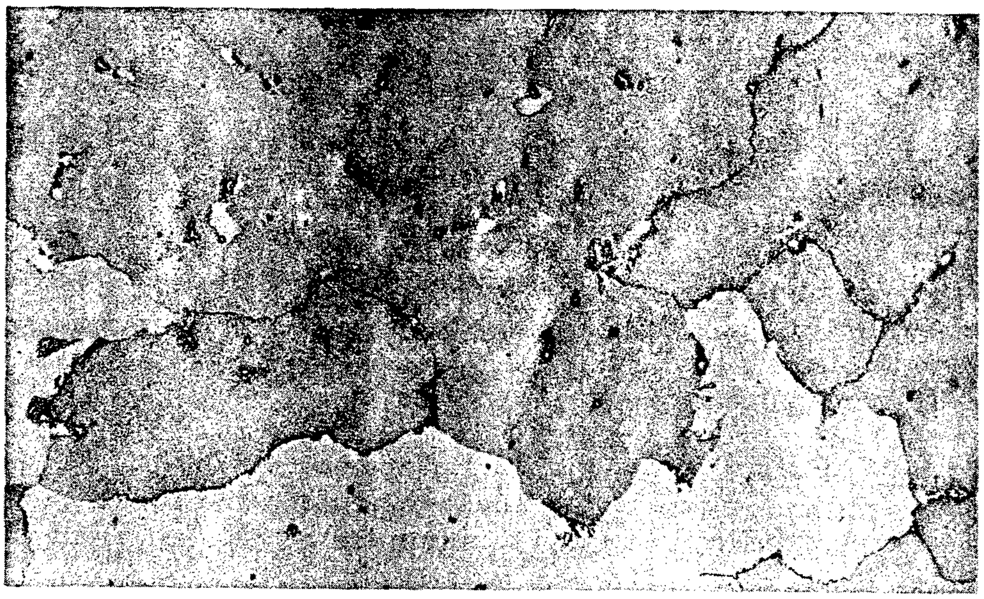
Alloy Identification

U-700 is a vacuum melted nickel base alloy which exhibits high strength and oxidation resistance in high temperature environments. The nominal composition of this material is as follows:

Ni-15.0Cr-18.5Co-5.0Mo-3.5Ti-4.2Al-0.8Fe-.12C

Plates for drilling tests were obtained as 4" x 4" x 1/4" castings, and coupons for grinding ratio tests were procured as castings 1" x 2" x 6". Tests were performed on this material in the as cast condition, the hardness of which was measured as 321-331 BHN.

The microstructure of this alloy, which is illustrated below, consists of some dispersed intermetallics and carbides in the nickel-cobalt solid solution matrix.



U-700 As Cast

Etchant: Kalling's Mag: 100X

Drilling (As Cast 331 BHN)

As shown in Figure 342, page 306, the feed in drilling U-700 in the as cast condition was very critical. At a feed of .003 in./rev., 55 holes were drilled, while at a feed of .002 in./rev. the drill life was less than 5 holes. Also, a drill life of 15 holes resulted at a feed of .005 in./rev.

5.7 U-700 (continued)

The cutting speed is also very critical in drilling this alloy, see Figure 343, page 306. At 12.5 ft./min. drill life was 75 holes. At speeds of 7.5 and 20 ft./min. drill life of less than 10 holes was obtained.

Surface Grinding (As Cast 321 BHN)

The effect of wheel speed on the wheel wear or G Ratio is shown in Figure 344, page 307, for the U-700 as cast alloy. Using a grade 32A46J8VBE wheel with a highly sulfurized oil as the cutting fluid and with a cross feed of .050 in./pass, a down feed of .001 in./pass and a table speed of 40 ft./min., the G Ratio increased from 6.7 at 2000 ft./min. to 9.6 at 6000 ft./min., Figure 344, page 307.

The effect of down feed on G Ratio is shown in Figure 345, page 307, for both 4000 and 6000 ft./min. The wheel speed of 4000 ft./min. maximum is recommended in grinding the U-700 to insure surface integrity of the finished component. At 4000 ft./min., the G Ratio increased from 7 to 9 as the down feed increased from .0005 to .002 in./pass.

Increasing the cross feed was likewise found to provide an improvement in G Ratio, Figure 346, page 308. The largest G Ratio obtained was 10 at a cross feed of .100 in./pass.

An appreciable increase in the grinding ratio was obtained with increasing table speeds, Figure 347, page 308. At the wheel speed of 4000 ft./min., the G Ratio increased from 5 to 16 as the table speed increased from 20 to 60 ft./min.

The conditions recommended for surface grinding as cast U-700 are given in Table 25, page 305. These conditions are specified to obtain adequate surface integrity and to minimize residual stress (see Chapter 7, pages 317-378) and consist of:

Grinding Wheel:	32A46J8VBE
Wheel Speed:	3000 to 4000 ft./min.
Down Feed:	
Roughing:	.001 in./pass
Finishing:	.0005 in./pass
Cross Feed:	.050 in./pass
Table Speed:	60 ft./min.
Grinding Fluid:	Highly Sulfurized Oil

The surface finish obtainable in grinding as cast U-700 is 10 to 20 microinches, arithmetical average, in finishing; and 20 to 35 microinches, arithmetical average, in roughing.

TABLE 25

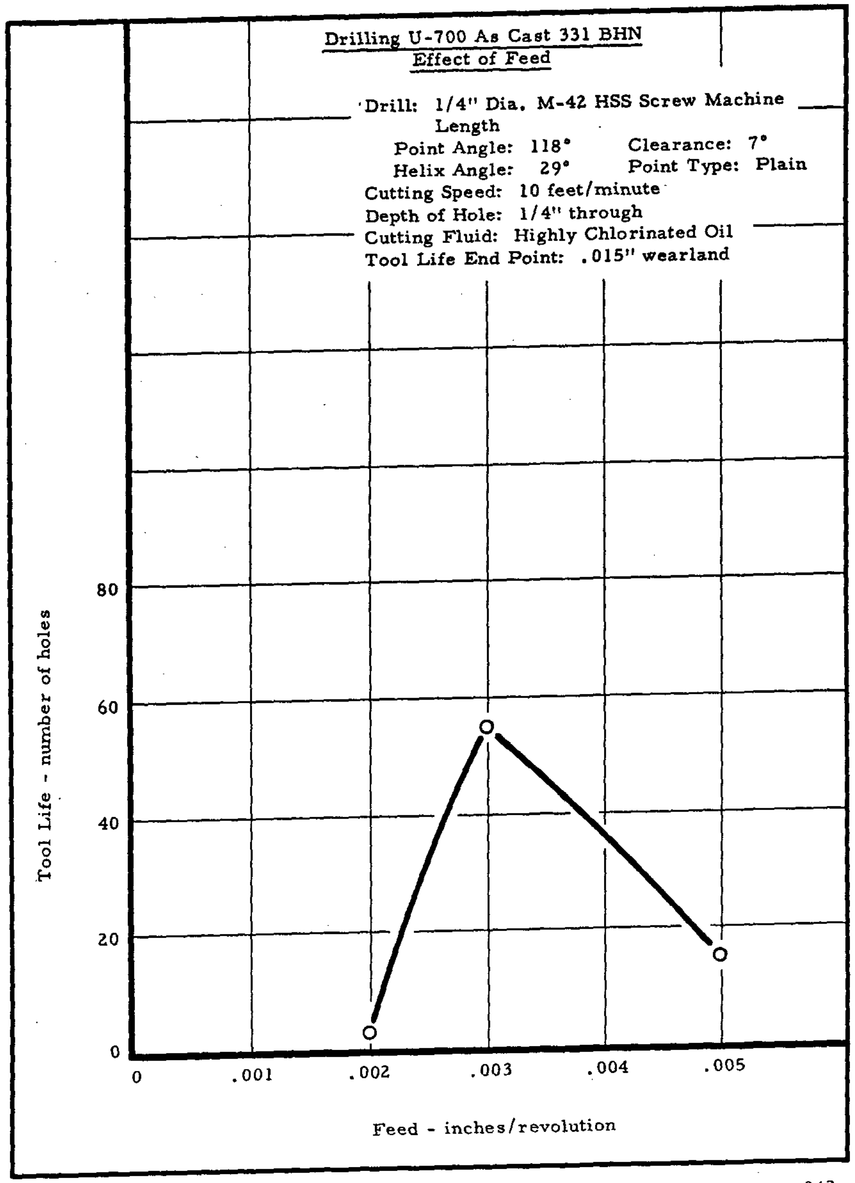
RECOMMENDED CONDITIONS FOR MACHINING
U-700 AS CAST 321 - 331 BHN

Cr	Co	Mo	Ti	Al	Fe	C	Ni
15.0	18.5	5.0	3.5	4.2	.8	.12	Bal

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	M-42 HSS	118° plain point 7° clearance angle	1/4" diameter drill 2 1/2" long	.250 thru	-	.003 in/rev	12.5	75 holes	.015	Highly Chlorinated Oil

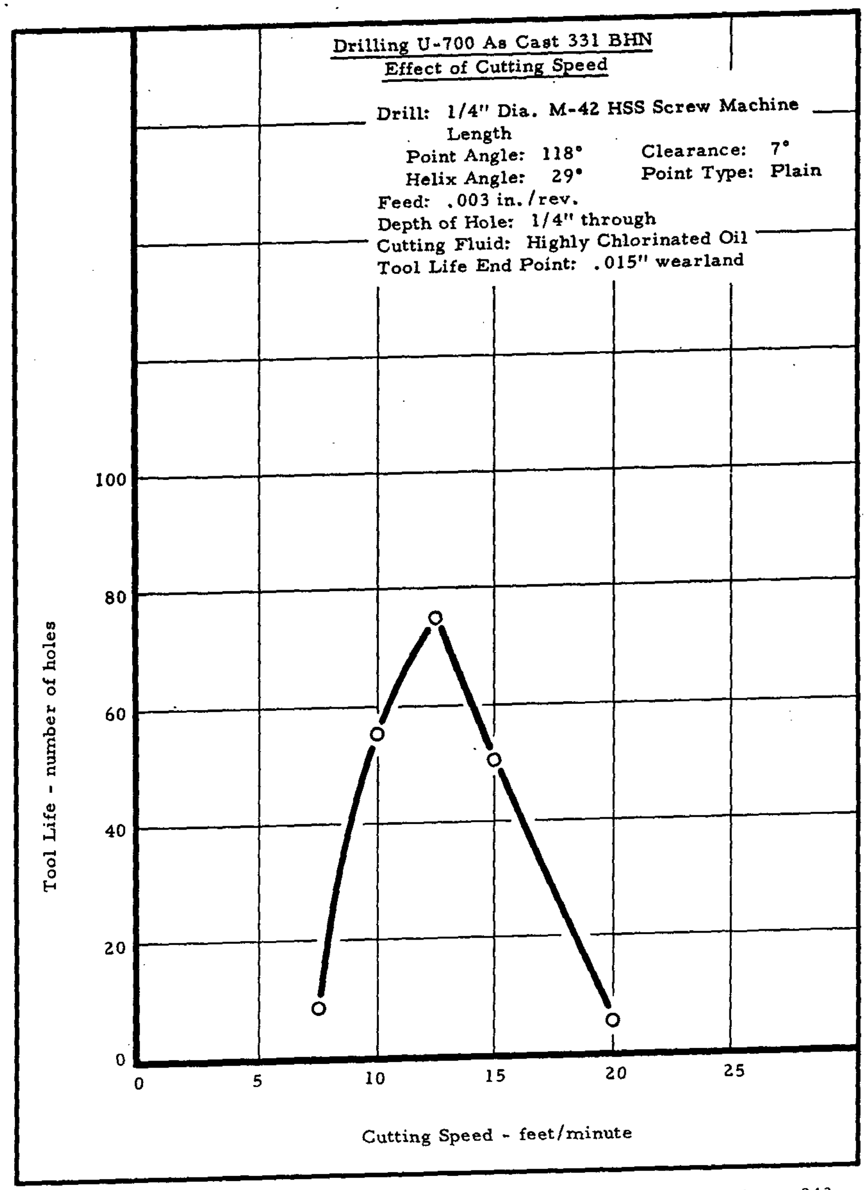
SURFACE GRINDING

Operation	Wheel Grade	Grinding Fluid	Wheel Speed Ft./Min.	Table Speed Ft./Min.	Down Feed In./Pass.	Cross Feed In./Pass.	G Ratio
Finishing	32A46J8VBE	Highly Sulphurized Oil	3000 - 4000	60	.0005	.050	12
Roughing	32A46J8VBE	Highly Sulphurized Oil	3000 - 4000	60	.001	.050	16



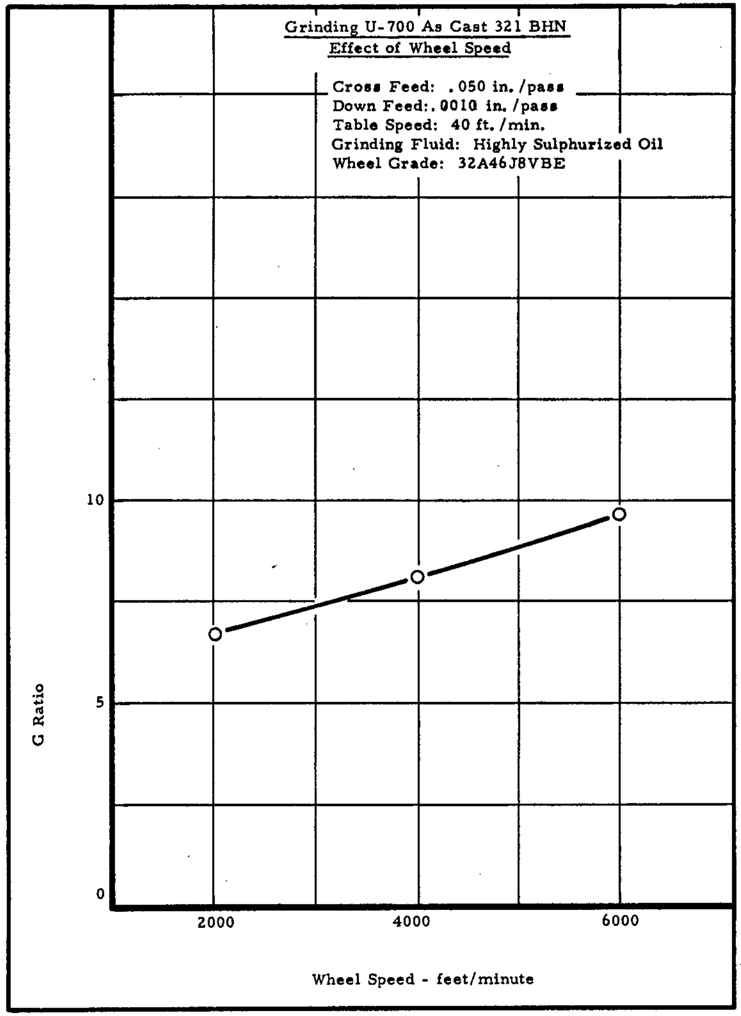
See text, page 303

Figure 342



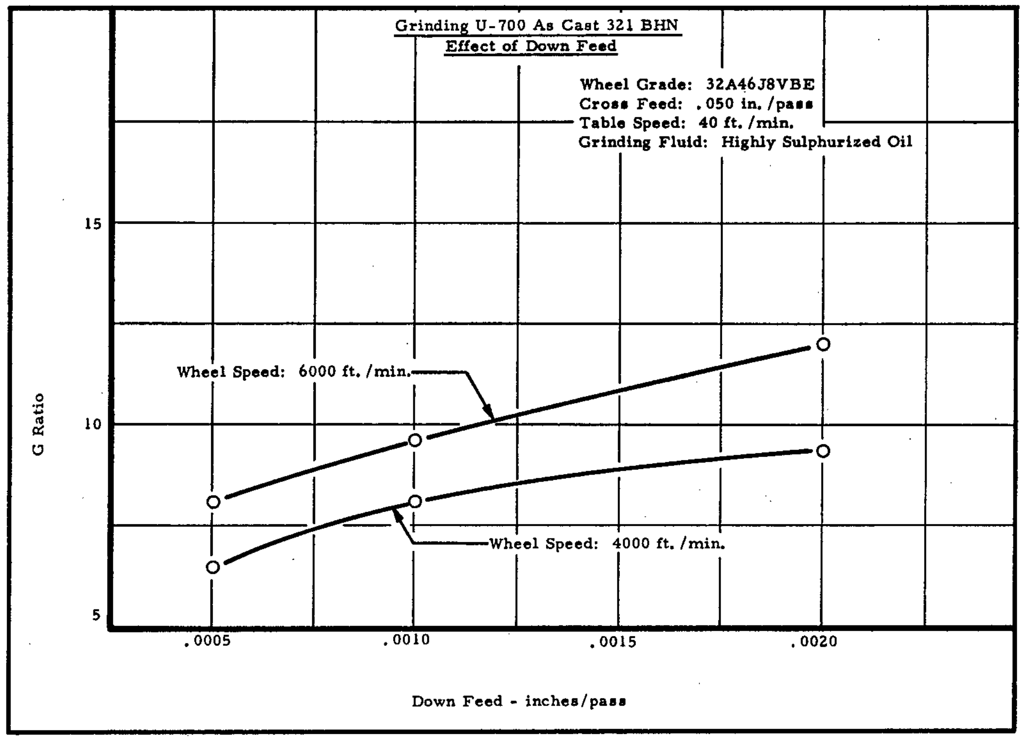
See text, page 304

Figure 343



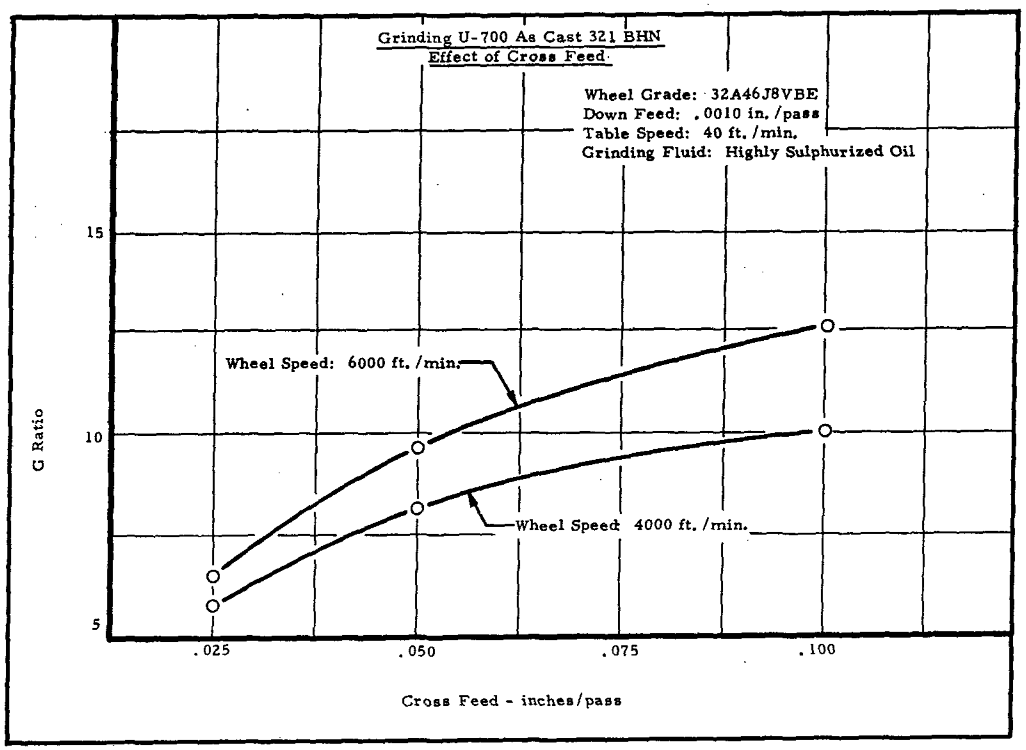
See text, page 304

Figure 344



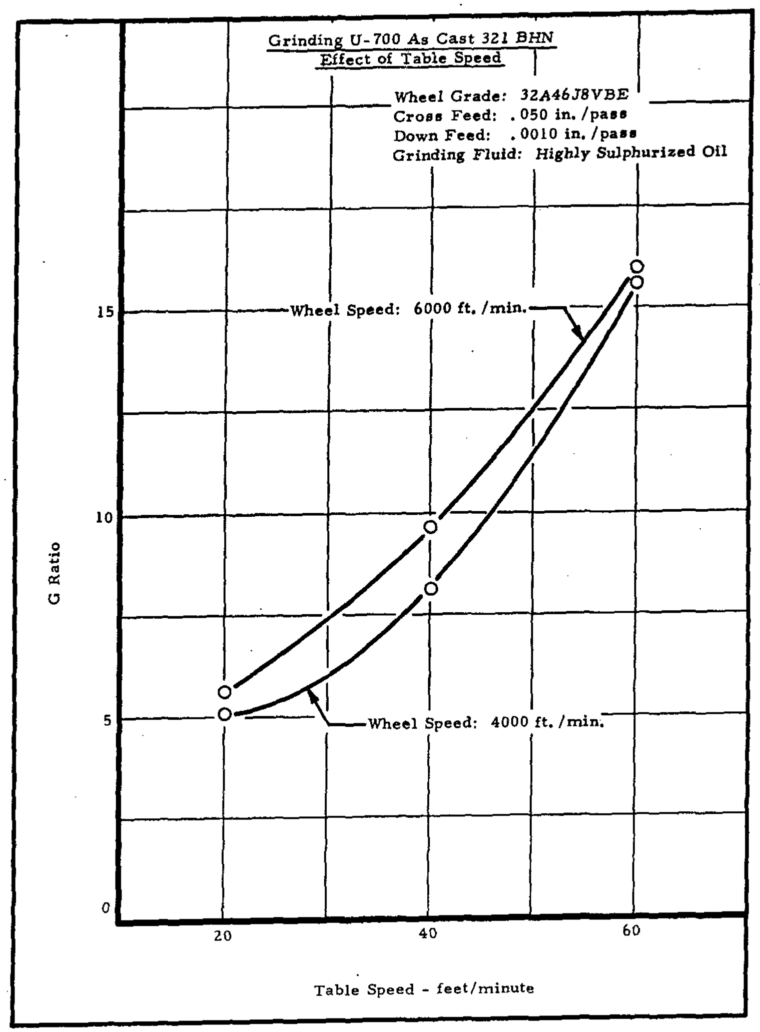
See text, page 304

Figure 345



See text, page 304

Figure 346



See text, page 304

Figure 347

6. MACHINING COBALT BASE ALLOYS

6.1 SM-302

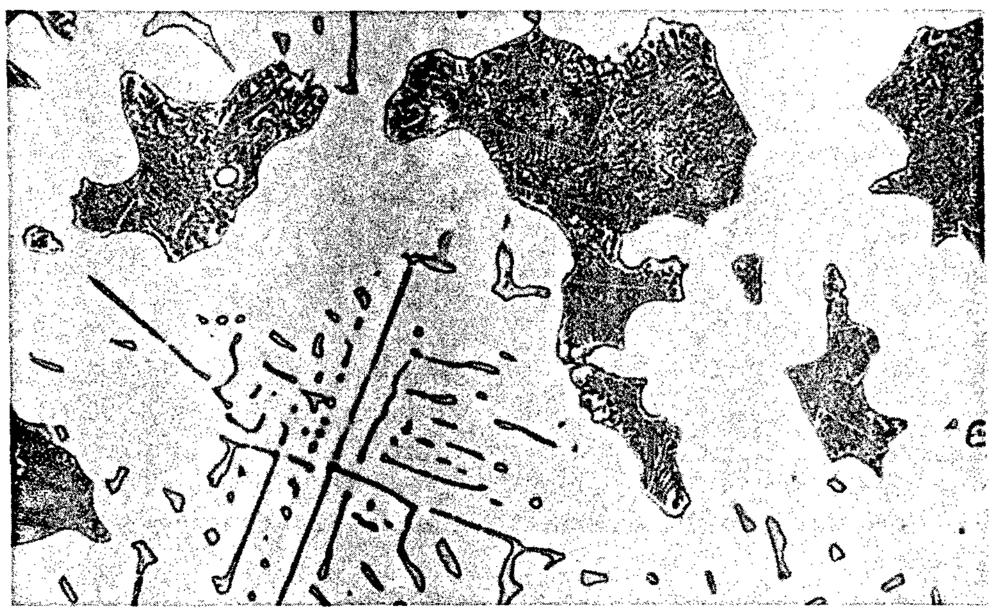
Alloy Identification

SM-302 is a cast, cobalt base alloy for elevated temperature service. The nominal composition of this material is as follows:

Co-22Cr-10W-9Ta-1Fe-.86C

The material for turning tests was procured as 3" diameter x 10" long castings. Plates for drilling tests were obtained as 4" x 4" x 1/4" castings, and coupons for grinding ratio tests were 1" x 2" x 6" castings. Tests were performed on this material in the as cast condition. Hardness was measured as 352-375 BHN.

The microstructure of this alloy, which is exhibited below, consists of dispersed but exotic complex refractory-metal carbides in a cobalt-rich matrix.



SM-302 As Cast

Etchant: Kalling's Mag: 500X

Turning (As Cast 375 BHN)

The relationship between tool life and cutting speed is shown in Figure 348, page 313 in turning as cast SM-302. Note the low cutting speeds. With a C-2 grade of carbide the tool life was only 15 minutes at a cutting speed of 30 ft. /min.

6.1 SM-302 (continued)

Figure 349, page 313, presents a comparison of four carbide grades. The C-2 grade (883) carbide produced slightly longer tool life than either the C-4 grade K11 or the C-3 grade K8. The tool life was very poor with the C-6 grade 370 carbide.

The effect of feed upon tool life is shown in Figure 350, page 314. Increasing the feed from .004 to .009 in./rev. reduced the tool life 20%, from 19 to 15 minutes. This reduction in tool life is compensated, however, by more than doubling the production rate.

Drilling (As Cast 352 BHN)

The drilling of SM-302 in the as cast condition is very difficult, as shown by the tool life curve in Figure 351, page 314. Under the best conditions determined in these tests, a maximum of 28 holes was drilled at a cutting speed of 20 ft./min. and a feed of .002 in./rev. At both higher and lower speeds the drill life decreased.

Surface Grinding (As Cast 375 BHN)

The effect of grinding wheel speed on G Ratio is shown in Figure 352, page 315. The G Ratio increased as the wheel speed increased from 2000 to 6000 ft./min. The highest value of G Ratio was 9 and was obtained at a wheel speed of 6000 ft./min. These tests were run with a 32A46J8VBE grinding wheel using .050 in./pass cross feed, .001 in./pass down feed, 40 ft./min. table speed and a highly sulfurized cutting oil.

The effect of down feed on G Ratio is given in Figure 353, page 315, for both 4000 and 6000 ft./min. The wheel speed of 4000 ft./min. maximum is recommended in grinding SM-302 to insure surface integrity of the finished component. At 4000 ft./min. wheel speed, the G Ratio reached a constant value of 4 at down feeds of .001 to .002 in./pass.

The cross feed was found to have a negligible effect on the G Ratio over a range of .025 to .100 in./pass cross feed, Figure 354, page 316. It was possible to obtain an appreciable improvement in G Ratio by increasing the table speed, Figure 355, page 316. At a table speed of 60 ft./min. and a wheel speed of 4000 ft./min., the G Ratio reached a value of 9.

6.1 SM-302 (continued)

The conditions recommended for surface grinding SM-302 are given in Table 26, page 312. These conditions are specified to obtain adequate surface integrity and to minimize residual stress (see Chapter 7, pages 317-378) and consist of:

Grinding Wheel:	32A46J8VBE
Wheel Speed:	3000 to 4000 ft. /min.
Down Feed:	
Roughing:	.001 in. /pass
Finishing:	.0005 in. /pass
Cross Feed:	.050 in. /pass
Table Speed:	60 ft. /min.
Grinding Fluid:	Highly Sulfurized Oil

The surface finish obtainable in grinding SM-302 is 15 to 40 microinches, arithmetical average, in finishing; and 25 to 45 microinches, arithmetical average, in roughing.

TABLE 26

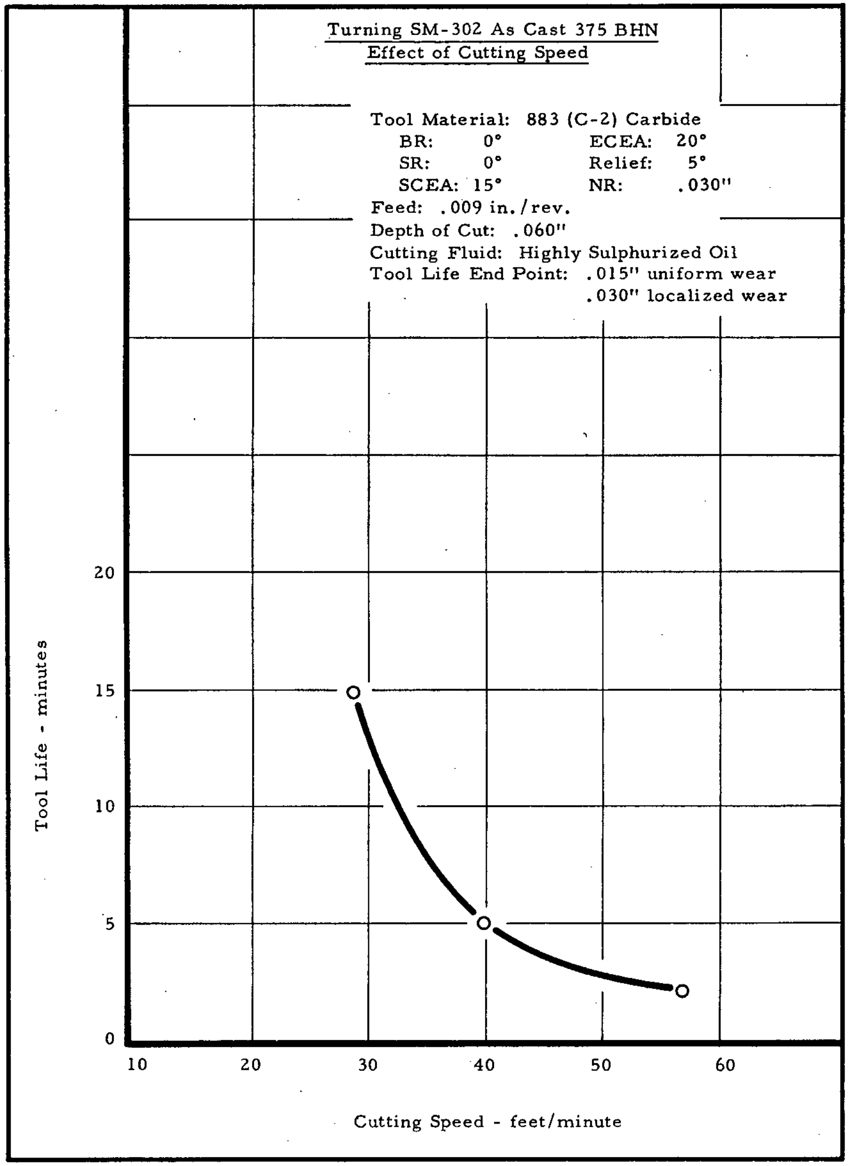
RECOMMENDED CONDITIONS FOR MACHINING
SM-302 AS CAST 352-375 BHN

Cr	W	Ta	Fe	C	Co
22	10	9	1	.86	Bal.

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	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: .030"	1/2" square throw-away insert	.060	--	.009 in./rev.	29	17 min.	.015	Highly Sulphurized Oil
Drilling	C-2 Carbide	118° plain point 7° clearance angle	1/4" diameter drill 2-1/2" long	.250 thru	--	.002 in./rev.	20	27 holes	.010	Highly Chlorinated Oil

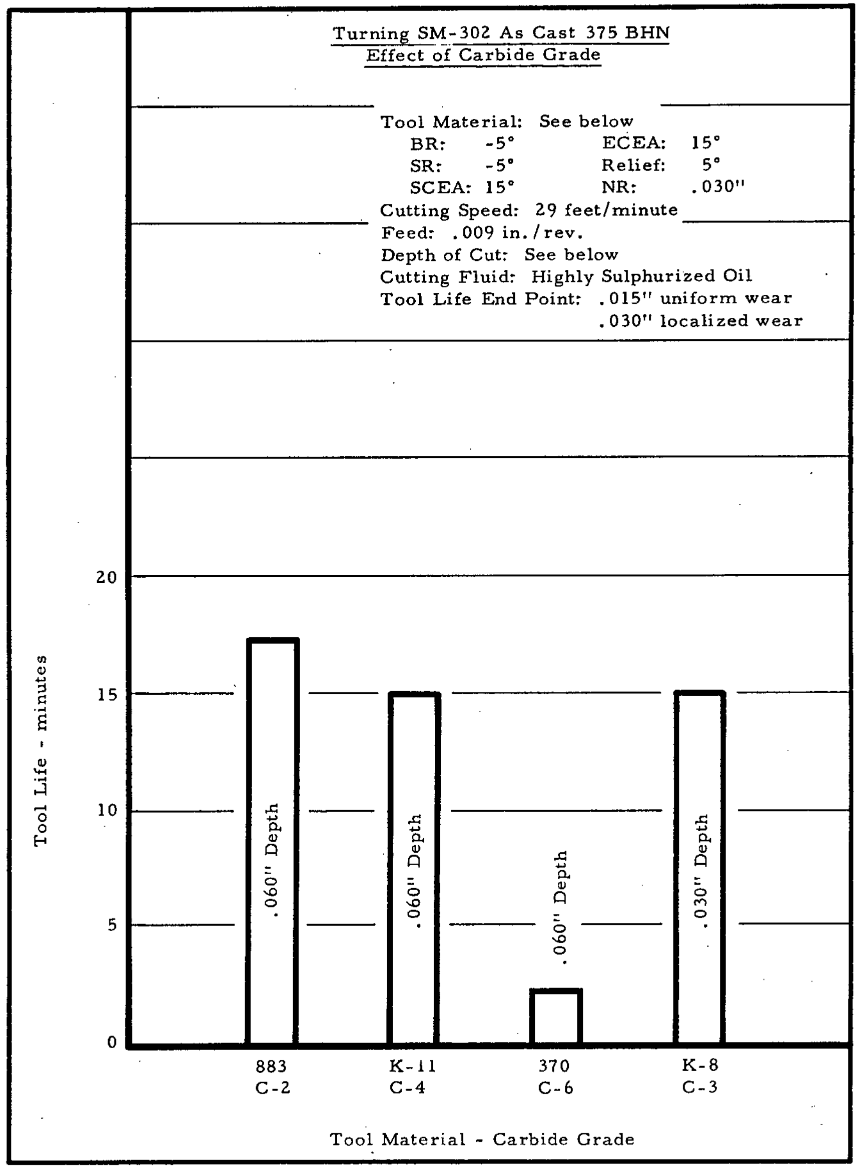
SURFACE GRINDING

Operation	Wheel Grade	Grinding Fluid	Wheel Speed Ft./Min.	Table Speed Ft./Min.	Down Feed In./Pass	Cross Feed In./Pass	G Ratio
Finishing	32A46J8VBE	Highly Sulphurized Oil	3000-4000	60	.0005	.050	4
Roughing	32A46J8VBE	Highly Sulphurized Oil	3000-4000	60	.001	.050	8.5



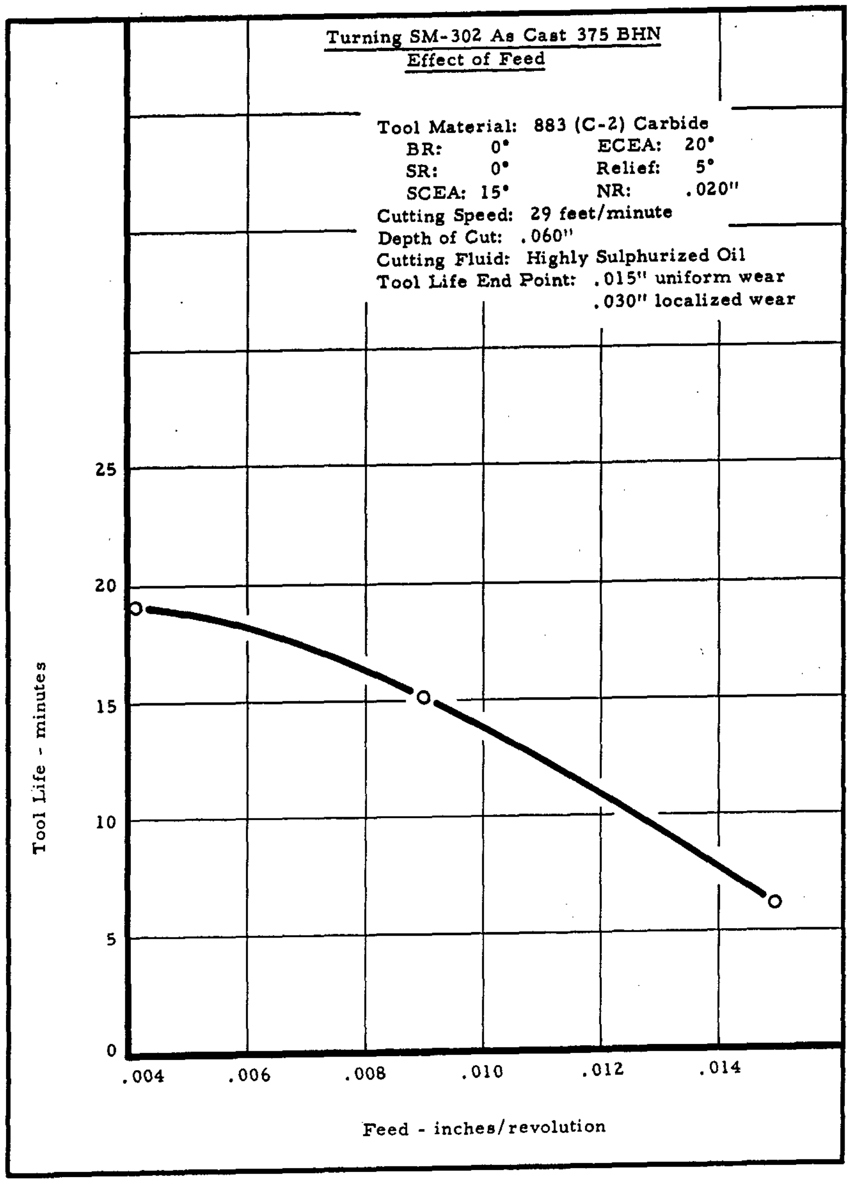
See text, page 309

Figure 348



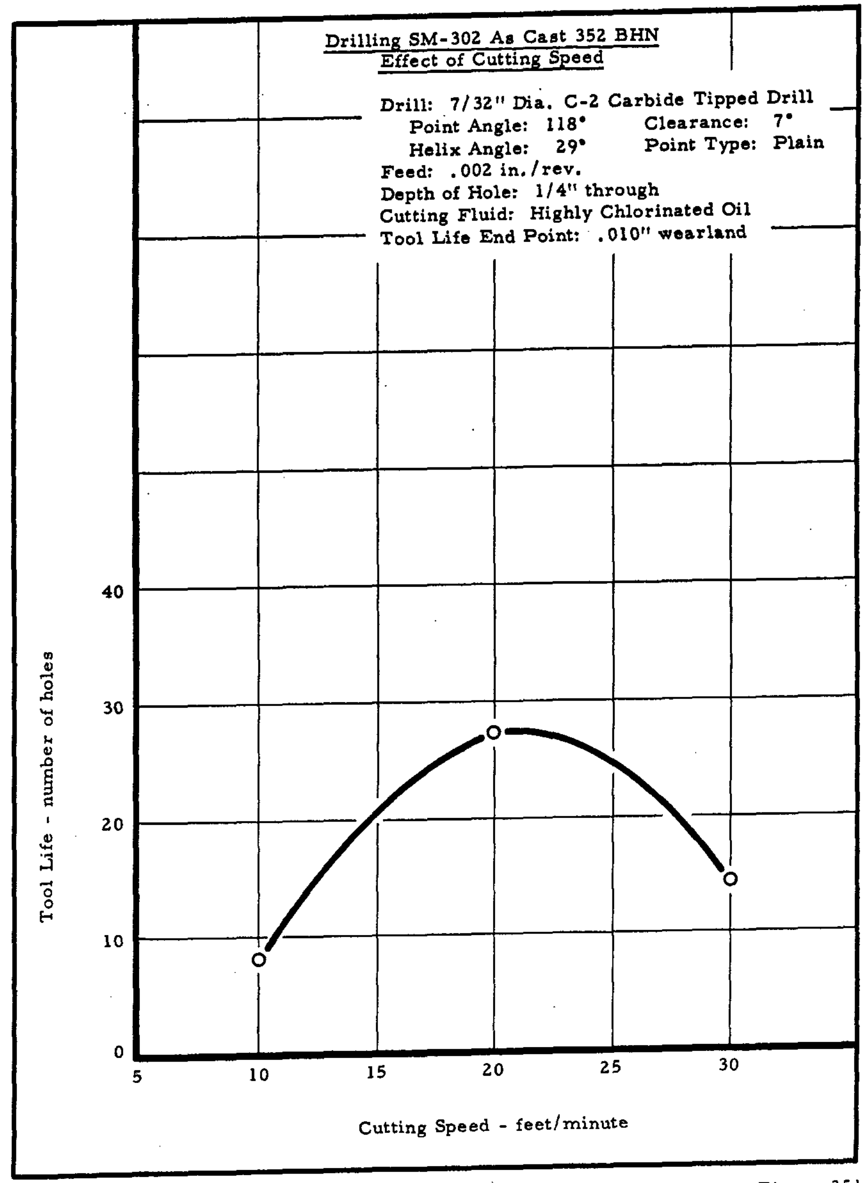
See text, page 310

Figure 349



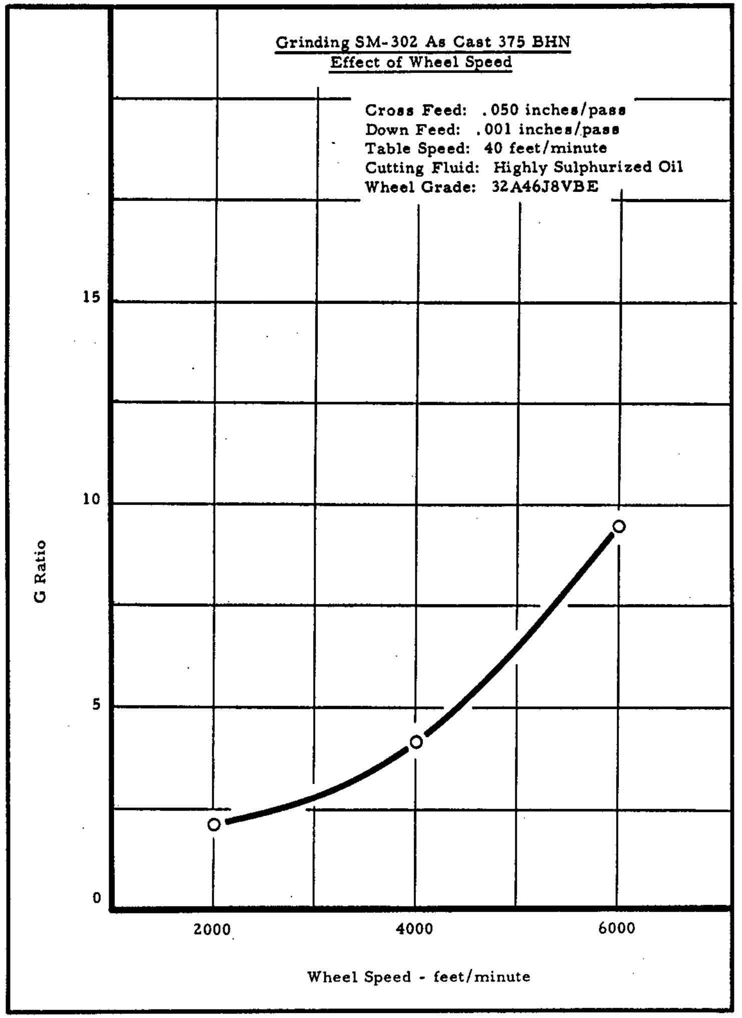
See text, page 310

Figure 350



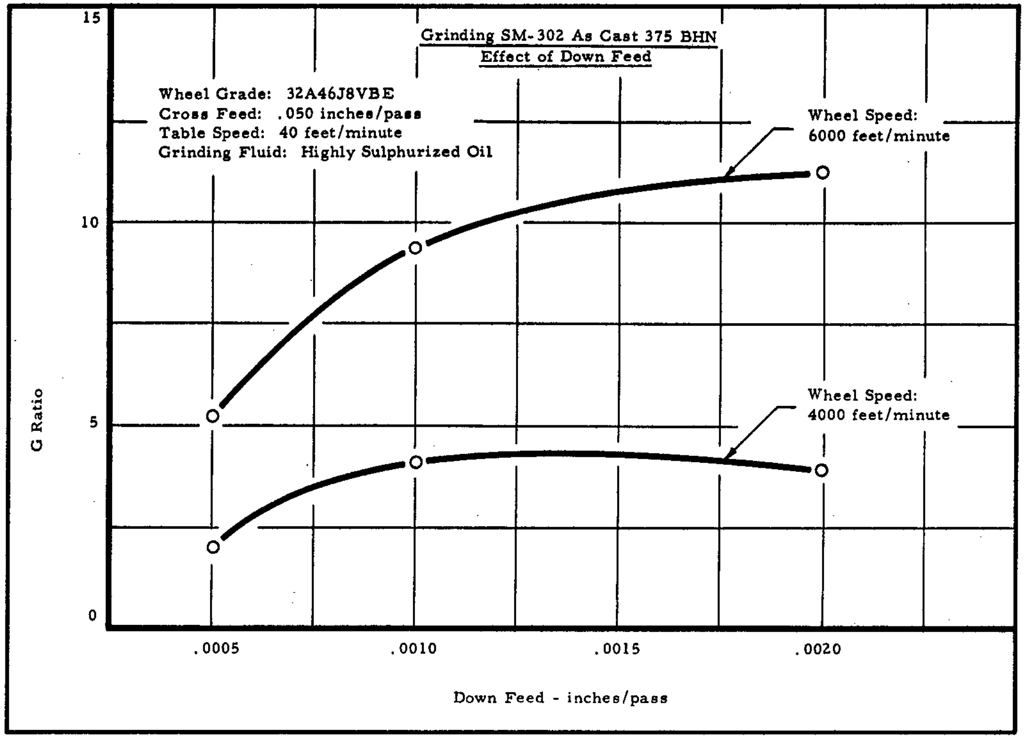
See text, page 310

Figure 351



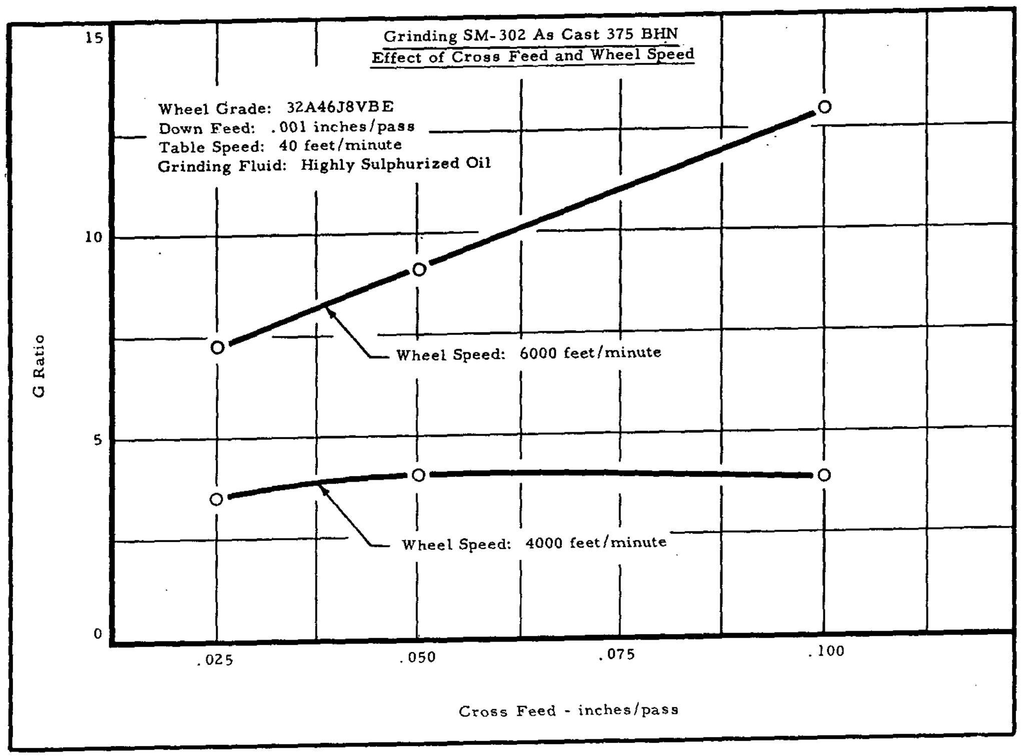
See text, page 310

Figure 352



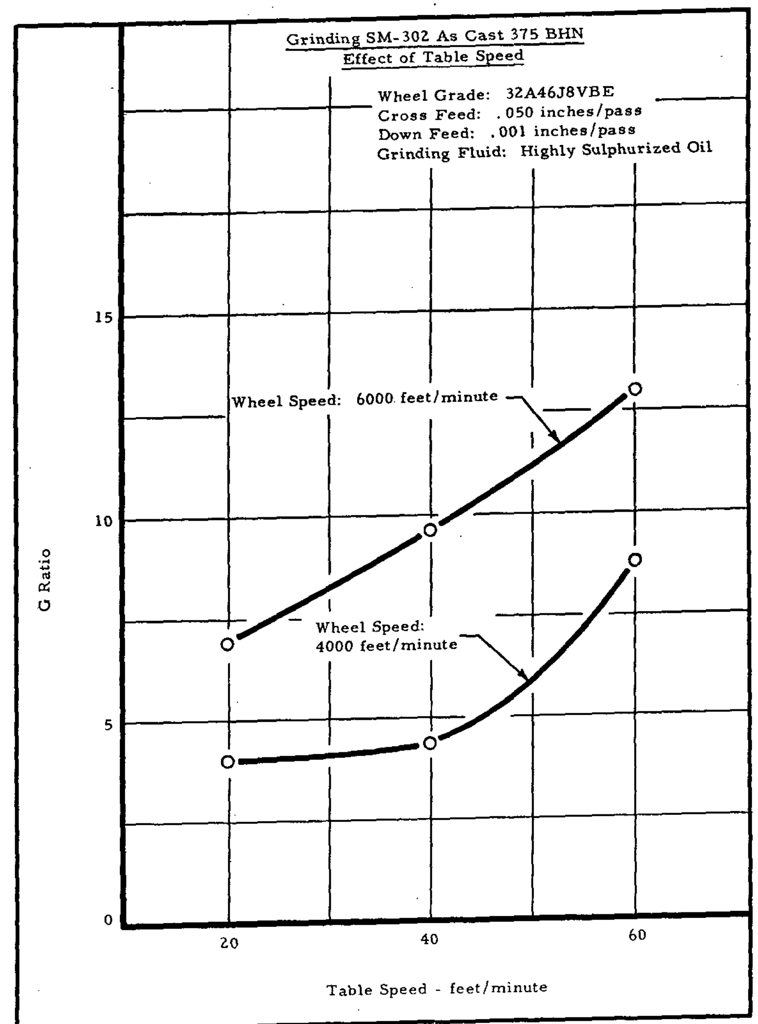
See text, page 310

Figure 353



See text, page 310

Figure 354



See Text, page 310

Figure 355

7. SURFACE INTEGRITY IN MACHINED AND GROUND AEROSPACE ALLOYS

Surface integrity of structural components becomes increasingly important as operating stresses are raised. This term can be loosely defined as the extent to which the surface represents and supports the nominal strength characteristics of the material. A variety of surface conditions, including residual stress, micro-cracking, phase changes and finish, are all involved in the total concept of surface integrity. Certain aspects of surface integrity, as affected by several different metal removal methods, are discussed in this section.

7.1 Distortion and Residual Stresses Developed During Face Milling and Surface Grinding

An investigation was made of the distortion and residual stress produced during face milling and surface grinding of 250 Grade Maraging Steel, Titanium 8Al-1Mo-1V, Inconel 718 and Waspaloy. Table 27, page 327, gives a summary of the variables investigated for each of these alloys.

Test Specimen Preparation

In the preparation of the test specimens, care was exercised to assure uniform quality and composition. Heat treating was carried out after the rough machining and prior to the finish grinding to size. A "low stress" grinding technique was used for finish grinding. The specimens were 3/4" wide, 4-1/4" long, with a thickness of .070" for grinding, and .100" for milling tests. A sketch of the specimen geometry is shown in Figure 356, page 328. The sample thickness after test machining was .060" for all specimens.

Test Procedure

The test specimens were held in a special fixture, Figure 357, page 329, for the milling and the grinding tests. The tapered clamp along the length of the sample provided positive clamping, which permitted uniform stock removal.

The face milling tests were performed on the Cincinnati No. 2 Dial Type Vertical Milling Machine shown in Figure 3, page 8. A 4" diameter single tooth inserted tooth cutter was used with the centerline of the cutter in line with the centerline of the test specimen.

A Norton 8" x 24" Hydraulic Surface Grinder equipped with a 2 HP variable speed spindle drive was used for the grinding tests. The grinder and the test setup are shown in Figure 8, page 13. The wheel size was 10" O. D. x 1" wide x 3" hole for all tests.

7.1 Distortion and Residual Stresses Developed During Face Milling and Surface Grinding (continued)

Distortion and Residual Stress Analysis Procedure

The curvature of each specimen over a 3.5" gage length was measured before and after test machining, using the fixture shown in Figure 358, page 329. A sketch, Figure 359, page 330, 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.

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. An electrolytic etch was used on 250 Grade Maraging Steel, Inconel 718 and Waspaloy. The setup for this method is shown in Figure 360, page 331. The test surface of the Titanium 8Al-1Mo-1V specimens were etched by immersing the specimens in the etchant, after coating the back of each specimen with lacquer. 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" with an indicating micrometer. The depth of stock removed versus change in deflection data was 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. *

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

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 deflection versus stock removed curve.

*Stablein, F. - "Spannungsmessungen an einsertig abgeloschten Knuppeln" - Kruppsche Monatshefte, Vol 12 (1931) pp 93-98.

Test Results, 250 Grade Maraging Steel (Aged 52 R_C)

Face Milling

Figure 361, page 332, shows the effect of tool wear and depth of cut on distortion when using a C-2 carbide cutter with no cutting fluid. The heavier cut, .040", shows no additional distortion effect over the .010" cut when the cutting tool was sharp. It was only when a .016" wearland was present that addition distortion was noted. A sharp tool gave a distortion of -.013" for both the .010" and the .040" depth of cut; while at .016" wearland the .010" cut gave -.047" distortion and the .040" cut gave -.062" distortion. The negative deflection indicates that the specimen distorted in a direction due to induced compressive stress in the machined surface.

Increasing tool wear results in increased distortion. With the .040" depth of cut the distortion increased from -.013" to -.062" as a result of increased tool wear.

The residual stresses were determined when using a .010" depth of cut with the C-2 carbide cutter and three different degrees of tool wear. Compressive residual surface stresses were found in all cases, Figure 362, page 332. The maximum compressive stress was higher with the sharp tool, 115,000 psi compression, while only 80,000 psi maximum compression resulted with the .016" wearland. These maxima were found within the first .002" below the surface. However, increased penetration of the stressed layer coupled with the increased area under the stress distribution curve indicate the greater total stress in the surface layers and, hence, the greater distortion as the tool wear increased. Residual compressive stresses were found up to .0080" below the surface with .016" wearland and only up to .0025" with the sharp cutter, Figure 362, page 332.

Surface Grinding

The effect of variations in wheel hardness, wheel speed and depth of feed were investigated using soluble oil as the cutting fluid. Additional tests were run at various wheel speeds with highly sulfurized oil as the cutting fluid.

The effect of wheel hardness on distortion at wheel speeds of 2000 to 6000 ft./min. is shown in Figure 363, page 333. When using a soft wheel, H hardness, the increasing wheel speed produces less additional distortion than did the harder K and M wheels. An increase in wheel hardness at a given wheel speed produces greater distortion. At 4000 ft./min. the H wheel yielded +.0030" distortion, and the M wheel +.0085" distortion.

At lower wheel speeds, highly sulfurized oil gave somewhat less distortion than did the soluble oil, Figure 364, page 333. This effect was not noted at the highest wheel speed.

The distortion produced by various down feed and wheel speed conditions is illustrated in the bar graph of Figure 365, page 334. The "low stress" down feed consisted of removing the last .010" of stock as follows:

First	.0080"	at .0005 in./pass
Next	.0008"	at .0004 in./pass
Last	.0012"	at .0002 in./pass

For small down feed conditions, up to .001 in./pass, the distortion was less than +.005" for wheel speeds up to 6000 ft./min. As noted earlier, distortion tends to increase as the wheel speed increases.

In general, far less distortion was found in the 250 Grade Maraging Steel than in the other three alloys investigated (Ti 8Al-1Mo-1V, Inconel 718 and Waspaloy).

The residual stress curves in Figures 366 through 368, pages 334 and 335, show the low stress levels found in this material, normally less than 25,000 psi under various grinding conditions. At "low stress" conditions (soft wheel, lower wheel speed) the surface stress tended to be compression. In general, the stressed region is within the first .001" depth. Figure 366, page 334, shows the effect of wheel speed on residual stresses with a soft 32A46H8VBE wheel and soluble oil as the grinding fluid. In Figure 367, page 335, a tension residual stress zone is found just below the surface when the harder M wheel was used at 6000 ft./min. This region was very small for the H and K wheels. Various down feed conditions, Figure 368, page 335, failed to show an appreciable residual stress pattern with up to .002 in./pass feed rate.

Test Results, Titanium 8Al-1Mo-1V (Aged 302 BHN)

Face Milling

An increased degree of distortion with increasing tool wear at both .010" and .040" depth of cut is evident in Figure 369, page 336. For a sharp cutting tool, the depth of cut had little effect on the degree of distortion. It was only after the cutting tool became dull (.008" and .016" wearland) that more distortion was produced at a greater depth of cut.

Residual stress curves at various degrees of tool wear are presented in Figure 370, page 336. Compressive residual stress patterns were obtained in the surface layers, a sharp tool giving a higher maximum stress than one with an appreciable degree of wear; -50,000 psi maximum at .000" wearland, -40,000 psi at .016" wearland. A greater penetration of the compressive layer occurs as the tool wear increases, producing a greater area under the stress curve.

Surface Grinding

The effect on distortion of using aluminum oxide wheels versus silicon carbide wheels is shown in Figure 371, page 337. Much greater distortion occurs with the aluminum oxide wheel, especially at high wheel speeds. At 6000 ft./min. the distortion was +.055" with an aluminum oxide wheel, 32A46H8VBE, and highly sulfurized oil as the grinding fluid. The silicon carbide wheel of the same hardness, 39C60H8VK, and under the same grinding conditions, distorted only +.010". Increasing wheel speed and increasing wheel hardness increased the amount of distortion for both aluminum oxide and silicon carbide wheels, see Figure 371, page 337. The Titanium 8Al-1Mo-1V is very susceptible to increased distortion with increasing wheel speed, even with a silicon carbide wheel, as is noted in Figure 372, page 337. The effect is much more prevalent with the harder J wheel.

The effect of the type of grinding fluid on the distortion produced when using a 39C60H8VK wheel is found in Figure 373, page 338. Highly chlorinated oil, highly sulfurized oil, and a 5% KNO_2 solution are compared at the .002 in./pass down feed. The greater distortion associated with the highly chlorinated oil over the other two fluids did not prevail at .001 in./pass down feed, as may be seen in Figure 374, page 338. However, the difference in the distortion resulting when different fluids were used was greater at .002 in./pass down feed and would lead one to expect more distortion with highly chlorinated oil at greater down feeds than with either highly sulfurized oil or KNO_2 solution.

The surface stresses produced by surface grinding Titanium 8Al-1Mo-1V are generally tensile. For the aluminum oxide wheel the effect of wheel speed and wheel hardness on the residual stresses is indicated in

7.1 Distortion and Residual Stresses Developed During Face Milling and Surface Grinding (continued)

Figures 375 and 376, page 339. Just below the surface, .0005", tension stresses up to 80,000 psi were found. As the wheel speed increased, the integrated area under the curve increased. In a similar fashion, greater wheel hardness increased the area.

The depth of penetration of the residual stress pattern when using a silicon carbide wheel was less than that produced with the aluminum oxide wheel, although the maximum stress can be higher in some cases. Tension stresses over 100,000 psi were noted under certain circumstances.

In Figures 377 through 379, pages 340 and 341, the residual stress patterns developed at three different wheel speeds when using different cutting fluids are shown for 39C60H8VK wheel (silicon carbide) and a .002 in./pass down feed. As was noted earlier, Figures 373 and 374, pages 338 and 339, greater distortion was obtained with the highly chlorinated oil as the cutting fluid. The residual stress curves tend to substantiate these conclusions. The set of curves for KNO_2 solution and highly sulfurized oil are very similar, Figures 377 and 378, page 340. Increasing the wheel speed increased the amount of tension stressed layer. Much higher maximum tension stresses, approximately 100,000 psi, and greater areas under the curves at higher wheel speeds when using highly chlorinated oil may be seen in Figure 379, page 341.

Greater distortion resulted when a higher hardness silicon carbide wheel was used at 6000 ft./min. with highly sulfurized oil, +.043" for the J wheel, and +.012" for the H wheel, see Figure 372, page 337. The residual stress patterns for these samples are shown in Figure 380, page 341. There is a greater area under the curve for the J wheel as well as a higher maximum tension stress, 150,000 psi, at .0004" below the surface.

In Figure 374, page 338, little difference in distortion was evident when a "low stress" down feed was used as compared to a .002 in./pass down feed when employing a 39C60H8VK wheel at 4000 ft./min. with KNO_2 grinding fluid. The residual stress curves also show little difference, as may be seen in Figure 381, page 342.

At .001" down feed with the 39C60H8VK wheel at 4000 ft./min., similar distortion resulted with KNO_2 solution and with highly chlorinated oil, Figure 374, page 338. The similar residual stress curves with these two grinding fluids is evident in Figure 382, page 342.

7.1 Distortion and Residual Stresses Developed During Face Milling and Surface Grinding (continued)

Figure 373, page 338, shows greater distortion for a 39C60H8VK wheel, .002 in./pass down feed, at 6000 ft./min. with highly chlorinated oil than with highly sulfurized oil or KNO_2 solution. Residual stress curves in Figure 383, page 343, indicate the greater magnitude of tensile residual stresses when the highly chlorinated oil was used.

Test Results, Inconel 718 (Solution Treated and Aged 41 R_c)

Face Milling

Milling studies were conducted using a T-15 HSS cutter and a C-2 (883) carbide cutter with highly chlorinated oil as the cutting fluid. The distortion associated with these operations was in a compressive direction and was greater with the carbide cutter than with the high speed steel cutter, see Figure 384, page 343. Likewise, increased tool wear resulted in a greater increase in the distortion with the carbide cutter than with the high speed steel cutter.

Residual stress analyses illustrated in Figures 385 and 386, page 344, show the larger proportion of residual compressive stresses associated with the carbide cutter; a maximum of -70,000 psi and a total maximum depth of compressive stressed layer of .010" (.016" wearland) while the high speed steel produced a maximum of -50,000 psi and a maximum depth of .0075" (.016" wearland). As the tool wearland increased, both the depth of stressed layer and the maximum stress values tended to increase.

