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UNIVERSITY OF MICHIGAN
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Final Report

THE EFFECT OF MICROSTRUCTURE ON THE MACHINABILITY OF X4340 STEEL AT SHOP CONDITIONS

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ABSTRACT

This investigation was conducted for the purpose of determining whether a change in microstructure of the steel as it is machined in the production shop could effectively increase tool life and thereby increase production. Prior discussions and an earlier survey in the production shop indicated that tool life was determined by the machine operator's men on the basis of visual evaluation of surface finish rather than on the tool wear. In other words, it was shop experience that surface finish deteriorated significantly at an earlier stage than prohibitive tool wear. This investigation demonstrates feasibility of delaying the onset of unsatisfactory surface finish by using an appreciably harder microstructure as represented by steel heat-treated to a strength in the range of 160,000 to 180,000 psi.

INTRODUCTION

This investigation arose from a problem existing in the production shop of the Bendix Products Division. It was observed by machine operators and other personnel that less difficulty was experienced in machining high-strength steels compared to material of lower strength. It was further observed that the difficulties experienced with lower-strength materials were associated with surface finish. It was stated that the softer or lower-strength steel was "gummy" and that these conditions tended to reduce tool life by making it necessary to resharpen tools at more frequent intervals for the specific purpose of maintaining smoother machined surfaces.

The question was raised as to whether a different microstructure might not improve this situation. This investigation was introduced to answer that question. It was considered to be a preliminary to further work, provided the substantially different microstructures to be studied during this investigation indicated that further investigation was worthwhile.

Four quite different microstructures were prepared by heat treatment of actual aircraft struts. These were milled at simulated shop conditions in the machine tool laboratory at the University of Michigan. In addition, laboratory specimens of X4340 steel in the form of 1- x 4- x 6-inch plates were heat-treated to three different microstructures and milled over a broad range of cutting conditions.

In brief the results of this investigation appear to indicate the feasibility of increasing tool life by changing microstructure where tool life is determined primarily by surface-finish characteristics. Thus, in a production shop where for various reasons of equipment limitations it is not desirable to increase cutting speeds, and where the decision to regrind cutters is based on visual observations, it is possible to select a microstructure that will result in less frequent tool regrinds even though the microstructure represents a higher hardness level which at other cutting conditions would cause a reduction in tool life.

PROGRAM OUTLINE

The laboratory investigation was divided into four phases, three of which are reported here. The first phase was preliminary in nature for the purpose of determining the general level of cutting conditions necessary to obtain the type of information desired. This phase did not yield any quantitative information and is therefore not recorded in this report. The three phases of the investigation, designated hereafter as Phase I, Phase II, and Phase III, each had specific objectives.

Phase I used milling cutters available in the laboratory to cut X4340 plates heat-treated to three different structures, a patent-anneal, a cycle-anneal, and 180,000-psi. The objective of this phase was to determine the rate of tool wear and the surface finish at a variety of speeds, sizes of cut, and cutter conditions.

Phase II was a series of cuts made with actual landing strut housings while using a set of cutters furnished by the sponsor. These cutters had been in actual use in the sponsor's plant. Four different microstructures were investigated during this series.

Phase III returned to the laboratory conditions using the steel plate specimens and laboratory cutters. This final phase was devoted to a more careful study of the effect of cutting speed on tool life and surface finish.

TEST RESULTS

PRELIMINARY RESULTS

Although no quantitative data were obtained from the preliminary tests, the test conditions as to cutters, etc., are listed in Table I to complete the record. The qualitative results made it possible to determine the general level of conditions for conducting subsequent tests.

TABLE I

CONDITIONS FOR PRELIMINARY SURVEY

(a) Cutters.

The following cutters were chosen for preliminary testing:

1. 6" dia., h.s.s. inserted tooth, 8 teeth, 1-1/4" bore, and width of 1-1/4";
2. 5" dia., h.s.s. inserted tooth, 12 teeth, 1-1/4" bore, and width of 7/8"; and

3. 5-1/8" dia., h.s.s. inserted tooth, 14 teeth, 1-1/4" bore, and width of 1".

