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UNIVERSITY OF MICHIGAN
ANN ARBOR

REPORT NO. 29

MACHINABILITY OF TITANIUM ALLOYS RC-110A AND 3Al-5Cr

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Project 1993

U. S. ARMY, ORDNANCE CORPS
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SUMMARY SHEET

I. Engineering Research Institute, University of Michigan, Ann Arbor, Michigan.

II. U. S. Army, Ordnance Corps.

III. Project No. 1993, Contract No. DA-20-018 ORD-11918, RAD No. ORDTB-1-12045

IV. Report No. WAL 401/109-29

V. Priority No. - None

VI. Investigation of machinability of titanium-base alloys

VII. Object:

The objective of this project was to conduct a machinability investigation of titanium alloys RC-110A and 3Al-5Cr in such a way as to give a comparison with commercially pure titanium and other titanium alloys tested previously. The results of the prior investigation are recorded in Report Nos. 1 through 28.

VIII. Summary:

Numerous laboratory studies were made with both alloys. The RC-110A alloy was investigated as to its machining properties in milling, turning, tapping, broaching, conventional drilling, deep-hole drilling, and band-sawing. Similar observations were made for the 3Al-5Cr alloy except for deep-hole drilling.

IX. Conclusions:

Both RC-110A and 3Al-5Cr titanium alloys demonstrate identically the same qualitative machining characteristics as all previously tested alloys with the exception of RC-130B, which was somewhat unique as emphasized in previous reports. The highlights of these machining characteristics are as follows:

1. It is relatively easy to obtain good surface finish when machining titanium.

2. The cutting speeds possible when machining titanium alloys are inversely proportional to the strength of these alloys not only among themselves, but as compared to common alloys of steel.

3. The cutting force and power requirements are substantially the same as for a medium-strength steel, except as the tools become dull in which case the force and power requirements increase several times faster than in the case of steel.

4. The necessary conditions for successful machining of titanium are as follows:

a. exceptional rigidity of the machine setup;

b. shop practice which will permit cutting tools to be worn not more than about one-third common practice when cutting steel; and

c. abnormally large relief angles for those operations which ordinarily provide little or no relief on the cutting tools (such operations are tapping, reaming, broaching, etc.).

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I. INTRODUCTION

This report presents the results of machinability studies of titanium alloys 3Al-5Cr and RC-110A. They were studied as a follow-up to an earlier investigation of commercially pure titanium and three alloys. The earlier studies involved many operations since there had been no prior experience with the machining of titanium. The experience gained previously made it possible to limit the laboratory investigations of the two additional alloys of titanium.

The results presented in this report show that the two new alloys have substantially the same cutting properties as those studied in the earlier investigation. Titanium does exhibit some unique machining properties as compared to other metals and steel in particular. In brief, it appears that the unique machining behavior is determined largely by a combination of lower modulus of elasticity, high strength, relatively low ability to dissipate heat, and a relatively low coefficient of friction. All titanium alloys studied to date exhibit the following machining properties:

1. Very little foreshortening in the formation of the chip. This gives rise to:

    a. exceptionally high pressures between the chip and the cutting tool,

    b. unusually high temperature in the cutting zone, and

    c. unusually high sensitivity to any flexibility or lack of rigidity in the machining setup.

2. Exceptionally good surface finish.

3. Highly susceptible to seizure. Despite a normally low coefficient of friction, titanium appears to be highly susceptible to seizure in metal cutting operations. This condition is most pronounced where small relief angles are used. Where it is possible to do so, relief angles should be of the magnitude of 5 to 10 degrees; however, with certain types of tools such as cutting taps this is not possible and a good extreme pressure lubricant must be used for successful operation.

4. Requires exceptional rigidity in the machine setup. The most important factor contibuting toward successful machining of titanium is that of rigidity of the entire machining setup. While this is the most important, it does not lend itself to numerical evaluation and one can say that exceptional measures must be taken to assure maximum rigidity.

5. Moderate power requirements. Most alloys of titanium require substantially the same amount of energy or power for cutting as does unhardened medium carbon steel.

An attempt was made to determine the residual stresses caused by machining titanium. It was found that it is very difficult to determine such stresses in titanium. However, a few reliable qualitative indications were obtained. These indicated that the residual stresses or the distortion associated with them increases very rapidly at relief angles less than 3 degrees. This was investigated by making cuts with tools having relief angles varying from 7 degrees down to no relief at all. These indications are particularly significant when compared to similar experience with steel. Hot-rolled SAE 1045 steel showed no measurable distortion at the same conditions. While the residual-stress investigation did not yield any quantitative results it nevertheless indicated that considerable difficulty will be encountered in controlling dimensions in machining titanium unless the cutting tools are resharpened more frequently than in cutting steel. In other words, tools should not be permitted to be worn as far as they are when cutting steel.

II. TOOL LIFE VERSUS RAKE ANGLE (TURNING)
(High-Speed Steel Tools)

The purpose of this study was to determine the influence of the side rake angle on tool life when turning titanium grades RC-110A and 3Al-5Cr. A previous study of this nature was reported for SAE 1045 steel, 304 stainless steel, RC-130B titanium, and Ti-150A titanium in Report No. 3, and on titanium grades Ti-75A and RC-130A in Report No. 26.

TEST CONDITIONS

All tests were conducted on a 14-inch-swing Monarch engine lathe equipped with a variable-speed drive. Cutting tools of the 18-4-1 high-speed steel type, manufactured by the Firth Sterling Steel Company under the trade name "Blue Chip", were ground to the ASA signature 0, variable, 6, 6, 6, 15, 0.010.

The size of cut was constant, consisting of a depth of cut of 0.050 inch and feed of 0.006 ipr. All tests were run without the use of cutting fluids.

PROCEDURE

A typical tool-life line was obtained with tools having side rake angles of 24 degrees. The velocity that would produce a 60-minute tool life (V_{60}) was then selected from this line. Cutting tools with side rake angles of 8, 16, 28, and 32 degrees were each tested at this cutting speed (V_{60}), and the tool lives that resulted were then plotted as a function of the side rake angle. A curve of this type indicates an optimum range of rake angles with respect to tool life. This procedure was followed for both grades of titanium, RC-110A and 3Al-5Cr.

TEST RESULTS

Figure 1 is a plot of the tool life in minutes at each side rake angle when turning RC-110A titanium at a cutting speed of 50 feet per minute. This cutting speed was used for comparison since it produced a tool life of 60 minutes with the most favorable side rake angle of 24 degrees. Other rake angles used were 8, 16, 28, and 32 degrees.

Figure 2 is a similar curve that shows the plot of side rake angle versus tool life when turning the 3Al-5Cr titanium alloy at a cutting speed of 46.5 fpm. Selection of this speed was based on the same reasoning expressed above.

These curves are quite similar to the ones previously obtained for the other grades of titanium, type 304 stainless steel and SAE 1045 steel. For all materials, the optimum side rake angle was in the range of +24 to +32 degrees.

Table I summarizes the cutting speed for a 60-minute tool life (V_{60}) for all the materials tested to date. These speeds are based on the optimum side rake angle for each material. Reports 3 and 26 contain the results listed in this table for all materials except the RC-110A and 3Al-5Cr grades of titanium.

TABLE I

CUTTING SPEED (V_{60}) FOR A 1-HOUR TOOL LIFE
AT MINIMUM RAKE ANGLE*

Material	Optimum Rake Angle, °	V_{60}, fpm	V_{60}, %
SAE 1045 steel	+32	187	100
Ti-75A	+24	124	66
304 Stainless Steel	+28	99	53
RC-130A	+28	80	43
Ti-150A	+32	74	39
RC-110A	+24	50	27
RC-130B	+32	48	26
3Al-5Cr	+24	46.5	25

*Feed is 0.006 ipr and depth of cut is 0.050 inch.

CONCLUSIONS

1. Optimum side rake angles for all materials tested fall in the range of 24 to 32 degrees.

2. Smaller rake angles (15 to 20 degrees) are recommended to prevent chipping or spalling of the cutting edge when cutting is done in less rigid machines.

III. TOOL LIFE VERSUS FEED RATE (TURNING)

The work covered in this section is a supplement to Report No. 4 and concerns the effect of feed rate on tool life when turning titanium RC-110A and the 3Al-5Cr alloys. Some of the results listed in the tables were actually obtained during the study covered in the aforementioned report and are included herein to permit comparisons of all work materials tested to date.

TEST CONDITIONS

Cutting tools of the 18-4-1 high-speed steel type, manufactured by the Firth Sterling Steel Company under the trade name of "Blue Chip", were ground to conform to the ASA signature 0, 24, 6, 6, 6, 15, 0.010. The side rake angle of 24 degrees was selected for these tests since it proved to be in the region of optimum rake angle in another study of the titanium alloys RC-110A and 3Al-5Cr.

A variable-feed series of tests was conducted on each alloy. This consisted of holding the depth of cut constant at 0.050 inch and obtaining a tool life curve for each of three feeds, 0.003, 0.006, and 0.012 ipr.

All tests were performed on a 14- x 30-inch Monarch engine lathe equipped with a variable-speed drive. No cutting fluid was used.

TEST RESULTS

The tool-life lines obtained for each combination of feed and work material are shown in Figs. 3 and 4, with the test points included. From these figures, the cutting speed for a 10-minute tool life (V_{10}) was plotted as a function of feed rate on logarithmic coordinates and these results are shown in Figs. 5 and 6. The cutting speed for a 60-minute tool life (V_{60}) was handled in a similar manner and these results are shown in Figs. 7 and 8.

As seen in Figs. 5 through 8, the selected reference speeds may be represented by straight lines and each line defined by an equation of the form $V_x = K_x f^a$ where V_x is the velocity for a particular tool life in feet per minute, K is a proportionality constant, f is the feed in inches per revolution, and "a" is the slope of the line.

Tables I and II summarize the equations for V_{10} and V_{60} as functions of the feed. Values of K and "a" previously derived for titanium grades RC-130B, RC-130A, Ti-75A, and Ti-150A, type 304 stainless steel, and SAE 1045 steel are also included in Tables II and III. These values were previously recorded in Report Nos. 4 and 26.

TABLE II

SUMMARY OF THE EFFECT OF FEED RATE ON CUTTING SPEED FOR TOOL LIFE, 10 MINUTES*

Work Material	$V_{10} = K_{10}f^a$		when f = 0.010 ipr	
	K_{10}	a	V_{10},fpm	V_{10},%
3Al-5Cr Titanium	1.44	-.70	35.5	25.1
RC-110A Titanium	3.35	-.54	40.5	28.6
RC-130B Titanium	2.51	-.61	41.5	29.3
Ti-150A Titanium	3.13	-.63	55.7	39.4
RC-130A Titanium	3.70	-.62	64.0	45.3
304 Stainless Steel	11.85	-.44	88.7	62.6
Ti-75A Titanium	17.40	-.42	122.0	86.4
SAE 1045 Steel	7.95	-.63	141.5	100.0

*Depth of cut is constant at 0.050 inch.

TABLE III

SUMMARY OF THE EFFECT OF FEED RATE ON CUTTING SPEED FOR TOOL LIFE, 60 MINUTES*

Work Material	$V_{60} = K_{60}f^a$		when f = 0.010 ipr	
	K_{60}	a	V_{60},fpm	V_{60},%
3Al-5Cr Titanium	1.30	-.70	32.5	25.4
RC-110A Titanium	3.10	-.54	37.4	29.2
RC-130B Titanium	2.36	-.60	37.8	29.6
Ti-150A Titanium	2.73	-.62	47.0	36.7
RC-130A Titanium	4.03	-.58	57.0	44.5
304 Stainless Steel	11.35	-.415	77.0	60.0
Ti-75A Titanium	12.70	-.45	100.0	78.2
SAE 1045 Steel	7.10	-.63	128.0	100.0

*Depth of cut is constant at 0.050 inch.

The equations listed in tables II and III are applicable only to the optimum rake angles used in this study. These angles (side rake) were +28 degrees for RC-130A titanium and type 304 stainless steel, +32 degrees for titanium grades RC-130B, and Ti-150A, and SAE 1045 steel, and +24 degrees for titanium grades RC-110A, Ti-75A, and the 3Al-5Cr alloy. The sensitivity to change in feed rate would be substantially the same at all practical rake angles.

CONCLUSIONS

1. The sensitivity of cutting speed to changes in feed is less than linear for all materials tested.

2. The sensitivity of cutting speed to changes in feed seems to be greater for the alloys of titanium than for the commercially pure titanium.

IV. THE EFFECT OF CUTTING FLUID ON TOOL LIFE

A solution of 5% sodium nitrite and 95% water proved to be the most effective cutting fluid for improving tool life for all previous grades of titanium. This fluid was selected for tests on titanium grade RC-110A and the 3Al-5Cr alloy. Dry-cutting again served as a basis for rating the effectiveness of the fluid.

TEST CONDITIONS

Cutting tools of 18-4-1 high-speed steel, made by the Firth Sterling Steel Company and known by the trade name, "Blue Chip", were ground to the ASA tool signature of 0, 24, 6, 6, 6, 15, 0.010. A feed of 0.006 ipr and depth of cut of 0.050 inch were held constant.

A 14- x 30-inch Monarch engine lathe equipped with a variable-speed drive was used for these tests. Work specimens were mounted between a 4-jaw independent chuck on the spindle and a live center in the tailstock. The 3Al-5Cr titanium specimens were 3 inches in diameter, while the grade RC-110A was in the form of 4-inch square bars, necessitating a "turning down" operation before testing.

TEST RESULTS

Conventional cutting-speed tool-life tests were conducted on both grades of titanium for dry-cutting and with a cutting fluid consisting of of 5% sodium nitrite and 95% water (weight ratio). The resulting test points were plotted on logarithmic coordinates as shown in Figs. 9 and 10. The basis used for evaluating the effectiveness of the cutting fluid was to select a particular tool life and determine the percent increase of cutting speed afforded by the cutting fluid as compared to dry-cutting. To be consistent with the previous tests, a standard tool life of 10 minutes was selected again. Using dry-cutting as a basis of 100%, this would give the sodium nitrite solution a rating of 153% on the 3Al-5Cr alloy, and a rating of 137% on the RC-110A alloy.

Table IV includes the results of the above comparisions and also indicates the values of the exponent and constant for the tool-life equation $VT^n = C$ which defines tool-life lines in Figs. 9 and 10. Similar information is given for all grades of titanium that were tested previously plus hot-rolled SAE 1045 steel. These are included in Report No. 12 and are entered in this report merely to summarize all results in one table.

TABLE IV

EFFECTIVENESS OF SODIUM NITRITE
CUTTING FLUID ON TITANIUM ALLOYS

Work Material	Cutting Fluid	$VT^n = C$ n	 C	V_{10} fpm	 %
Ti-75A	Dry	.09	180	146	100
Ti-75A	$NaNO_2$	.13	260	194	133
RC-130A	Dry	.10	110	88	100
RC-130A	$NaNO_2$	.09	147	121	138
Ti-150A	Dry	.07	91	78.5	100
Ti-150A	$NaNO_2$	.10	122	96	122
RC-130B	Dry	.05	64	57	100
RC-130B	$NaNO_2$	.06	91	80	140
SAE 1045 Steel (H.R.)	Dry	.04	218	200	100
SAE 1045 Steel (H.R.)	$NaNO_2$	.05	295	260	130
RC-110A	Dry	.05	62	55	100
RC-110A	$NaNO_2$	.05	84	75.5	137
3Al-5Cr	Dry	.05	57	51	100
3Al-5Cr	$NaNO_2$	.07	92	78	153

It will be noted that the sodium nitrite gave an increase in cutting speed of 37% for the RC-110A alloy; this falls between the extremes determined for the grades of titanium tested previously. A 53% increase was with the same fluid on the 3Al-5Cr alloy; this is the greatest increase obtained in the entire study. An explanation for this is readily apparent since it was found that the cutting temperatures that result when turning the 3Al-5Cr alloy were much higher than those that prevailed with any of the other types of titanium. It would follow that the effectiveness of a coolant would be augmented at higher cutting temperatures.

CONCLUSIONS

1. A solution consisting of 5% (by weight) crystalline sodium nitrite and 95% (by weight) water is an effective and practical cutting fluid for machining RC-110A and 3Al-5Cr alloys of titanium.

2. Cutting speeds for the same tool life may be increased over those for dry-cutting by from 22 to 53% depending on the titanium alloy.

3. The use of sodium nitrite solution at the same speed as dry-cutting can be expected to produce a tool life from ten to twenty times as great.

V. CUTTING FORCES AND POWER

Information regarding the magnitude and behavior of the forces that result when machining materials provided a means for evaluating power requirements and may be used to determine the cutting efficiency from a power viewpoint. A comparison of rigidity requirements can also be made. This study was conducted for the purpose of comparing the forces that result when turning six grades of titanium and hot-rolled SAE 1045 steel.

MATERIALS TESTED

Materials used were hot-rolled SAE 1045 steel and titanium grades Ti-75A, Ti-150A, RC-130A, RC-130B, RC-110A, and the 3Al-5Cr alloy.

TEST CONDITIONS

High-speed-steel tools, marketed by the Bethlehem Steel Company under the trade name "Bethlehem 66", were ground to the ASA signature 0, variable, 6, 6, 2, 0, 0, where values of 0, 8, 16, and 24 degrees were used for the variable side rake angles. The cutting velocity was 15 fpm for all tests, and the depth of cut was held constant at 0.050 inch. Feed rates of 0.003, 0.006, 0.009, and 0.012 ipr were used for the four side rake angles. All tests were run without cutting fluid and at a surface speed of 15 fpm.

PROCEDURE

Work materials in the form of 3-inch-diameter test logs were mounted in a 14- x 30-inch Monarch engine lathe equipped with a variable-speed drive. A cutting tool was mounted in the cutting force dynamometer which served as a tool holder. As cutting progressed, the forces were recorded continuously on charts.

TEST RESULTS

Values of cutting force (F_c) and feeding force (F_f), for each combination of rake angle and work material, were plotted on logarithmic coordinates as a function of the feed rate. Both forces varied with the feed in a straight-line relationship that could be described by an equation of the form $y = Cx^n$, where y is the dependent variable (cutting or feeding force), C is a proportionality constant, x is the independent variable (feed rate), and n is the slope of the straight line. The equations for the forces are given as $F_c = Cf^a$ and $F_f = Kf^b$ where values of "a" and "b" are the slopes of the lines and C and K are constants.

No curves are reported for this information since it can be expressed reliably with equations. The appropriate constants and exponents for all test conditions are summarized in Table V. In addition, the last four columns give actual forces and unit horsepower for convenient comparison of materials. The forces are for a cut 0.050 inch deep at a feed rate of 0.010 ipr.

TABLE V

SUMMARY OF CUTTING FORCE AND POWER DATA

Work Material	Side Rake Angle, Degrees	Cutting Force* $F_c = Cf^a$		Feeding Force* $F_f = Kf^b$		F_c,** lb	F_f,** lb	Unit HP_c**	Avg. Unit HP_c**
		a	C	b	K				
SAE 1045 Steel	0	1.00	20,700	0.84	4,780	207	100	1.04	0.86
	8	1.00	18,000	0.76	2,560	180	78	0.91	
	16	1.02	16,700	0.71	1,530	151	58	0.76	
	24	1.03	16,400	0.60	660	143	42	0.72	
Titanium Ti-150A	0	0.93	12,900	0.69	2,200	178	92	0.90	1.03
	8	1.03	20,900	0.70	1,770	183	70	0.93	
	16	1.09	33,400	0.75	1,540	221	50	1.11	
	24	1.09	35,500	0.77	1,350	235	38	1.18	
Titanium RC-130A	0	1.00	16,600	0.75	2,780	166	90	0.84	0.70
	8	1.00	14,700	0.69	1,520	147	63	0.74	
	16	1.03	14,500	0.69	1,030	126	43	0.64	
	24	1.10	18,000	0.66	580	114	28	0.58	
Titanium RC-130B	0	0.95	12,900	0.71	2,150	163	82	0.82	0.71
	8	0.97	12,900	0.73	2,100	148	73	0.75	
	16	0.98	12,100	0.76	1,980	133	60	0.67	
	24	1.00	12,000	0.78	1,380	120	38	0.61	
Titanium Ti-75A	0	0.98	13,600	0.66	1,790	150	85	0.76	0.71
	8	1.05	16,700	0.70	1,560	133	62	0.67	
	16	1.09	18,000	0.71	985	120	38	0.60	
	24	1.09	17,600	0.72	825	117	30	0.59	
Titanium 3Al-5Cr	0	0.99	14,600	0.80	2,800	154	70	0.78	0.64
	8	1.05	16,700	0.80	2,100	132	53	0.66	
	16	1.11	19,100	0.80	1,400	116	35	0.58	
	24	1.14	20,500	0.83	1,360	108	30	0.54	
Titanium RC-110A	0	1.10	23,900	1.03	9,070	151	79	0.76	0.63
	8	1.03	15,700	0.85	3,040	137	60	0.69	
	16	1.03	12,600	0.75	1,320	110	44	0.53	
	24	0.98	9,340	--	--	103	--	0.517	

* Depth of cut constant at 0.050 inch and feed rate between range of 0.003 and 0.012 ipr.

** Values calculated for depth of cut of 0.050 inch and a feed rate of 0.010ipr.

CONCLUSIONS

1. Both the tangential and feeding forces produced when turning the six grades of titanium and SAE 1045 steel show an orderly, mathematical relationship with changes in feed rate.

2. In practically all cases, the cutting force, F_c, varied linearly (on the average) with feed, while the feeding force, F_f, varies less than linearly with the feed rate.

3. In general, hot-rolled SAE 1045 steel produces higher cutting and feeding forces in turning than any of the grades of titanium.

4. The cutting force F_c can be predicted reliably for any size of cut and tool shape from the average unit horsepower (last column in Table V).

5. Previous studies have indicated that cutting forces vary linearly for all depths of cut on all types of metals.

VI. CUTTING TEMPERATURES

It is known that tool life is strongly dependent on cutting temperature; the smaller the slope of the tool-life curve (see Report No. 3), the greater this dependency. Thus there will be an inverse relationship between cutting speed for a fixed tool life and cutting temperature at constant cutting speed for a range of work materials. The purpose of this study was to extend that relationship to include these two titanium alloys with those reported previously in Report No. 16. Continuous turning cuts were made over ranges of feed rate and depth of cut.

TEST CONDITIONS

Molybdenum high-speed tools, made by Bethlehem Steel Company, type 66, were used for all tests.

All tool shapes conformed to the ASA signature 0, 32, 6, 6, 6, 15, 0.010. A constant cutting velocity of 25 fpm was used for all tests. One series of tests was run with a constant feed of 0.006 ipr, while the depth of cut was varied in steps of 0.010, 0.025, 0.050, 0.100, and 0.150 inch. The second series of tests was run with a constant depth of cut (0.050 inch), while the feed was varied in steps at 0.006, 0.009, 0.012, and 0.015 ipr. A special toolholder made of laminated plastic was used to insulate the tool from the lathe. A 14-inch-swing Monarch lathe equipped with a variable-speed drive was used in all tests. Work materials were in the form of 3-inch-diameter bars except SAE 1045 steel, which has a 4-inch diameter. One end of these bars was mounted in a 4-jaw chuck and the other end held against a live center. All tests were run without a cutting fluid.

PROCEDURE

Essentially the same procedure was employed as in previous tests (see Report No. 16) with the exception that contact potentials were determined using a Leeds and Northrup Speedomax high-speed recording potentiometer. Since the temperatures were much higher than those previously measured, check runs were made on the SAE 1045 steel and the tool-work thermocouples were recalibrated to insure a maximum degree of accuracy.

TEST RESULTS

The test data for all materials included in this program are plotted in Figs. 11 through 13. Figure 12 shows the results obtained at depths of cut from 0.010 to 0.150 inch; larger depths increased the temperature only slightly. Figure 12 shows that there was a greater sensitivity to increases in chip thickness of feed rate.

Figure 13 is the curve resulting from plotting the cutting speed, V_{60}, for a 1-hour tool life as determined previously against the temperature at a constant cutting speed of 25 fpm. The tool shape and size of cut were identical for both the tool life and the cutting temperature tests.

The data plotted in Fig. 13 are summarized in Table VI. It will be noted that the 3Al-5Cr titanium alloy showed markedly higher cutting temperatures than any of the grades previously tested, the temperature being in the range of 1000°F as compared to 800°F for the next highest cutting temperature encountered (RC-110A).

Both the 3Al-5Cr alloy and the RC-110A fit the correlation previously indicated between tool life and cutting temperatures. Titanium alloy RC-130B is exception to this correlation.

TABLE VI

A COMPARISON OF CUTTING SPEED V_{60} FOR A 1-HOUR TOOL LIFE WITH CUTTING TEMPERATURE AT 25 FPM

Work Material	Cutting Speed V_{60fpm}	Cutting Temperature, °F
3Al-5Cr	46.5	965
RC-130B	48	552
RC-110A	50.0	800
Ti-150A	74	645
RC-130A	80	590
304 Stainless Steel	99	455
Ti-75A	124	400
SAE 1045 Steel	187	367

This table is a comparison of cutting temperatures and cutting speeds for a 1-hour tool life, with a feed of 0.006 ipr and depth of cut of 0.050 inch.

The effect of a coolant-type cutting fluid such as sodium nitrite in increasing tool life bears a direct relationship to the high cutting temperatures noted.

CONCLUSIONS

1. The cutting temperatures measured (under identical test conditions) is markedly higher for the 3Al-5Cr alloy than for any of the other titanium alloys previously measured.

2. The rate of tool wear is influenced to a large degree by the high temperatures encountered and anything which reduces the temperature (such as a coolant-type cutting fluid) or makes the tool less susceptible to thermal failures will increase tool life.

3. The basic causes for the high cutting temperatures encountered have not been found. However, they may be related to the thermal conductivity, density, and specific heat as well as the microstructure of the alloy.

4. The relative cutting speeds to be used for different metals can be predicted from cutting temperature.

VII. CONVENTIONAL DRILLING

The object of the tests on the two titanium alloys, RC-110A and 3Al-5Cr, was to determine the torque thrust and unit horsepower variations as affected by speed, feed, and drill diameter and to correlate and compare them to similar values found for the previously tested titanium alloys.

PROCEDURE

These tests were run on the same equipment and under the same conditions as the previous tests described in Report No. 20. The drills used were standard high-speed-steel jobber drills with an oxide surface treatment. The drill diameters were 1/4; 3/8; 1/2 and 1 inch. The feeds used were 0.004, 0.006, 0.009, 0.014, and 0.021 ipr. The cutting speed was kept constant at approximately 25 fpm for the various drill sizes. The torque and thrust were measured with an electrical strainage dynamometer recorded continuously on charts.

RESULTS

Figures 14 and 15 are summary curves showing the torque and thrust values vs feed and diameter on all materials run, including those previously tested and recorded in Report No. 20. Figures 16 and 17, and 18 and 19 are the individual curves of torque and thrust vs feed and drill diameter for the alloys 3Al-5Cr and RC-110A, respectively.

Figure 20 is a summary of all pertinent information gained from this study. It includes the exponents and constants for the torque and thrust equations applicable to each material. In addition, the last three columns record calculated values of torque, thrust, and unit horsepower for a 1/2-inch-diameter drill used at a feed of 0.009 ipr. All values are conservatively high, particularly for titanium. Experience subsequent to these tests indicates that lower speed and the use of sulfurized oil will reduce both the torque and thrust. Variations in drill point grinding will also affect the level of forces.