Surface Grinding

The effect on distortion of wheel hardness, wheel speed and down feed was determined with an aluminum oxide wheel and highly sulfurized oil as the grinding fluid. The effect of wheel speed and wheel hardness at .001 in./pass down feed may be seen in Figure 387, page 345. The softer H wheel produced the least distortion. The harder wheels did show a greater increase in the distortion with increasing wheel speeds than did the softer H wheel; the distortion increased from .004" at 2000 ft./min. to .032" at 6000 ft./min. for the harder L wheel, but only increased from .002" to .015" for the softer H grinding wheel operating over the same range of wheel speeds, Figure 387, page 345.

When different grinding fluids were used at .001 in./pass down feed with a 32A46J8VBE wheel operating at 4000 ft./min., the soluble oil produced more distortion than either highly chlorinated oil or the highly sulfurized oil, Figure 388, page 345. In the same figure it may be noted that increased distortion resulted when the down feed was increased.

Residual stress analyses were determined on samples prepared under various grinding conditions with highly sulfurized oil as the grinding fluid.

As the wheel speed increased, Figure 389, page 346, the residual stress curves were displaced in the direction of a greater quantity of the tension stressed layer. A maximum tensile stress of 55,000 psi was found .0015" below the surface when grinding at 6000 ft./min., the stress remaining in tension until a depth of .0065" was reached.

The softer H wheel gave a smaller stressed layer in terms of magnitude as well as depth of penetration of stress than did the harder J and L wheels. This result is noted in Figure 390, page 346, at a wheel speed of 6000 ft./min.

When a wheel speed of 4000 ft./min. was used with the 32A46J8VBE wheel, there was a lesser degree of tension residual stressed condition at a "low stress" down feed than with the .001 in./pass or .002 in./pass down feed, see Figure 391, page 347.

Test Results, Waspaloy (Solution Treated and Aged 390 BHN)

Face Milling

As with the Inconel 718, face milling tests were conducted with a T-15 HSS cutter and a C-2 carbide cutter with the highly chlorinated oil as the cutting fluid and various degrees of tool wear as the parameter.

More distortion was developed with a carbide cutter than with the high speed steel cutter, see Figure 392, page 347. As the tool wear increased the distortion increased, a greater increase being associated with the carbide cutter. The residual stress curves showed a maximum residual compressive stress of over 125,000 psi in each of the curves associated with three different degrees of tool wear, Figures 393 and 394, page 348. With a tool wear of .016" on the carbide cutter, a high tension residual stress was found on the surface, 100,000 psi, which decreased rapidly to 160,000 psi compressive stress at .001" below the surface, Figure 393, page 348. It was not until a depth of

7.1 Distortion and Residual Stresses Developed During Face Milling and Surface Grinding (continued)

.0065" was reached that the stress returned to a low tension level. When a sharp carbide cutter was used the high compressive stressed layer was confined to the first .003" of depth, and no tension stresses were found on the surface.

Residual stress curves developed for the high speed steel cutter with various degrees of tool wear also showed compressive residual stress patterns, but the magnitude and depth were not as great as when the carbide cutter had been used, see Figure 394, page 348.

Surface Grinding

In Figure 395, page 349, the effect of wheel speed and wheel hardness on distortion is illustrated. A down feed of .001 in./pass with highly sulfurized oil grinding fluid was used for these tests. Results similar to those experienced with Inconel 718 were noted. The distortion was found to increase with increasing wheel speed. At the higher speeds, 4000 and 6000 ft./min., there is a greater difference between the distortion results of the H and the J wheels than between the J and the L wheels.

At 4000 ft./min. the increasing distortion accompanying increasing down feed at two different wheel hardness levels is evident in Figure 396, page 349. The softer H wheel produced less distortion than the J wheel.

When three different grinding fluids were used with a 32A46J8VBE wheel operating at 4000 ft./min. with a .001 in./pass down feed, the least distortion was obtained when highly sulfurized oil was used, Figure 397, page 350.

The residual stress curves showed sharper peaks than were found with Inconel 718, see Figures 398 through 400, pages 350 and 351. The residual stress patterns obtained when a 32A46J8VBE wheel was used at various wheel speeds are found in Figure 398, page 350. The resulting stress in the outer layer is tension. At 2000 ft./min. a maximum tension of 20,000 psi was observed at a depth of .001". When the wheel speed was increased to 6000 ft./min. this maximum was at .0005" below the surface and was of a magnitude greater than 200,000 psi. Greater grinding wheel speeds increased not only the maximum tension stress, but also the thickness of the tension layer.

7.1 Distortion and Residual Stresses Developed During Face Milling and Surface Grinding (continued)

As wheel hardness was increased the maximum tension stress increased, Figure 399, page 351. Using a wheel speed of 6000 ft./min. with wheels of three different degrees of hardness showed the stresses increasing to tension maxima within about the first .001" below the surface. The greatest tension stress found when using an H wheel was 40,000 psi. For the harder L wheel the stress was over 200,000 psi.

If a "low stress" down feed was used, surface stresses were found to be compressive in nature, the area under the stress curve being rather small and wheel hardness having a minor effect, Figure 400, page 351.

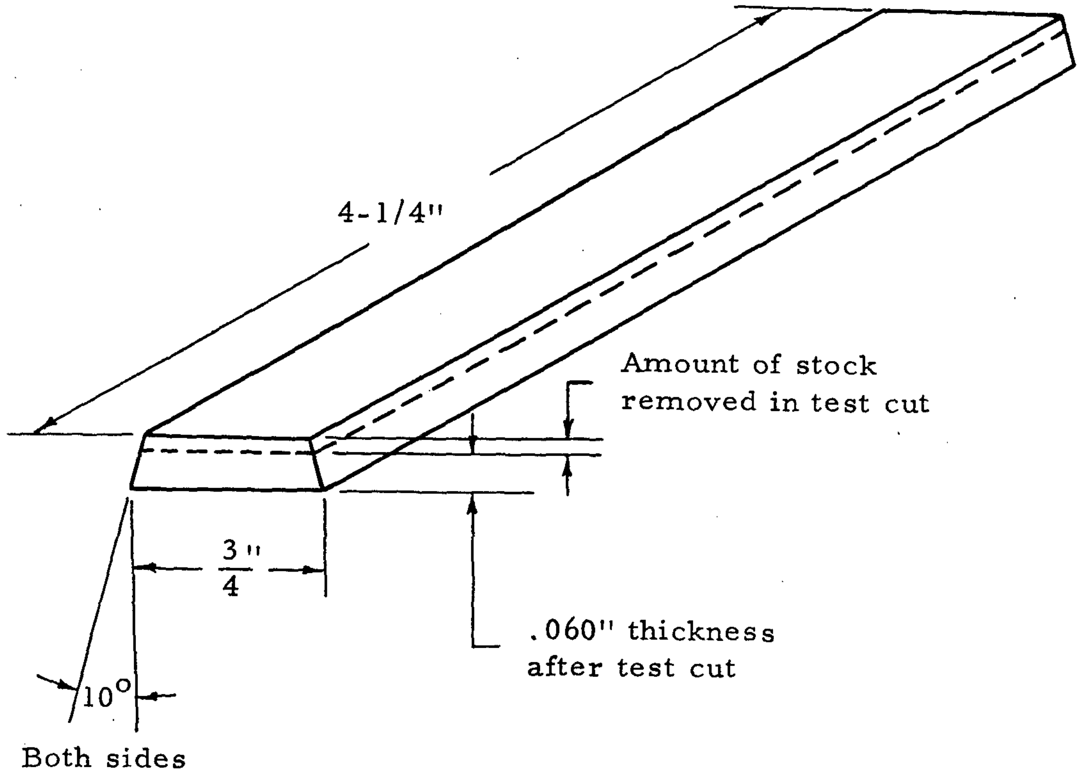
When the down feed was changed from the "low stress" to .001 and .002 in./pass values, the stress became tension in sign at .0005" below the surface, passed through maxima at .001", then decreased, but remained in tension to a depth of at least .003", Figure 401, page 352. A 32A46J8VBE wheel operating at 4000 ft./min. with highly sulfurized oil was used for these tests.

TABLE 27

FACE MILLING AND SURFACE GRINDING

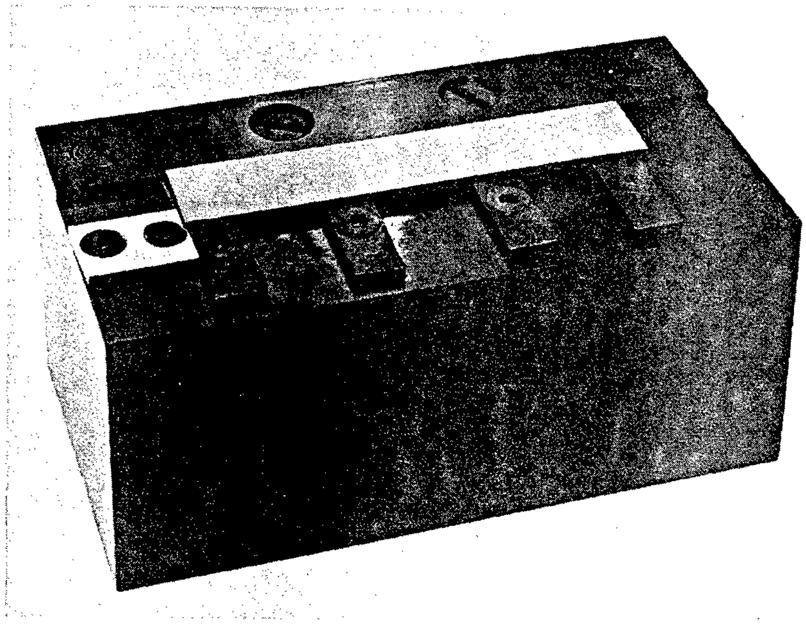
VARIABLES INVESTIGATED

Alloy	Variable - Face Milling: Tool Wearland	Tool Material	Depth of Cut	Variable - Surface Grinding: Wheel Speed	Wheel Hardness	Type Abrasive	Down Feed	Cutting Fluid
250 Grade Maraging Steel Aged, 52 R_C	X		X	X	X		X	X
Ti 8Al-1Mo-1V Aged, 302 BHN	X		X	X	X	X	X	X
Inconel 718 Solution Treated and Aged, 41 R_C	X	X		X	X		X	X
Waspaloy Solution Treated and Aged, 390 BHN	X	X		X	X		X	X



Distortion and Residual Stress Test Specimen.

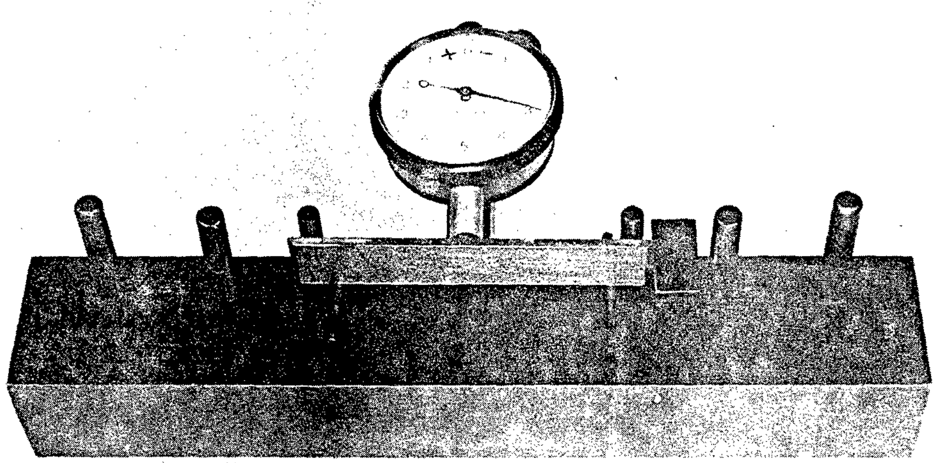
See text, page 317



Distortion Specimen Holding Fixture

See text, page 317

Figure 357

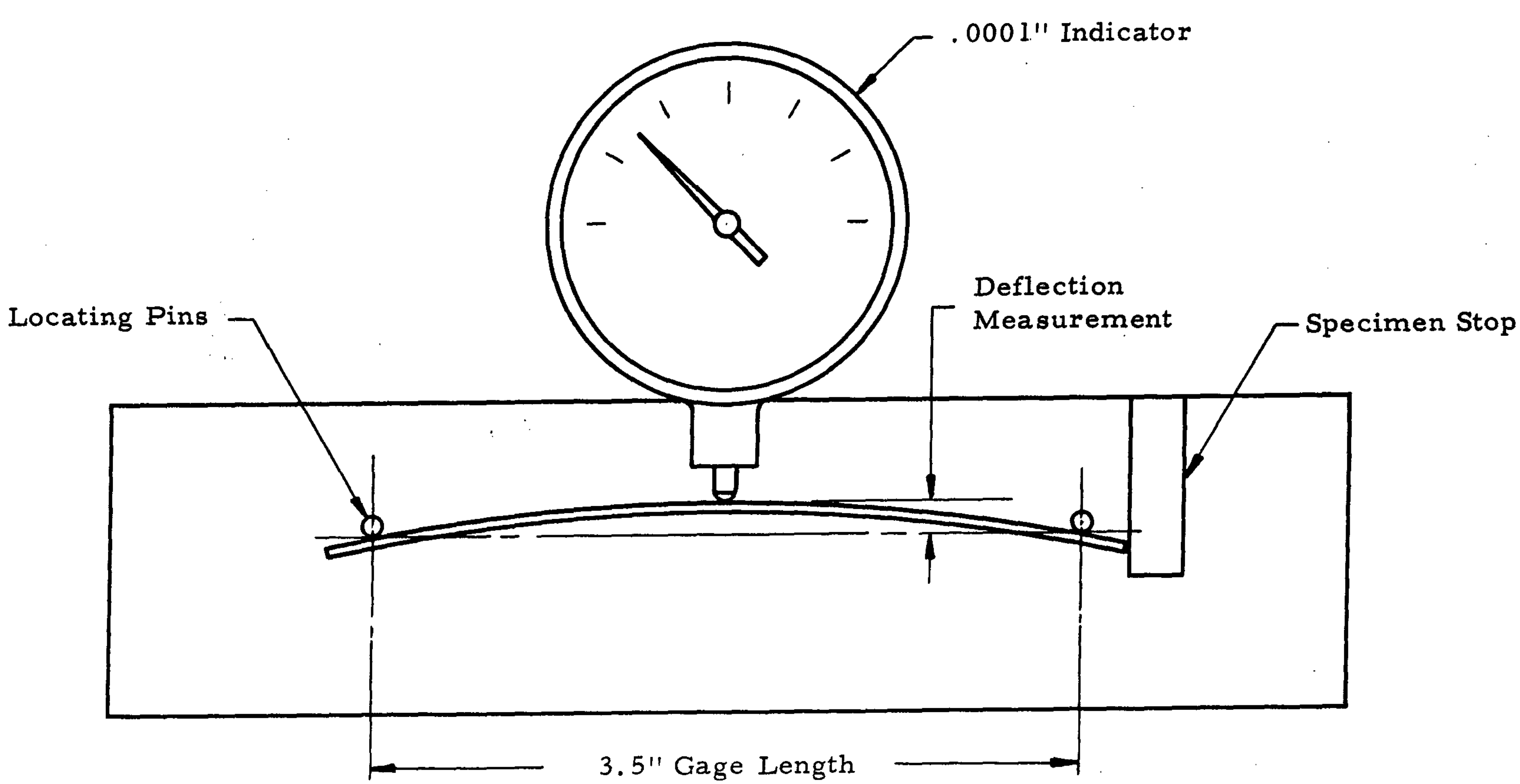


Fixture for Measuring Deflection of Distortion Test Specimen

See text, page 318

Figure 358

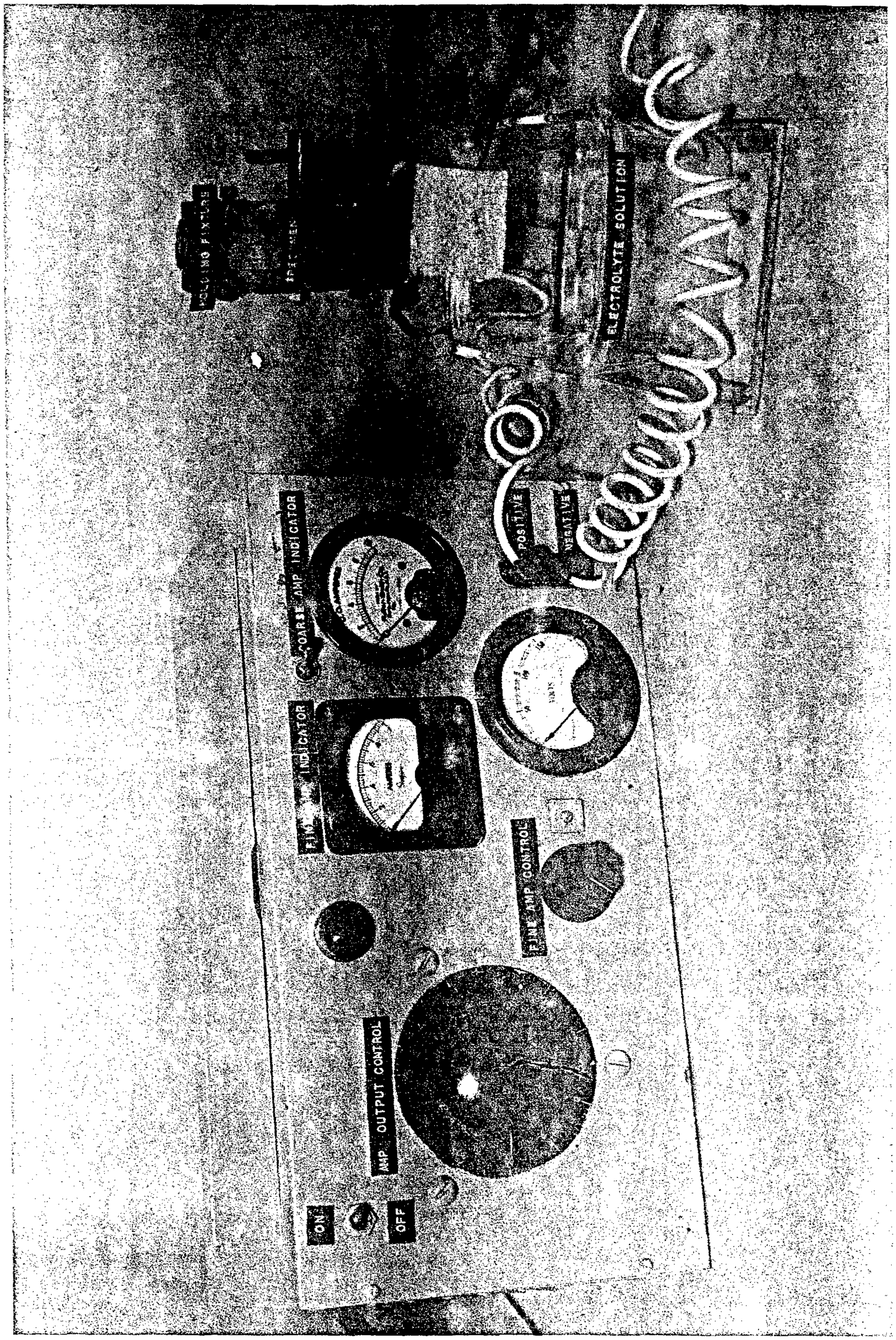
DEFLECTION MEASUREMENT FIXTURE



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

See text, page 318

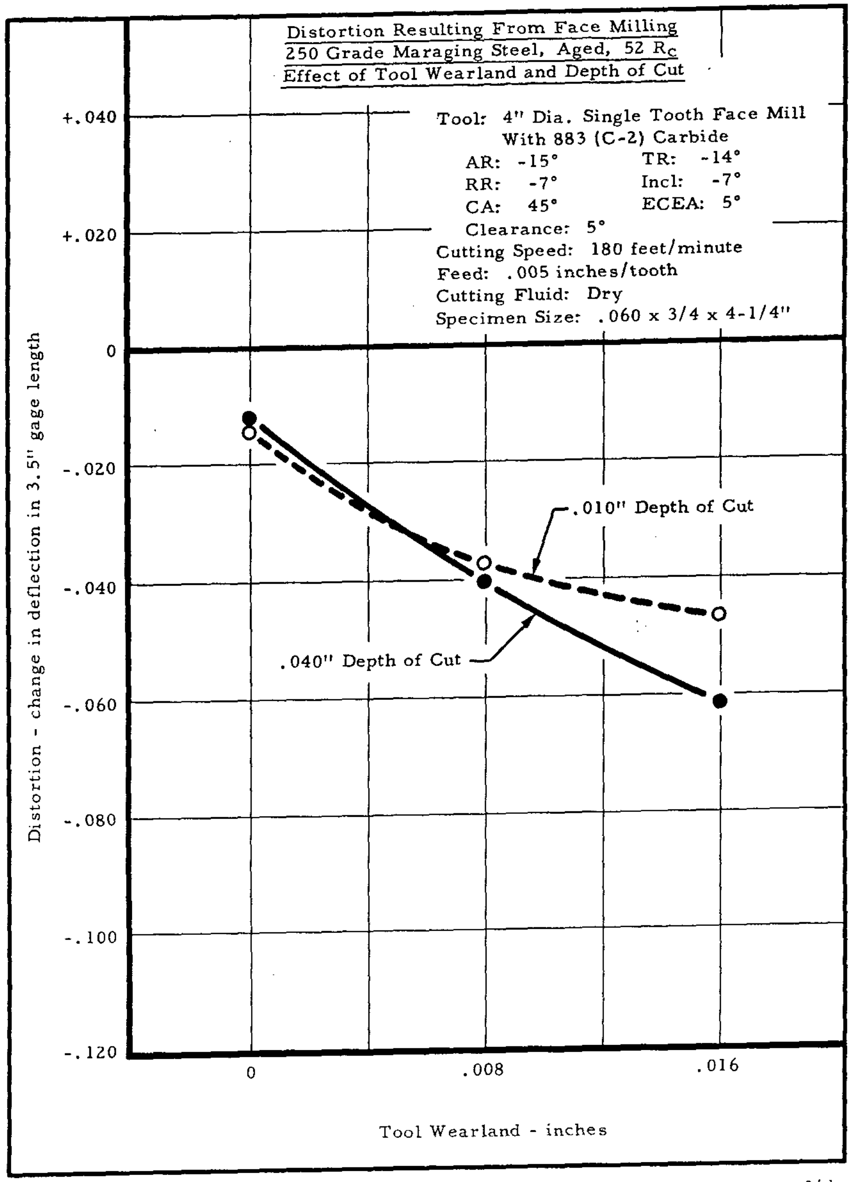
Figure 359



Electrolytic apparatus used for differential etching of residual stress specimens

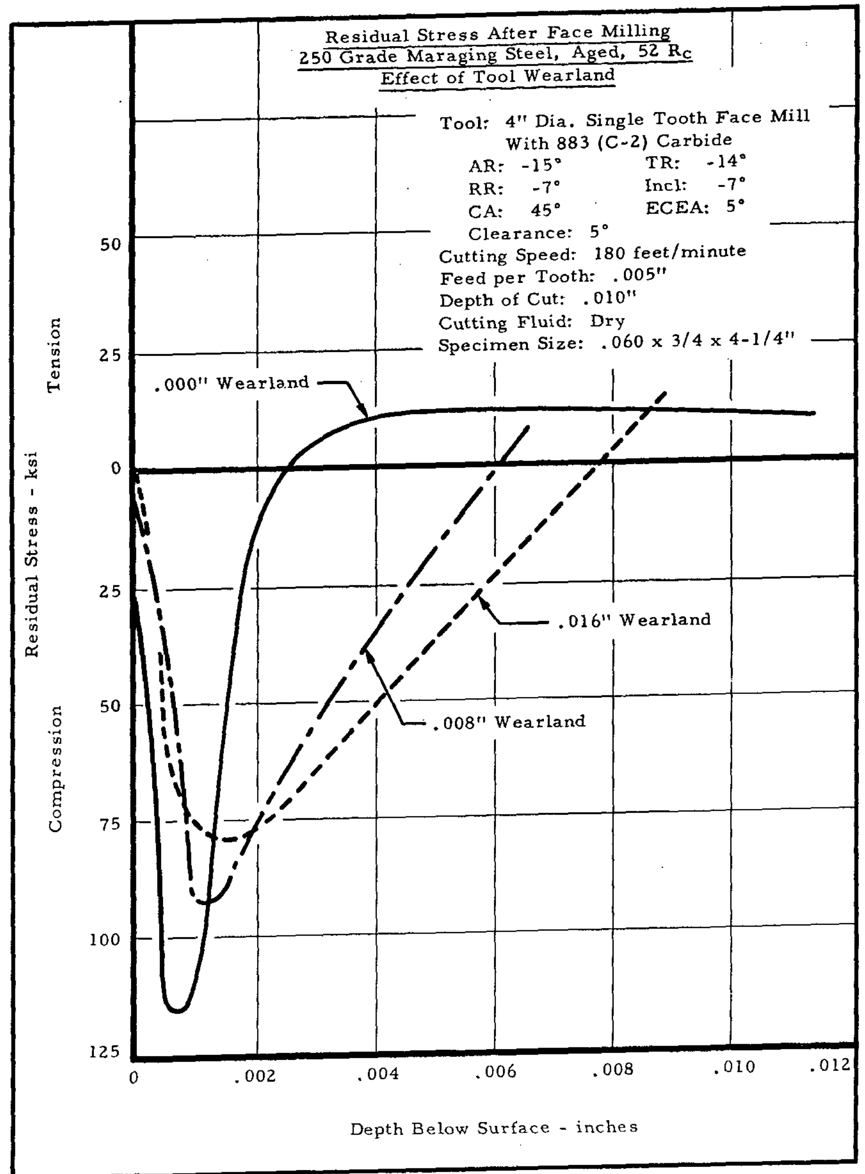
See text, page 318

Figure 360



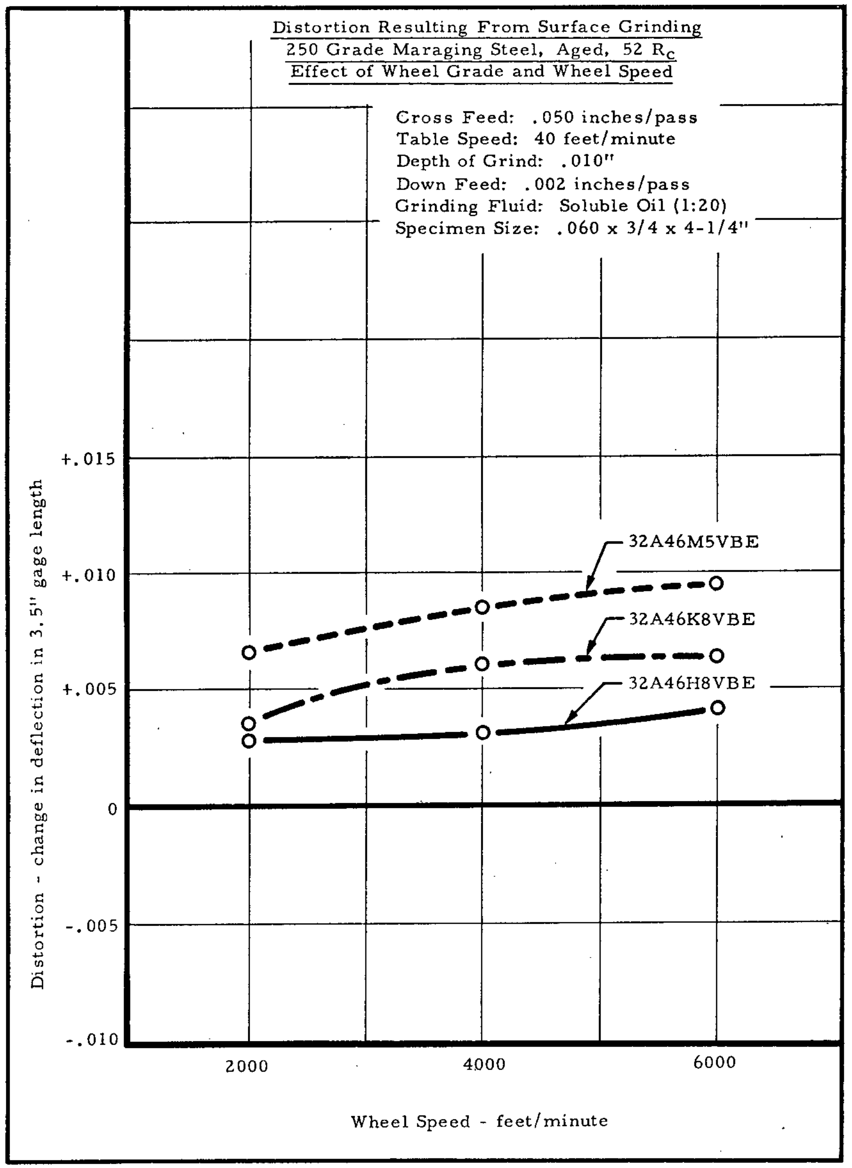
See text, page 319

Figure 361



See text, page 319

Figure 362



See text, page 319

Figure 363

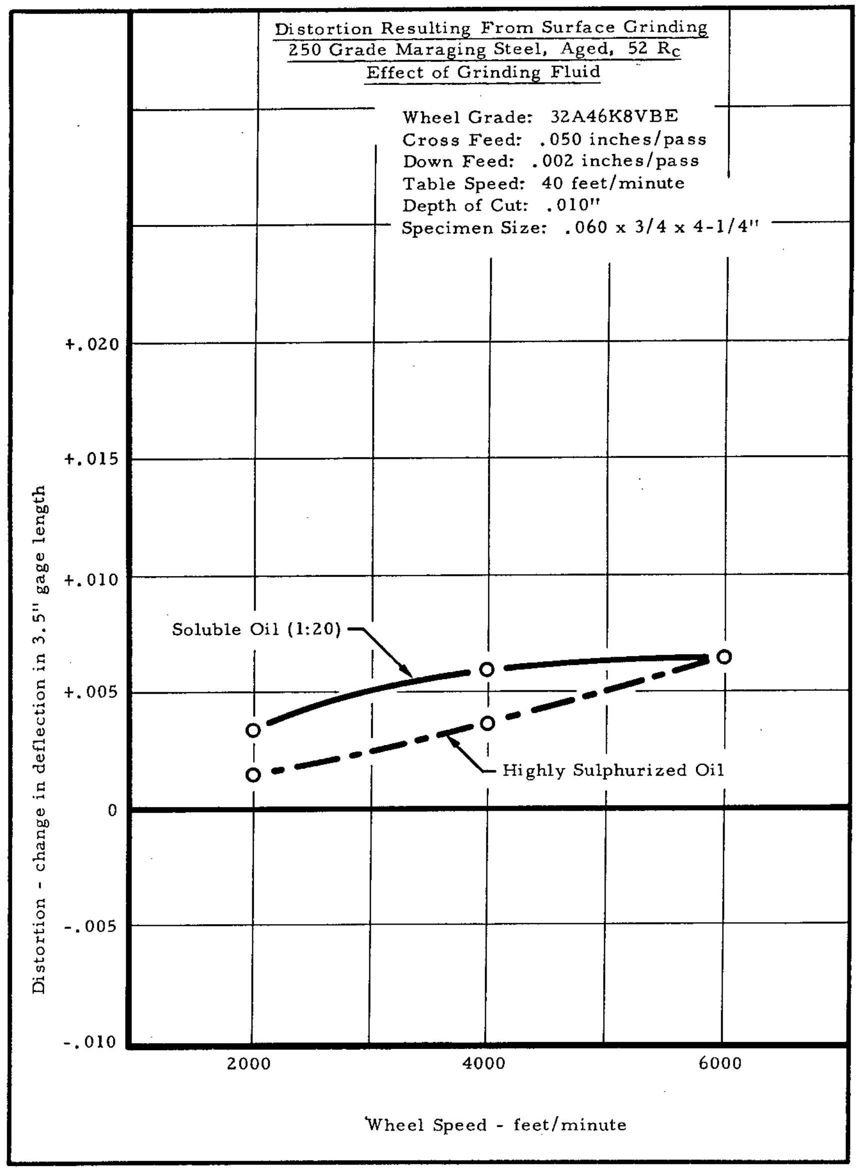


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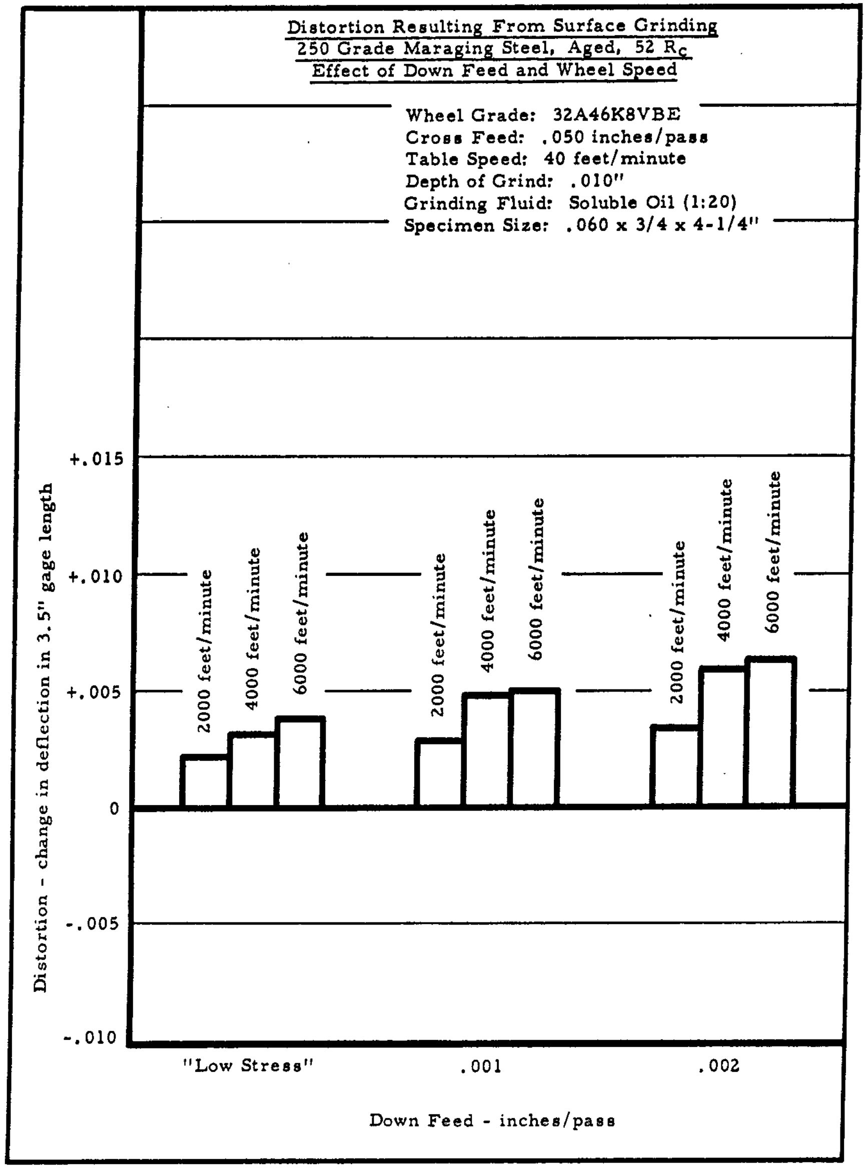
Figure 364



See text, page 320

Figure 365

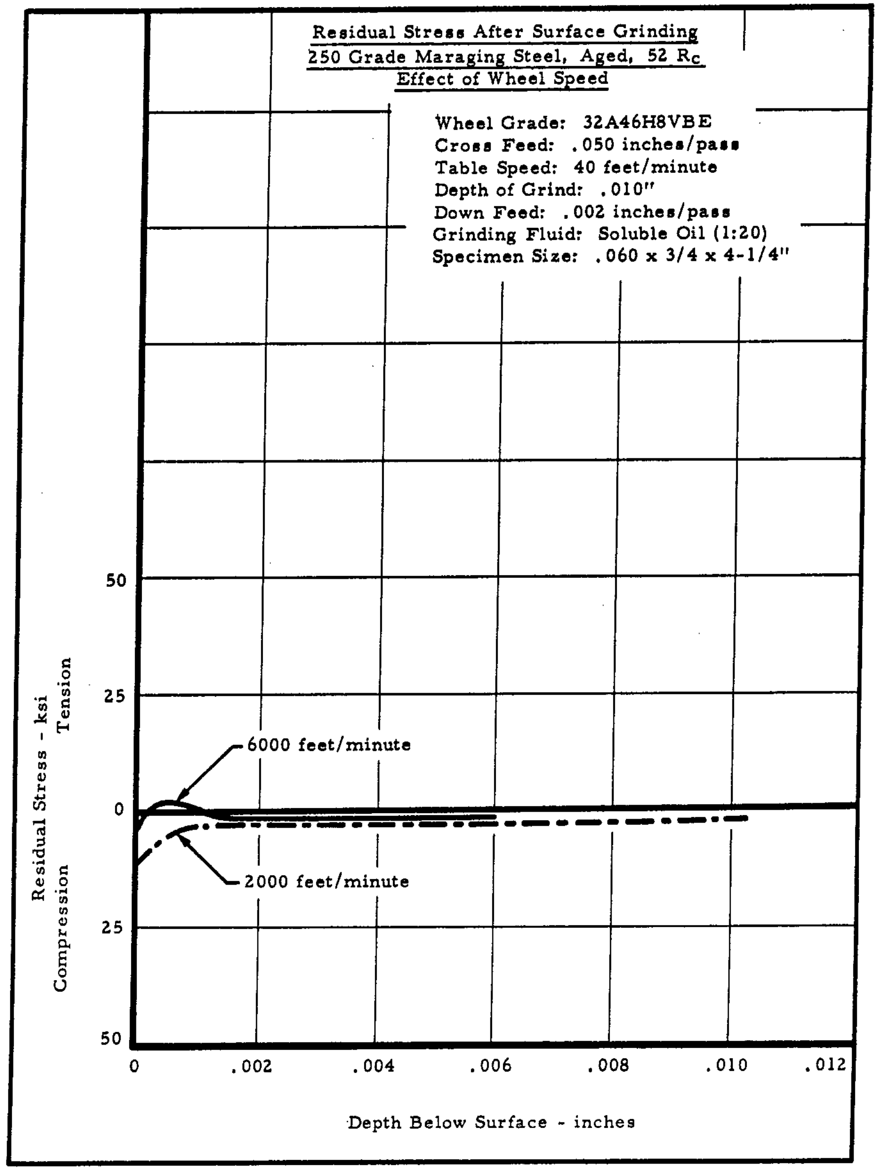


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Figure 366

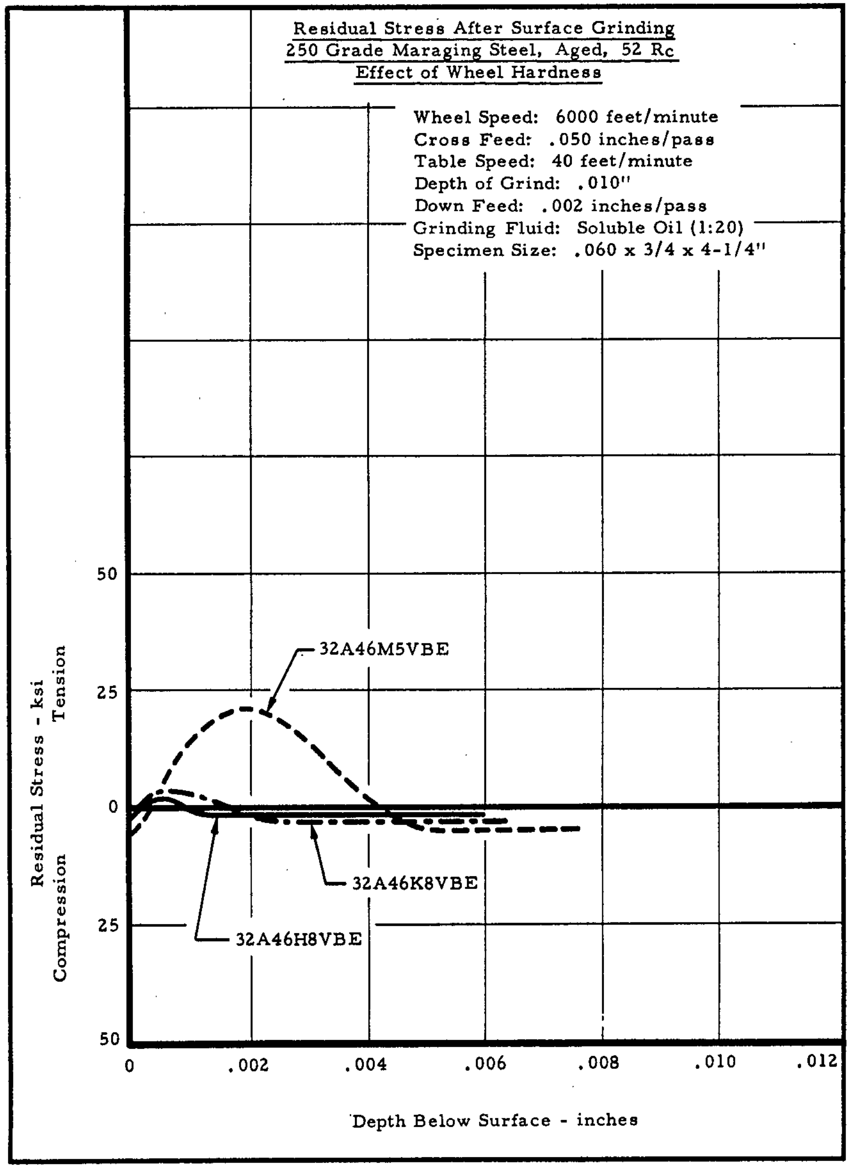

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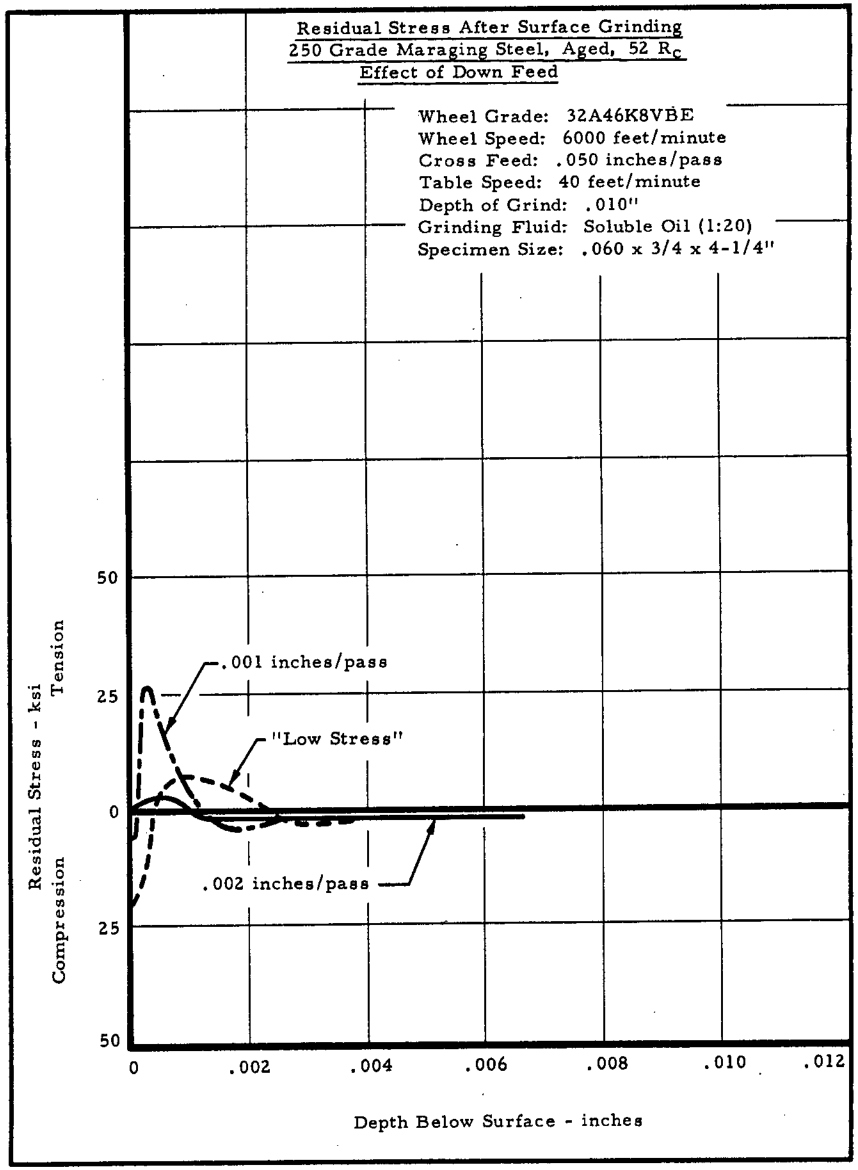
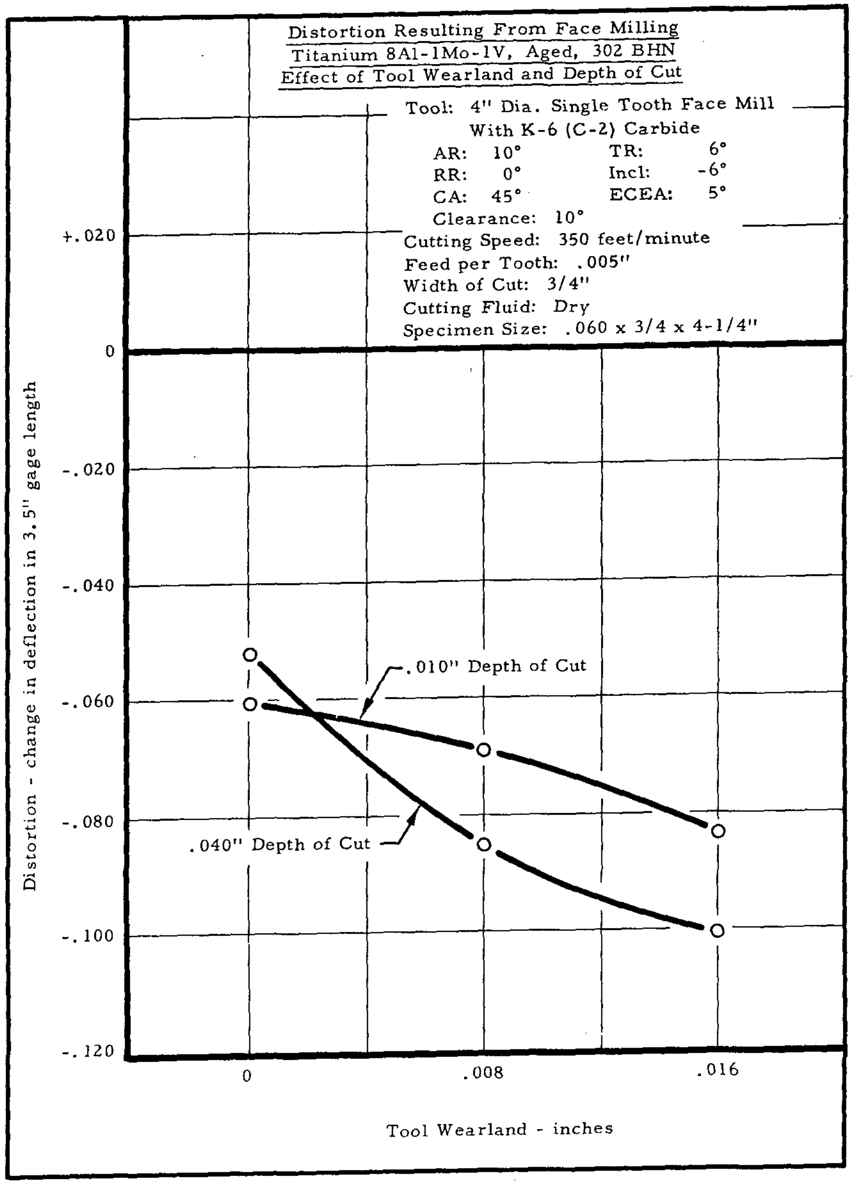
Figure 367



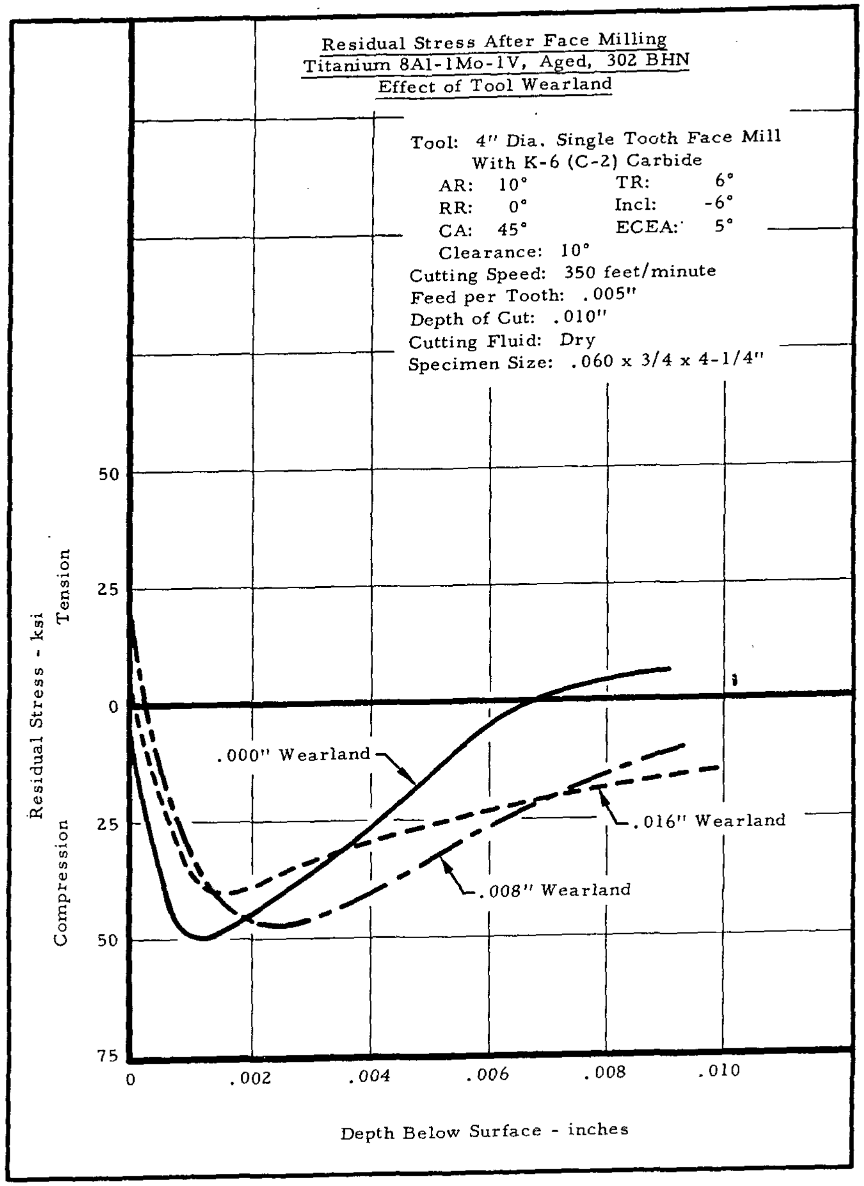
See text, page 320

Figure 368



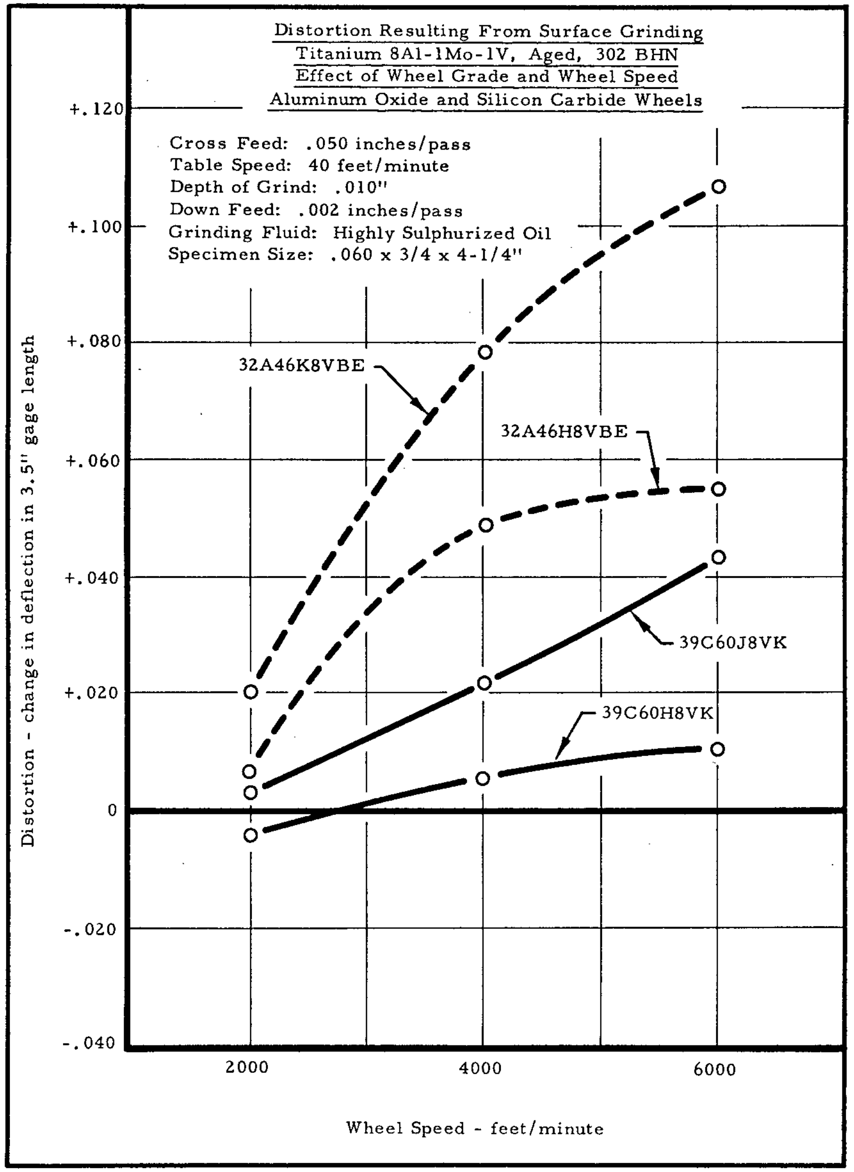
See text, page 320

Figure 369



See text, page 321

Figure 370



See text, page 321

Figure 371

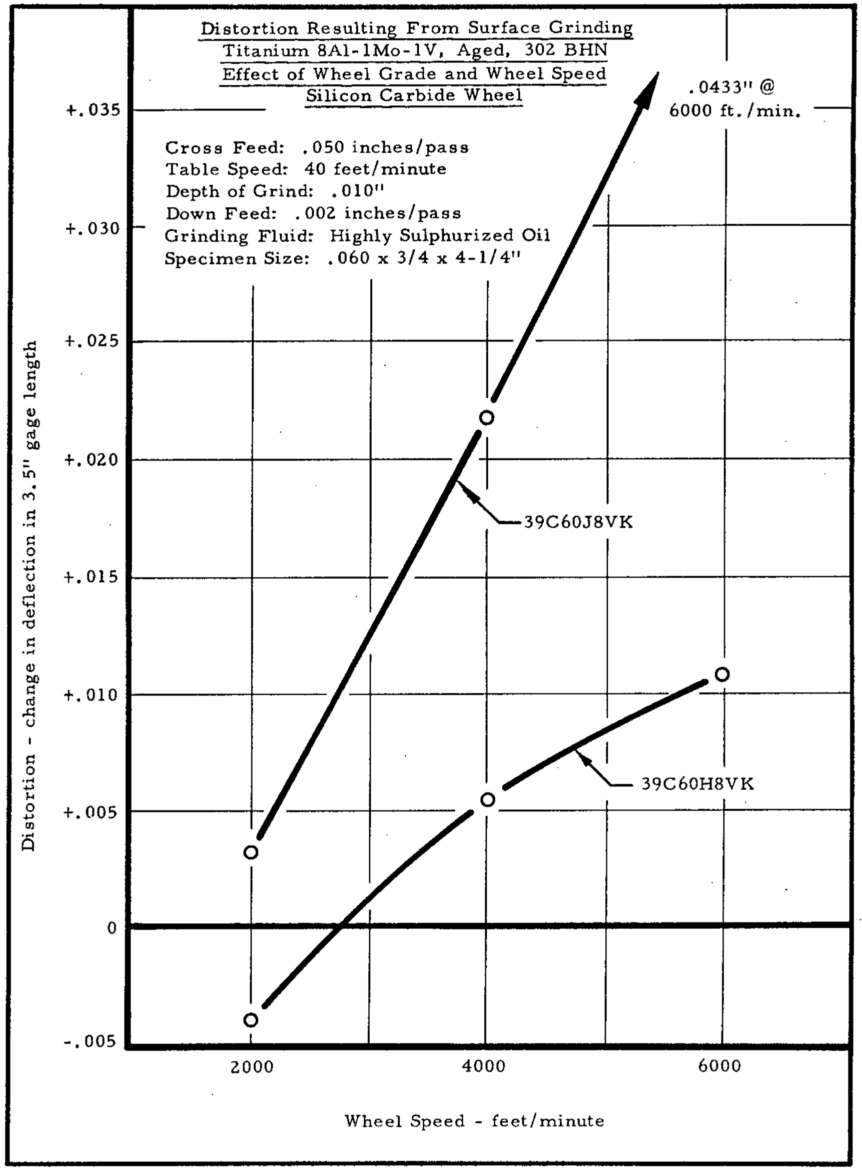


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Figure 372

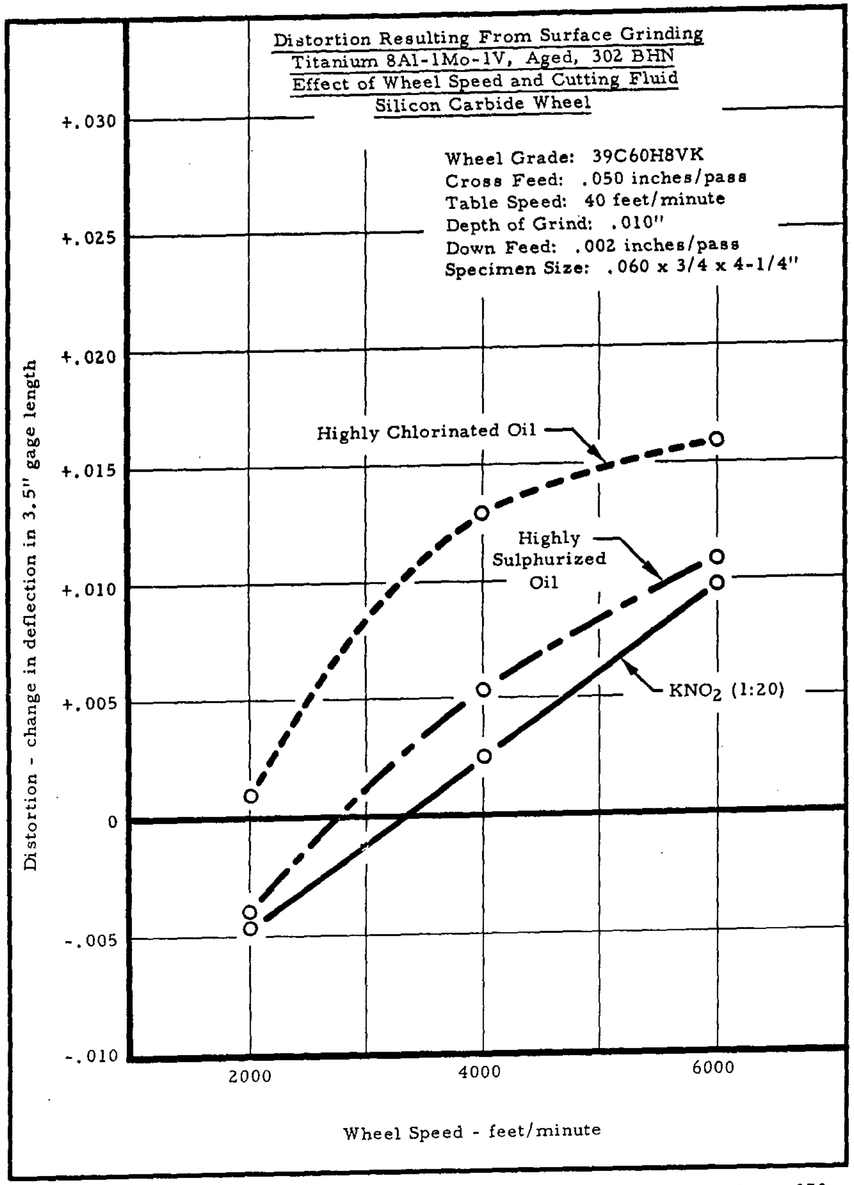

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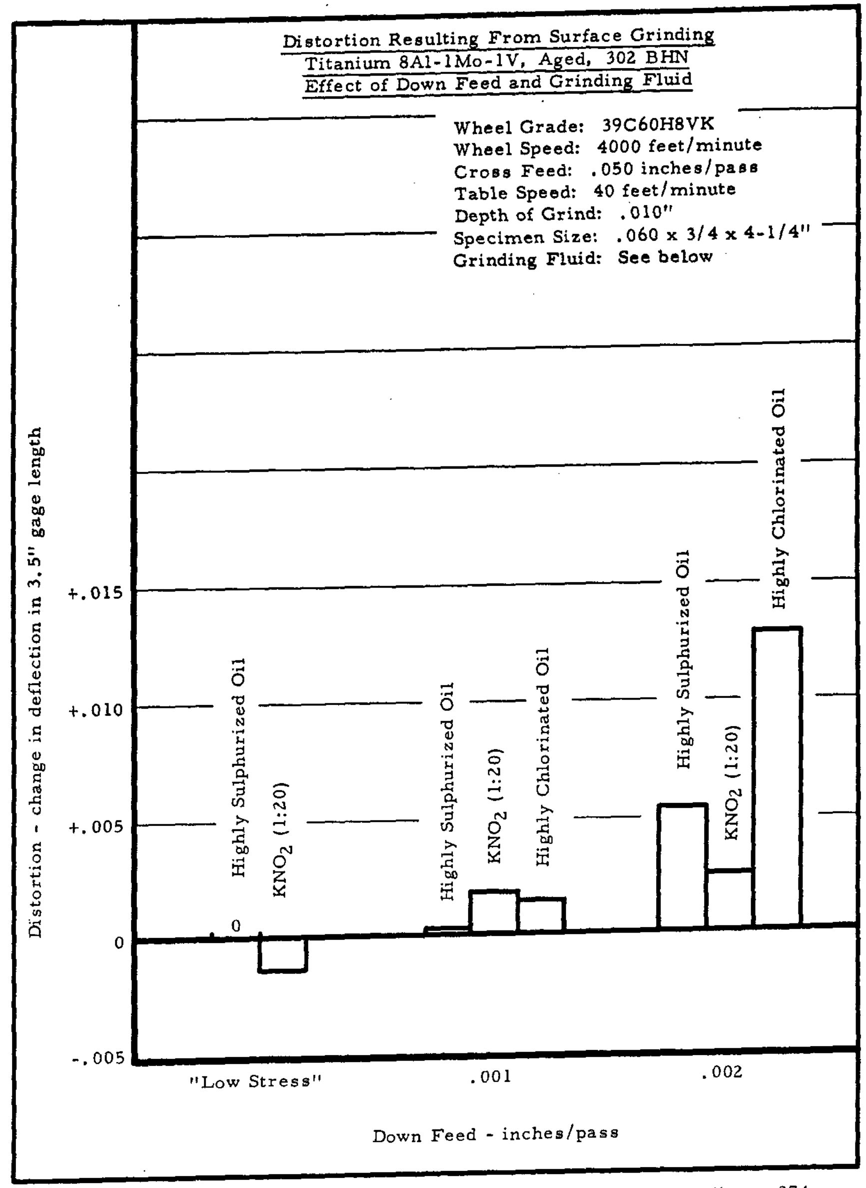
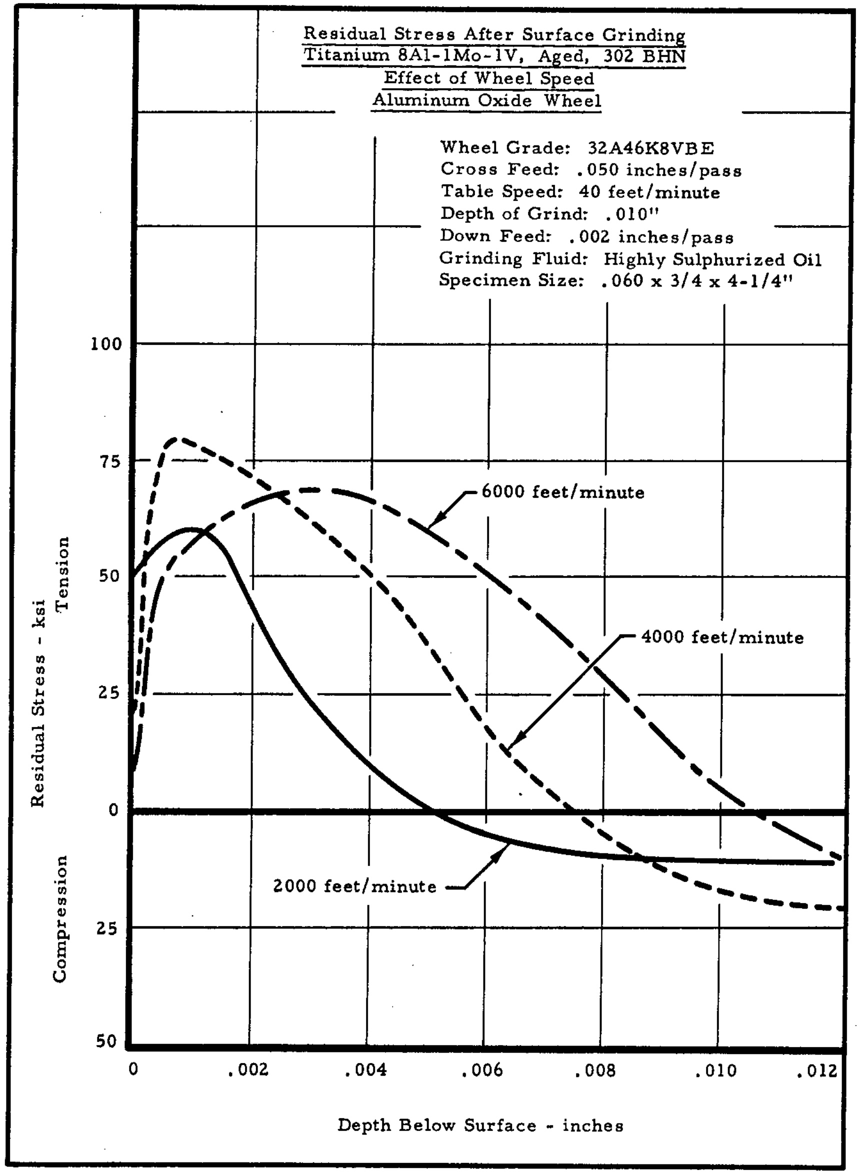
Figure 373