(Rake angles and corner radii are given in the phase and steps in which the cutters were used.)

(b) Cutting Conditions.

Material: Bx-200-C (1 x 4 x 6) patent anneal.

Cutter: 6" dia., h.s.s., 8 teeth, rake angles, 6° radial, 8° axial, and 1/8" corner radius.

1. Cutting speed, varied, 42, 56, 75 fpm; feed, 0.004 ipt.
2. Cutting speed, 104 fpm; feed, varied, 0.0005, 0.0012, 0.005 ipt.
3. Cutting speed, 140.5 fpm; feed, 0.0036 ipt.

(c) Results.

Appreciable wear occurred in three cuts at cutting speed of 140 to 150 fpm; feed, 0.0036 ipt.

PHASE I

Phase I consisted of five distinct steps involving milling cuts with arbor-mounted cutters where the width and depth of cut were held constant at approximately 0.150 and 0.750 inch, respectively. Three microstructures were studied in this phase; a patent-anneal structure, a cycle-anneal structure, and a structure giving a strength of 180,000 psi. The heat-treating conditions are given in Table II. The work specimens consisted of plates 1 x 4 x 6. The first three steps were made at substantially the same feed and cutting speed, but with decreasing corner radii on the cutters. The fourth step was made at a substantially reduced speed duplicating that which is in current use at the sponsor's plant. The last step investigated the effect of feed by using two feed rates at a ratio of 10 to 1.

Step 1.—In this series of tests three cuts were taken with 6-inch diameter, 8-tooth high-speed steel cutters at a cutting speed of 140 to 150 fpm and a feed rate of 0.0035 inch per tooth. At the end of each cut the wear on each of the eight teeth was measured and averaged. The results are plotted in Fig. 1. It will be noted that the wear was substantially the same after the first cut on the three metals since the average was between 0.007 and 0.008 inch. The wear progressed somewhat more slowly after the first cut. To the extent that the differences are significant, it would appear that the cycle-anneal structure produces less wear.

Step 2.—The tests made in Step 2 were at the same conditions as in Step 1 except that the cutter radius was reduced from 1/8 to 1/16 inch. The

TABLE II

HEAT TREATMENT OF 1 x 4 x 6 SPECIMENS OF X4340 STEEL

Specimen Code	Heat Treatment		Resultant Hardness Brinell	Rockwell-C
Bx-200-C Bx-200-E	Patent Anneal	1575°F, 3 hours; air cool; reheat to 1250°F, 3 hours; air cool.	255	25
Bx-200-J Bx-200-K	Cycle Anneal	1575°F, 3 hours; cool to 1190° in 45 min (1190°F, furnace No. 2 after 5-min set; furnace to 1210°F, 8 hours.	217	18
Bx-300-3	180,000 psi	1575°F, 2 to 3 hours; oil quench; (agitate thoroughly); temper for 2 hours (950°F).	363	38

cutter diameter was only 5 inches, however, so that the nearest comparable cutting speed was 161 fpm. The test procedure was the same as in Step 1 and yielded tool wear results as plotted in Fig. 2. In this series there was a substantial difference between the three microstructures indicating that the cycle anneal produced lowest wear; the patent anneal, intermediate; and the 180,000-psi structure, substantially greater wear than the other two.

Step 3.—The principal change in cutting conditions involved a cutter radius of zero, in other words, a sharp corner on the teeth and a slight increase in cutting speed up to 167 fpm. Once more the cycle anneal seemed to produce slightly less wear than the patent anneal while the cutter failed quite abruptly during the first cut on the 180,000-psi structure. The results for this step are plotted in Fig. 3.