CONCLUSIONS

1. The 3Al-5Cr titanium alloy is comparable to Ti-150A titanium and to hot-rolled SAE 1045 steel in the drilling force requirements.

2. RC-110A titanium also is comparable to hot-rolled SAE 1045 steel as to torque and thrust requirements.

3. RC-130B is outstandingly more difficult to drill than all the other titanium alloys tested.

4. All titanium alloys must be drilled at substantially lower cutting speeds than can be used for hot-rolled SAE 1045 steel. Otherwise, tool life is greatly reduced and cutting forces will increase substantially.

VIII. DEEP-HOLE DRILLING OF RC-110A TITANIUM

The more extensive tests reported in Report No. 21 revealed desirable operating conditions for deep-hole drilling of titanium. These favorable conditions were tried with RC-110A titanium alloy with satisfactory results. Two different drill designs and two different hardnesses of tungsten carbide were included in the test variables.

PROCEDURE

Four samples of 1-inch round stock 6 inches long were drilled with four different 1/2-inch-diameter drills as follows:

Carboloy 883 carbide-tipped, conventional center-cut drill
Carboloy 883 carbide-tipped, trepanning target drill
Carboloy 905 carbide-tipped, conventional center-cut drill
Carboloy 905 carbide-tipped, trepanning target drill

The speed was kept constant at 1065 rpm or 139.6 fpm. The feed used was 0.005 ipr. The other test conditions and equipment used were identical with those in Report No. 21.

RESULTS

The results of the four test runs on RC-110A are summarized in the following table:

TABLE VII

SUMMARY OF OBSERVATIONS

Test No.	Drill Design	uHP_c	Tool Wear Flank Wear	Tool Wear Drill Appearance	Hole Appearance
1	883 center cut	2.58	<.002	Slight amount of pickup on land.	Large amount of rough spots due to chip interference.
2	883 target	2.18	<.003	Chip on point is 0.010" along face, 0.018" wide, and 0.005" deep.	Good, fairly smooth hole.
3	905 center cut	2.77	<.003	Chip on point is 0.010 along face, 0.015" wide, and 0.005" deep.	Three large areas of rough run due to chip interference.
4	905 target	1.80	<.002	3-4 small chips out of the face of the carbide along the cutting edge 0.004 long, 0.006 wide, and 0.002 deep, approximately.	Good, fairly smooth hole,

Test Conditions were as follows:

material cut: RC-110A
oil pressure: 600 psi
oil: Stanoil No. 75
feed: 0.0005 ipr
speed: 1065 rpm or 139.6 fpm
length of hole: 6 inches (time of cut = 11.3 minutes)

The tool wear was measured on the flank of the tool below the cutting edge. The unit horsepower was calculated from the power consumption as recorded on the wattmeter. The hole appearance was judged after the specimen had been milled so as to expose the length of the hole.

The total input power was recorded continuously during all tests. These records indicated that the standard design, center-cut drill caused power surges of more than 200% while the trepanning-type target drill never deviated from the mean by more than 15% and remained within ± 5% most of the time. The power surges were caused both by chip-rubbing in the flute and by seizure of the drill on the wall of the hole.

Visual observations and tool-wear measurements appeared to favor the harder grade of carbide as a tool material for this operation. However, some difficulty was experienced with spalling or "chipping" with both grades, generally it is worse with harder grades.

CONCLUSIONS

1. Titanium alloy RC-110A can be deep-hole drilled successfully and economically.

2. Trepanning-type deep-hole drills give distinctly improved performance over standard center-cut drills.

IX. FACE-MILLING 3Al-5Cr AND RC-110A ALLOYS

The objective of this study has been to compare the cutting-speed—tool-life relationships of 3Al-5Cr and RC-110A titanium alloys with other titanium and ferrous alloys in controlled laboratory tests.

The results of these tests indicate, with a good degree of certainty, the tool-life—cutting-speed relationships which might be expected in typical, commercial face-milling applications (see also Report Nos. 23a, b, c, and d).

Both high-speed steel and sintered-carbide cutting tools were used under conditions previously found to be most satisfactory for these materials. Using high-speed steel, face-milling cutters the 3Al-5Cr titanium alloy was found to be intermediate between Ti-150A and RC-130B alloys. Cutting speeds ranged from approximately 48 fpm for a 1-minute tool life to 33 fpm for a 30-minute tool life under the cutting conditions used. The RC-110A gave results similar to those previously reported for Ti-150A and the two curves are coincidental.

The 3Al-5Cr and RC-110A alloys were face-milled with sintered-carbide cutting tools at the higher speeds used in the previous program, and the results indicate a range of 1000 fpm for a 1-minute tool life to 430 fpm for a 30-minute tool life for the 3Al-5Cr alloy as compared to a range of 1115 fpm for a 1-minute tool life to 446 fpm for a 30-minute tool life with the RC-110A alloy. These materials allow higher cutting speeds for a given tool life than the Ti-150B material originally reported, but are lower than either Ti-150A or RC-130B in this factor.

EQUIPMENT

The same Kearney-Trecker 5-HM milling machine was used for these as in other face-milling tests (see Report Nos. 23a, b, c and d). Single-tooth face-milling cutters of 9 inches and 4 inches were used with sintered-carbide Grade 883 and Mo-Max high-speed-steel tools. The bar width was 3 inches for the 3Al-5Cr and 4 inches for the RC-110A; the bar was positioned on the center line of the cutter.

The single-tooth cutter was used to conserve metal and tool shapes and was ground to the following signature:

Mo-Max high-speed steel:
- axial rake angle, 7°
- radial rake angle, 4°
- face relief angle, 6°
- peripheral relief, 6°
- face-cutting edge angle, 2°
- peripheral cutting edge angle, 0°
- champer, 0.070 inch wide x 45°

Grade 883 carbide tools:
- 0
- 0
- 12N
- 12N
- 2
- 45°

PROCEDURE

The cutting-speed tool-life tests were run at varying speeds using the procedure described in Report No. 23a and the recommended feeds reported in Report No. 23d.

Tool wear was measured at frequent intervals and plotted. The tool was considered to have failed when the wear land on the flank of the tool reached 0.030 inch.

Constant conditions were as follows:

high-speed steel:
depth of cut, 0.100 inch
cutting fluid, none
feed, 0.010 inch per tooth

sintered carbide:
depth of cut, 0.100 inch
cutting fluid, none
feed, 0.002 inch per tooth

The tool-life time reported in machine-cutting time corrected for tool contact with a 4-inch bar mounted on the center line of the cutter.

RESULTS

The types of failures encountered were very familiar to those reported previously and shown in previous photographs. Cratering of the high-speed steel near the cutting edge was found in all failures. Chipping of the carbide tools was not encountered (except for accidental chipping due to stopping the cutter in contact with the workpiece).

The results of the tests (Fig. 21 for high-speed steel [HSS] and Fig. 22 for carbides) show the following:

Alloy	Tool	Tested Feed	Cutting Speed 60-Min Life	Cutting Speed 100-Min Life
3Al-5Cr	HSS	.010 ipt	33.5 fpm	29.5 fpm
	Carbide	.002 ipt	360.0 fpm	315.0 fpm
RC-110A	HSS	.010 ipt	38.5 fpm	36.6 fpm
	Carbide	.002 ipt	371.0 fpm	324.0 fpm

CONCLUSIONS

1. The results of tests on 3Al-5Cr and RC-110A with Mo-Max high-speed-steel tools show the RC-110A identical to Ti-150A and the 3Al-5Cr alloy between Ti-150A and RC-130B in performance. The slopes of the cutting-speed—tool-life curves are similar to those originally reported for the other alloys.

2. The results of tests with carbide tools indicate that RC-110A can be milled at slightly higher cutting speeds than the 3Al-5Cr alloy and the flank-wear rate is less for both materials than the results previously reported for Ti-150A.

X. SURFACE BROACHING

This investigation supplements the work reported earlier in Report No. 10. Broaching tests were conducted on the 3Al-5Cr and RC-110A alloys at the most favorable conditions revealed in the earlier work. This permits comparison with the other alloys whose machining properties are already well known. The results show that both the 3Al-5Cr and the RC-110A alloys can be broached with little difficulty.

PROCEDURE

Blocks of each alloy, 1 x 2 x 2 inches in size, were prepared as work specimens. These in turn were mounted in a suitable work fixture. The cutting tools consisted of 6-tooth cutters, 1 inch wide with 0.002 inch rise per tooth ground to 5° rake, 5° relief angle, and 0° helix; the cutter teeth were spaced 1/2 inch apart. "Circle-C" high-speed steel was used as the tool material.

All test cuts were made without the aid of cutting fluid and at a constant cutting speed of 20 fpm. An American 6T-6-24 vertical broaching machine was used for all tests. A pressure-sensitive pickup and recording device was used to monitor and record the cutting force continuously during tests. Surface roughness measurements of the machined surface were made at regular intervals. One hundred fifty cuts were made at each test condition.

RESULTS

Cutting force and surface finish data for the 3Al-5Cr alloy are shown plotted in Figs. 23 and 24, respectively. Similar data for the RC-110A alloy are shown in Figs. 25 and 26.

Table VIII summarizes the pertinent results of the study by giving a comparison of unit-power cutting force at test conditions, and range of surface roughness for all materials studied in this program. It will be noted that the additional alloys compare favorably with all those tested previously. Only the RC-130B gave better surface finish and only Ti-75A required less power.

TABLE VIII

SUMMARY OF POWER REQUIREMENTS AND SURFACE FINISH IN SURFACE BROACHING

Material	Tool Rise per Tooth, Inches	Unit HP_c	Cutting Force Avg. for 150 Cuts	Surface Finish Range for 150 Cuts
SAE 1045	.002	1.291	4,090	115-135
	.005	1.305	10,360	100-150
Ti-75A	.002	1.205	3,820	13-23
	.005	1.144	9,080	10.5-14
Ti-150A	.002	1.814	5,750	19-28
	.005	1.298	10,300	32.5-50
Ti-150B	.002	1.825	5,780	11.5-13.5
	.005	1.868	14,820*	37**
RC-130B	.002	1.64	5,190	6-11
	.005	1.023	8,120	7.5-14.5
3Al-5Cr	.002	1.27	4,015	15-20
RC-110A	.002	1.20	3,800	15-17

* Three cuts only
** First cut

The use of a cutting fluid could be expected to reduce the power requirements appreciably and to increase tool life substantially. In many respects, the titanium alloys are easier to broach than hot-rolled SAE 1045 steel; this is especially applicable to behavior in connection with surface finish, chip formation, and power requirements.

CONCLUSIONS

1. Like the other alloys of titanium studied in this program, RC-110A and the 3Al-5Cr alloy can be broached as readily as hot-rolled SAE 1045 steel, providing that the relief angle is of the magnitude 5°.

2. A cutting speed of 20 fpm will yield economically long tool life.

3. The rise per tooth or chip thickness should not exceed about 0.002 inch.

XI. BAND SAWING

The results of band-sawing tests on 3Al-5Cr and RC-110A titanium alloys are included in this report to supplement the original Report No. 11 of June, 1953.

All conditions of machine, cutting speed, feed rate, blade geometry, and force dynamometer were repeated in this work according to the specifications of the preceding report.

PROCEDURE

Bars of 3Al-5Cr and RC-110A titanium, 1-inch thick by 2 inches wide by 4 inches long, were band-sawed at cutting speeds of 52 and 77 fpm and feeds of 80, 100, 120, 200, and 300 x 10^{-6} inches per tooth (ipt) with a 6-pitch, 3/4-inch wide, Simonds "hard-edge" band. Power feeds were obtained by the special drive mechanism discussed in the original report and the two-component tool dynamometer in combination with the 2-channel Sanborn recorder-oscillograph were used in measuring the cutting and feeding forces.

Tests were conducted by sawing 1-inch thick titanium alloy bars, until the feeding force reached a value of 100 pounds, which was again used in the definition of tool life.

RESULTS

Figures 27 and 28 show the values of feeding force in pounds as ordinate vs time in minutes as abscissa for the 3Al-5Cr and RC-110A alloys, respectively. On each of the materials, the higher speeds of 77 fpm and the higher feed rates of 100 to 200 x 10^{-6} ipt gave relatively short tool life. The tool life as defined by the attainment of 100-pound feeding force was higher for the RC-110A than for the 3Al-5Cr at 52 fpm and each of two feeds 80 x 10^{-6} and 100 x 10^{-6}, the value for the former on RC-110A being 38.7 minutes tool life as compared to 14 minutes tool life for the 3Al-5Cr at 80 x 10^{-6} feed (condition No. 6 listed on each graph). At 120 x 10^{-6} feed rate and 52 fpm, the RC-110A gave 20.6 minutes tool life as compared to 12.1 tool life for the 3Al-5Cr material shown (item No. 5 on each of these figures).

Figures 29 and 30 show the results of cutting-speed—tool-life tests on the two materials with cutting speed plotted as ordinate and tool life in minutes as abscissa. The slopes of the curves are steeper at the light feed rate of 80 microinches than for the heavier feed of 120 microinches with values of 0.203 for RC-110A and 0.225 for the 3Al-5Cr at the former feed as compared to 0.189 for the RC-110A and 0.1415 for the 3Al-5Cr at the latter feed rate. The values of height of the curve are very similar for the two materials indicating that they react very similarly in the cutting-speed—tool-life relation.

Figures 31 and 32 show the square inches of material cut vs the feed rate x 10^{-6} ipt at cutting speeds of 52 and 77 fpm. The values obtained for the areas of cut on these two materials are definitely above those originally reported for RC-130B but are lower than those reported for Ti-75A, RC-130A, and Ti-150A alloys.

Figures 33 and 34 show the results of tests on cutting force and feeding force in the band-sawing operation with each of the forces plotted vs feed rate x 10^{-6} ipt. The curves indicate the same general relationship for each of the two materials with feeding force higher than cutting force in each case. In Fig. 33, the cutting force is approximately 67 to 72% of the feeding force for the 3Al-5Cr material and for the RC-110A (Fig. 34) the cutting force ranges from 73 to 78% of the feeding force.

Figures 35 and 36 show the same plots on logarithmic coordinates as were given in the preceding figures on cartesian coordinates with the same general indication of results originally listed.

Table IX gives the computed velocities for a 60-minute tool life at feeds of 80 and 120 x 10^{-6} ipt. This table was given as Table I in the original report, but it now includes the two new alloys, 3Al-5Cr and RC-110A. The velocity for a 60-minute tool life is of the same magnitude as that for the RC-130B at the 80 x 10^{-6} feed. However, it is higher for each of the materials at the heavier feed of 120 x 10^{-6} and closely approaches the results shown for Ti-150A.

TABLE IX

CUTTING SPEEDS (FPM) FOR 60-MINUTE TOOL LIFE AT 80-AND 120-MICROINCH FEEDS

Material	$f = 80 \times 10^{-6}$ ipt		$f = 120 \times 10^{-6}$ ipt	
	Velocity	SAE 1045 Value, %	Velocity	SAE 1045 Value, %
SAE 1045	218	100	197	100
Ti-75A	98	45	85	43
Ti-130A	70	32	59	30
Ti-150A	65	30	51	26
RC-130B	43	20	35	18
3Al-5Cr	44	20	46	23
RC-110A	47.4	22	42.4	21.5

Table X lists the computed values of n (slope of curve) and C (velocity for a 1-minute tool life) in the equation $VT^n = C$ for the feeds of 80 and 120 x 10^{-6} ipt. The value C, indicating the height of the curve, shows that each of the new materials 3Al-5Cr and RC-110A are higher than RC-130B, but slightly lower than Ti-150A at each of the two feeds. Each of these materials show steeper slopes, 0.225 for 3Al-5Cr and 0.203 for RC-110A, at the lower feed of 80 microinches and a lesser slope of 0.1415 for the 3Al-5Cr at 120 microinches as compared to the 0.189 slope for RC-110A (similar to the slope obtained on RC-130B in the original report).

TABLE X

VALUES OF "n" AND "C" FOR THE VARIOUS MATERIALS FOR $VT^n = C$

Material	n		C	
	f = 80 microinches	f = 120 microinches	f = 80 microinches	f = 120 microinches
SAE 1045	0.123	0.122	358	326
Ti-75A	0.153	0.142	182	151
RC-130A	0.180	0.156	140	112
Ti-150A	0.152	0.164	120	99
RC-130B	0.163	0.190	84	76
3Al-5Cr	0.225	0.1415	110	81.5
RC-110A	0.203	0.189	109	92

Table XI shows the computed values of area cut at two speeds and two feed rates with the new alloys added to the four original materials. These values were computed from curves of feed vs time on log-log plots as the area of cut for a function of feed in inches per minute and thickness of the workpiece. Results indicate that the two new alloys give larger areas of cut than the RC-130B, but lower than the other materials Ti-75A, RC-130A, and Ti-150A.

TABLE XI

AREAS OF CUT FOR THE VARIOUS MATERIALS

Material*	V = 52 fpm		V = 78 fpm	
	f = 80 micro-inches	f = 120 micro-inches	f = 80 micro-inches	f = 120 micro=inches
Ti-75A	420	294	49	21
RC-130A	42	19.9	7.2	2.4
Ti-150A	19.5	10.4	3.7	1.2
RC-130B	1.8	1.0	0.34	0.2
3Al-5Cr	2.8	3.6	.72	.33
RC-110A	3.86	3.08	.576	.377

*SAE 1045 steel not included because of excessive extrapolation at these speeds.

Table XII gives the relative values of tool life in minutes and area of cut in square inches for two speeds and two feeds from the same feed vs tool-life curves as those used in Table XI. Comparisons of these two materials with the Ti-75A are made on a percentage basis in this table.

Table XIII gives the cutting force F_{co} at 0 feed and the value of K_c from the equation $F_c = F_{co} + K_c f$, where f equals the feed rate x 10^{-6} ipt. The values of force at 0 feed for each of the two new alloys are lower than the original materials listed and the K values are of the same magnitude as Ti-75A and RC-130A.

TABLE XII

TOOL LIFE AND AREA OF CUT FOR THE VARIOUS MATERIALS

Material*	Feed Rate x 10^{-6} ipt	Tool Life				Area Cut			
		52 fpm		78 fpm		52 fpm		78 fpm	
		Minutes	Ti-75A, %	Minutes	Ti-75A, %	Square Inches	Ti-75A, %	Square Inches	Ti-75A, %
Ti-75A	80	4200	100	215	100	420	100	49	100
	120	1960	100	92	100	294	100	21	100
RC-130A	80	420	10	32	15	42	10	7.2	15
	120	133	6.8	10.8	12	20	6.8	2.4	12
Ti-150A	80	195	4.7	16.5	7.7	19.5	4.7	3.7	7.6
	120	69	3.5	5.2	5.7	10.4	3.5	1.2	5.7
RC-130B	80	17.8	.42	1.5	0.7	1.8	.42	.34	0.7
	120	6.9	.35	0.88	0.96	1.0	.35	.2	0.96
3Al-5Cr	80	28	.67	4.9	2.3	2.8	.67	.67	1.47
	120	24	1.2	1.5	1.6	3.6	1.2	.33	1.57
RC-110A	80	39	.93	5.25	2.44	3.86	.92	.576	1.18
	120	20.5	1.05	2.4	2.61	3.08	1.05	.377	1.8

* SAE 1045 steel not included because of excessive extrapolation at these speeds.

TABLE XIII

F_{co} AND K_c IN THE EQUATION $F_c = F_{co} + K_c f$*

Material	F_{co}	K_c
SAE 1045	6	0.100
Ti-75A	11.5	0.105
RC-130A	7.5	0.125
Ti-150A	12	0.130
RC-130B	15.5	0.180
3Al-5Cr	2.0	0.110
RC-110A	1.1	0.129

* F_c = force of cutting in pounds
F_{co} = initial force of cutting at 0 feed
f = feed rate x 10^{-6} ipt
V = 52 fpm

Table XIV shows the values of F_o and K_f from the equation $F_f = F_{fo} + K_f f$ where f equals the feed rate x 10^{-6} ipt, and in this case, as in Table XIII, the two new alloys show lower feeding force at 0 feed (F_{fo}) than the other titanium materials.

TABLE XIV

F_{fo} AND K_f IN THE EQUATION $F_f = F_{fo} + K_f f$*

Material	F_{fo}	K_f
SAE 1045	4	0.0425
Ti-75A	11	0.105
RC-130A	14	0.125
Ti-150A	21.5	0.130
RC-130B	33	0.195
3Al-5Cr	2.5	0.148
RC-110A	3.1	0.156

* F_f = force of feed in pounds
F_{fo} = initial force of feed in pounds at 0 feed
f = feed rate x 10^{-6} ipt
V = 52 fpm

Table XV shows the values of C_c and a slope "a" for the equation $F_c = C_c f^a$, where f is the feed rate x 10^{-6} ipt and "a" is the slope of the curves in Figs. 35 and 36. The values of the slope "a" are consistent with metal-cutting practice. C_c might be used in making predictions of the magnitude of cutting forces at conditions other than the points on the curves.

TABLE XV

C_c AND "a" IN THE EQUATION $F_c = C_c f^a$*

Material	C_c	a
SAE 1045	0.4	0.79
Ti-75A	1.07	0.65
RC-130A	0.66	0.74
Ti-150A	1.3	0.65
RC-130B	1.8	0.64
3Al-5Cr	1.94	0.91
RC-110A	1.94	0.86

* F_c = cutting force
C_c = constant
f = feed rate x 10^{-6} ipt
a = slope of curves in Figs. 35 and 36.

Table XVI shows values of C_f and the slope "b" in the equation $F_f = C_f f^b$ where f is the feed rate x 10^{-6} ipt and "b" is the slope of the curves on Fig. 21 of the original report and Figs. 35 and 36 of this Report. C_f (constant for feeding-force curve) might be used in predicting points other than those shown on the curves.

The cutting force data give higher values C_c and exponent "a" for each of the new alloys as compared to those originally reported, and the feeding forces show C_f values of the new alloys to be similar to Ti-150A and the slopes "b" to be higher than those originally reported.

TABLE XVI

C_f AND "b" IN THE EQUATION $F_f = C_f f^b$*

Material	C_f	b
SAE 1045	0.39	0.67
Ti-75A	1.05	0.65
RC-130A	1.52	0.62
Ti-150A	3.3	0.52
RC-130B	4.5	0.53
3Al-5Cr	2.56	0.914
RC-110A	2.28	0.91

* F_f = feeding force
C_f = constant for feeding force curve
f = feed rate x 10^{-6} ipt
b = slope of curves in Figs. 35 and 36.

Table XVII shows the additional information on 3Al-5Cr and RC-110A on the original table as listed.

TABLE XVII

UNIT HORSEPOWERS FOR THE VARIOUS MATERIALS

Material	F_c at f = 80	F_c at f = 320	uHP_c at 80 x 10^{-6} ipt*	uHP_c at 320 x 10^{-6} ipt**
SAE 1045	14	37.5	4.0	2.6
Ti-75A	20	44.5	5.7	4.0
RC-130A	17.5	47.5	5.0	3.5
Ti-150A	22.5	53.5	6.4	4.5
RC-130B	30	73	8.6	6.0
3Al-5Cr	11	37	3.16	2.65
RC-110A	11.6	38	3.33	2.63

$$*uHP_c(\text{at } f = 80) = \frac{F_c \times 52}{33{,}000 \times .055 \times 80 \times 10^{-6} \times 1/3 \times 72 \times 52} = 0.287\ F_c$$

$$**uHP_c(\text{at } f = 320) = \frac{F_c \times 52}{33{,}000 \times .055 \times 320 \times 10^{-6} \times 1/3 \times 72 \times 52} = 0.0692\ F_c$$

$$uHP_c = \frac{F_c \qquad V_c}{33{,}000 \text{ x } CSAII^2} \text{ x } F \text{ (in. per min)}$$

where

width of cut = 0.055 inch
thickness of pieces = 1.00 inch
V = 52 fpm

In the formula for unit horsepower,

$$\text{hp unit} = \frac{F_c \qquad V_c}{33{,}000 \text{ x } CSA \text{ (in.}^2\text{) x } f \text{ (in. per min)}},$$

the following definitions are valid:

uhp_c = horsepower per cubic inch minute
F_c = cutting force in pounds
V_c = cutting speed in feet per minute
CSA = cross-sectional area of cut in square inches
f = feed rate in inches per minute obtained from $f \times 10^{-6}$ ipt

Table XVIII shows the additional data of the two alloys in the original table of coefficient of friction for the various materials. The values of cutting and feeding forces were lower than those originally listed for the other titanium materials, but the coefficient of friction for the 3Al-5Cr is comparable to that of the Ti-75A whereas the RC-110A material shows a relatively low coefficient of friction (below any of those reported before).

TABLE XVIII

COEFFICIENT OF FRICTION FOR THE VARIOUS MATERIALS

Material	F_{co}	F_{fo}	μ*
SAE 1045	6.0	4.0	1.5
Ti-75A	11.5	11.0	1.05
RC-130A	7.5	14.0	0.54
Ti-150A	12.0	21.5	0.56
RC-130B	15.5	33.0	0.47
3Al-5Cr	2.0	2.5	0.80
RC-110A	1.1	3.1	0.355

* $\mu = \dfrac{F_{co}}{F_{fo}}$

CONCLUSIONS

1. Both of the new titanium alloys 3Al-5Cr and RC-110A are machinable by the band-sawing process. The degree of success depends on the conditions of operation.

2. 3Al-5Cr and RC-110A give a response to cutting speed for a 60-minute tool life that is similar to that obtained on the Ti-150A in the previous report.

3. Cutting speed is very critical in the band-sawing of the two new alloys.

4. Feed rate in inches per tooth is critical and positive feeds must be insured in the band-sawing of these alloys as well as the others previously reported.

5. The cutting forces of the new alloys 3Al-5Cr and RC-110A are approximately 75% of the feeding forces as measured with a two-tool dynamometer.

6. The unit-horsepower values obtained in the band-sawing of the new alloys are very similar to those that had been previously obtained and reported.

XII. SURFACE FINISH

This investigation supplements the work reported earlier in Report No. 17 of June, 1953. Turning tests were conducted on the 3Al-5Cr and RC-110A alloys at the same conditions that were used in the preceding work.

PROCEDURE

Round bars of the 3Al-5Cr and RC-110A titanium were machined in an American Pacemaker engine lathe at speeds of 50, 100, 200, 300, 400, and 500 fpm with a depth of cut of 0.025 inch and a feed of 0.015 ipr to obtain the effect of the cutting speed in fpm on the resulting surface finish in microinches, root mean square. A second series of tests was conducted with feed as the variable and the following increments of 0.005, 0.010, 0.015, and 0.020 ipr with a velocity constant at 100 fpm and depth of cut constant at 0.025 inch.

The actual tests consisted of machining a representative cylindrical surface with a newly ground tool of "905" carbide (Carboloy Company). This tool was supported in a tool holder to give a tool signature of -7° back and side rakes, 7° end and side relief, 15° end-cutting and side-cutting angles and a nose radius of 3/64 inch.

RESULTS

Figure 37 shows the original summary of the various materials included in Report No. 17 with the addition of the two alloys, 3Al-5Cr and RC-110A as indicated in the key. Except for the feed rate of 0.020 ipr on the RC-110A, the results of these two materials are very similar to those reported previously. There is an indication however that the surface finish at the fine feed rate, 0.005 ipr, on each of these two materials was slightly higher than the surface-finish readings given for the materials tested previously.

Figure 38 shows the actual data points in microinches, root mean square, obtained with a profilometer on the titanium 3Al-5Cr material. The results are typical of those normally expected in this type of operation with values ranging from 60 to 270 across the feed marks, and from 25 to 30 parallel with the feed marks.

