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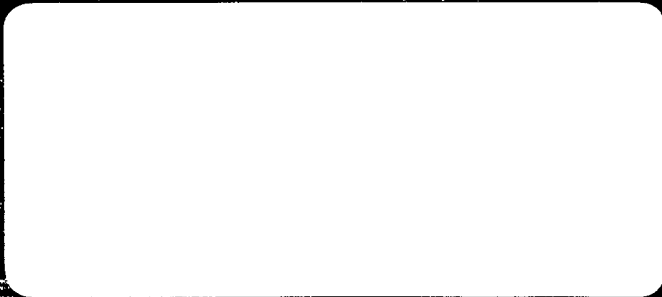
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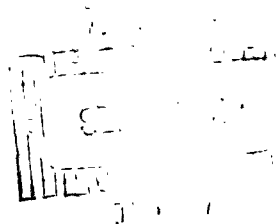
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MACHINABILITY OF  
NICKEL-TITANIUM ALLOYS

Contract N60921-6814  
Metcut Report No. 573-4062-1

for  
U. S. Naval Ordnance Laboratory  
White Oak  
Silver Spring, Maryland



METCUT RESEARCH ASSOCIATES INC.

John V. Gould, Project Engineer

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Approved:

Norman Zlatin, Director  
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## INTRODUCTION

The purpose of this project was to determine the machining characteristics of the ductile intermetallic compound NiTi alloys. This was accomplished by conducting tool life tests in turning, face milling, drilling and tapping these alloys. In addition, grinding tests were also made.

The results of these tests were then used in establishing the recommended cutting speeds, feeds, tool geometries, cutting fluids and grinding conditions for machining the alloys.

While the scope of this investigation was somewhat limited by the availability of each of the alloys, the tests were designed to extract as much machining data as possible from the shapes and quantities supplied.

## CONCLUSIONS

This investigation has shown that specific machining conditions must be used if these nickel-titanium alloys are to be machined with any degree of success. The cutting speed, feed, tool geometry and type of cutting fluid must be carefully selected. Tool wear is rapid with these alloys because the materials tend to work harden and are abrasive. In addition, the chips do not flow readily; thus, the chips tend to clog the flutes of the cutting tools.

1. These NiTi alloys can be turned 10 to 20 times faster with carbide tools, compared with high speed steel tools. It is not practical to turn the following alloys with high speed steel tools:
  - a. 56 Ni - 44 Ti Furnace Cooled 321 BHN
  - b. 56 Ni - 44 Ti Quenched 50 R<sub>C</sub>
  - c. 60 Ni - 40 Ti Quenched 60 R<sub>C</sub>
2. Feeds of .003 to .005 in./rev. should be used in turning.
3. The optimum tool geometry for face milling these alloys is 0° axial rake and 0° radial rake.
4. A feed of .005 in./tooth should be used in face milling. At higher and lower feeds, tool life decreases very rapidly.
5. For the 55 Ni - 45 Ti (as received) 217 BHN and the 60 Ni - 40 Ti (furnace cooled) 302 BHN, maximum tool life in face milling was obtained at a cutting speed of 220 feet/minute; while, with the 56 Ni - 44 Ti alloy (furnace cooled) 321 BHN and (quenched) 363 BHN, the optimum cutting speed was 125 feet/minute.
6. On the 55 Ni - 45 Ti, 56 Ni - 44 Ti and the 60 Ni - 40 Ti alloys, the drilling speed with carbide was 5 to 10 times greater than with M-33 high speed steel drills. Also, only carbide drills can be used for the 60 Ni - 40 Ti alloy quenched to 60 R<sub>C</sub>.

## CONCLUSIONS (continued)

7. The drilling speed is very critical for all of the alloys tested. A deviation in cutting speed of only 5 feet/minute from the optimum will result in a decrease in tool life of over 50%.
8. Light feeds must be used in drilling these alloys. Feeds greater than .002 in./rev. will result in very little tool life.
9. An active cutting oil is required in order to obtain a reasonable drill life. Drill life is extremely short with a soluble oil cutting fluid.
10. Silicon carbide wheels should be used in surface grinding the nitinol alloys.
11. A highly chlorinated oil is far more effective than soluble oil in surface grinding.
12. On all of the alloys tested, except the 55 Ti - 45 Ni alloy, the grinding ratio does not change significantly with changes in wheel speed over a range of 2000 to 5000 feet/minute.
13. In surface grinding, a down feed of .002 in./pass provided the best G ratio on all of the alloys tested, except the 55 Ti - 45 Ni alloy. The maximum G ratio on this alloy occurred at a down feed of .001 in./pass.
14. On most of the alloys tested, a cross feed of .050 in./pass produced the best G ratio.
15. Abrasive sawing appears to be the only satisfactory method of cutting off.
16. Tapping these alloys is very difficult. At best, one or two holes can be obtained before the tap breaks.

## TEST PROCEDURE

A wide range of machining variables was investigated for each operation performed. The machines used and the overall range of test conditions are listed below.

### Turning Conditions

Turning tests were made using carbide and high speed steel tools.

Machine: The turning tests were made on a 16" x 30" American Pacemaker lathe equipped with a variable speed drive to provide exact cutting speed control.

Work Material: The turning test bars varied in diameter from 7/8" to 1-5/8". A skin cut of .030" was taken on each piece, prior to testing, to remove any surface effects.

Cutting Tools: Turning tests were made using brazed tipped carbide tools and 5/8" square high speed steel tool bits.

### Tool Geometry:

#### Carbide

BR: 0°    SCEA: 15°  
SR: 6°    ECEA: 5°  
Relief: 5°    NR: 1/32"

BR: 0°    SCEA: 15°  
SR: 15°    ECEA: 5°  
Relief: 5°    NR: .030"

### Machining Conditions - Carbide:

Cutting Speed: 30 to 200 feet/minute  
Feed: .003 to .015 in./rev  
Depth of Cut: .030"  
Cutting Fluid: Soluble Oil (1:20)  
Tool Life End Point: .015" Wearland

### Machining Conditions - HSS:

Cutting Speed: 5 to 30 feet/minute  
Feed: .009 in./rev.  
Depth of Cut: .030"  
Cutting Fluid: Soluble Oil (1:20)  
Tool Life End Point: .060" Wearland



## TEST PROCEDURE (continued)

### Face Milling Conditions

Face milling tests were made using a special single tooth experimental cutter body, employing carbide tipped blades.

Machine: The tests were performed on a Cincinnati No. 3, Horizontal Dial Type milling machine. The milling test pieces were firmly clamped in a milling machine vise.

Work Material: The milling test pieces were approximately 1" square by 8" long. A surface skin cut was taken on all sides to eliminate any surface skin effects.

Tool Material: Grade 883 (C-2) carbide tipped blades were used for all tests.

### Tool Geometry:

AR: 0°                      ECEA: 5°  
RR: 0°                      CA: 45°  
Peripheral Clearance: 10°

### Machining Conditions:

Cutting Speed Range: 75 to 300 feet/minute  
Feed Range: .003 to .009 in./tooth  
Depth of Cut: .050"  
Width of Cut: 1.0"  
Cutting Fluid: Highly Chlorinated Oil  
Tool Life End Point: .015" Wearland on peripheral flank or tool  
breakdown

### Drilling Conditions

Drilling tests were made with No. 21 (.159") drills.

Machine: Drill life testing was done on a Cincinnati 16" sliding head box column drill equipped with variable speed and feed drive motors to provide exact cutting speed and feed control.

TEST PROCEDURE (continued)

Drilling Conditions (continued)

Work Material: The drilling test specimens were cut from the stock supplied and were 3/8" thick to provide 3/8" through holes.

Drill Material: Type M-33 and Type M-1 HSS drills and grade C-2 solid carbide drills were used.

Drill Geometry:

Point Angle: 118°  
Clearance Angle: 7° to 10°  
Point Style: Split  
Drill Style: Screw machine length  
Helix Angle: 29°

Drilling Conditions:

Cutting Speed: 10 to 30 feet/minute  
Feed: .0005 to .005 in./rev.  
Depth of Hole: 3/8" through hole  
Cutting Fluid: Highly Chlorinated Oil  
Drill Life End Point: .015" wearland or drill breakdown

Tapping Conditions

Tapping tests were made using 1/4-28 NF taps.

Machine: A Fosdick 25" Upright tapping machine was used for all tests.

Work Material: Tapping tests were made using test specimens which were previously drilled and reamed to the correct hole size.

Tap Materials: Type M-10 HSS and solid carbide taps were used for these tests.

Tap Styles: Four flute taper, four flute plug, three flute spiral plug and two flute chip driver plug taps were used in these tests.

Percent Thread: 60% and 75% threads were tapped.

TEST PROCEDURE (continued)

Tapping Conditions (continued)

Machining Conditions:

Cutting Speeds: 4 feet/minute to 50 feet/minute  
Depth of Hole: 3/8" through hole  
Cutting Fluid: Highly Chlorinated Oil  
                  Highly Sulphurized Oil  
                  Inhibited 1-1-1 Trichlorethane  
Tap Life End Point: Tap breakage

Surface Grinding Conditions

Surface grinding tests were performed to determine the effect of grinding variables on wheel wear.

Machine: The grinding tests were made on a Norton 8" x 24" Hydraulic Surface grinder equipped with a two H. P. variable speed spindle drive.

Grinding Wheels: To evaluate the effect of wheel abrasive and wheel hardness on G ratio, five different grinding wheels were tested. The wheels were designated as follows:

<u>Aluminum Oxide</u>	<u>Silicon Carbide</u>
32A46H8VBE	GC60I6VP
32A46J8VBE	GC60L6VP
32A46L8VBE	

Wheel size was 10" x 1" x 3".

Grinding Fluids: A highly chlorinated oil and a water soluble oil were used for the grinding tests.

Machining Conditions:

Wheel Speeds: 2000 to 5000 feet/minute  
Table Speeds: 20 to 60 feet/minute  
Down Feeds: .0005 to .005 in./pass  
Cross feeds: .025 to .100 in./pass

## TEST PROCEDURE (continued)

### Surface Grinding Conditions (continued)

Test Procedure: Before the grinding tests were started, a .030" deep x 1/2" wide step was dressed in the grinding wheel. This step was used as a reference in measuring wheel wear. A .0001" dial indicator, mounted on a fixture attached to the wheel housing, was brought into contact with this step, and the indicator was set to read .0000. The indicator was then moved across the wheel on the upper step or grinding surface and an initial reading was taken. Indicator readings were taken after every .025" metal was removed. The difference between the initial indicator reading and successive readings was the amount of wheel removed from the wheel radius. The initial outside diameter of the grinding wheel was carefully measured using vernier calipers. The volume of wheel removed was calculated from the initial and final wheel measurements.

Grinding ratio (G) is defined as:

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

G ratios were calculated at each .025" stock removed, and an average taken to arrive at a final G ratio.

### Abrasive Cutoff Conditions

All of the alloys were cut off to size using an abrasive cutoff machine. Power hacksawing does not appear to be feasible.

Machine: Fifteen H. P. Radiac Special Type "C" Abrasive Cutoff Machine.

Cutoff Wheel: 16" diameter x 1/8" thick, A60-R10-R30.

Grinding Fluid: Soluble oil (1:40).

### Cutoff Machining Conditions:

Wheel Speed: 2050 rpm = 8600 feet/minute for 16" diameter wheel  
Down Feed: Hand plunge

## TEST RESULTS

Tables 1 through 4 give the recommended conditions for machining and grinding the nitinol alloys. Figures 1 through 18 present the test data obtained in chart form showing effects of different machining variables on tool life.

### Turning

In turning, with carbide tools, the 55 Ni - 45 Ti as received (217 BHN) alloy, a tool life of 36 minutes was obtained at a cutting speed of 125 feet/minute and a feed of .005 in./rev. See Figure 1. When the cutting speed was increased to 150 feet/minute, tool life decreased to 24 minutes, and at a cutting speed of 200 feet/minute, tool life was seven minutes.

A tool life of 35 minutes was obtained on the 60 Ni - 40 Ti furnace cooled (302 BHN) alloy at a cutting speed of 100 feet/minute. However, tool life decreased to about six minutes at a cutting speed of 150 feet/minute. In turning the 56 Ni - 44 Ti furnace cooled (321 BHN) alloy, a cutting speed of 75 feet/minute provided a tool life of 30 minutes. At 100 feet/minute, tool life was reduced to 15 minutes, and at 150 feet/minute, less than five minutes tool life was obtained.