Step 4.—In this series the speed was reduced to 42.6 fpm and the feed was reduced to 0.0023 ipt. These conditions were substantially the same as those in current use at the Bendix production shop. The same cutters as were used in Step 1 were used for this series. These cutters had 1/8-inch corner radii. The wear results are plotted in Fig. 4. Two things will be noted from this figure. First, the rate of wear is considerably less than in previous tests. Second, there was no noticeable difference in wear between the patent and cycle anneals while the 180,000-psi steel caused about 50 percent greater wear than either of the other structures.

Step 5.—Four tests were made using only the cycle-anneal and patent-anneal structures. The cutting conditions varied not only as to the feed rate but also as to the cutters. The tool-wear results are plotted in Fig. 5, and cutting conditions are designated as A, B, and C. These conditions are recorded in Table III. The tool wear was relatively low for the cycle-anneal material when milled with a feed of 0.0007 ipt. The heavier feed produced a faster rate of wear on the same structure as might be expected; however, it is significant that there was little difference in wear due to the difference in feed when milling the patent-anneal structure.

TABLE III

CUTTING CONDITIONS FOR STEP 5 OF PHASE I*

Condition A.
- Cutting speed, 160.9 fpm; feed, 0.00068 ipt.
- Cutter:
  - Radial rake, 10°
  - Axial rake, 9°
  - Corner radius, 1/16"

Condition B.
- Cutting speed, 160.9 fpm; feed, 0.0067 ipt.
- Cutter:
  - Radial rake, 10°
  - Axial rake, 9°
  - Corner radius 1/16"

Condition C.
- Cutting speed, 150.7 fpm; feed, 0.00062 ipt.
- Cutter:
  - Radial rake, 6°
  - Axial rake, 8°
  - Corner radius, 1/8"

*Applies to Fig. 5.

Surface Finish.—Surface-finish measurements were made with a profilometer for all of the cuts throughout Steps 1 to 5, inclusive. The results of these measurements are plotted in Figs. 6, 7, and 8. Figure 6 is for the patent-anneal structure, Fig. 7 for the cycle-anneal, and Fig. 8 for the 180,000-psi steel. In most cases the roughness measurements did not change appreciably with tool wear. However, there was little or no correlation between roughness on the one hand and cutting speed, feed rate, and cutter on the other. Roughness measurements for the patent-anneal material ranged from 100 microinches up to 275 microinches. Similarly, it varied from 80 microinches to 300 microinches for the cycle-anneal material. It is believed significant that the range for the 180,000-psi steel was only from 60 microinches up to 175 microinches. These data do correlate with a visual evaluation of the surfaces in that all observers agreed that the milled surfaces on the 180,000-psi steel looked better and were less variable than either of the other structures.

PHASE II

In the second phase of this investigation four landing-gear strut housings or forgings were heat-treated at the Bendix plant to four different conditions designated as cycle anneal, patent anneal, 160,000 and 200,000 psi. Two studies were carried out on these struts using cutters furnished by Bendix. The cutter specifications are recorded in Figs. 9 and 11 along with the data obtained from them.

Step 1.—In Step 1 a series of cuts was made at a cutting speed of 176 fpm and a feed of 0.0035 ipt. This speed is relatively high, but preliminary tests at a speed of 127 fpm on the 200,000-psi steel resulted in no measurable wear with a significant number of cuts; consequently, the speed was increased in view of the limited amount of metal available for test purposes. The tool-wear results are plotted in Fig. 9. The data are about as expected in light of the results obtained in Phase I. Cycle anneal produced the least wear; patent anneal was next; and then 160,000 psi and 200,000 psi in that order. Surface-roughness measurements were made after all cuts and the data are shown plotted in Fig. 10. It is significant that the cycle-anneal structure produced the greatest average roughness despite its having the lowest rate of tool wear and therefore the sharpest cutters. Only a limited amount of information was available for the 200,000-psi steel since it failed at the third cut. However, it is significant that the measured roughness was only 60 microinches during the first two cuts as compared to a range of 120 to 160 microinches for the cycle-anneal structure. The patent anneal appeared to be relatively good in that the readings averaged about 100 microinches after the first two cuts. Surface-roughness measurements and tests made at these conditions are complicated by the fact that chatter is not completely eliminated. It was not present at all times, but would show up in some areas during some of the cuts and no attempt was made to avoid these areas in making the roughness measurements. In general, it appeared that the tendency to chatter increased with increased strength of the work material. On the other hand, it can be concluded that if the rigidity of fixtures and tool mounting in a production setup is adequate to prevent chatter, then the harder materials will produce better finish and effectively longer, useful tool life.