Figure 39 shows the actual data obtained on the surface of the RC-110A material with values shown from 57 to 560 across the feed marks and 26 to 27 parallel with the feed marks.

Figure 40 shows results obtained in surface-finish microinches, root mean square, vs cutting speed in fpm. The range of values measured across the feed marks is 175 to 250 with the peak value shown at 300 fpm which is similar to the original results shown for 304 stainless steel. This form of curve varies slightly from those shown in the original report for Ti-75A and RC-130A and it gives an indication of better surface finish up to 100 fpm or between 400 to 500 fpm.

Figure 41 shows values of 190-low to 310-high microinches showing an indication of the beneficial effect of lower cutting speeds (less than 100 fpm) as preferred in obtaining the lower values of surface-finish microinches, root mean square.

Table XIX shows the original curve of the surface finish of the test materials included in Report No. 17 with the addition of values for 3Al-5Cr and RC-110A. The values listed in this table are compared directly to theoretical curve units at each of the selected feed rates.

TABLE XIX

COMPARISON OF THE SURFACE FINISH OF TEST MATERIALS* IN MICROINCHES

Feed, ipr	Theor. Curve	SAE 1045 Steel	304 Stainless Steel	Ti-75A	Ti-150A	RC-130A	RC-130B	3Al-5Cr	RC-110A
0.005	1	70	21	26	11.5	17.5	16	30	2.9
0.010	1	19.3	7	8.7	6.4	7.8	6.7	7.3	8.3
0.015	1	10	4.9	5.5	4.3	5.4	4.7	4.3	5.8
0.020	1	7	4.2	4.2	3.4	4.3	3.9	3.2	6.6

*Values used are from the theoretical curve as the unit at each selected feed rate.

TABLE XX

SURFACE ROUGHNESS IN MICROINCHES

Feed, ipr	Best Surface Possible	SAE 1045 Steel	304 Stainless Steel	Ti-75A	Ti-150A	RC-130A	RC-130B	3Al-5Cr	RC-110A
0.005	2	140	42	52	23	35	32	60	57
0.010	15	290	105	130	96	117	100	110	125
0.015	44	443	215	240	190	238	207	190	255
0.020	85	595	360	360	287	370	335	270	560

Table XX shows the original table for all materials with actual values of surface roughness in microinches for all test materials and the "Best Surface Possible". The results of 3Al-5Cr and RC-110A have been added for convenient comparison.

CONCLUSIONS

1. Definite improvements in the quality of surface finish have been observed as a function of a reduction of feed in ipr on each of the work materials included in this report. These results appear to be consistent with the conclusions on the materials reported previously.

2. The 3Al-5Cr material shows the best surface quality up to 100 fpm and from 400 to 500 fpm. The intermediate speeds of 200 to 300 fpm indicate higher values of surface finish.

3. The RC-110A material shows a high value of surface finish of 310 with improved values of surface quality at 100 fpm or less and slightly lower values of surface quality at 300 to 400 fpm.

4. Similar results in the condition of the finish was observed on both grades of titanium, 3Al-5Cr and RC-110A and were superior to those attained on SAE 1045 steel.

5. In general these materials react in surface quality in a similar manner to those previously reported as far as surface finish is concerned.

XIII. TAPPING

A number of tapping tests were made at substantially the same conditions used initially for other titanium alloys as recorded in Report No. 22. In addition two new tap designs were tried. The new designs involved different lengths of chamfer on the end of the tap. The principle objective of this series of tests was to determine the tapping behavior of titanium alloys RC-110A and 3Al-5Cr as compared to hot-rolled SAE 1045 steel and other titanium alloys. For this purpose the best tap addition found in previous tests was used for this series. This was an 11° spiral-point angle tap sometimes known as "chip-driver" or "gun tap". These were chamfered for a length of four threads.

The two alloys of titanium were tapped at five different speeds ranging from 14.5 up to 71.9 fpm. The tests were conducted in a Detroit Precision lead tapper with the work specimens mounted in a dynamometer capable of giving continuous indications of the torque required both to cut and to back the tap out of the work. The 1/2-13 taps were mounted directly in the spindle.

The results of the first series of tests on RC-110A and the 3Al-5Cr are summarized in Fig. 42 along with corresponding data for hot-rolled SAE 1045 steel and other titanium alloys. It may be noted that both the new titanium alloys behaved similar to the other titanium alloys in that the torque required to tap increased very rapidly beyond what might be called a "critical speed". It would appear to be significant that the RC-110A did not show any increase in torque until the speed was increased beyond 50 fpm. All other titanium alloys caused significant increases in torque at speeds between 30 to 50 fpm.

One of the most unique tapping properties of titanium in the torque required to back the tap out. This is sensitive to both the cutting fluid and the tap design. A lithipone paste was applied to the tap during the variable velocity test series. The back-out torque varied from a trace to as much as 1.3 lb-ft for the RC-110A. It is significant that the back-out torque was greatest at the lowest cutting speed and it decreased to only a trace at the highest speed. Similarly, the back-out torque varied from 3.2 to 5.2 lb-ft for the 3Al-5Cr titanium. Once again the greatest back-out torque was required at the lowest cutting speed and the least at the highest practical speed.

Additional tests were run with the same tap design at a speed of 21.8 fpm, but using a heavy sulphochlorinated oil as a cutting fluid. At this condition the tap stalled in the work with both alloys of titanium; however, these alloys were tapped successfully with two recent new designs of taps. These designs are characterized as "short chamfer" and "long chamfer". They were four-flute taps in contrast to the three-flute taps used for the first tests reported in Fig. 42. The "short-chamfer" tap was chamfered for five threads in contrast to a four-thread chamfer on the three-flute taps. The "long'chamfer" taps were chamfered for 15 threads. As mentioned previously, both four-flute taps were used successfully in tapping both the 3Al-5Cr and RC-110A alloys of titanium and while using the sulphochlorinated oil as a cutting fluid.

The short-chamfer four-flute tap required 17 and 18 lb-ft of torque when tapping the 3Al-5Cr titanium with sulphochlorinated oil and lithopone paste, respectively. Only a trace of back-out torque was observed with the lithipone paste whereas the sulphochlorinated oil required more torque for back-out than for cutting. Similarly the long-chamfer four-flute tap required 9.1 and 11 lb-ft of torque for the sulphochlorinated oil and lithipone paste, respectively. On the same tests the back-out torque was 7 and 4.5 lb-ft, respectively.

In tapping the RC-110A with four-flute taps the long chamfer required 12 lb-ft of torque for cutting and 11 lb-ft for back-out when the sulphochlorinated oil was used. When lithipone paste was used with this same tap design the cutting torque was 13.3 lb-ft and back-out torque was only 3 lb-ft. The short-chamfer tap stalled and could not be used with the sulphochlorinated oil; however, with lithipone paste the short-chamfer tap required 15 lb-ft of torque for cutting and only 2.8 lb-ft for back-out.

CONCLUSIONS

1. The difficulties in tapping titanium are dependent on cutting speed, cutting fluid, and size of cut.

2. The inherently small relief angle peculiar to taps makes them susceptible to seizure both during cutting and particularly during back-out; consequently, an effective lubricant must be used. It may be necessary in many cases to result to mechanical separators in the cutting fluid as in the case of the lithipone paste.

3. Titanium and titanium alloys have demonstrated a marked sensitivity to cutting speed in that the torque increases precipitously. beyond the threshhold speed peculiar to each alloy; thus, it is important that the tapping speed be limited.

4. The incidence of seizure is related to the size of the individual chips taken by each tooth of the tap in that larger chips require more torque and cause more frequent stalling for the same size thread.

These tests have demonstrated the advisability of using long chamfers and relatively large numbers of flutes, both of which results in smaller chips for the same size of thread.

TAPPING TITANIUM

78% THREAD DEPTH

TI-75A, RC-130A, TI-3%AL 5% CR

RC-130B, TI-150A, SAE 1045 STEEL, RC-110-A

SPIRAL POINT TAP 1/2X13 NC HSS

FLUID : LITHOPONE PASTE

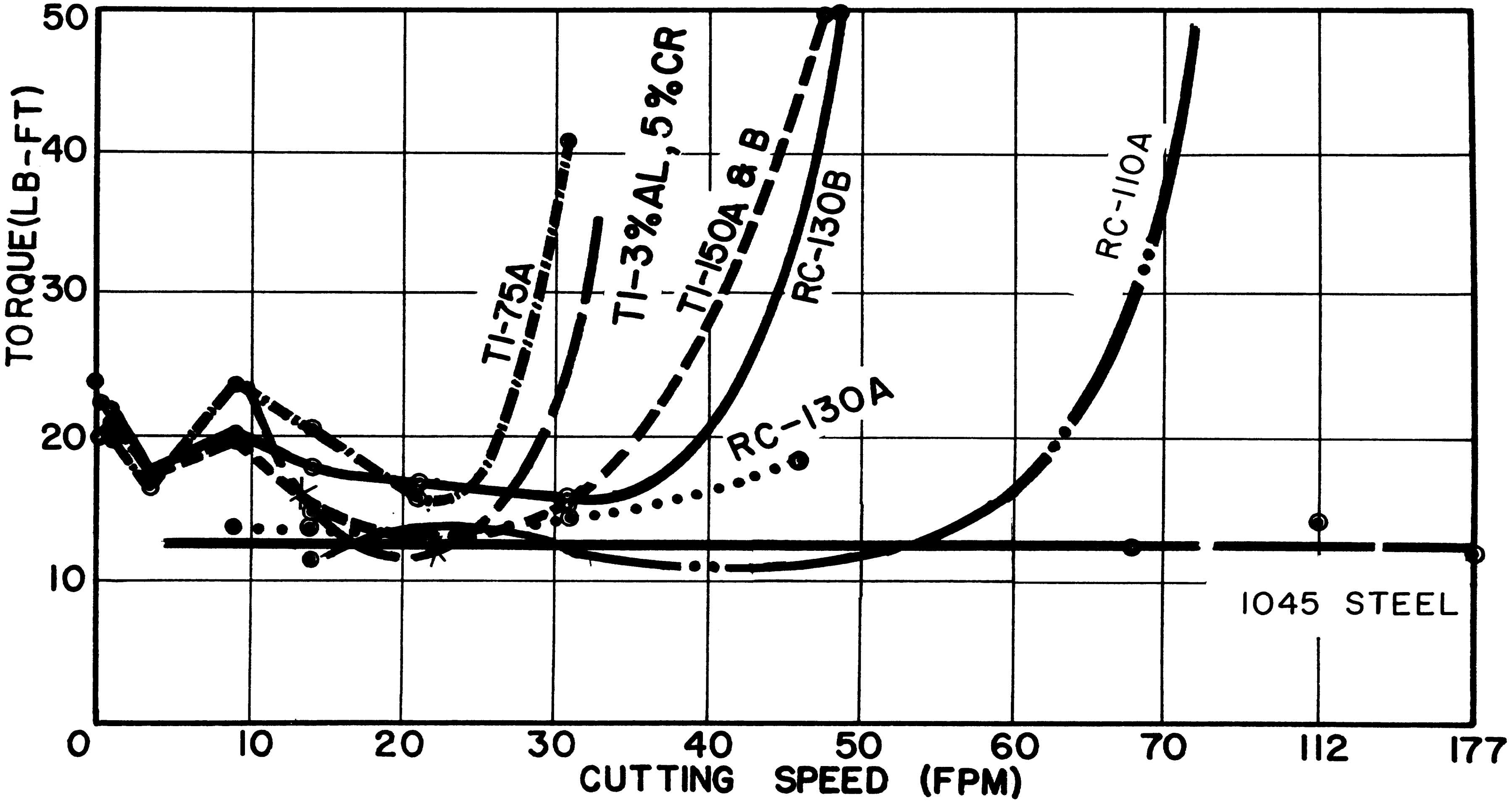

FIG. 42

TOOL LIFE vs SIDE RAKE ANGLE

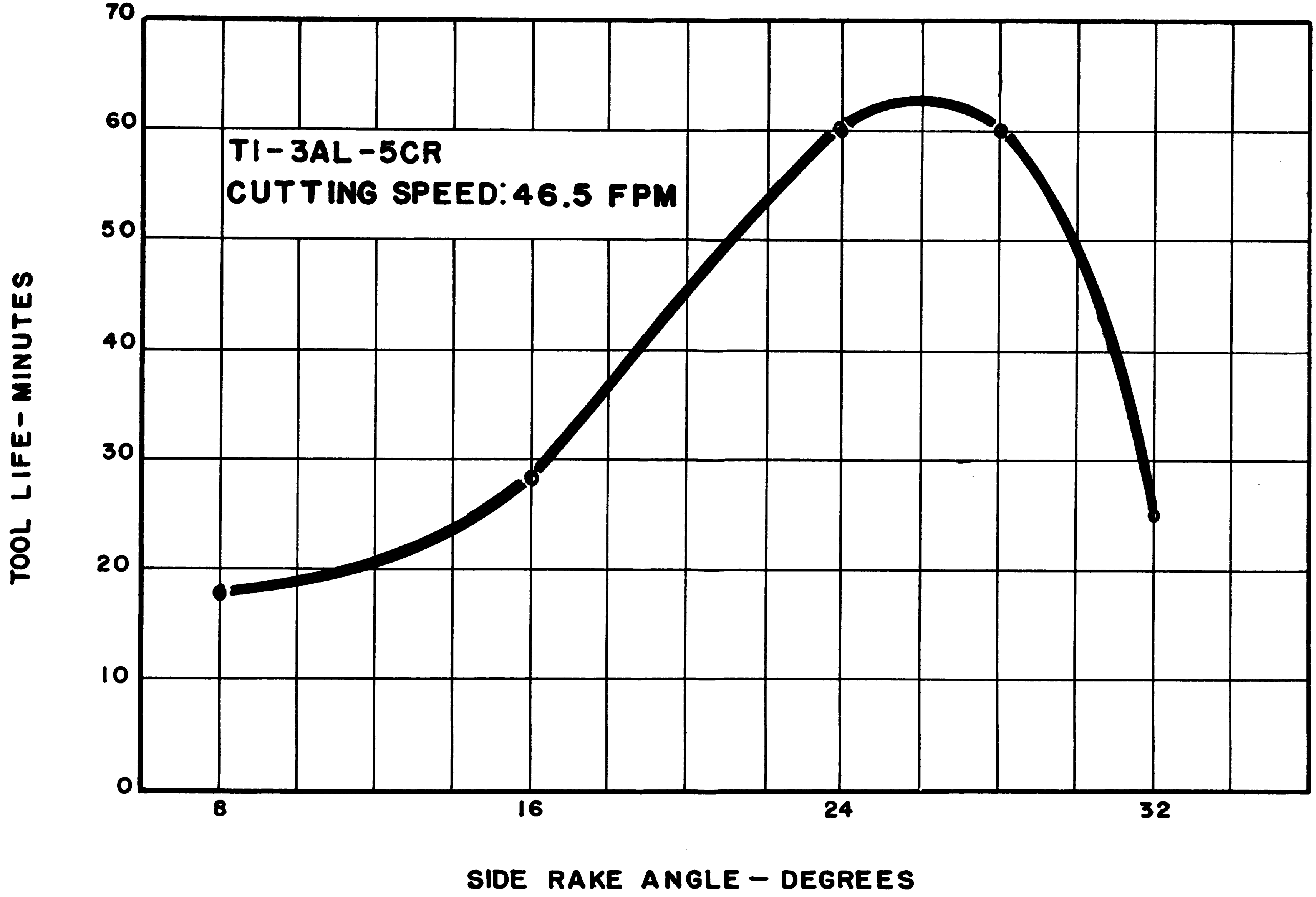

FIG. 1

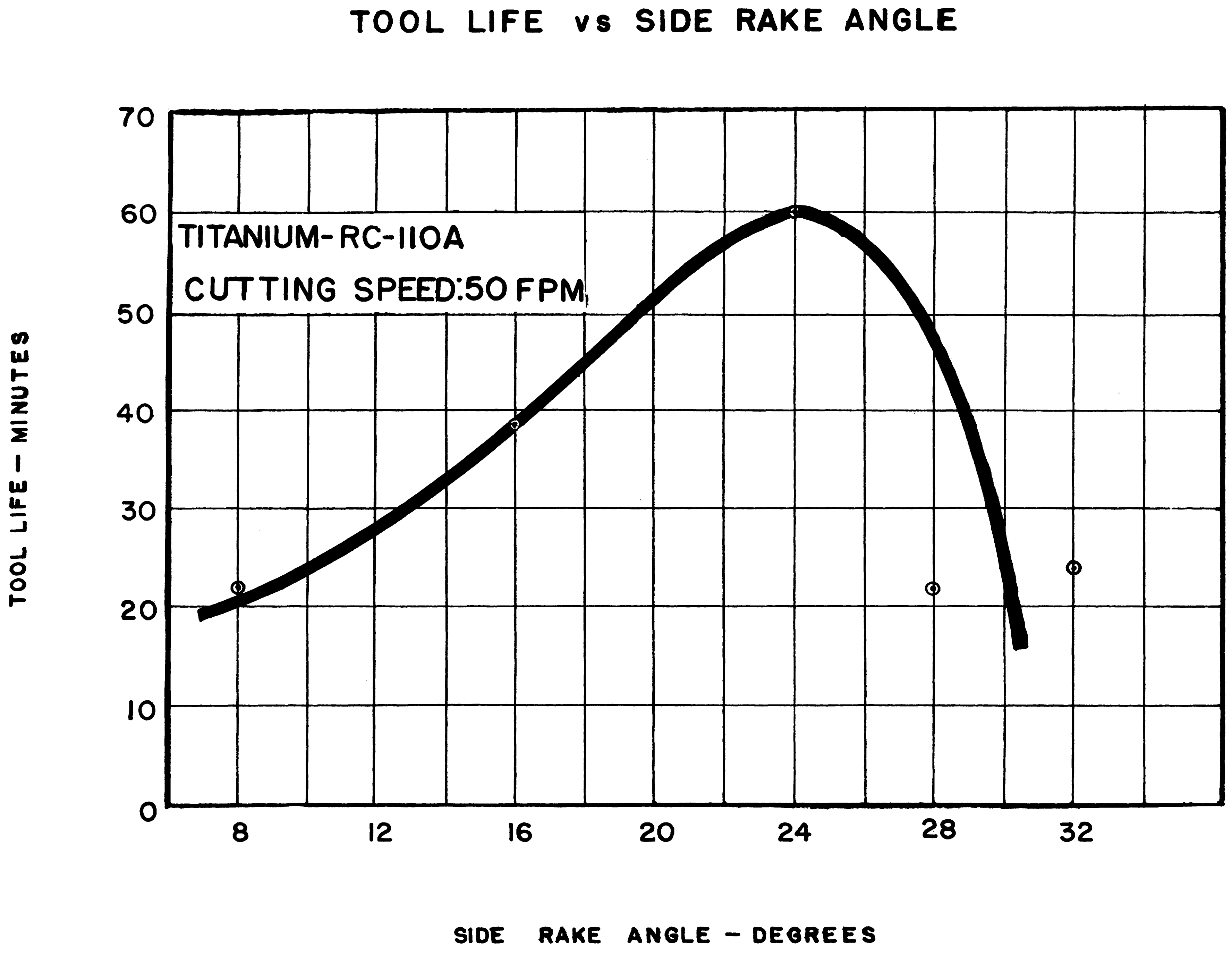
TOOL LIFE vs SIDE RAKE ANGLE
TITANIUM-RC-110A
CUTTING SPEED: 50 FPM.
TOOL LIFE – MINUTES
0
10
20
30
40
50
60
70
8
12
16
20
24
28
32
SIDE RAKE ANGLE – DEGREES