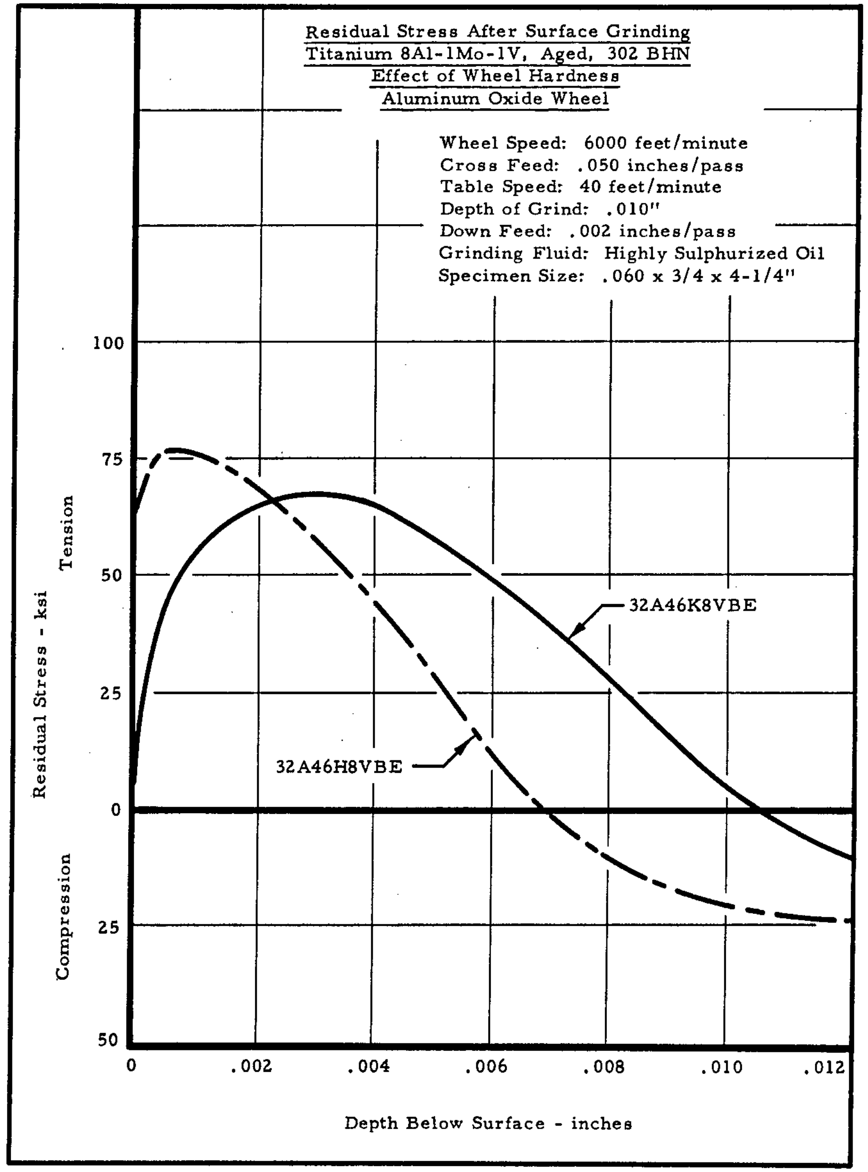
See text, page 321

Figure 374



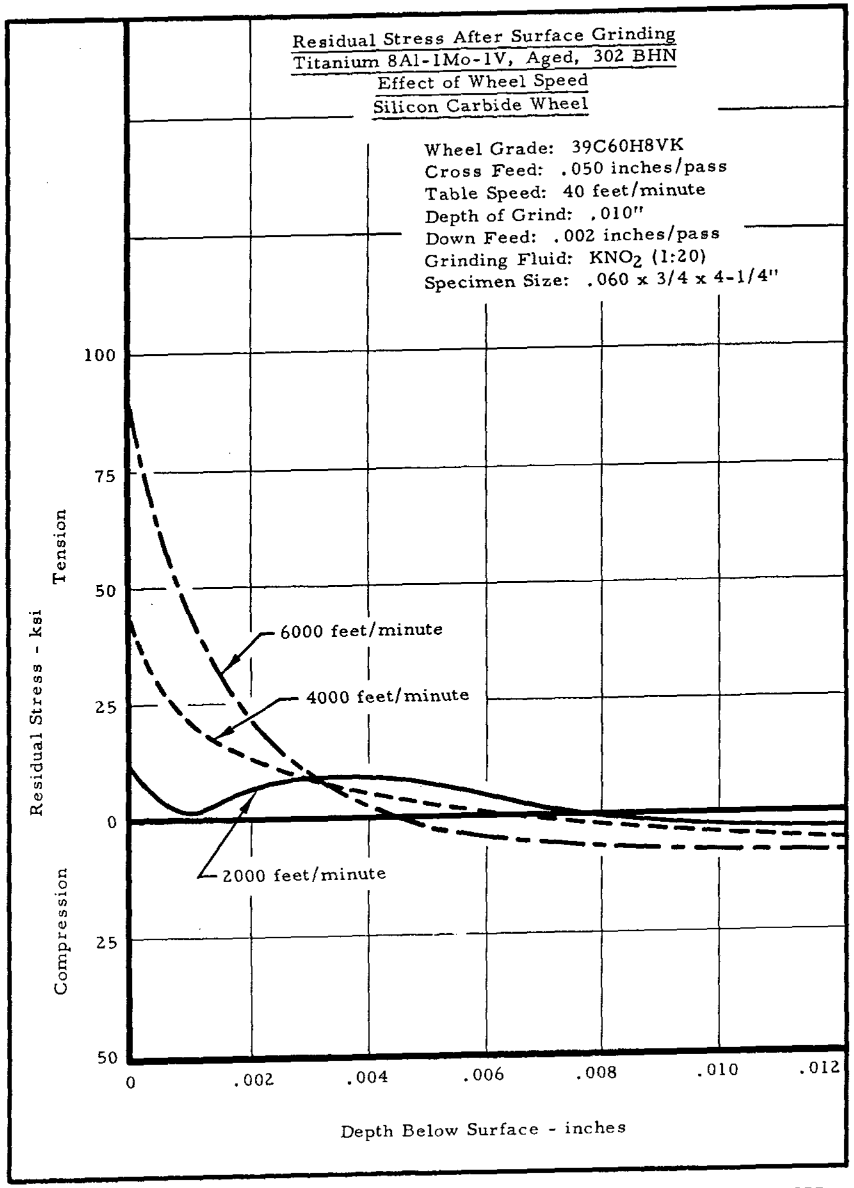
See text, page 322

Figure 375



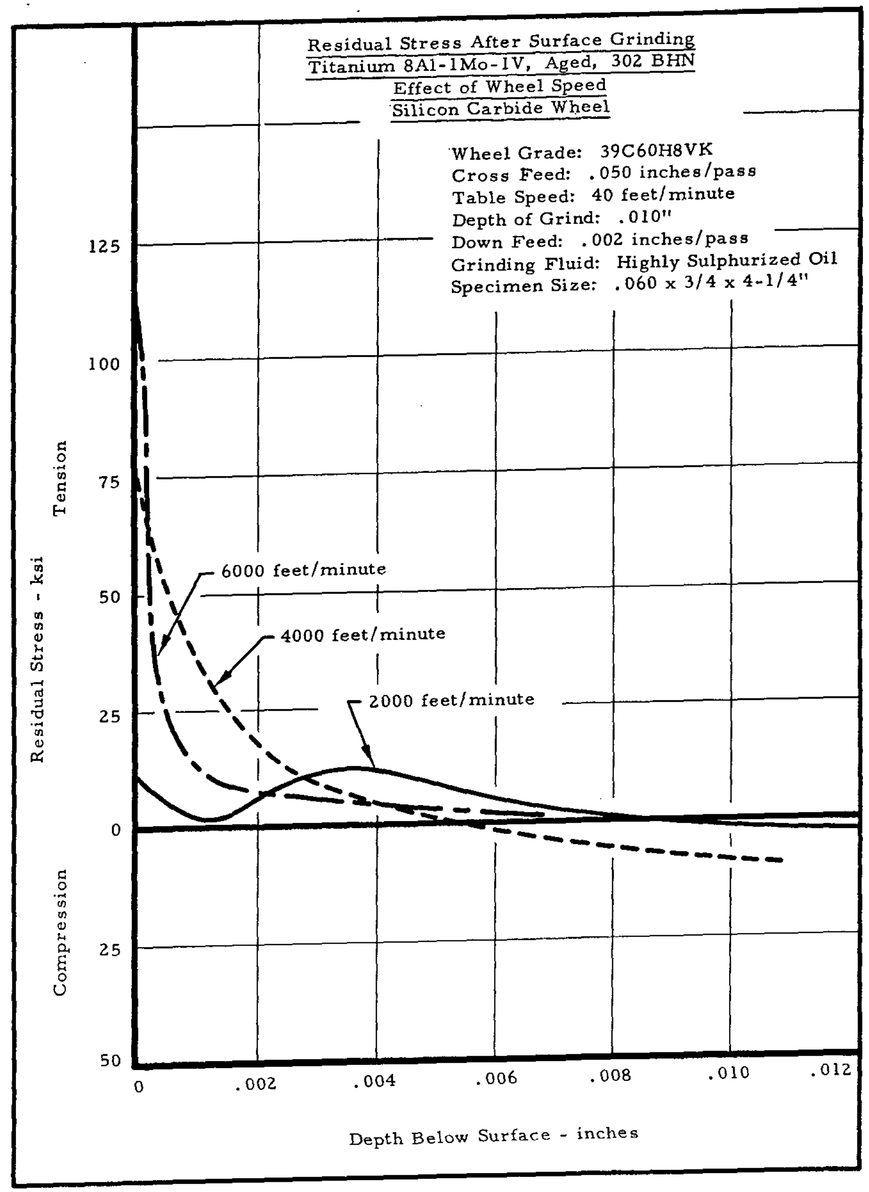
See text, page 322

Figure 376



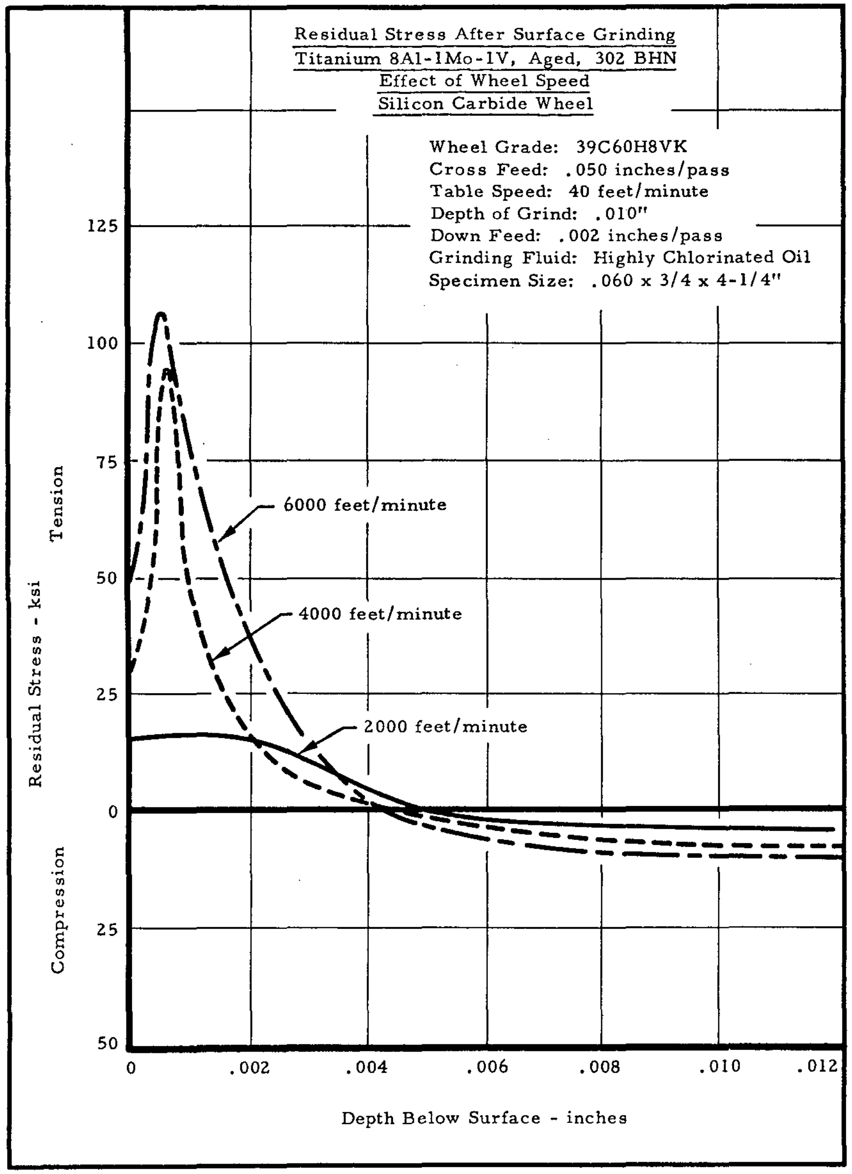
See text, page 322

Figure 377



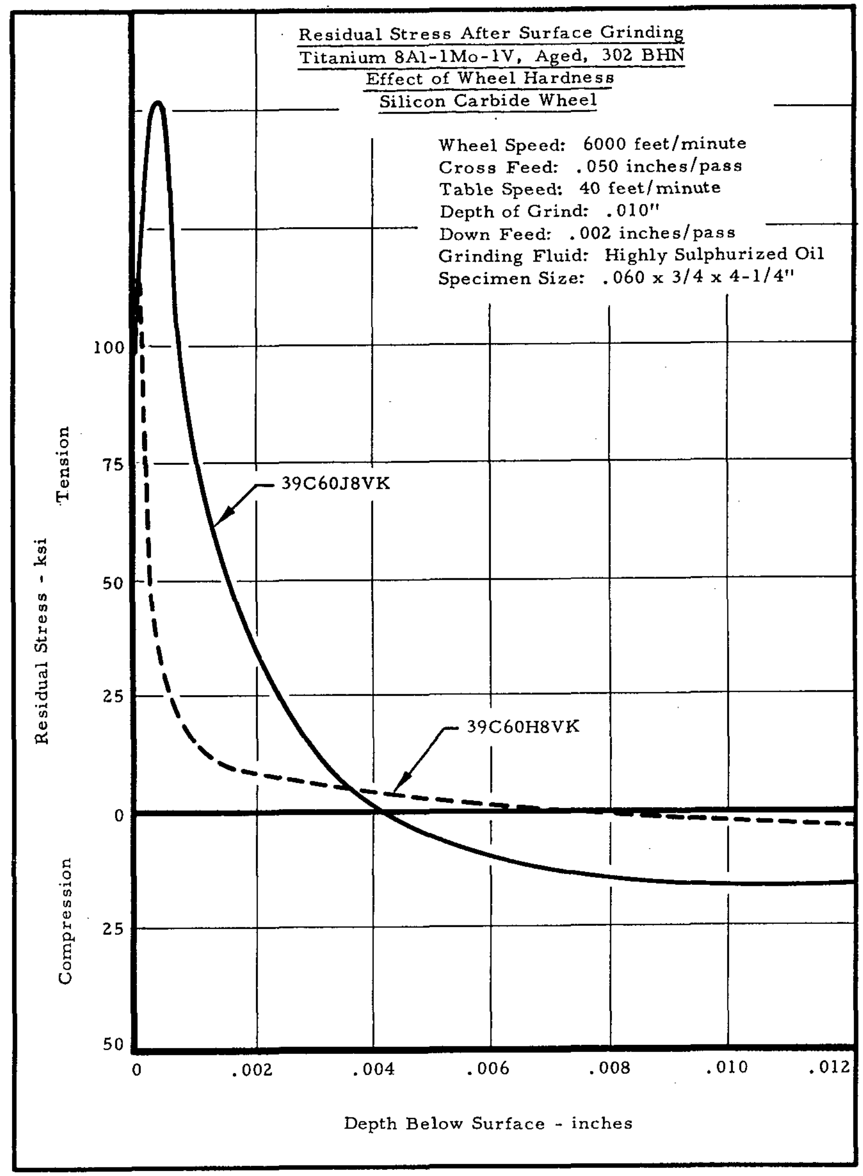
See text, page 322

Figure 378



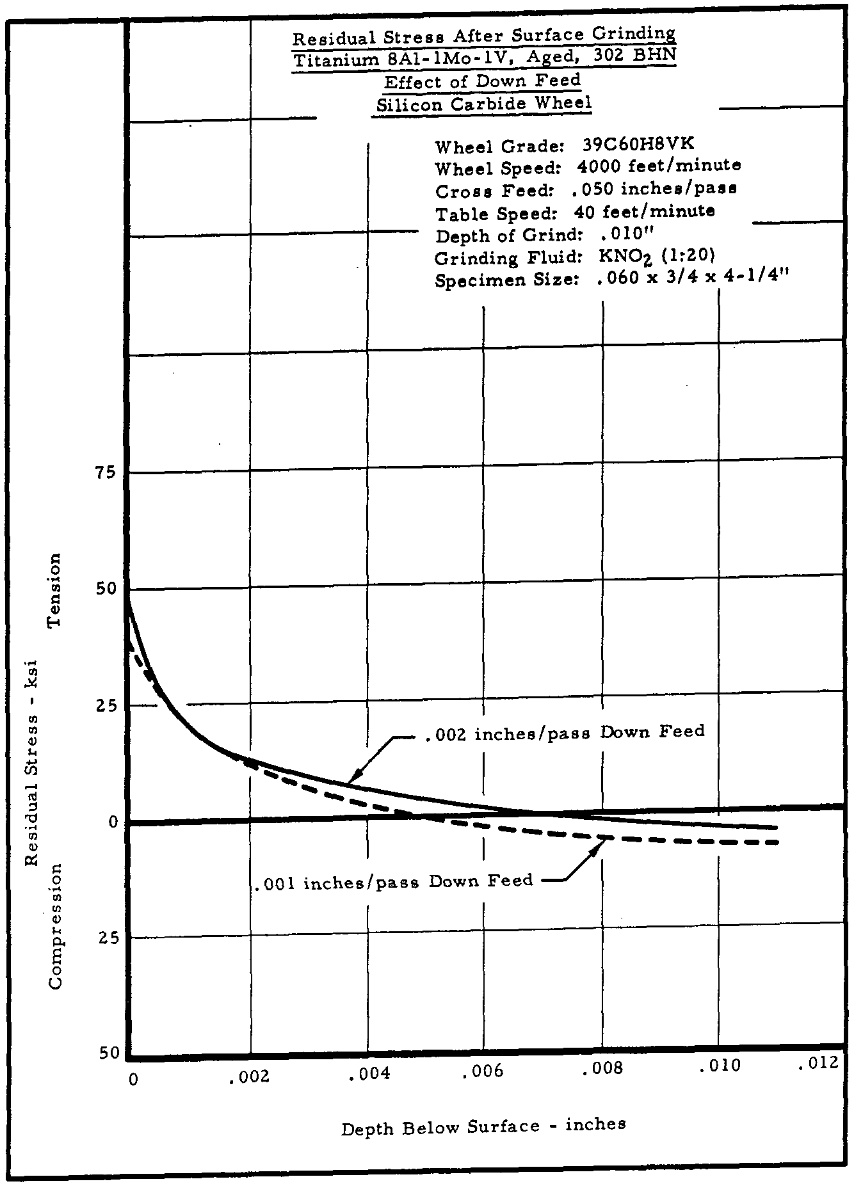
See text, page 322

Figure 379



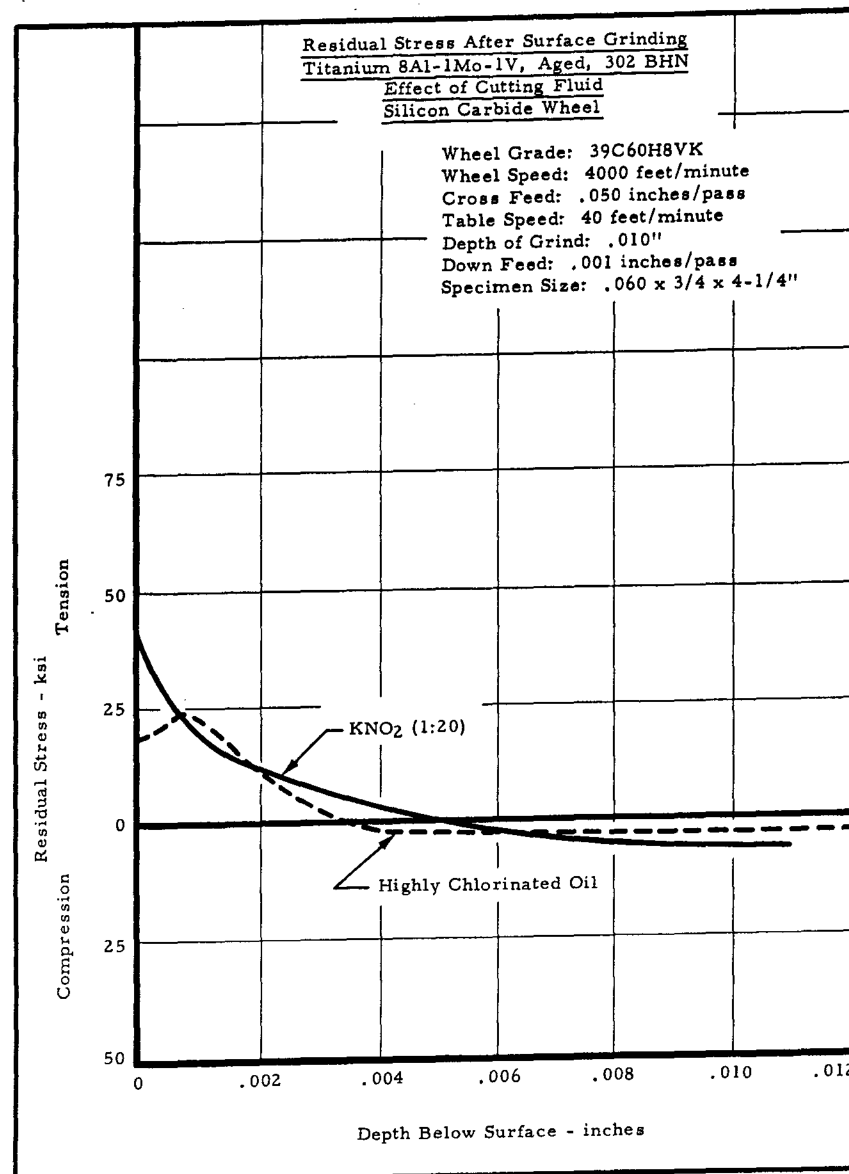
See text, page 322

Figure 380



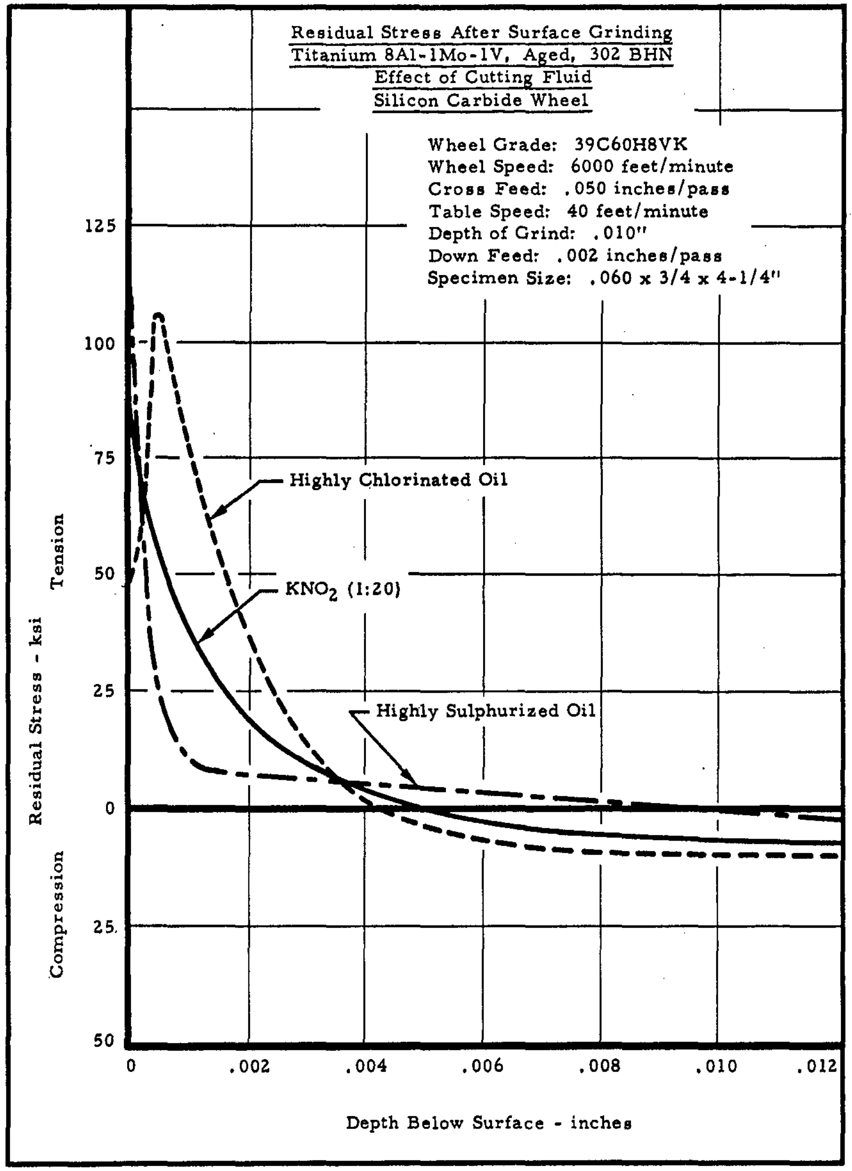
See text, page 322

Figure 381



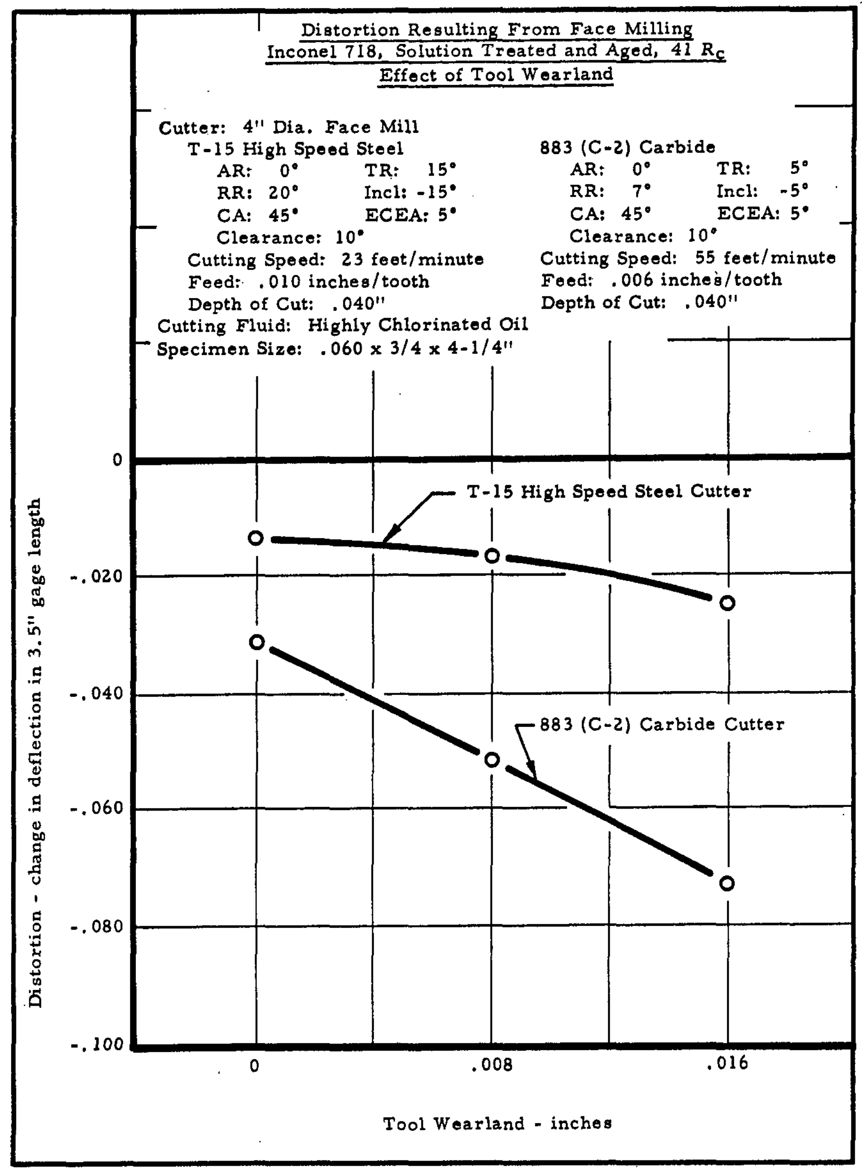
See text, page 322

Figure 382



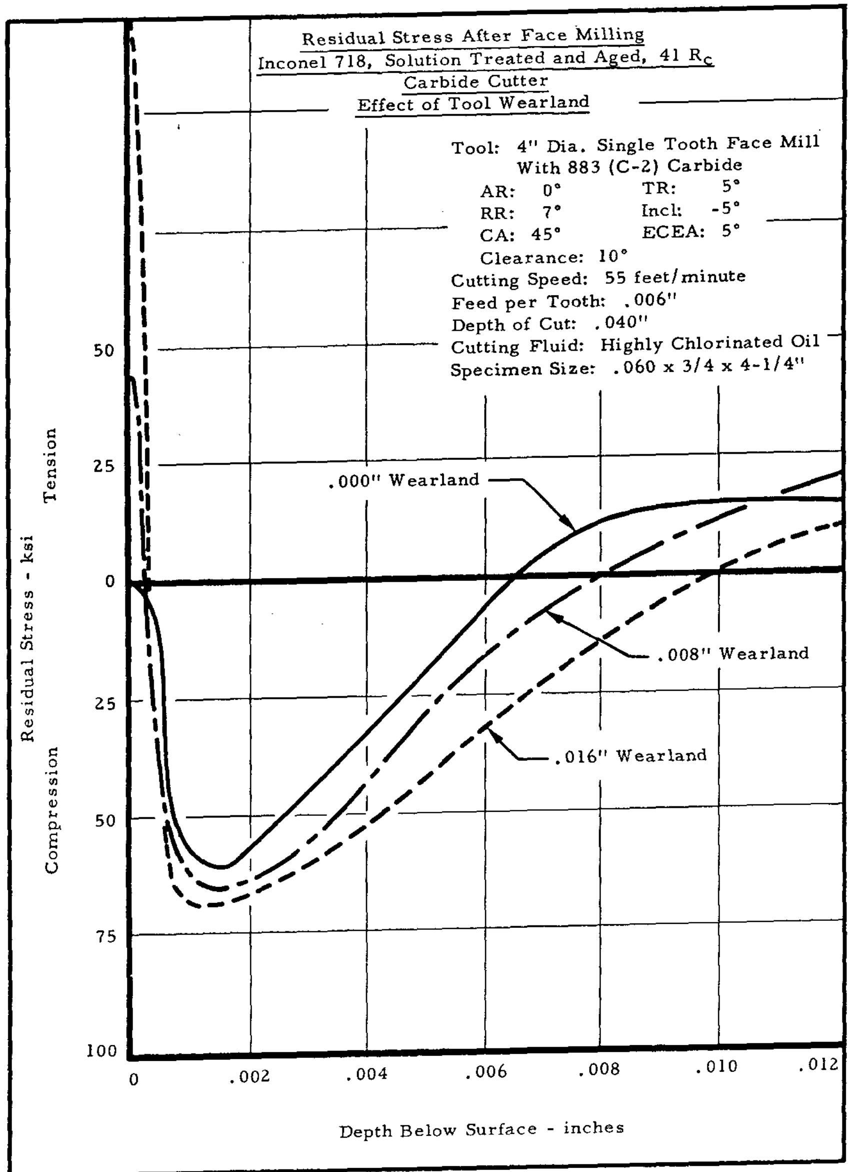
See text, page 323

Figure 383



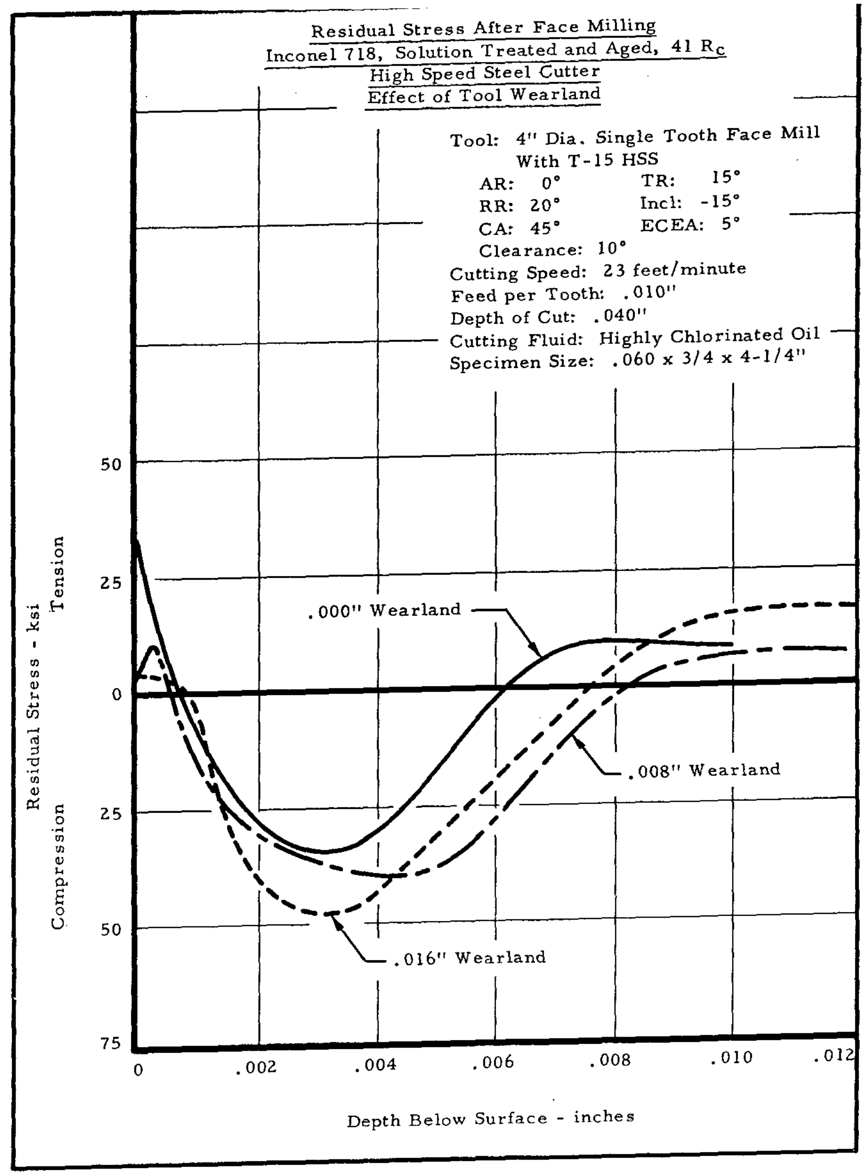
See text, page 323

Figure 384



See text, page 323

Figure 385



See text, page 323

Figure 386

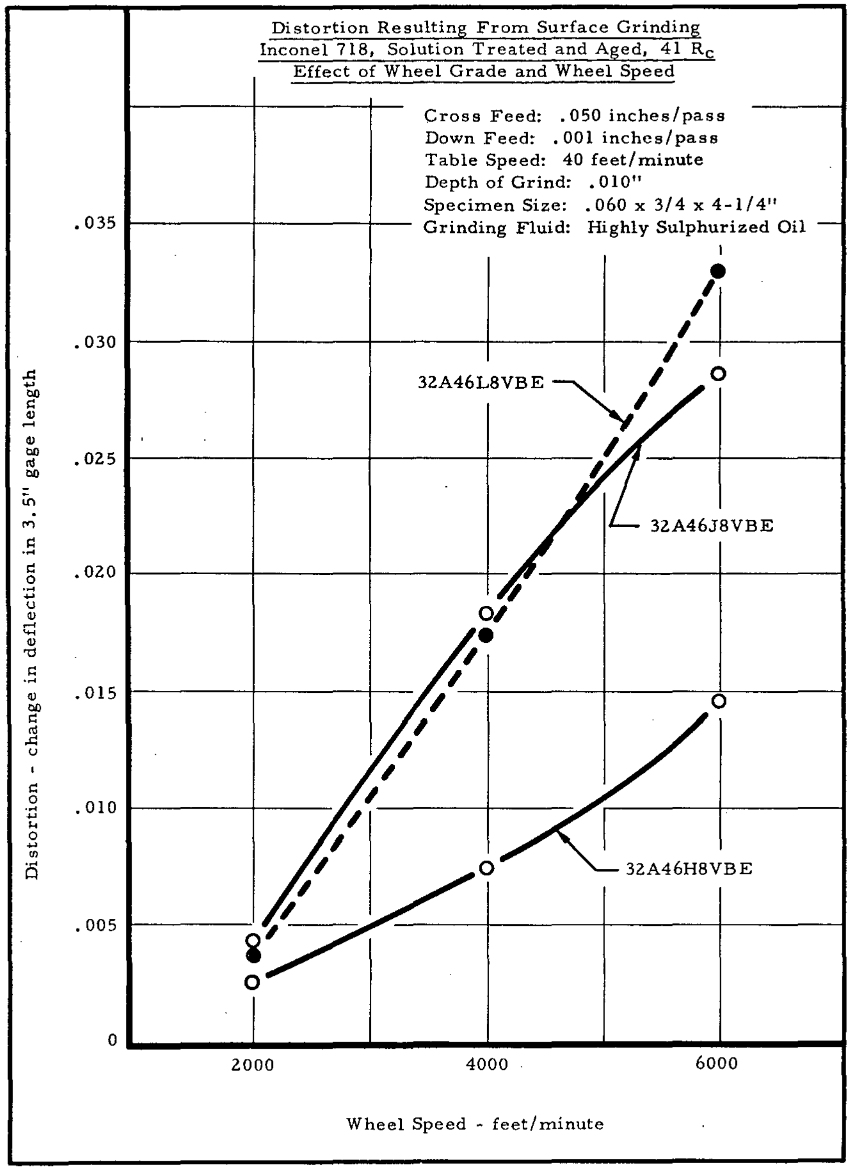


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Figure 387

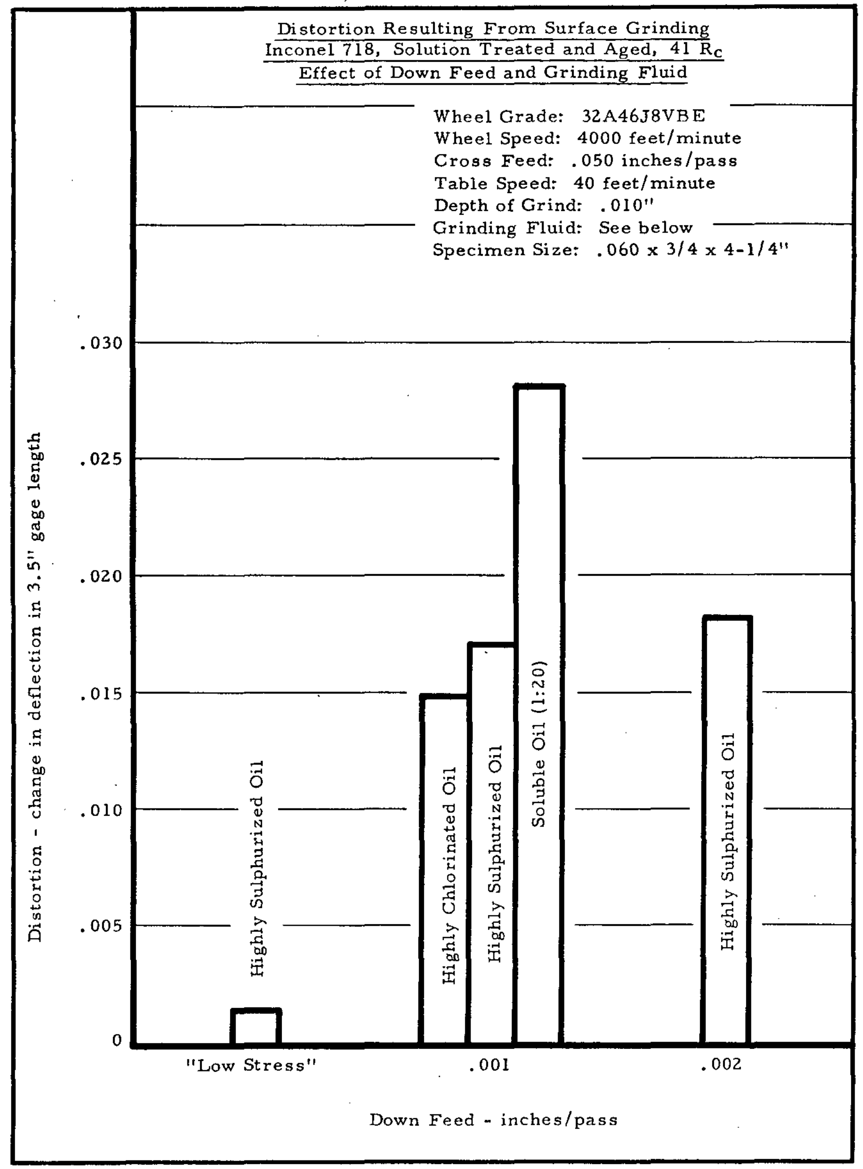

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Figure 388

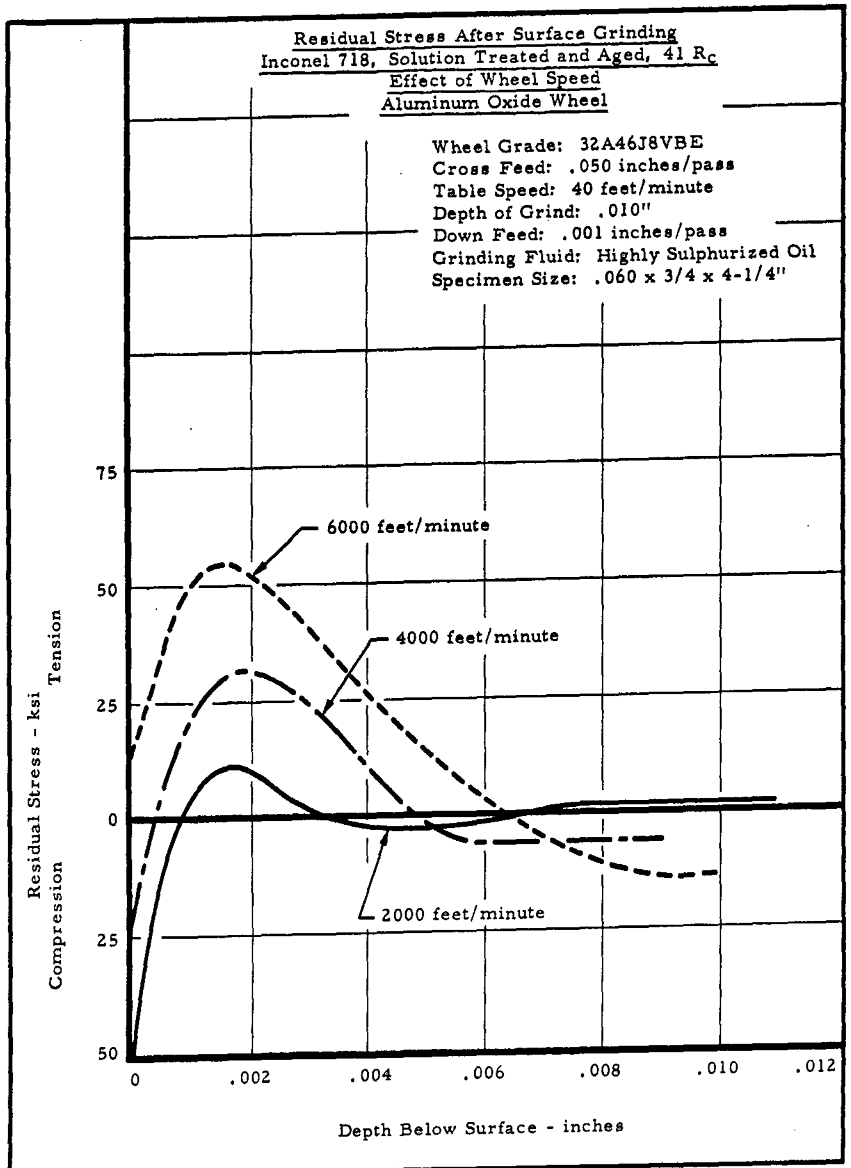

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Figure 389

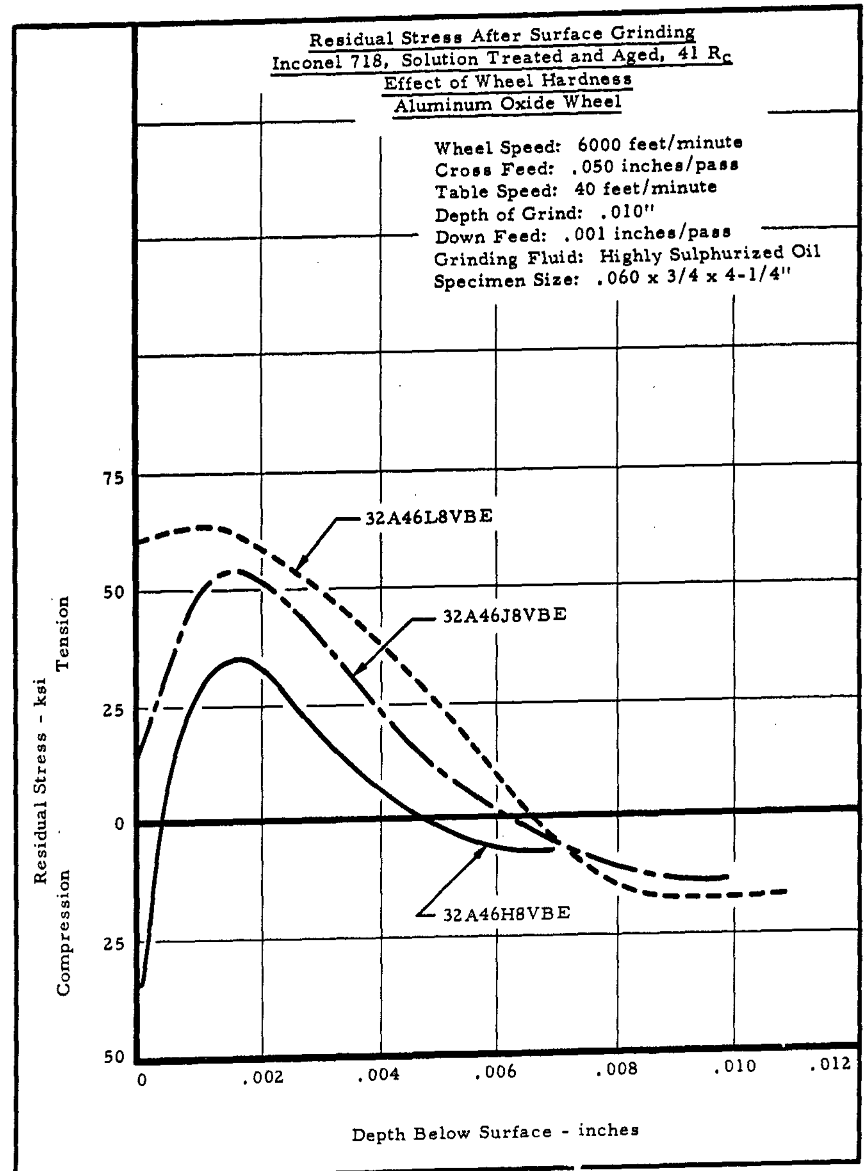

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Figure 390

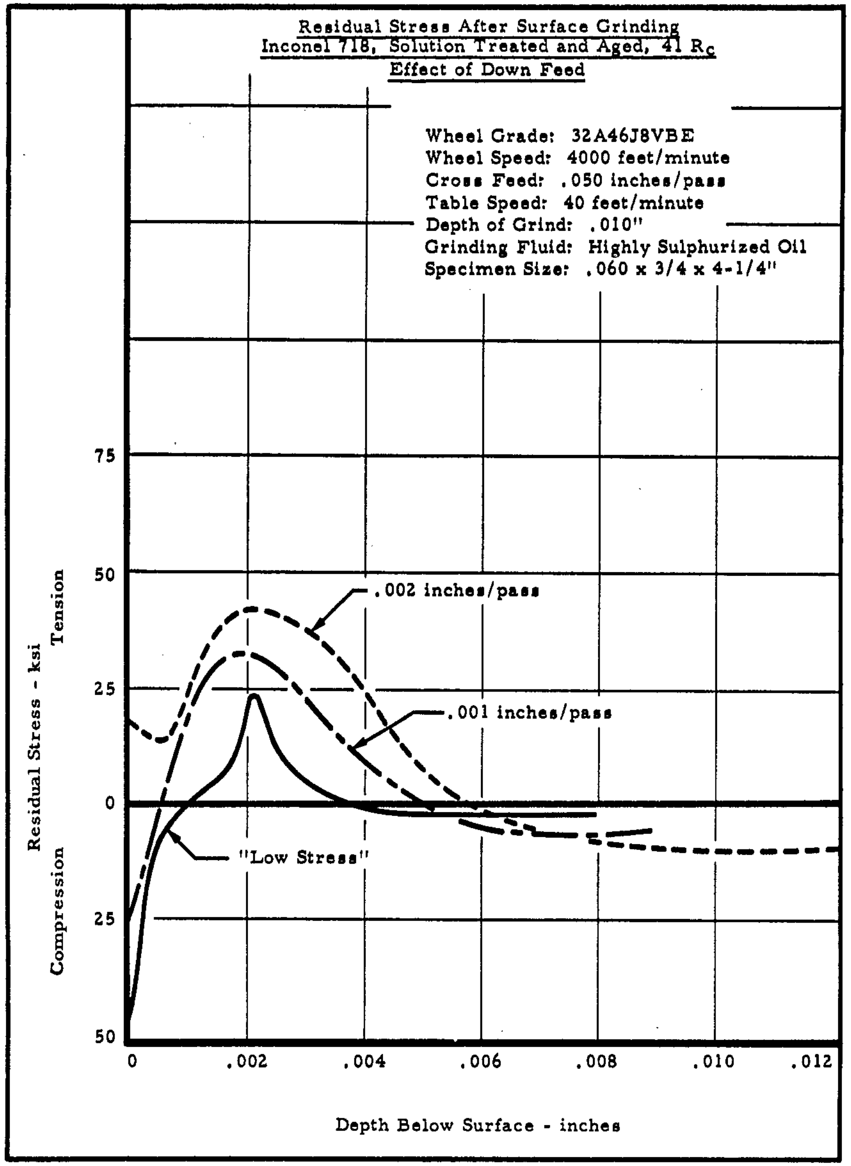

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Figure 391

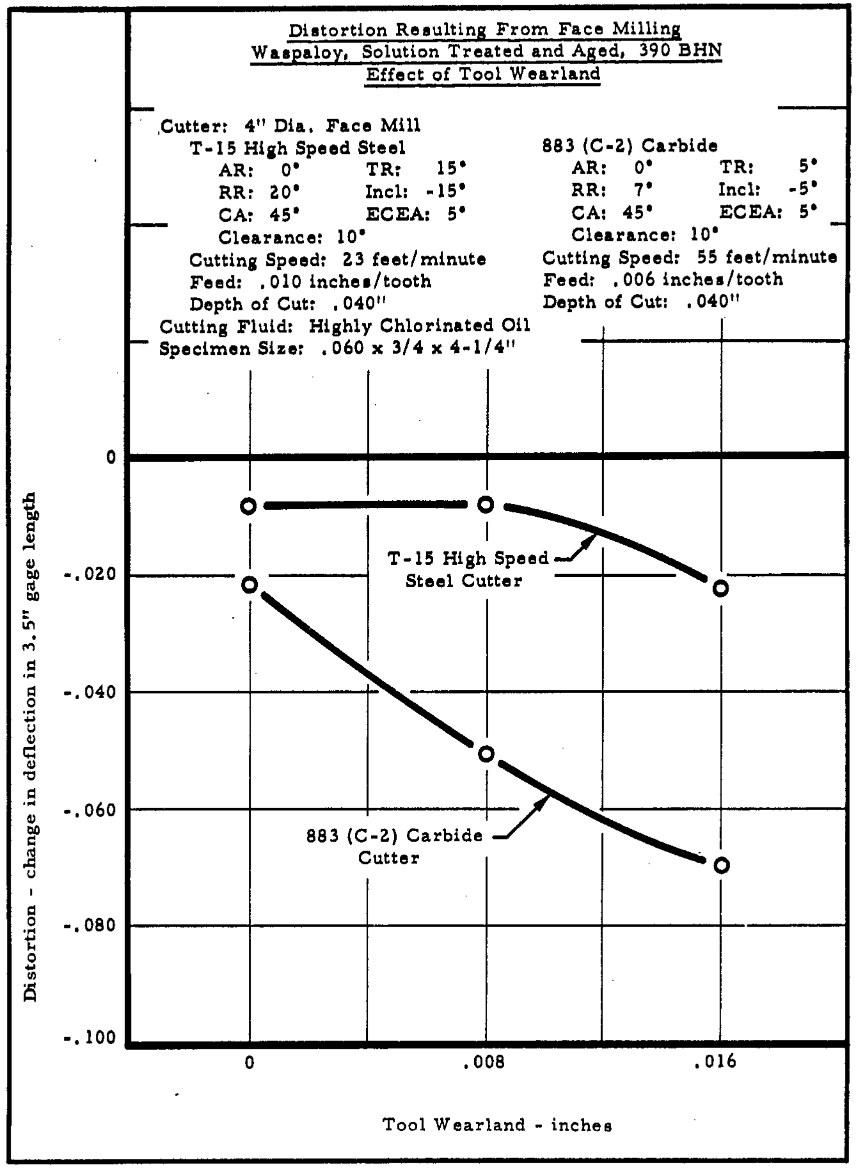

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Figure 392

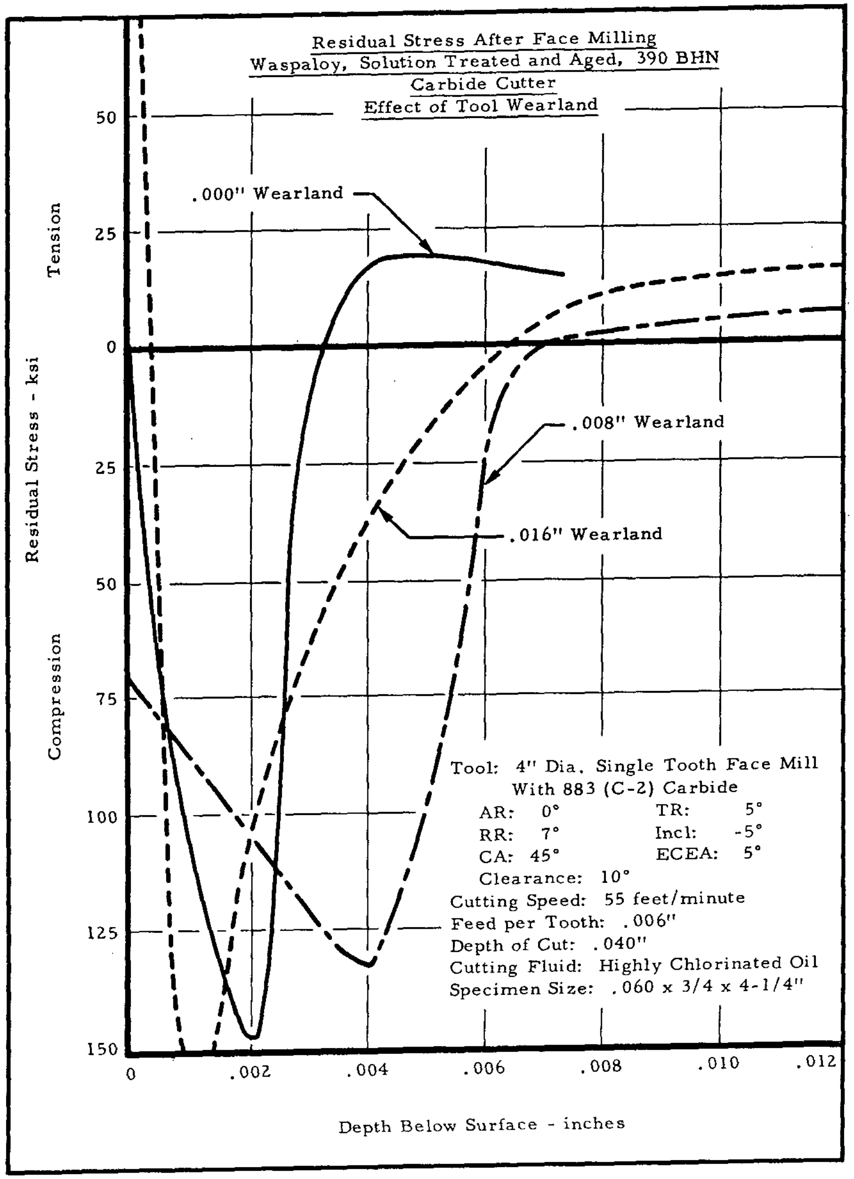

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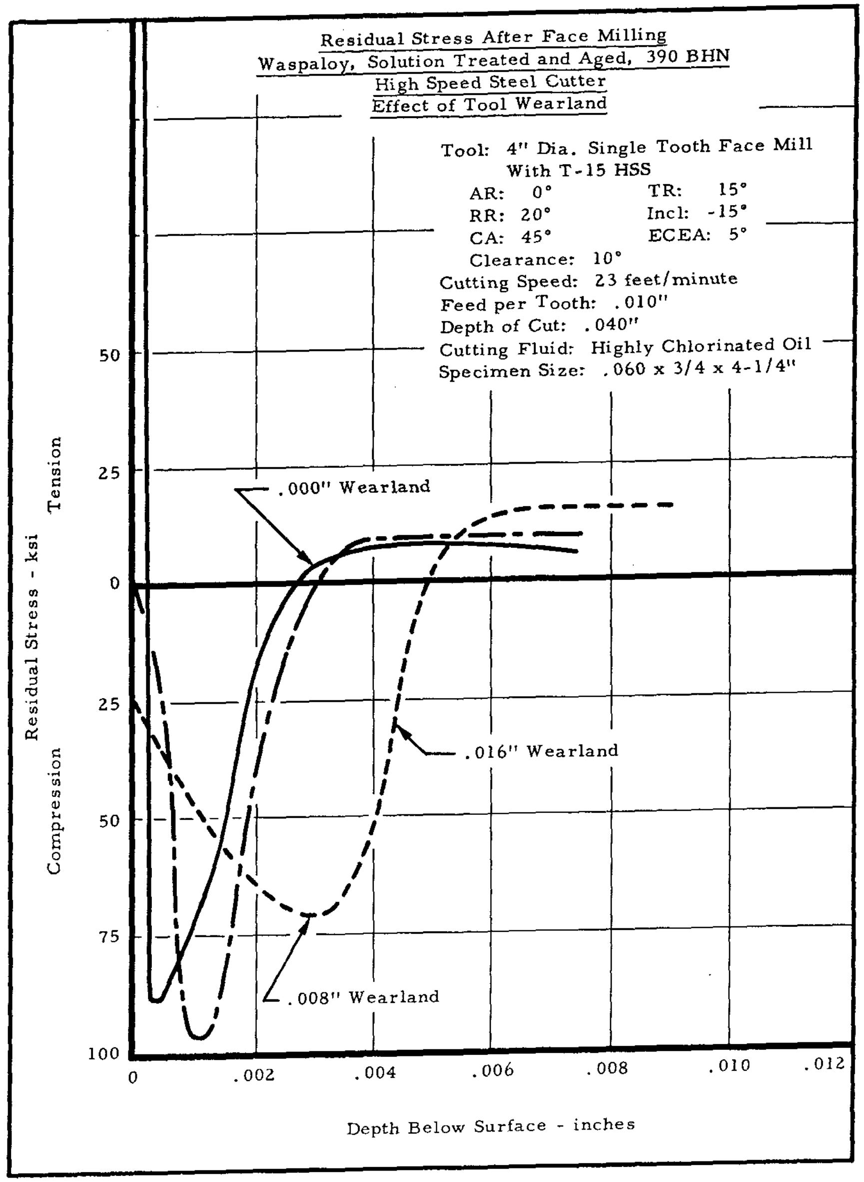
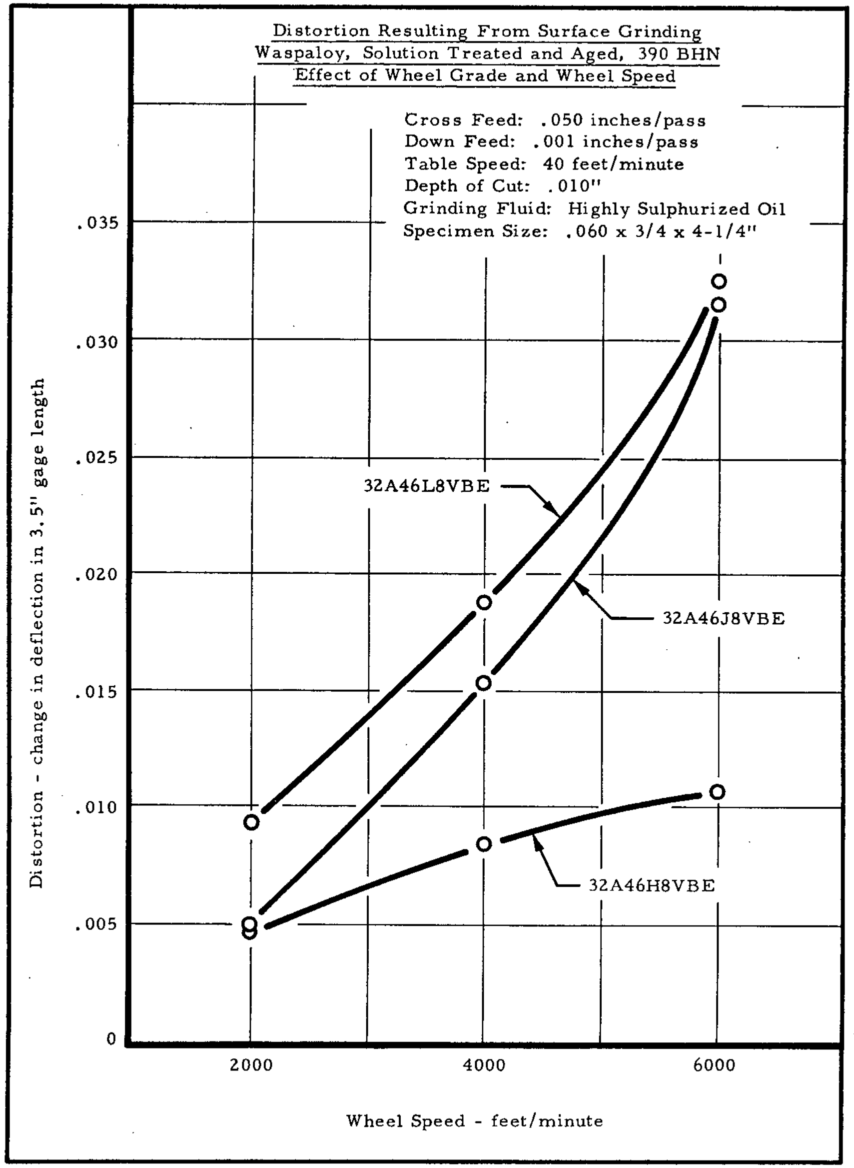
Figure 393