Step 2.—A second series of cuts was made with the same materials and cutters, but for the sole purpose of evaluating the effect of cutting speed on surface finish while using the same cutting fluid in current use at the Bendix plant. These results are plotted in Fig. 11. They seem to be at variance with the data plotted in Fig. 10 and with some of the information obtained during Phase I. The cycle-anneal structure in this case produced the lowest average readings varying from 90 to 125 microinches. This particular series of tests was complicated by chatter when the work specimens were already quite thin as a result of material removed in Step 1. Consequently, the data shown in this figure are not to be conclusive.

PHASE III

A final series of tests was made with the cycle-anneal and 180,000-psi structures using the laboratory cutters and 1- x 4- x 6-inch plates. The prime objective of this series was to evaluate the effect of a range of cutting speed on tool wear and surface finish for these two representative structures. The results for the cycle-anneal structure are plotted in Figs. 12 and 13 while corresponding information for the 180,000-psi structure is plotted in Figs. 14 and 15.

Tool-wear data obtained for milling of the cycle-anneal material are plotted in Fig. 12 for the five different cutting speeds ranging from 66.7 fpm up to 160.9 fpm. It will be noted that the level of wear increases with speed as expected. However, the curve for 125.6 fpm is higher than that for 160.9 fpm. This is the result of chance since a single tooth may be subject to sudden abnormal wear which will affect the rest of the cutter. It is suspected that this may have occurred at both the 102.1- and 125.6-fpm speeds. The surface-roughness measurements for this series of cuts are plotted in Fig. 13, indicating a range from 130 to 340 microinches.

The corresponding tool-wear data for the 180,000-psi structure are plotted in Fig. 14. The level of wear is greater than for the cycle-anneal structure although it is not prohibitive in the speed range of 60 to 85 fpm. Surface-roughness measurements for the structure are plotted in Fig. 15. It is most significant that the range varies only from 100 to 170 microinches compared to the 130 to 340 microinches for the cycle-anneal material. It is especially significant that the roughness decreases with an increase in cutting speed.