Figure 1 also shows that the 56 Ni - 44 Ti quenched (50 R<sub>C</sub>) alloy could be turned at a cutting speed of 50 feet/minute to obtain a tool life of 23 minutes. However, at this cutting speed, the 60 Ni - 40 Ti quenched (60 R<sub>C</sub>) alloy provided a tool life of only eight minutes.

The effect of feed in turning with carbide is presented in Figure 2. Maximum tool life was obtained using a feed of .005 in./rev. for the 55 Ni - 45 Ti as received (217 BHN) alloy, the 60 Ni - 40 Ti furnace cooled (302 BHN) alloy, and the 56 Ni - 44 Ti quenched (50 R<sub>C</sub>) alloy. In turning the 60 Ni - 40 Ti quenched (60 R<sub>C</sub>) alloy, the best tool life was obtained when using a feed of .003 in./rev. Tool life decreased rather rapidly when the feed was increased above .005 in./rev. for all of the alloys tested.

## TEST RESULTS (continued)

### Turning (continued)

Figure 3 presents the tool life data obtained in turning the nitinol alloys with type T-15 high speed steel tools. At a cutting speed of 15 feet/minute and a feed of .009 in./rev., a tool life of 19 minutes was obtained on the 55 Ni - 45 Ti as received (217 BHN) alloy. The 60 Ni - 40 Ti furnace cooled (302 BHN) alloy provided a tool life of about one minute at this cutting speed. However, when the cutting speed was reduced to 5 feet/minute, tool life was increased to almost 25 minutes for this alloy. In turning the 56 Ni - 44 Ti furnace cooled (321 BHN) alloy at 5 feet/minute, a tool life of about eight minutes was obtained.

### Face Milling

The effect of radial rake angle in face milling the 55 Ni - 45 Ti as received alloy and the 56 Ni - 44 Ti furnace cooled alloy is shown in Figure 4. The optimum radial rake angle for both alloys was 0°, when the axial rake angle was kept constant at 0°. Tool life dropped off rapidly when a negative radial rake of -10° was used, and when a high positive rake of 20° was used.

Figure 5 shows the effect of cutting speed in face milling the nitinol alloys. Maximum tool life, 30 in./tooth, was obtained at a cutting speed of 220 feet per minute on the 55 Ni - 45 Ti as received alloy (217 BHN). When the cutting speed was reduced below 220 feet/minute and increased above 220 feet/minute, tool life decreased significantly. The 60 Ni - 40 Ti furnace cooled alloy (302 BHN) also could be face milled at 220 feet/minute for best tool life. This alloy, however, provided a maximum tool life of 19 in./tooth at this cutting speed.

The 56 Ni - 44 Ti alloy, in both the furnace cooled (321 BHN) and the quenched (363 BHN) condition could best be face milled at a cutting speed of 130 feet per minute. At this cutting speed, a tool life of 24 in./tooth was obtained on

## TEST RESULTS (continued)

### Face Milling (continued)

the furnace cooled alloy, while the quenched alloy provided a tool life of 17 minutes. At cutting speeds above and below 130 feet/minute, tool life dropped off very rapidly. The 60 Ni - 40 Ti quenched alloy (60 R<sub>C</sub>) is very difficult to face mill. At a cutting speed of 75 feet/minute, a tool life of only four in./tooth was obtained.

The effect of feed in face milling is shown in Figure 6. The best feed for all of the alloys tested was .005 in./tooth. Feeds above and below this value reduced tool life significantly.

### Drilling

The drill life curves presented in Figure 7 show how critical cutting speed is in drilling the nitinol alloys. A change in cutting speed of 5 feet/minute will reduce drill life very significantly. In drilling the 55 Ni - 45 Ti as received alloy (217 BHN), best drill life, 34 holes, was obtained at a cutting speed of 20 feet/minute when using type M-33 HSS drills. A cutting speed of 15 feet per minute provided the best drill life, 34 holes, for the 56 Ni - 44 Ti alloy. The quenched 56 Ni - 44 Ti alloy (363 BHN) and the furnace cooled 60 Ni - 40 Ti alloy (302 BHN) provided maximum drill life at 10 feet/minute.

Figure 8 shows the effect of cutting speed and feed on drill life when drilling the 55 Ni - 45 Ti as received alloy (217 BHN). Maximum drill life was 34 holes at a cutting speed of 20 feet/minute when using a feed of .001 in./rev. When the feed was increased to .002 in./rev., a maximum drill life of 20 holes was obtained at a cutting speed of 12.5 feet/minute. At this cutting speed and feed, only three holes could be drilled in this alloy when using type M-1 high speed steel drills.

The effect of feed rate, Figure 9, shows that when drilling at a cutting speed

## TEST RESULTS (continued)

### Drilling (continued)

of 20 feet/minute, the feed is very critical. A deviation of .0005 in./rev. from the optimum of .001 in./rev. will reduce drill life over 50%. When the cutting speed was reduced to 12.5 feet/minute, changes in feed rate were not as critical, but the lower feeds, of the order of .001 in./rev., provided maximum drill life.

Figure 10 shows the effect of cutting fluid in drilling the 55 Ni - 45 Ti as received alloy (217 BHN). An active cutting oil is far superior to a water base soluble oil. This chart also shows that a highly chlorinated oil is more effective than a highly sulphurized oil.

### Tapping

All attempts to successfully tap the 55 Ni - 45 Ti alloy have failed. It was believed that the drilling might strain harden the holes to a degree that would cause tapping difficulty. Therefore, some of the drilled holes were sectioned and hardness checks were made using a light-load Tukon microhardness testing machine.

By conversion from microhardness measurements, impressions on the surface of the drilled holes were found to range from 50-55 R<sub>C</sub>. Impressions made at a point where a tap wore out were found to be somewhere in the vicinity of 62 R<sub>C</sub>.

Readings taken on a section normal to the walls of the hole showed evidence that there is definite strain hardening to depths of .005".

Tapping tests made on the other alloys also failed. Solid carbide taps broke immediately after entering the hole.



## TEST RESULTS (continued)

### Surface Grinding

The effect of wheel specification in grinding the 55 Ni - 45 Ti, 56 Ni - 44 Ti, and 60 Ni - 40 Ti alloys is presented in Figures 11, 12 and 13. These three charts show that for each of these alloys the silicon carbide grinding wheels outperformed the aluminum oxide type. In grinding the 60 Ni - 40 Ti alloy, the superiority of the silicon carbide wheels is not as great as when grinding the other two alloys.

Figure 14 shows the effect of wheel speed on the grinding ratio in surface grinding the nitinol alloys. Increasing the wheel speed from 2000 feet/minute to 4000 feet/minute increased the G ratio from about 2 to 27 for the 55 Ni - 45 Ti as received (217 BHN) alloy. When the wheel speed was increased to 5000 feet/minute, the G ratio remained constant at about 27. Varying the wheel speed for the other alloys tested did not significantly change the grinding ratio. A G ratio of about 20 was obtained for the 56 Ni - 44 Ti furnace cooled (321 BHN) alloy over a wheel speed range of 2000 to 5000 feet/minute, while this alloy in the quenched condition provided a G ratio of about 18 over the same wheel speed range. The 60 Ni - 40 Ti alloy in the quenched condition (60 R<sub>C</sub>) provided a fairly constant G ratio of about nine over this wheel speed range, and a G ratio of about five was obtained for this alloy over the 2000 feet/minute to 5000 feet/minute wheel speed range.

The effect of down feed in surface grinding the nitinol alloys is also very critical. See Figure 15. This chart shows that for the 55 Ni - 45 Ti alloy, the best G ratio was obtained with a down feed of .001 in./pass. The G ratio decreased considerably when the down feed was increased beyond .001 in./pass. In grinding the 56 Ni - 44 Ti quenched and furnace cooled alloys and the 60 Ni - 40 Ti furnace cooled alloy, the maximum G ratio was obtained at a down feed of .002 in./pass. The G ratio dropped off rapidly when down feeds above and below .002 in./pass were used. The effect of down feed in surface grinding

## TEST RESULTS (continued)

### Surface Grinding (continued)

the 60 Ni - 40 Ti quenched (60 R<sub>C</sub>) alloy was less significant. At down feeds of .001 and .002 in./pass, a G ratio of about nine was obtained; when the down feed was increased to .005 in./pass, the G ratio was reduced to about four.

Figure 16 shows the effect of cross feed. Little or no change was observed in the G ratio when the cross feed was varied from .025 in./pass to .100 in./pass in grinding the 60 Ni - 40 Ti furnace cooled and quenched alloys. In grinding the 56 Ni - 44 Ti furnace cooled alloy and the 55 Ni - 45 Ti as received alloy, the best G ratio was obtained at a cross feed of .050 in./pass, while the best G ratio for the 56 Ni - 44 Ti quenched alloy was obtained using a cross feed of .025 in./pass.

The effect of table feed, presented in Figure 17, shows that the 60 Ni - 40 Ti alloy in the two heat treated conditions is relatively insensitive to changes in table speed. The 56 Ni - 44 Ti alloy in the two heat treated conditions, however, is very sensitive to table speed changes. The best G ratio for this alloy was obtained at a table speed of 20 and 40 feet/minute. When the table speed was increased to 60 feet/minute, the G ratio decreased considerably. In grinding the 55 Ni - 45 Ti as received alloy, G ratio increased when the table speed was increased from 20 to 40 feet/minute and remained rather constant when the table speed was increased from 40 feet/minute to 60 feet/minute.

A highly chlorinated oil performs best when grinding the 55 Ni - 45 Ti as received alloy. The data presented in Figure 18 shows that at a wheel speed of 5000 feet/minute, a G ratio of 27 was obtained using the highly chlorinated oil, while a water soluble oil (1:20) provided a G ratio of about eight.

**Table 1**  
**Recommendations for Turning Nitinol Alloys**

	<u>55 Ni - 45 Ti As Received (217 BHN)</u>	<u>56 Ni - 44 Ti Furnace Cooled (321 BHN)</u>	<u>56 Ni - 44 Ti Quenched (50 Rc)</u>	<u>60 Ni - 40 Ti Furnace Cooled (302 BHN)</u>	<u>60 Ni - 40 Ti Quenched (50 Rc)</u>
<b>Tool Material</b>	Grade C-2 Carbide	Grade C-2 Carbide	Grade C-2 Carbide	Grade C-2 Carbide	Grade C-2 Carbide
<b>Tool Geometry</b>	BR: 0° SCEA: 15° SR: 5° ECEA: 5° Relief: 5°	Same	Same	Same	Same
<b>Cutting Speed - feet/minute</b>	125	75	50	100	30
<b>Feed - in./rev.</b>	.005	.005	.005	.005	.003
<b>Depth of Cut - inches</b>	.030	.030	.030	.030	.030
<b>Cutting Fluid</b>	Sol. Oil (1:20)	Sol. Oil (1:20)	Sol. Oil (1:20)	*Sol. Oil (1:20)	Sol. Oil (1:20)
<b>Tool Life - min. (carbide)</b>	36	30	23	35	35
<b>Tool Life - min. (HSS, 15 ft./min.)</b>	18	--	--	2	--

**General Instructions**

1. This material has a high capacity to "work harden;" therefore, tool wear should be limited to .015".
2. If gouging at the skin level of the tool occurs, increase SCEA to reduce the thickness of the chip.
3. A cutting fluid with the ability to absorb heat should be used. Coolants not only increase tool life, but also prevent heat distortion of parts.

**Table 2**  
**Recommendations for Face Milling Nitinol Alloys**

	55 Ni - 45 Ti As Received (217 BHN)	56 Ni - 44 Ti Furnace Cooled (321 BHN)	56 Ni - 44 Ti Quenched (363 BHN)	60 Ni - 40 Ti Furnace Cooled (302 BHN)	60 Ni - 40 Ti Quenched (60 Rc)
<b>Tool Material</b>	Grade C-2 Carbide	Grade C-2 Carbide	Grade C-2 Carbide	Grade C-2 Carbide	Grade C-2 Carbide
<b>Tool Geometry</b>	AR: 0° RR: 0° Clearance: 12° CA: 45° ECEA: 10°	AR: 0° RR: 0° Clearance: 12° CA: 45° ECEA: 10°	AR: 0° RR: 0° Clearance: 12° CA: 45° ECEA: 10°	AR: 0° RR: 0° Clearance: 12° CA: 45° ECEA: 10°	AR: 0° RR: 0° Clearance: 12° CA: 45° ECEA: 10°
<b>Cutting Speed - feet/minute</b>	220	125	125	220	75
<b>Feed - inches/tooth</b>	.005	.005	.005	.005	.005
<b>Depth of Cut - inches</b>	.050	.050	.050	.050	.050
<b>Width of Cut - inches</b>	1	1	1	1	1
<b>Cutting Fluid</b>	Highly Chlorinated Oil	Highly Chlorinated Oil	Highly Chlorinated Oil	Highly Chlorinated Oil	Highly Chlorinated Oil
<b>Tool Life - inches/tooth</b>	30	24	18	19	4

**General Instructions**

1. Limit tool wear to approximately .015" to minimize work hardening.
2. Keep setup as rigid as possible.
3. Flood cutter liberally with cutting oil.
4. Climb cut wherever possible.