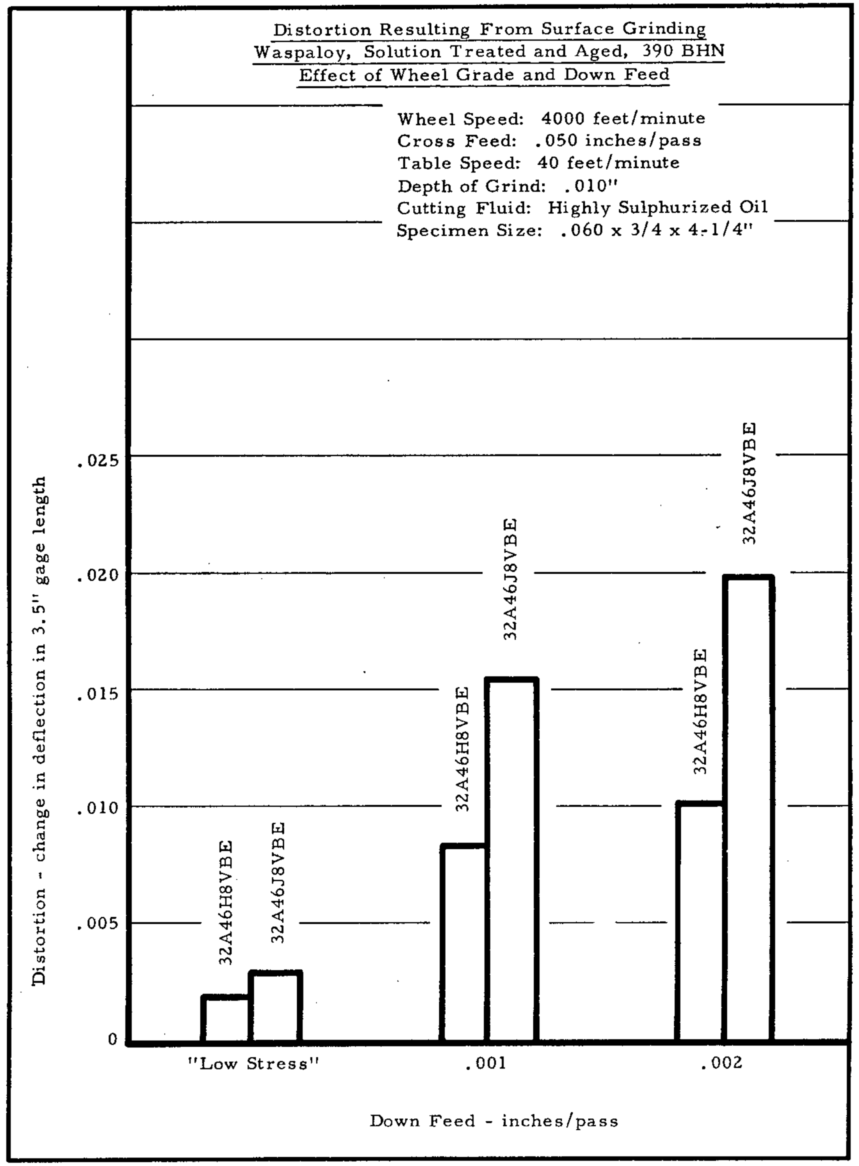
See text, page 324

Figure 394



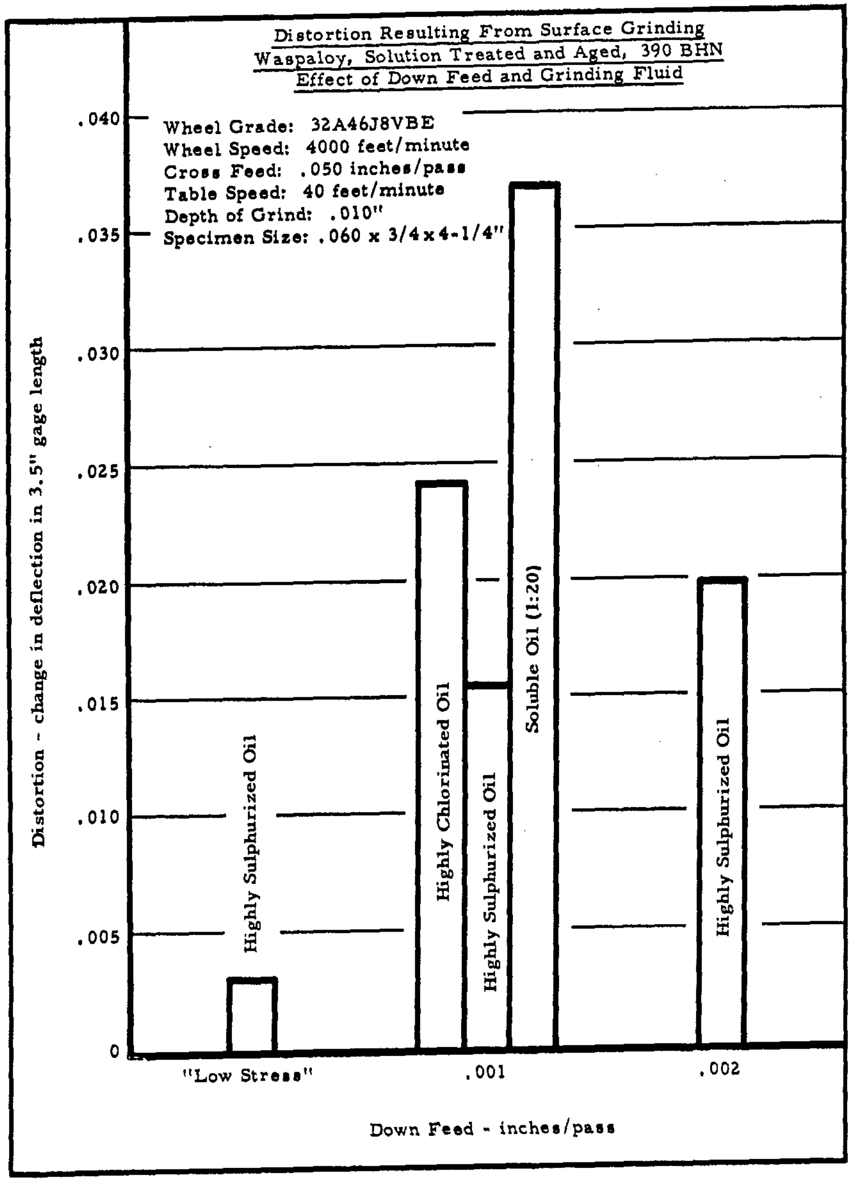
See text, page 325

Figure 395



See text, page 325

Figure 396



See text, page 325

Figure 397

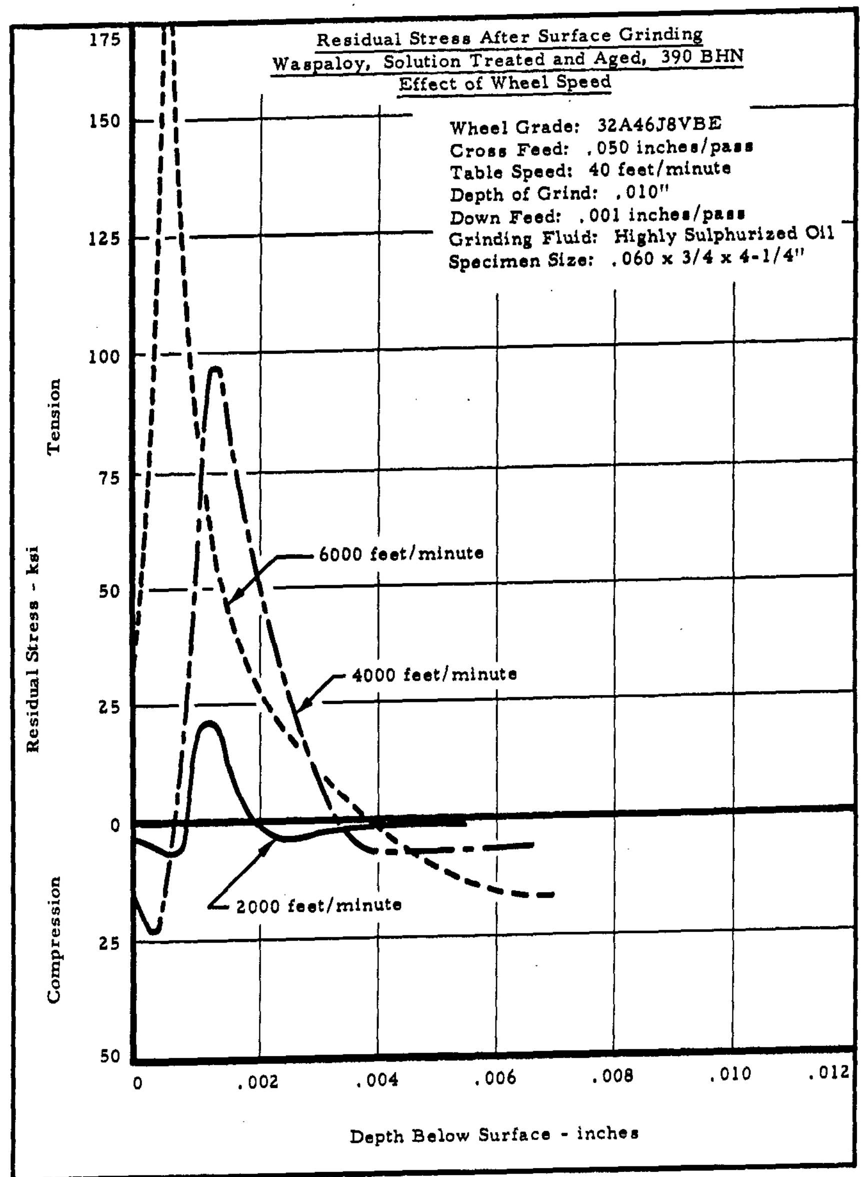


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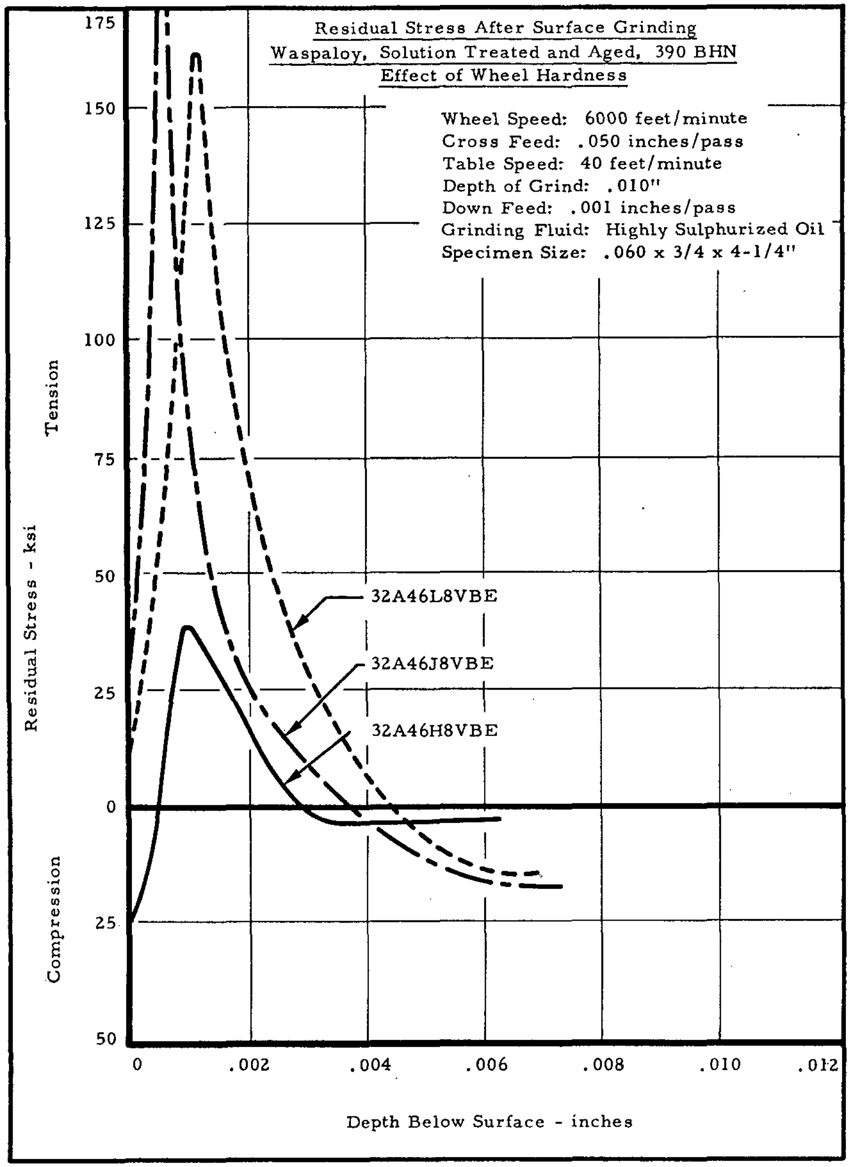
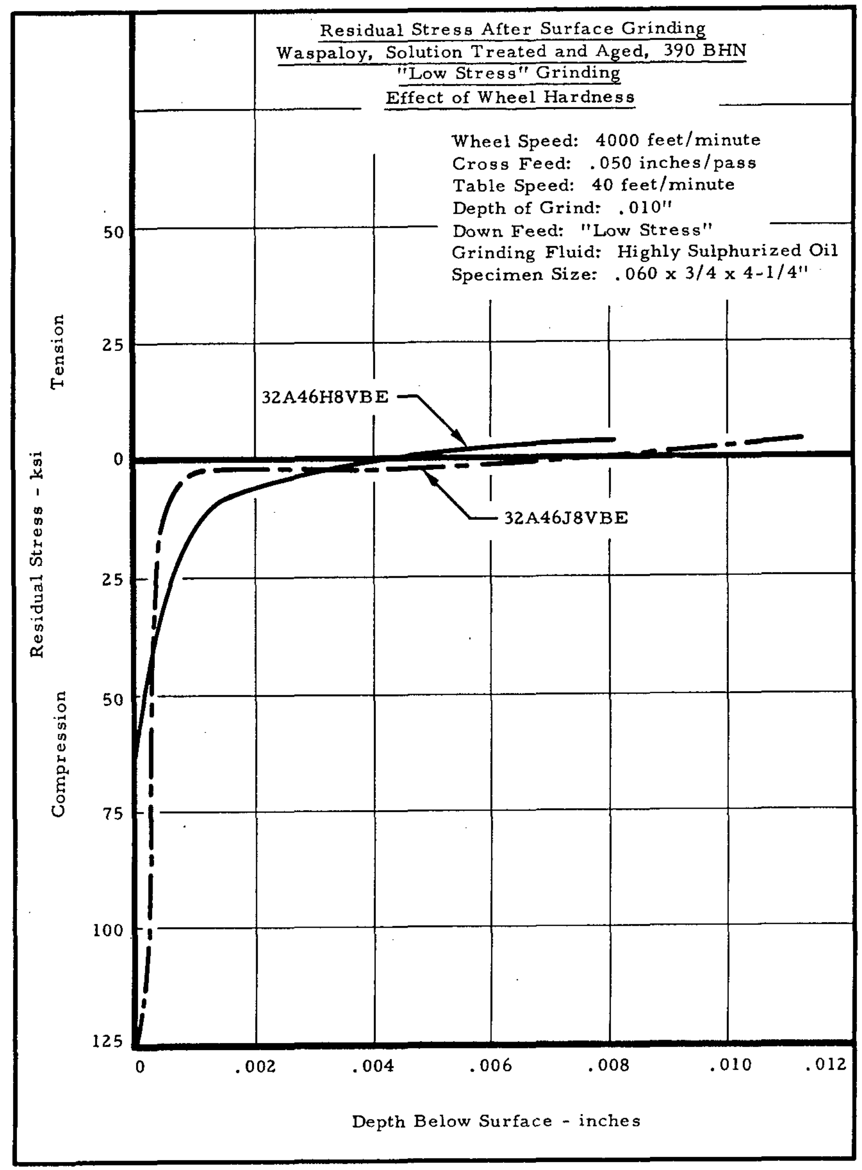
Figure 398



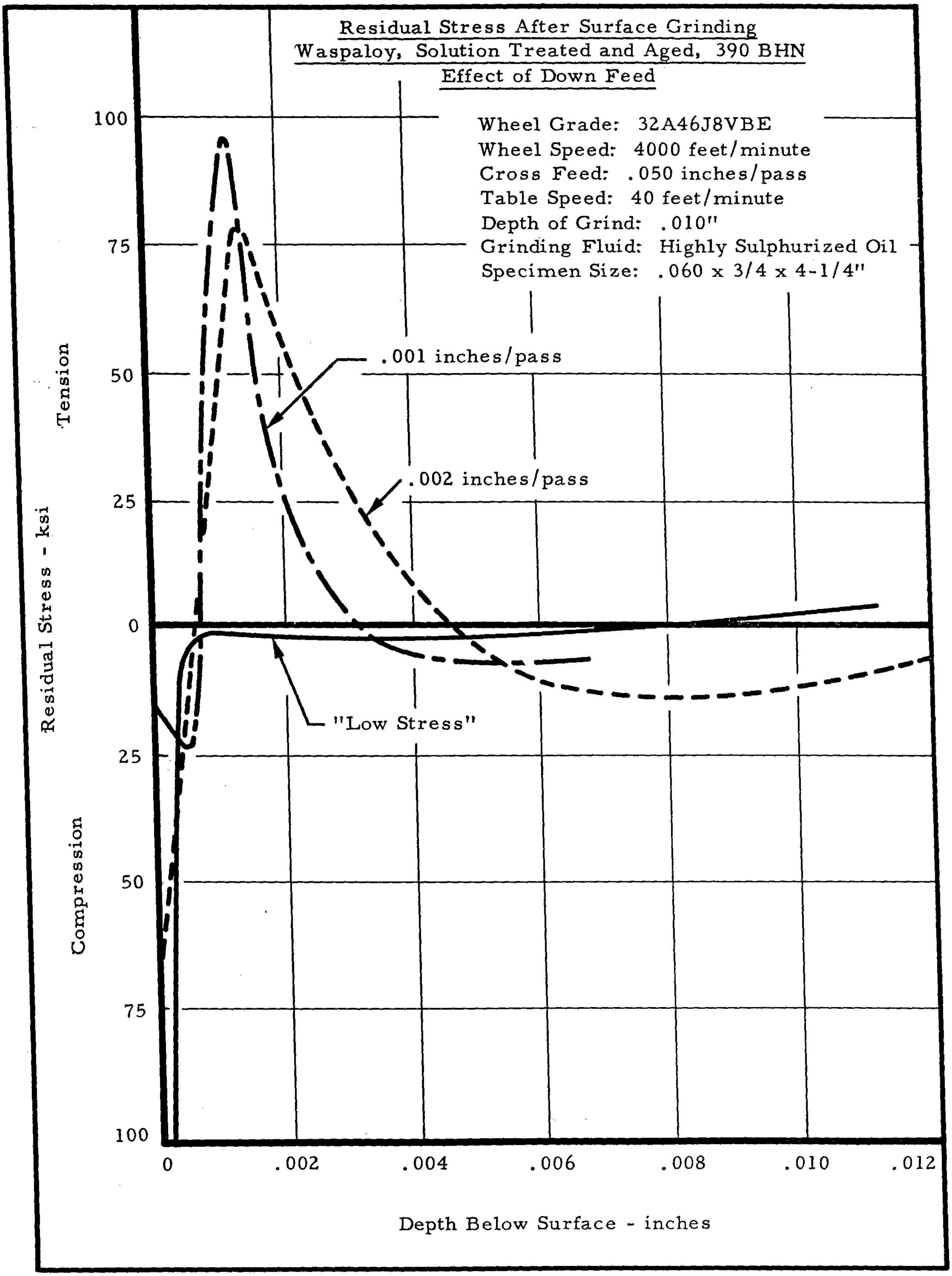
See text, page 326

Figure 399



See text, page 326

Figure 400



See text, page 326

Figure 401

7.2 Comparison of Surface Effects Produced by Conventional and Non-Conventional Machining Methods

A review has been made of surface conditions which may be encountered on high strength structural materials. These surface conditions have been produced by selected conventional and non-conventional machining methods. Data developed under a previous contract is included for comparison. The following processing methods were used:

Abrasive grinding, gentle and abusive
Face milling, gentle and abusive
Electrochemical grinding (ECG), finishing and roughing
Electrical discharge grinding (EDG), finishing and roughing

Materials included in this study were:

250 Grade maraging steel fully aged to 50 R_c
AISI 4340 steel at 50 R_c
D6AC steel at 50 R_c
Titanium 8Al-1Mo-1V at 35 R_c

It has been recognized for some time that control of the conventional processes (milling, grinding, drilling, etc.) is important with regard to surface integrity of the finished product. It can be demonstrated that adequate controls are also required in working with electrical metal removal methods in order that suitable surface quality be achieved.

The resulting surface produced in machining or grinding may contain surface alterations such as plastic deformation, metallurgical transformations, overtempering, macrocracks and microcracks. The surfaces are usually subjected to very high temperature gradients during machining, and the presence of large amounts of plastic strain together with the higher temperature gradients result in residual stress patterns in the surface layer which in turn cause distortion of the component.

Mechanical properties are affected by surface conditions, the most sensitive usually being fatigue resistance and stress corrosion susceptibility.

The purpose of this brief study was to illustrate the range and magnitude of effects obtainable using both mechanical and electrical methods on typical alloys.

7.2 Comparison of Surface Effects Produced by Conventional and Non-Conventional Machining Methods (continued)

Experimental Procedure

Samples suitable for machining by the various metal removal methods were sectioned from hot rolled stock of the four test materials. The configuration of the finished specimen was the same as used for residual stress and distortion studies, Figure 356, page 328. Oversize blanks of each material were heat treated before finish machining, as shown below:

18% Nickel 250 Grade Maraging steel, aged to 50 R_c
AISI 4340 steel, quenched and tempered, 50 R_c
D6AC steel, quenched and tempered, 50 R_c
Titanium 8Al-1Mo-1V, solution annealed, 35 R_c

After heat treatment, the specimens were prepared by "low stress" grinding procedures to the finished dimensions. Then the various test cuts were made on the specimens using the machining and grinding conditions indicated in Tables 28 through 31, pages 360 through 363.

The surface abrasive grinding, Table 28, page 360, was done on a Norton 8" x 24" hydraulic surface grinder. In general, the gentle grinding differed from the abusive grinding as follows:

	Gentle Grind	Abusive Grind
Type of Wheel:	Soft	Hard
Wheel Speed:	Low	High
Down Feed:	Small increments	Large increments
Grinding Fluid:	Highly active chemical oil	Dry

In each case, the gentle grinding conditions were in accordance with recommended practice for machining the materials involved. The abusive grinding condition used is one which an uninformed machine shop operator might very well employ if he were accustomed to grinding the average steel on a tool room grinder.

The gentle face milling conditions used, Table 29, page 361, are those recommended for machining the four respective alloys. The abusive conditions were actually identical with the gentle conditions, the only difference being the sharpness of the tool. In the gentle conditions, a freshly sharpened tool was used having a wearland of 0 to .004". In the abusive face milling, a dull cutter was employed having a wearland of .045 to .050". All face milling was done on a Cincinnati No. 2 Vertical Milling Machine.

The electrochemical grinding was done on a Setco special electrolytic surface grinder using an Anocut power supply and an aluminum oxide metal bonded wheel. Detailed conditions are shown in Table 30, page 362. The finishing ECG conditions differed from the roughing ECG conditions principally in the magnitude of the down feed, .001" versus .003". In both cases, however, the metal removal was primarily by electrolytic action rather than abrasive action.

The electrical discharge grinding was done on an Elox grinder using a graphite wheel as an electrode. The finish EDG was done with low current, while the rough EDG was done with high current, see Table 31, page 363. In finishing, three passes were taken; the first pass at .009" depth, the second at .002" depth, and the third at .0015" depth. In roughing, the entire .010" was removed in one pass. Approximately .010" of stock removal was accomplished by each of the machining methods being studied.

Distortion and Residual Stress

Distortion measurements were made as previously described, section 7.1, using deflection fixturing per Figures 358 and 359, pages 329 and 330. A summary of the distortion exhibited by the various alloys and metal removal methods is shown in Figures 402 and 403, pages 364 and 365. Figure 402, page 364, summarizes abrasive grinding and face milling behavior, while Figure 403, page 365, illustrates the distortion produced by ECG and EDG. In all cases, the total distortion of the specimen is an indication of the integrated residual stresses in the machined surface. The magnitude of the distortion cannot be considered, however, as an indication of the direction or level of the maximum stress. It is, on the other hand, the result of the integrated intensity-depth of the stressed layer. It is interesting to note that the maraging steel is by far the least subject to distortion under the various conditions studied. The maraging alloy exhibited minor distortion under abusive milling conditions and practically no distortion under any of the other test conditions. All of the alloys were essentially distortion free under the gentle or finishing parameters using both mechanical and electrical metal removal methods. Under abusive conditions, the titanium was the most subject to distortion. The two martensitic steels, AISI 4340 and D6AC, exhibited about half of the distortion shown by titanium.

It is also interesting to note that the various grinding operations, both mechanical and electrical, tended to develop tensile stresses in the materials' surfaces. On the other hand, the milling cuts, without exception, produce an overall compressive stress. Again, it is to be emphasized, however, that these indications are not necessarily those

7.2 Comparison of Surface Effects Produced by Conventional and Non-Conventional Machining Methods (continued)

of the outer fiber stress, but are rather an integration of the surface stressed condition. The magnitude of various residual stress and distortion effects as influenced by machining variables can readily be seen by a review of section 7.1.

Metallographic Observations

Samples removed from the ends of all test specimens were mounted and polished by conventional techniques. Care was taken in the preparation in order to obtain maximum resolution at the edges of the test surfaces. All samples were studied at both high and low magnifications in order to ascertain the type and extent of visible surface changes. Photomicrographs at 500X illustrating the surface conditions produced on each alloy as a result of the various metal removal methods were taken. Knoop microhardness surveys were made of each of these alloy surfaces and are also included in this section.

Photomicrographs of the maraging steel are presented as Figures 404 and 405, pages 366 and 367. A summary of microhardness data is shown in Figure 406, page 368. In the case of the abrasive grinding operation on the maraging steel, the abusive condition produced a partially resolutioned surface layer .007" deep. This layer had a minimum hardness of 38 R_C. This layer was relatively uniform, but varied somewhat in depth, as shown in Figures 404B and 416A, pages 366 and 378. The gently ground specimens showed a slight trace of a surface layer of the order of .0001" deep, Figure 404A, page 366. In the case of the abrasively ground specimens, it is presumed that the extreme localized heating resulting from the abusive grinding in particular caused a partial resolutioning or reaustenitizing of the material. On cooling, a part of the austenite reverted to secondary martensite. This martensite in turn was relatively soft since it was in the unaged condition. It is believed, therefore, that the surface layer in the abusively ground specimen (Figure 404B, page 366) is, in fact, a combination of unaged martensite, resolutioned austenite and unaged secondary martensite. Both the milled (Figures 404C and 404D, page 366) and ECG samples (Figures 405A and 405B, page 367) of the maraging steel showed essentially no effects from the metal removal process as judged by both microstructure and microhardness. Trace layers may be visible on the milled specimens, but they cannot be identified. The EDG specimens, however, do show some effects. The finish ground specimen had a slightly softened layer approximately .002" deep, Figure 405C, page 367. There was some metallographic evidence of spattered recast metal on the surface. The rough ground EDG specimen shows a layer of spattered recast material approximately .001" deep, Figure 405D, page 367. The hardness of this layer was

7.2 Comparison of Surface Effects Produced by Conventional and Non-Conventional Machining Methods (continued)

measured as 52 R_C. The same samples show a heat affected zone approximately .010" deep beneath the recast metal having a minimum hardness of 39 R_C. These conditions are illustrated in Figure 406, page 368.

Photomicrographs of AISI 4340 steel are included in Figures 407 and 408, pages 369 and 370. The microhardness data is presented in Figure 409, page 371. Abusive grinding produced the most significant effect on this material. As shown in Figures 407B, page 369, and 416B, page 378, the surface was reaustenitized producing an untempered martensitic layer .008" deep having a maximum hardness of 63 R_C. Beneath this layer was found a zone of overtempered primary martensite approximately .006" deep having a minimum hardness of 46 R_C. The hardened layer on the ground specimens tended to be scalloped or irregular. This effect is shown in the 100X photomicrographs, Figure 416B, page 378. The gently milled AISI 4340 samples showed virtually no surface effects. The abusively milled sample exhibited a layer of untempered martensite .0003" deep, followed by a shallow overtempered zone having a minimum hardness of 47 R_C, Figure 407D, page 369. While the outer white layer was too thin to be directly measured by Tukon, a scratch test indicated that the layer was considerably harder than the matrix. It was concluded, therefore, that the layer was untempered martensite resulting from surface reaustenitizing having a hardness similar to that produced by abusive grinding.

The ECG process produced no measurable surface effects under finish conditions, Figure 408A, page 370. It did, however, produce a slightly pitted surface and occasional isolated pieces of untempered martensite (indicating reaustenitizing) under roughing conditions, Figure 408B, page 370. The EDG process produced spattered recast metal along with surface roughness on both samples. The effect was considerably more pronounced, however, under roughing conditions than under finishing conditions. In the roughing EDG specimen, Figure 408B, page 370, a trace of white layer plus an overtempered sub-zone can also be found. In all cases, the phase changes in AISI 4340 are well known metallurgically. High localized heating at the surface causes a reaustenitization. The sub-quenching of this reaustenitized layer in turn transforms it to untempered martensite having high hardness. The zone immediately beneath the reaustenitized layer exhibits a drop in hardness below that of the base metal as a result of the high temperatures reached and resulting overtempering action.

The general behavior of D6AC steel under the various metal removal conditions (Figures 410 through 412, pages 372 through 374), is quite similar to that exhibited by AISI 4340. In general, the gentle or finish-

7.2 Comparison of Surface Effects Produced by Conventional and Non-Conventional Machining Methods (continued)

ing cuts produced no surface effects except in the case of EDG. The abusive or roughing cuts produced rehardened layers quite similar to those found on 4340. An interesting exception, however, is in the case of EDG roughing, Figure 411D, page 373. In these samples, D6AC exhibited a significant layer of untempered martensite in contrast to only an occasional trace of martensite on the untempered AISI 4340, Figure 408D, page 370.

As seen in Figures 413 through 415, pages 375 through 377, titanium 8Al-1Mo-1V exhibited no major changes in surface hardness or layer formation except in the samples cut under EDG roughing conditions. In this case, a discontinuous layer of spattered recast metal was formed, Figure 414D, page 376. The thickness of the layer varied from .003" to .009". The hardness of this layer was measured as 47 R_C. Underneath the recast layer was found a rather deeply affected zone. The maximum depth of penetration was .015" which was associated with a hardness drop of 30 R_C. A 500X photomicrograph is shown in Figure 414D, page 376, illustrating the recast layer plus the sub-zone whose structure has been substantially altered. Except for this variable, the only other effect observed was a moderate surface roughening produced by the electrical metal removal methods.

Analysis of Data

The following general conclusions may be drawn from this study:

From a general evaluation of gentle and abusive processing conditions, it may be concluded that while gentle processing procedures eliminate surface alterations to a large extent, it should be recognized that most processes still create some minor alterations. These, for the most part, have not been given extensive consideration and may or may not be of practical importance.

On the other hand, the so-called abusive conditions, for the most part, create extensive surface changes which are readily interpretable as surface damage which is detrimental to part performance in service.

In comparing various processes, such as noted in this study, electrochemical grinding (ECG) consistently provided the least amount of recognizable surface alteration. On the other hand, rough EDG and abusive abrasive grinding, particularly when tied in with heavy stock removal, produced major changes in the surface.

Some interesting observations were made with respect to the effect of various processes on specific alloys. It was surprising to note that maraging steels, in contrast with steels such as AISI 4340 and D6AC, produced a softened layer and a very small amount of distortion, which indicates low residual stresses. No work was performed with respect to evaluation of the softened layer of maraging steels in relationship to any type of simulated service requirements.

The AISI 4340 and D6AC steels developed hard white layers of untempered martensite with subsurface overtempering below this layer. The white layer is highly stressed and in most applications where higher stresses and stress corrosion environments are encountered it would be considered detrimental. In the titanium studied, namely Ti 8Al-1Mo-1V, microstructural surface alterations were not apparent at magnifications up to 1500X even when abusive conditions were employed, except for spattered metal attached to the surface in the case of high amperage EDG.

With respect to considerations of distortion, the resultant stress is generally tensile in the case of abrasive grinding and EDM. The resultant residual stress is compressive in the case of carbide face milling. It is possible to obtain a small resultant compressive stress in the gentle or "low stress" grinding technique on high strength steels. ECG tends to produce very small tensile stresses.

From an overall or general point of view, it may be concluded that evaluations of manufacturing processes as they influence surfaces of components are important. Variation in response, such as noted herein, indicates the need for individual consideration of specific alloy-process-service situations.

The various observations concerning the surface alterations described are highly significant in all applications where emphasis is placed on components requiring high strength subjected to a variety of environments. Thus, experimental programs must be developed to obtain data necessary for designing parts having structural integrity. The fact that surface alterations are produced does not mean that these necessarily influence mechanical and physical properties of all types of parts in service. Certain components are not stressed sufficiently in service to develop failures even when surface effects produced in metal removal processes, such as EDM and abrasive grinding, are present.

For many critical applications in the aerospace industry, more data must be obtained relating the effects of these surface changes to the mechanical and physical properties of materials. For marginal situations, an awareness, at least, of the potential significance of manufacturing processes as they influence surfaces is considered imperative.

TABLE 28

SURFACE ABRASIVE GRINDING CONDITIONS

	Maraging Steel 50 R_c		4340 Steel 50 R_c		D6AC Steel 50 R_c		Ti-8Al-1Mo-1V 35 R_c	
	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive
Type Wheel	A46HV	A46MV	A46HV	A46MV	A46HV	A46MV	C60HV	A46MV
Wheel Speed, ft./min.	2000	6000	2000	6000	2000	6000	2000	6000
Cross Feed, in./pass	.050	.050	.050	.050	.050	.050	.050	.050
Table Speed, ft./min.	40	40	40	40	40	40	40	40
Down Feed, in./pass	L.S.*	.002	L.S.*	.002	L.S.*	.002	L.S.*	.002
Grind Fluid	HCO**	Dry	HCO**	Dry	HCO**	Dry	HCO**	Dry

Machine: Norton 8" x 24" Hydraulic Surface Grinder
Total Stock Removed = .010"

*L.S. = .008" stock removed at .0005 in./pass
last .002": .0004, .0004, .0002, .0002
.0002, .0002, .0002, .0002

**HCO = Highly Chlorinated Oil

TABLE 29

FACE MILLING CONDITIONS

	Maraging Steel 50 R_c		4340 Steel 50 R_c		D6AC Steel 50 R_c		Ti-8Al-1Mo-1V 35 R_c	
	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive
Cutter Axial Rake, deg.	-15	-15	3	3	3	3	10	10
Cutter Radial Rake, deg.	-7	-7	-18	-18	-18	-18	0	0
Tool Material, Carbide	C-2	C-2	C-6	C-6	C-6	C-6	C-2	C-2
Feed per tooth, inches	.005	.005	.005	.005	.005	.005	.005	.005
Cut Speed, ft./min.	180	180	150	150	150	150	350	350
Tool Flank Wear, in.	0-.004	.045-.050	0-.004	.045-.050	0-.004	.045-.050	0-.004	.045-.050

Machine: No. 2 Cincinnati Vertical High Speed Dial Type Miller
Cutter: 4" dia., single tooth face mill; 45° corner angle; 5° clearance
Depth of Cut: .010"
Width of Cut: 3/4"
Cutting Fluid: None

TABLE 30

ELECTROCHEMICAL GRINDING CONDITIONS*

	Maraging Steel 50 R_c		4340 Steel 50 R_c		D6AC Steel 50 R_c		Ti-8Al-1Mo-1V 35 R_c	
	Finish	Rough	Finish	Rough	Finish	Rough	Finish	Rough
Voltage	7	10	7	10	7	10	6	15
Current, amperes	80-100	120-140	80-100	120-140	80-100	120-140	10-20	100-150
Table Speed, in. /min.	30	6	30	6	30	6	50	6
Down Feed, in. /pass	.001	.003	.001	.003	.001	.003	.001	.003

Machine: Setco Special Electrolytic Surface Grinder with Anocut Model 600B (600 amp.) Power Supply
Electrode Wheel: 6" dia. x 1-1/4" wide; aluminum oxide metal bonded wheel
Electrolyte: Setco Type "A"
Wheel rpm: 3600
Stock Removed: .010"

*Electrochemical grinding done at and by courtesy of Standard Electrical Tool Company, Cincinnati, Ohio.

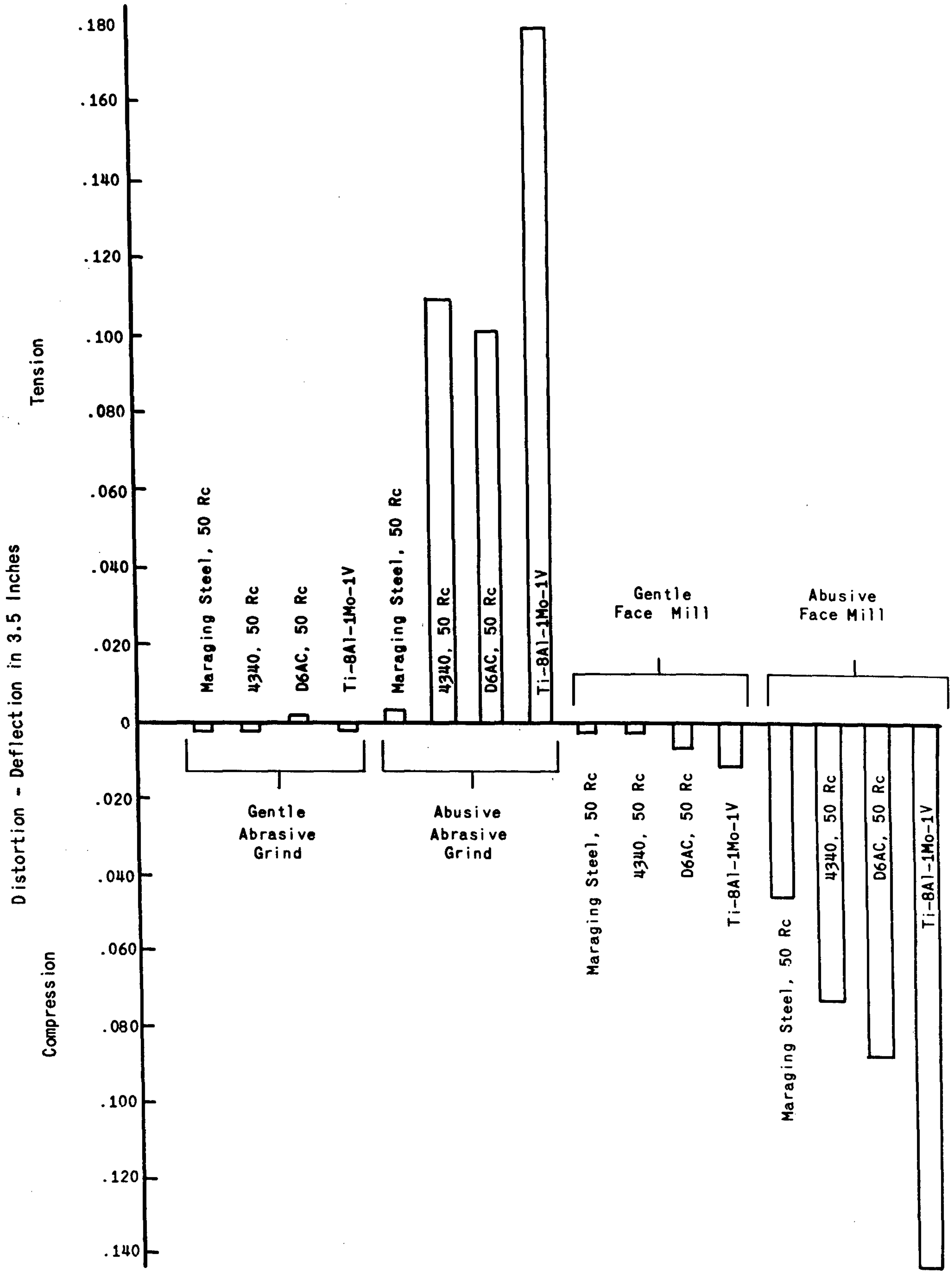
TABLE 31

ELECTRICAL DISCHARGE GRINDING CONDITIONS*

	Maraging Steel 50 R_c		4340 Steel 50 R_c		D6AC Steel 50 R_c		Ti-8Al-1Mo-1V 35 R_c	
	Finish	Rough	Finish	Rough	Finish	Rough	Finish	Rough
Voltage	80	70	80	70	80	70	80	80
Current, amperes	.5-3	20	.5-3	20	.5-3	20	1-5	5-10
Table Speed, in./min.	.4	1.4	.4	2.1	.4	2.1	.5	.4
Depth 1st pass	.009	.010	.009	.010	.009	.010	.009	.010
Depth 2nd pass	.002	--	.002	--	.002	--	.002	--
Depth 3rd pass	.0015	--	.0015	--	.0015	--	.0015	--

Machine: Elox Grinder, #1NPS-D60B-318 Power Supply
Dielectric Standard Eloxol #G
Electrode: Graphite Wheel
Stock Removed: .010"

*Electrical discharge grinding done at and by courtesy of the Elox Corporation of Michigan, Detroit, Michigan.



SPECIMEN DISTORTION PRODUCED BY CONVENTIONAL MACHINING METHODS.

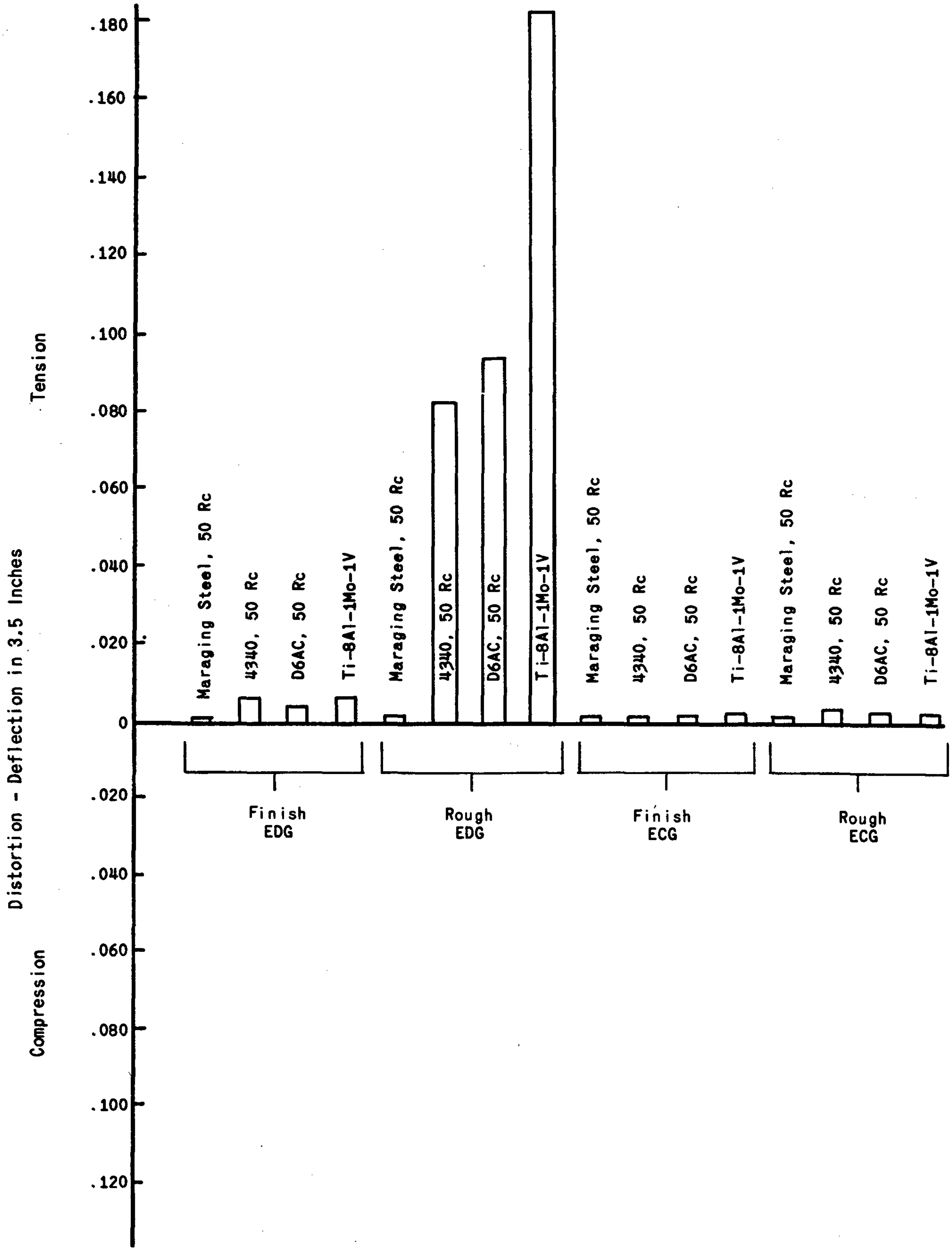
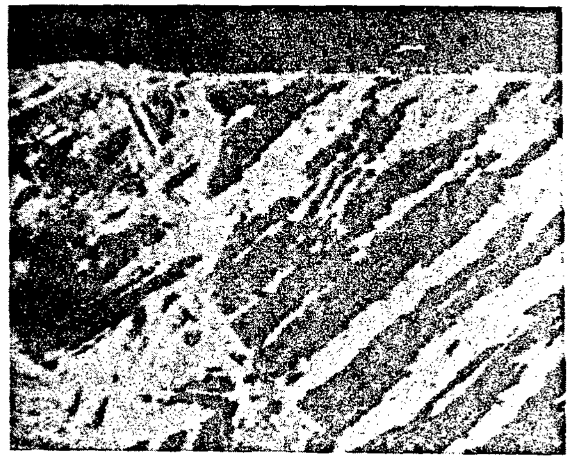


FIGURE 10. SPECIMEN DISTORTION PRODUCED BY NON-CONVENTIONAL MACHINING METHODS.

A. GENTLE ABRASIVE GRIND.
Surface Layer: Trace, no measurable hardness change.

B. ABUSIVE ABRASIVE GRIND.
Surface Layer: .007" deep resolutioned austenite with minimum hardness of 38 Rc

C. GENTLE FACE MILL (sharp cutter)
Surface Layer: Trace, no measurable hardness change



D. ABUSIVE FACE MILL (dull cutter)
Surface Layer: Trace, no measurable hardness change

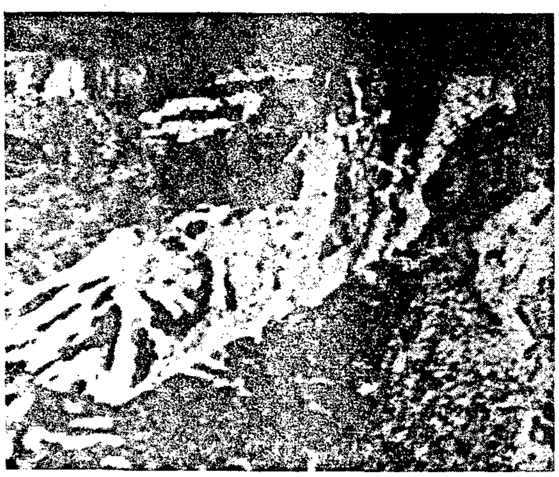
SURFACE EFFECTS ON 18% NICKEL 250 GRADE MARAGING STEEL AGED TO 50 Rc. 500X

See text, page 356

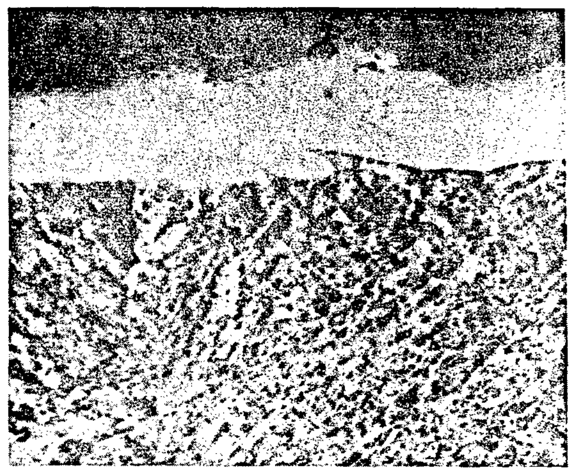
Figure 404

A. FINISH GRIND BY ECG.
Surface Layer: None, no measurable hardness change.

B. ROUGH GRIND BY ECG.
Surface Layer: None, no measurable hardness change.



C. FINISH GRIND BY EDG.
Surface Layer: Trace.
Sub-zone .002" deep with minimum hardness of 46 Rc.

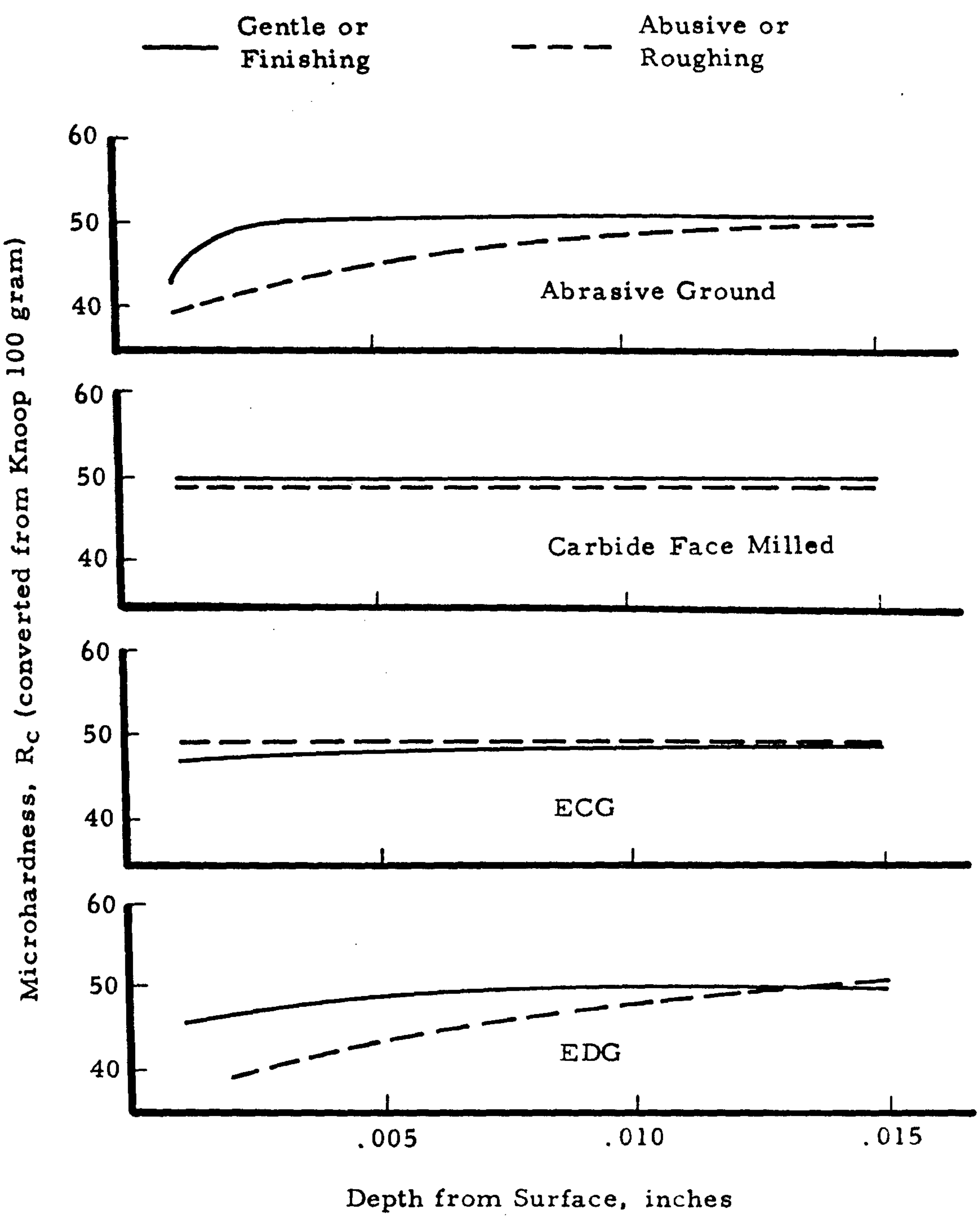


D. ROUGH GRIND BY EDG.
Surface Layer: Spattered recast metal .001 deep at 52 Rc. Sub-zone .010" deep with minimum hardness of 39 Rc.

SURFACE EFFECTS ON 18% NICKEL 250 GRADE MARAGING STEEL AGED TO 50 Rc. 500X

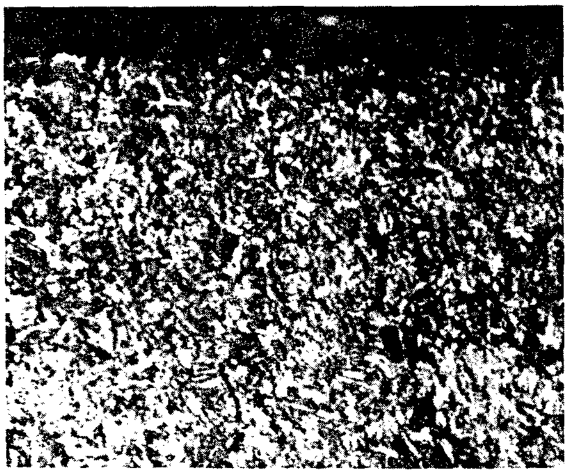
See text, page 356

Figure 405

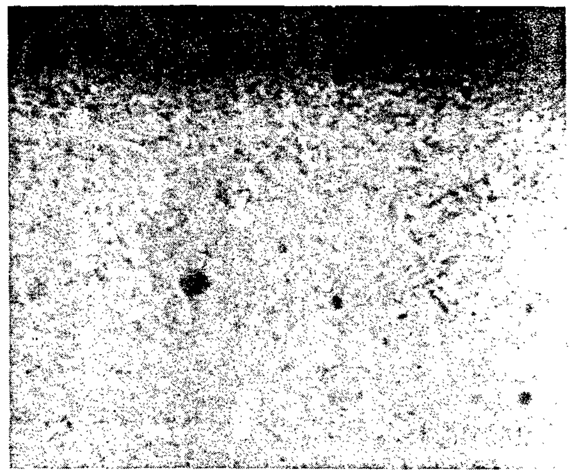


Microhardness of Surface Layer of 250 Grade Maraging Steel, 50 R_C

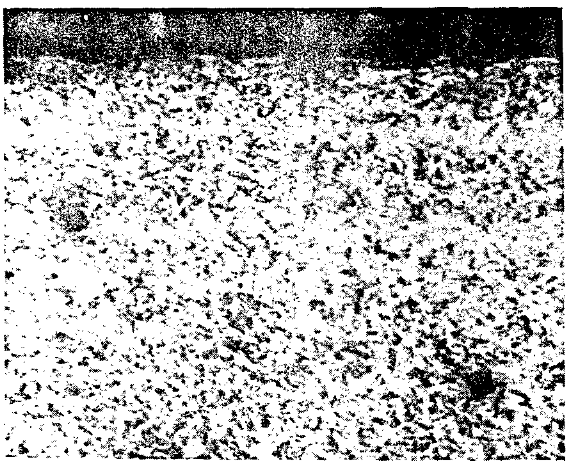
See text, page 356



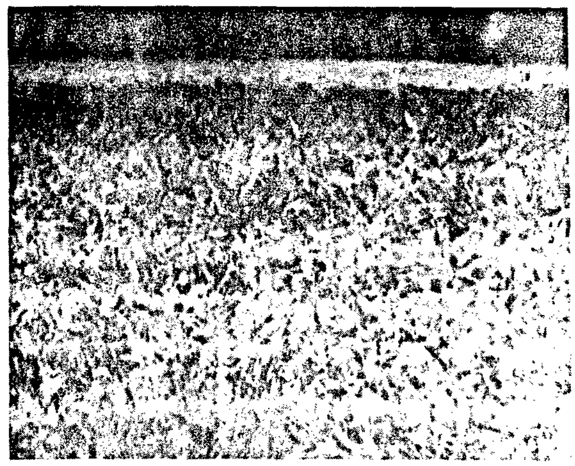
A. GENTLE ABRASIVE GRIND.
Surface Layer: None, no hardness change.



B. ABUSIVE ABRASIVE GRIND.
Surface Layer: Up to .008" deep untempered martensite at 63 Rc. Sub-zone .006" deep overtempered to 46 Rc minimum.



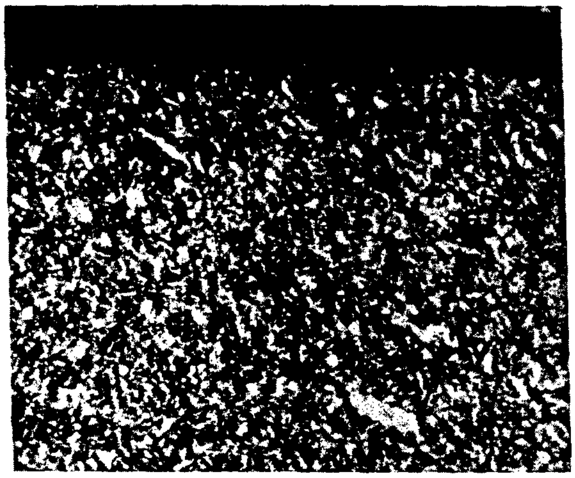
C. GENTLE FACE MILL (sharp cutter).
Surface Layer: None, no hardness change.



D. ABUSIVE FACE MILL (dull cutter)
Surface Layer: .0003" deep untempered martensite, approximately 63 Rc. Sub-zone overtempered approximately .001" deep.

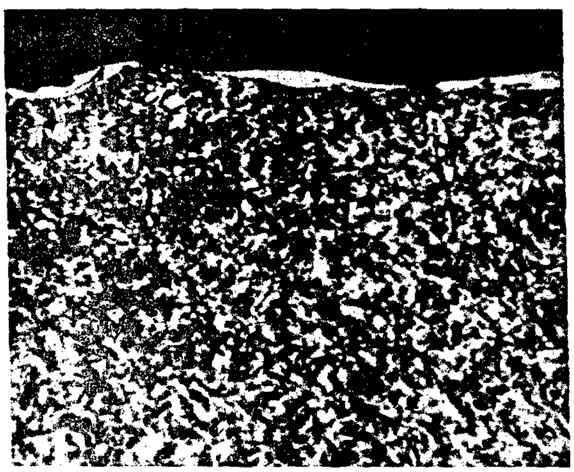
SURFACE EFFECTS ON AISI 4340 QUENCHED AND TEMPERED TO 50 Rc. 500X

See text, page 357

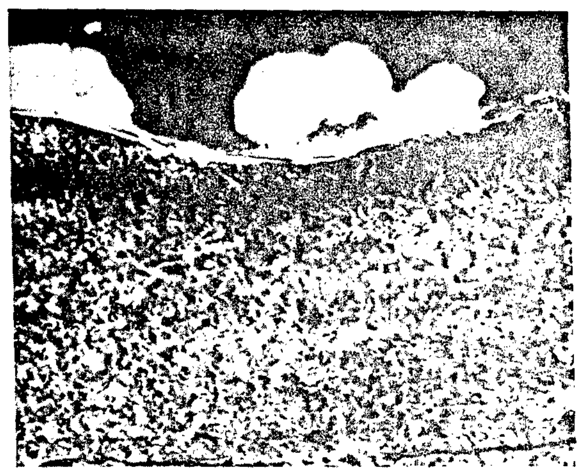


A. FINISH GRIND BY ECG.
Surface Layer: None, no measurable hardness change.

B. ROUGH GRIND BY ECG.
Surface Layer: Slight pitting, discontinuous untempered martensite layer approximately .0008" deep maximum.