CONCLUSIONS

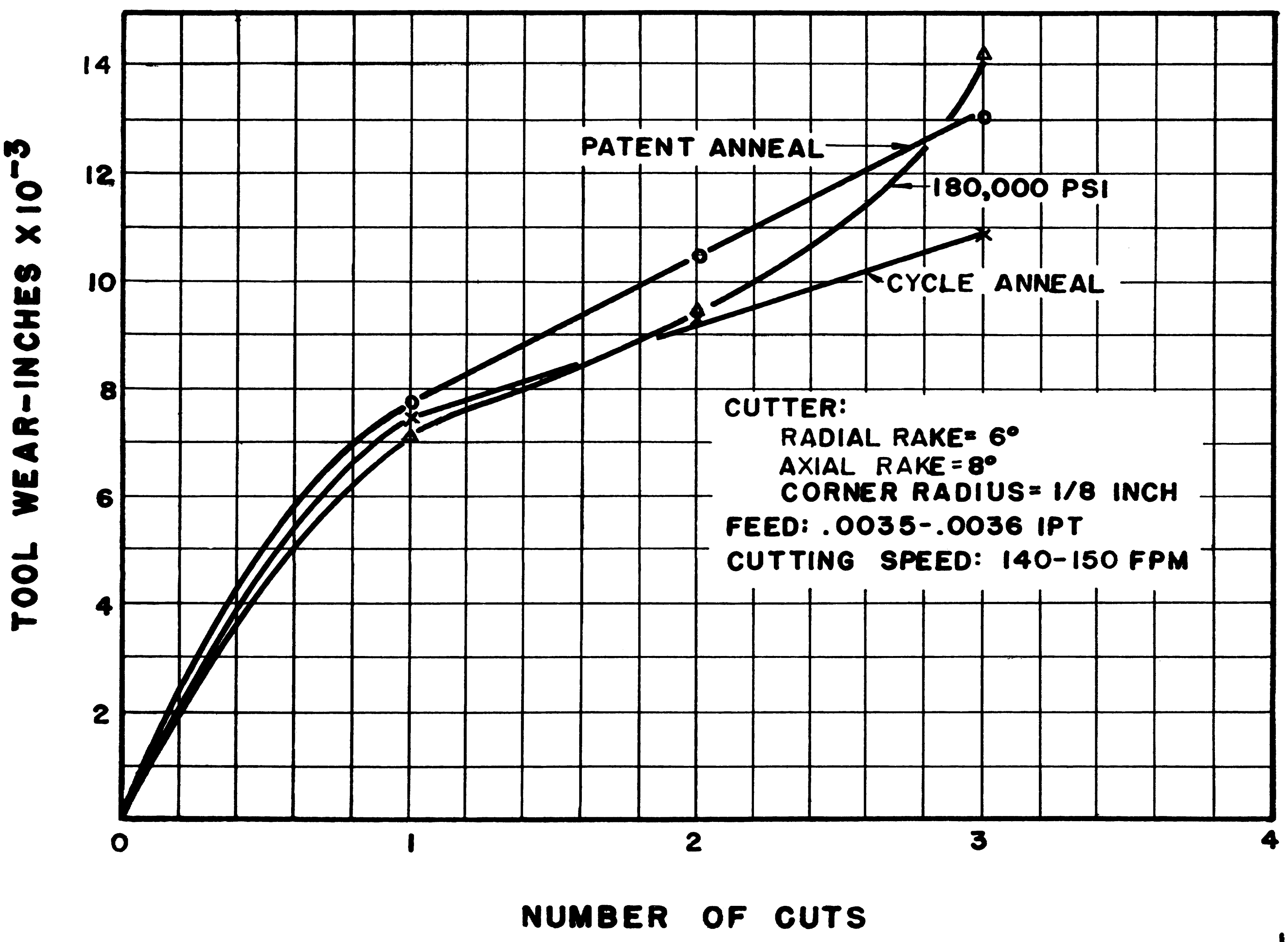
1. An increase in the strength of steel invariably increases the rate of tool wear for a given set of cutting conditions.

2. An increase in strength of steel can decrease the level of surface roughness.

3. Compared at a cutting speed of approximately 65 fpm, the 180,000-psi structure and the cycle-anneal structure both produce moderate and acceptable rates of tool wear, but the surface finish is substantially improved in the case of the 180,000-psi steel since it shows an average roughness of only 160 microinches compared to 200 to 250 for the cycle-anneal structure cut at the same conditions.