FIG. 2

CUTTING SPEED — TOOL LIFE

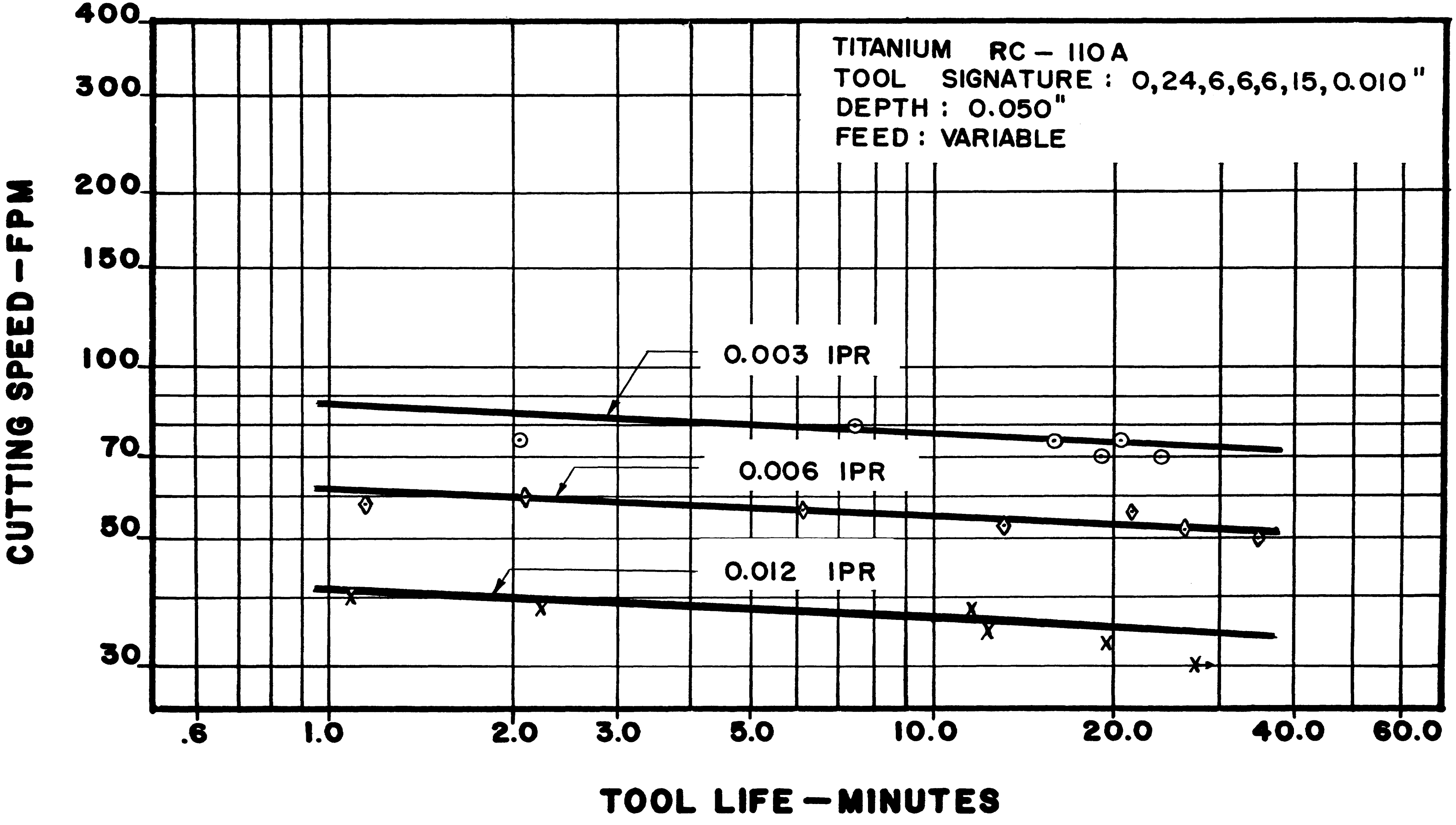

FIG. 3

CUTTING SPEED — TOOL LIFE

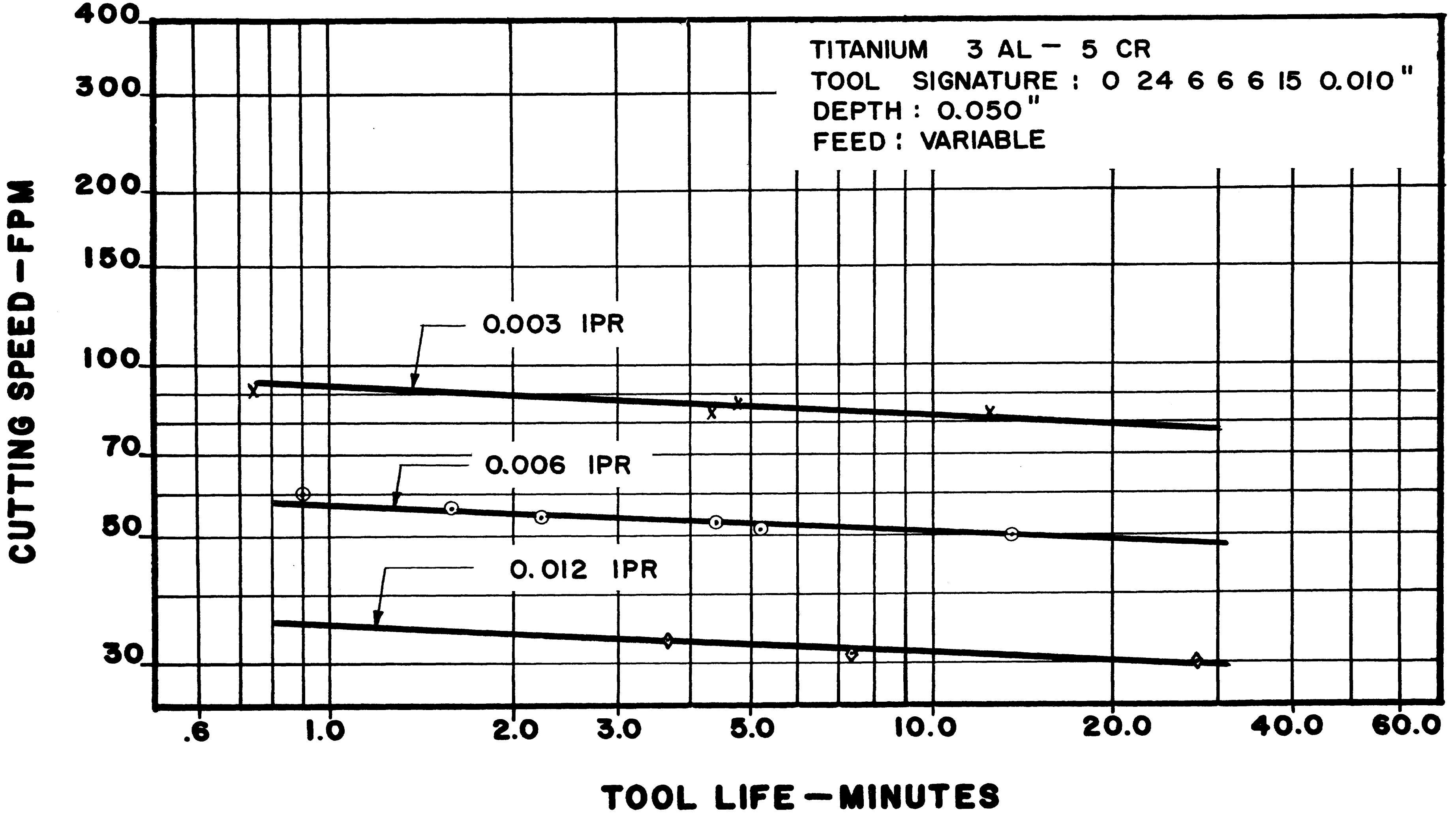

FIG. 4

CUTTING SPEED — FEED

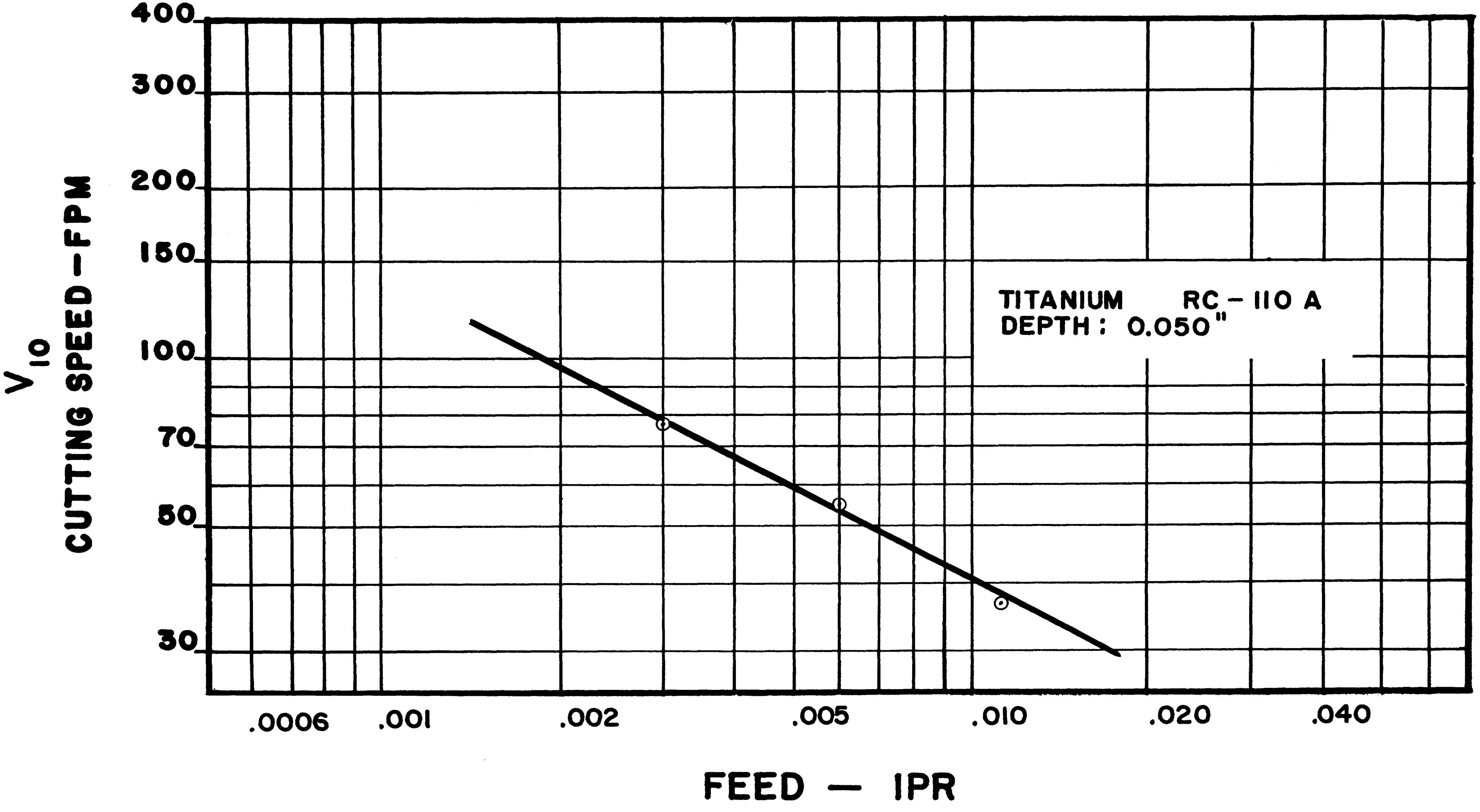

FIG. 5

CUTTING SPEED — FEED

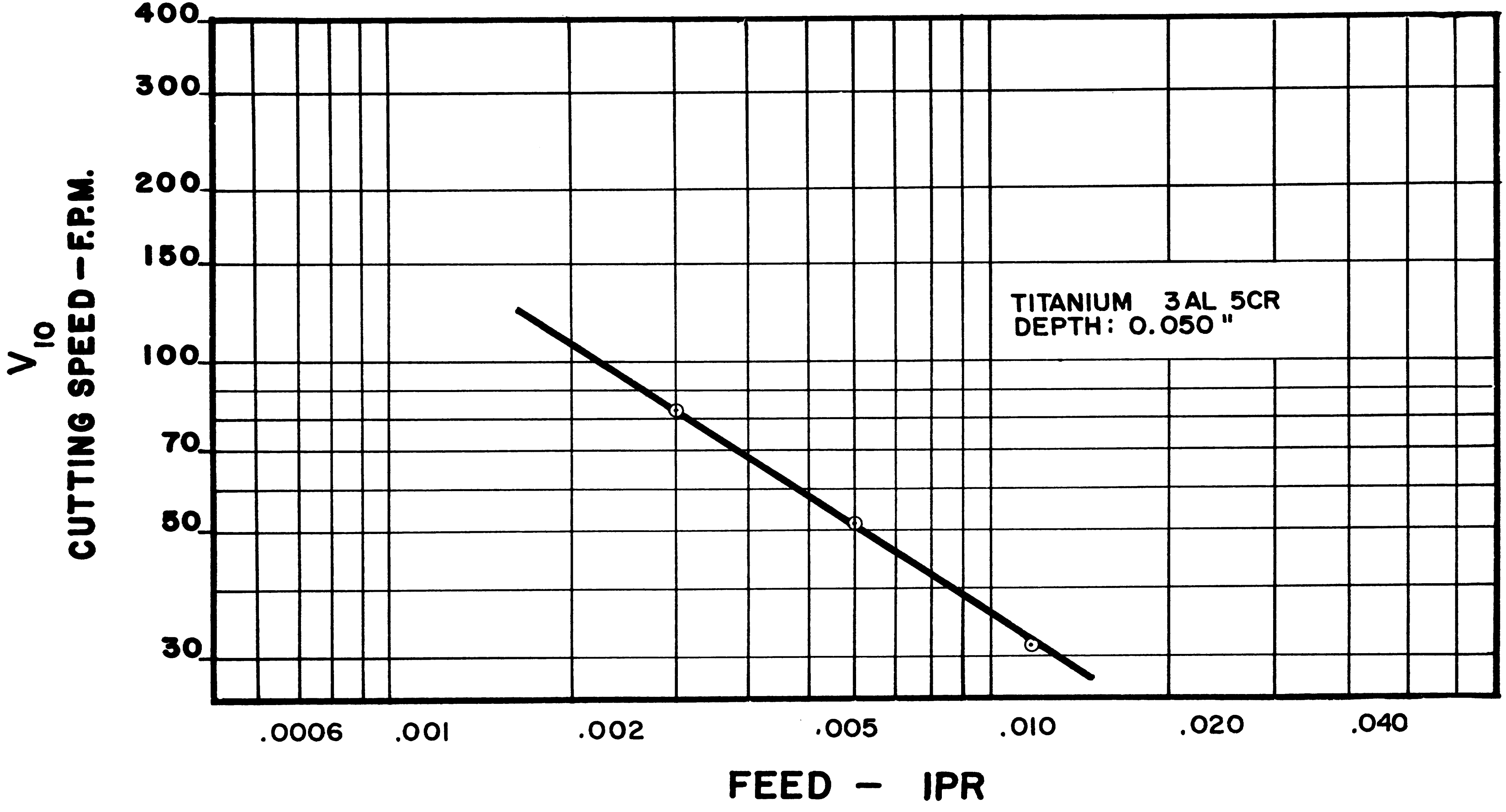

FIG. 6

CUTTING SPEED — FEED

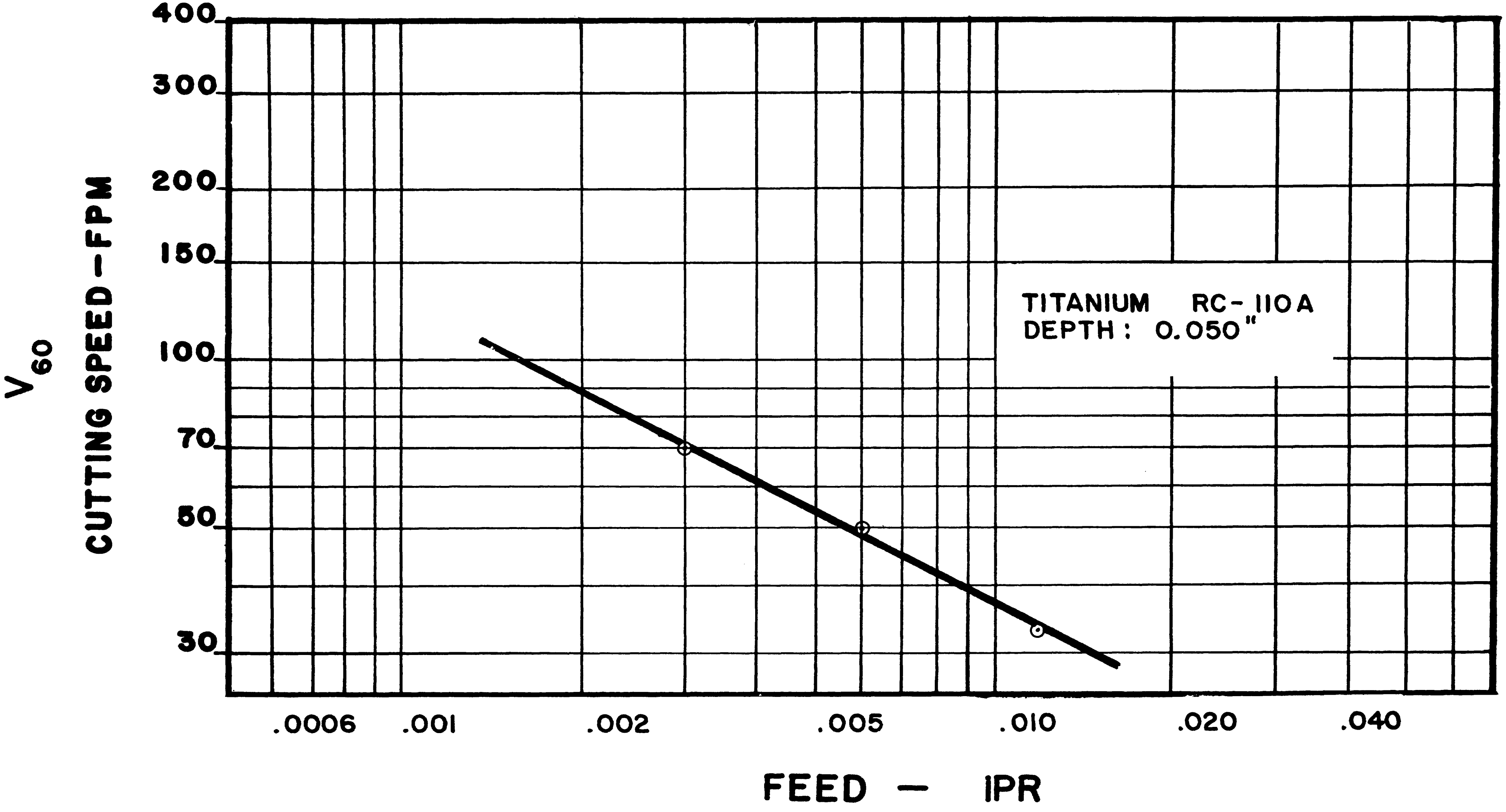

FIG. 7

CUTTING SPEED — FEED

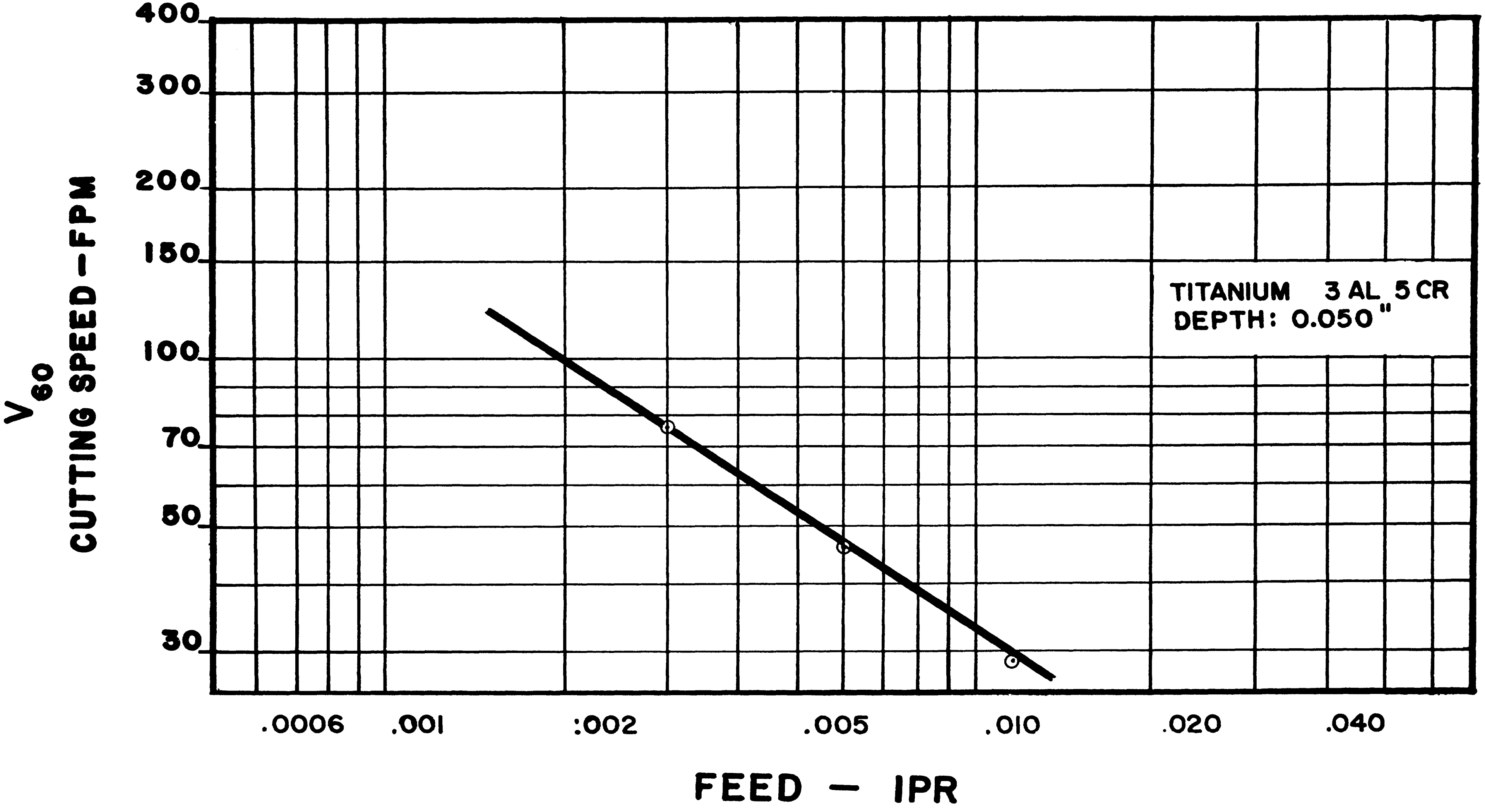

FIG. 8

CUTTING SPEED — TOOL LIFE

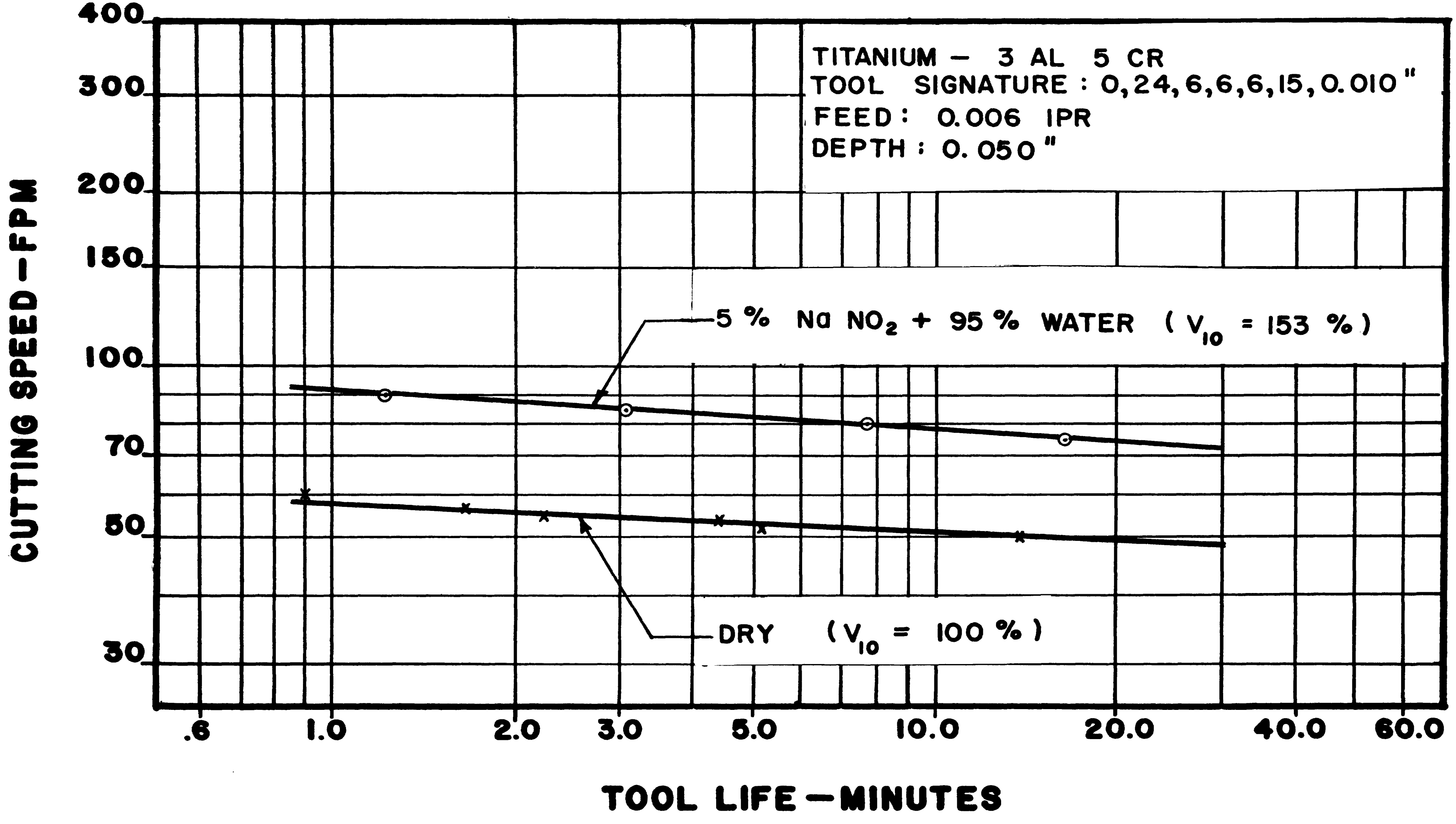

FIG. 9

CUTTING SPEED — TOOL LIFE

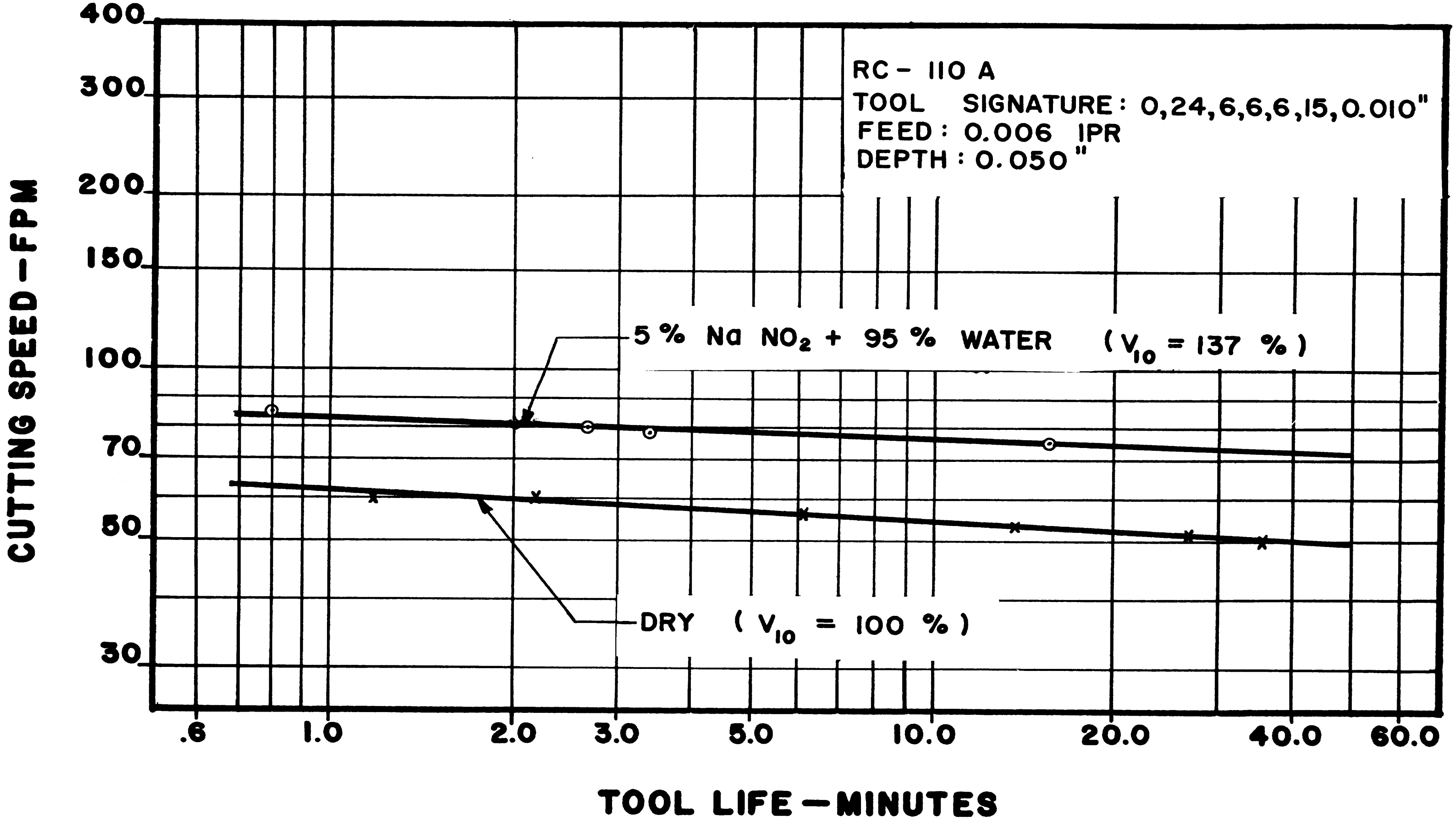

FIG. 10

CUTTING TEMPERATURE VS DEPTH OF CUT