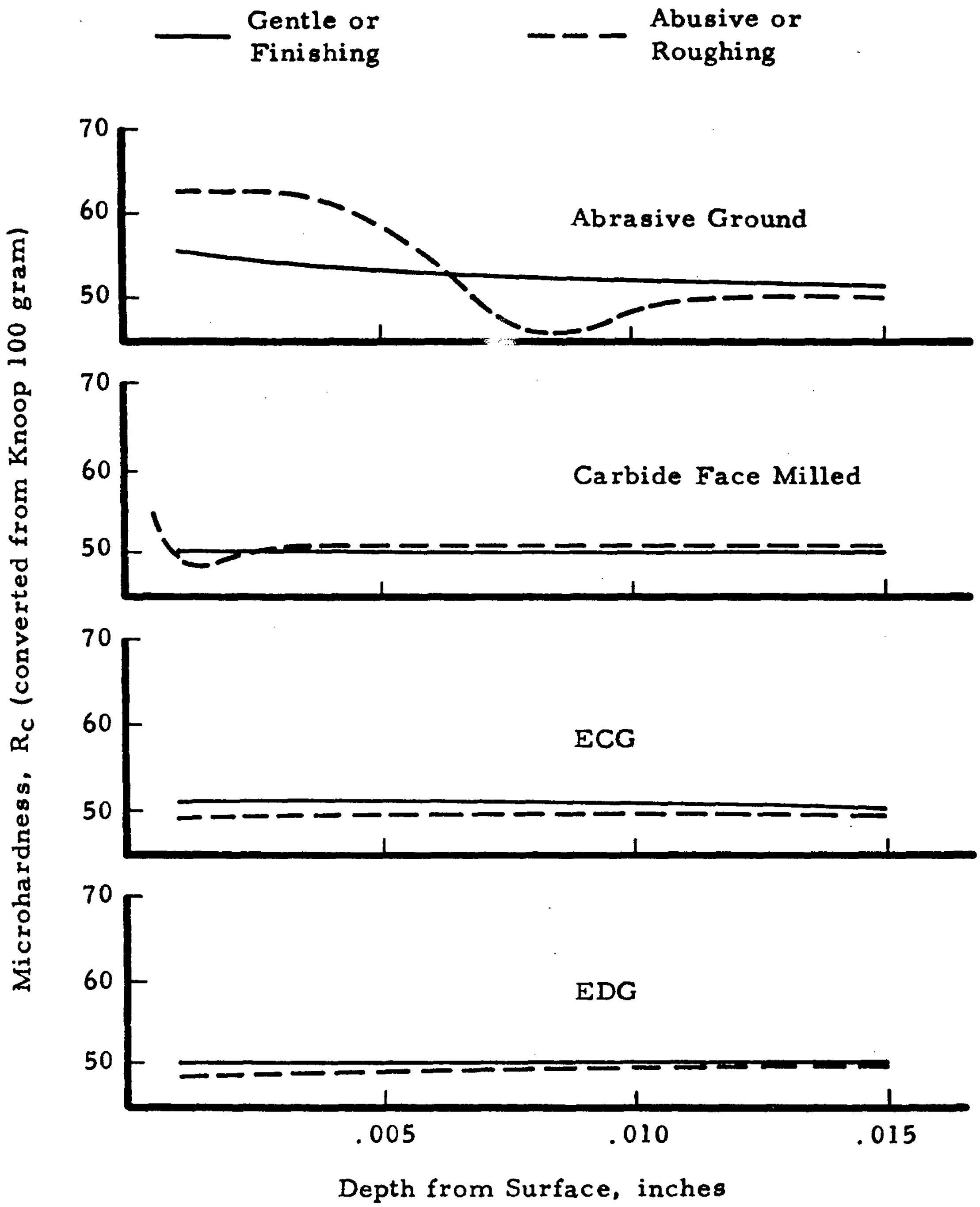


C. FINISH GRIND BY EDG.
Surface Layer: Trace recast spattered metal, no measurable hardness change.



D. ROUGH GRIND BY EDG.
Surface Layer: Pitting and spattered recast metal .001" deep. Shallow over-tempered sub-zone.

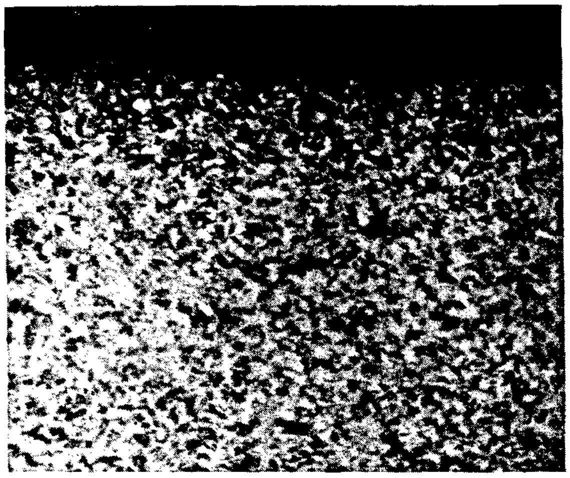
SURFACE EFFECTS ON AISI 4340 QUENCHED AND TEMPERED TO 50 Rc. 500X



Microhardness of Surface Layer of 4340 Steel, 50 R_c

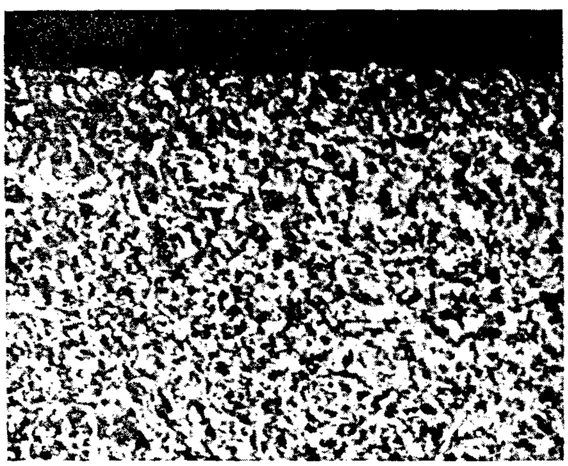
See text, page 357

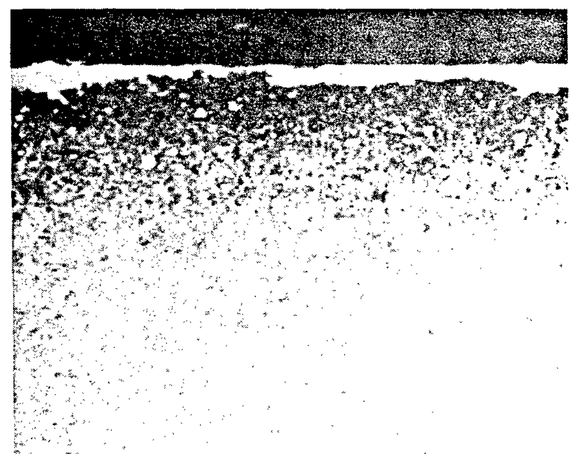
Figure 409



A. GENTLE ABRASIVE GRIND.
Surface Layer: None, no measurable hardness change.

B. ABUSIVE ABRASIVE GRIND.
Surface Layer: .004" deep untempered martensite at 68 Rc. Sub-zone .004" deep overtempered to 47 Rc minimum.





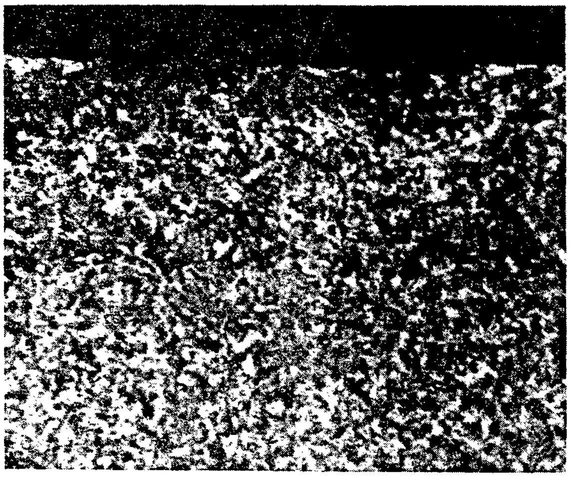
C. GENTLE FACE MILL (sharp cutter)
Surface Layer: None, no measurable hardness change.

D. ABUSIVE FACE MILL (dull cutter)
Surface Layer: .0005" deep untempered martensite at 54 Rc. Sub-zone .003" deep overtempered martensite at 47 Rc minimum.

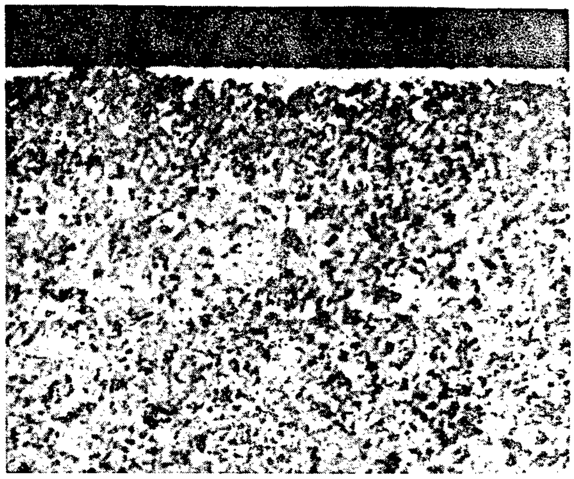
SURFACE EFFECTS ON D6AC QUENCHED AND TEMPERED TO 50 Rc. 500X

See text, page 357

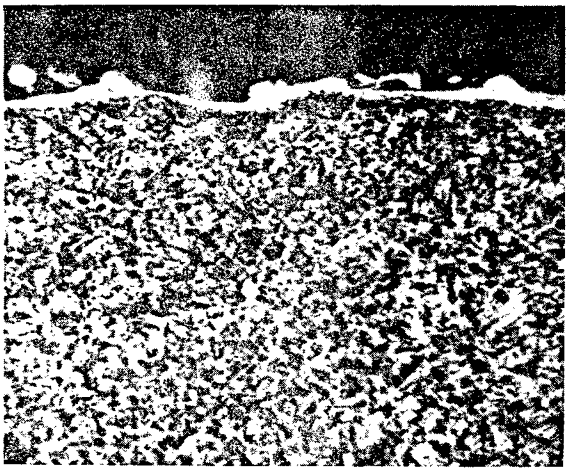
Figure 410



A. FINISH GRIND BY ECG.
Surface Layer: None, no measurable hardness change.



B. ROUGH GRIND BY ECG.
Surface Layer: Trace of untempered martensite less than .0003". No measurable sub-zone hardness change.

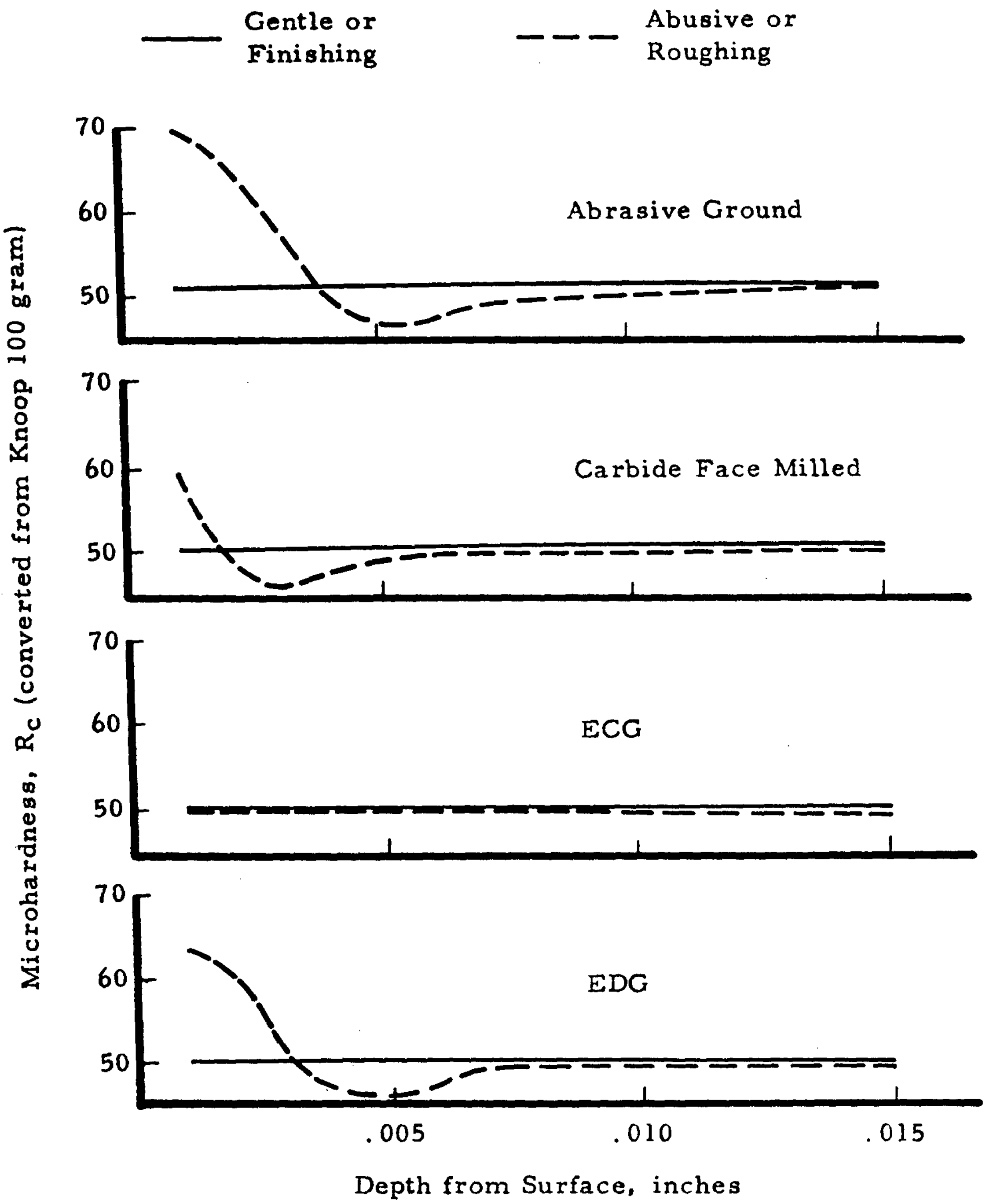


C. FINISH GRIND BY EDG.
Surface Layer: Trace of recast spattered metal. Depth less than .0003". No measurable sub-zone hardness change.

D. ROUGH GRIND BY EDG.
Surface Layer: Spattered recast metal .0003" thick. Untempered martensite .0015" deep at 63 Rc. Overtempered sub-zone .004" deep at 46 Rc minimum.

SURFACE EFFECTS ON D6AC QUENCHED AND TEMPERED TO 50 Rc. 500X

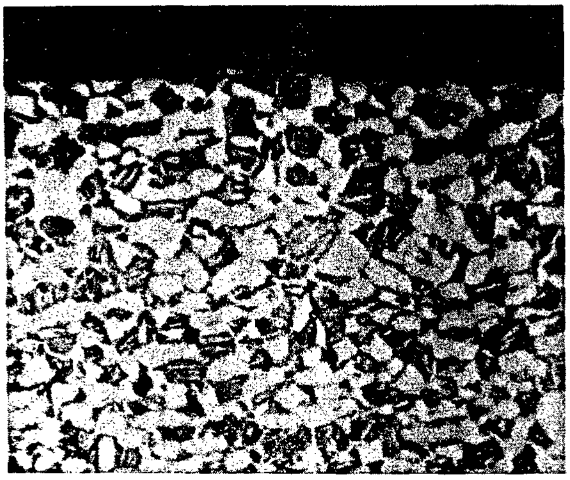
See text, page 357



Microhardness of Surface Layer of D6AC Steel, 50 R_c

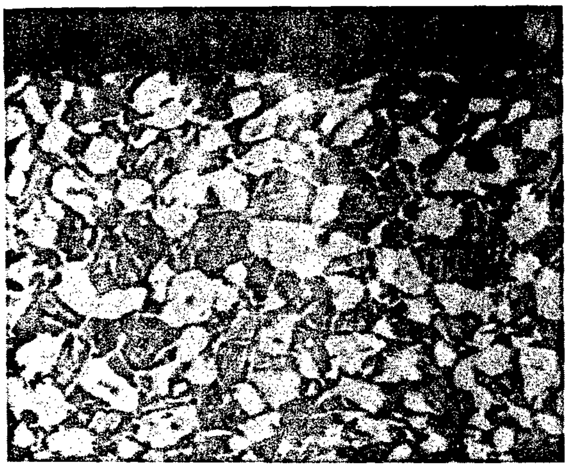
See text, page 357

Figure 412



A. GENTLE ABRASIVE GRIND.
Surface Layer: None, no measurable hardness change.

B. ABUSIVE ABRASIVE GRIND.
Surface Layer: None visible, hardness buildup to 38 Rc for .001" depth.



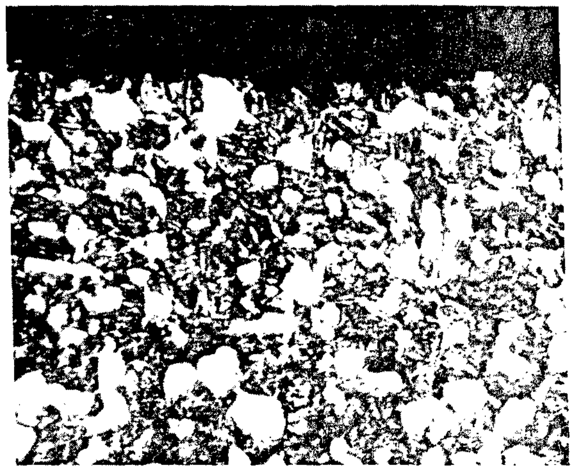
C. GENTLE FACE MILL (sharp cutter)
Surface Layer: None.

D. ABUSIVE FACE MILL (dull cutter)
Surface Layer: None.

FIGURE 19. SURFACE EFFECTS ON Ti-8Al-1Mo-1V AT 35 Rc. 500X

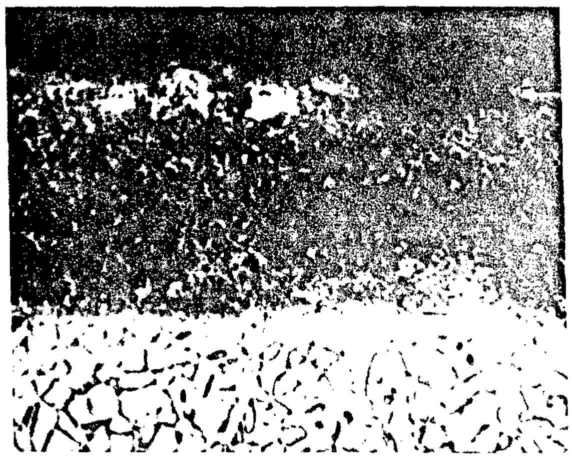
See text, page 358

A. FINISH GRIND BY ECG.
Surface Layer: Less than .0005" deep.



B. ROUGH GRIND BY ECG.
Surface Layer: None, pitted .0005" deep.

C. FINISH GRIND BY EDG.
Surface Layer: None, pitted .001" deep.



D. ROUGH GRIND BY EDG.
Surface Layer: Spattered recast metal (discontinuous) .003-.009" deep at 47 Rc. Heat affected sub-zone .015" deep.

FIGURE 20. SURFACE EFFECTS ON Ti-8Al-1Mo-1V AT 35 Rc. 500X

See text, page 358

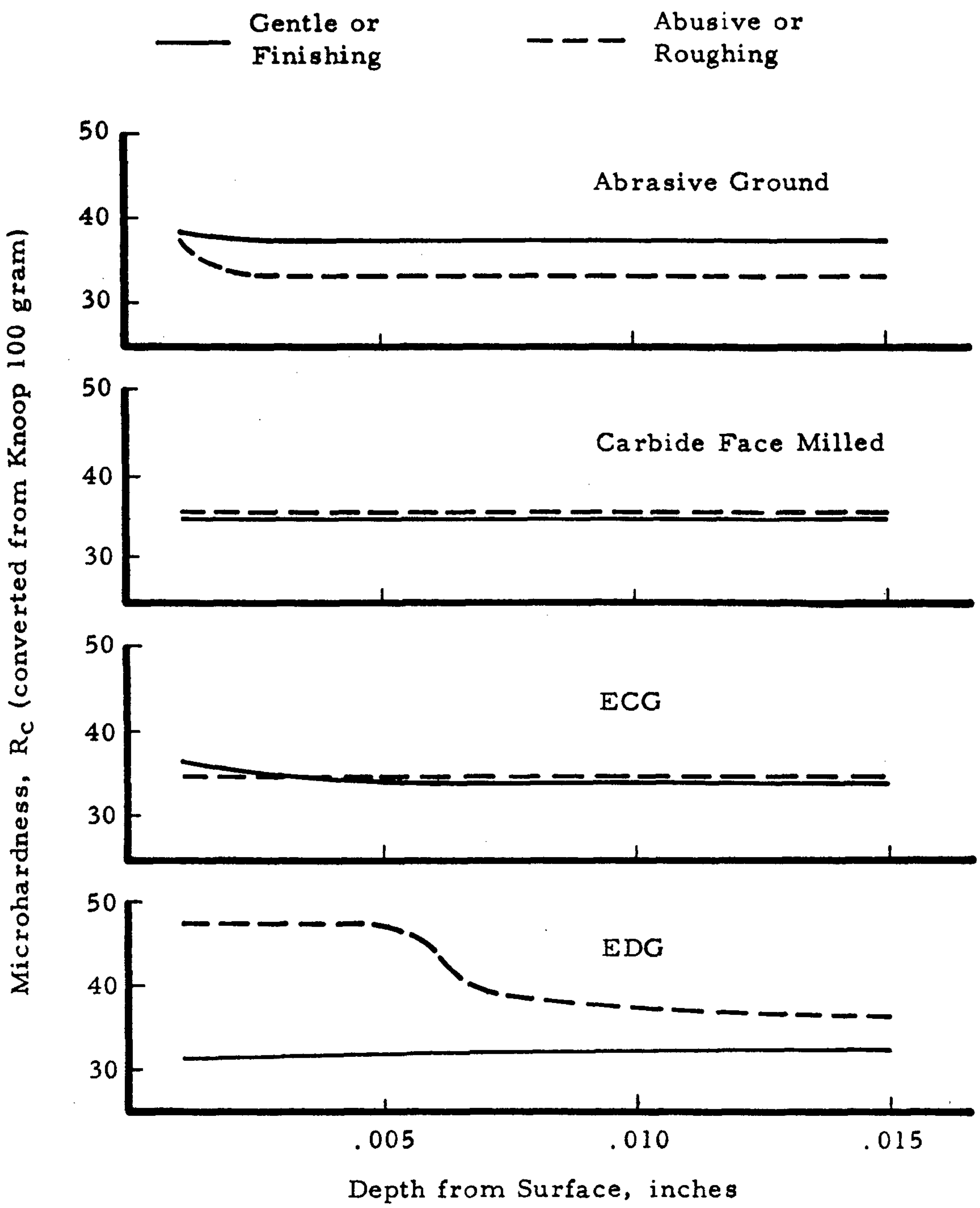
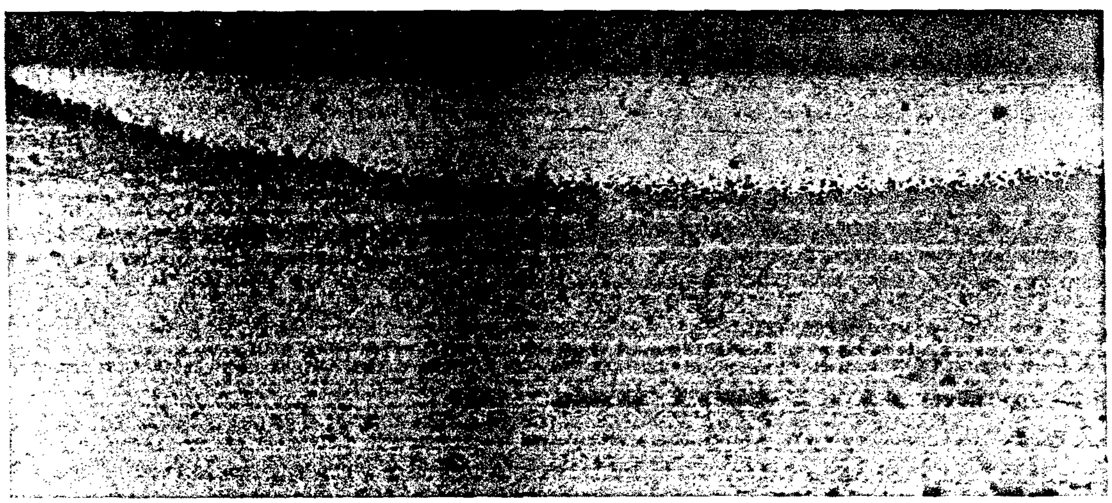


Figure 25. Microhardness of Surface Layer of Ti-8Al-1Mo-1V, 35 R_c

See text, page 358

A. 250 GRADE MARAGING STEEL, 50 Rc.
Abusive abrasive ground with layer .007" deep of resolutioned austenite, 38 Rc.
See Figure 404B



B. AISI 4340, 50 Rc.
Abusive abrasive ground with surface layer up to .008" deep of untempered martensite, 63 Rc. See Figure 407B

PHOTOMICROGRAPHS SHOWING OVERALL CHARACTERISTICS OF DEEP SURFACE LAYERS. 100X

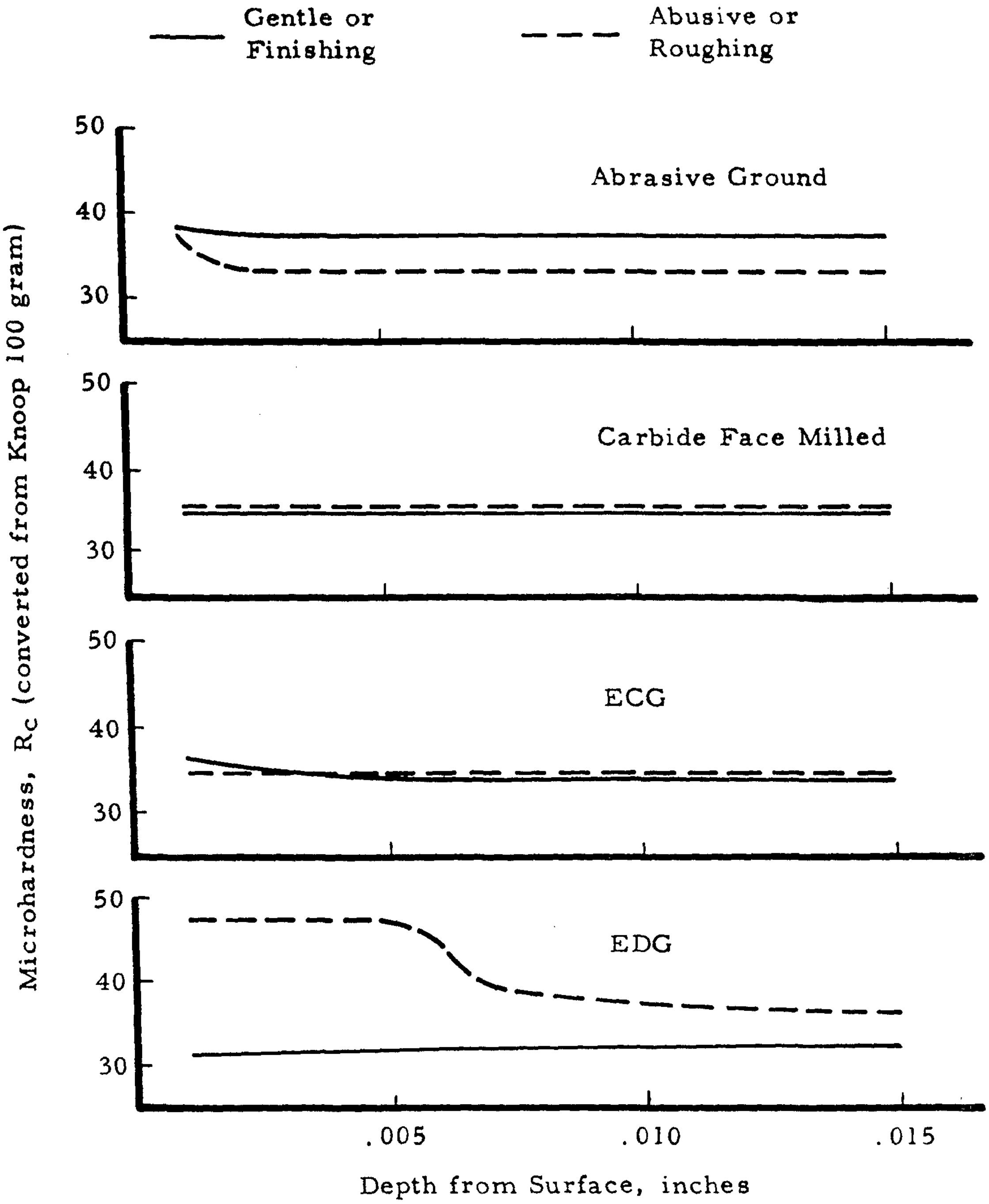


Figure 25. Microhardness of Surface Layer of Ti-8Al-1Mo-1V, 35 R_c

TABLE 32

AVERAGE UNIT POWER AND COEFFICIENT OF FRICTION FOR TURNING WITH SHARP TOOLS

Tool Material: See Below

Cutting Fluid: Soluble Oil (1:20)

Depth of Cut: .062"

Tool Geometry:	HSS	Carbide
BR:	0°	5° Neg.
SR:	10°	5° Neg.
NR:	.030"	.030"

Work Material	Tool Material	Feed in./rev.	Cutting Speed ft./min.	Average Coefficient of Friction	Average Unit Power hp/cu. in./min.
250 Grade Maraging Steel Annealed 341 BHN	883 Carbide	.009	475	.51	1.4
	M-2 HSS	.009	80	.74	1.1
250 Grade Maraging Steel Solution Treated & Aged 52-53 R_c	883 Carbide	.009	275	.66	1.7
	M-2 HSS	.009	40	.58	1.3
300 Grade Maraging Steel 302 BHN	883 Carbide	.009	500	.49	1.2
	M-2 HSS	.009	40	.79	1.3
300 Grade Maraging Steel Solution Treated & Aged 54 R_c	883 Carbide	.009	180	.47	1.6
	M-2 HSS	.009	20	.80	1.2
HP 9-4-25 Annealed 375 BHN	370 Carbide	.009	300	.40	1.5
	M-2 HSS	.009	50	.69	2.1
HP 9-4-25 Quenched & Tempered 415 BHN	370 Carbide	.009	300	.44	1.7
	M-2 HSS	.009	50	.74	1.8

TABLE 32 (continued)

AVERAGE UNIT POWER AND COEFFICIENT OF FRICTION FOR TURNING WITH SHARP TOOLS

Work Material	Tool Material	Feed in. /rev.	Cutting Speed ft. /min.	Average Coefficient of Friction	Average Unit Power hp/cu. in. /min.
Titanium 8Al-1Mo-1V Annealed 311 BHN	883 Carbide	.005	250	.47	1.3
	M-2 HSS	.005	60	.64	1.0
Titanium 8Al-1Mo-1V Solution Treated & Aged 341 BHN	883 Carbide	.005	225	.47	1.3
	M-2 HSS	.005	40	.76	1.2
Titanium 6Al-6V-2Sn Annealed 331 BHN	883 Carbide	.005	200	.60	1.6
	M-2 HSS	.005	60	.86	1.2
Titanium 6Al-6V-2Sn Solution Treated & Aged 429 BHN	883 Carbide	.005	175	.58	1.7
	M-2 HSS	.005	40	.62	1.2
Titanium 7Al-4Mo Annealed 341 BHN	883 Carbide	.005	270	.47	1.3
	M-2 HSS	.005	40	.60	1.0
Titanium 7Al-4Mo Solution Treated & Aged 388 BHN	883 Carbide	.005	200	.46	1.5
	M-2 HSS	.005	40	.76	1.2
Inconel 718 Solution Treated 277 BHN	883 Carbide	.009	90	.61	2.0
	M-2 HSS	.007	20	.75	1.9
Inconel 718 Solution Treated & Aged 45 R_c	883 Carbide	.009	90	.59	1.7
	M-2 HSS	.005	20	.73	2.3
Waspaloy Solution Treated 341 BHN	883 Carbide	.009	125	.55	2.0
	M-2 HSS	.009	20	.62	2.0
Waspaloy Solution Treated & Aged 388 BHN	883 Carbide	.009	110	.55	2.0
	M-2 HSS	.009	20	.60	1.8

9. SURFACE FINISH

The surface finishes obtained in turning, face milling, side milling, peripheral end milling and end mill slotting on most of the metals tested in this program are listed in Tables 33 through 37, pages 383 through 395. 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 wearland of .060" and the carbide .015" 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 type of wear that develops on the tool and the workpiece material.

TABLE 33

SURFACE FINISH MEASUREMENTS IN TURNING

Work Material	Tool Material	Tool Geometry	Cutting Speed ft./min.	Feed in./rev.	Cutting Fluid	Surface Finish microin. -AA. Sharp Tool	Dull Tool
250 Grade Maraging Steel, Annealed 321-341 BHN	M-2 HSS	BR: 0° SCEA: 15° SR: 10° NR: .030"	80	.009	Soluble Oil (1:20)	120	60
	C-3 Carbide	BR: -5° SCEA: 15° SR: -5° NR: .030"	475	.009	Soluble Oil (1:20)	140	150
250 Grade Maraging Steel, Aged 50-53 R_c	T-15 HSS	BR: 0° SCEA: 15° SR: 10° NR: .030"	60	.005	Soluble Oil (1:20)	75	95
	C-3 Carbide	BR: -5° SCEA: 15° SR: -5° NR: .030"	275	.009	Soluble Oil (1:20)	130	150
300 Grade Maraging Steel, Annealed 302-355 BHN	T-15 HSS	BR: 0° SCEA: 15° SR: 10° NR: .030"	95	.009	Soluble Oil (1:20)	140	110
	C-6 Carbide	BR: -5° SCEA: 15° SR: -5° NR: .030"	450	.009	Soluble Oil (1:20)	180	100
300 Grade Maraging Steel, Aged 52-54 R_c	T-15 HSS	BR: 0° SCEA: 15° SR: 10° NR: .030"	35	.009	Soluble Oil (1:20)	135	100
	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° NR: .030"	175	.009	Soluble Oil (1:20)	140	275
HP 9-4-25 Steel, Annealed 341-375 BHN	M-2 HSS	BR: 0° SCEA: 15° SR: 10° NR: .030"	70	.009	Soluble Oil (1:20)	70	85
	C-6 Carbide	BR: -5° SCEA: 15° SR: -5° NR: .030"	300	.009	Soluble Oil (1:20)	135	200

TABLE 33 (continued)

SURFACE FINISH MEASUREMENTS IN TURNING

Work Material	Tool Material	Tool Geometry	Cutting Speed ft./min.	Feed in./rev.	Cutting Fluid	Surface Finish microin. -AA.	
						Sharp Tool	Dull Tool
HP 9-4-25 Steel, Quenched and Tempered, 415-444 BHN	T-15 HSS	BR: 0° SCEA: 15° SR: 10° NR: .030"	75	.009	Soluble Oil (1:20)	80	140
	C-6 Carbide	BR: -5° SCEA: 15° SR: -5° NR: .030"	300	.009	Soluble Oil (1:20)	100	400
Ti-8Al-1Mo-1V Annealed, 302-311 BHN	M-2 HSS	BR: 0° SCEA: 15° SR: 15° NR: .030"	60	.005	Soluble Oil (1:20)	45	55
	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° NR: .030"	250	.005	Soluble Oil (1:20)	60	90
Ti-8Al-1Mo-1V Solution Treated and Aged, 302-341 BHN	M-2 HSS	BR: 0° SCEA: 15° SR: 15° NR: .030"	60	.005	Chlorinated Oil	40	50
	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° NR: .030"	225	.005	Soluble Oil (1:20)	40	90
Ti-6Al-6V-2Sn Annealed, 331 BHN	M-2 HSS	BR: 0° SCEA: 15° SR: 10° NR: .030"	55	.005	Soluble Oil (1:20)	45	30
	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° NR: .030"	200	.005	Soluble Oil (1:20)	65	50
Ti-6Al-6V-2Sn Solution Treated and Aged, 429 BHN	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° NR: .030"	175	.005	Soluble Oil (1:20)	40	90

TABLE 33 (continued)

SURFACE FINISH MEASUREMENTS IN TURNING

Work Material	Tool Material	Tool Geometry	Cutting Speed ft./min.	Feed in./rev.	Cutting Fluid	Surface Finish microin.-AA.	
						Sharp Tool	Dull Tool
Ti-7Al-4Mo Annealed, 341 BHN	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° NR: .030"	250	.005	Soluble Oil (1:20)	45	70
Ti-7Al-4Mo Solution Treated and Aged, 388 BHN	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° NR: .030"	200	.005	Soluble Oil (1:20)	40	35
Inconel 718 Solution Treated 245-332 BHN	T-15 HSS	BR: 0° SCEA: 15° SR: 15° NR: .030"	25	.005	Soluble Oil (1:20)	100	50
	C-2 Carbide	BR: 0° SCEA: 15° SR: 5° NR: .030"	90	.009	Soluble Oil (1:20)	110	115
Inconel 718 Solution Treated and Aged, 41-45 R_c	T-15 HSS	BR: 0° SCEA: 15° SR: 5° NR: .030"	35	.005	Highly Sulfurized Oil	80	35
	C-2 Carbide	BR: 0° SCEA: 15° SR: 5° NR: .030"	90	.009	Soluble Oil (1:20)	200	150
Waspaloy Solution Treated 293-341 BHN	T-15 HSS	BR: 0° SCEA: 15° SR: 10° NR: .030"	20	.009	Soluble Oil (1:20)	160	145
	C-2 Carbide	BR: 5° SCEA: 45° SR: 0° NR: .030"	122	.009	Soluble Oil (1:20)	120	110

TABLE 33 (continued)

SURFACE FINISH MEASUREMENTS IN TURNING

Work Material	Tool Material	Tool Geometry	Cutting Speed ft./min.	Feed in./rev.	Cutting Fluid	Surface Finish microin. -AA.	
						Sharp Tool	Dull Tool
Waspaloy Solution Treated and Aged, 388 BHN	M-44 HSS	BR: 0° SCEA: 15° SR: 10° NR: .030"	20	.009	Soluble Oil (1:20)	170	145
	C-2 Carbide	BR: 5° SCEA: 45° SR: 0° NR: .030"	110	.009	Soluble Oil (1:20)	110	170

TABLE 34

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
250 Grade Maraging Steel, Annealed 321-341 BHN	M-2 HSS	AR: 5° CA: 45° RR: 5°	140	.005	Highly Chlorinated Oil	30	80
	C-2 Carbide	AR: 10° CA: 45° RR: 0°	330	.005	Dry	100	70
250 Grade Maraging Steel, Aged 50-53 R_c	T-15 HSS	AR: 5° CA: 45° RR: 5°	75	.005	Highly Chlorinated Oil	25	40
	C-2 Carbide	AR: -15° CA: 45° RR: -7°	180	.004	Dry	80	60
300 Grade Maraging Steel, Aged 52-54 R_c	T-15 HSS	AR: 5° CA: 45° RR: 5°	60	.005	Highly Chlorinated Oil	55	60
	C-2 Carbide	AR: -7° CA: 45° RR: -7°	140	.004	Dry	50	20
HP 9-4-25 Steel Annealed 341-375 BHN	T-15 HSS	AR: 5° CA: 45° RR: 5°	117	.005	Soluble Oil (1:20)	25	50
	C-6 Carbide	AR: -7° CA: 45° RR: -7°	220	.007	Dry	150	170
HP 9-4-25 Steel, Quenched and Tempered, 415-444 BHN	M-2 HSS	AR: 5° CA: 45° RR: 5°	114	.005	Chlorinated Oil	20	30
	C-5 Carbide	AR: -7° CA: 45° RR: -7°	175	.008	Dry	100	45

TABLE 34 (continued)

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
Ti-8Al-1Mo-1V Annealed, 302-311 BHN	T-15 HSS	AR: 5° CA: 45° RR: 5°	90	.005	Highly Chlorinated Oil	45	30
	C-2 Carbide	AR: 10° CA: 45° RR: 0°	410	.005	Dry	150	160
Ti-8Al-1Mo-1V Solution Treated and Aged, 302-341 BHN	T-15 HSS	AR: 5° CA: 45° RR: 5°	90	.005	Highly Chlorinated Oil	40	25
	C-2 Carbide	AR: 10° CA: 45° RR: 0°	400	.005	Highly Chlorinated Oil	120	95
Inconel 718 As Forged 245-332 BHN	T-15 HSS	AR: 0° CA: 45° RR: 30°	25	.010	Highly Chlorinated Oil	75	85
Inconel 718 Solution Treated and Aged, 41-45 R_c	T-15 HSS	AR: 0° CA: 45° RR: 30°	20	.010	Highly Chlorinated Oil	80	100
Waspaloy Solution Treated 293-341 BHN	M-44 HSS	AR: 0° CA: 45° RR: 30°	32	.011	Highly Chlorinated Oil	80	90

TABLE 35

SURFACE FINISH MEASUREMENTS IN SIDE MILLING

Work Material	Tool Material	Tool Geometry	Cutting Speed ft. /min.	Feed in. /tooth	Cutting Fluid	Surface Finish microin. -AA.	
						Sharp Tool	Dull Tool
250 Grade Maraging Steel, Annealed 321-341 BHN	C-2 Carbide	AR: 5° RR: 5° CA: 45°	670	.005	Dry	70	70
250 Grade Maraging Steel, Aged 50-53 R_c	C-2 Carbide	AR: -15° RR: -7° CA: 45°	300	.004	Dry	45	45
300 Grade Maraging Steel, Aged 52-54 R_c	C-2 Carbide	AR: -7° RR: -7° CA: 45°	175	.004	Dry	25	100
HP 9-4-25 Steel Annealed 341-375 BHN	C-2 Carbide	AR: -7° RR: -7° CA: 45°	225	.006	Dry	50	50
HP 9-4-25 Steel, Quenched and Tempered, 415-444 BHN	C-5 Carbide	AR: -7° RR: -7° CA: 45°	225	.008	Dry	30	30

TABLE 36

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
AISI 4340 Steel Annealed 200-217 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	190	.004	Highly Sulfurized Oil	80	90
AISI 4340 Steel Normalized 321-341 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	70	.004	Soluble Oil (1:20)	175	200
D6AC Steel Annealed 217-229 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	190	.004	Soluble Oil (1:20)	80	100
250 Grade Maraging Steel, Annealed 321-341 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	225	.004	Soluble Oil (1:20)	40	45
250 Grade Maraging Steel, Aged 50-53 R_c	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	80	.001	Highly Chlorinated Oil	30	35

TABLE 36 (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
300 Grade Maraging Steel, Aged 52-54 R_c	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	40	.001	Highly Chlorinated Oil	35	20
HP 9-4-25 Steel Annealed 341-375 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	80	.004	Soluble Oil (1:20)	70	90
Ti-8Al-1Mo-1V Annealed 302-311 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	150	.004	Soluble Oil (1:20)	55	65
Ti-8Al-1Mo-1V Solution Treated and Aged, 302-341 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	150	.004	Soluble Oil (1:20)	60	55
Inconel 718 As Forged 245-332 BHN	T-15 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	75	.002	Highly Chlorinated Oil	65	95

TABLE 36 (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	Dull
Inconel 718 Solution Treated and Aged, 363-388 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	11	.002	Highly Sulfurized Oil	60	90
Waspaloy Solution Treated 293-341 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	35	.002	Highly Sulfurized Oil	70	95

TABLE 37

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
AISI 4340 Steel Annealed 200-217 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	124	.004	Highly Sulfurized Oil	175	225
AISI 4340 Steel Normalized 321-341 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	45	.002	Soluble Oil (1:20)	160	175
D6AC Steel Annealed 217-229 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	125	.002	Soluble Oil (1:20)	200	125
250 Grade Maraging Steel, Annealed 321-341 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	140	.002	Highly Chlorinated Oil	50	40
250 Grade Maraging Steel, Aged 50-53 R_C	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	40	.001	Highly Chlorinated Oil	20	15
	C-2 Carbide	AR: -7° CA: 45° RR: -7°	312	.002	Dry	40	80

TABLE 37 (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
300 Grade Maraging Steel, Aged 52-54 R_c	T-15 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	43	.001	Highly Chlorinated Oil	30	40
HP 9-4-25 Steel Annealed 341-375 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	81	.002	Highly Chlorinated Oil	75	90
17-4 PH Steel Solution Treated 352 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	80	.002	Highly Sulfurized Oil	55	60
Ti-8Al-1Mo-1V Annealed 301-311 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	97	.003	Water Base Synthetic (1:15)	55	65
Ti-8Al-1Mo-1V Solution Treated and Aged, 302-341 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	97	.004	Water Base Synthetic (1:15)	85	75

TABLE 37 (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 718 As Forged 245-332 BHN	T-15 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	11	.003	Highly Chlorinated Oil	45	50
Inconel 718 Solution Treated and Aged, 41-45 R_c	T-15 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	15	.002	Highly Sulfurized Oil	50	65
Waspaloy Solution Treated 293-341 BHN	M-2 HSS	Helix Angle: 30° RR: 10° CA: 45° x .060"	12	.003	Highly Chlorinated Oil	65	80

10. MACHINING NON-METALLIC MATERIALS

10.1 General Electric Grade 11584

Material Identification

The General Electric Grade 11584 is a fiber reinforced plastic. Specifically, it may be defined as a laminated epoxy bonded material reinforced with continuously woven high temperature glass. The material, which conforms to NEMA Grade G-11, is designed specifically for high strength and maximum strength retention at elevated temperatures. The plastic falls into the tensile-compressive strength range of 40,000 to 60,000 psi and has an elastic modulus of approximately 2.5×10^6 psi.

Face Milling

The relationship between cutting speed and cutter life in face milling the non-metallic General Electric G-11 with two different C-2 grades of carbide tools is shown in Figure 417, page 398. The K-68 carbide provided about three times the cutter life that was obtained with a K-6 grade at a cutting speed of 1050 ft./min.

Note in Figure 418, page 398, that cutter life decreased rapidly as the feed was increased beyond .015 in./tooth. At a feed of .015 in./tooth the cutter life was 215 inches of work travel, as compared to 105 inches at a feed of .020 in./tooth.

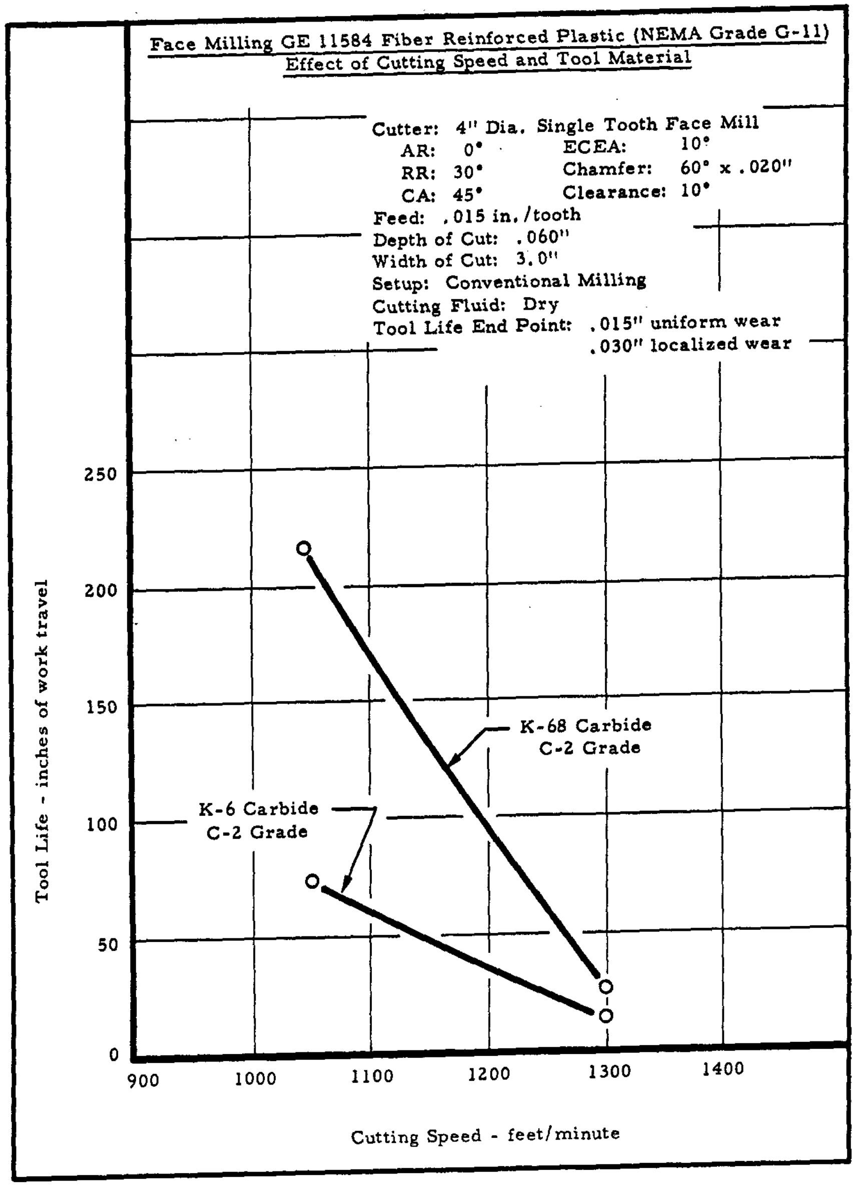
Drilling

The drill life results presented in Figure 419, page 399, indicate the advantage of the heavier feeds in drilling the General Electric G-11 non-metallic material. As the feed was increased from .005 in./rev. to .015 in./rev., the drill life increased from 60 to 175 holes.

TABLE 38

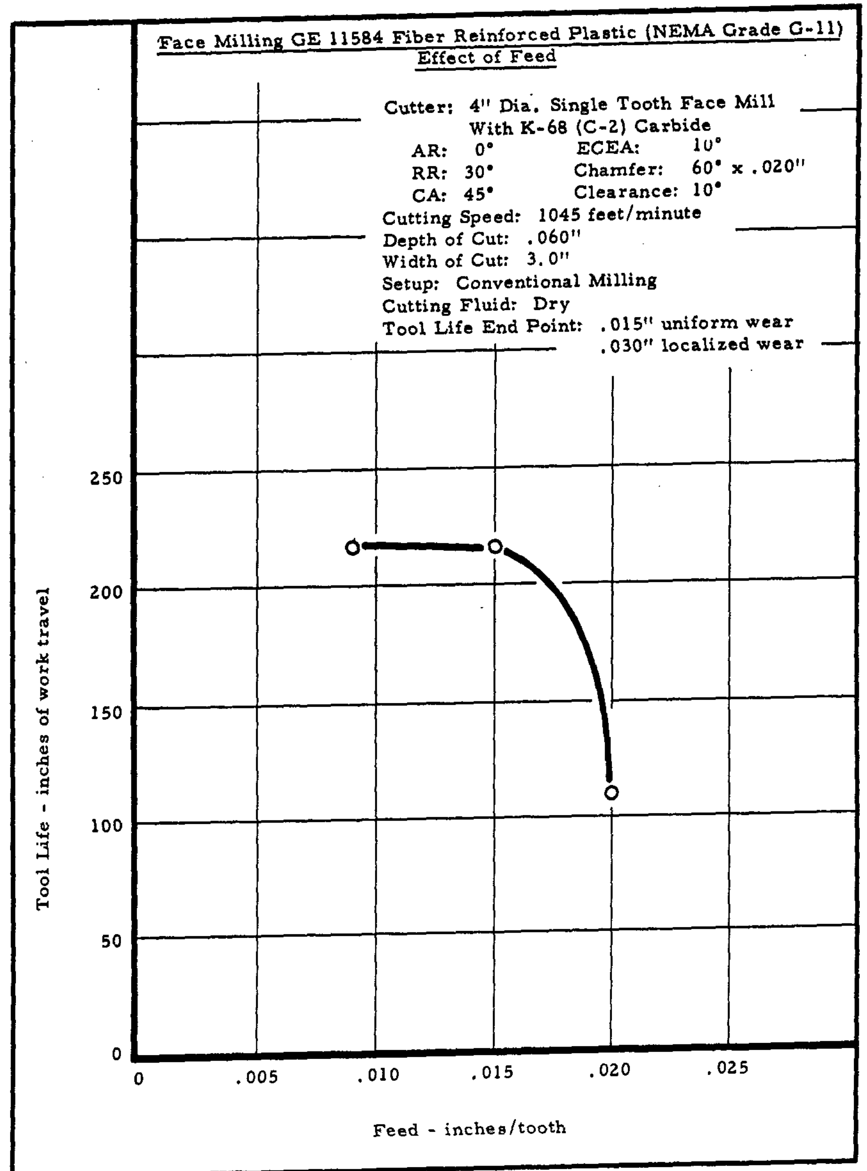
RECOMMENDED CONDITIONS FOR MACHINING
GE 11584 FIBER REINFORCED PLASTIC (NEMA GRADE G-11)

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	C-2 Carbide	AR: 0° ECEA: 10° RR: 30° CA: 45° Clearance: 10°	4" diameter Single Tooth Face Mill	.060	3	.015 in/ tooth	1050	220" Work Travel	.015	Dry
Drilling	M-1 HSS	118° Plain Point 7° Clearance	1/4" diameter HSS Drill 2 1/2" long	.500" thru	-	.015 in/ tooth	125	250 holes	.015	Dry



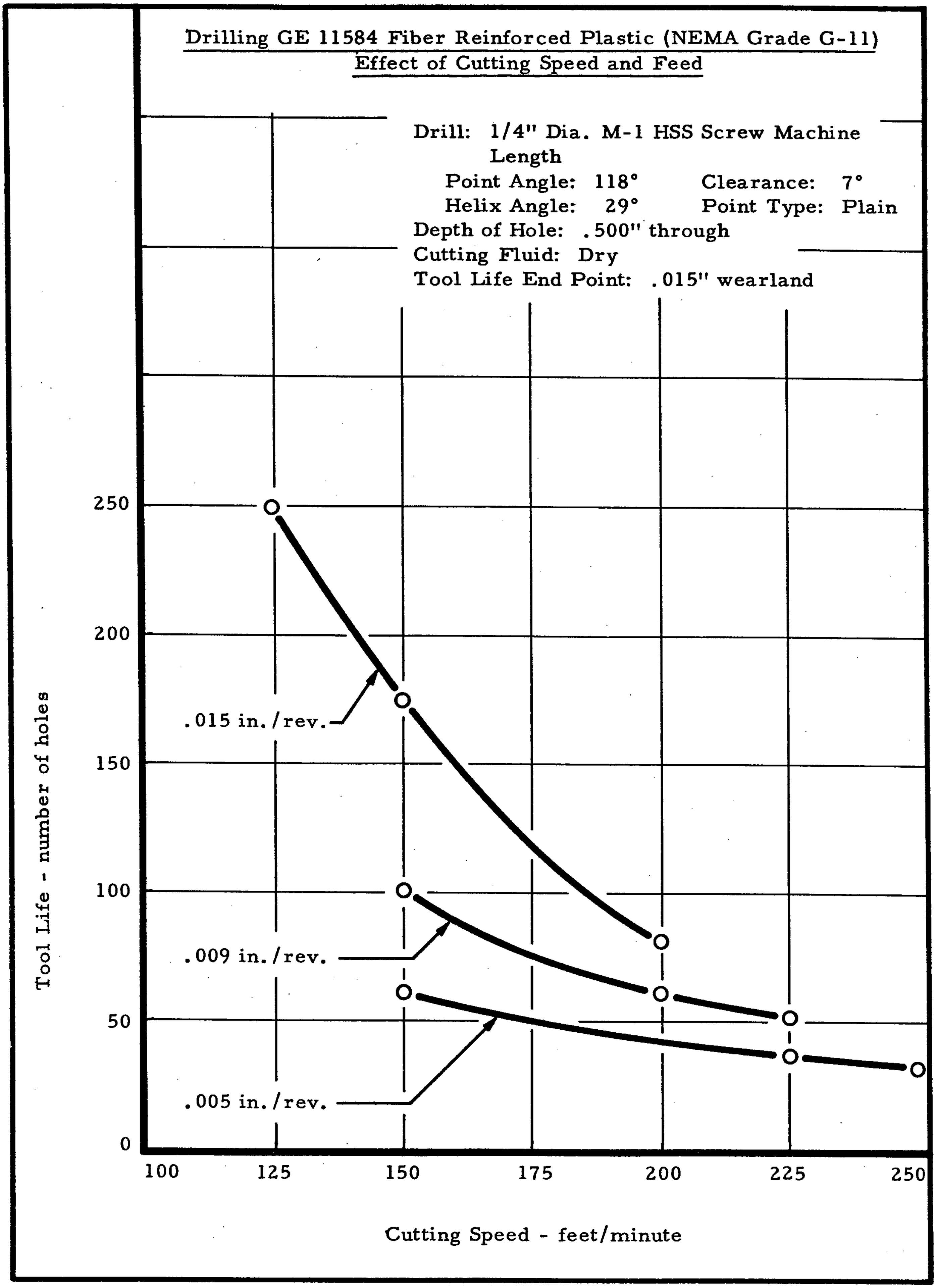
See text, page 396

Figure 417



See text, page 396

Figure 418



See text, page 396

Figure 419

11. HIGH SPEED EDGE MILLING

High speed edge milling of sheet materials, otherwise known as sheet trimming, has been used for a number of years on the low density aircraft skin alloys. In recent years there has been increased need to perform similar operations on stainless steel and other higher strength sheet materials as they become used in similar skin applications. Previous work has indicated promise on a variety of materials, including precipitation hardening stainless steel, titanium, and nickel base alloys. The work summarized herein covers our most recent efforts in this area on a group of aerospace alloys for which machining data is currently being developed.

11.1 Materials and Heat Treatment

High speed edge milling tests were run on the following materials in the conditions indicated:

Waspaloy Sheet, Solution Treated to 92 R_B
Waspaloy Sheet, Solution Treated and Aged to 42 R_C
Inconel 718 Sheet, Solution Treated to 94 R_B
Inconel 718 Sheet, Solution Treated and Aged to 40 R_C
Titanium 8Al-1Mo-1V Sheet, Annealed to 40 R_C
Titanium 5Al-2.5Sn Sheet, Annealed to 37 R_C
17-4 PH Sheet, Solution Treated to 40 R_C
17-4 PH Sheet, Solution Treated and Aged to 47 R_C

A metallographic description of the various alloys is summarized in this section.

Inconel 718

Material for edge milling tests was procured as .063" thick sheet in the hot rolled mill annealed condition. The annealing cycle performed at the mill was at 1750°F in accordance with PWA Specification 1033-A.

This treatment resulted in a hardness of 94 R_B.

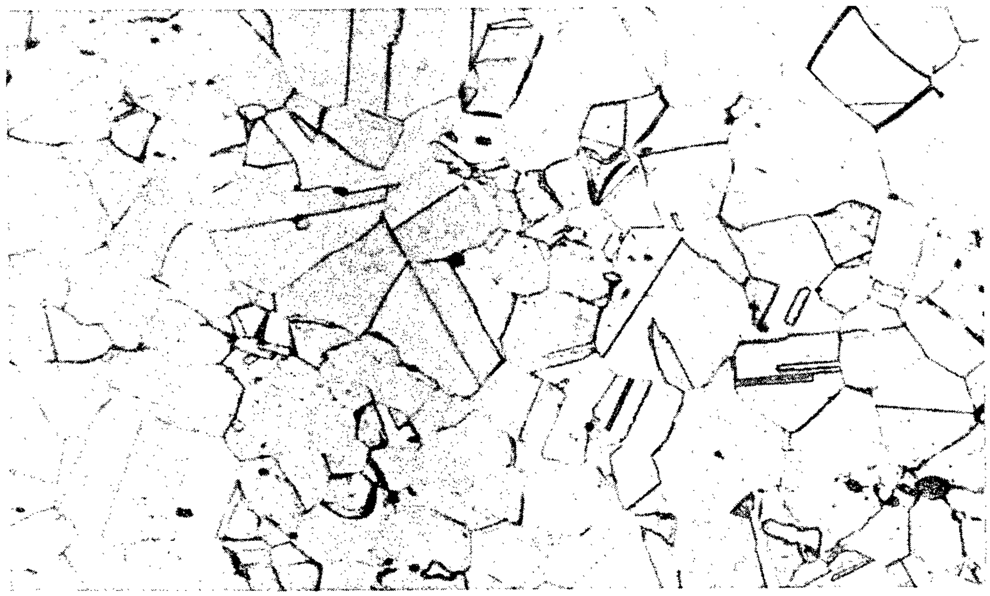
In order to compare the aged to the annealed condition, the previously annealed sheet was aged as follows:

1325°F/8 hours/furnace cool to 1150°F
Hold at 1150°F until total aging time equals 18 hours/air cool

Aging produced a hardness of 40 R_C.

11.1 Materials and Heat Treatment (continued)

The microstructure of the alloy in both heat treated conditions consisted of random distributed carbide particles in a single-phase grained matrix. Precipitation of carbides during aging accentuates the grain boundaries.



Inconel 718 Sheet
Solution Treated and Aged

Etchant: Kalling's Mag: 500X

Waspaloy

The material for edge milling tests was procured as .050" thick sheet in the mill annealed condition. The anneal cycle performed at the mill was as follows:

1975F/water quench

In this condition the material exhibited a hardness of 92 R_B.

In order to compare the solution treated and aged to the mill annealed, the sheet material was heat treated in the following manner:

Solution Treatment:	1850F/2 hours/air cool
Aging Treatment:	1550F/4 hours/air cool to 1400F Hold at 1400F until total aging time equals 16 hours/air cool

The aging treatment yielded a hardness of 42 R_C.

11.1 Materials and Heat Treatment (continued)

The microstructure of the alloy in both the annealed and the solution treated and aged conditions consists of randomly distributed carbides in an equiaxed grained matrix. Aging strengthens the matrix by precipitation of carbides in the grain boundaries.