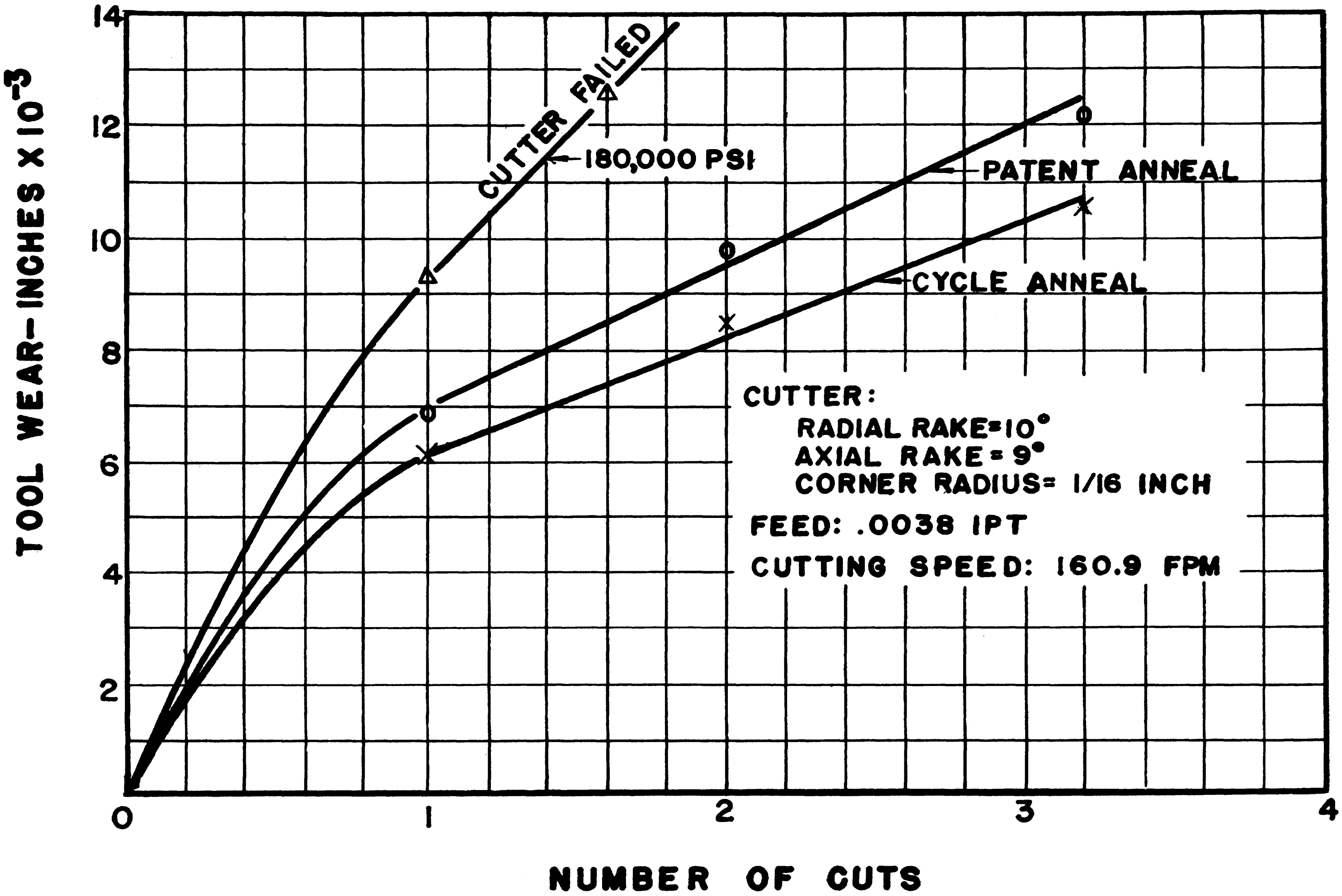
4. Based on the probable assumption that tool life in a production shop is based more on surface finish than on tool wear, this investigation demonstrates the feasibility of increasing effective tool life through the use of a harder or stronger microstructure.