Table 3  
 Recommendations for Drilling Nitinol Alloys

Tool Material	55 Ni - 45 Ti As Received (217 BHN)	56 Ni - 44 Ti Furnace Cooled (321 BHN)	56 Ni - 44 Ti Quenched (363 BHN)	60 Ni - 40 Ti Furnace Cooled (302 BHN)	60 Ni - 40 Ti Quenched (60 Rc)
	Cobalt HSS	Cobalt HSS	Cobalt HSS	Cobalt HSS	Cobalt HSS Not practical
Drill Geometry (#21 dia. drill)	Point Angle: 118° Point Style: Split Clearance: 7-10°	Point Angle: 118° Point Style: Split Clearance: 7-10°	Point Angle: 118° Point Style: Split Clearance: 7-10°	Point Angle: 118° Point Style: Split Clearance: 7-10°	Point Angle: 1 Point Style: Split Clearance: 7-10°
Cutting Speed - feet/minute	20	15	10	10	--
Feed - inches/rev.	.001	.001	.001	.001	--
Cutting Fluid	Highly Chlorinated Oil	Highly Chlorinated Oil	Highly Chlorinated Oil	Highly Chlorinated Oil	--
Drill Life - HSS	34 holes	34 holes	25 holes	30 holes	--
Drill Life - (carbide at 100 fpm, .001 in./rev.)	65*	28*	29*	40*	13*

General Instructions

1. Use as short a drill as possible.
2. Always use power feeds.
3. Flood work liberally with cutting fluid.
4. Heavier feeds can be used with larger diameter drills.

\* Tool life with carbide tipped drills is not satisfactory. Small diameter solid carbide drills provide erratic results.

**Table 4**  
**Recommendations for Surface Grinding Nitinol Alloys**

	<u>55 Ni - 45 Ti As Received (2.17 BHN)</u>	<u>56 Ni - 44 Ti Furnace Cooled (321 BHN)</u>	<u>56 Ni - 44 Ti Quenched (363 BHN)</u>	<u>60 Ni - 40 Ti Furnace Cooled (302 BHN)</u>	<u>60 Ni - 40 Ti Quenched (60 Rc)</u>
<b>Wheel Specification</b>	GC60L6VP	39C60I8VK	39C60I8VK	39C60I8VK	39C60I8VK
<b>Wheel Speed - ft./min.</b>	5000	5000	5000	5000	5000
<b>Down Feed - in./pass</b>	.001	.002	.002	.002	.002
<b>Table Speed - ft./min.</b>	60	40	20	20	60
<b>Cross Feed - in./pass</b>	.050	.050	.050	.050	.050
<b>Grinding Fluid</b>	Highly Chlorinated Oil	Highly Chlorinated Oil	Highly Chlorinated Oil	Highly Chlorinated Oil	Highly Chlorinated Oil

**General Instructions**

1. Silicon carbide wheels outperform aluminum oxide wheels
2. Highly chlorinated oil provides higher grinding ratios than soluble oil.

**Turning Nitinol Alloys**  
**Effect of Cutting Speed With Carbide**

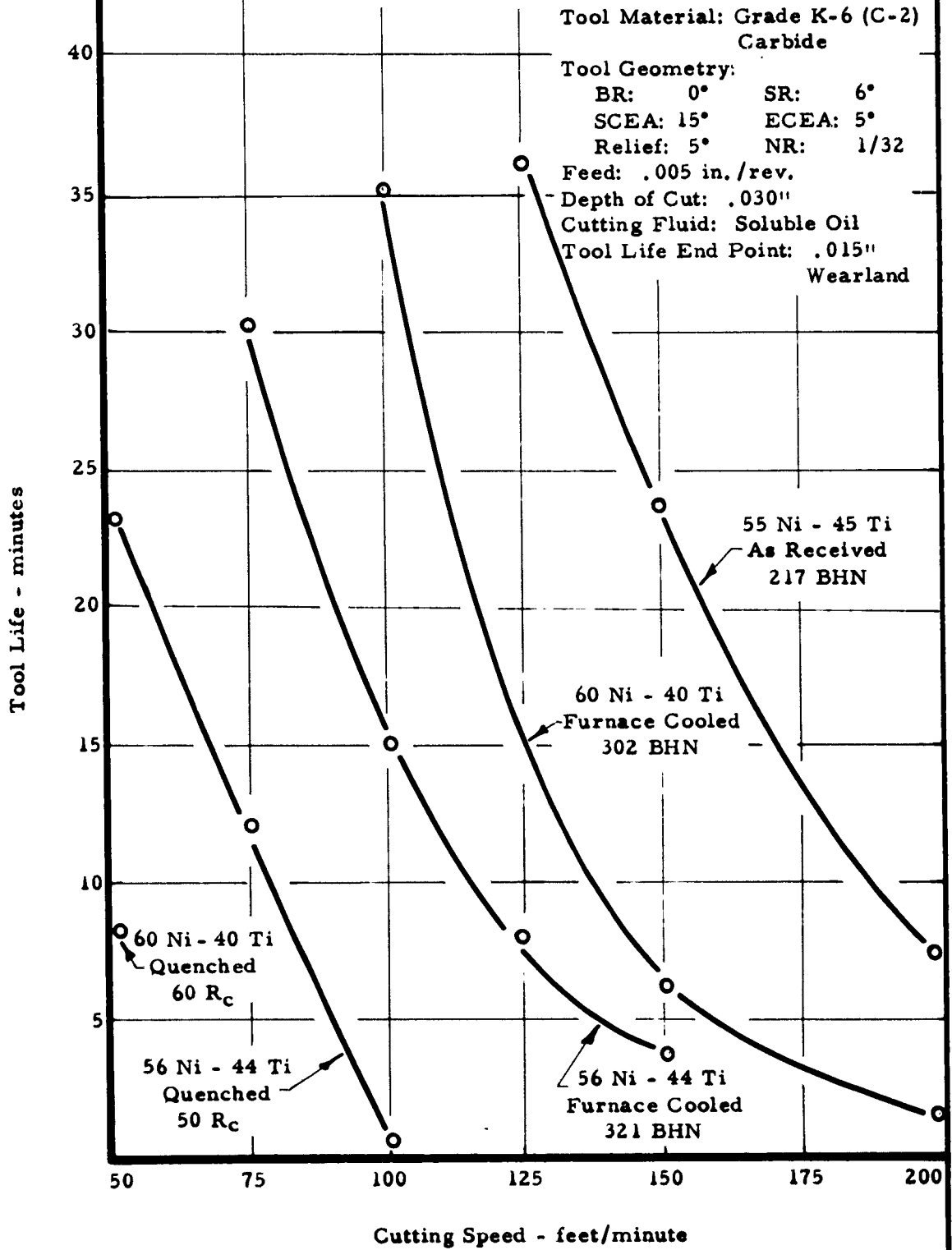


Figure 1

**Turning Nitinol Alloys  
Effect of Feed With Carbide**

Tool Material: Grade K-6 (C-2)  
Carbide

Tool Geometry:

BR: 0° SR: 6°

SCEA: 15° ECEA: 5°

Relief: 5° NR: 1/32

Cutting Speed: See below

Feed: See below

Depth of Cut: .030"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .015" Wearland

Tool Life - minutes

40

35

30

25

20

15

10

5

55 Ni - 45 Ti  
As Received  
217 BHN  
125 ft./min.

60 Ni - 40 Ti  
Quenched  
60 Rc  
30 ft./min.

60 Ni - 40 Ti  
Furnace  
Cooled  
302 BHN  
100 ft./min.

56 Ni - 44 Ti  
Quenched  
50 Rc  
50 ft./min.

.005

.010

.015

Feed - inches/revolution

Figure 2



Turning Nitinol Alloys  
Effect of Cutting Speed With HSS

Tool Material: Type T-15 HSS

Tool Geometry:

BR: 0° SR: 15°

SCEA: 15° ECEA: 5°

Relief: 5° NR: .030

Feed: .009 in./rev.

Depth of Cut: .030"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .060" Wearland

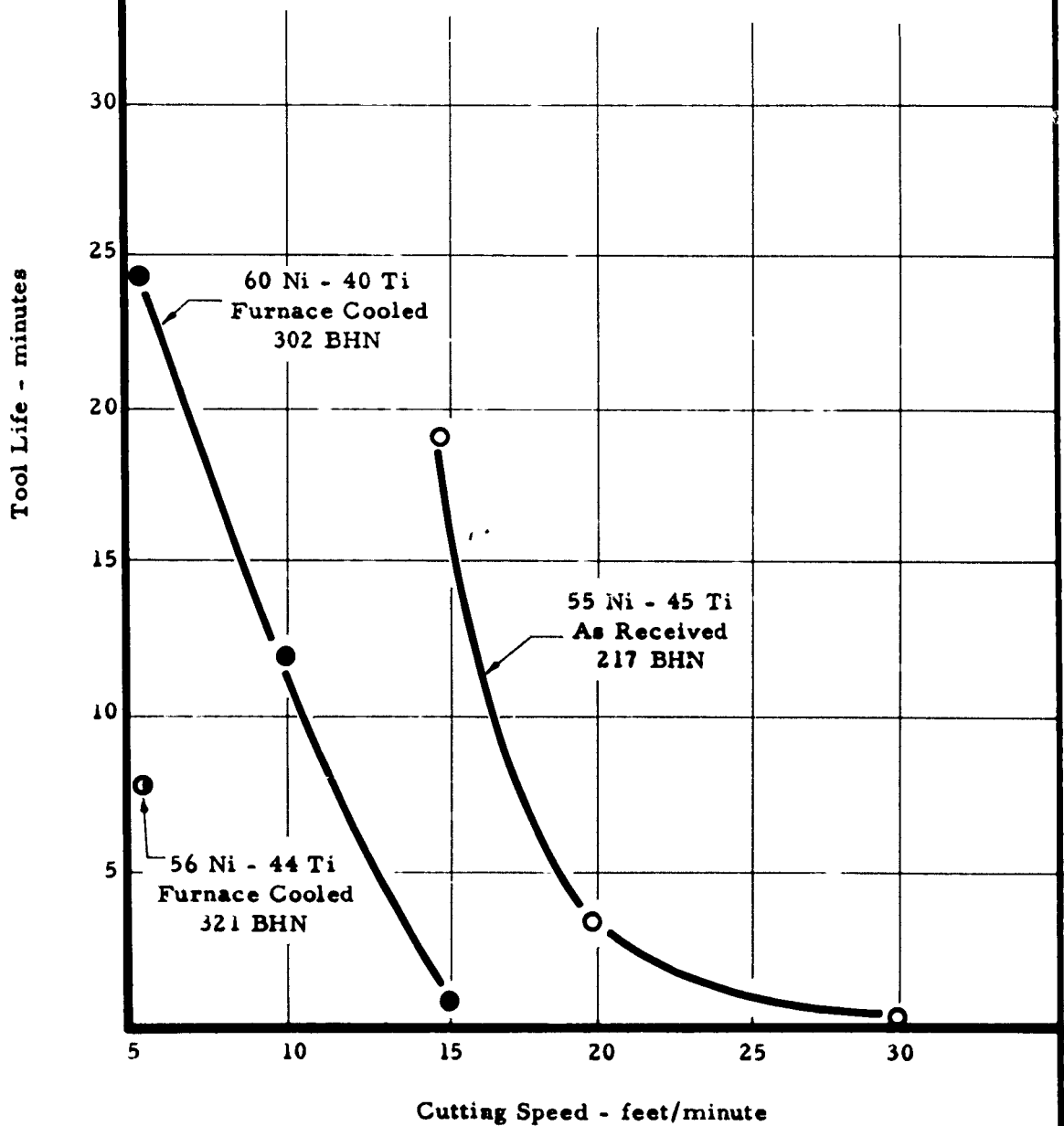


Figure 3

**Face Milling Nitinol Alloys**  
**Effect of Radial Rake Angle**

Cutter: 4" Dia. Single Tooth Face Mill  
Carbide: Grade 883 (C-2)  
Tool Geometry:  
AR: 0° RR: (See below)  
Peripheral Clearance: 10°  
CA: 45°  
Cutting Speed: See below  
Feed: .005 in./rev.  
Depth of Cut: .050"  
Width of Cut: 1"  
Cutting Fluid: Highly Chlorinated Oil  
Tool Life End Point: .015" Wearland