Waspaloy Sheet, Solution Treated and Aged

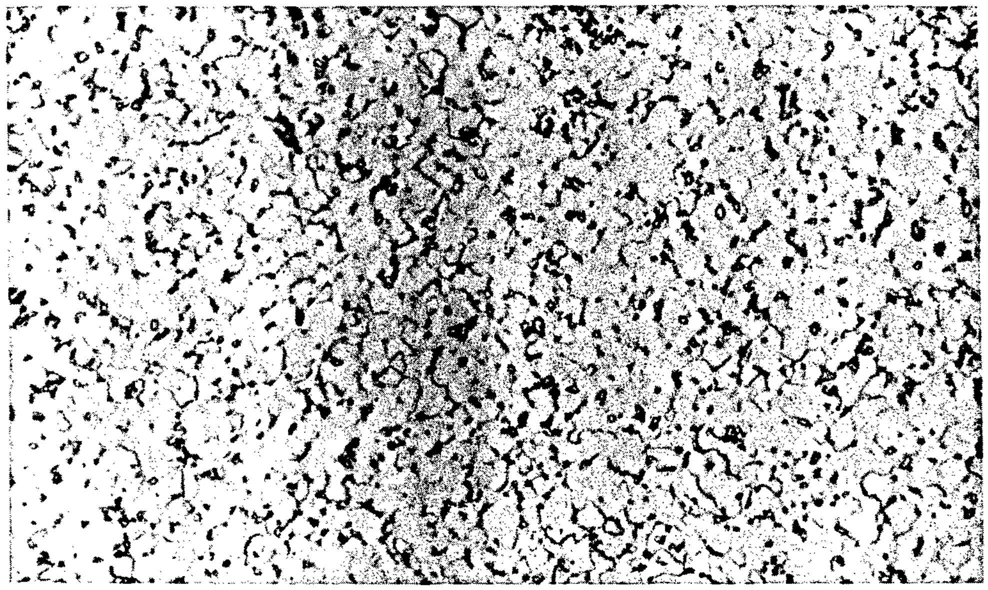
Etchant: Kalling's Mag: 500X

Titanium 8Al-1Mo-1V

The material for edge milling tests was procured as .060" thick sheet in the hot rolled annealed condition.

Hardness of this material as received was 40 R_C.

The microstructure of this alloy is essentially alpha but with a random dispersion of beta and carbides.



Titanium 8Al-1Mo-1V Sheet, Annealed

Etchant: HF-NHO_3-Glycerol Mag: 500X

Titanium 5Al-2.5Sn

Titanium 5Al-2.5Sn is an alpha titanium base alloy which exhibits attributes such as weldability and retention of strength at high temperatures. The nominal composition of this alloy is as follows:

Ti - 5 Al - 2.5 Sn - .02 C - .44 Fe

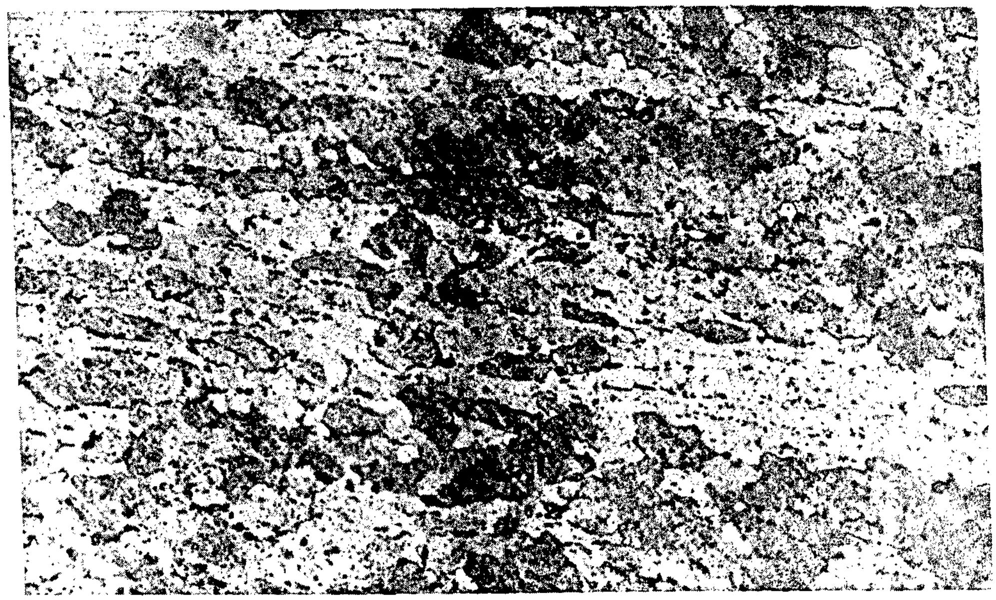
The material for edge milling tests was procured as hot rolled, annealed .063" x 24" sheet. The annealing cycle at the mill was as follows:

1500 $\pm$ 25F/20 minutes/air cool

The resulting hardness was 37 R_c.

The microstructure of this alloy is illustrated below. It consists of alpha platelets elongated in the direction of rolling of the sheet.

11.1 Materials and Heat Treatment (continued)



Titanium 5Al-2.5Sn, Annealed

Etchant: HF-HNO_3-Glycerol Mag: 500X

17-4 PH Stainless Steel

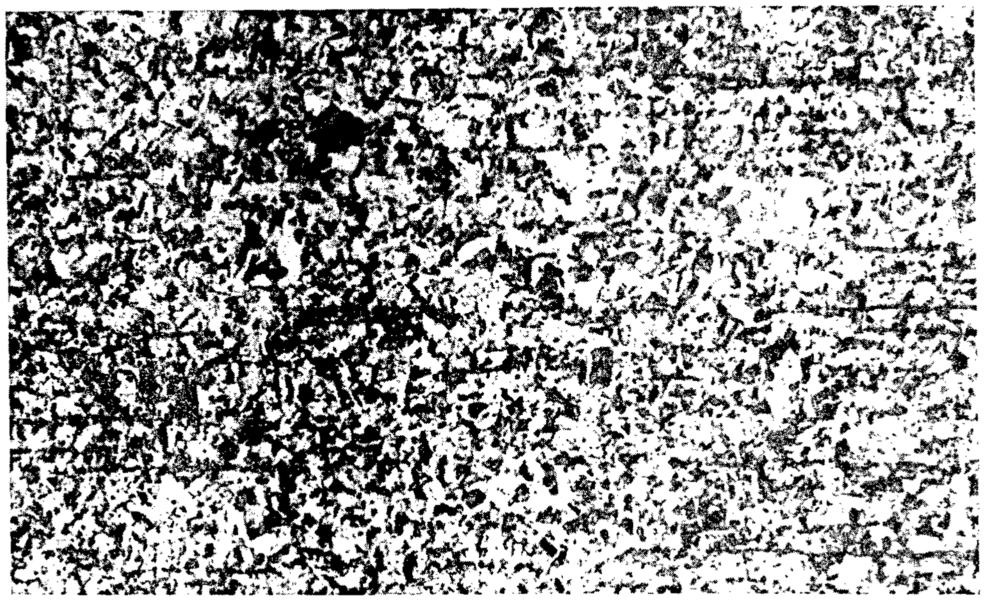
The material for high speed edge milling tests was procured as .062" thick sheet in the hot rolled and solution treated condition. The sheet was then subjected to the following aging treatment:

900F/1 hour/air cool

Hardness of the solution treated material was 40 R_c, while the aged condition produced a hardness of 47 R_c.

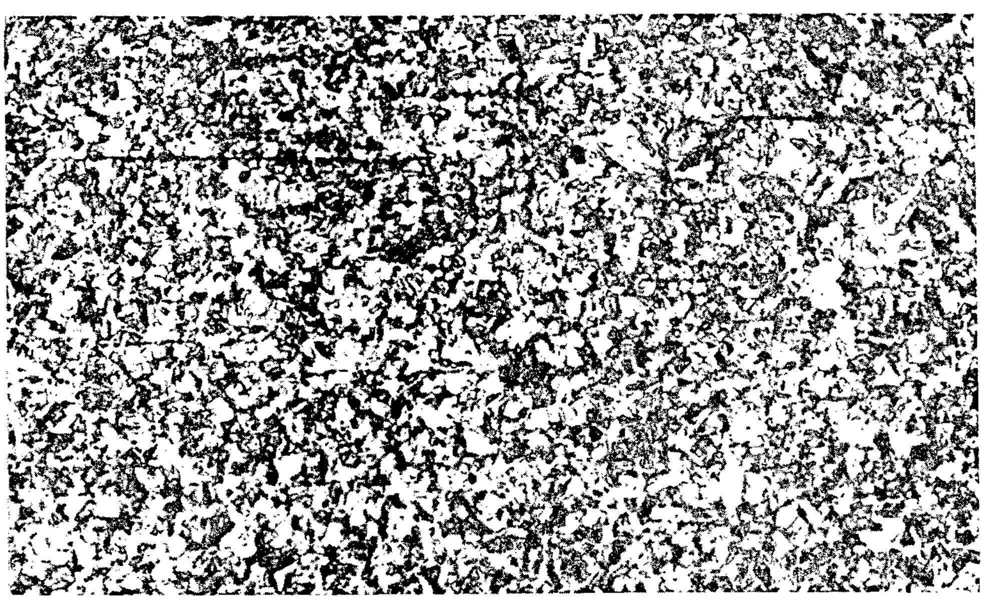
The microstructures of the material in both conditions are illustrated below. The solution treated microstructure consists of coarse martensite elongated in the direction of rolling. Aging strengthens the matrix by the precipitation of a copper rich phase and various carbides.

11.1 Materials and Heat Treatment



17-4 PH Sheet, Solution Treated

Etchant: Kalling's Mag: 500X



17-4 PH Sheet, Solution Treated and Aged

Etchant: Kalling's Mag: 500X

11.2 High Speed Edge Milling Conditions

High speed edge milling was performed on a 30" x 6' Gray planer with a special high speed milling head attached to the rail, Figure 420, page 413. The planer was selected for the trimming and edge milling operation in order to obtain the required high table speeds and rigidity. With this machine, table speeds from 40 to 400 in. /min. were available. The special milling head had a continuously variable speed in order to provide spindle speeds ranging from 150 to 9000 rev. /min. The planer was modified to provide variable table speeds ranging from 20 to 400 in. /min. This range of table speeds provided feed rates of .005 to .020 in. /tooth. A cutting speed range of 500 to 3000 ft. /min. was obtained using a 1-1/2" diameter inserted tooth throwaway type carbide tipped end mill, Figure 421, page 414. The sheet material tested in this program was sheared into test panels 2' wide by 3 to 4' long. The test panels were securely held down on the planer table with a special clamping fixture.

Cutting was done dry and also with liquid CO_2 and a soluble oil spray mist. The liquid CO_2 and the soluble oil mist were directed onto the tool and work material by means of a pair of nozzles, Figure 422, page 415.

Various depths of cut were taken using the peripheral cutting edge of the inserted tooth cutter. Several tests were made with one set of carbide inserts by moving the cutter head up or down to expose an unused portion of the periphery of the inserts. The width of the cut is defined as the thickness of the sheet material tested. The depth of cut was obtained by moving the cutter into the workpiece in a direction perpendicular to the direction of feed.

11.3 Edge Milling Data and Characteristics

Waspaloy Sheet (Solution Treated 92 R_B)

Cuts were taken with the periphery of a 1-1/2" diameter 3 tooth end mill with inserted carbide tips. The tool life obtained with grade 883 (C-2) carbide inserts at a feed of .010 in. /tooth and a depth of .025" is shown in Figure 423, page 416. Tool life in inches of work travel is plotted against cutting speed for a width of cut of .050". Cuts were taken both dry and with liquid CO_2. It is observed that the maximum tool life of 96 inches of work travel was obtained at a cutting speed of 1000 ft. /min. using liquid CO_2. The tool life decreased abruptly at cutting speeds lower or higher than 1000 ft. /min. The tool life characteristics in cutting dry were very similar to those obtained with the liquid CO_2.

The effect of feed on tool life is shown in Figure 424, page 416. At a cutting speed of 1000 ft./min. and at a depth of cut of .025", the maximum tool life of 190 inches of work travel was obtained at a feed of .015 in./tooth using liquid CO_2 as the cutting fluid. At the same depth and feed per tooth, the tool life decreased to 120" when cutting dry. There was a marked decrease in tool life at .050" depth. With liquid CO_2 only 60 inches of work travel could be obtained at .050" depth and this occurred at a feed of .010 in./tooth.

A soluble oil mist (1:20) was also tried as a cutting fluid. Comparison of the soluble oil mist with liquid CO_2 and cutting dry is shown in Figure 425, page 417, where tool life is plotted against cutting speed at a feed of .010 in./tooth and a depth of .050". It is seen that the maximum tool life was obtained with the liquid CO_2 at 1000 ft./min. Cutting dry gave the next highest tool life at a cutting speed of 500 ft./min. The soluble oil mist did not offer any advantages over cutting dry.

The effect of feed on edge milling of the solution treated Waspaloy sheet is shown in Figure 426, page 417, for dry cutting. The greatest tool life of 120 inches of work travel was obtained at .015 in./tooth at a depth of .025" and a cutting speed of 1000 ft./min. When the depth was increased to .050", the tool life dropped markedly for both 1000 ft./min. and 2000 ft./min. cutting speeds.

An investigation was made to determine the effectiveness of a variety of carbide grades on the tool life in edge milling of the solution treated Waspaloy sheet. Tests were run at a cutting speed of 1000 ft./min. and a feed of .015 in./tooth. The results in cutting dry are shown in Figure 427, page 418, while those using liquid CO_2 are shown in Figure 428, page 418. Tests were made at both .025" and .050" depths of cut. In cutting dry, Figure 427, page 418, the greatest tool life was obtained with K-2S, a C-5 carbide. The next best results were obtained with the 370, a C-6 carbide, followed by K-6 and 883, which are C-2 carbides. The poorest results were obtained using K-11, a C-4 carbide. While cutting with liquid CO_2, Figure 428, page 418, the maximum tool life was obtained using 370, a C-6 carbide, while grades 883, K-6 and K-2S gave the next best tool life results.

Waspaloy Sheet (Solution Treated and Aged 42 R_c)

The high speed edge milling of the Waspaloy sheet, solution treated and aged to 42 R_c, is shown in Figures 429 through 431, pages 419 and 420. The effect of cutting speed on tool life for .025" depth of cut and a feed of .010 in./tooth is given in Figure 429, page 419, when cutting dry and with liquid CO_2. The tool life when cutting dry is seen to increase as the speed decreased, with the greatest life of 96 inches occurring at a cutting speed of 500 ft./min. The tool life when milling with the liquid CO_2 was poorer than that of cutting dry. With the liquid CO_2 an appreciable tool life of 70 inches of work travel was obtained only at a speed of 1000 ft./min., with the tool life dropping sharply at lower or higher cutting speeds.

The superiority of cutting dry over using liquid CO_2 when machining the aged Waspaloy is again evident in Figure 430, page 419, where cutting speed is plotted against feed per tooth at a constant cutting speed of 500 ft./min. At a depth of cut of .025", the maximum tool life of 96" was obtained at a feed of .010 to .015 in./tooth. At a .050" depth of cut the maximum tool life was 48 inches of work travel and occurred at the same feeds, .010 to .015 in./tooth. The use of liquid CO_2 as a cutting fluid decreased the tool life markedly. At .025" depth, the maximum tool life was only 24 inches of work travel.

A comparison of the effectiveness of liquid CO_2, soluble oil mist and cutting dry is given in Figure 431, page 420, for a depth of cut of .050" and a feed of .010 in./tooth. The greatest tool life was obtained at 500 ft./min. with soluble oil mist and dry cutting giving about the same tool life of approximately 45 to 48 inches of work travel.

Inconel 718 Sheet (Annealed 94 R_B)

The tool life obtained in high speed edge milling of annealed Inconel 718 is shown in Figures 432 through 437, pages 420 through 423. In taking .025" depth of cut and with a feed of .010 in./tooth, the maximum tool life was obtained at a cutting speed of 1000 ft./min., Figure 432, page 420. Liquid CO_2 provided a substantial improvement in tool life over cutting dry, 118 inches versus 80 inches of work travel.

The combined influence of depth and feed in milling at 1000 ft./min. is shown in Figure 433, page 421. A much higher tool life was obtained in cutting at .025" depth over .050" depth. The liquid CO_2 appeared to give about the same life results as milling dry, except at .020" feed where a substantial increase in tool life was obtained in using the liquid CO_2.

The benefit of liquid CO_2 is further demonstrated in Figure 434, page 421, where a comparison is made between cutting dry, liquid CO_2 and soluble oil. Maximum tool life was obtained with the liquid CO_2 at cutting speeds of 500 to 1000 ft./min. A further comparison of the combined effects of feed and speed at both .025" and .050" depths is shown in Figure 435, page 422. Here it is seen that the maximum life of 120 inches of work travel was obtained at 1000 ft./min. cutting speed, .025" depth and at a feed of .015 in./tooth.

The effect of carbide grade on tool life in edge milling the annealed Inconel 718 is shown in Figure 436, page 422, for cutting dry and in Figure 437, page 423, for milling with liquid CO_2, at both .025" and .050" depths.

Inconel 718 Sheet (Solution Treated and Aged 40 R_c)

The tool life obtained in carbide edge milling of the solution treated and aged Inconel 718 is illustrated in Figures 438 through 443, pages 423 through 426. In taking a .025" depth of cut and .062" width of cut, the tool life increased with decreasing cutting speed with the maximum life being obtained at 500 ft./min., Figure 438, page 423. There was little difference between the liquid CO_2 versus cutting dry.

The effect of feed and depth of cut is illustrated in Figure 439, page 424. Here at a cutting speed of 1000 ft./min. the maximum tool life was obtained at a feed of .020 in./tooth, under which conditions the liquid CO_2 appeared to give superior results compared to cutting dry.

A comparison of cutting fluids indicates that there were only small differences in life between liquid CO_2, cutting dry and soluble oil mist at speeds of 1000 ft./min. and higher, Figure 440, page 424. However, the soluble oil mist shows approximately a 50% improvement in tool life at a cutting speed of 500 ft./min.

The combined effects of depth, cutting speed, and feed are plotted in Figure 441, page 425. The maximum life of 72 inches of work travel was obtained at 1000 ft./min. cutting speed and a feed of .020 in./tooth.

A carbide evaluation was made on edge milling of the aged Inconel 718 at .025" and .050" depths of cut when milling dry, Figure 442, page 425, and with liquid CO_2, Figure 443, page 426. No carbide appeared to be outstanding in the dry milling, Figure 442, page 425. However, the K-68 appeared to provide the highest life of 100 inches of work travel when used with the liquid CO_2, Figure 443, page 426. The next best carbide provided 60 inches of work travel under the same conditions, Figure 443, page 426.

11.3 Edge Milling Data and Characteristics (continued)

Titanium 8Al-1Mo-1V Sheet (Annealed 40 R_c)

The tool life obtained in edge milling the .050" thick titanium 8Al-1Mo-1V sheet is shown in Figures 444 through 447, pages 426 through 428. The effect of cutting speed on tool life at a feed of .010 in./tooth while cutting dry is indicated in Figure 444, page 426, for three depths of cut, .025", .050" and .100". The tool life is seen to increase as the cutting speed decreases. The greatest tool life of 300 feet of work travel was obtained at .025" depth at a cutting speed of 500 ft./min. As the depth increased, the tool life decreased. Thus, at 500 ft./min., the tool life was 180 feet of work travel at .050" depth and 60 feet of work travel at .100" depth.

The effect of feed on tool life is indicated in Figure 445, page 427, for a depth of cut of .025". Approximately the same tool life characteristics were obtained at feeds of .005 and .010 in./tooth, with somewhat lower tool life produced at .015 in./tooth.

When the depth was increased to .050", the effect of feed was found to be similar to that experienced previously with the .025" depth. Thus, it is seen from Figure 446, page 426, that about the same tool life was obtained with the .005 and .010 in./tooth feeds. A drastic decrease in tool life was evident when the feed, however, was increased to .015 in./tooth.

Liquid CO_2 was found to decrease, rather than increase, tool life on high speed edge milling of titanium 8Al-1Mo-1V, see Figure 447, page 428. At speeds of 1000 to 2500 ft./min. where tool life was relatively low, the liquid CO_2 showed a small improvement in tool life. However, at 500 ft./min., a very marked decrease in tool life was obtained with the liquid CO_2. Thus, at .025" depth and 500 ft./min., the tool life decreased from 280 feet of travel to 140 feet of travel by using liquid CO_2 instead of cutting dry. Similar decreases in tool life were obtained at .050 and .100" depths of cut by the application of liquid CO_2.

Titanium 5Al-2.5Sn Sheet (Annealed 37 R_c)

The effect of cutting speed on the tool life in edge milling of titanium 5Al-2.5Sn is shown in Figures 448 through 451, pages 428 through 430. These tests were run using grade 883 (C-2) carbide inserts. The titanium sheet was .060" thick. The effect of cutting speed on tool life is shown in Figure 448, page 428, for a feed of .010 in./tooth cutting dry. The greatest tool life was obtained at .025" depth of cut. The tool life was 236 feet of work travel at a cutting speed of 500 ft./min. At the same speed, the tool life decreased to 90 feet of work travel at .050" depth and 44 feet of work travel at .100" depth of cut.

The effect of feed on tool life at various speeds is shown in Figure 449, page 429, for a depth of .025". A feed of .005 in./tooth gave the maximum tool life of 300 feet of work travel at 500 ft./min. The tool life decreased as the feed increased. Thus, at 500 ft./min., the tool life was 236 feet at .010 in./tooth and 200 feet of work travel at .015 in./tooth.

The effect of feed per tooth on tool life for .050" depth of cut is shown in Figure 450, page 429. The tool life at .005 in./tooth was again 300 feet of work travel at 500 ft./min. However, when the feed was increased to .010 in./tooth at the same speed, the tool life dropped to 90 feet of work travel. The tool life was again decreased to 64 feet of work travel when the feed was increased to .015 in./tooth at a cutting speed of 500 ft./min.

The use of liquid CO_2 was found to decrease tool life over that of edge milling dry, Figure 451, page 430. Thus, at .025" depth, the tool life at 500 ft./min. decreased from 236 to 110 feet of work travel by the application of liquid CO_2 instead of cutting dry. A major reduction in tool life was also obtained by using liquid CO_2 at .050" and .100" depths of cut.

17-4 PH Sheet (Solution Treated 40 R_c)

The tool life obtained in milling the solution treated 17-4 PH sheet is illustrated in Figures 452 through 456, pages 430 through 432. Figure 452, page 430, shows the combined effect of depth and cutting speed. The tool life increased with decreasing speed and decreasing depth. The longest life of 265 feet of work travel was obtained at a depth of .025" and a speed of 500 ft./min. There was a drastic decrease in tool life from 268 feet down to 124 feet of work travel when changing from .025" to .050" depth at a cutting speed of 500 ft./min.

The influence of feed on tool life is given in Figure 453, page 431, for a depth of cut of .025". The .010 in./tooth feed provided the greatest tool life of 268 feet of travel at 500 ft./min. However, at a cutting speed of 1000 ft./min., the .015 in./tooth feed provided the longer tool life than either the .010 or .005 in./tooth feeds.

When the depth of cut was increased to .050", it was found that the .005 in./tooth feed provided longer tool life than the .010 or .015 in./tooth feeds at a cutting speed of 500 ft./min., Figure 454, page 431.

11.3 Edge Milling Data and Characteristics (continued)

The combined effect of depth of cut and cutting fluid is illustrated in Figure 455, page 432. The life again is shown to increase with decreasing cutting speeds. There was little difference in performance between milling dry or using liquid CO_2. At a cutting speed of 500 ft./min., the tool life was inversely proportional to the depth. For example, in milling dry, the life was 268 feet at .025" depth; the life was 150 feet at .050" depth; and the life decreased to 24 feet work travel at .100" depth.

A comparison between a C-2 and a C-6 grade of carbide is illustrated in Figure 456, page 432. The C-2 grade gave better performance at 500 ft./min. while the C-6 grade performed better at the higher cutting speeds.

17-4 PH Sheet (Solution Treated and Aged 47 R_c)

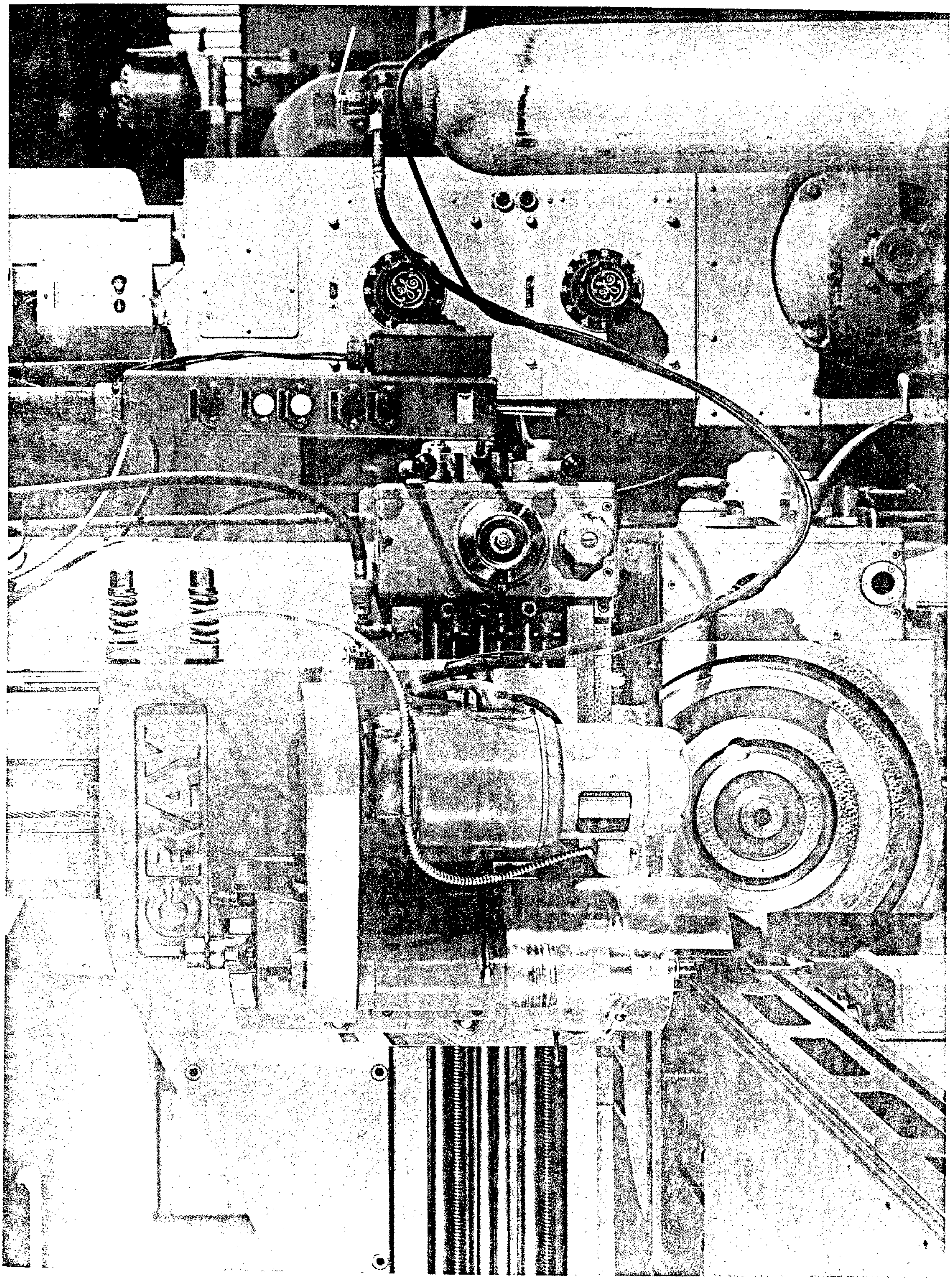
The tool life characteristics in high speed edge milling of solution treated and aged 17-4 PH are given in Figures 457 through 461, pages 433 through 435. In general, it should be noted that there was a major decrease in tool life in milling the aged 17-4 PH compared to milling the solution treated 17-4 PH, as previously described in Figures 452 through 456, pages 430 through 432.

The effect of depth of cut and cutting speed in milling the aged material is shown in Figure 457, page 433. A major improvement in tool life was obtained when the depth was confined to .025". A life of 115 feet of work travel was obtained at speeds of 500 to 1000 ft./min. with the life decreasing drastically at higher cutting speeds.

The effect of feed is illustrated in Figure 458, page 433, for a depth of cut of .025". All three feeds of .005, .010 and .015 in./tooth provided approximately the same milling life at all cutting speeds with the exception of 1000 ft./min. Here the .010 in./tooth feed provided a substantial improvement in milling life. When the depth of cut was increased to .050", Figure 459, page 434, it was found that approximately the same tool life in linear feet of work travel was obtained at all three feeds over the full range of cutting speeds.

The combined effect of depth, cutting fluid and cutting speed in edge milling the solution treated and aged 17-4 PH is shown in Figure 460, page 434. Cutting dry provided a higher milling life than seen using liquid CO_2. It should be observed here that the tool life at the lowest cutting speed of 5000 ft./min. was influenced by the chipping rather than by uniform flank wear.

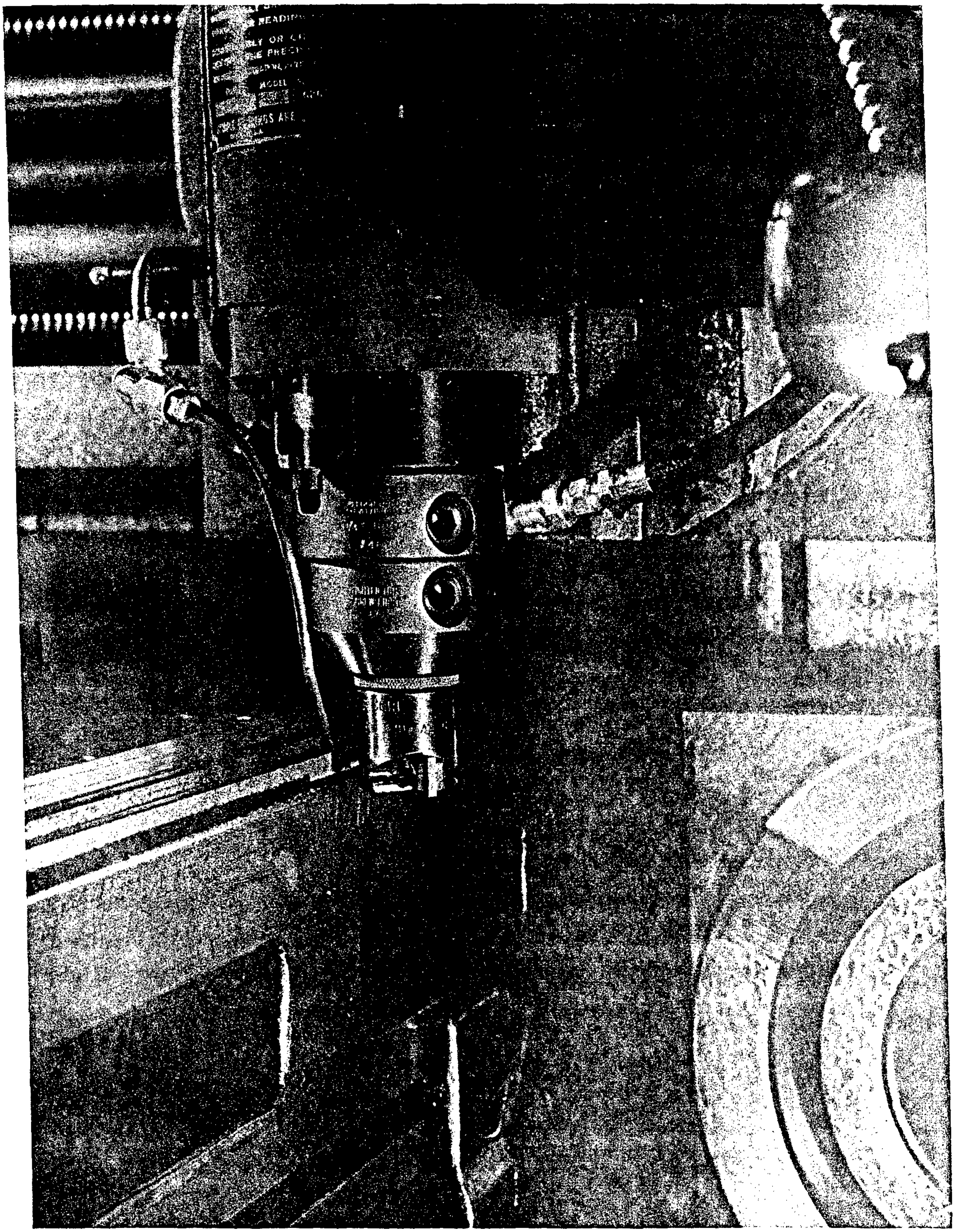
A comparison of a C-2 grade and a C-6 grade on tool life in milling the aged 17-4 PH, Figure 461, page 435, indicates that the C-2 grade gave an appreciably higher life than the C-6 grade. For example, at 500 ft./min., 70 feet of travel was obtained with the C-2 grade compared to 38 feet of travel with the C-6 grade.



An overall view of 30" x 6' Gray planer and high speed milling head applied to this machine. The planer provides continuously variable table speeds ranging from 40 inches/minute to 400 inches/minute. Spindle speeds ranging from 150 rpm to 9000 rpm are available on the milling head.

Figure 420

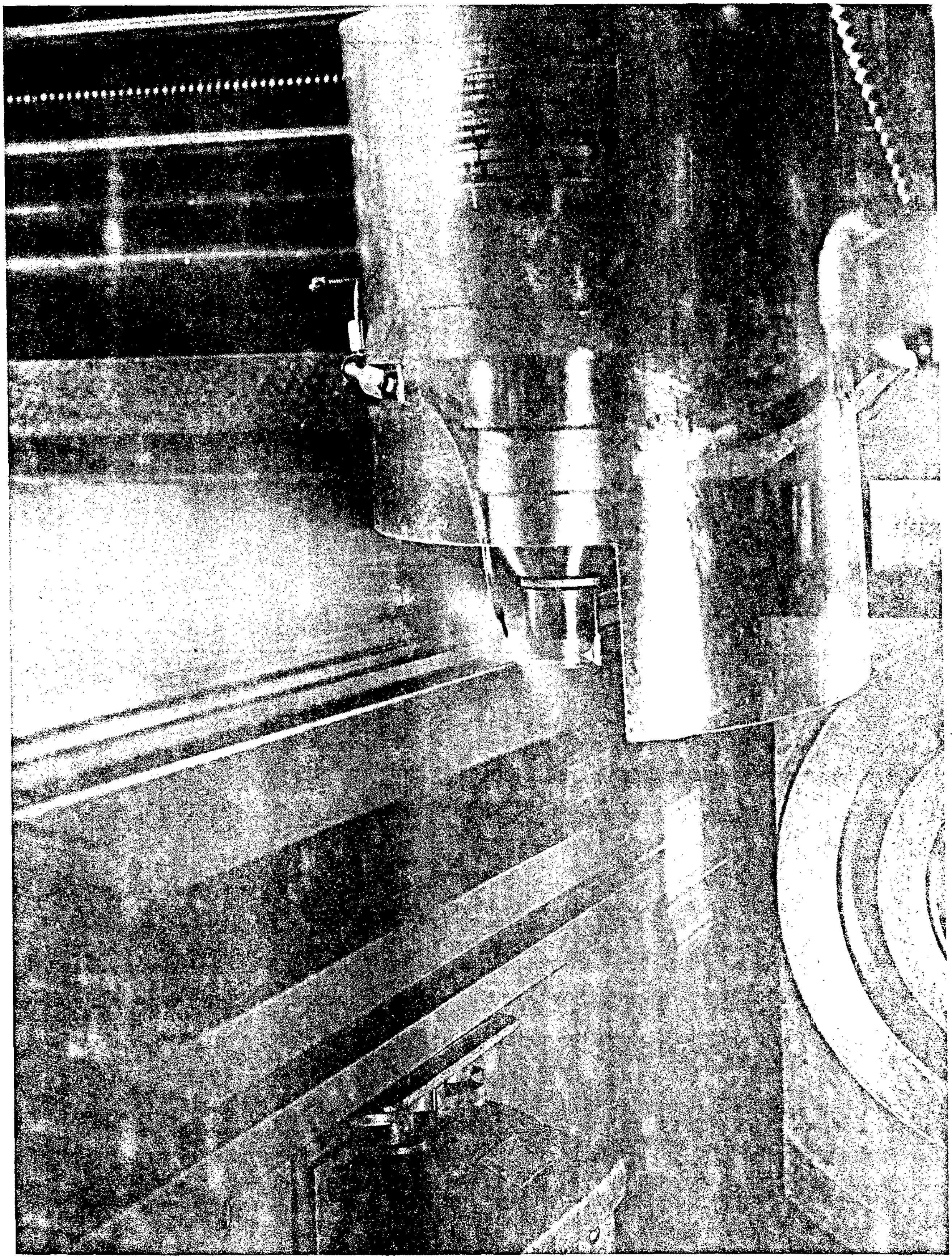
See Text, page 406



Close-up view of high speed milling cutter head and carbide throw-away type end mill. One of the two nozzles used to direct liquid CO_2 on the cutter and workpiece is shown.

Figure 421

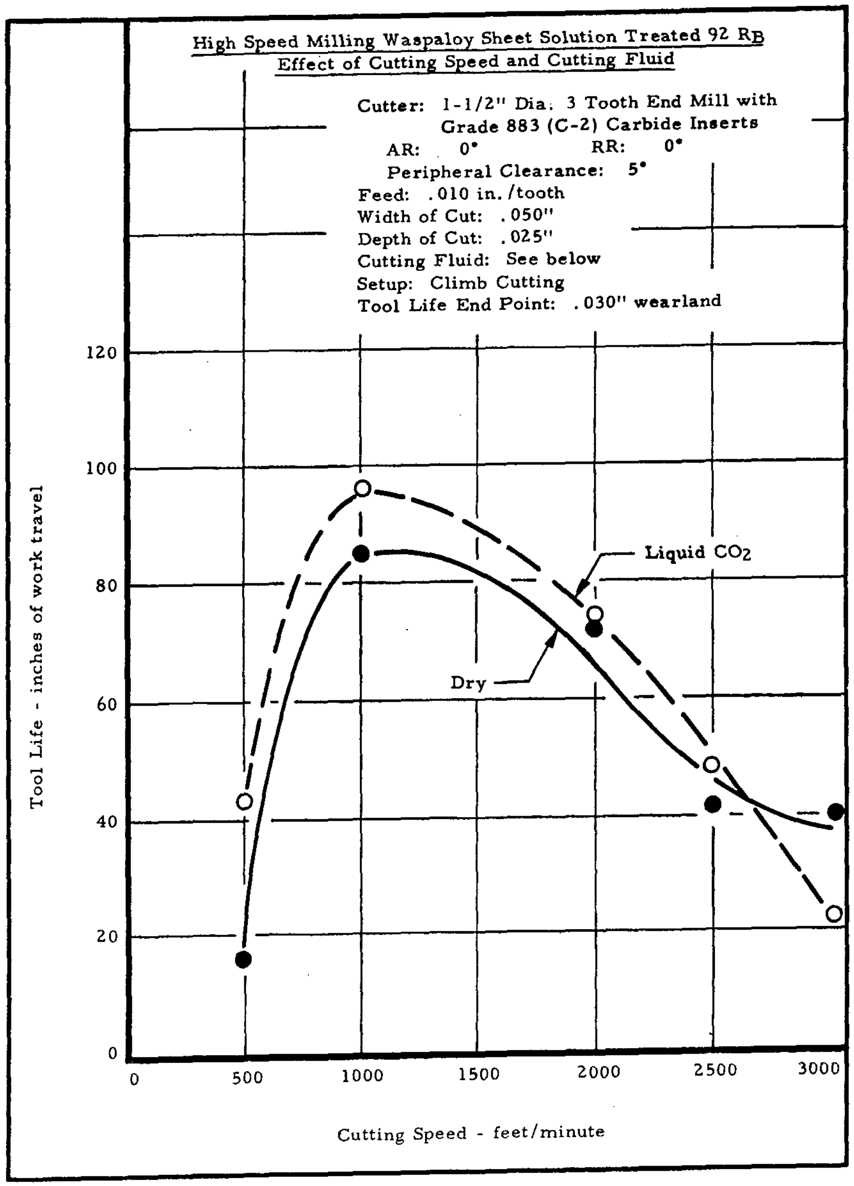
See Text, page 406



Close-up of high speed edge trimming operation with liquid CO_2 spraying on workpiece and cutter. The cutter was revolving at 6000 rpm (2000 feet per minute) and the table was traveling at 270 inches/minute.