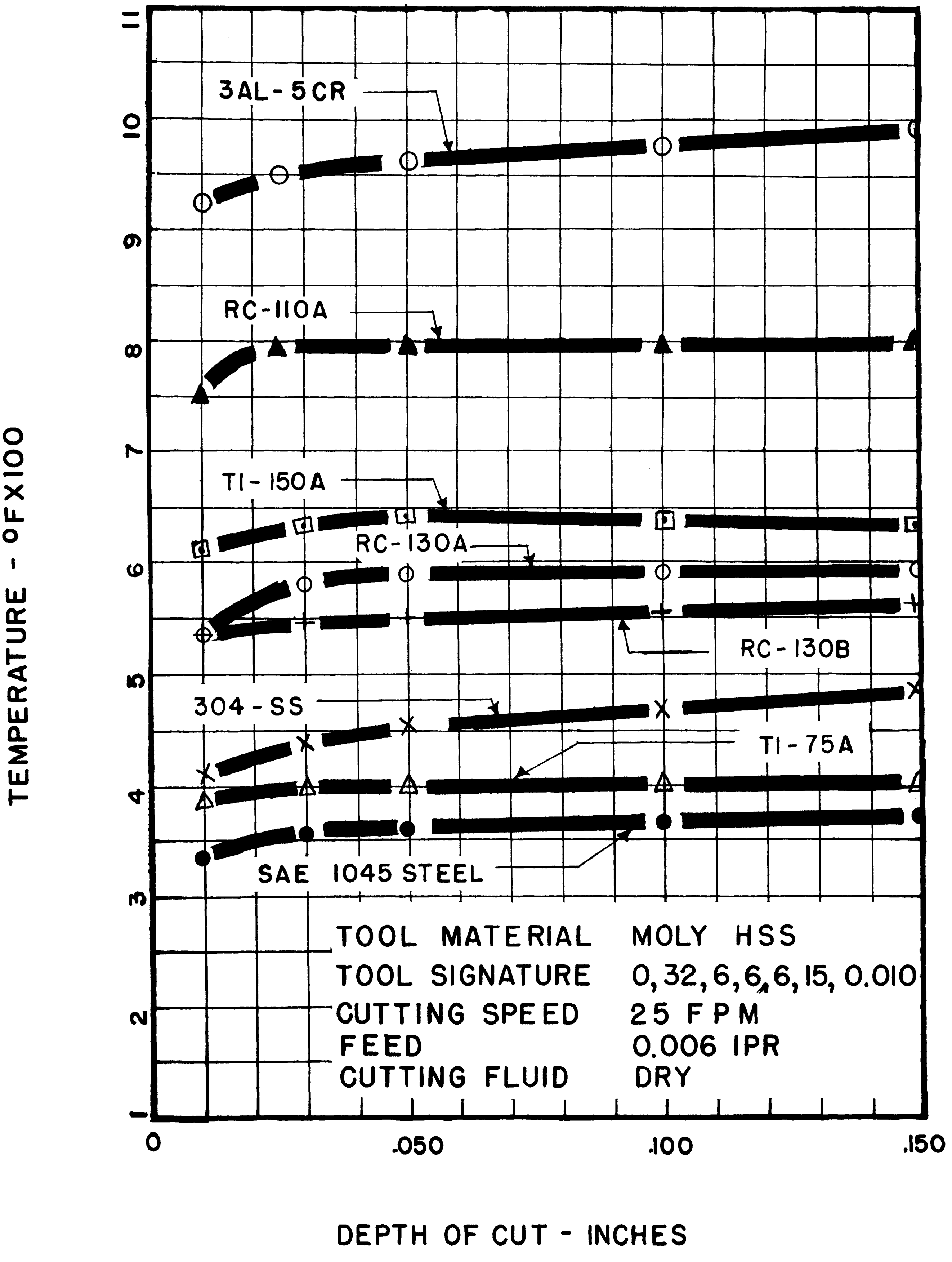

FIG. 11

CUTTING TEMPERATURE VS FEED

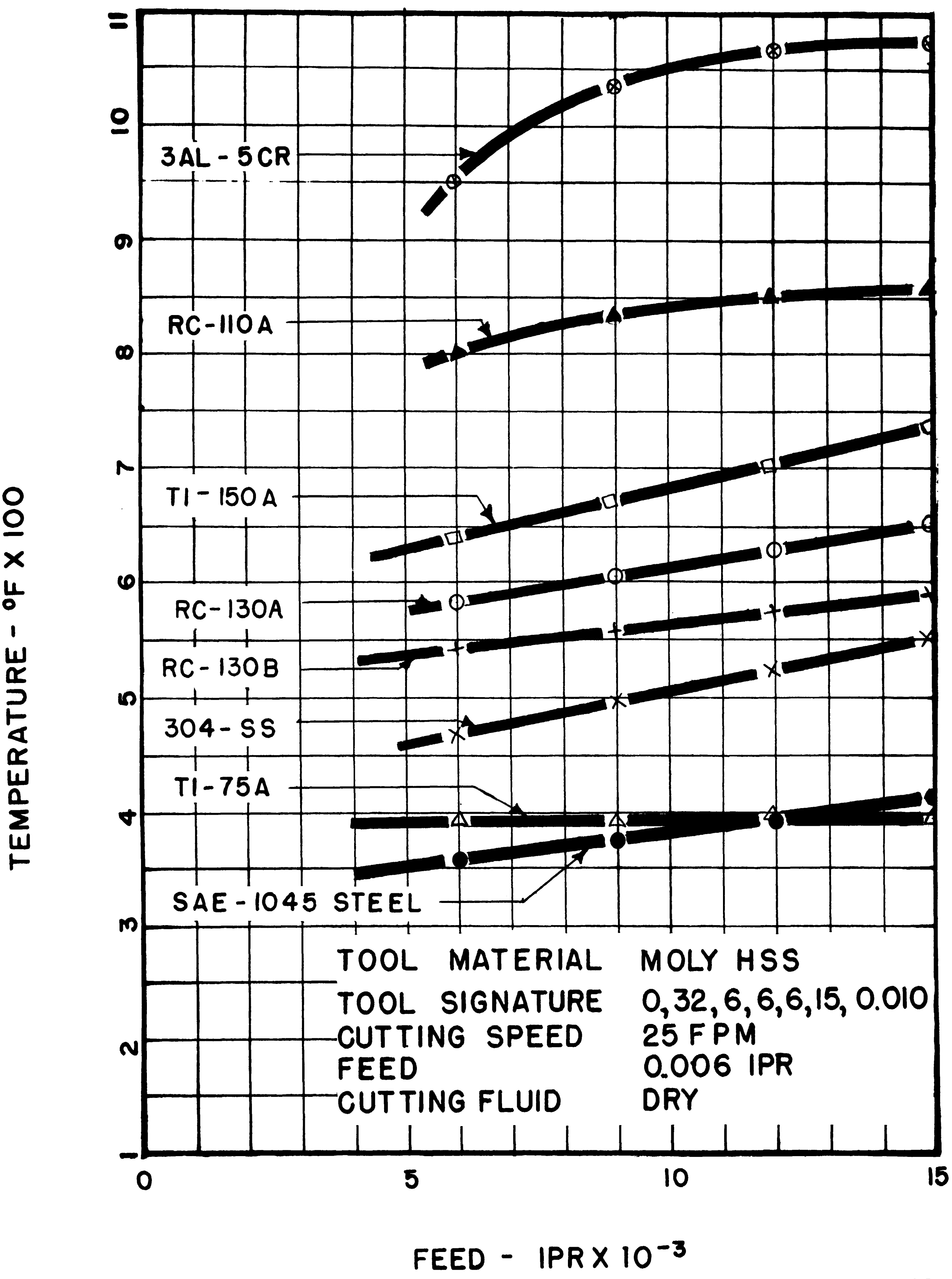

FIG. 12

CUTTING SPEED VS CUTTING TEMPERATURE

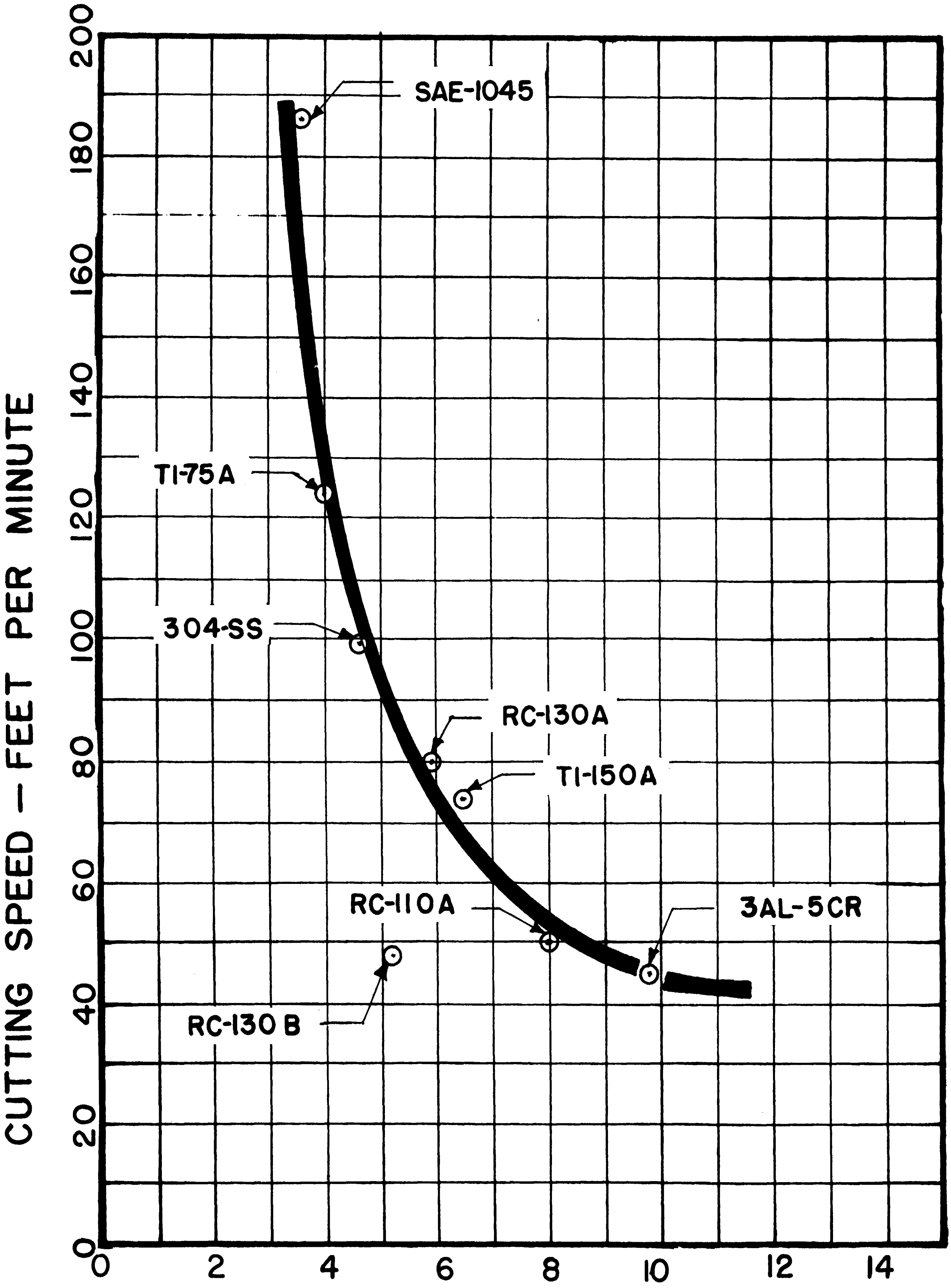

FIG. 13

DRILLING TITANIUM

COMPOSITE CURVES FOR TORQUE AND THRUST VALUES WHEN DRILLING
TI-75A, TI-150A, 3AL5CR, RC130A, RC130B, RC110A, & SAE 1045 DRILL: 1/2" HSS-SPEED 29.4FPM

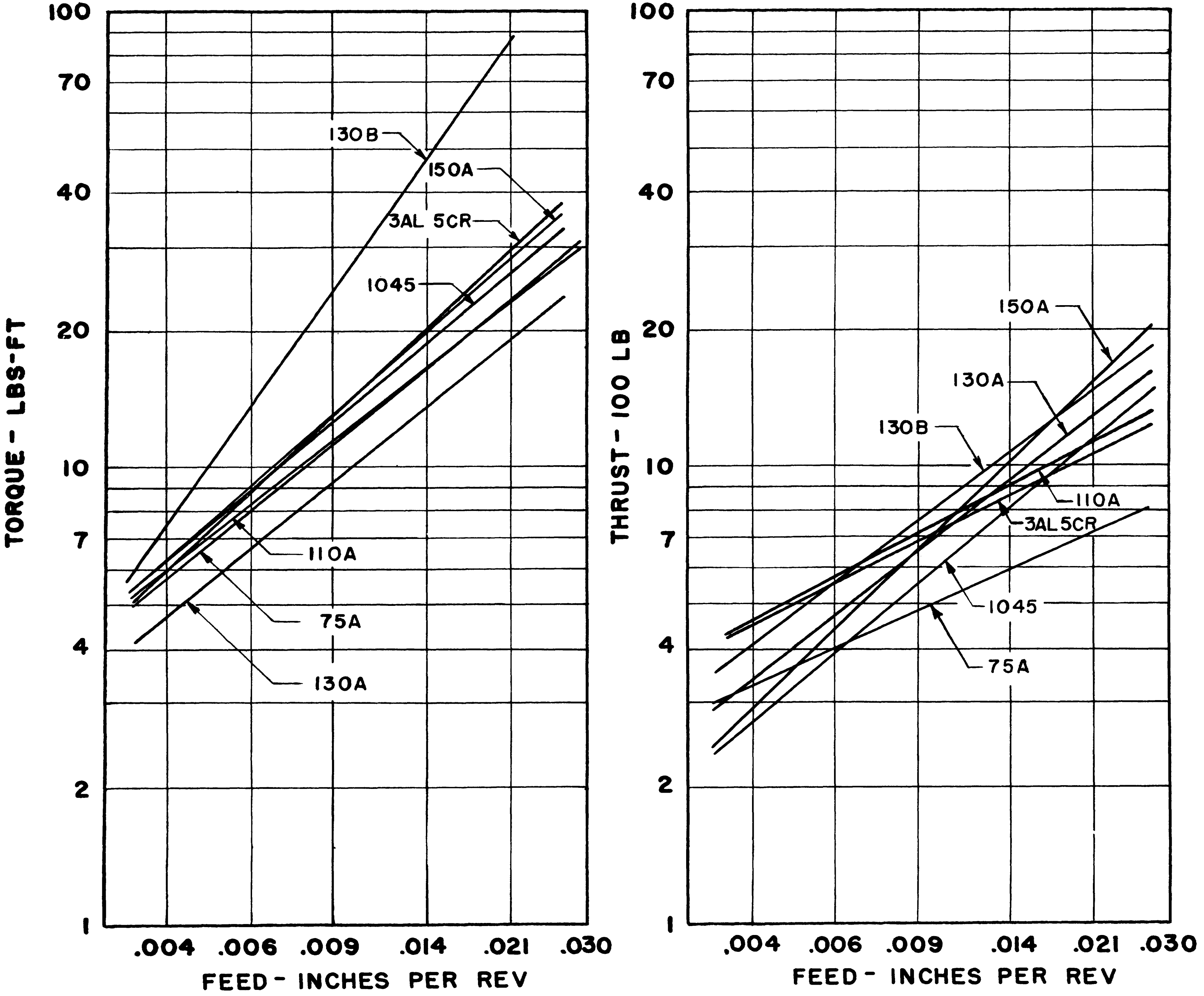

FIG 14

DRILLING TITANIUM

COMPOSITE CURVES FOR TORQUE AND THRUST VALUES WHEN DRILLING
TI 75A, TI 150A, RC 130A, RC 130B, TI 3AL 5CR, & SAE 1045 SPEED: 29.4 FPM, FEED: 0.009 IPR