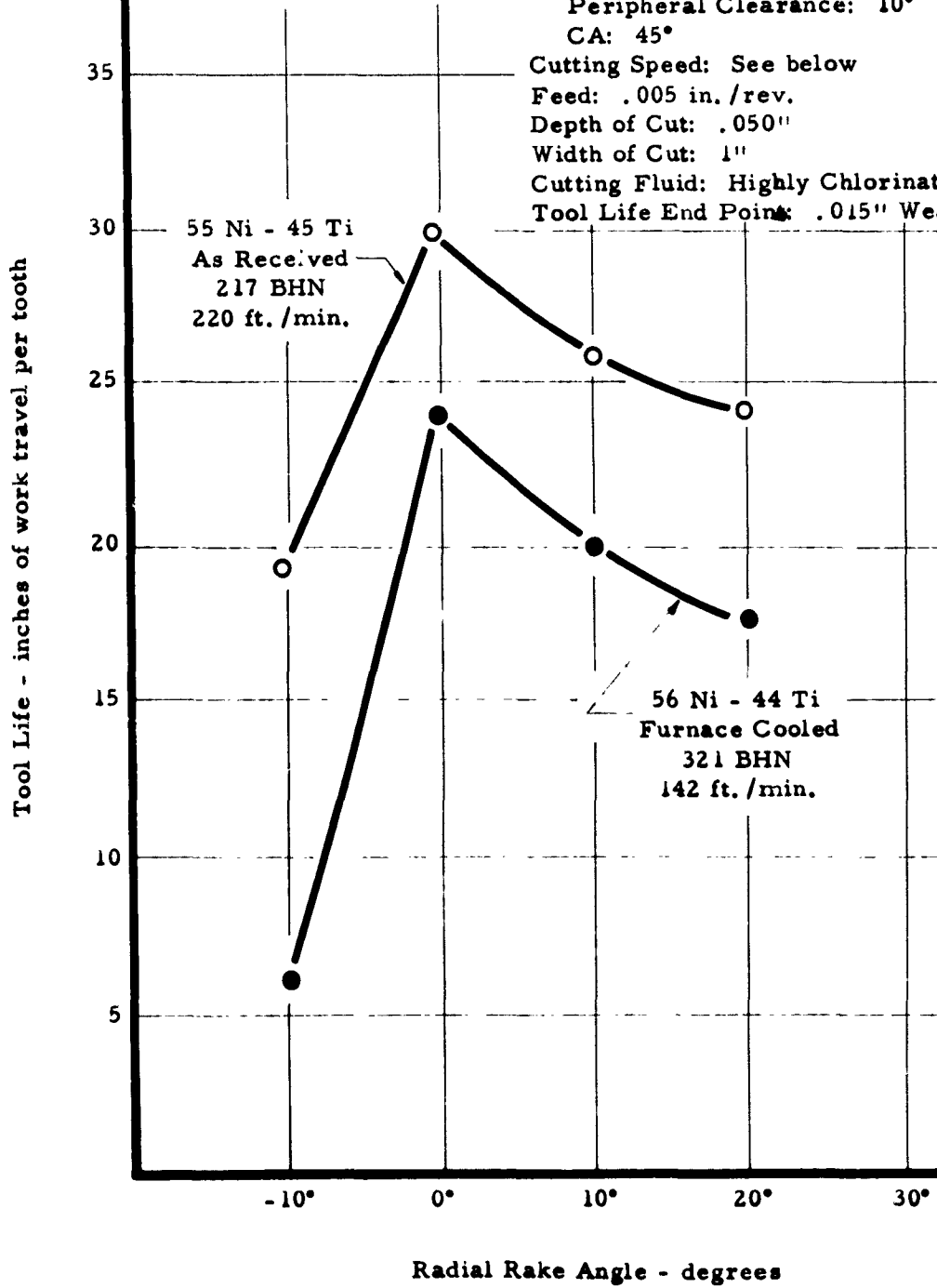


Figure 4

**Face Milling Nitinol Alloys  
Effect of Cutting Speed**

Cutter: 4" dia. Single Tooth Face Mill  
 Carbide: Grade 883 (C-2)  
 Tool Geometry:  
 AR: 0° RR: 0°  
 Peripheral Clearance: 10°  
 CA: 45°  
 Feed: .005 in./tooth  
 Depth of Cut: .050"  
 Width of Cut: 1"  
 Cutting Fluid: Highly Chlorinated Oil  
 Tool Life End Point: .015" Wearland

Tool Life - inches of work travel per tooth

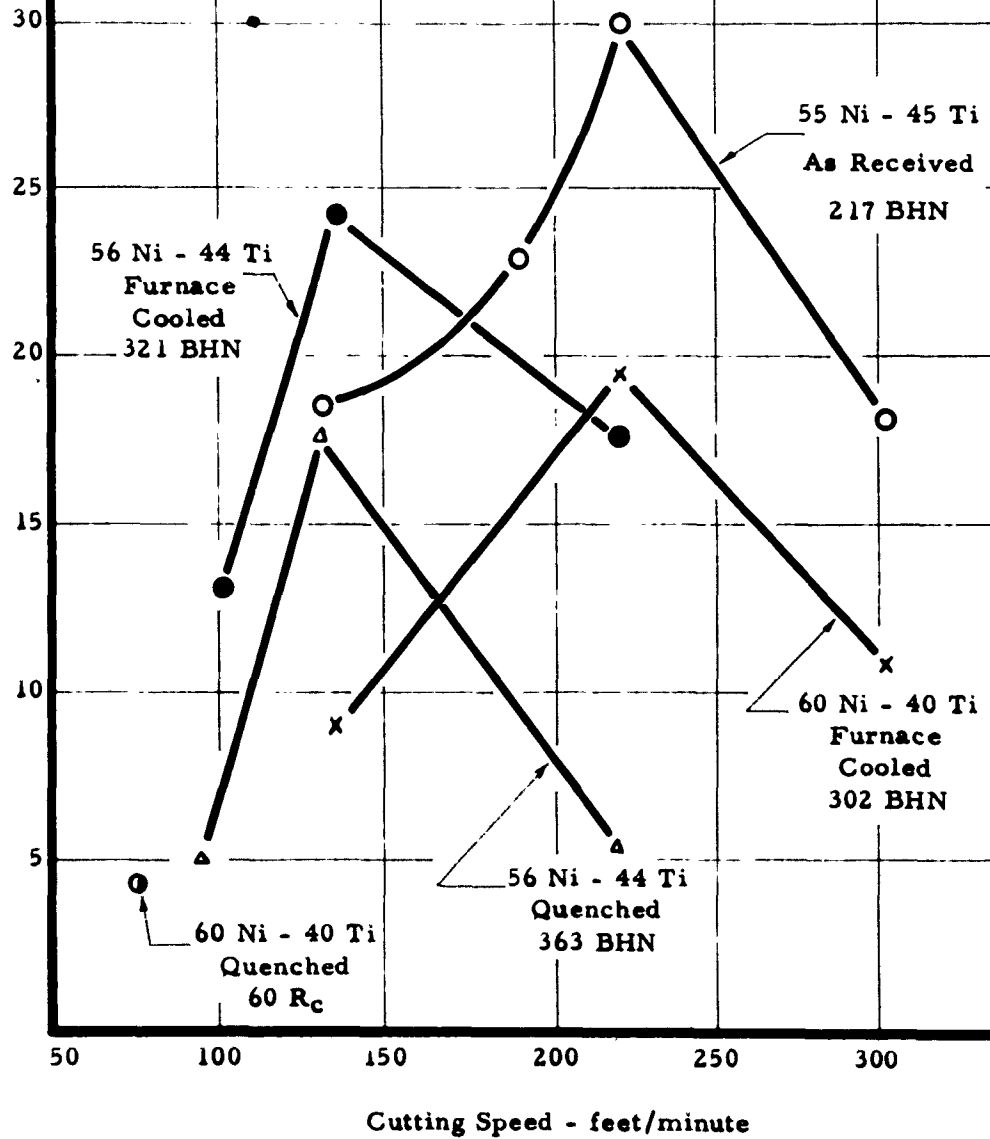


Figure 5

**Face Milling Nitinol Alloys**  
**Effect of Feed**

Cutter: 4" Dia. Single Tooth Face Mill  
 Carbide: Grade 883 (C-2)  
 Tool Geometry:  
 AR: 0° RR: 0°  
 Peripheral Clearance: 10°  
 CA: 45°  
 Cutting Speed: See below  
 Depth of Cut: .050"  
 Width of Cut: 1"  
 Cutting Fluid: Highly Chlorinated Oil  
 Tool Life End Point: .015" Wearland