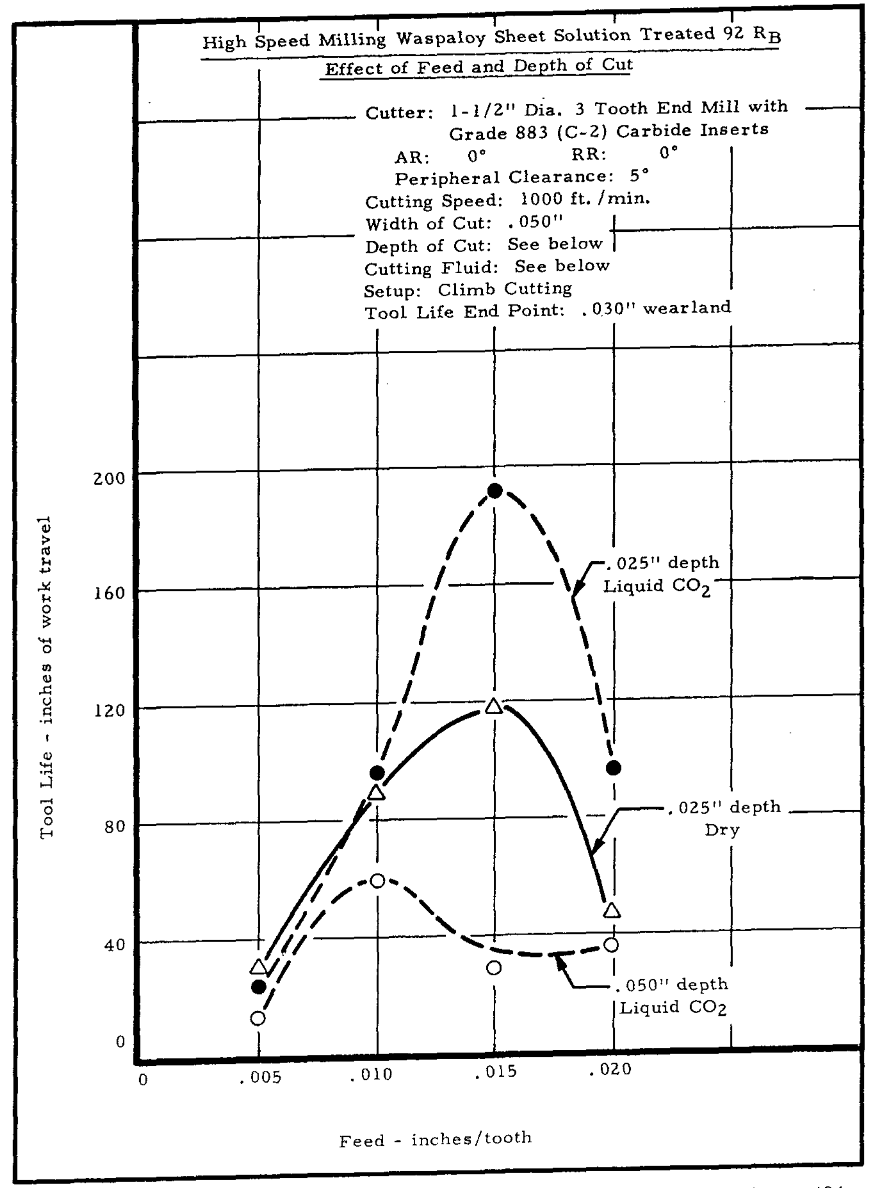
Figure 422

See Text, page 406



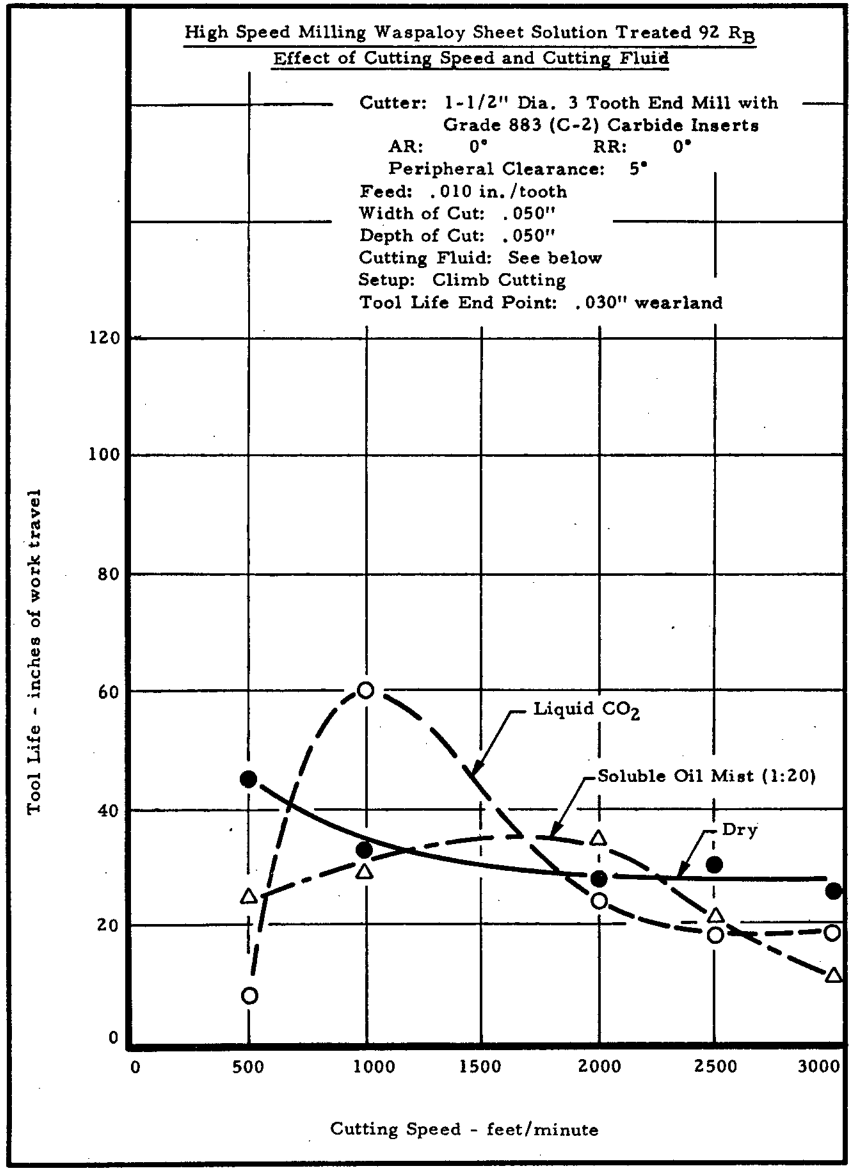
See text, page 406

Figure 423



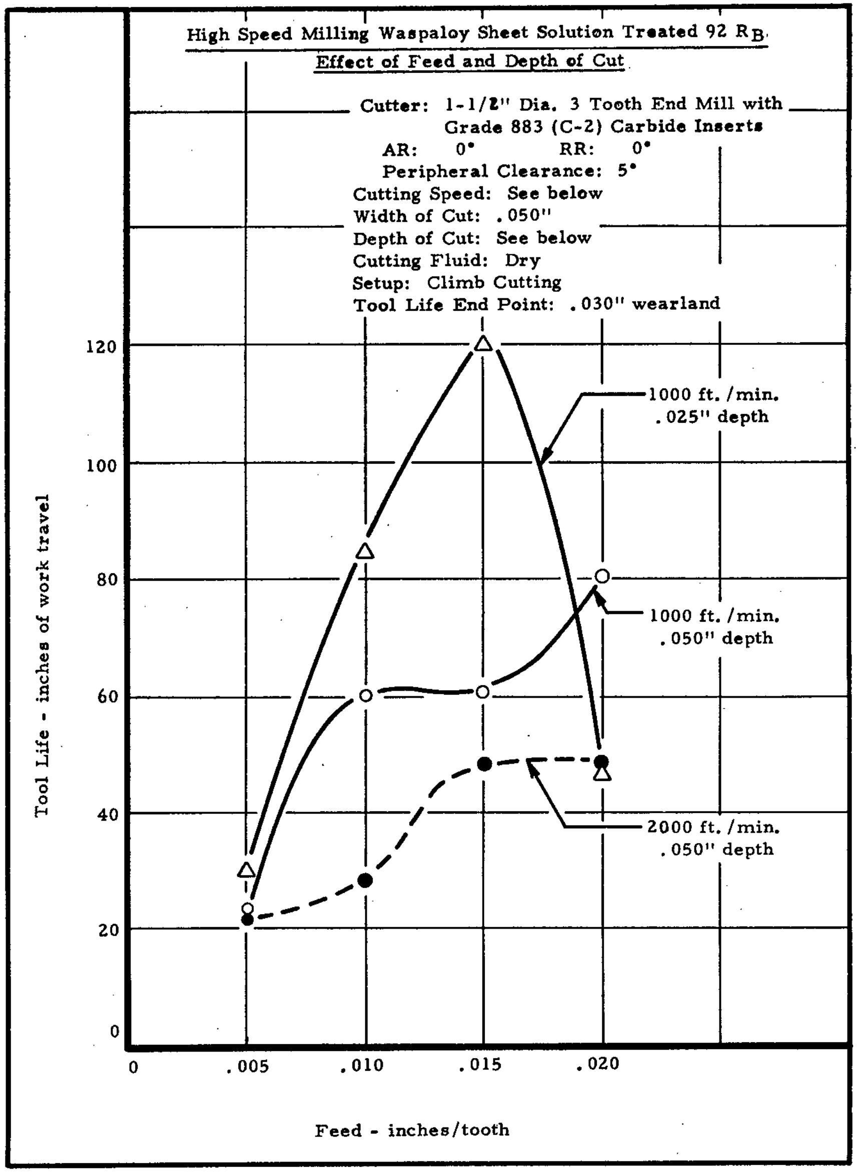
See text, page 407

Figure 424



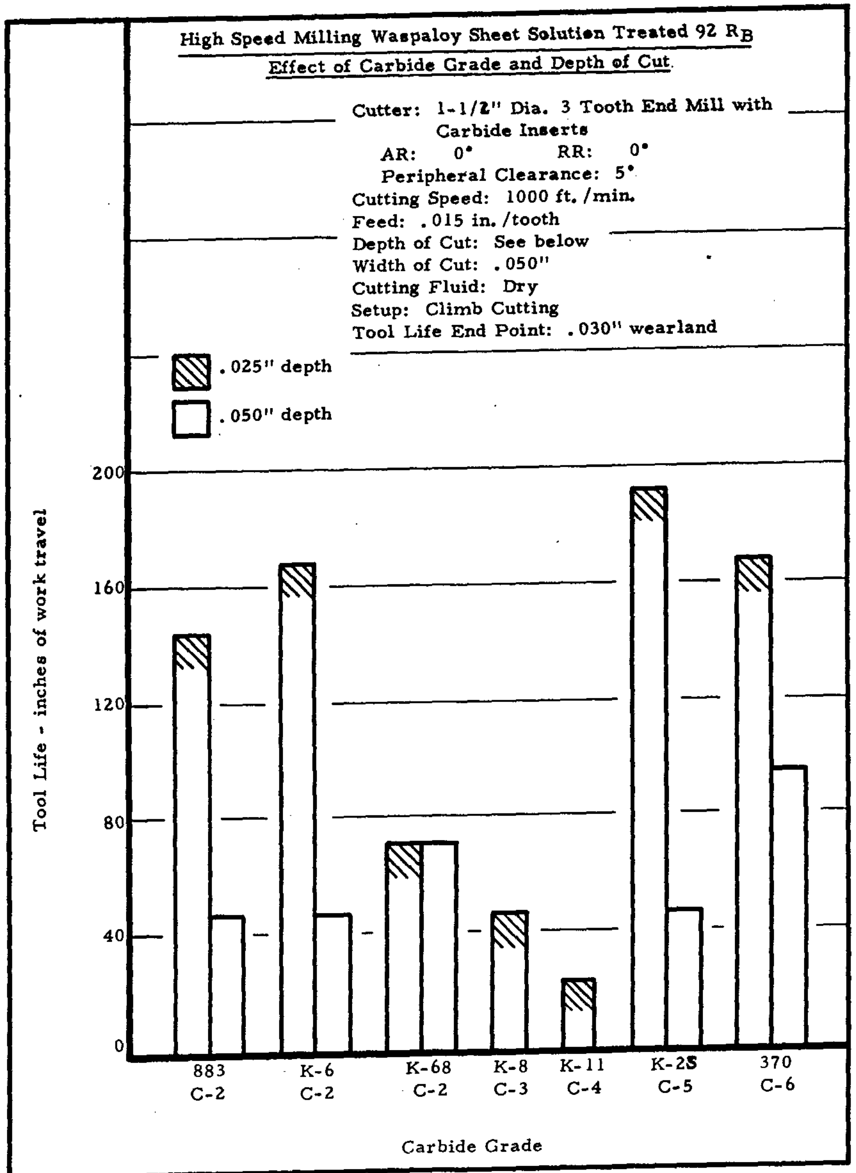
See text, page 407

Figure 425



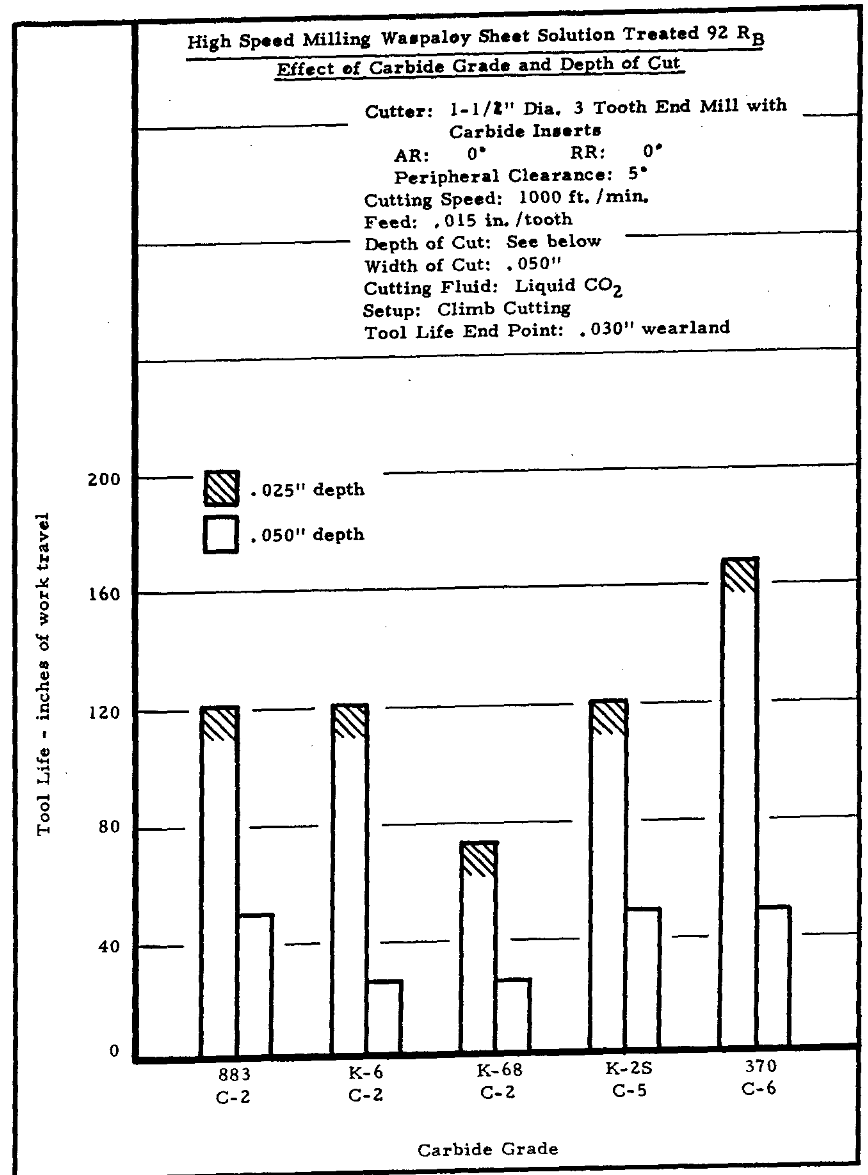
See text, page 407

Figure 426



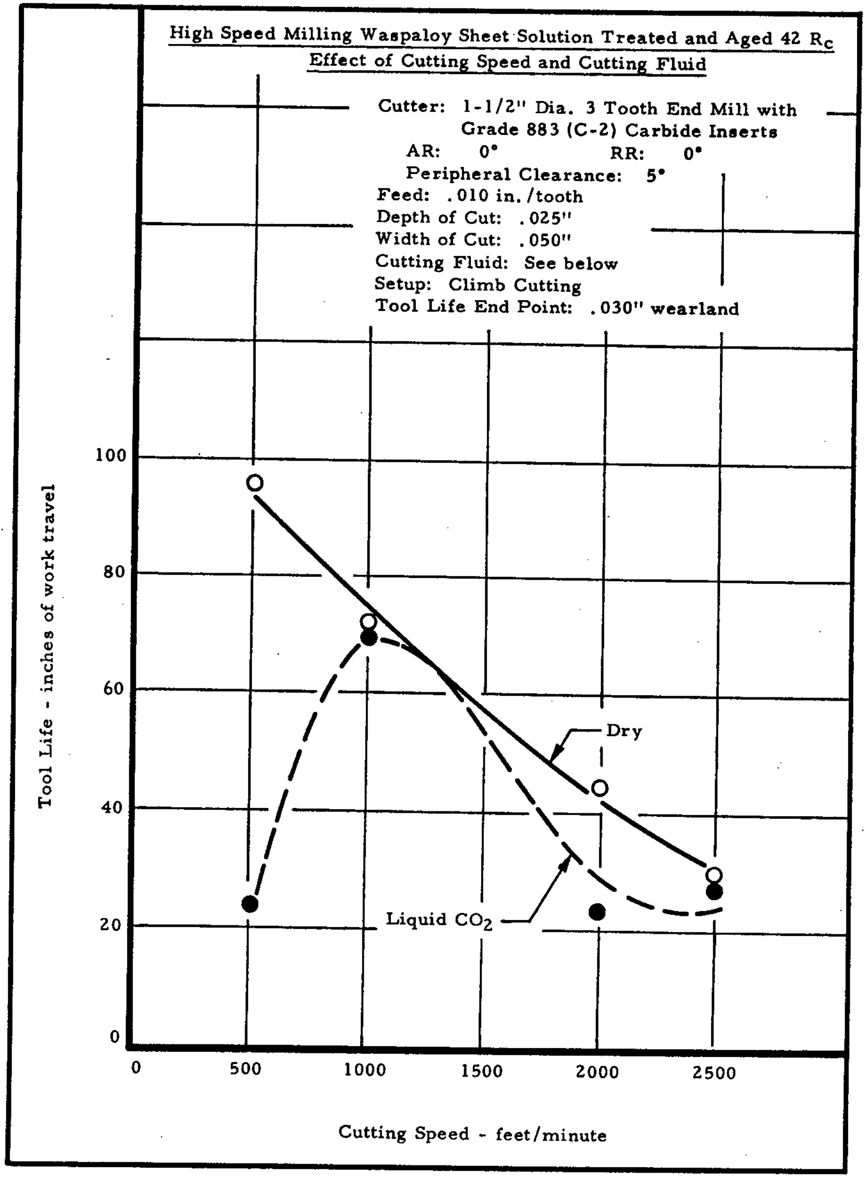
See text, page 407

Figure 427



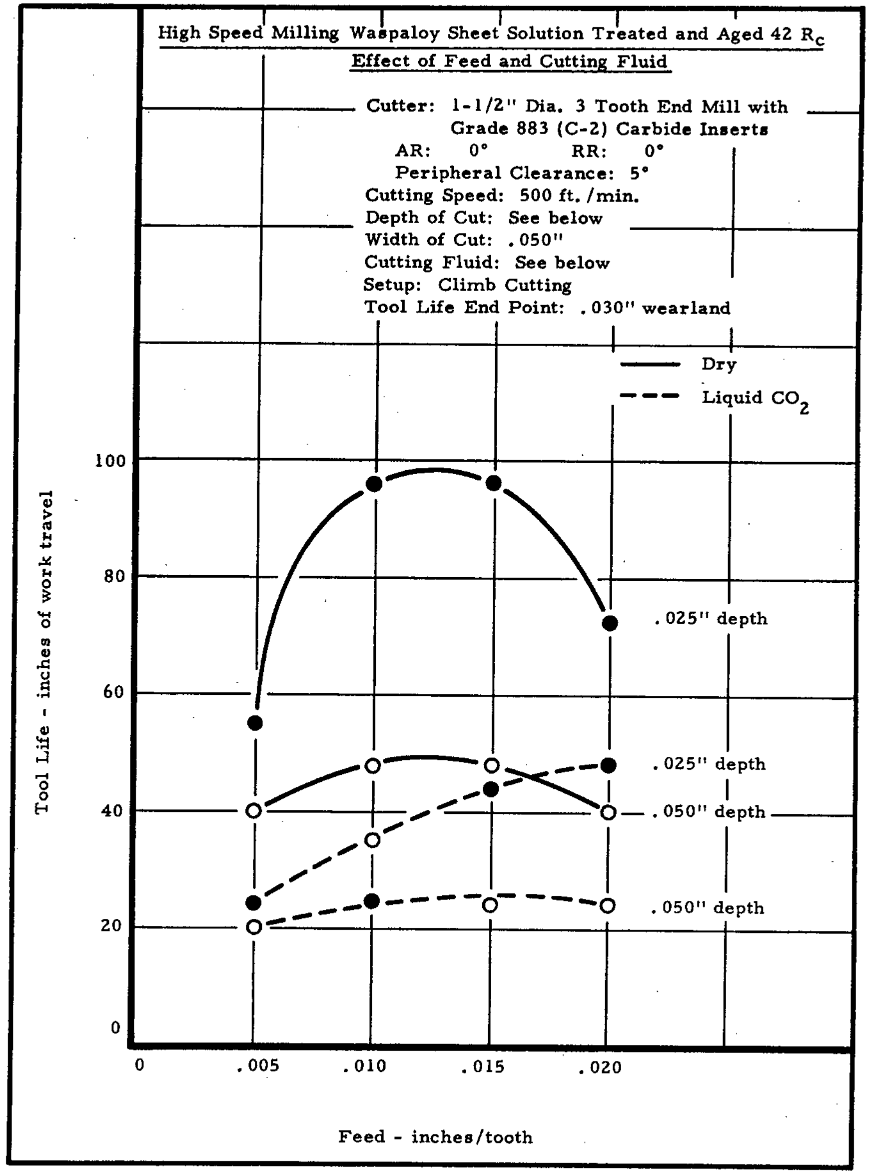
See text, page 407

Figure 428



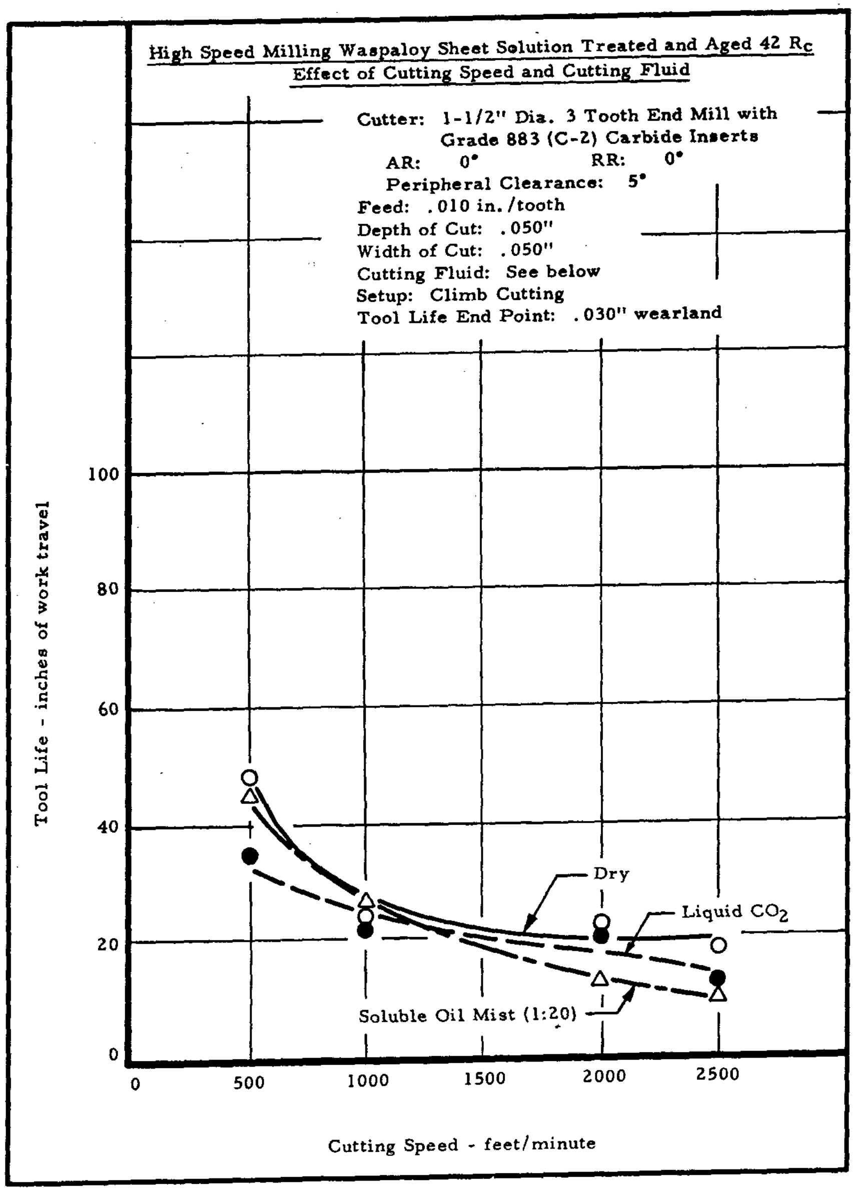
See text, page 407

Figure 429



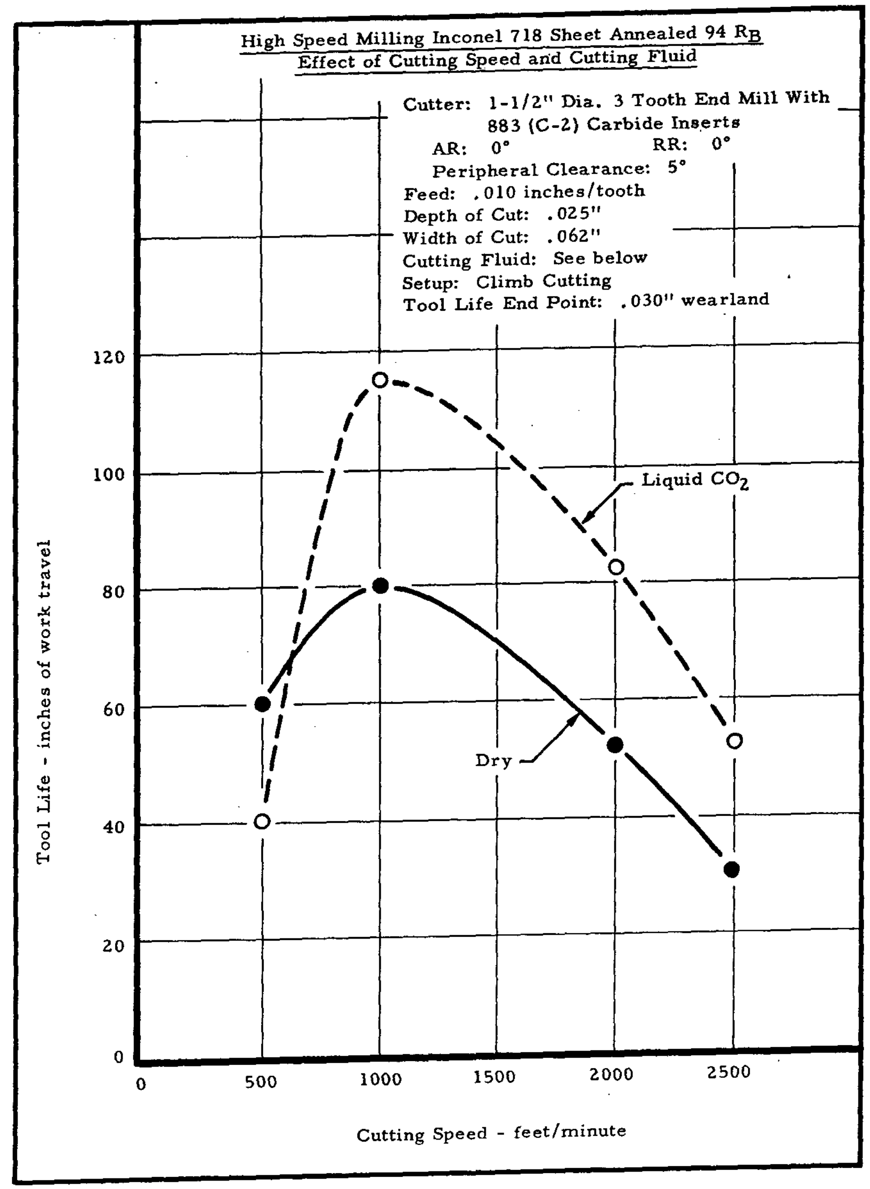
See text, page 408

Figure 430



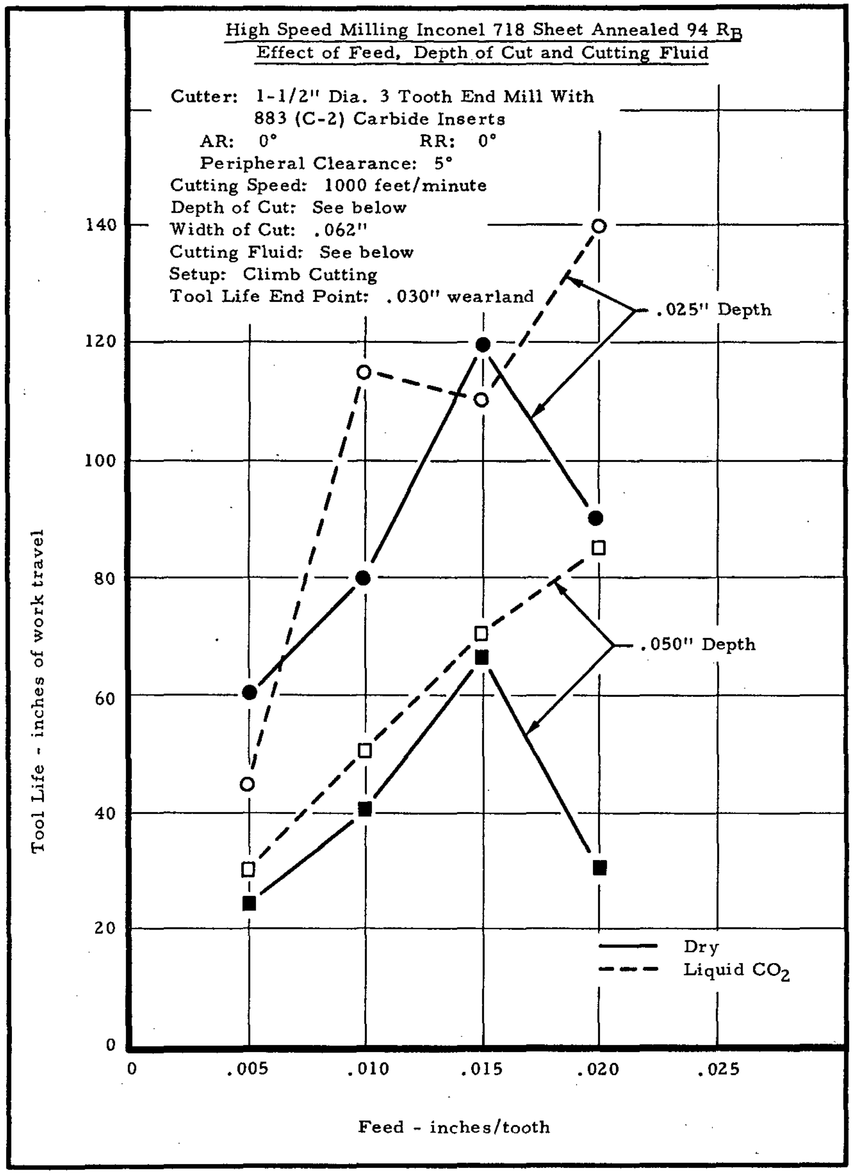
See text, page 408

Figure 431



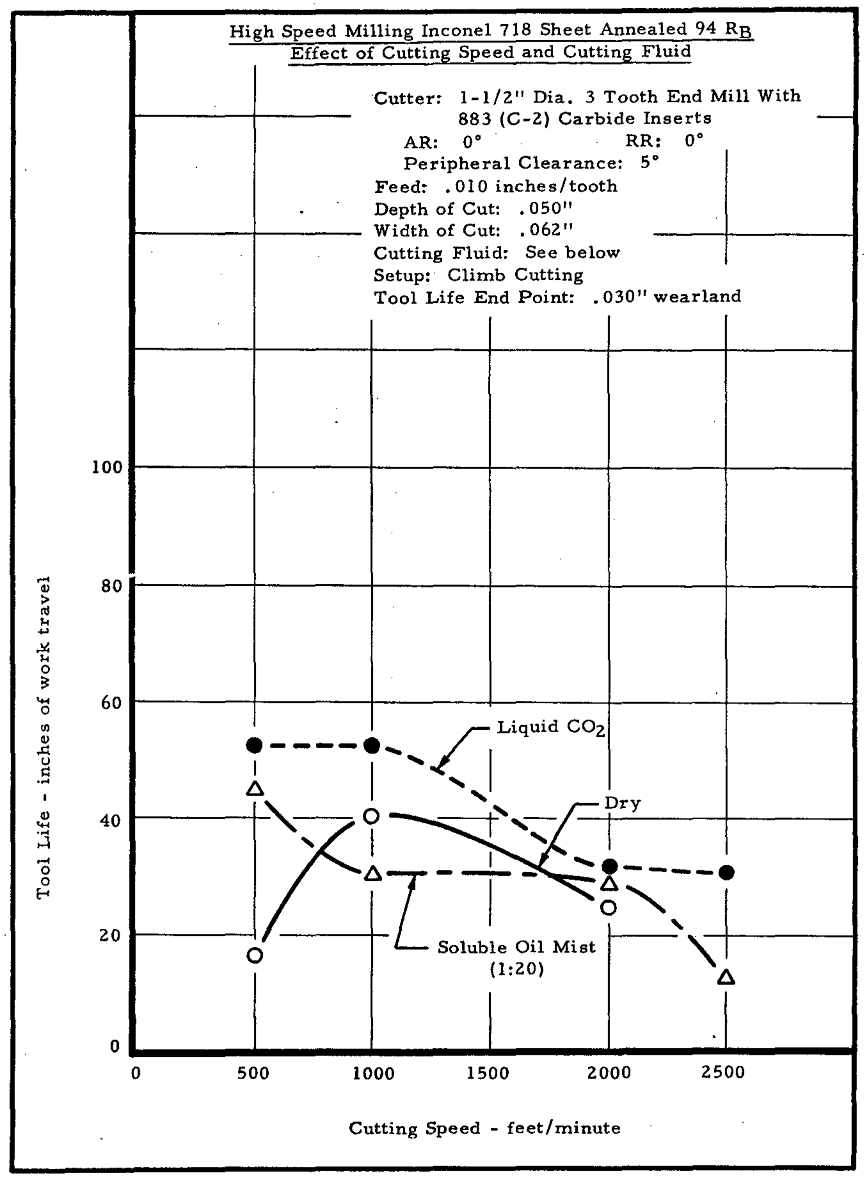
See text, page 408

Figure 432



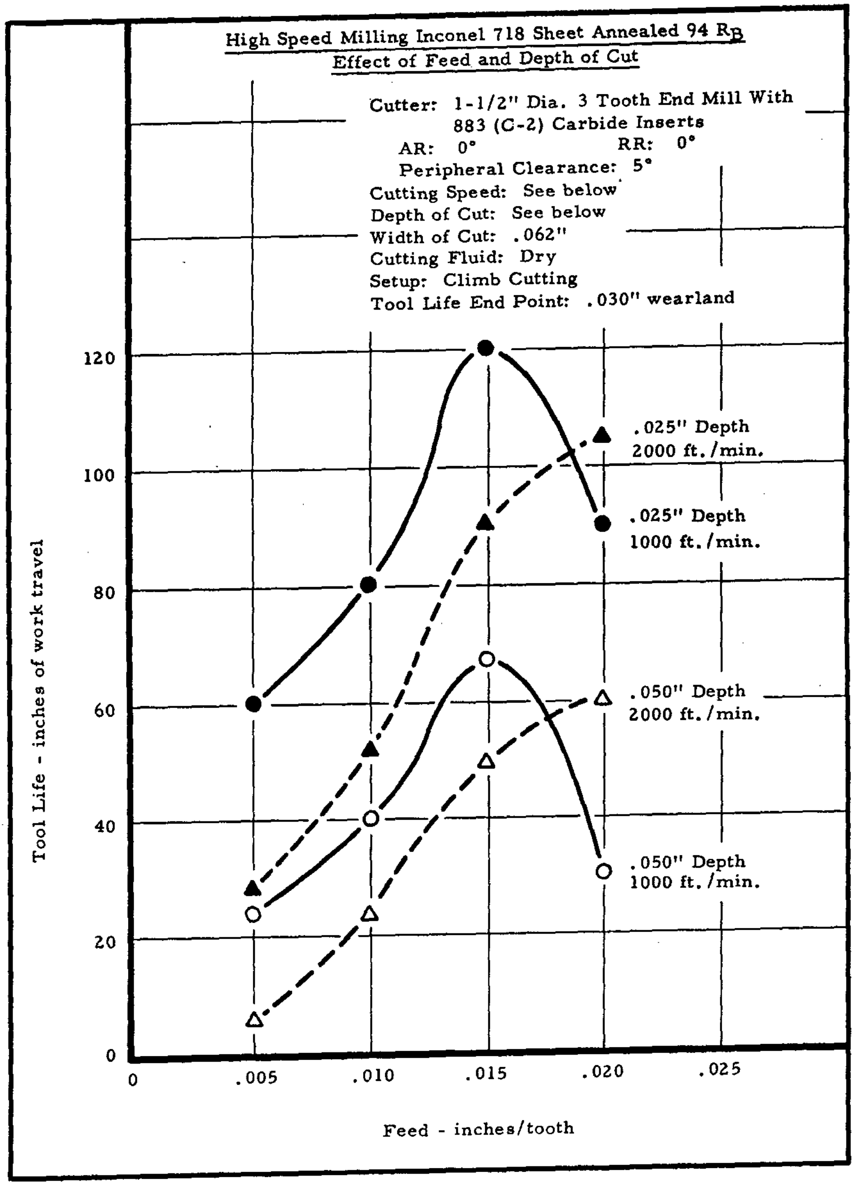
See text, page 408

Figure 433



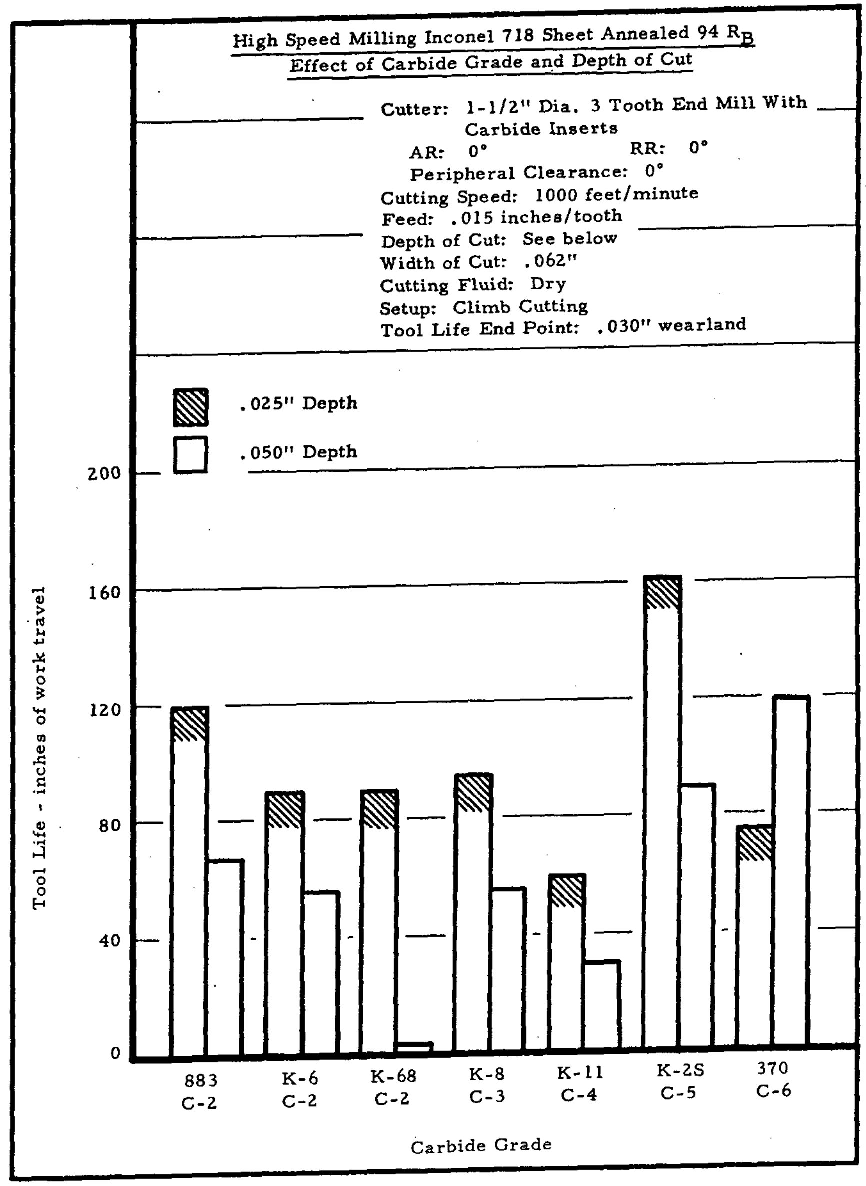
See text, page 408

Figure 434



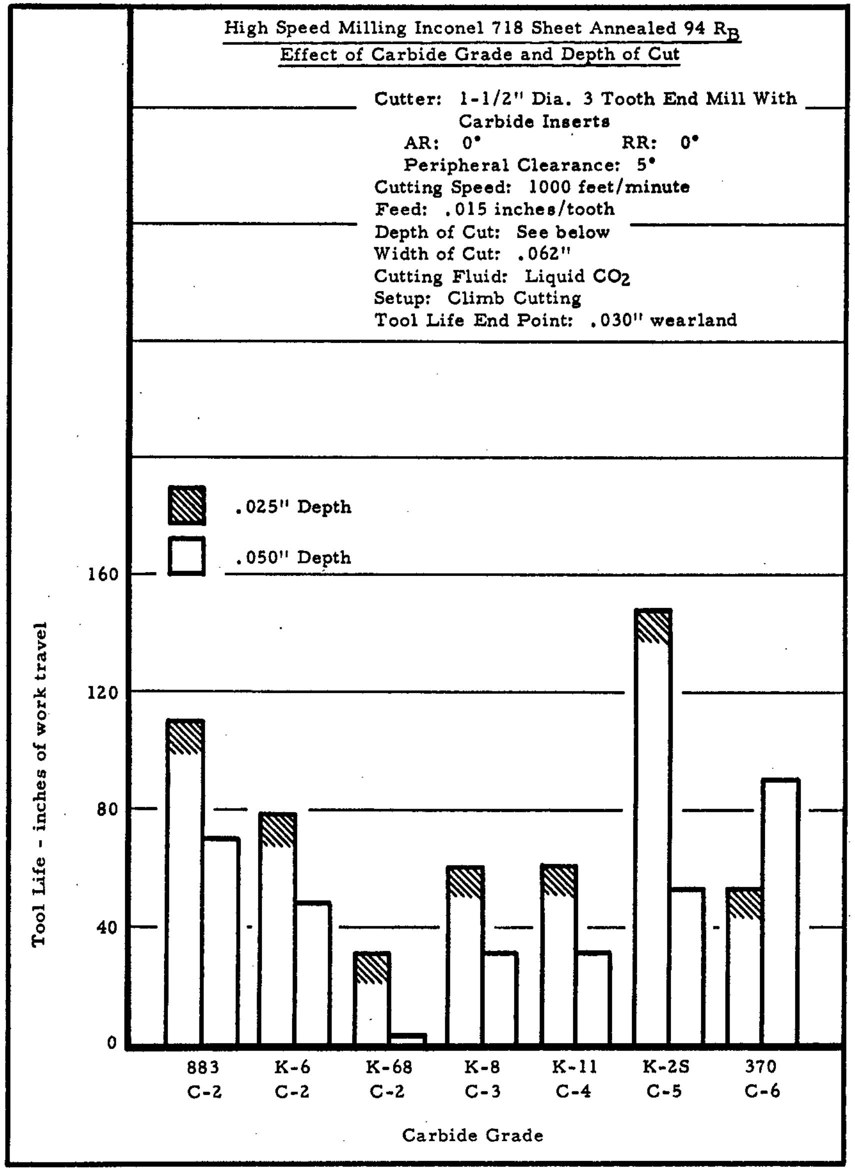
See text, page 409

Figure 435



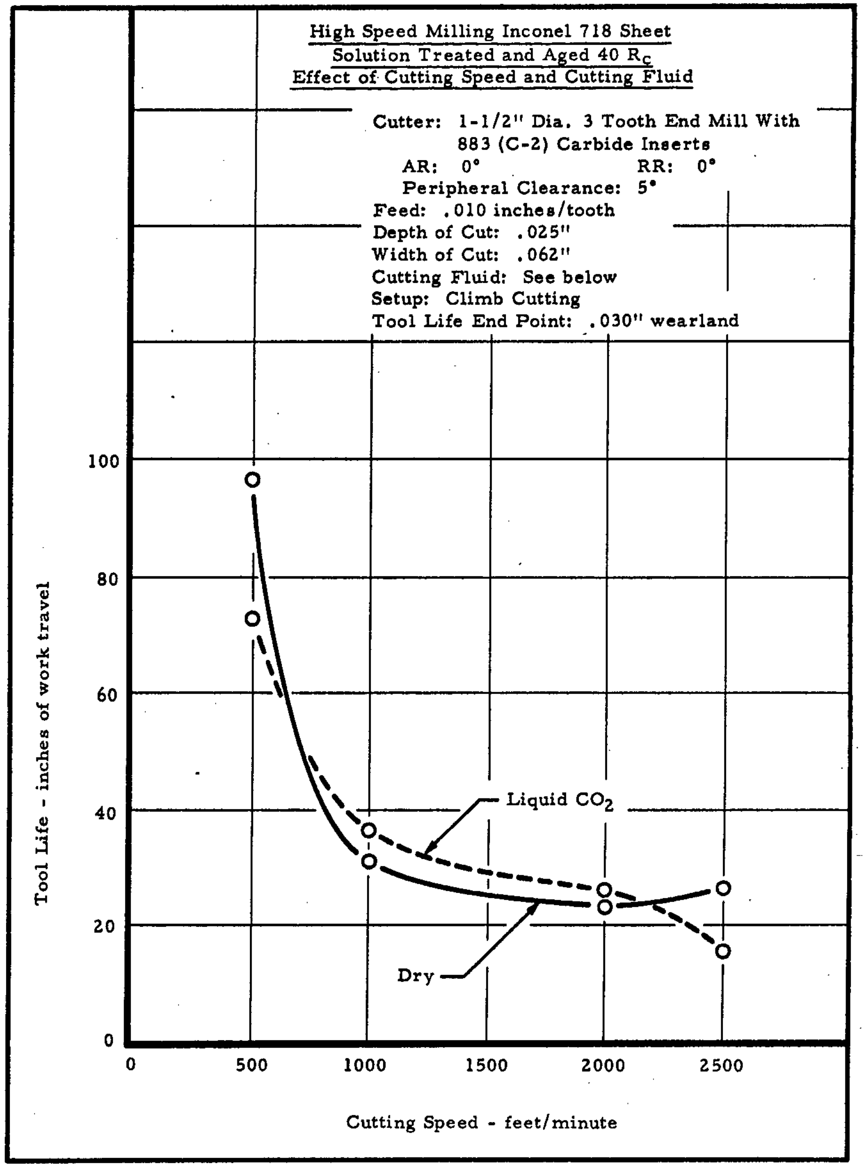
See text, page 409

Figure 436



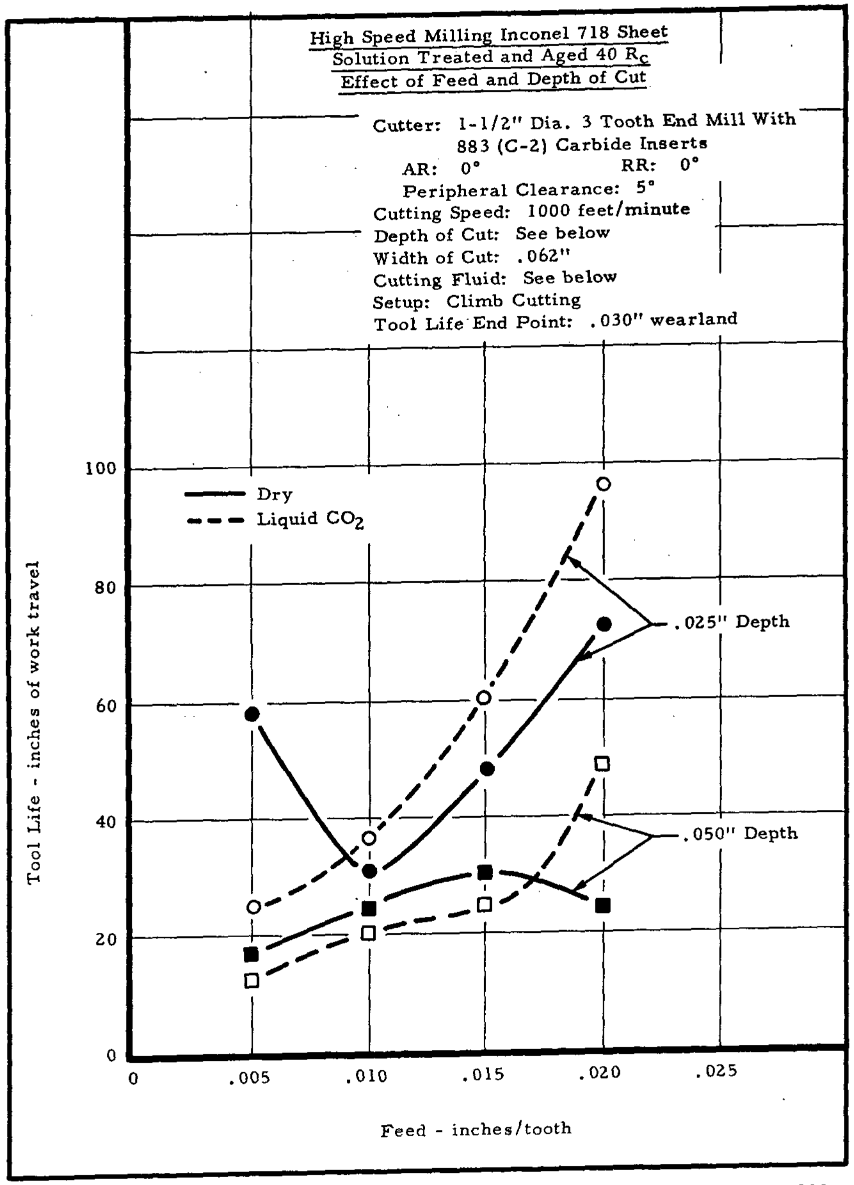
See text, page 409

Figure 437



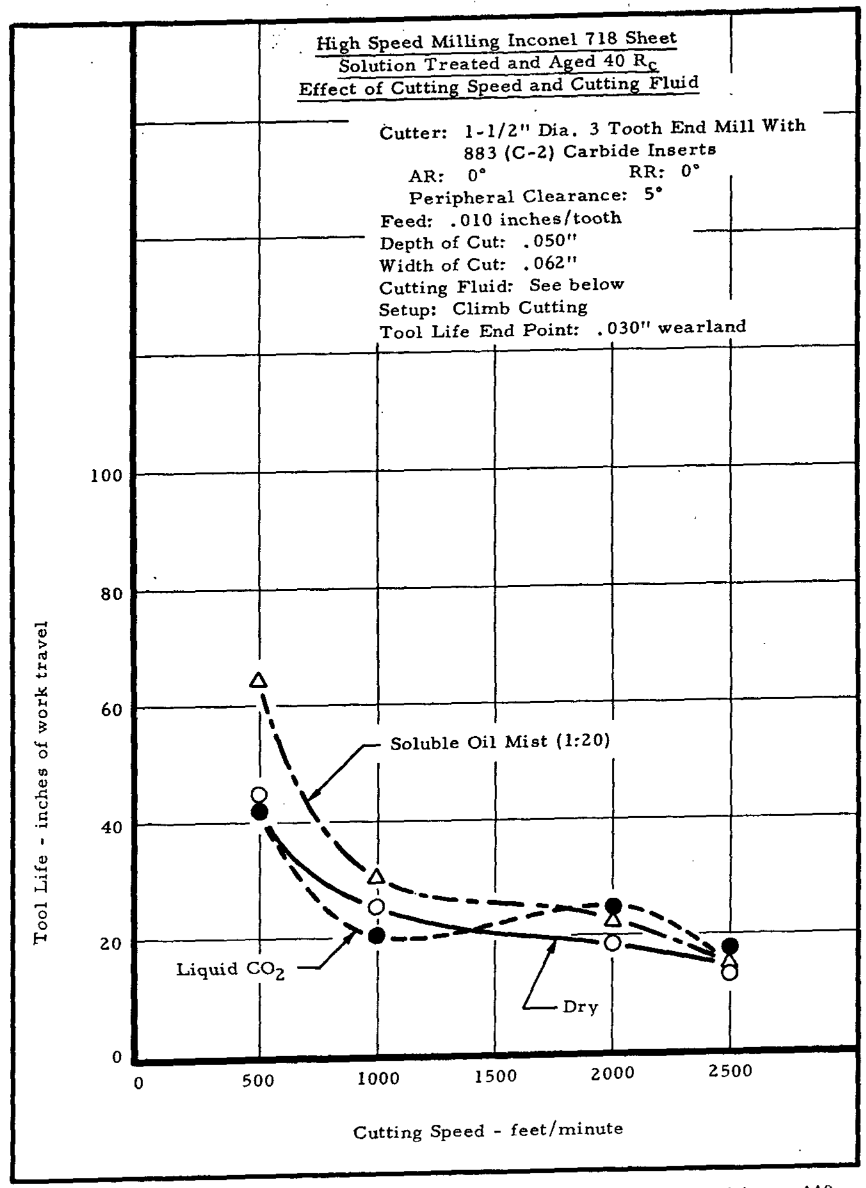
See text, page 409

Figure 438



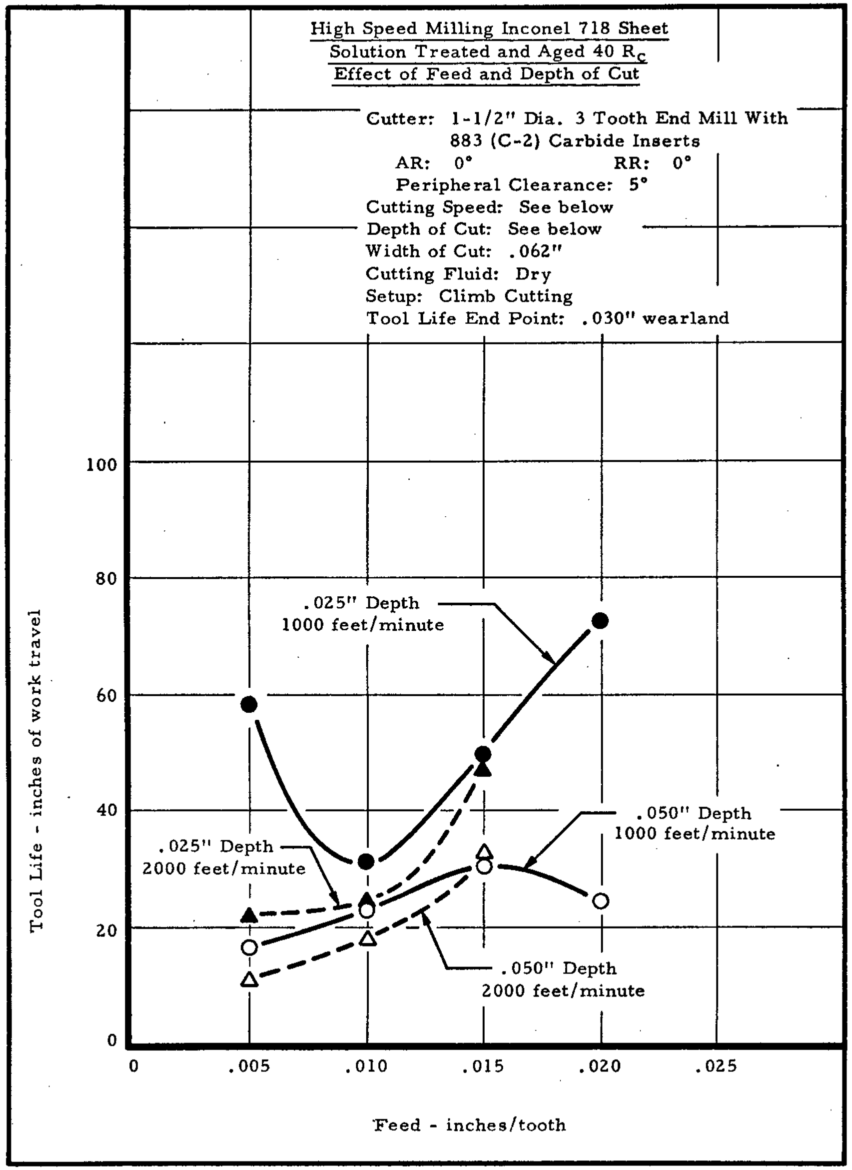
See text, page 409

Figure 339



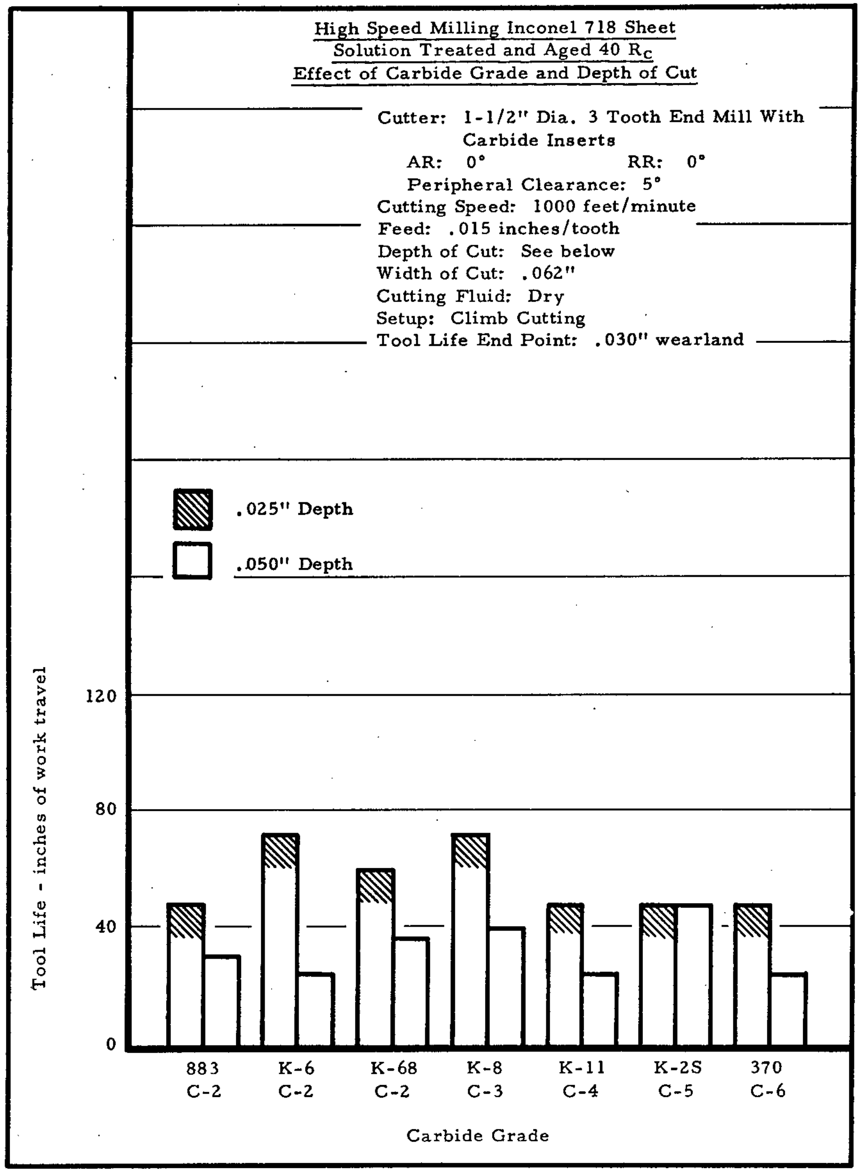
See text, page 409

Figure 440



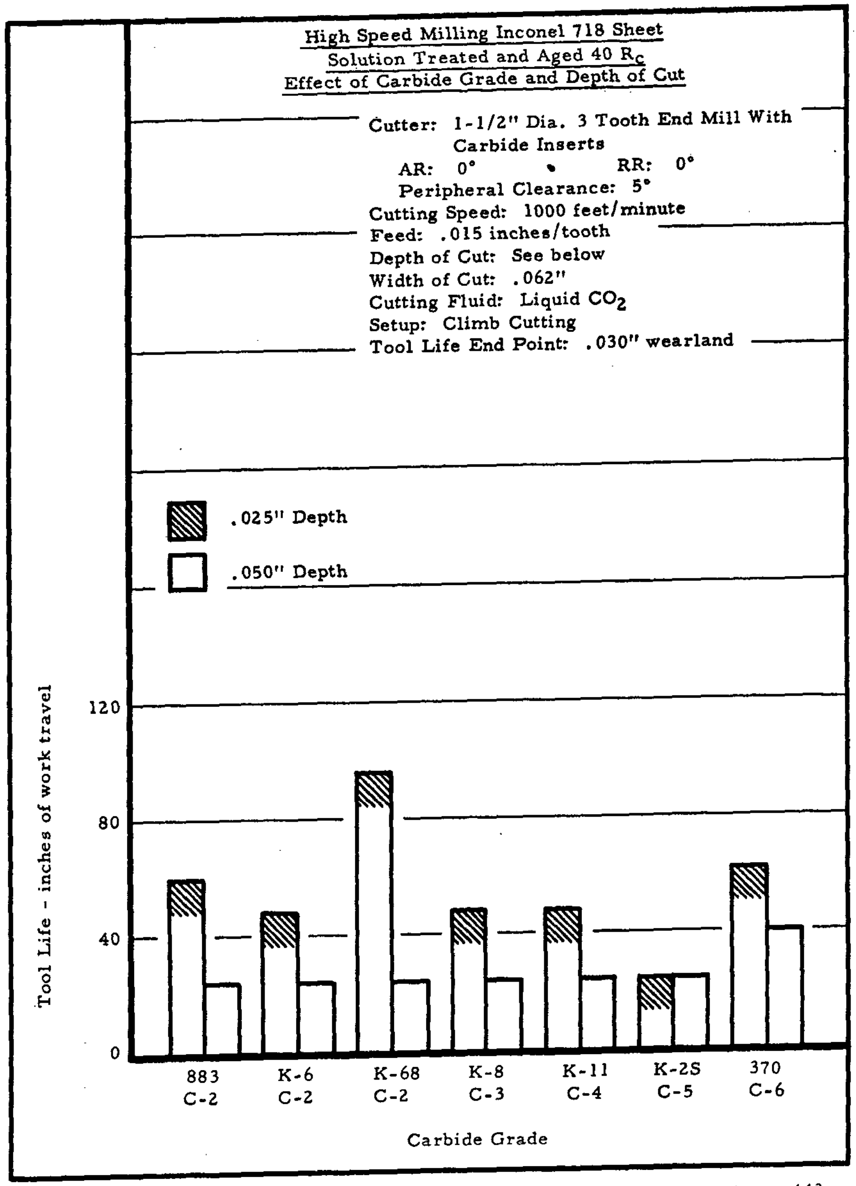
See text, page 409

Figure 441



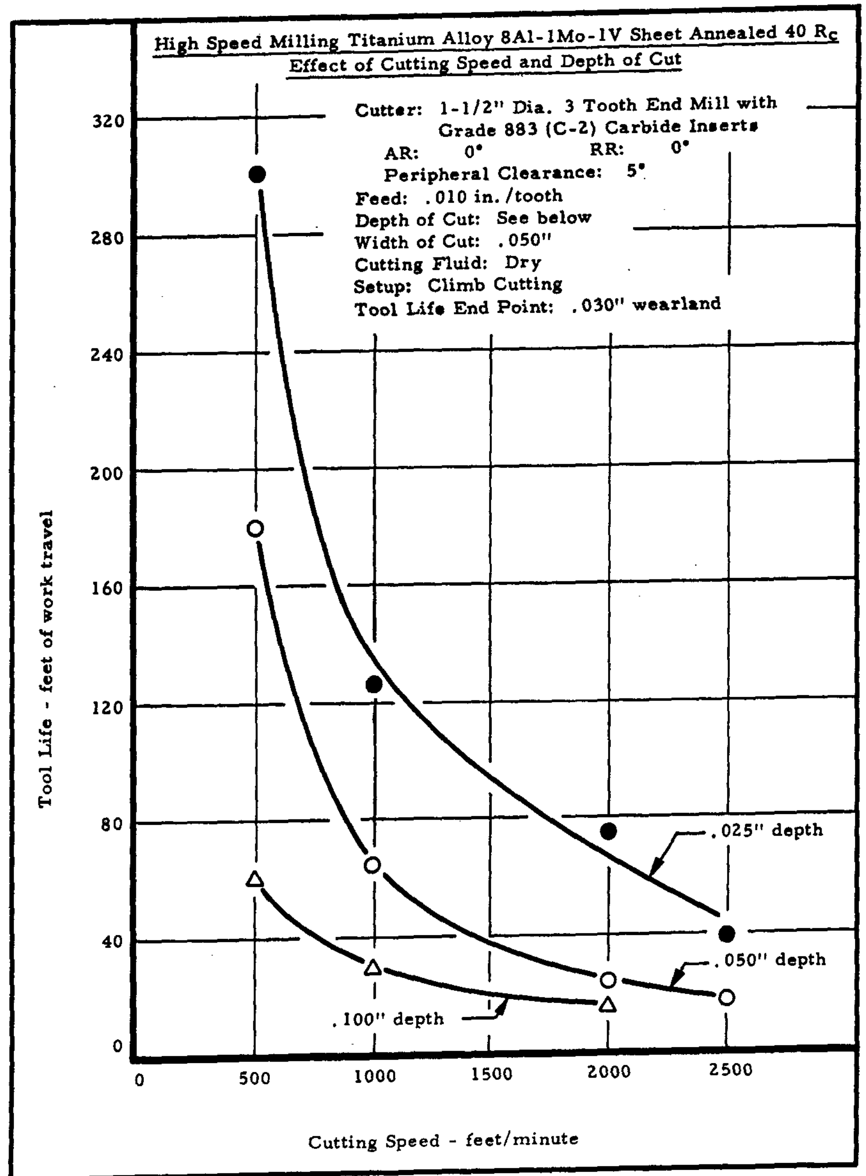
See text, page 409

Figure 442



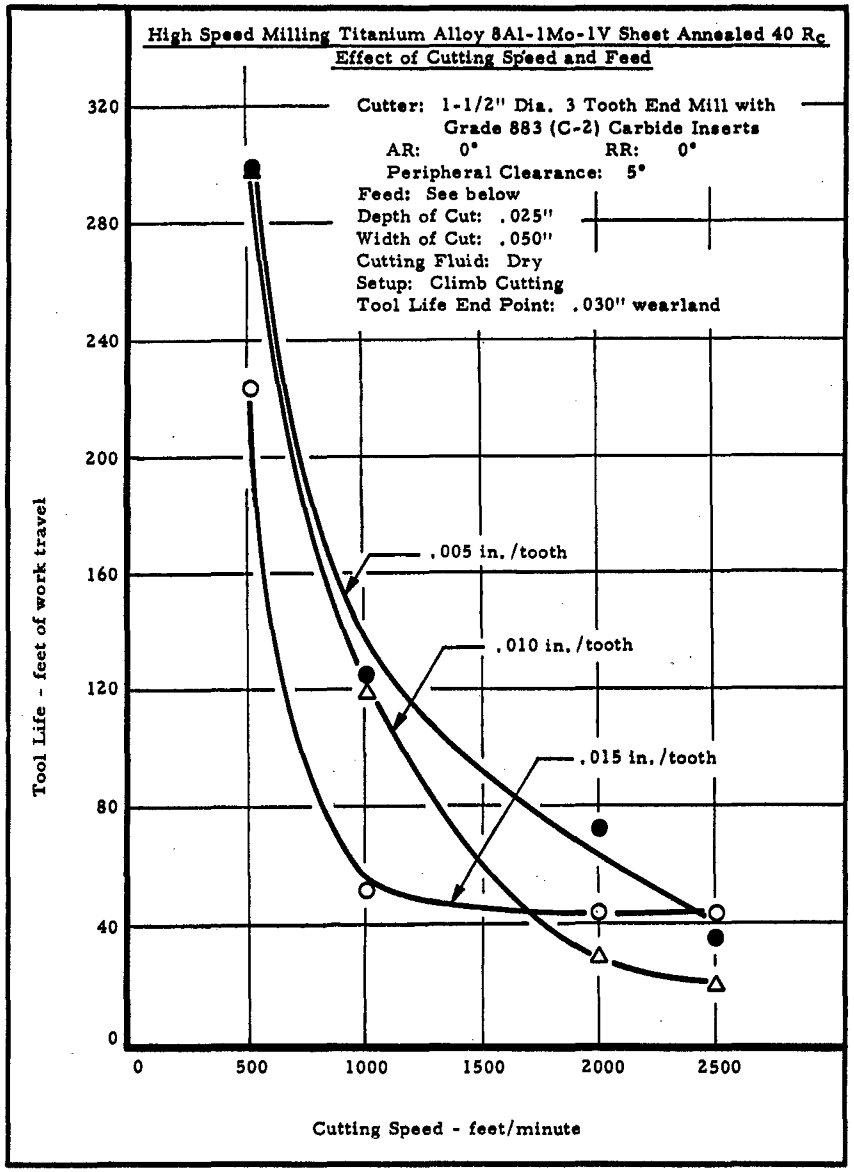
See text, page 409

Figure 443



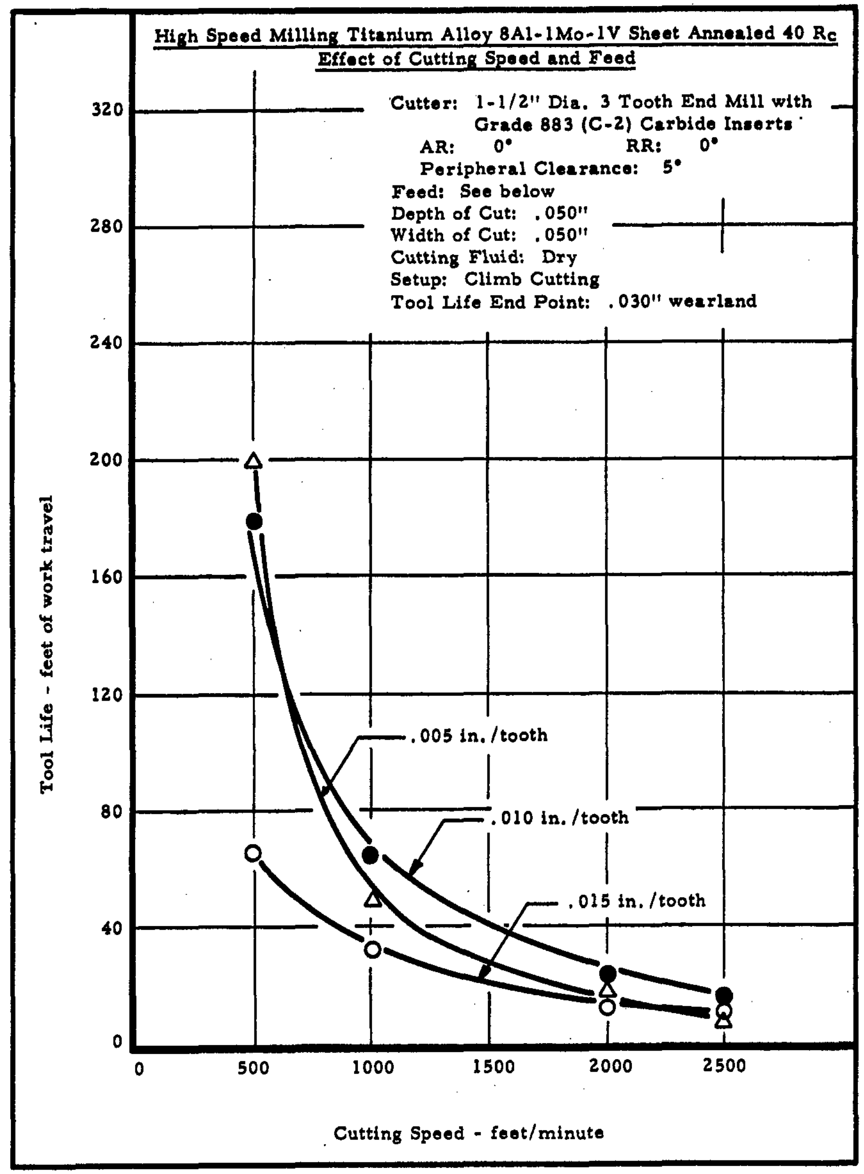
See text, page 410

Figure 444



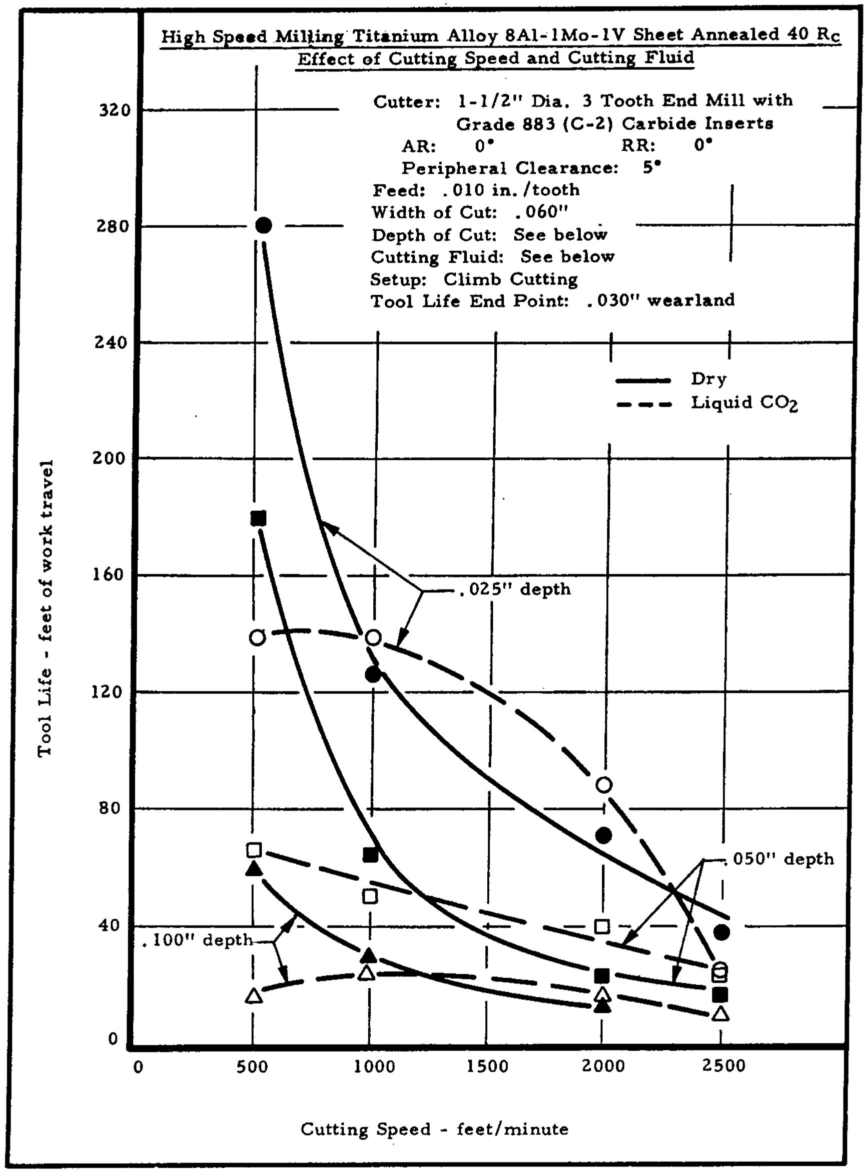
See text, page 410

Figure 445



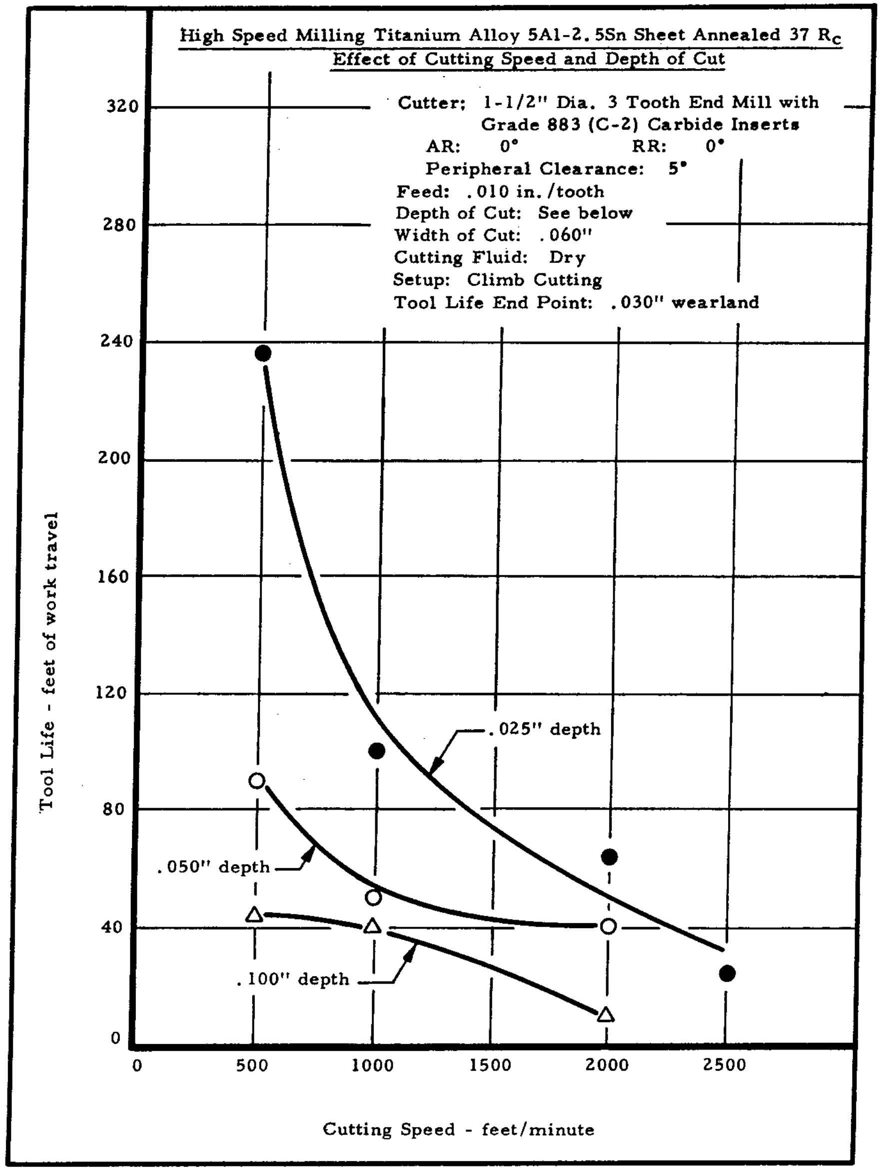
See text, page 410

Figure 446



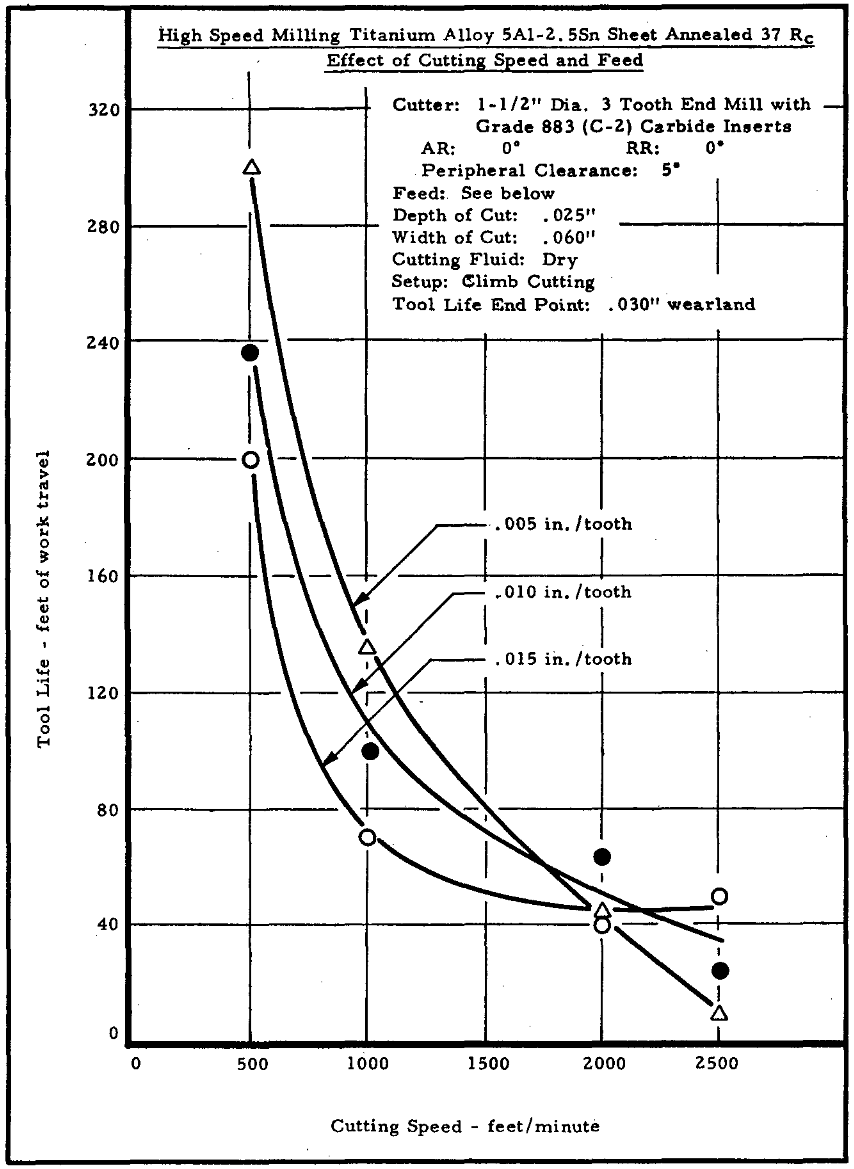
See text, pages 410

Figure 447



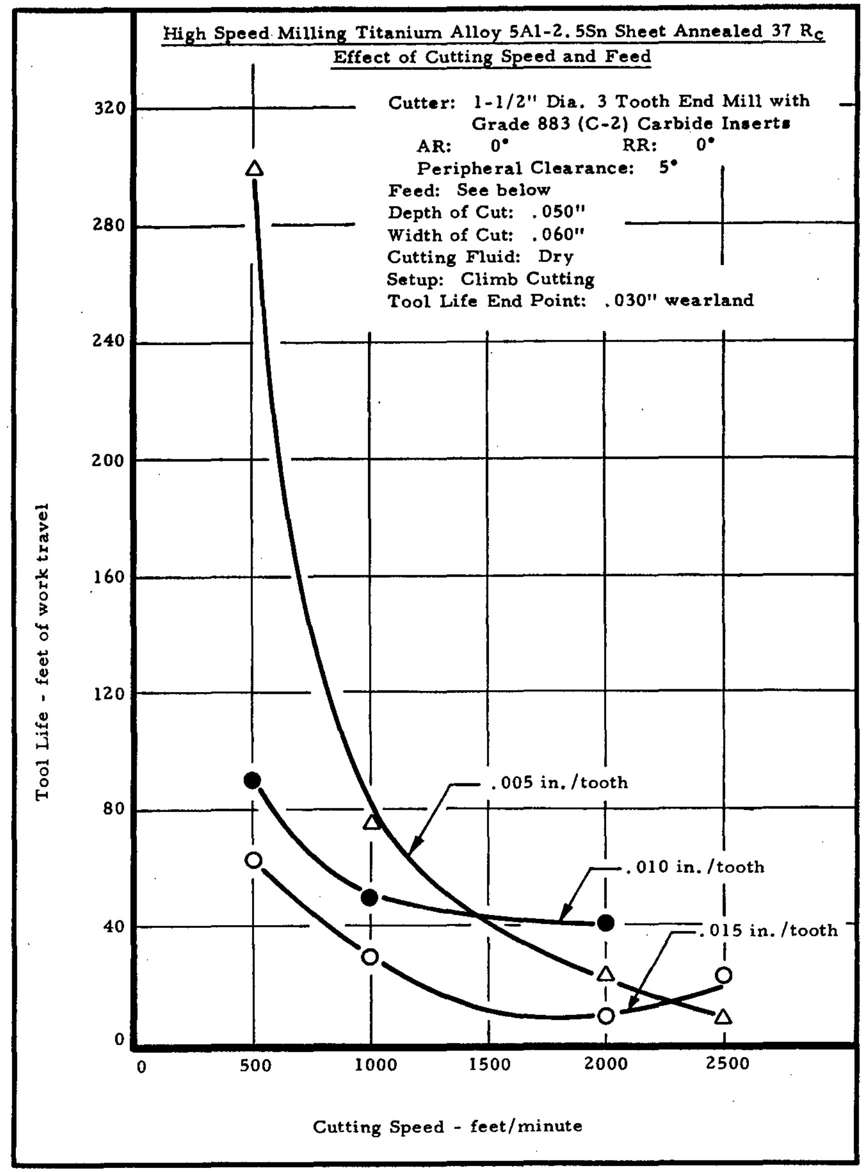
See text, page 410

Figure 448



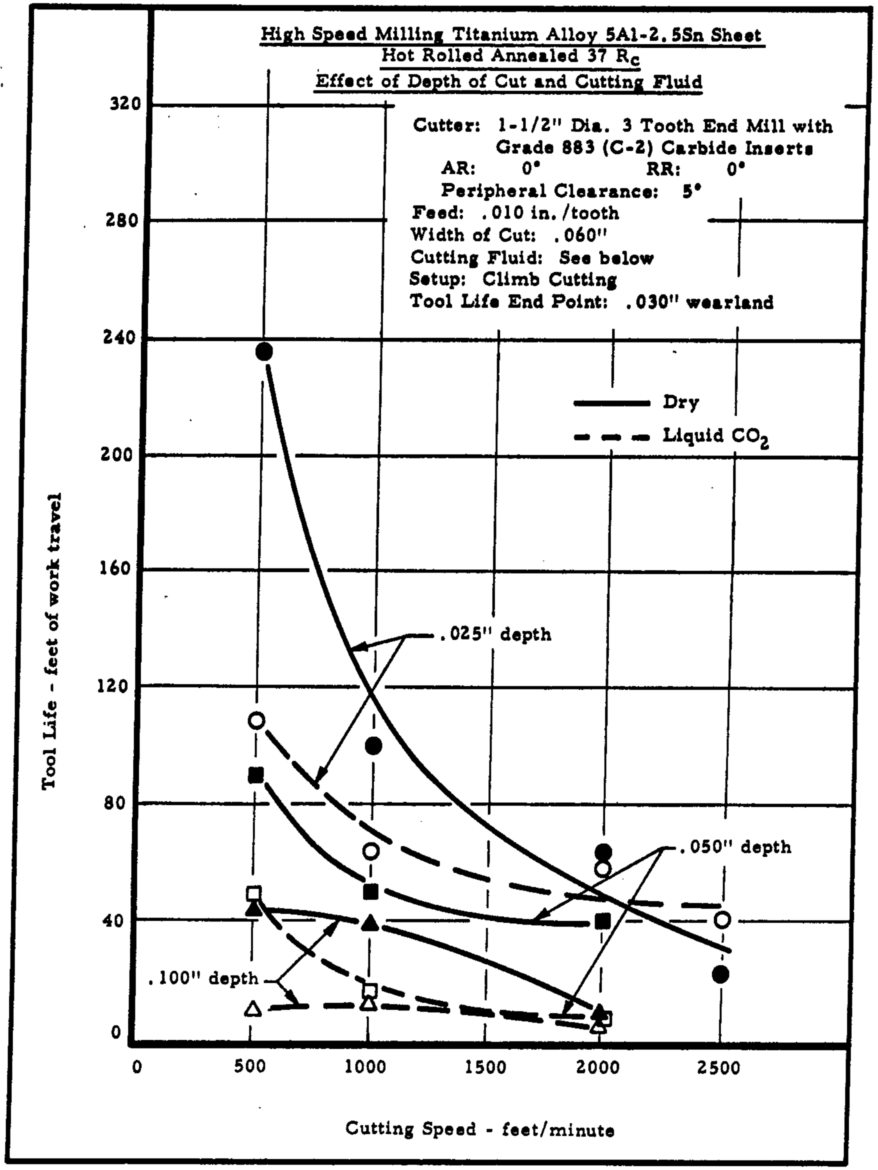
See text, page 410

Figure 449



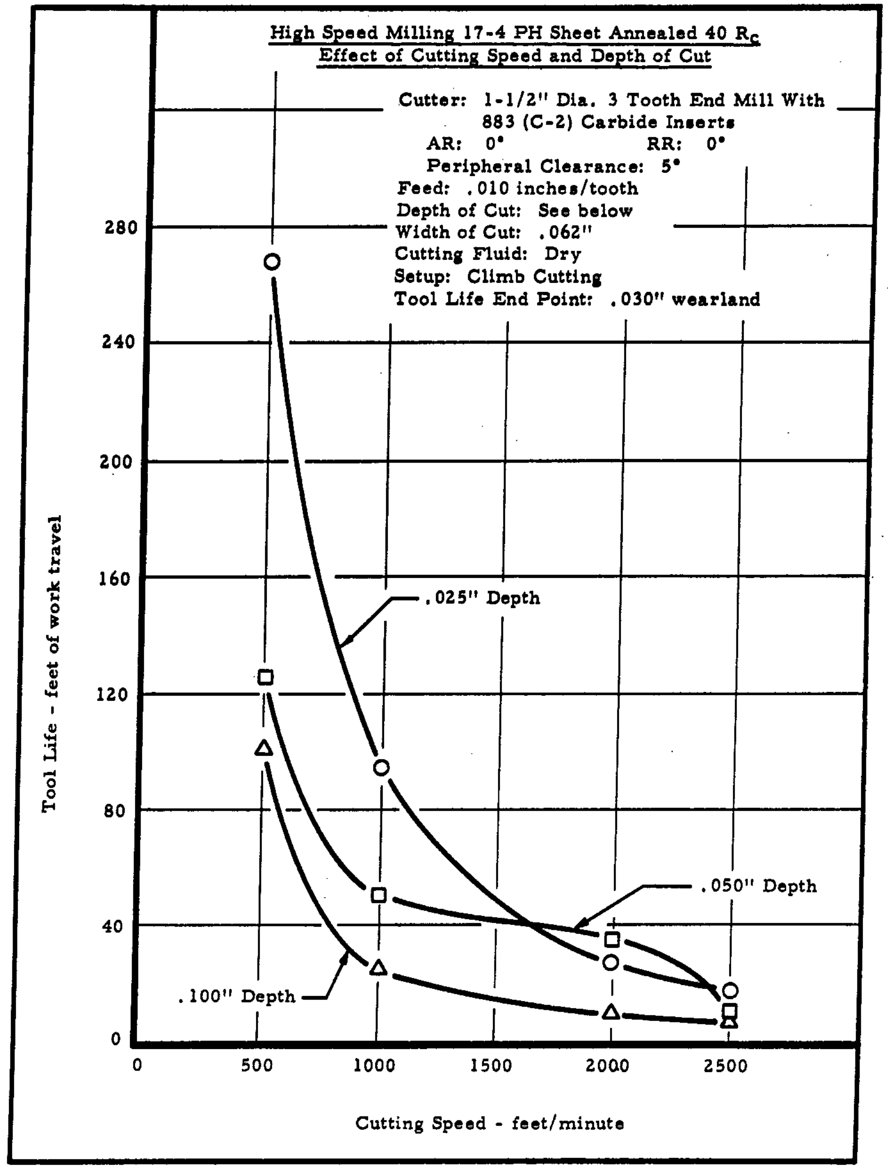
See text, page 410

Figure 450



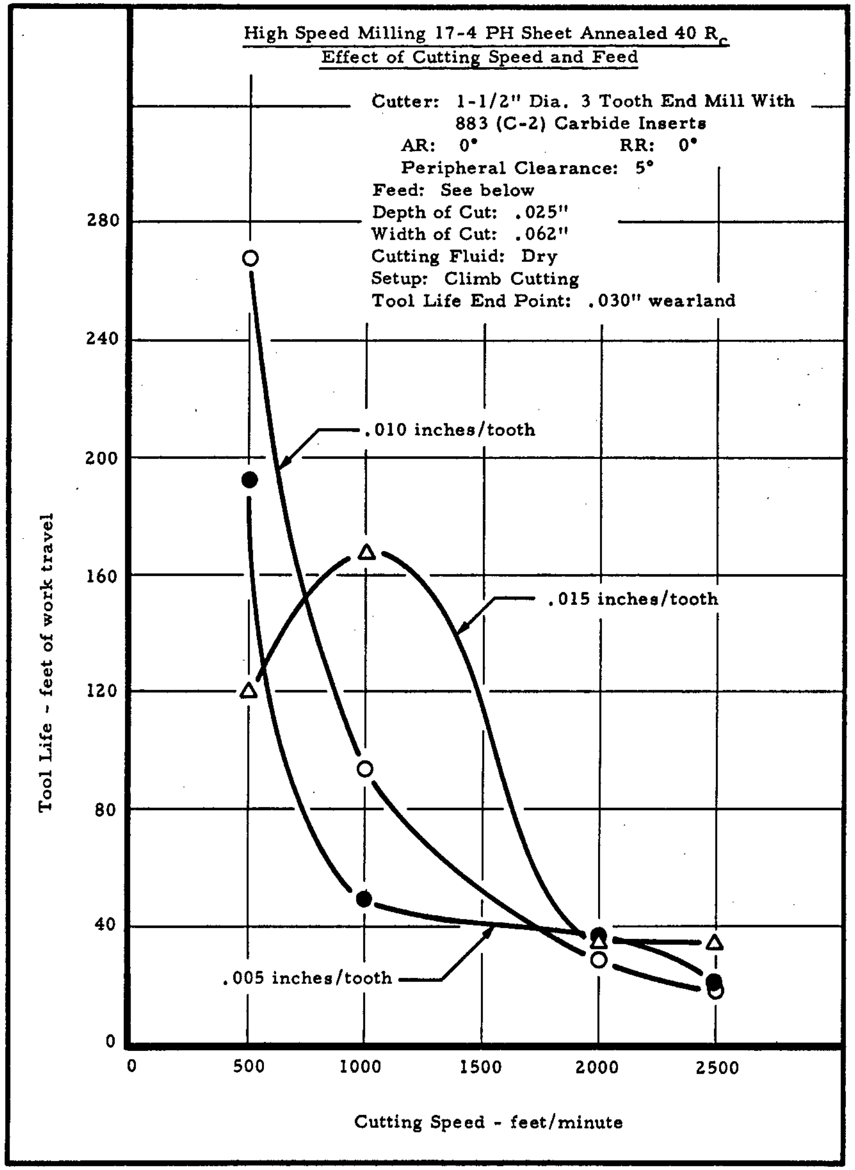
See text, page 410

Figure 451



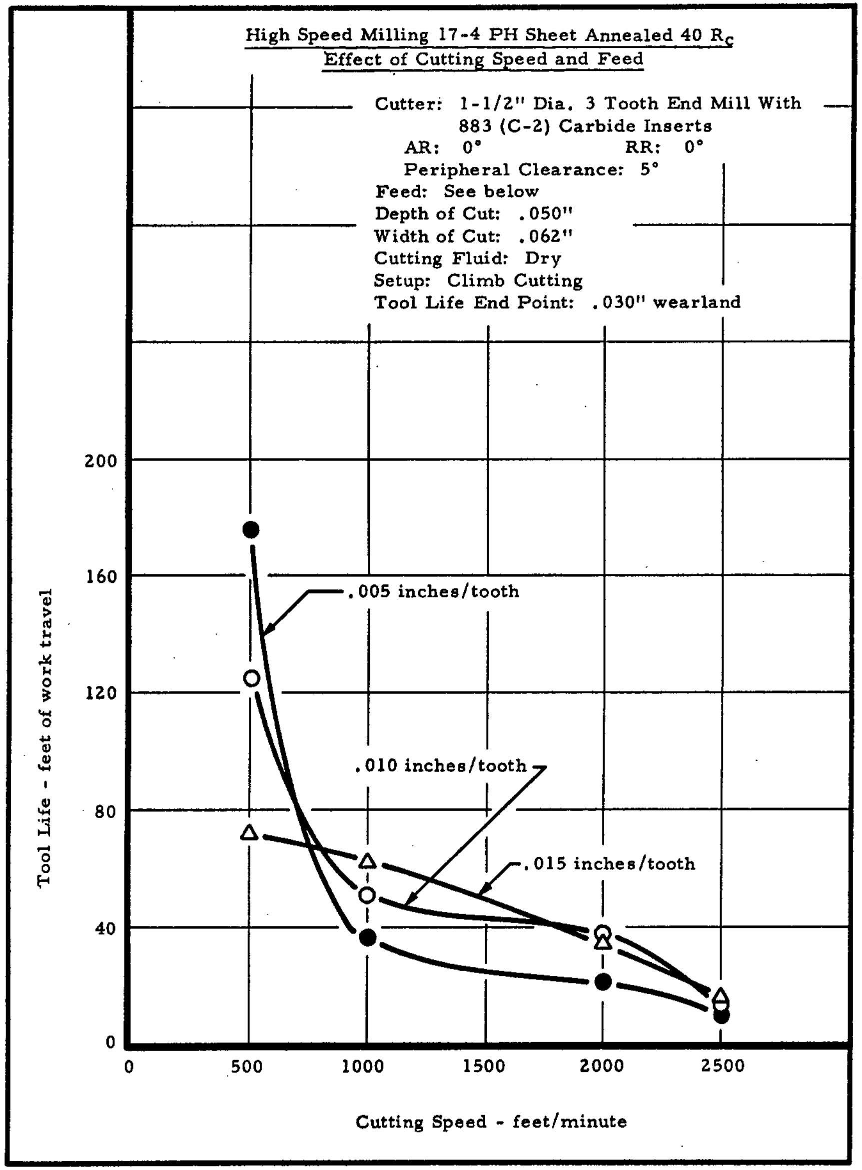
See text, page 411

Figure 452



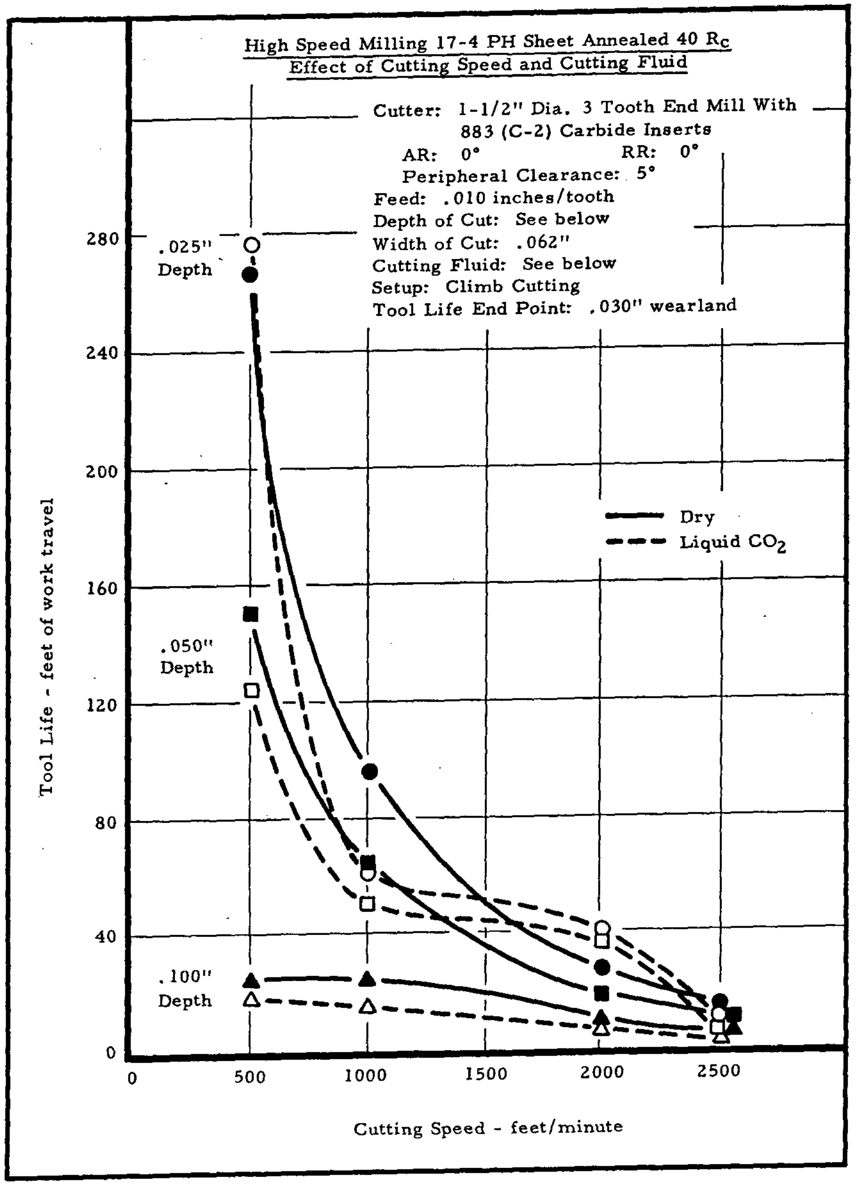
See text, page 411

Figure 453



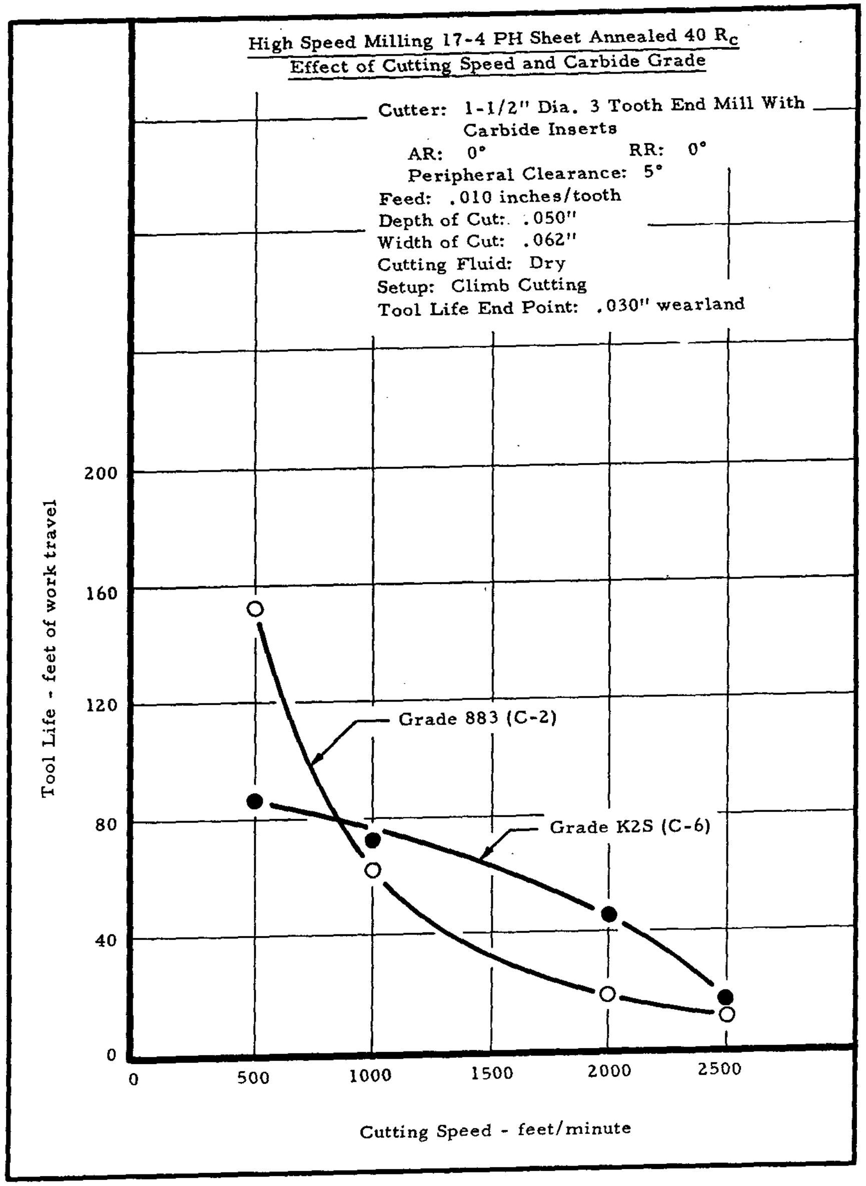
See text, page 411

Figure 454



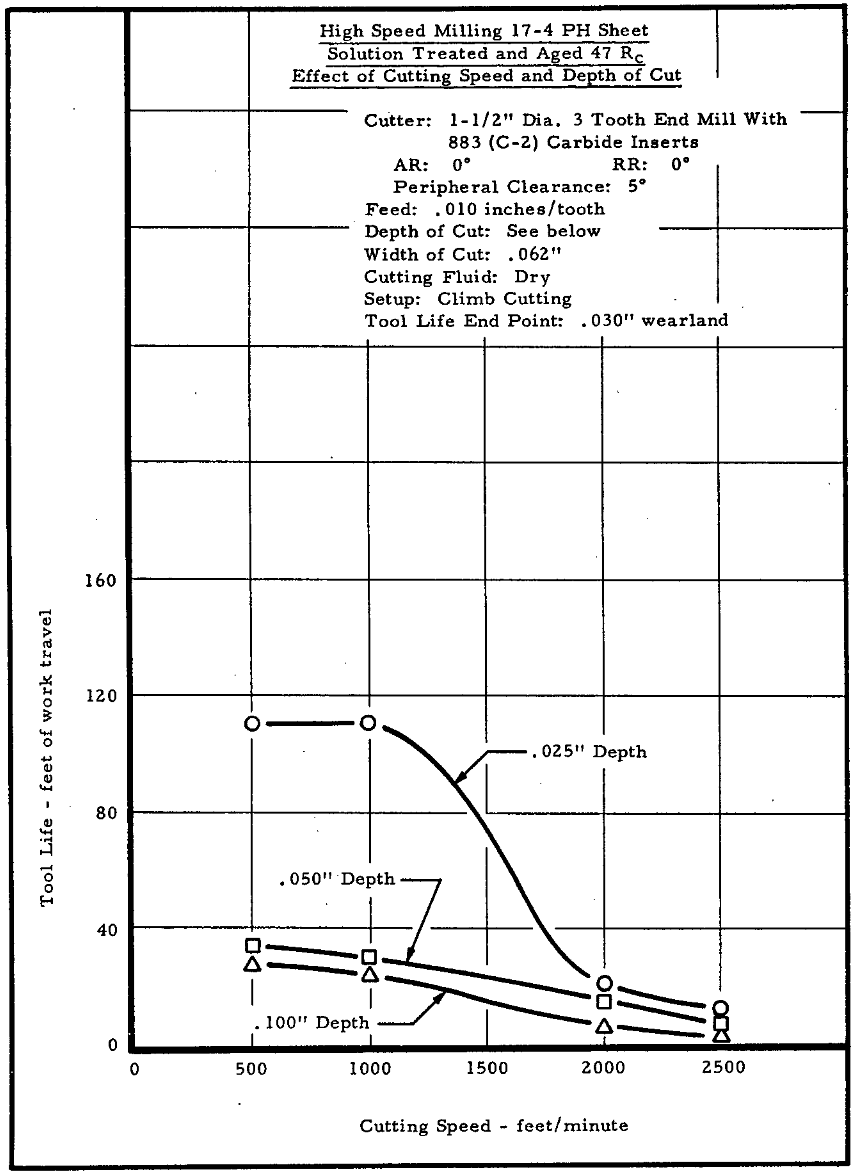
See text, page 411

Figure 455



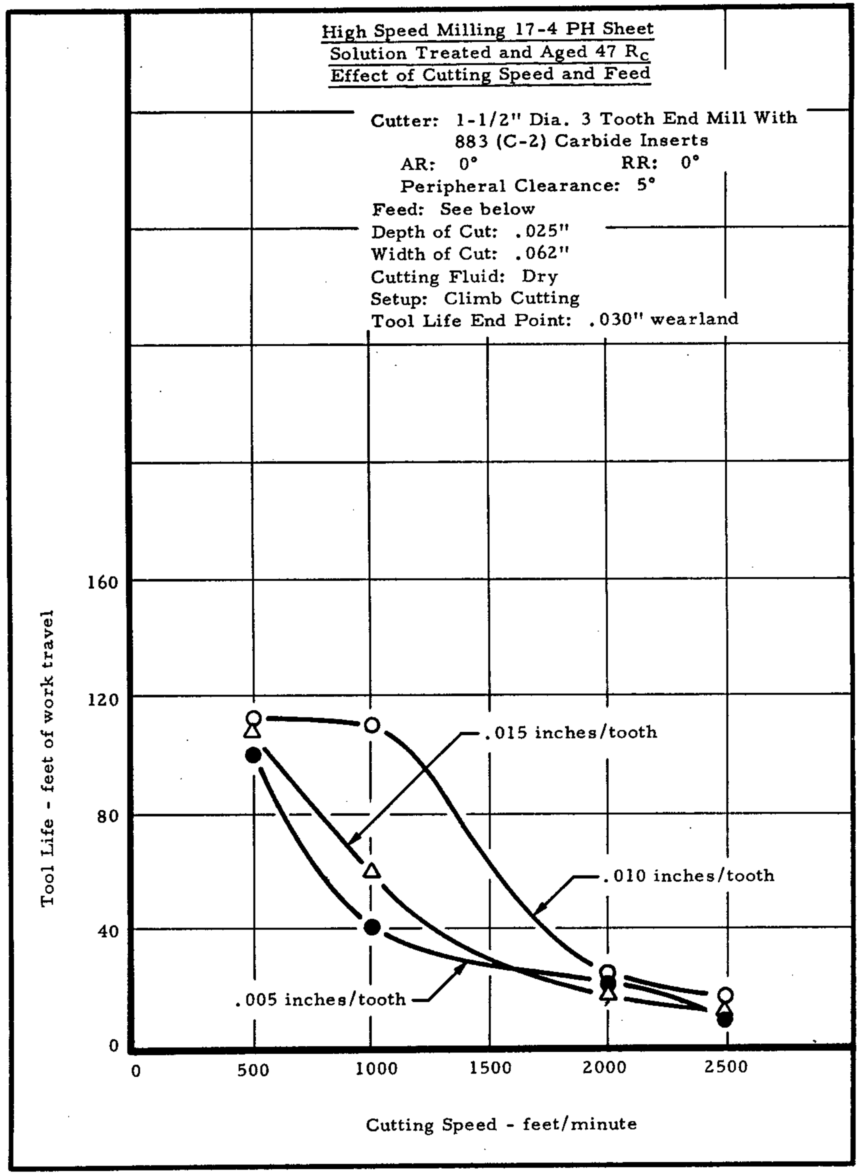
See text, page 411

Figure 456



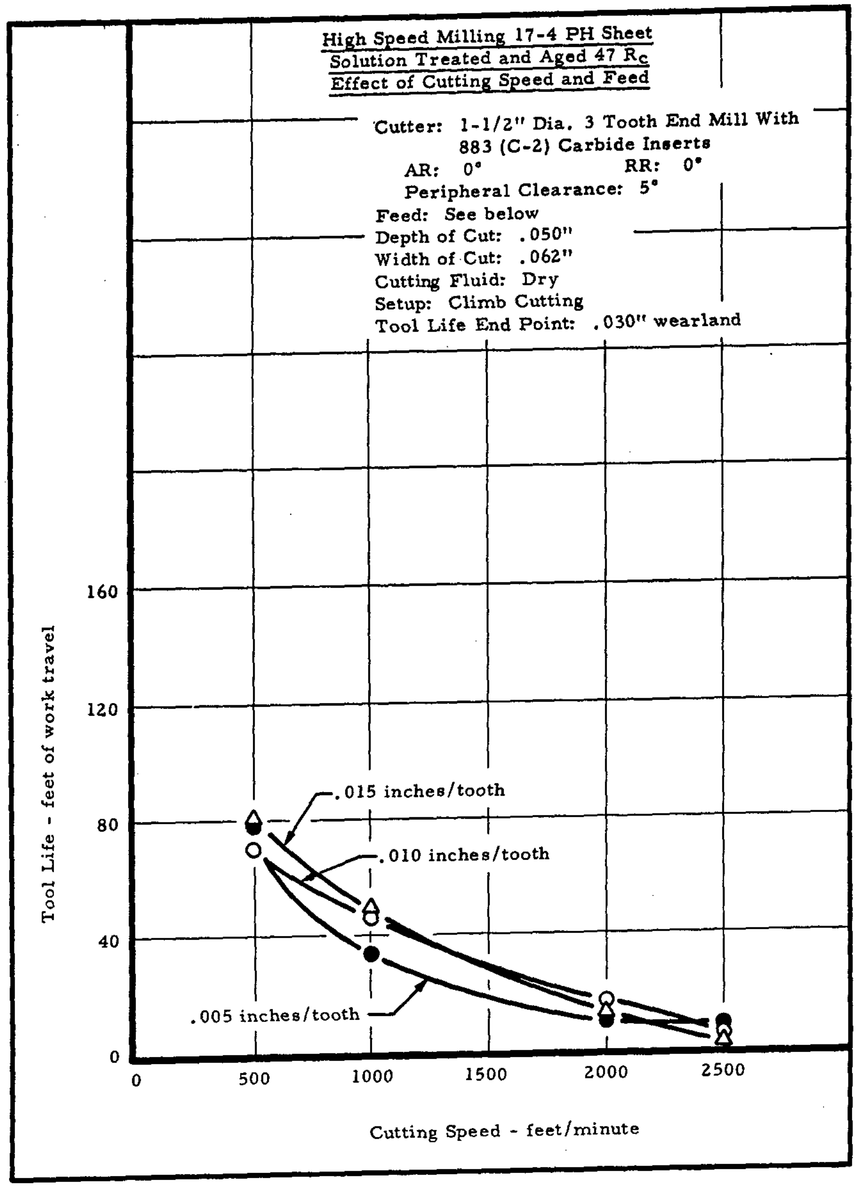
See text, page 412

Figure 457



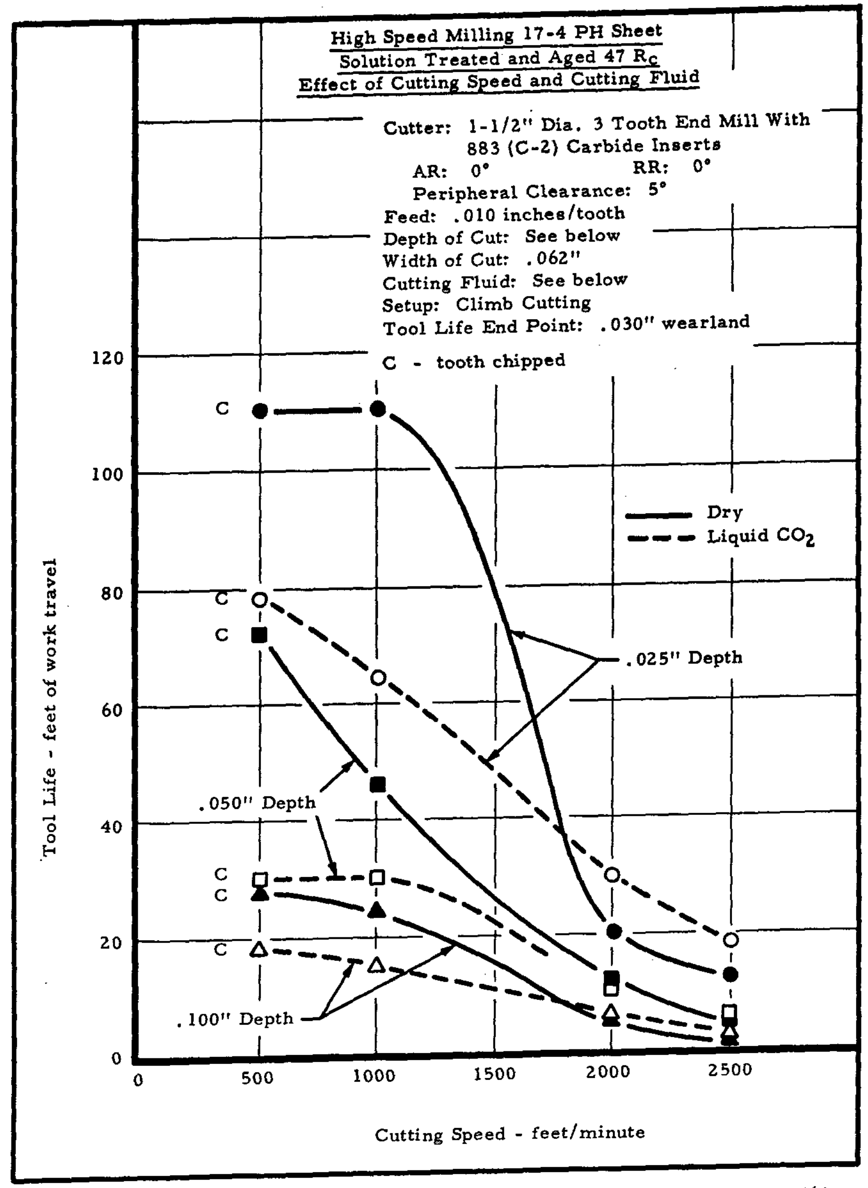
See text, page 412

Figure 458



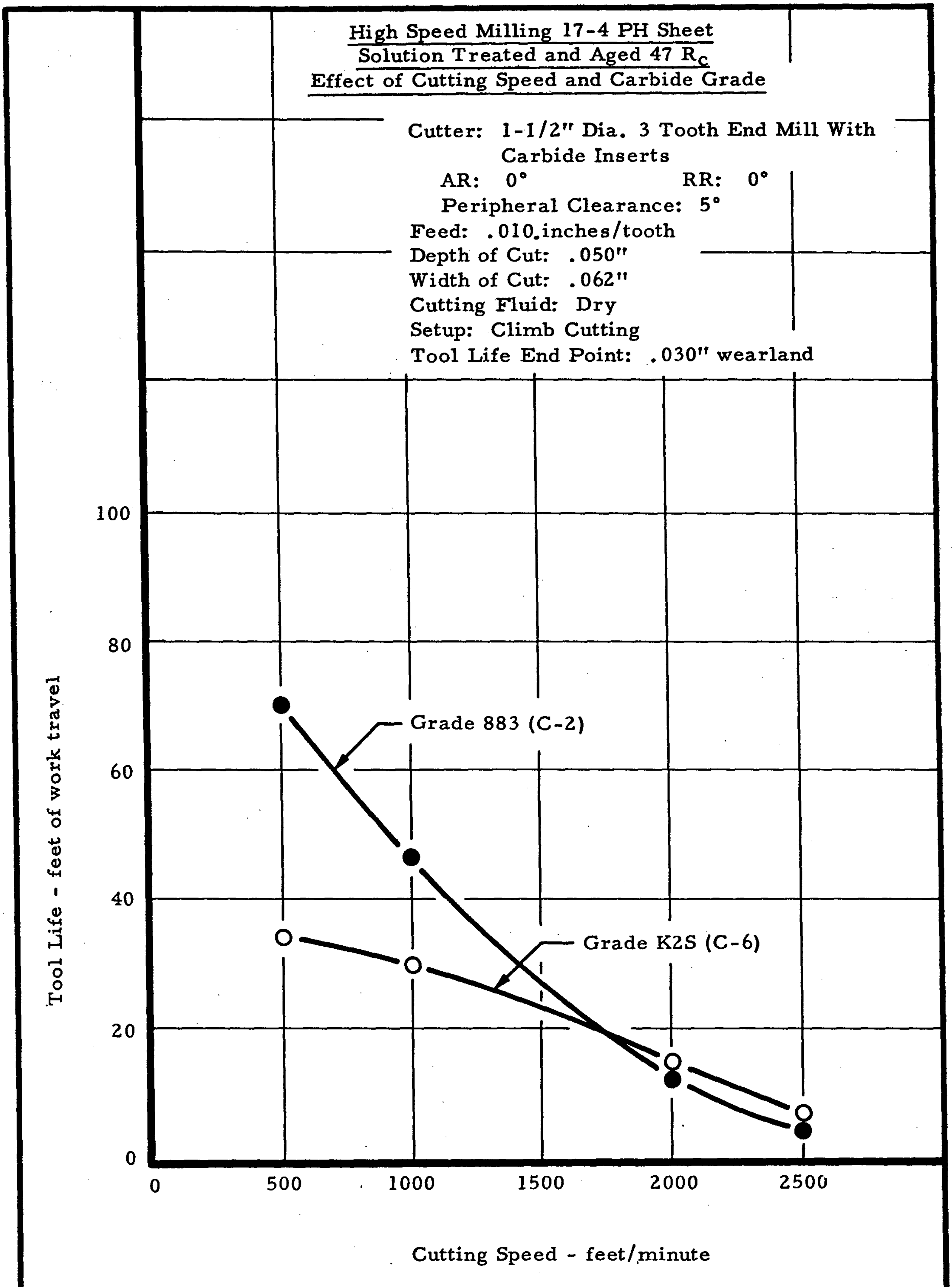
See text, page 412

Figure 459



See text, page 412

Figure 460



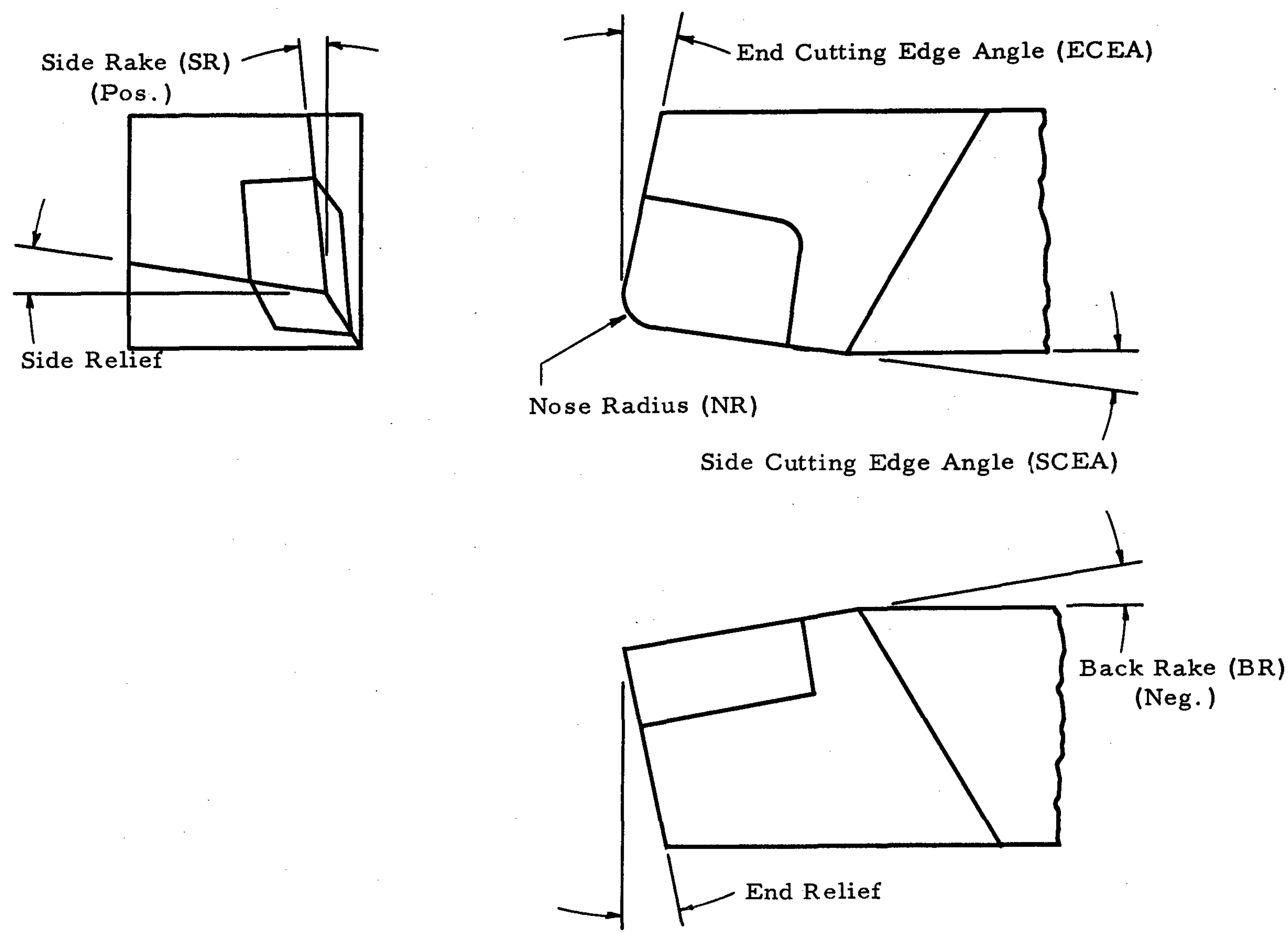
See text, page

Figure 461

12. APPENDIX

APPENDIX A

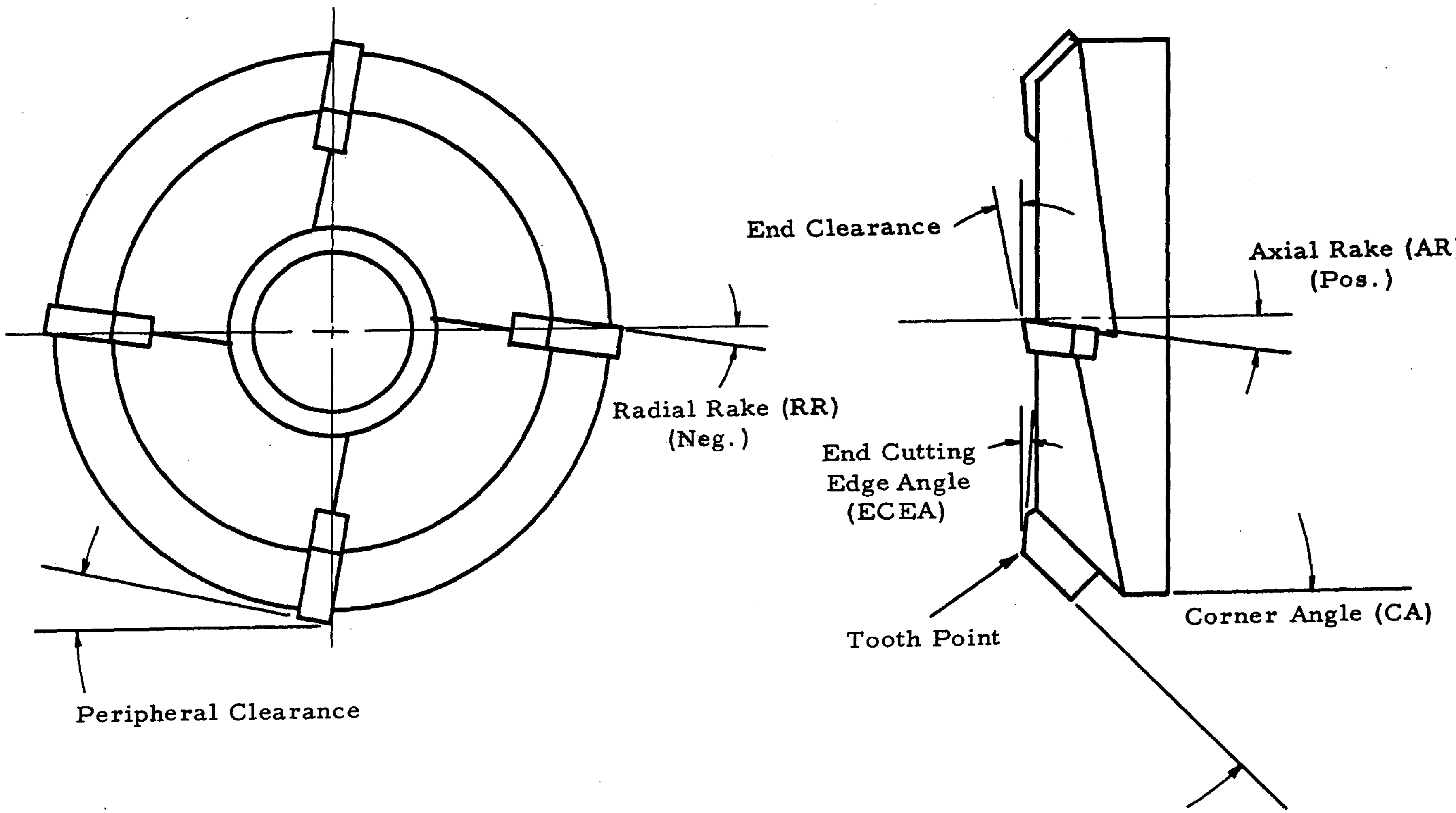
LATHE TOOL NOMENCLATURE



See Text, page 2

APPENDIX B

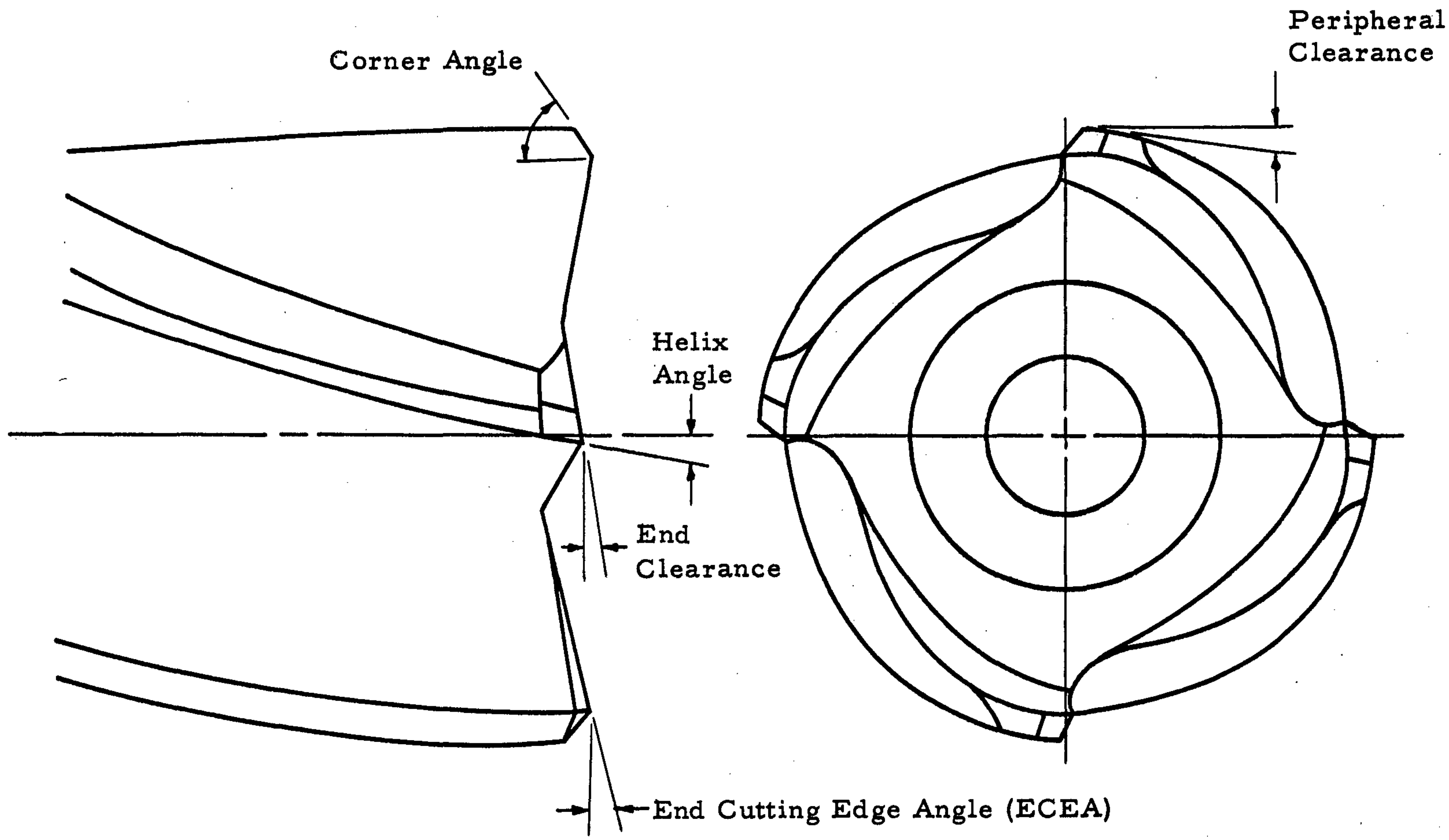
FACE MILL NOMENCLATURE



See Text, page 2

APPENDIX C

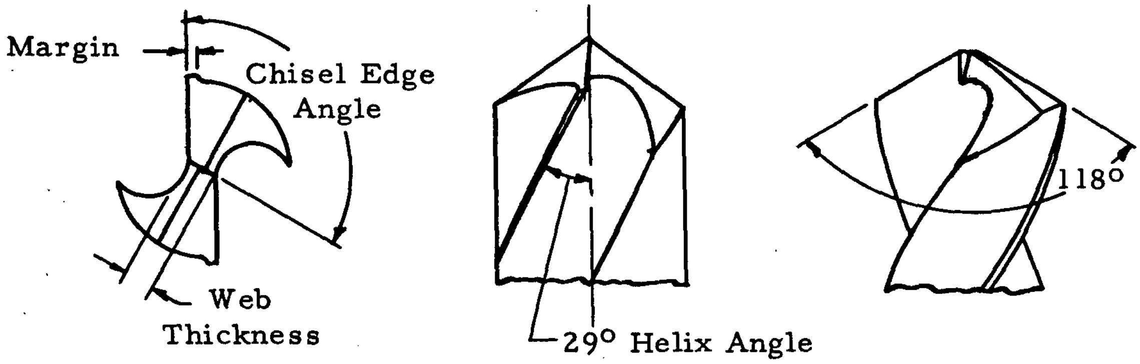
END MILL NOMENCLATURE



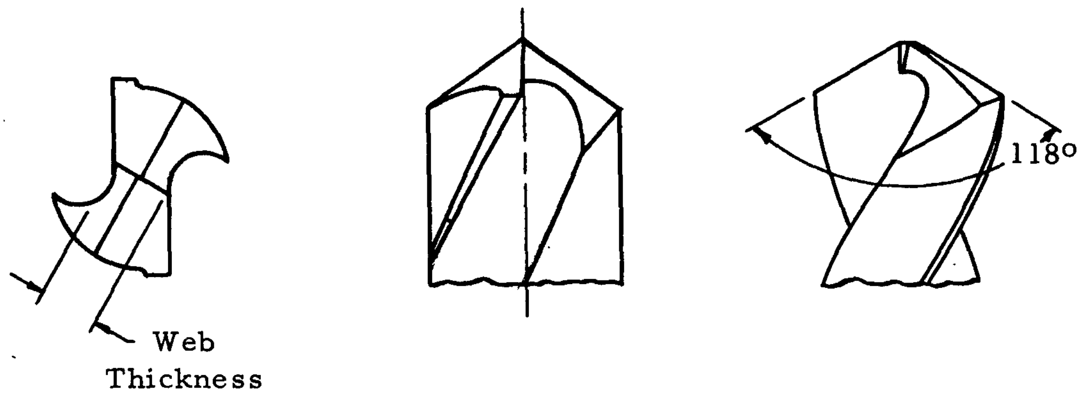
See Text, page 3

APPENDIX D

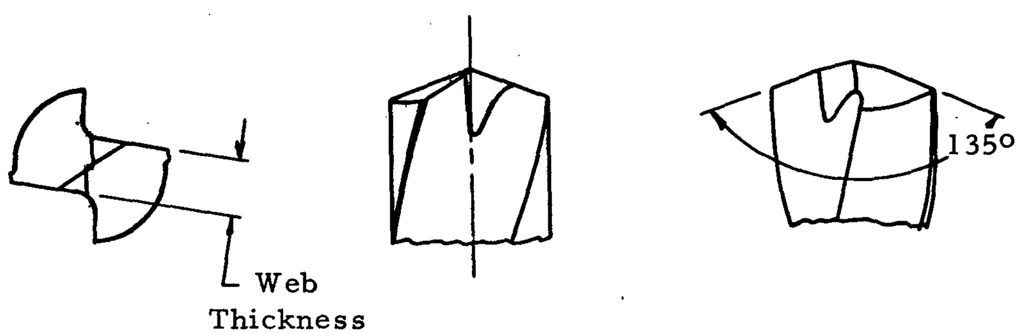
DRILL STYLES



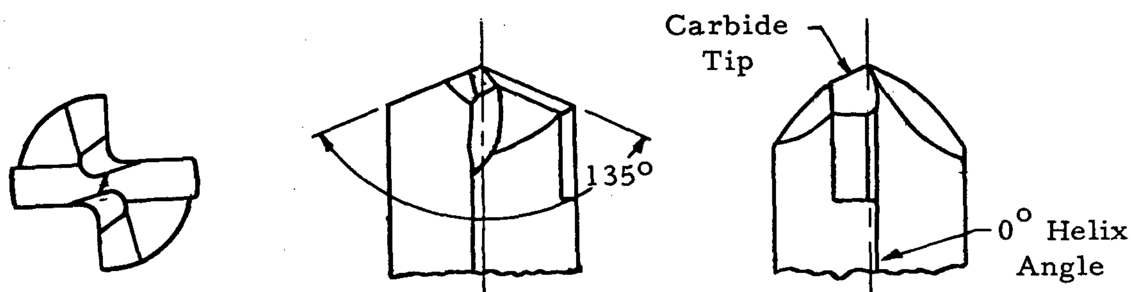
Standard Twist Drill - 29° Helix, Split Point



Heavy Web Drill - 29° Helix, Split Point



Heavy Web Drill - 12° Low Helix, Notched Point

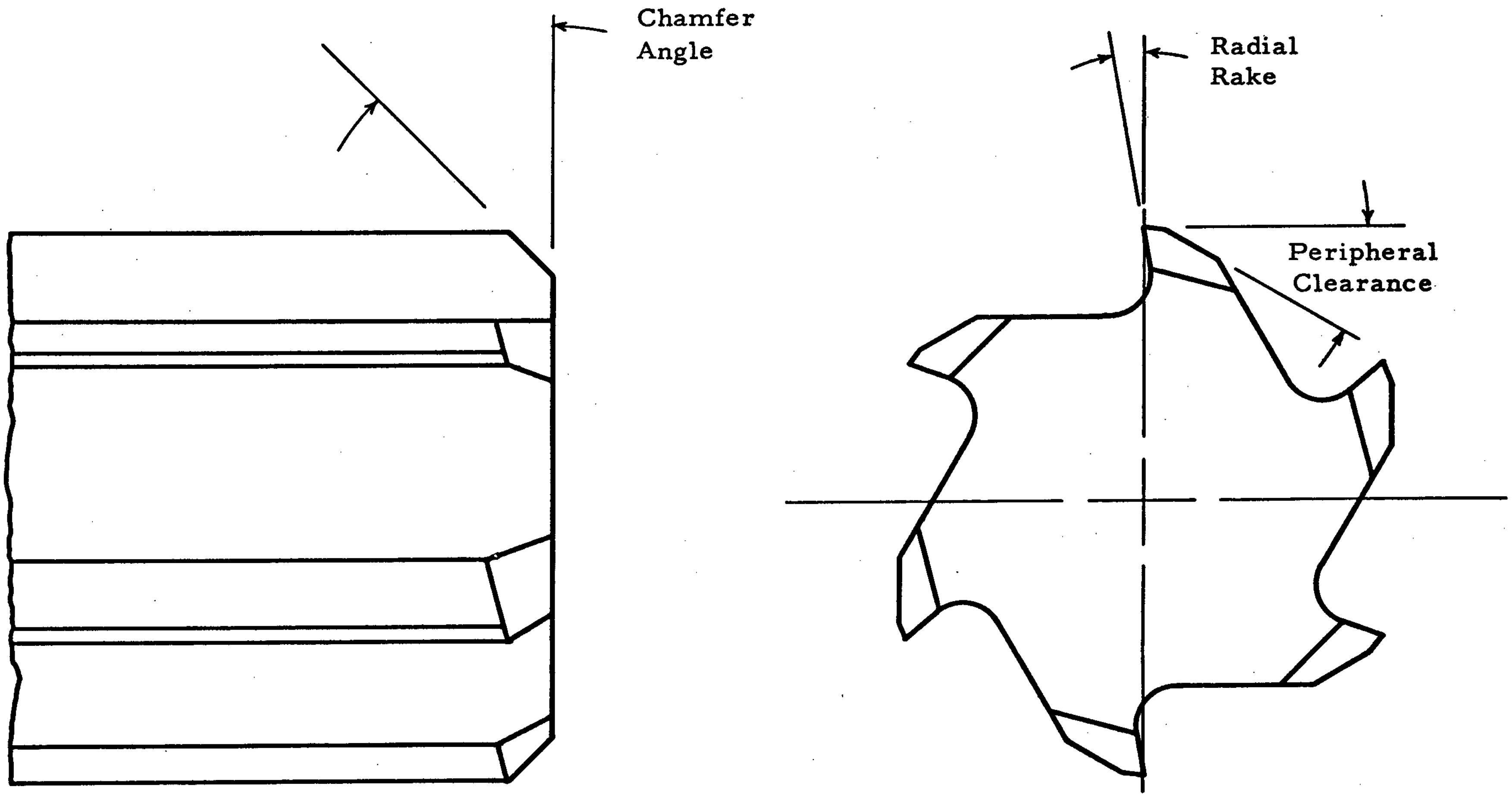