TOOL WEAR

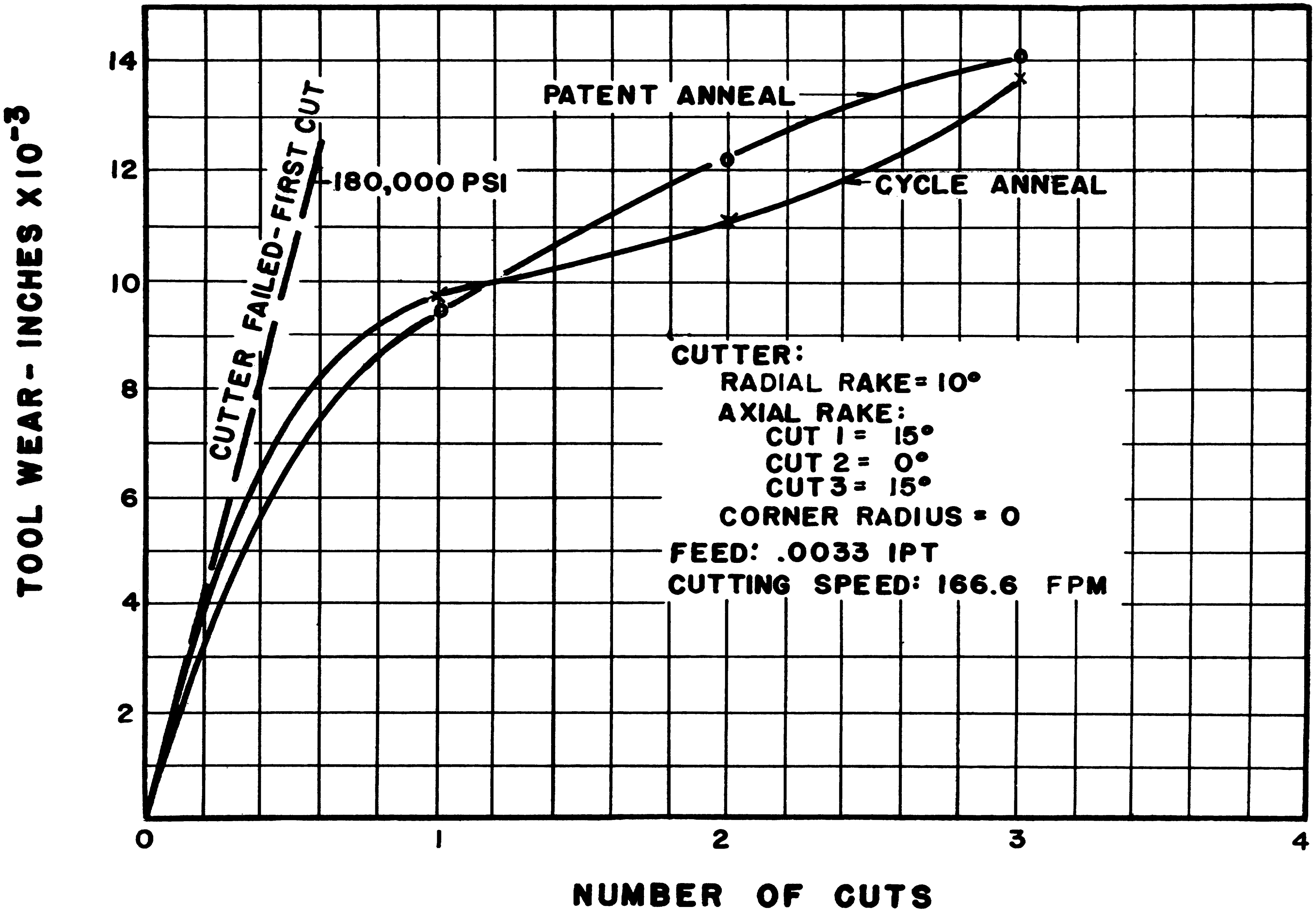


TOOL WEAR-INCHES X 10^-3
14
12
10
8
6
4
2
0
1
2
3
4
PATENT ANNEAL
180,000 PSI
CYCLE ANNEAL
CUTTER:
RADIAL RAKE= 6°
AXIAL RAKE=8°
CORNER RADIUS= 1/8 INCH
FEED: .0035-.0036 IPT
CUTTING SPEED: 140-150 FPM
NUMBER OF CUTS