Tool Life - inches of work travel per tooth

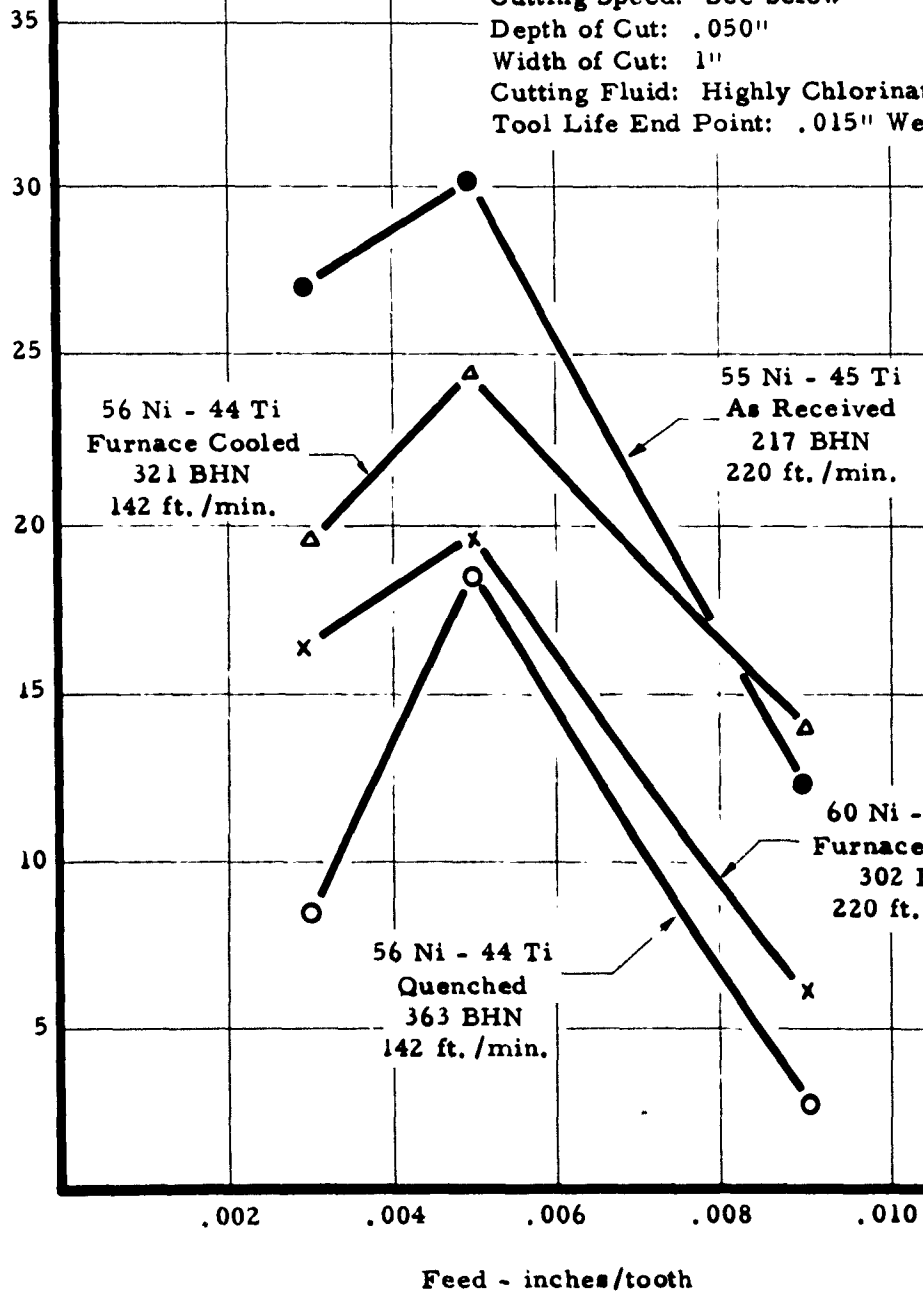


Figure 6

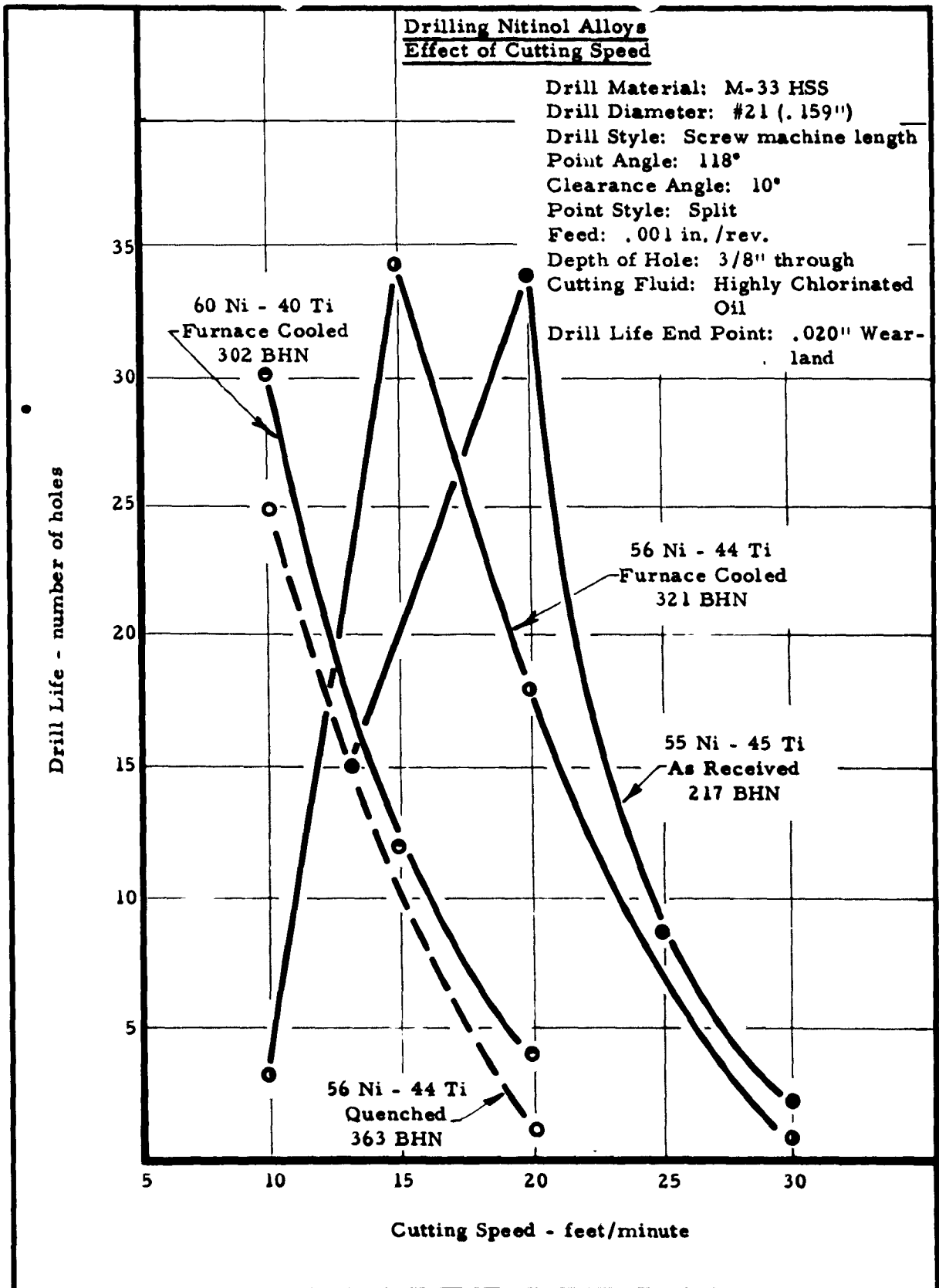


Figure 7

**Drilling 55 Ni - 45 Ti Alloy, 217 BHN**  
**Effect of Cutting Speed and Feed**

Drill Material: M-33 HSS  
Drill Diameter: #21 (.159")  
Drill Style: Screw machine length  
Point Angle: 118°  
Clearance Angle: 10°  
Point Style: Split  
Feed: See below  
Depth of Hole: 3/8" through  
Cutting Fluid: Highly Chlorinated Oil  
Drill Life End Point: .020" Wearland

Drill Life - number of holes

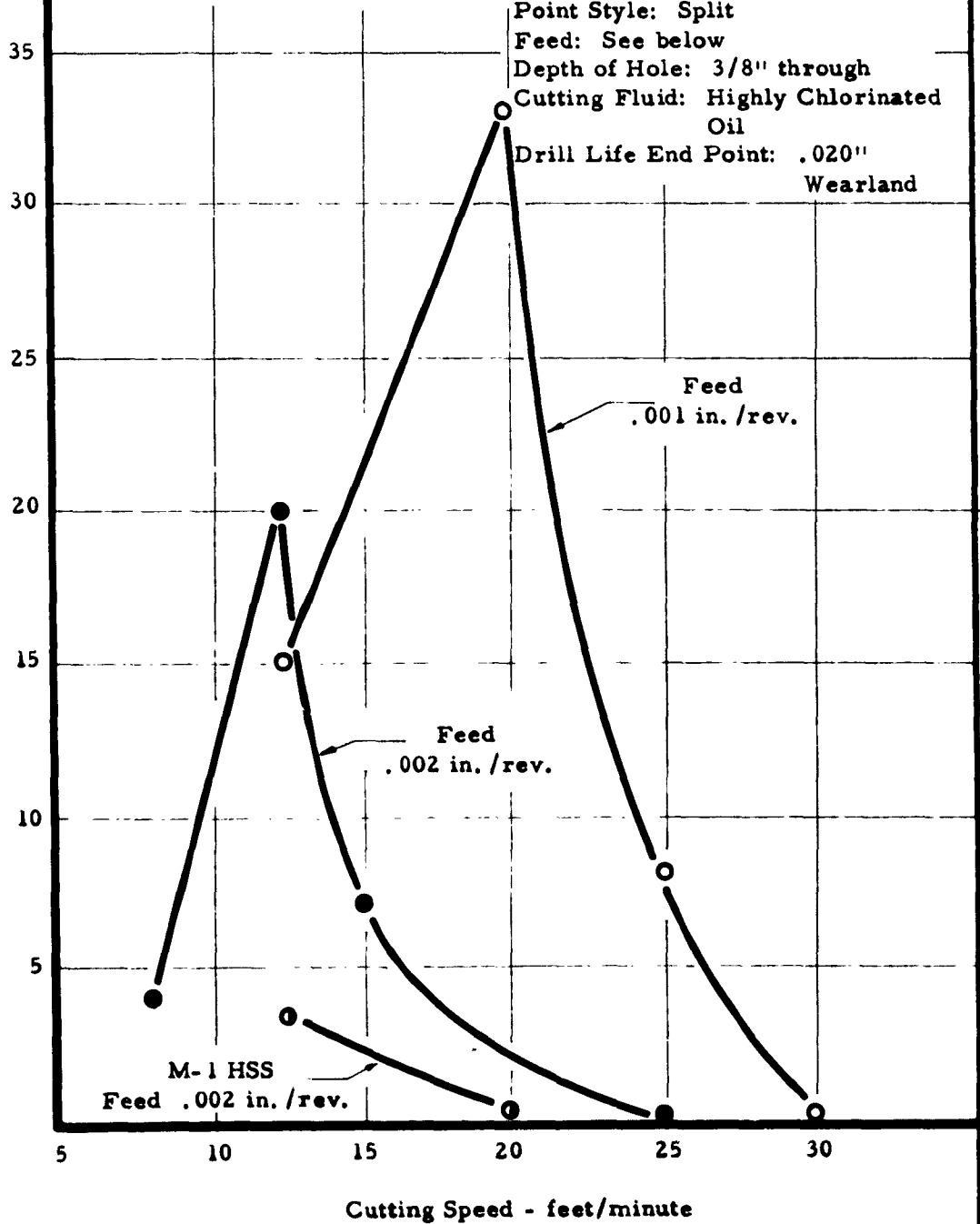


Figure 8

Drilling 55 Ni - 45 Ti Alloy, 217 BHN  
Effect of Feed and Cutting Speed

Drill Material: M-33 HSS  
Drill Diameter: #21 (.159")  
Drill Style: Screw machine length  
Point Angle: 118°  
Clearance Angle: 10°  
Point Style: Split  
Cutting Speed: See below  
Depth of Hole: 3/8" through  
Cutting Fluid: Highly Chlorinated Oil  
Drill Life End Point: .020" Wearland

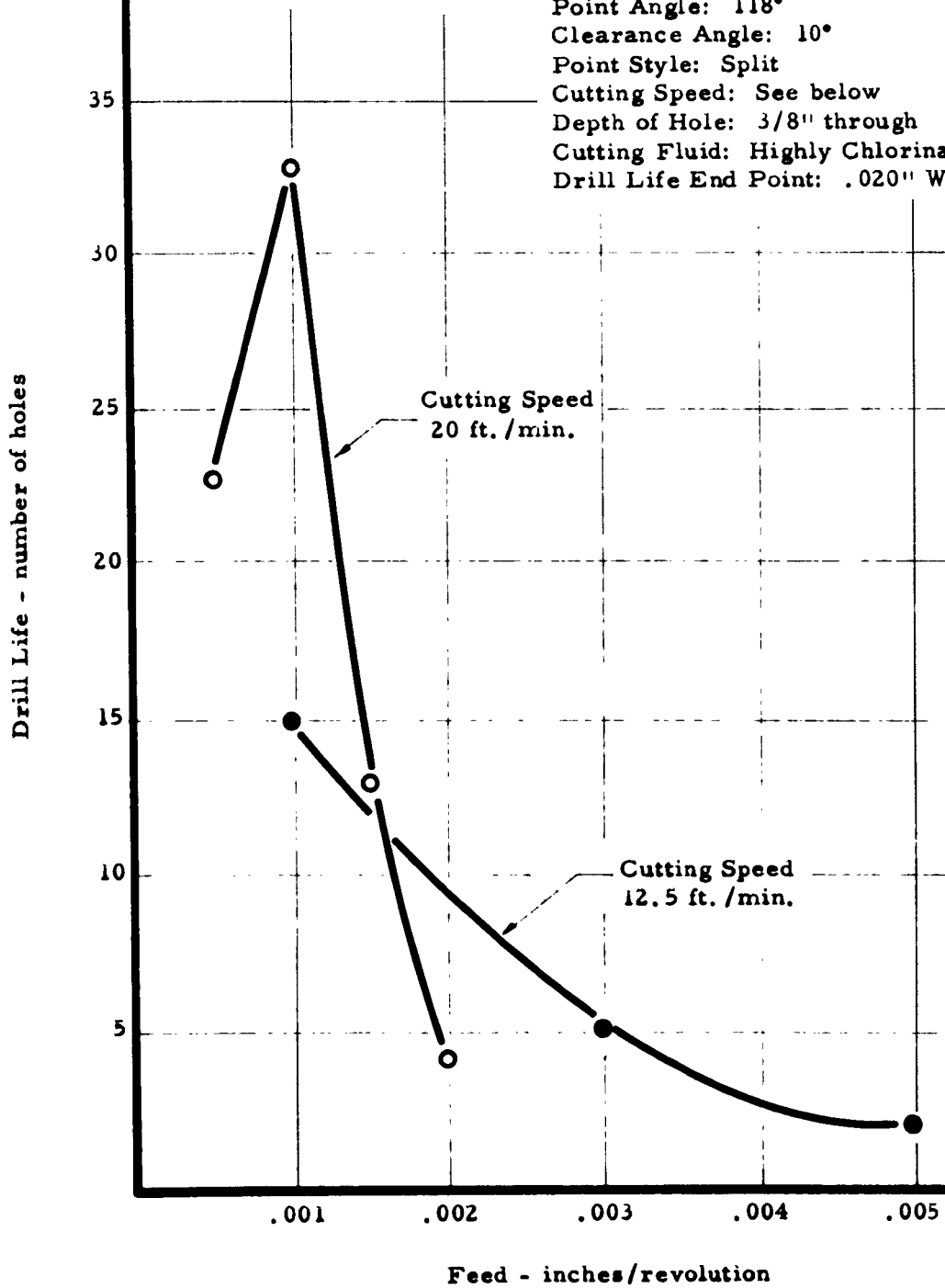


Figure 9

Drilling 55 Ni - 45 Ti Alloy, 217 BHN

Effect of Cutting Fluid

Drill Material: M-33 HSS  
Drill Diameter: #21 (.159")  
Drill Style: Screw machine length  
Point Angle: 118°  
Clearance Angle: 10°  
Point Style: Split  
Feed: .001 in./rev.  
Cutting Speed: 20 feet/minute  
Depth of Hole: 3/8" through  
Drill Life End Point: .020" Wearland