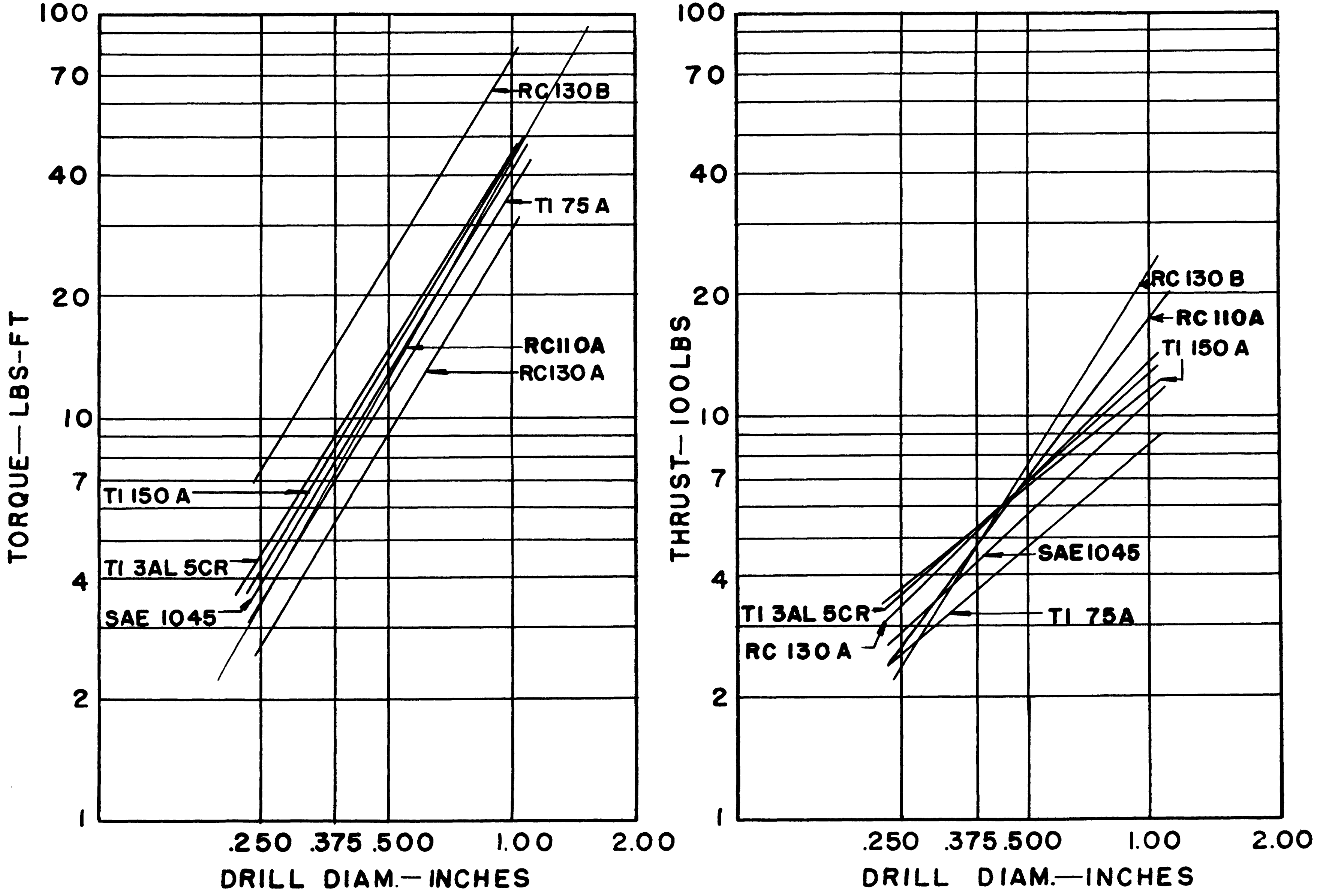

FIG. 15

DRILLING TITANIUM

TORQUE VS DRILL DIAMETER VS FEED
HSS DRILLS - CHISEL EDGE ANGLE 120°

MATERIAL CUT - 3AL 5CR
DECEMBER 14-1954

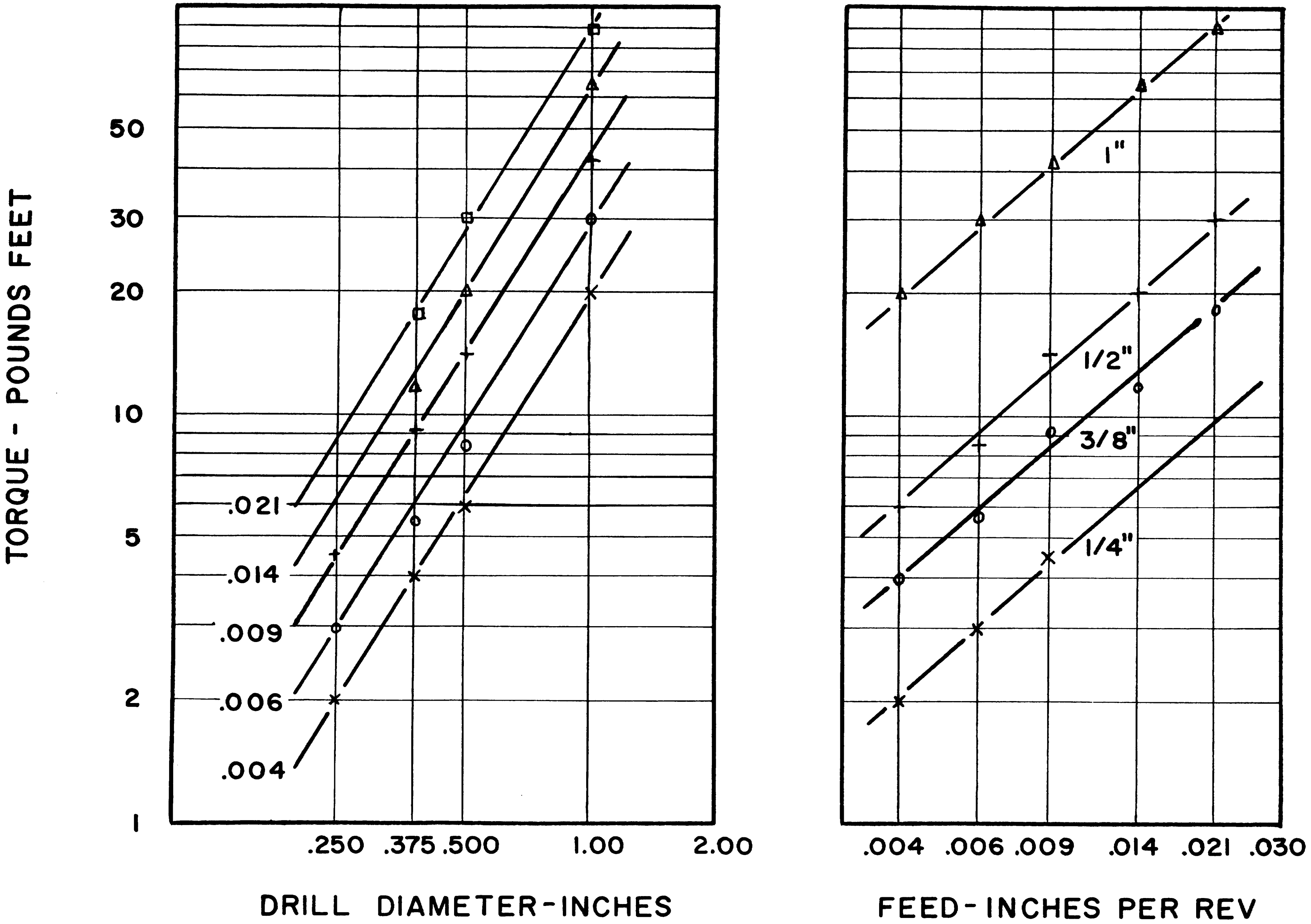

FIG. 16

DRILLING TITANIUM

THRUST VS DRILL DIA VS FEED MAT'L. CUT— TI 3 AL 5CR
H S S DRILLS– CHSL. EDGE– ANGLE 120° DEC. 14, 1954

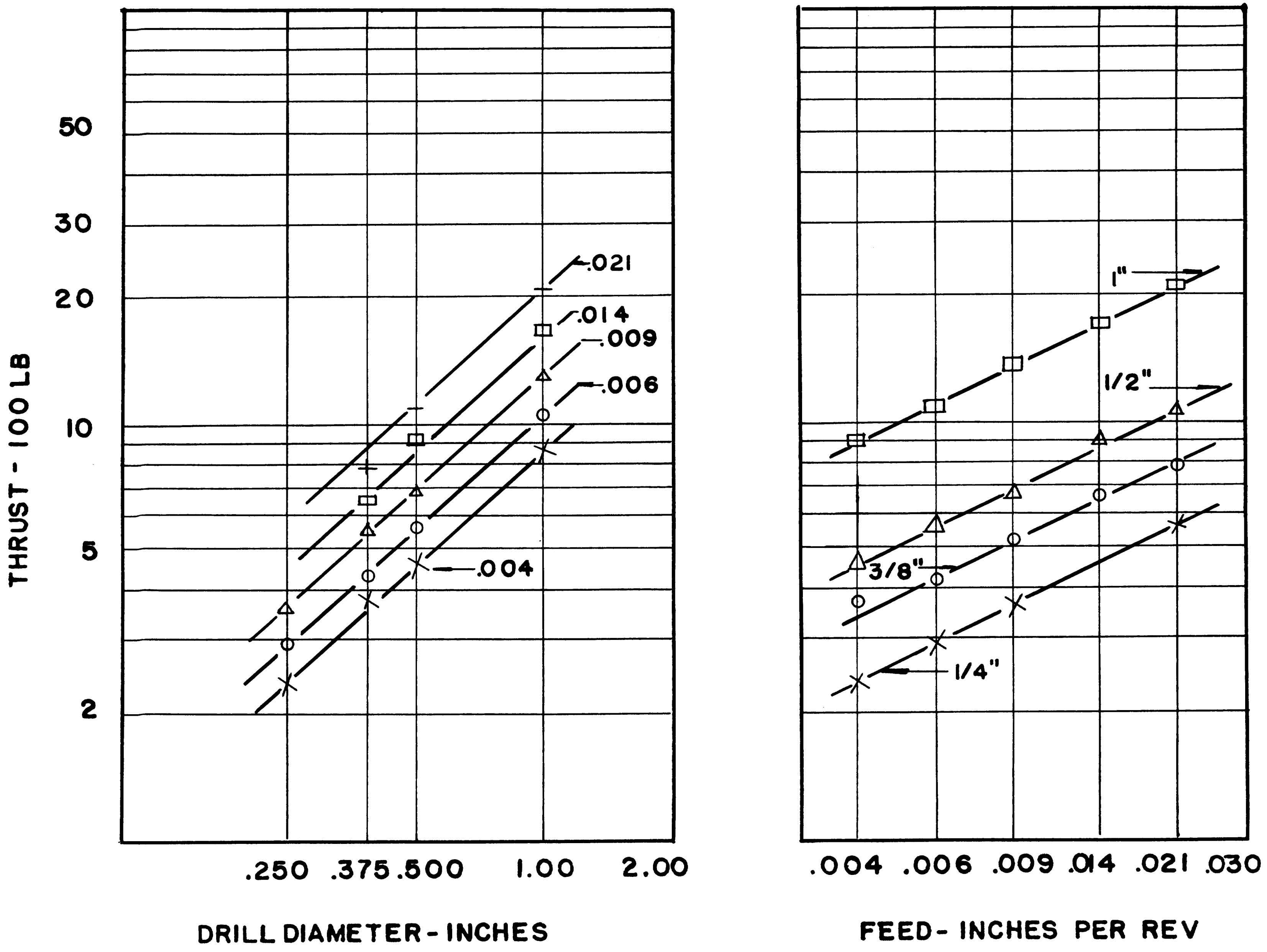

FIG. 17

DRILLING TITANIUM

TORQUE VS DRILL DIA VS FEED
HSS DRILLS CHISEL EDGE ANGLE 120°

MATERIAL CUT — R C 110 A
JANUARY 3-1955

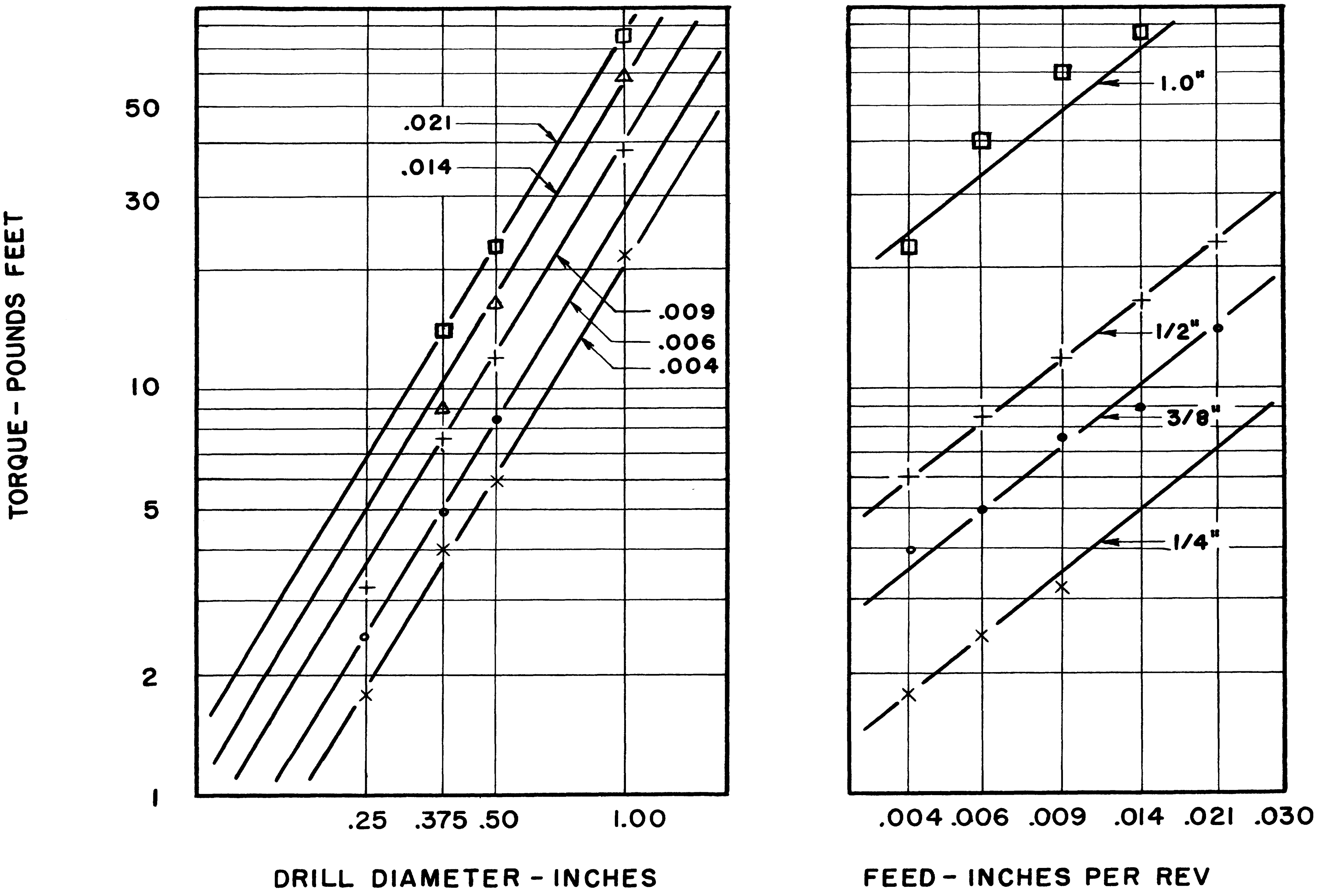

FIG. 18

DRILLING TITANIUM

THRUST VS DRILL DIA VS FEED
H S S DRILLS-CHISEL EDGE ANGLE 120°

MATERIAL CUT-RC 110A
JANUARY 3, 1955

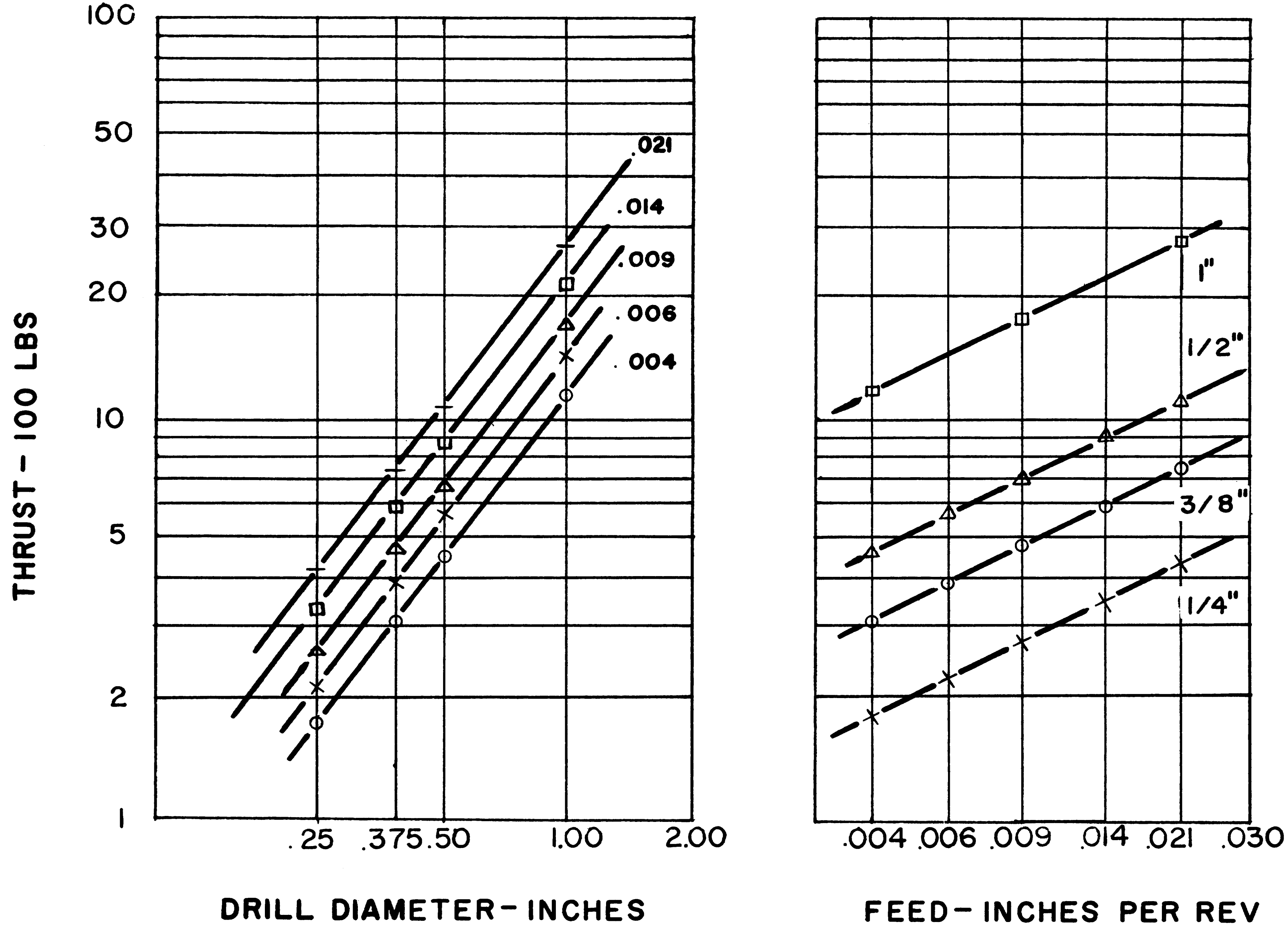

FIG. 19

DRILLING TORQUE & THRUST FORMULAS WITH CONSTANTS AND EXPONENTS FOR TITANIUM ALLOYS

MATERIAL	TORQUE (1)			THRUST (2)			1/2"HSS DRILL,225 RPM,.009IPR		
	a	b	C	z	y	K	TORQUE LB.FT.	THRUST LBS	HP/in^3/min
TI–75A	0.84	1.73	1900	0.42	0.84	6300	10.9	480	1.18
TI–150A	0.87	1.73	2550	0.96	0.78	101000	13.2	642	1.42
RC–130B	1.43	1.73	65000	0.81	1.60	105000	23.4	732	2.52
RC–130A	0.84	1.73	1680	0.82	1.00	63800	9.2	665	0.99
TI-3AL–5CR	0.97	1.68	4150	0.55	0.945	17950	13.5	700	1.45
RC-110A	0.78	1.80	1635	0.55	1.36	24900	12.0	725	1.29
SAE 1045	0.85	1.73	2310	0.90	1.00	75500	13.0	532	1.40

(1) TORQUE = $T = C f^{a} D^{b}$

(2) THRUST = $B = K f^{z} D^{y}$

FIG. 20

CUTTING SPEED – TOOL LIFE TESTS

HIGH SPEED STEEL – FACE MILLING

TOOL MATERIAL : MO-MAX HIGH SPEED STEEL
TOOL SHAPE : 7, 4, 6, 6, 2, 0, 0.070-45°
NO. OF TEETH : 1
DEPTH : 0.100 IN.
WORK MATERIAL : 4 IN. WIDE
CUTTING FLUID : DRY
FEED : 0.010 IPT

$VT^n = C$

MATERIAL		SYMBOL	C	N	V(20)
TI-75A (INT.)	=	Δ	165	.086	129
TI-75A SCALE	=	□	141	.089	108
TI-150A	=	○	58	.100	43
RC-130B	=	+	42	.104	31
C.I.	=			.094	
TI-150B	=	ϕ	34	.118	24
TI-3AL 5CR	=	¤	48.5	.108	35
TI-110A	=	X	58	.100	43

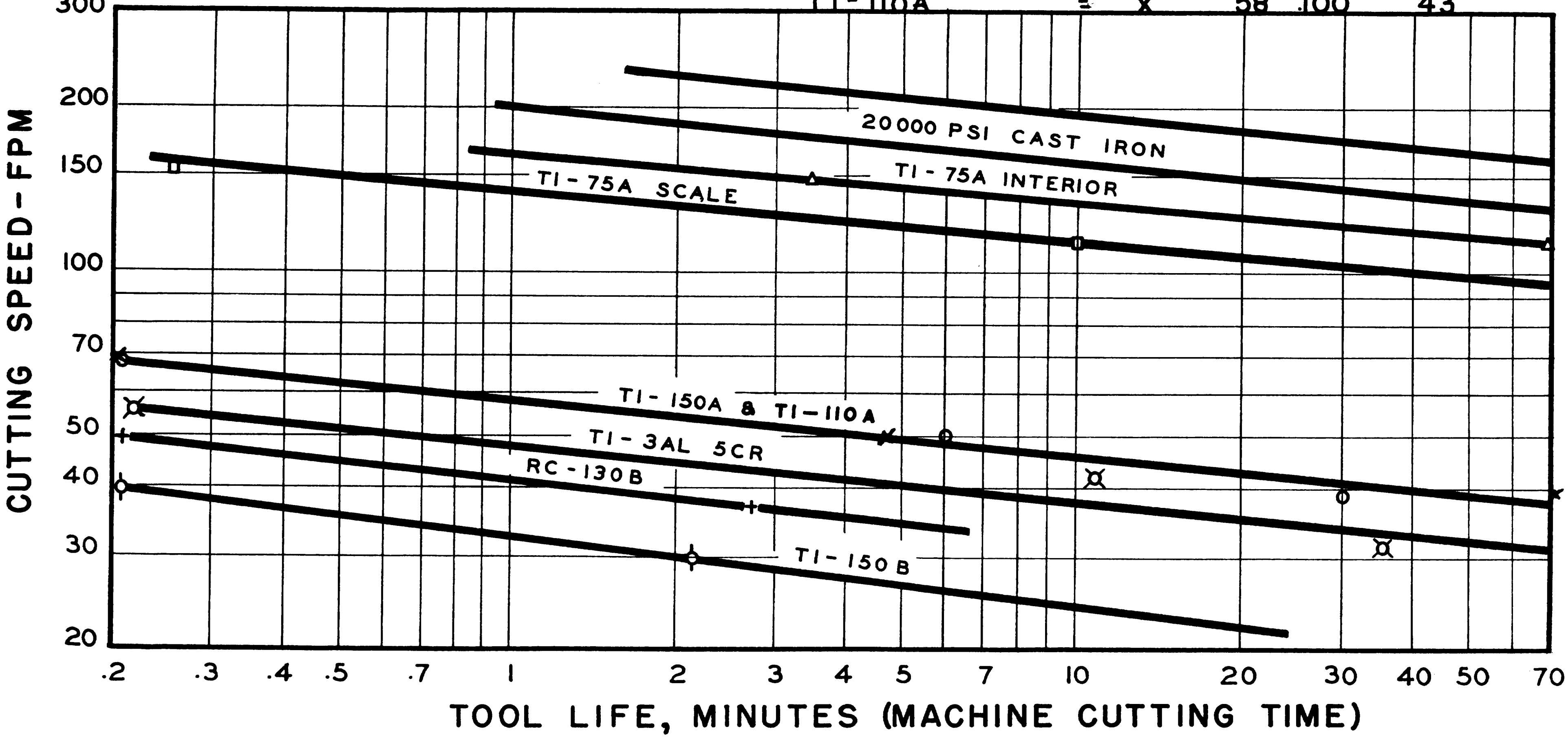

FIG. 21

CUTTING SPEED — TOOL LIFE TESTS

TOOL MATERIAL: CARBIDE 883
TOOL SHAPE: 0,0,12N,12N,2,45
DEPTH: 0.100 INCHES
FEED: 0.002 IPT
WORK MATERIAL: VARIED
CUTTING FLUID: DRY