Carbide Tipped Die Drill - 0° Helix, Notched Point

See Text, page 4

APPENDIX E

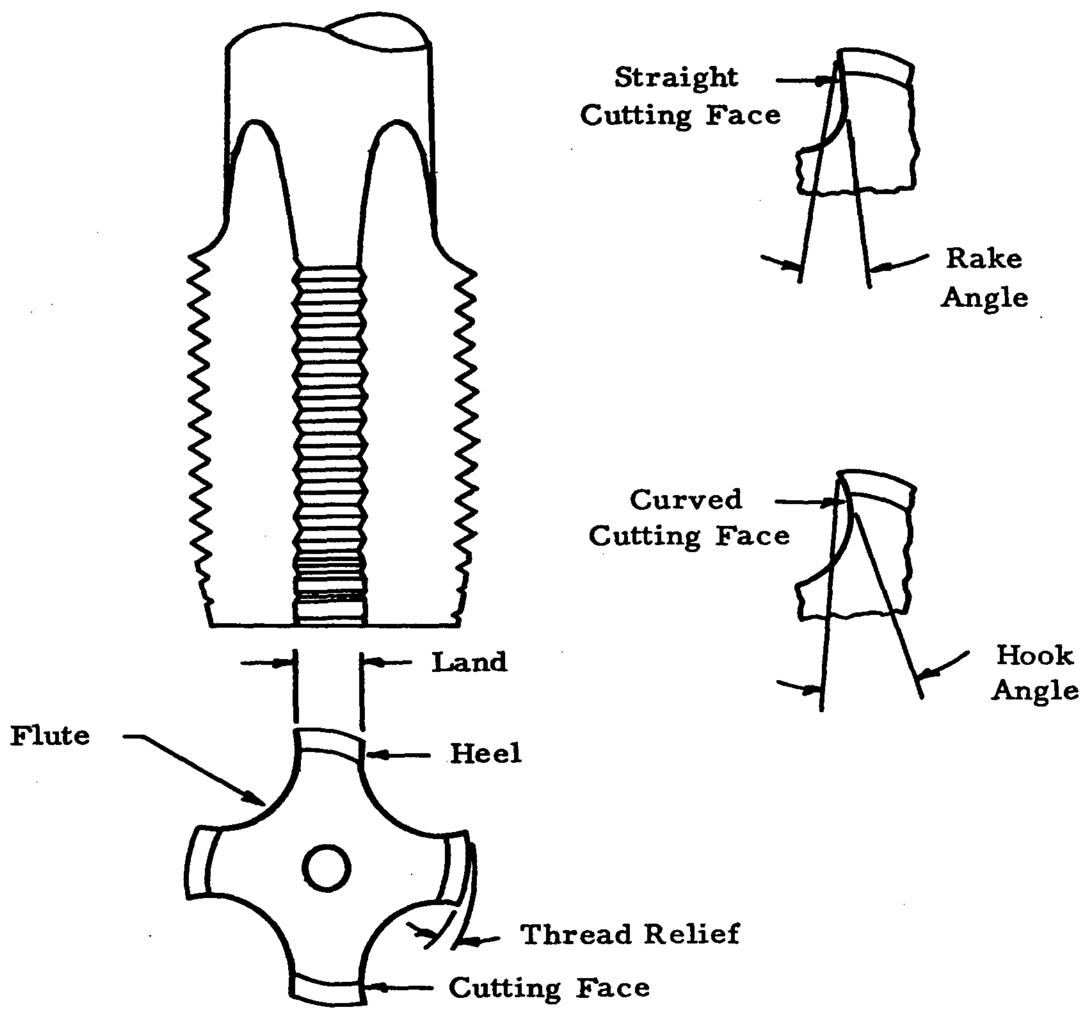
REAMER NOMENCLATURE



See Text, page 4

APPENDIX F

TAP NOMENCLATURE



See Text, page 4

APPENDIX G

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 H
CARBIDE GRADE CHART

C-1 to C-8
MACHINING APPLICATIONS

CARBIDE MANUFACTURERS	INDUSTRY CODE							
	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8
ADAMAS	B	A AM PWX	PWX AA	AAA	DD 5X 434	6X D	7X C 548 Titan 80*	CC Titan 80*
AMCARB	--	D15 D13	--	--	--	--	--	--
BESLY-WELLES	B101	B106 B168	B108	B211	B109 B221	B102	B103 B104 B205 B245	B207 B365*
CARBOLOY	44A	883 860	883 905 895	999 895 320	370 78B	370 78B 78 350	350 78 320	320
CARMET	CA-3	CA-4 CA-443	CA-7	CA-8	CA-610 CA-740	CA-606 CA-720	CA-711	CA-704
COROMANT	H20	H20 H1P	H1P	H05	S6 S4	S2	S1P	F02*
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 H-23	HE	HF	T04 NTA	TXH T22	T22 TXL	T31 WF*
FUTURMILL	--	DMC21	--	--	DMC30 DMC32	DMC32	DMC35	--
KENNAMETAL	K1	K6 C8735 K68	K68 K8	K11	KM K21 K2S	K2S K3H K4H K45	K45 K5H K7H	K7H K165*
MULTI METALS	OM1	OM2	OM3	OM4	4M5	--	--	--
NEWCOMER	N10	N20	N30	N40	N50	N60	N70 NM-93*	N80 NM-93* NM-95*
SINTERCAST	Ferro-Tic J	Ferro-Tic J	--	--	Ferro-Tic J	Ferro-Tic J	--	--
SPEEDICUT MITIA	A	B	C	C	TA10 TA5	TTA	TE	TE
TALIDE	C-89	C-91	C-93	C-95	S-880	S-901	S-92 S-900	S-94
TUNGSTEN ALLOY	9	9H	9C	9B	11T 9S 10T	9S 10T 5S	8T 5S	5S
UNIMET	U10	U20	U30	U40	U53	U53 U60	U70 U73	U73 U80 U88*
VALENITE	VC-1	VC-2 VC-22 VC-28	VC-3	VC-4	VC-125 VC-55	VC-125 VC-6	VC-7	VC-8 VC-83* VC-85*
VR/WESSON	2A-68 VR-54	2A-5 VR-54	2A-7	VR-52 2A-7 VR-65*	WS VR-77 VR-89 VR-75	VR-75 WM	VR-73 WH HV VR-65*	HV VR-73 VR-65*
WALMET	WA-141 WA-1 WA-159	WA-2 WA-63 WA-149	WA-35 WA-3	WA-4	WA-66 WA-5	WA-5 WA-6	WA-147 WA-7	WA-8
WENDT-SONIS	CQ12	CQ2	CQ3	CQ4	CY12 CY16	CY16 CY5	CY14 CY2 T18*	CY31 T18*
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CAST IRON, NON-FERROUS AND NON-METALLIC MATERIALS

- C-1 Roughing
- C-2 General Purpose
- C-3 Finishing
- C-4 Precision Finishing

STEEL AND STEEL ALLOYS

- C-5 Roughing
- C-6 General Purpose
- C-7 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 50% Titanium Carbide.*

APPENDIX I

IDENTIFICATION OF CUTTING FLUIDS

Cutting Fluid	Description
Soluble Oil	1:20 Emulsified Mineral Oil
Water Base Synthetic	1:15 (composition is proprietary)
Ti-Kut Water Base	1:10 (composition is proprietary)
Ti-Kut Oil	(composition is proprietary)
Highly Sulfurized Oil	Mineral Oil containing 3% Sulfur
Highly Chlorinated Oil	Mineral Oil containing 20% Chlorine

APPENDIX J

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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Most of the conventional machining operations on these alloys can be performed with reasonable tool life, providing that specific machining conditions are followed. This report presents recommendations for particular machining operations. It should be noted, however, that even small departures from suggested variables, such as cutting speed, feed, cutting fluid, as well as tool material and geometry, may result in a significant reduction in tool life.

High speed edge milling tests were also run on a select group of materials. This particular operation is becoming increasingly important in airframe fabrication. In addition, residual stress and distortion studies were run on four high strength structural alloys. The data developed give an indication of the large variations possible in surface integrity as a function of machining conditions employed.

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