Drill Life - number of holes

35  
30  
25  
20  
15  
10  
5

Highly  
Chlorinated  
Oil

Highly  
Sulphurized  
Oil

Soluble  
Oil  
(1:20)

Cutting Fluid

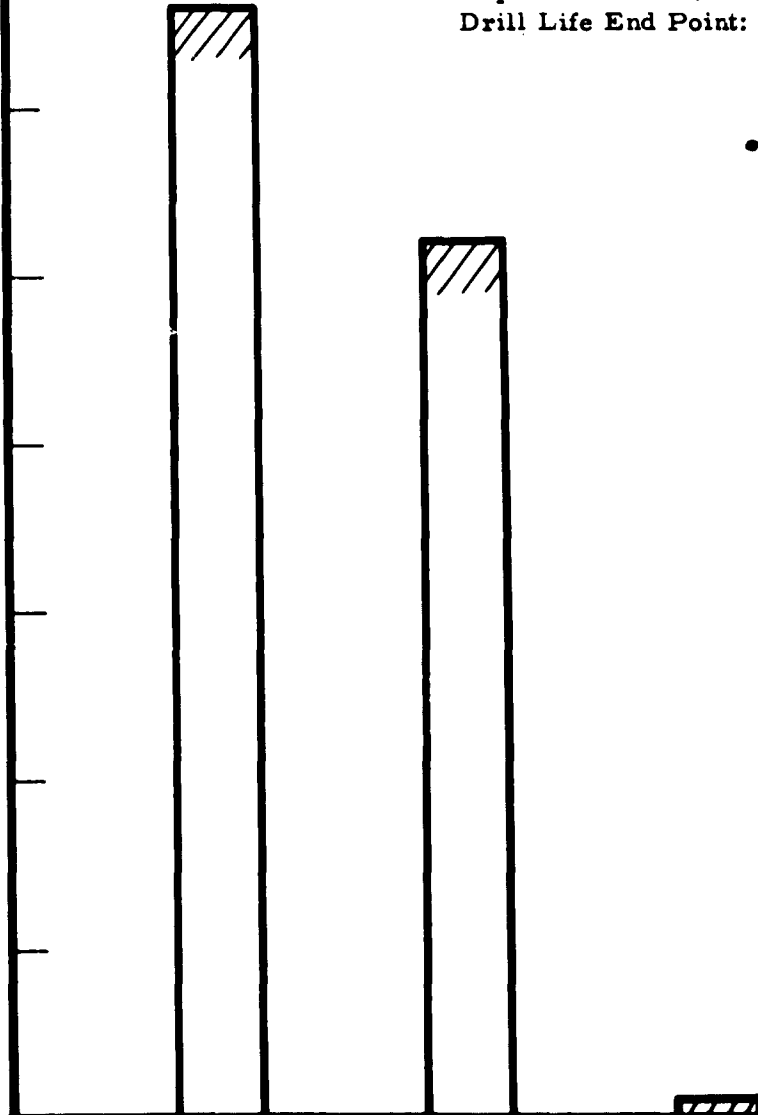


Figure 10



Grinding 55 Ni - 45 Ti Alloy, 217 BHN  
Effect of Wheel Specification

Wheel Grade: See below  
Wheel Speed: 5000 feet/minute  
Table Speed: 40 feet/minute  
Down Feed: .001 in./pass  
Cross Feed: .050 in./pass  
Grinding Fluid: Soluble Oil (1:20)

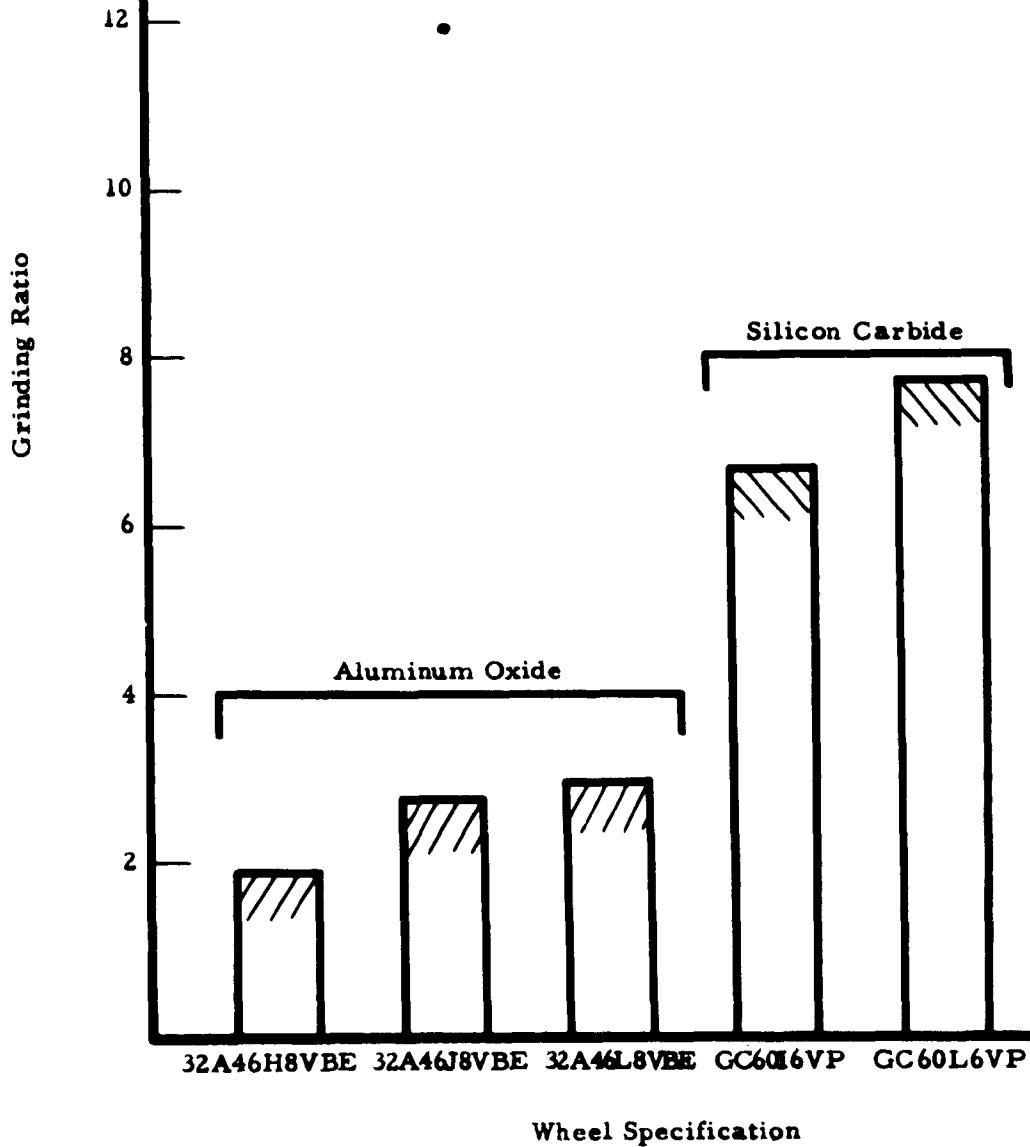


Figure 11

Surface Grinding 56 Ni - 44 Ti Alloy  
Furnace Cooled - 321 BHN  
Effect of Wheel Specification

Wheel Grade: See below  
Wheel Speed: 5000 feet/minute  
Table Speed: 40 feet/minute  
Down Feed: .001 in./pass  
Cross Feed: .050 in./pass  
Grinding Fluid: Highly Chlorinated Oil

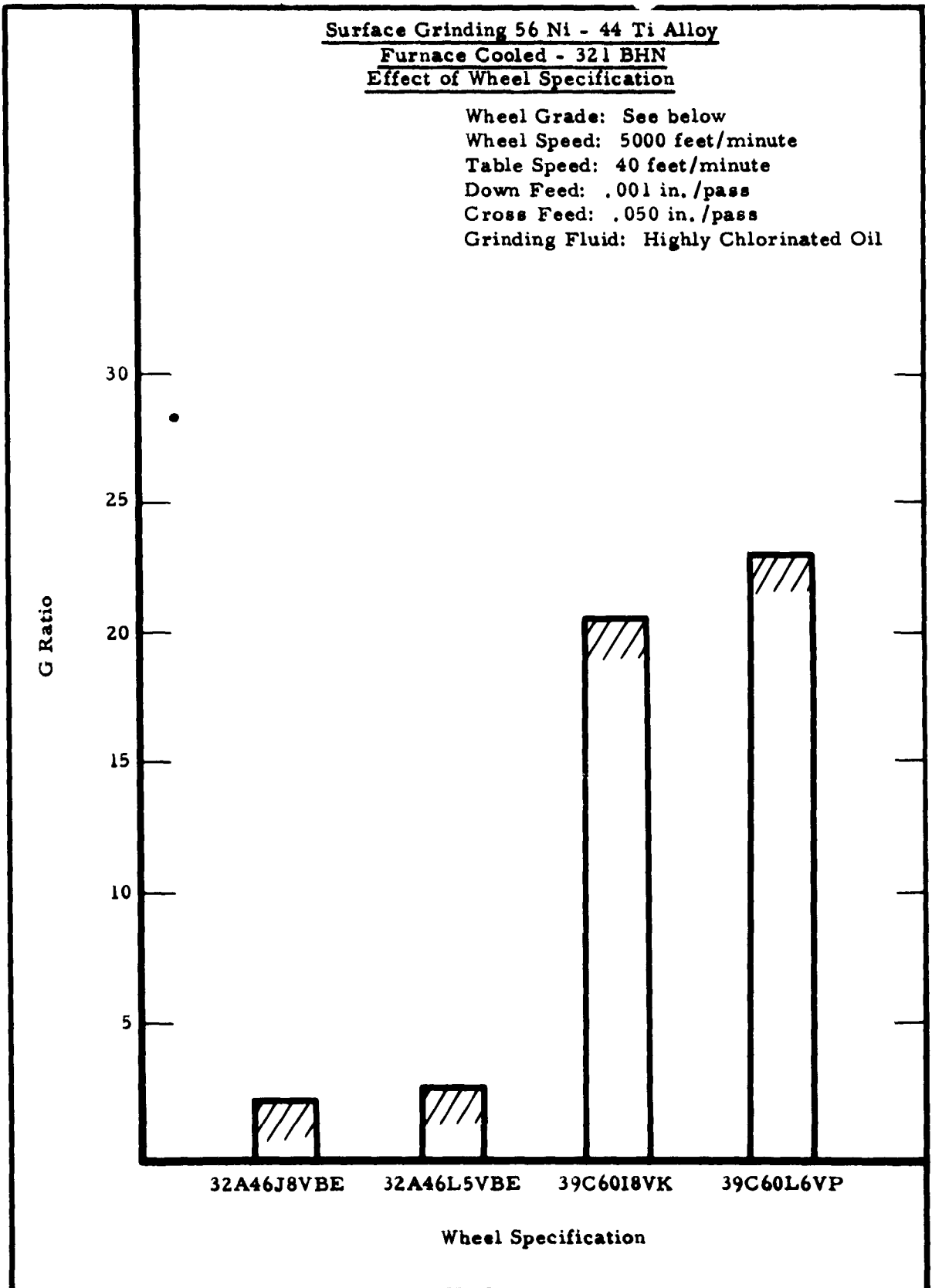


Figure 12

Surface Grinding 60 Ni - 40 Ti Alloy  
Furnace Cooled - 302 BHN  
Effect of Wheel Specification