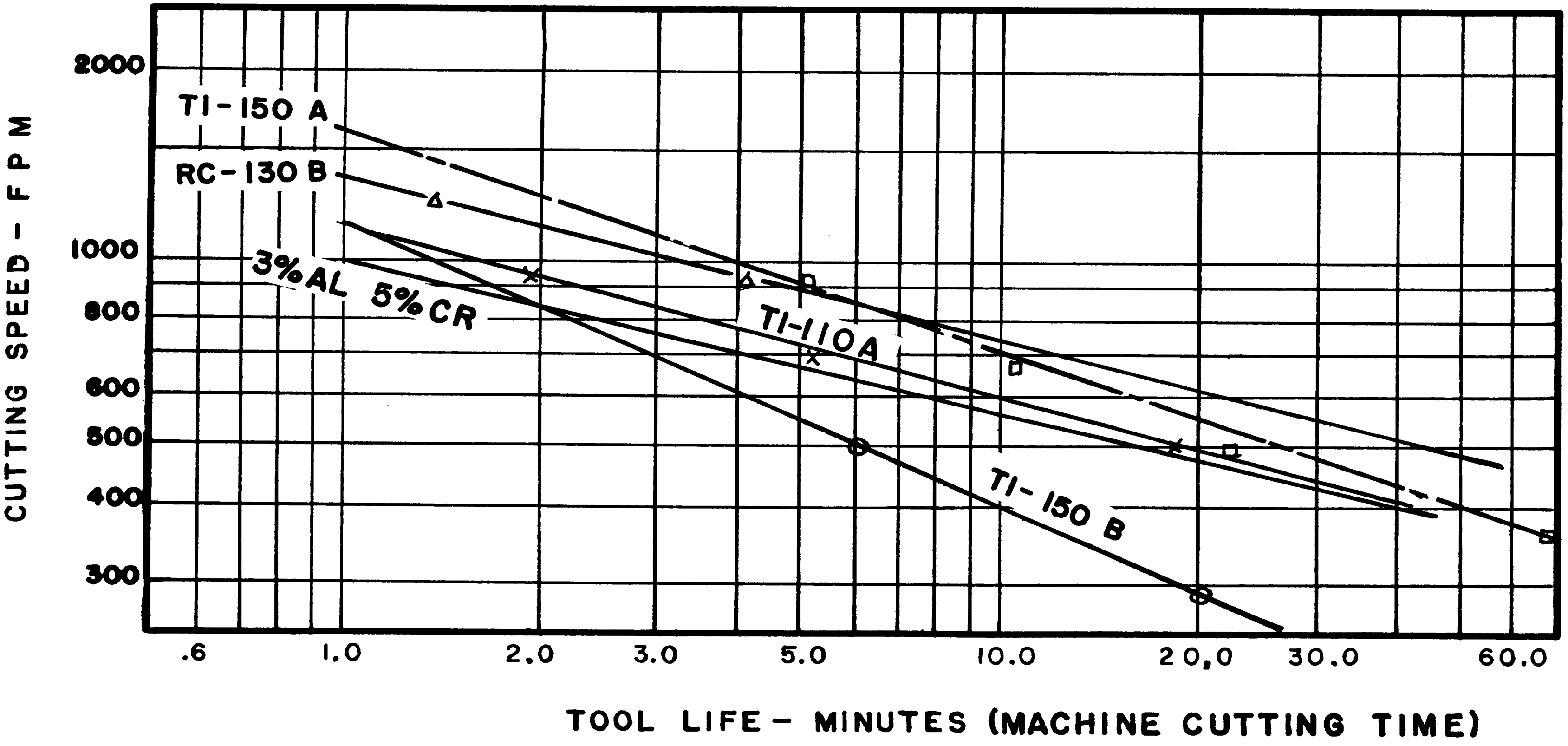

FIG. 22

BROACHING

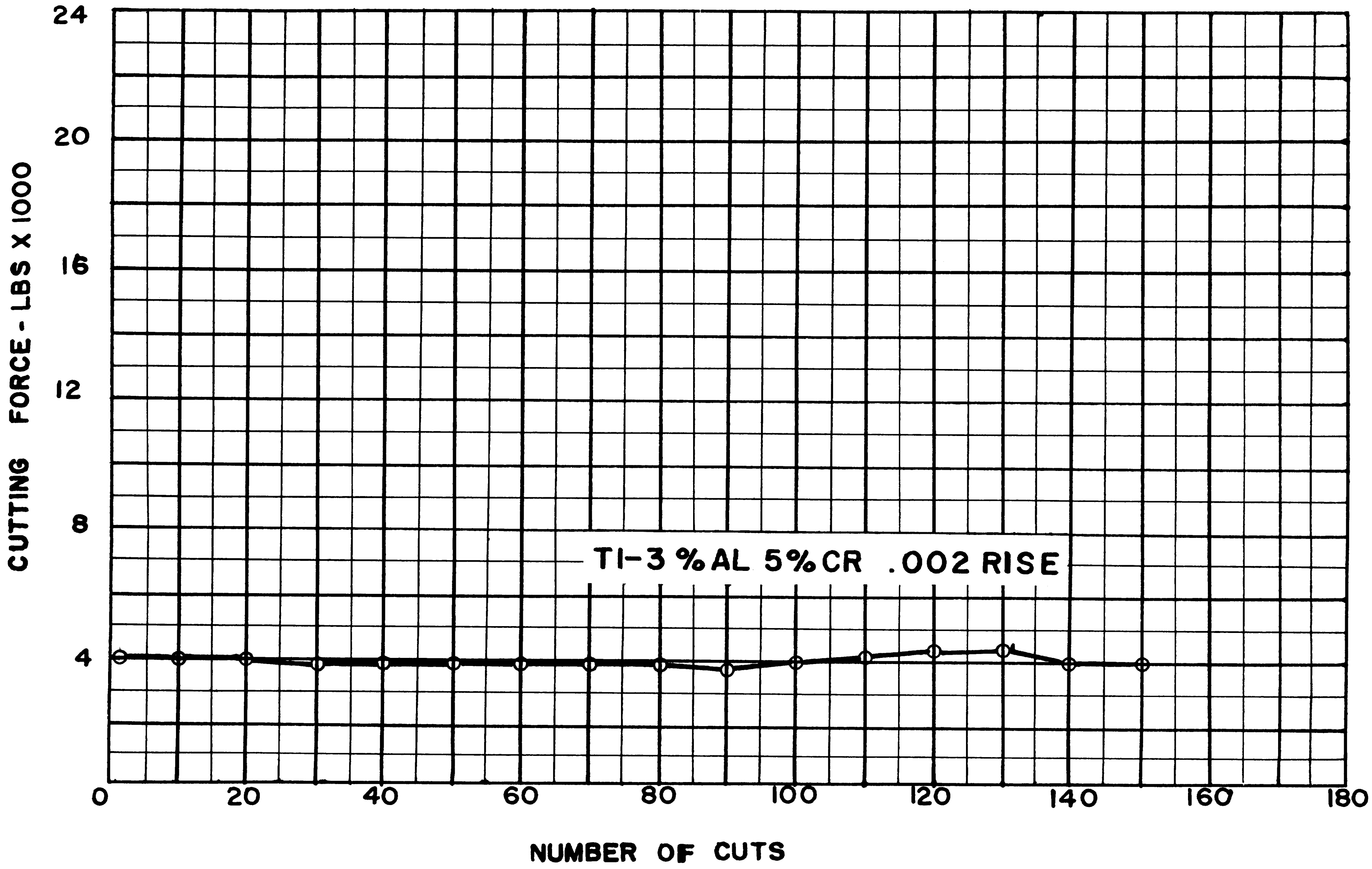

FIG. 23

BROACHING

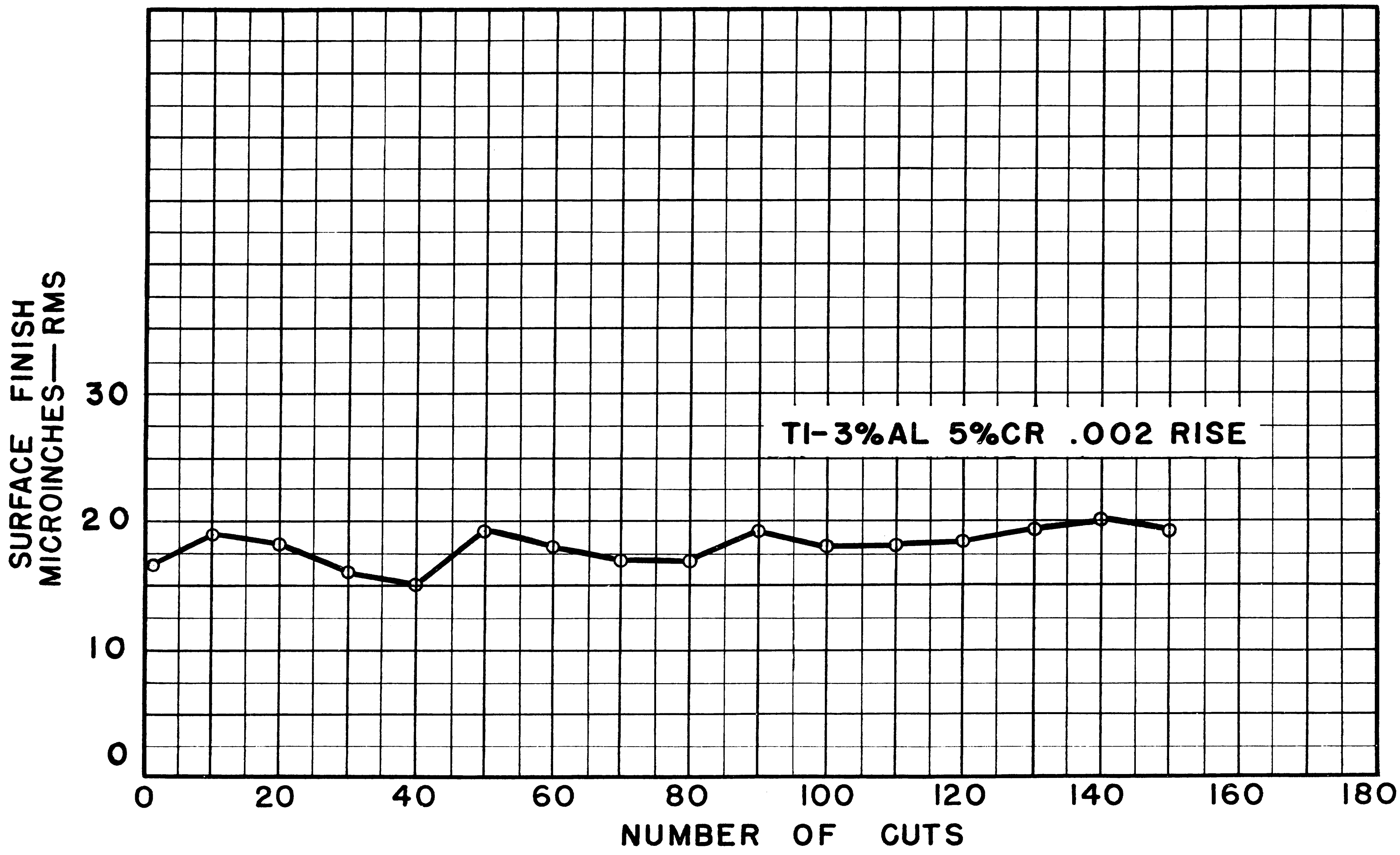

FIG. 24

BROACHING

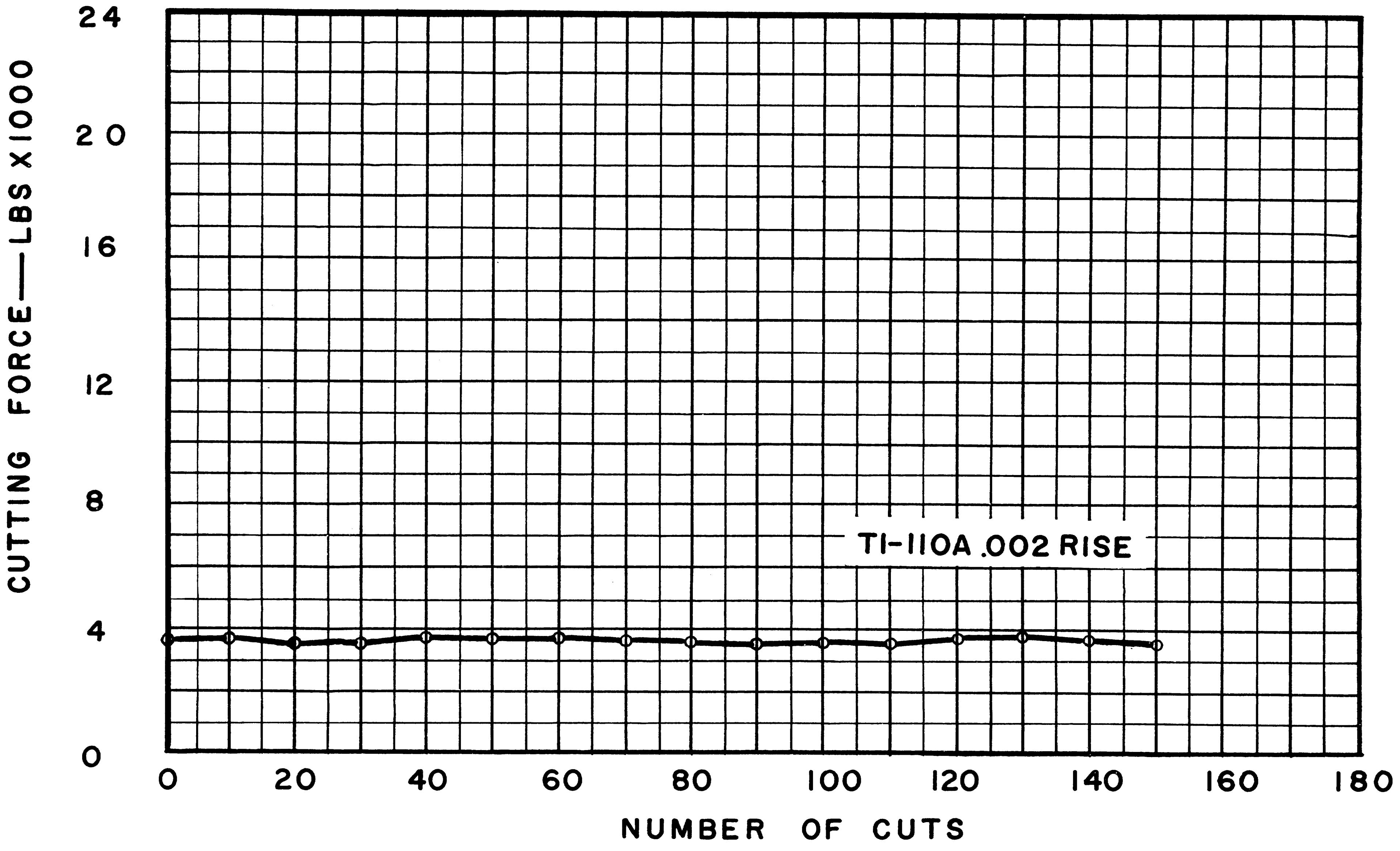

FIG. 25

BROACHING

FIG. 26

BANDSAWING FEED RATE: VARIABLE

MATERIAL: 3AL 5CR

FORCE TESTS VELOCITY: VARIABLE

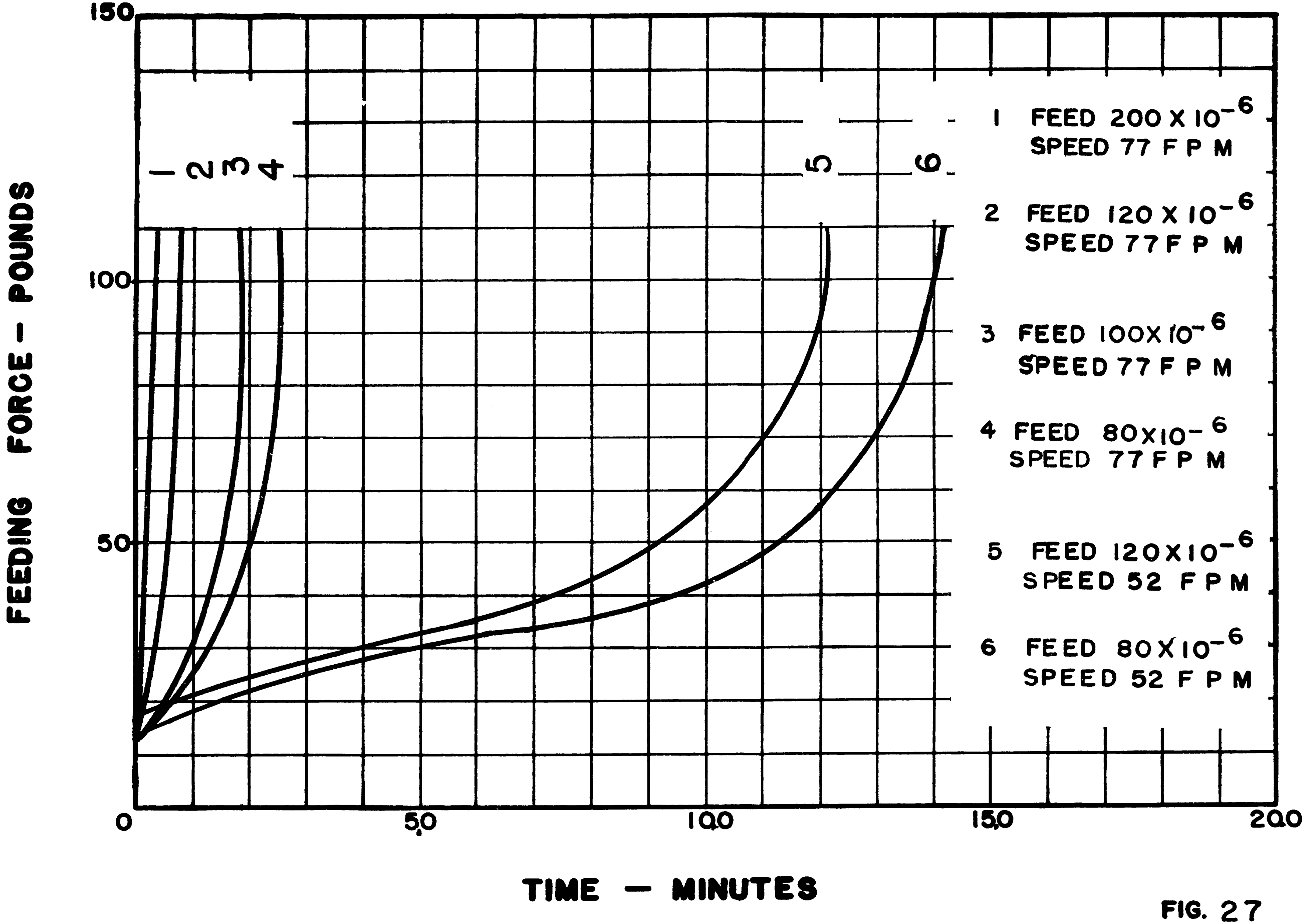

FIG. 27

BANDSAWING
FEEDING FORCE - TIME

MATERIAL - RC-110A
FEED RATE - VARIABLE
VELOCITY - VARIABLE

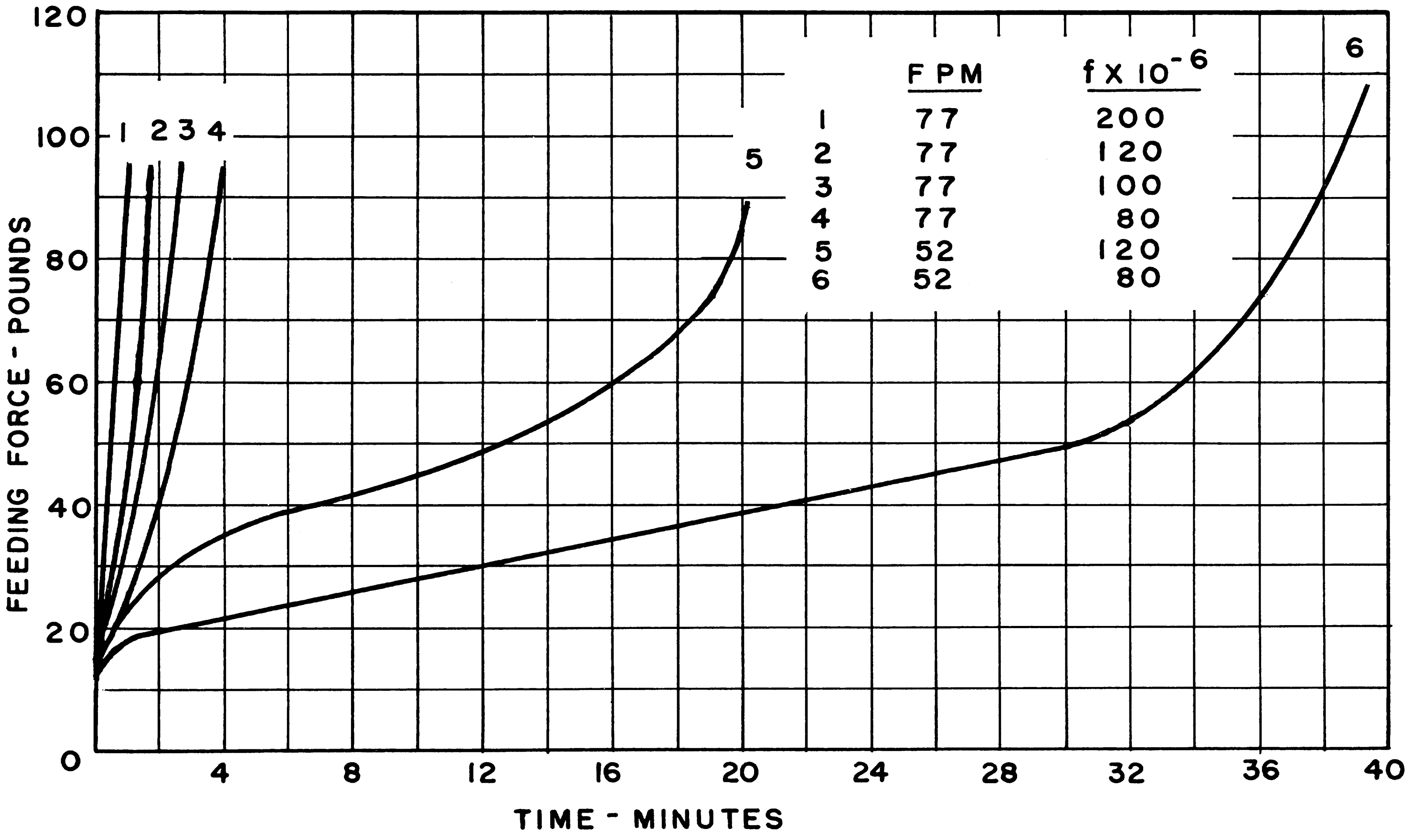

FIG. 28

BANDSAWING

CUTTING SPEED — TOOL LIFE

3/4" WIDE, 6 PITCH, SIMONDS, "HARD EDGE" BLADES

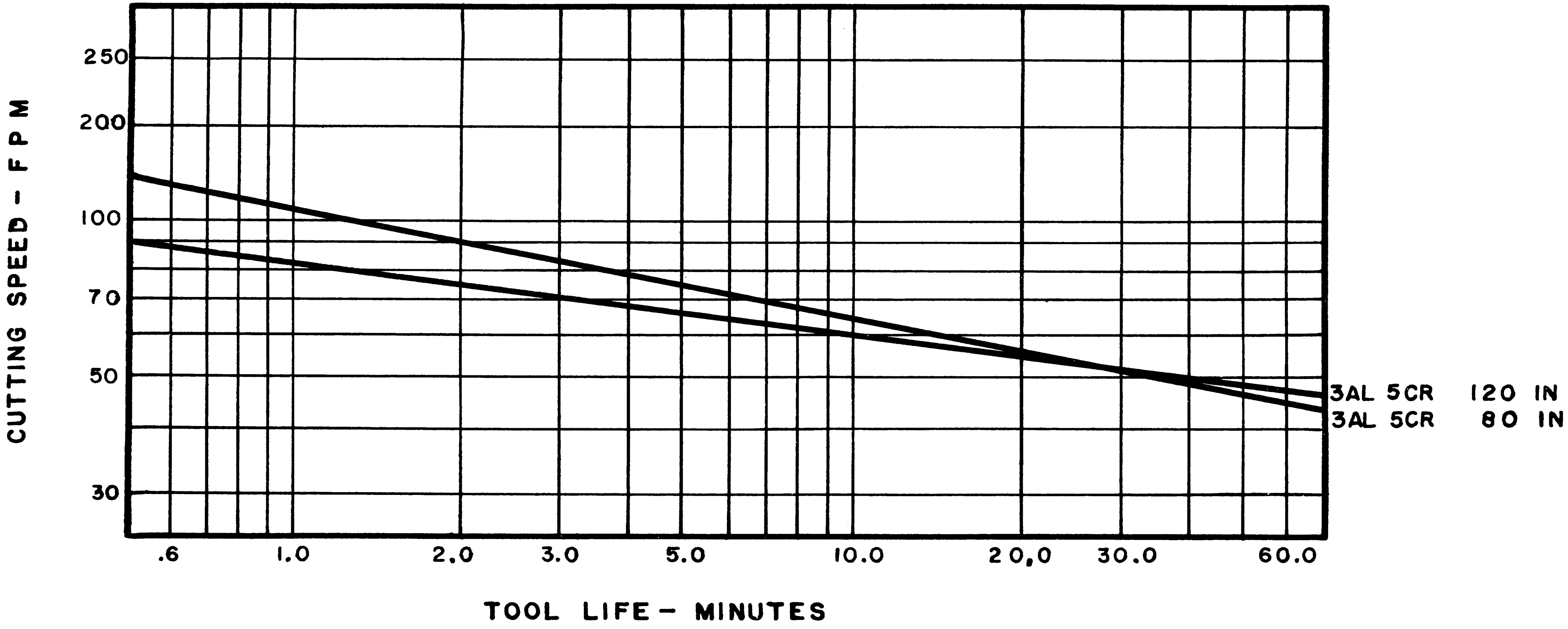

FIG. 29

BANDSAWING

CUTTING SPEED - TOOL LIFE

MATERIAL: RC-110A
VELOCITY: VARIABLE

FEED: 80×10^{-6} &
120×10^{-6}

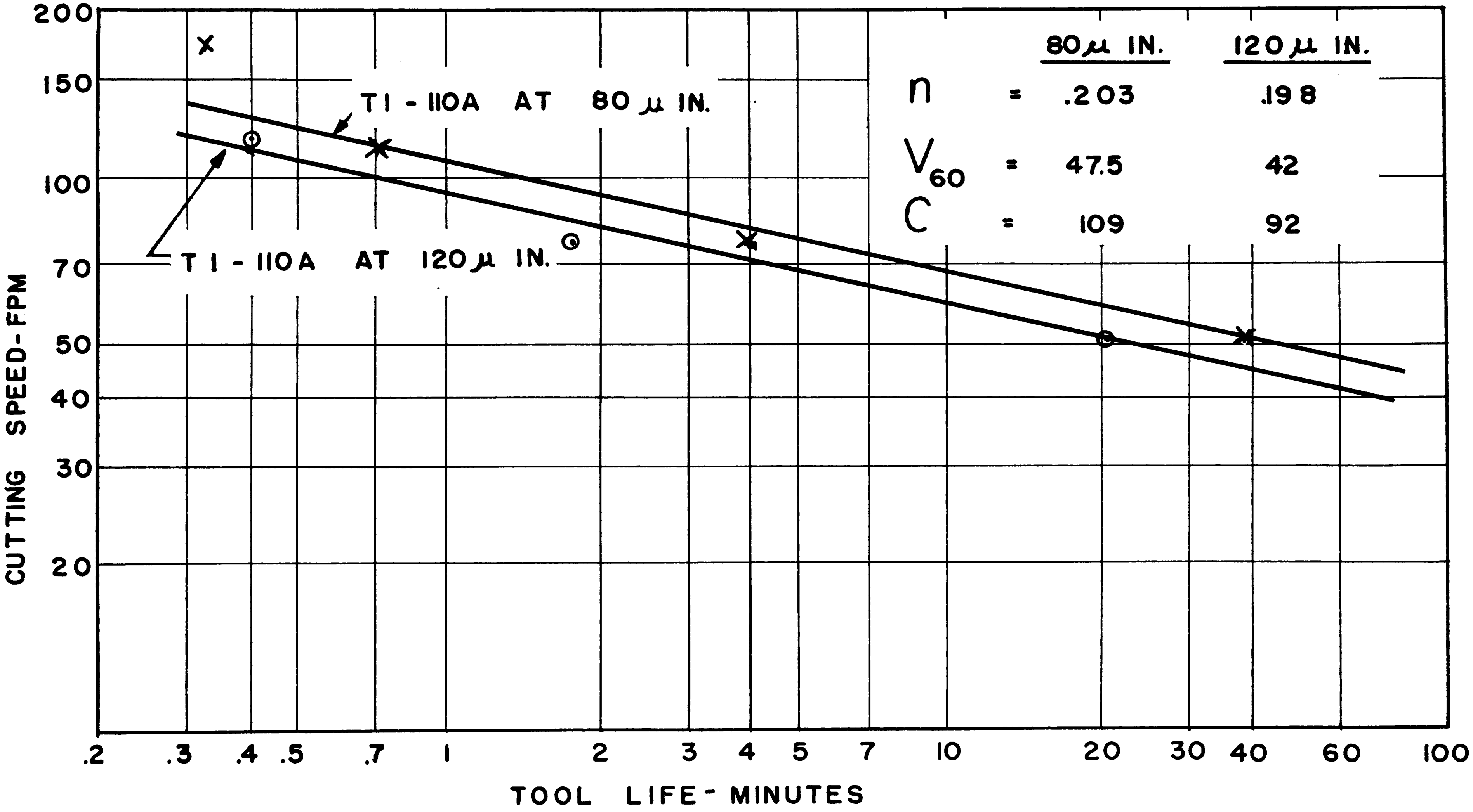

FIG. 30

BANDSAWING

MATERIAL: 3AL 5CR

SPEED VARIABLE

AREA OF CUT

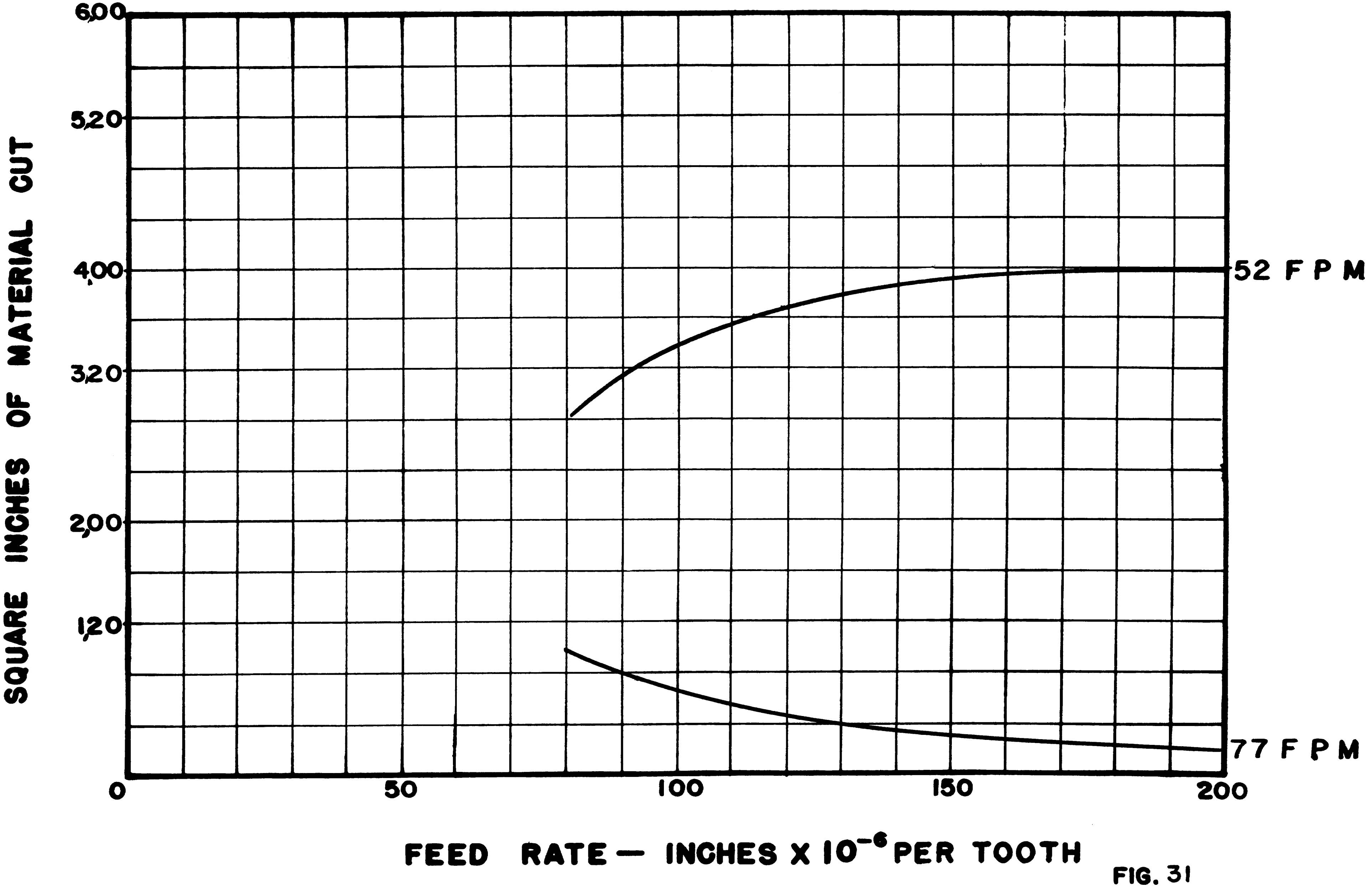

FIG. 31

BANDSAWING

MATERIAL CUT- FEED RATE

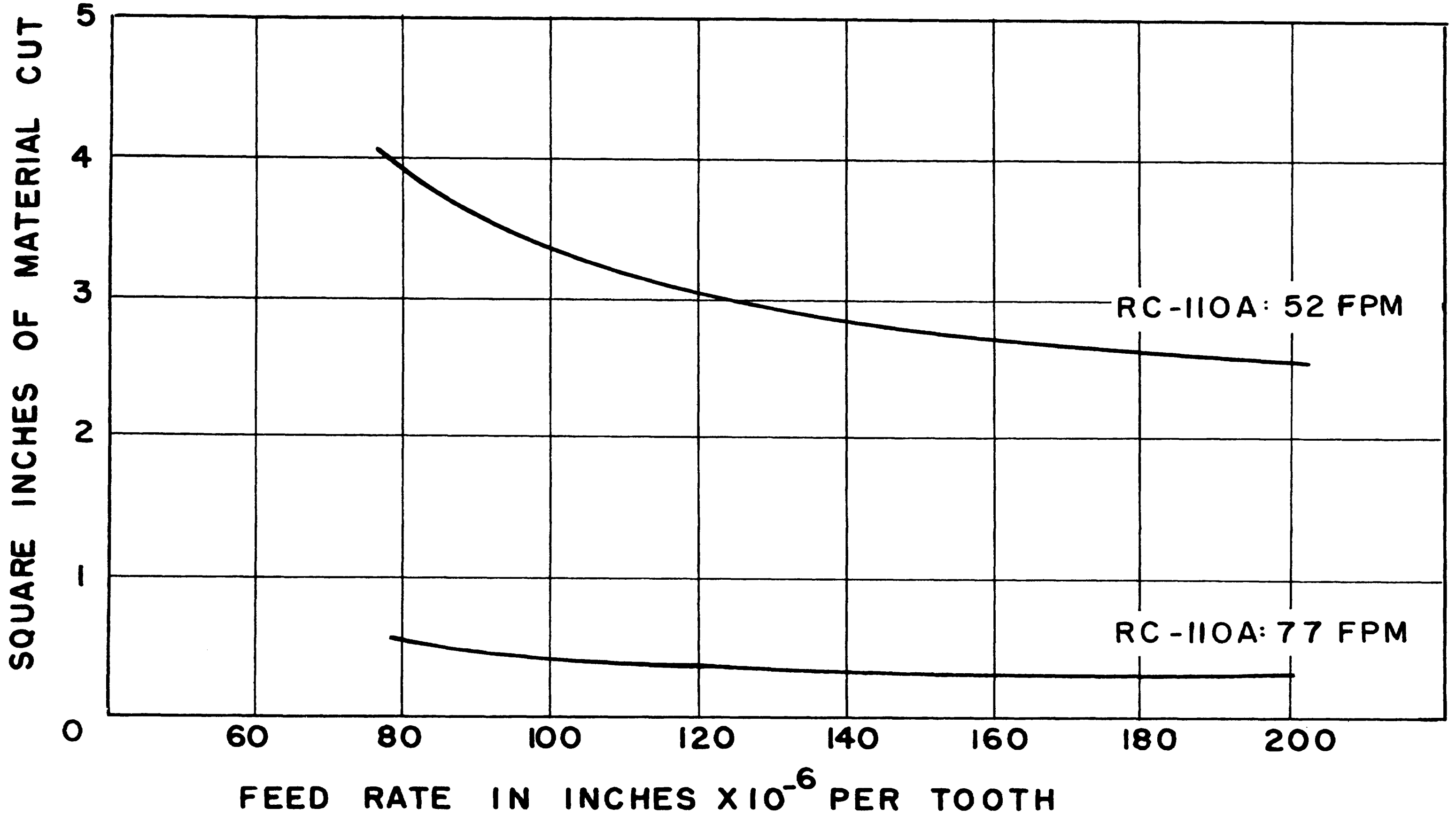

FIG. 32

VELOCITY: 52 FPM
MATERIAL: 3AL 5CR

BANDSAWING

FEED RATE: VARIABLE

FORCE TESTS

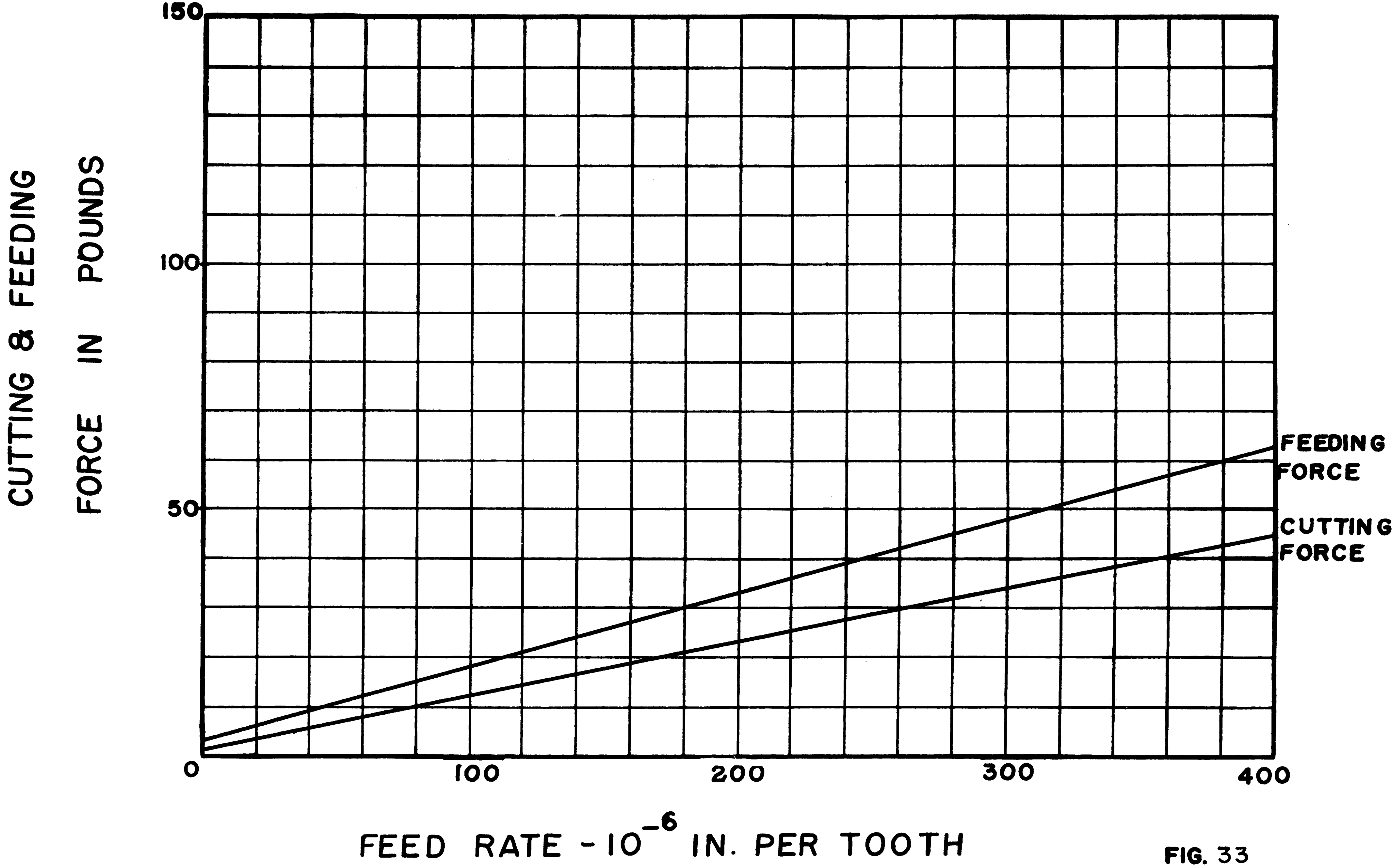

FIG. 33

BANDSAWING

FORCE TESTS

MATERIAL : RC-110A

VELOCITY: 52 FPM

FEED RATE: VARIABLE

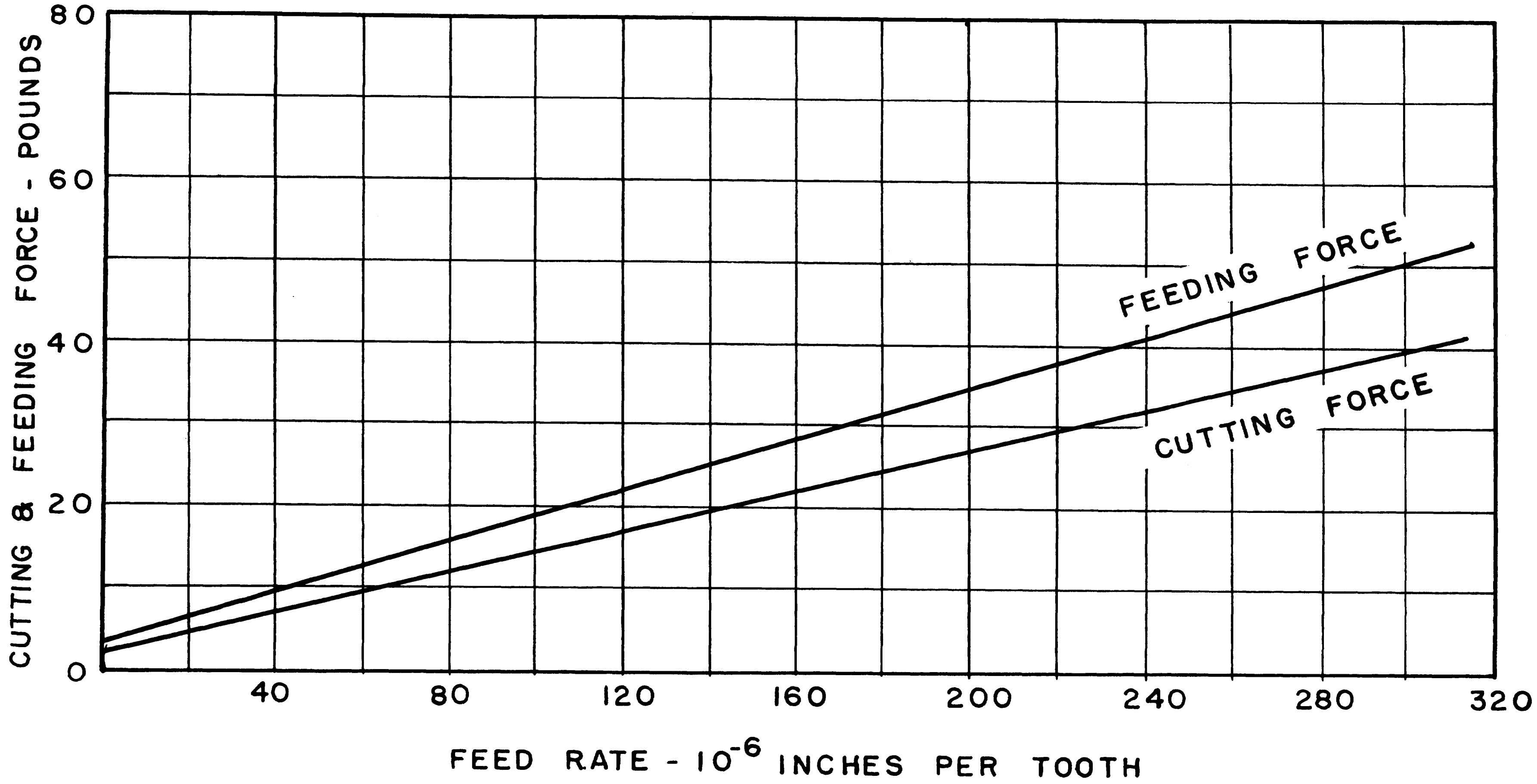

FIG. 34

VELOCITY 52 FPM

FEED RATE VARIABLE

BANDSAWING

FORCE TESTS

MATERIAL 3AL 5CR

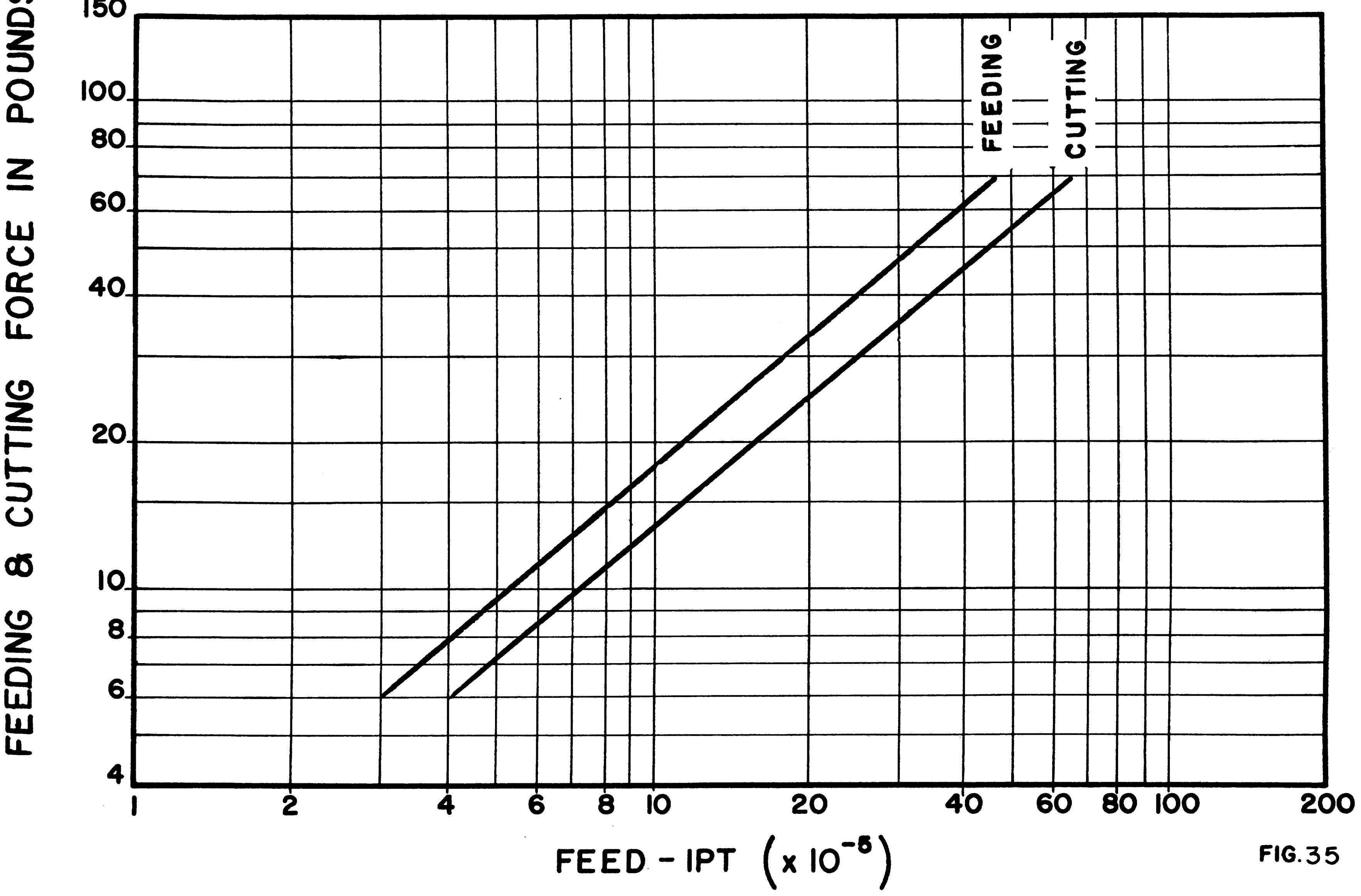

FIG. 35

BANDSAWING

CUTTING & FEEDING FORCE VS FEED

MATERIAL: RC-110A

VELOCITY: 52 FPM

FEED: VARIABLE

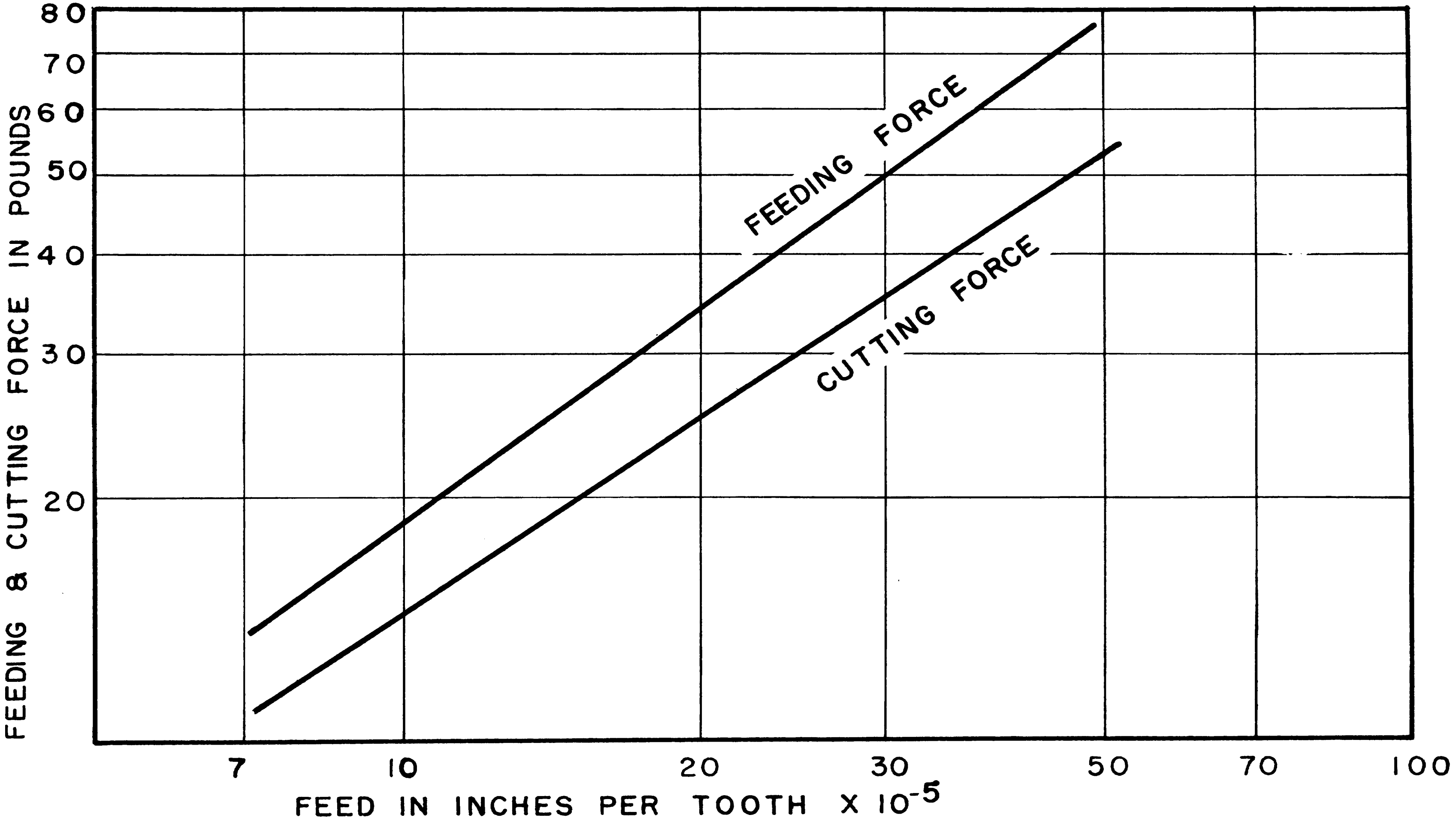

FIG. 36

SURFACE FINISH VS FEED

(TURNING)

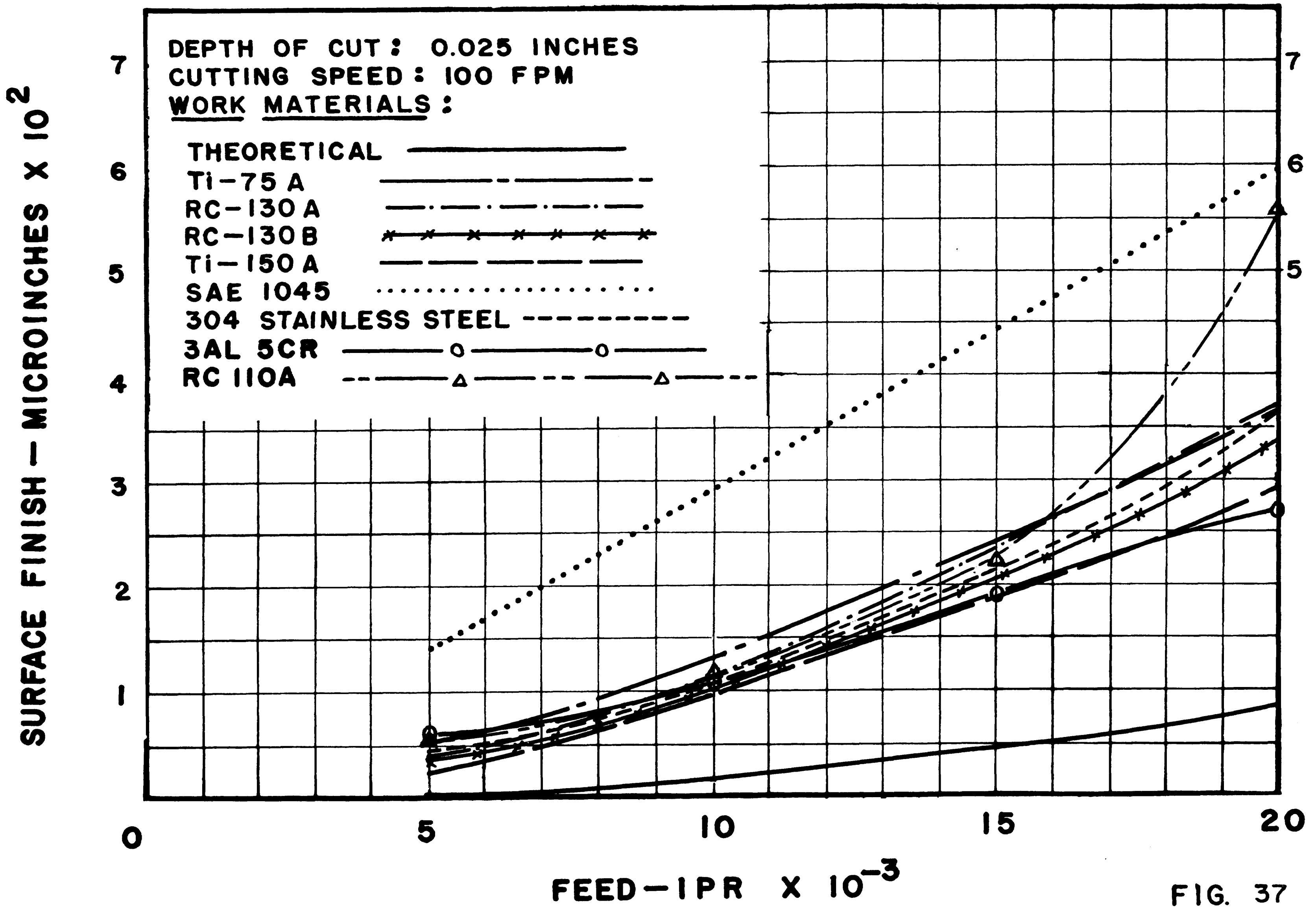

FIG. 37

SURFACE FINISH VS FEED

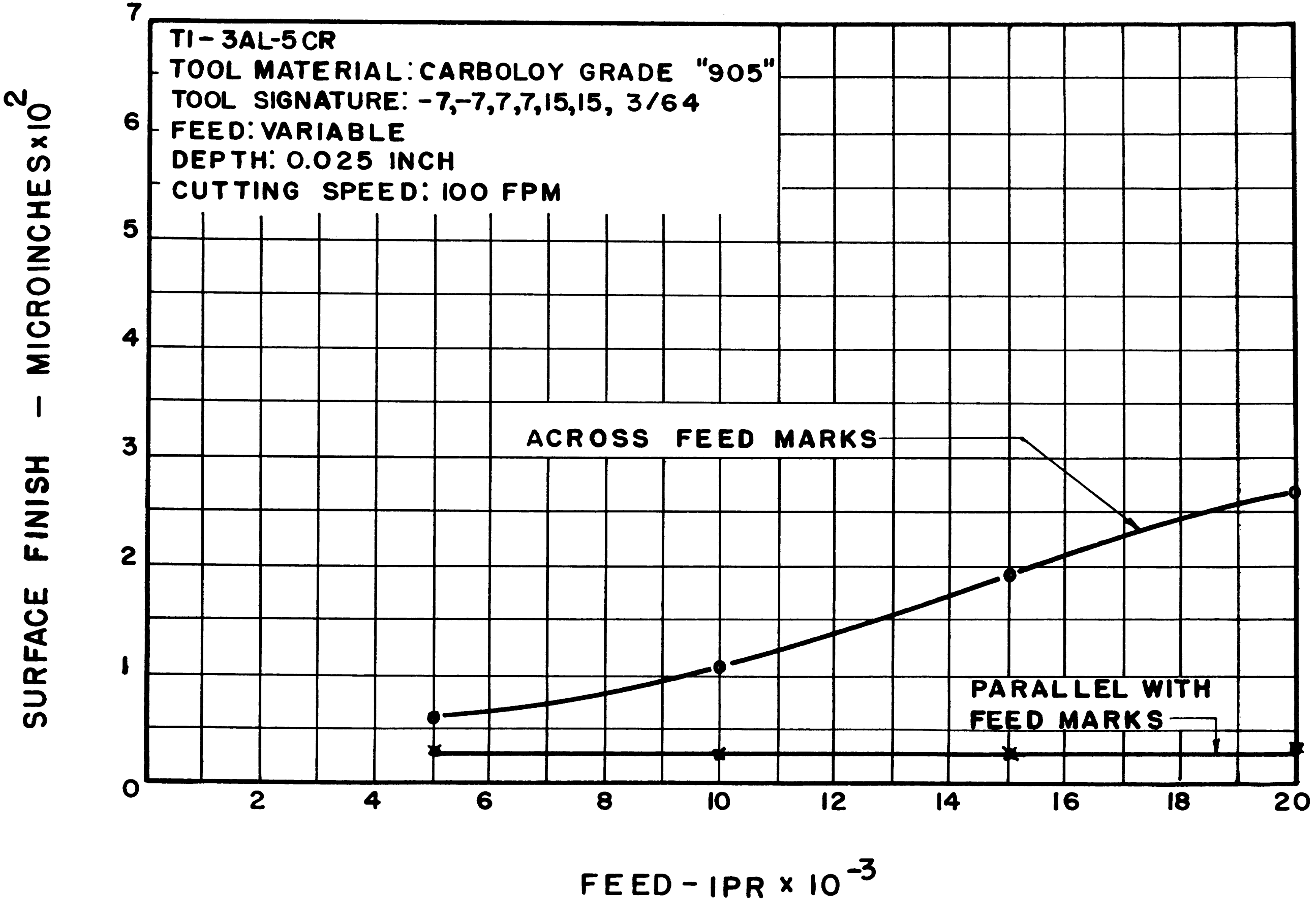

FIG. 38

SURFACE FINISH VS FEED

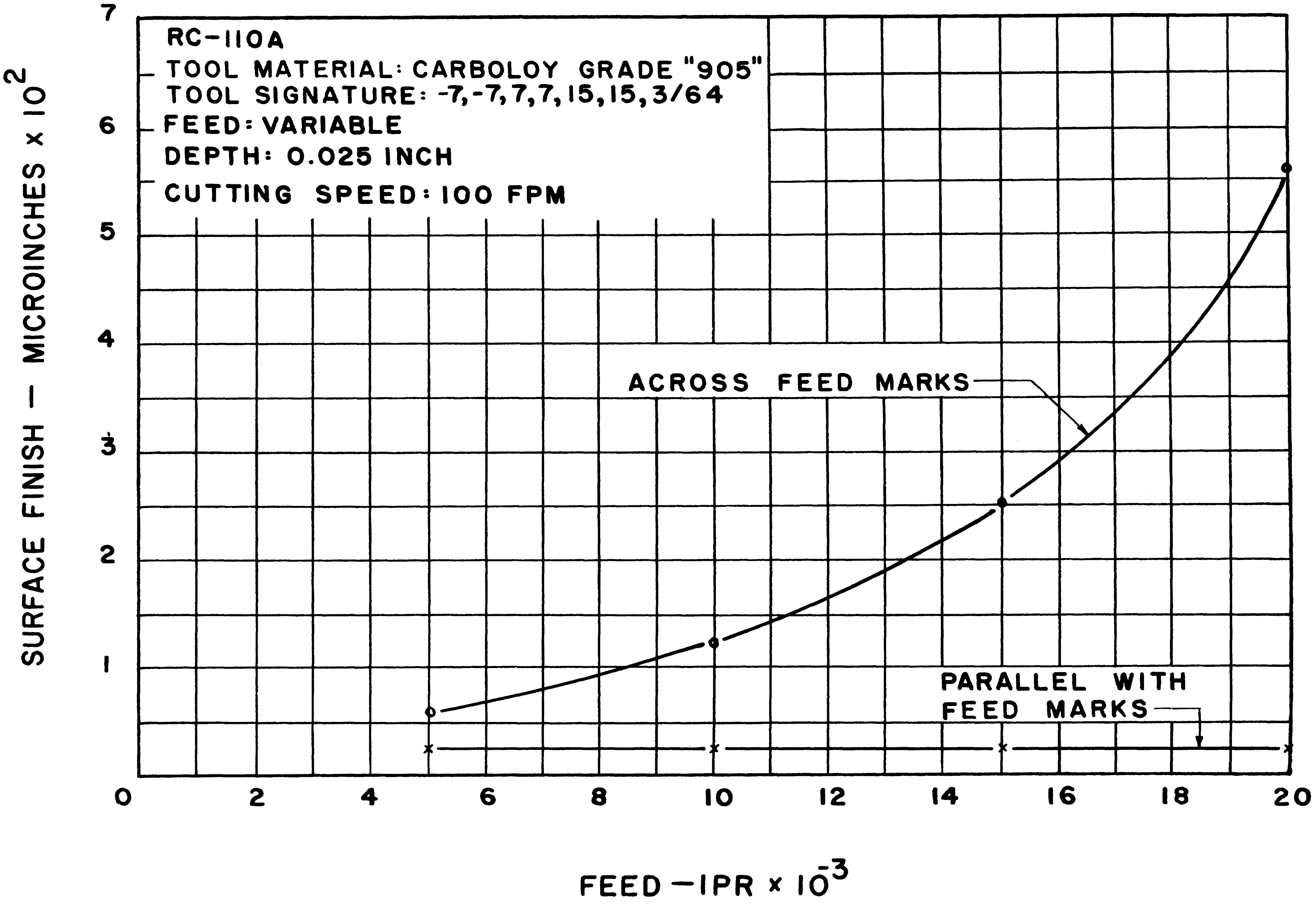

FIG. 39

SURFACE FINISH VS CUTTING SPEED

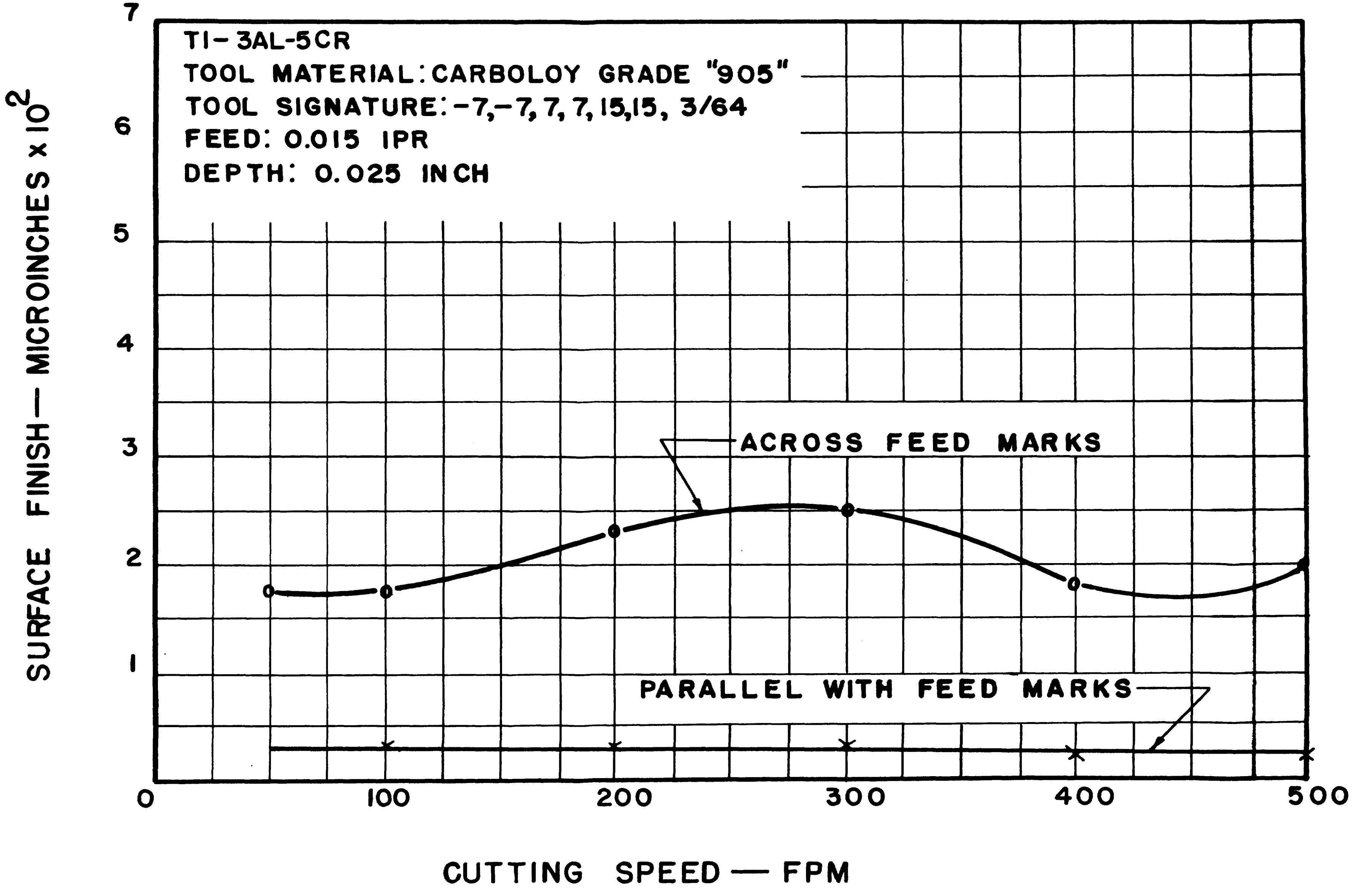

FIG. 40

SURFACE FINISH VS CUTTING SPEED

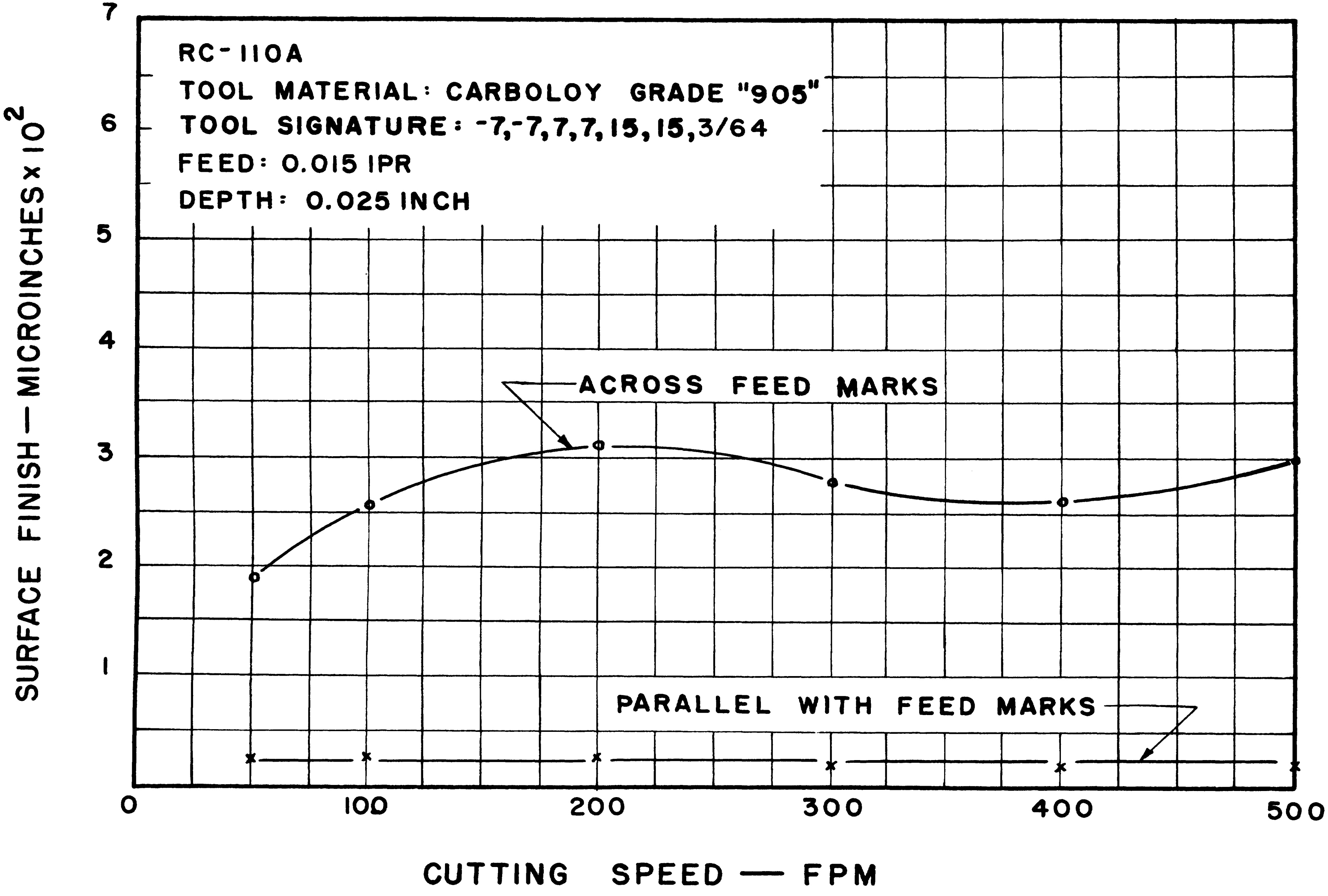

FIG. 41