Wheel Grade: See below  
Wheel Speed: 5000 feet/minute  
Table Speed: 40 feet/minute  
Down Feed: .001 in./pass  
Cross Feed: .050 in./pass  
Grinding Fluid: Highly Chlorinated  
Oil

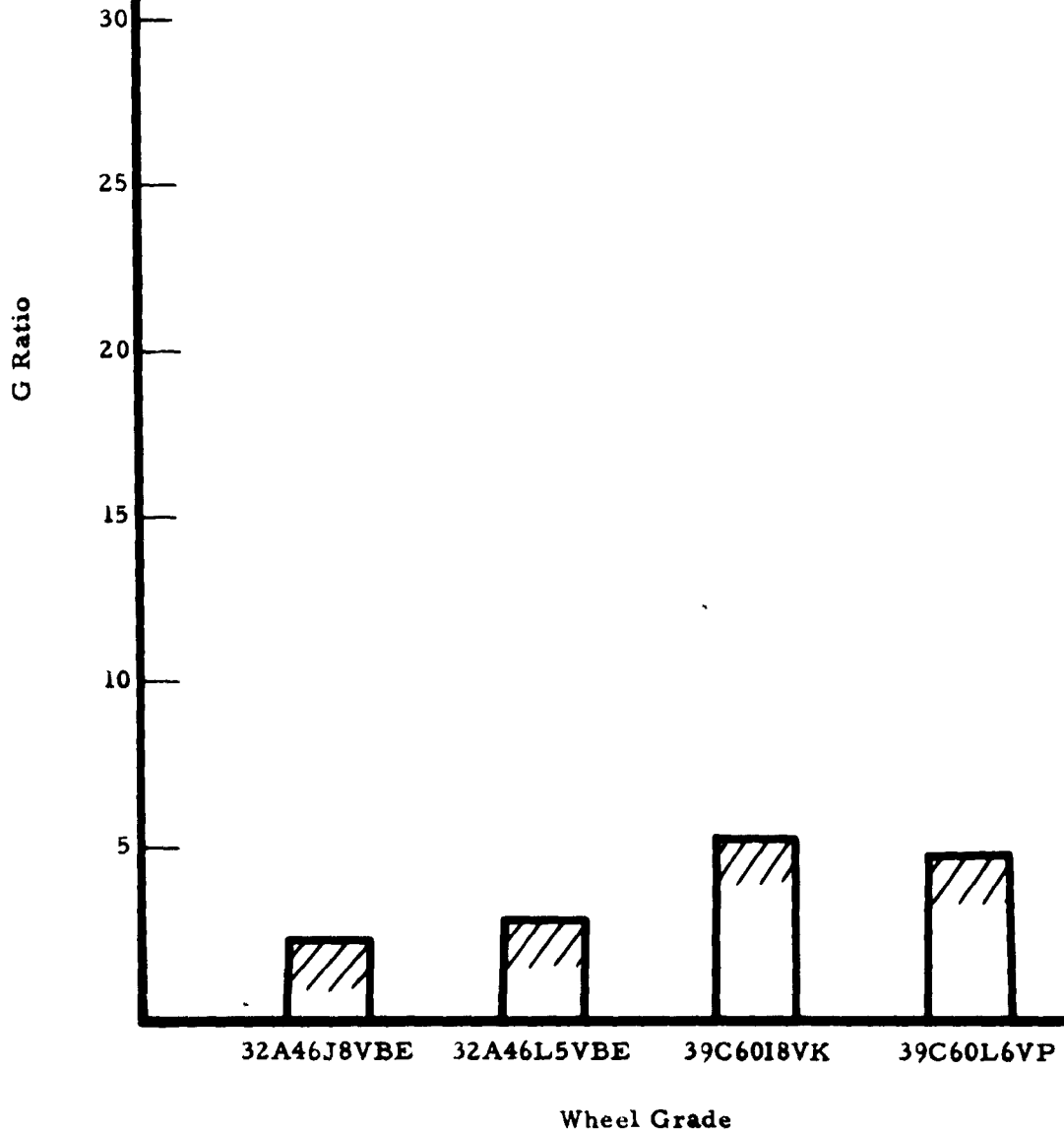


Figure 13

Surface Grinding Nitinol Alloys  
Effect of Wheel Speed

Wheel Grade: 39C6018VK (except where noted)  
Wheel Speed: See below  
Table Speed: 40 feet/minute  
Down Feed: .001 in./pass  
Cross Feed: .050 in./pass  
Grinding Fluid: Highly Chlorinated Oil

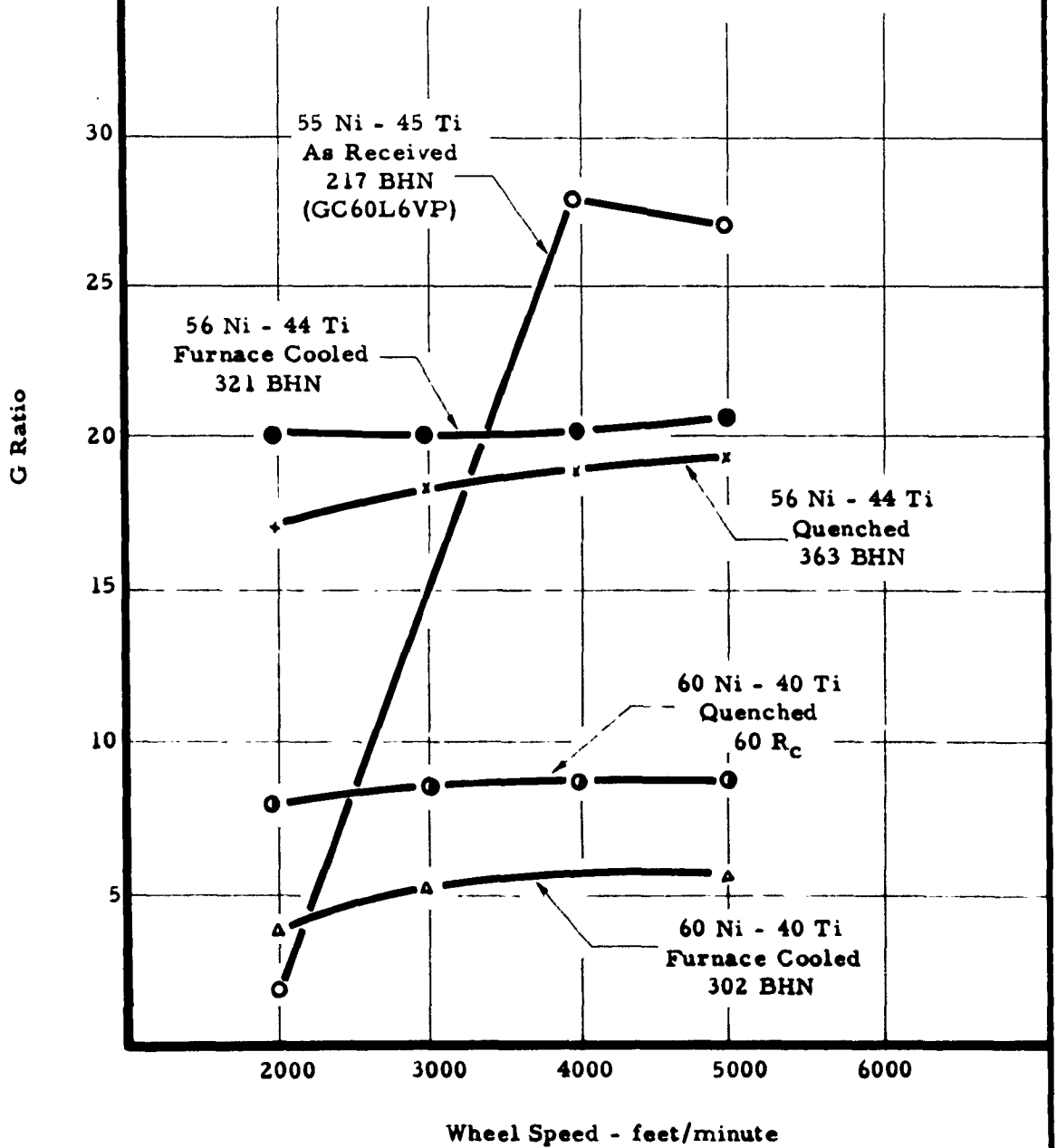


Figure 14

Surface Grinding Nitinol Alloys  
Effect of Down Feed

Wheel Grade: 39C60I8VK (except where noted)  
Wheel Speed: 5000 feet/minute  
Table Speed: 40 feet/minute (except where noted)  
Cross Feed: .050 in./pass  
Grinding Fluid: Highly Chlorinated Oil

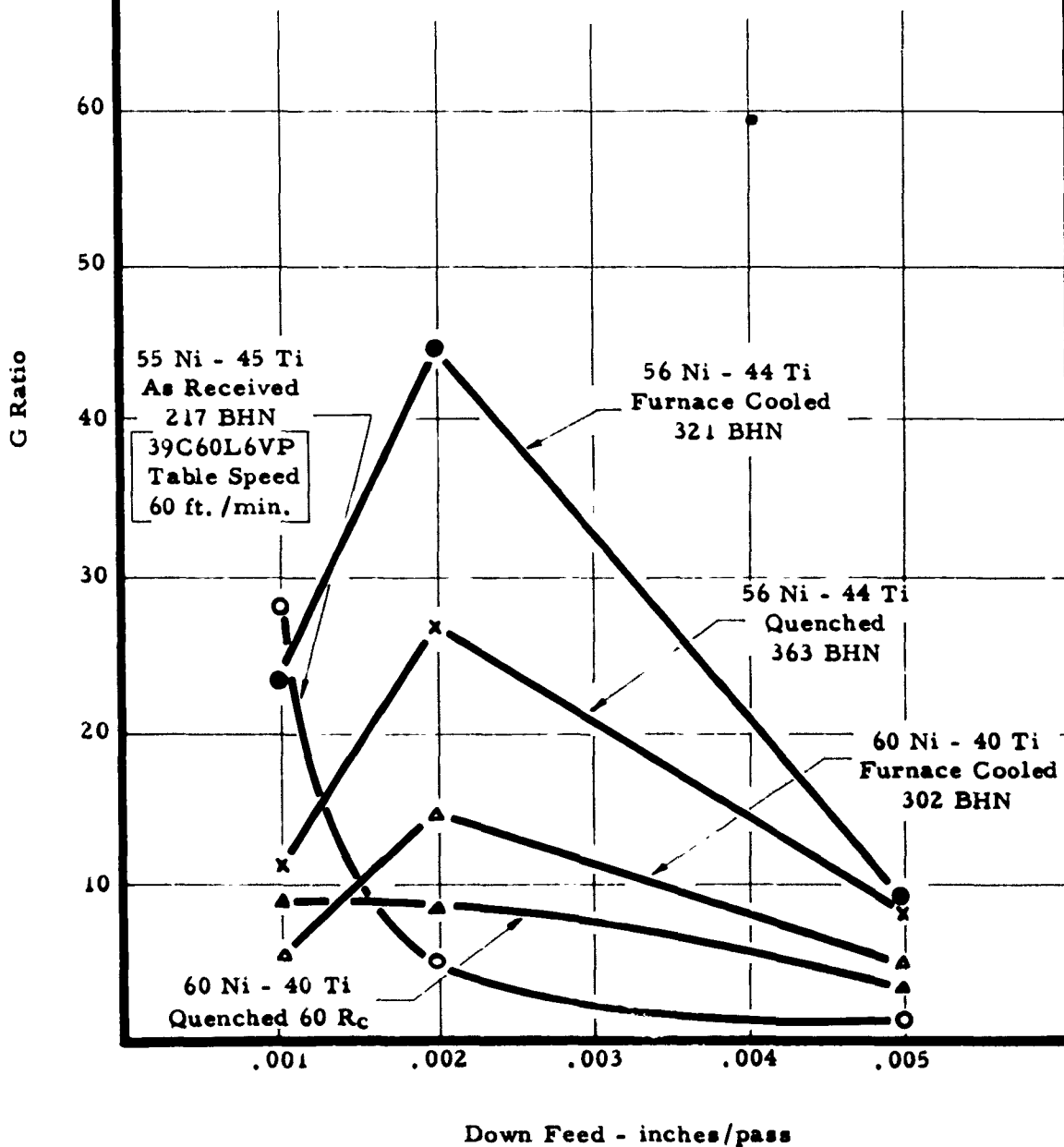


Figure 15

**Surface Grinding Nitinol Alloys**  
**Effect of Cross Feed**

Wheel Grade: 39C60I8VK (except where noted)  
 Wheel Speed: 5000 feet/minute  
 Table Speed: 60 feet/minute (except where noted)  
 Down Feed: .002 in./pass (except where noted)  
 Cross Feed: .050 in./pass  
 Grinding Fluid: Highly Chlorinated Oil

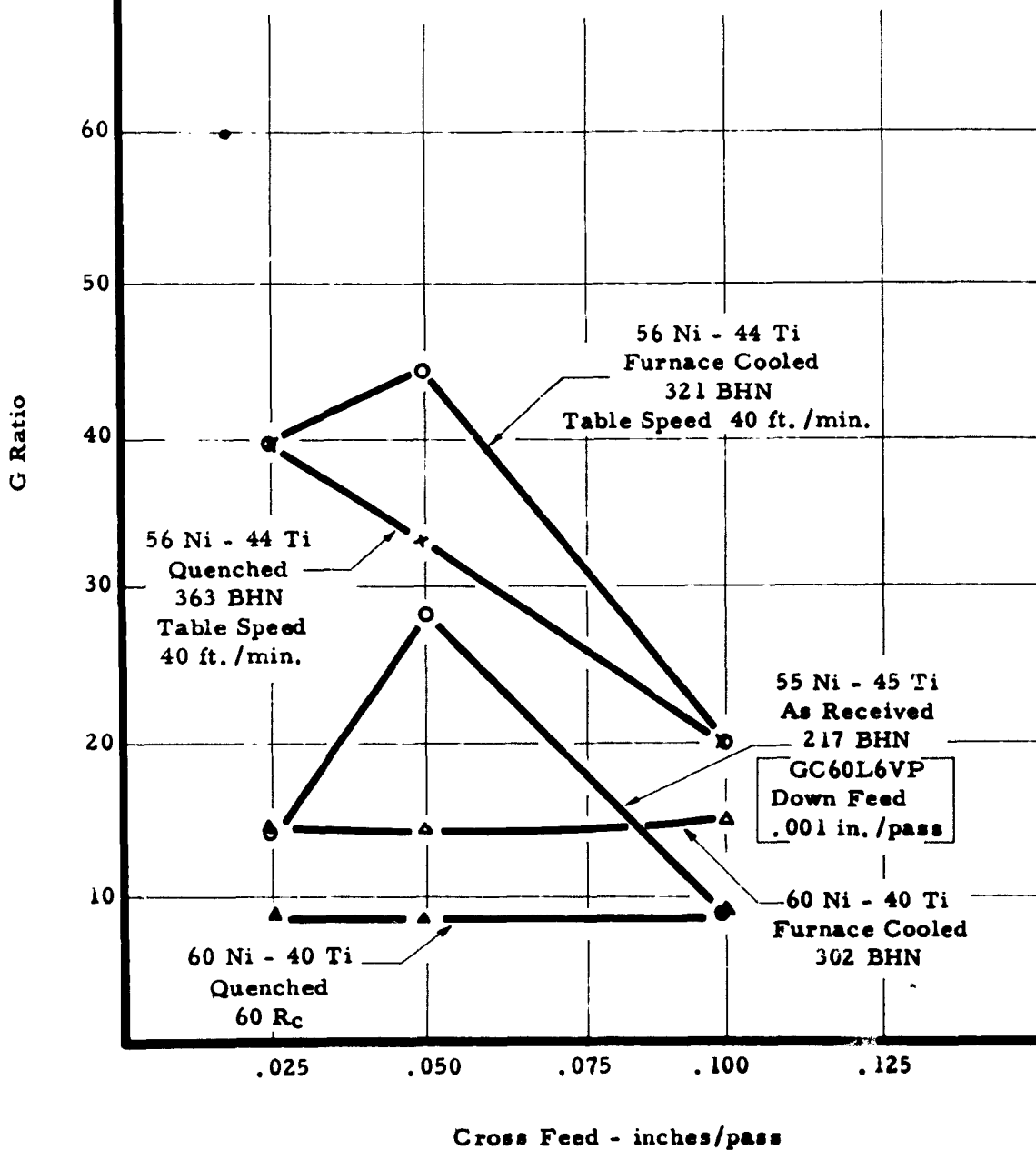


Figure 16

Surface Grinding Nitinol Alloys  
Effect of Table Speed

Wheel Grade: 39C60I8VK (except where noted)  
 Wheel Speed: 5000 feet/minute  
 Table Speed: See below  
 Down Feed: .002 in./pass (except where noted)  
 Cross Feed: .050 in./pass  
 Grinding Fluid: Highly Chlorinated Oil

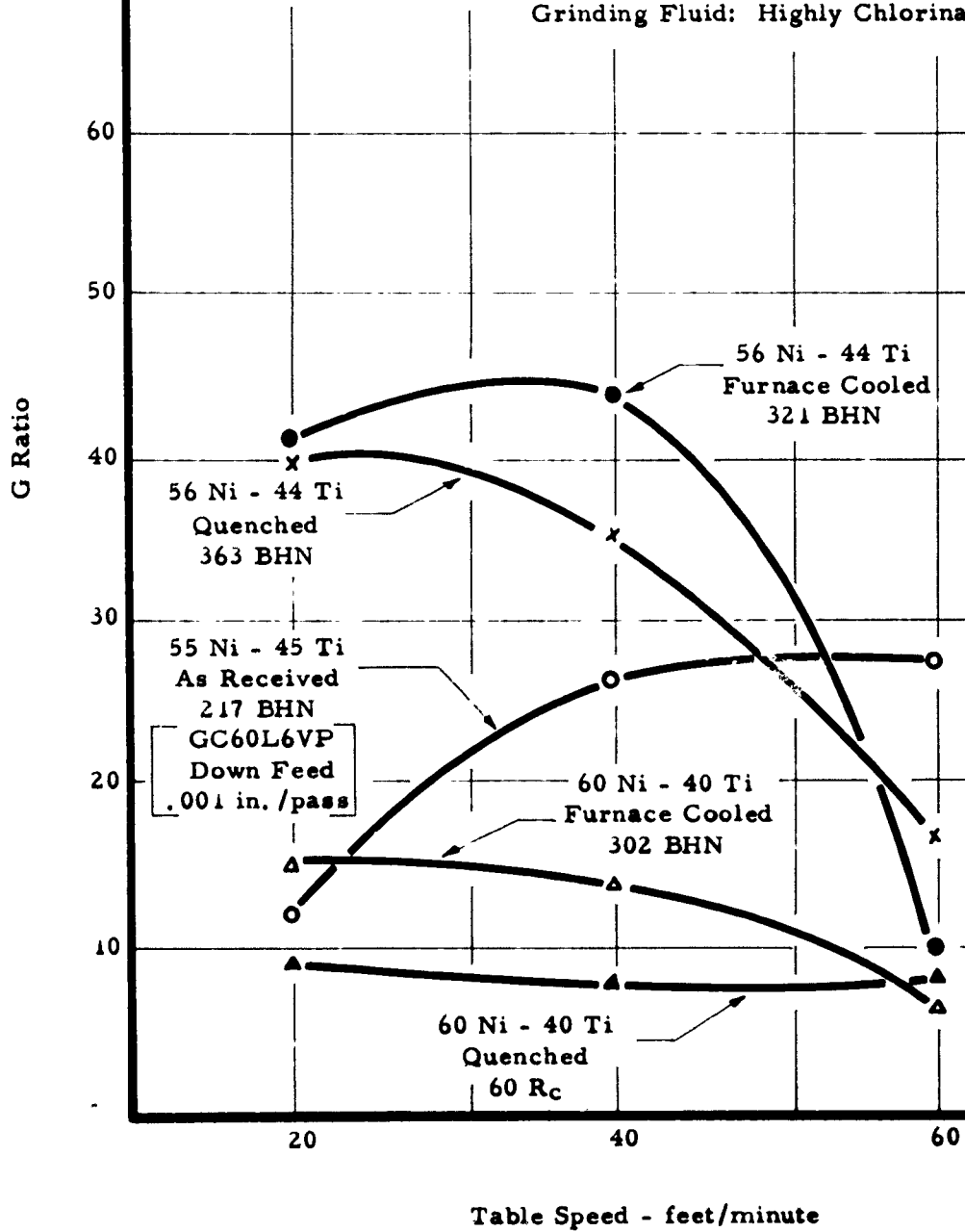


Figure 17

Grinding 55 Ni - 45 Ti Alloy, 217 BHN  
Effect of Wheel Speed

Wheel Grade: GC60L6VP  
Table Speed: 40 feet/minute  
Down Feed: .001 in./pass  
Cross Feed: .050 in./pass  
Grinding Fluid: See below

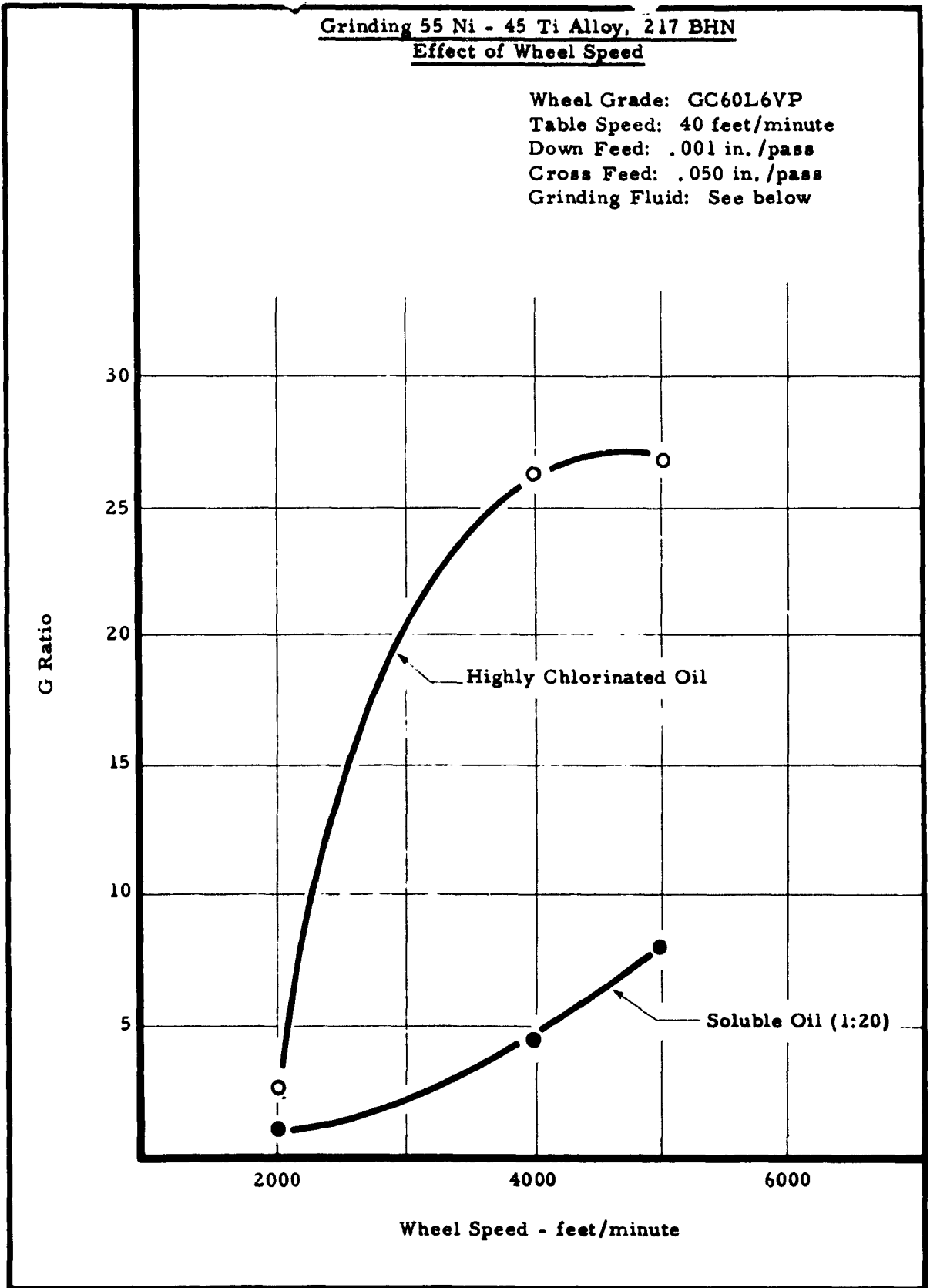


Figure 18