TOOL WEAR

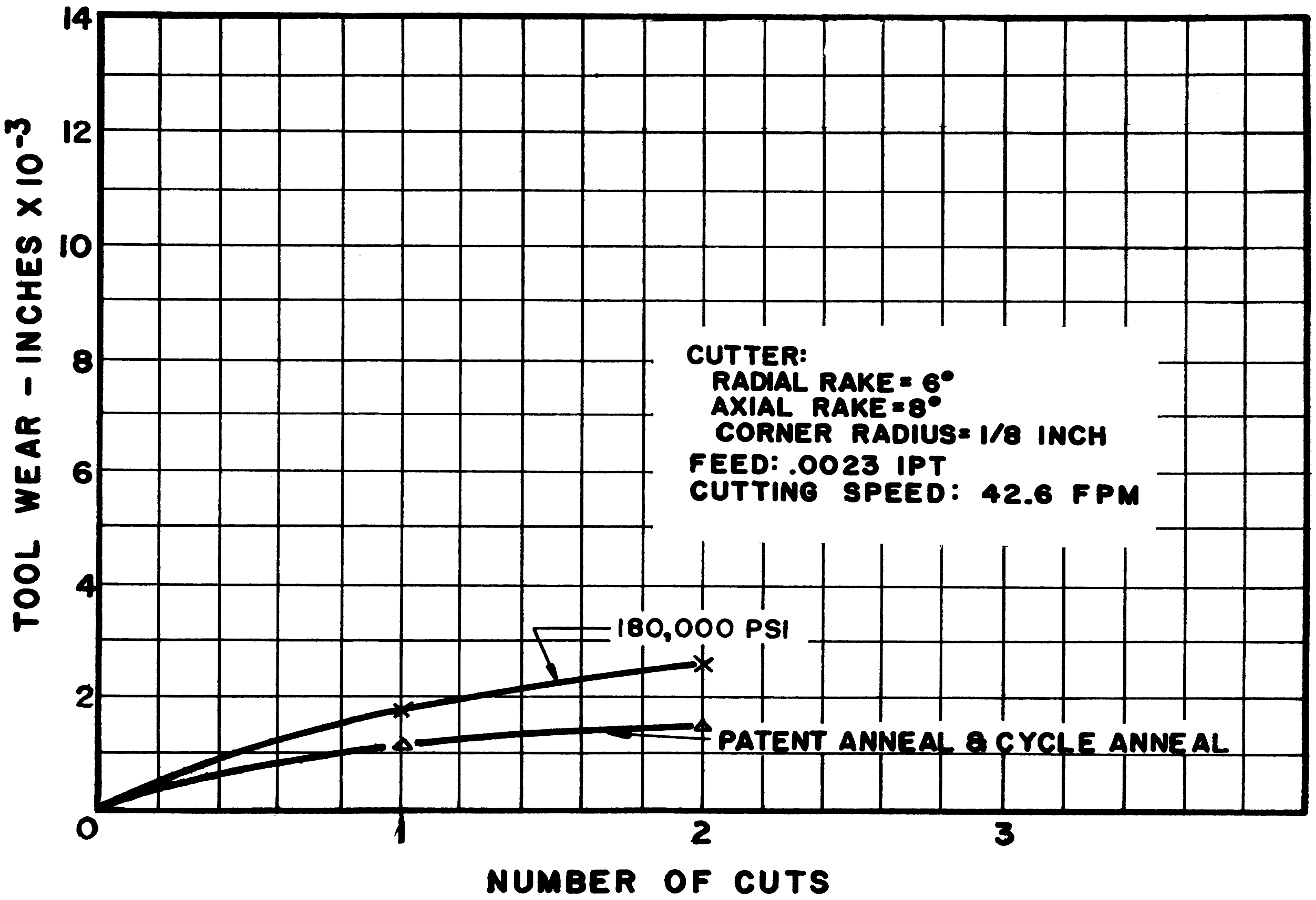

TOOL WEAR-INCHES X 10^{-3}
0
2
4
6
8
10
12
14
1
2
3
4
CUTTER FAILED
180,000 PSI
PATENT ANNEAL
CYCLE ANNEAL
CUTTER:
RADIAL RAKE=10°
AXIAL RAKE=9°
CORNER RADIUS= 1/16 INCH
FEED: .0038 IPT
CUTTING SPEED: 160.9 FPM
NUMBER OF CUTS

TOOL WEAR



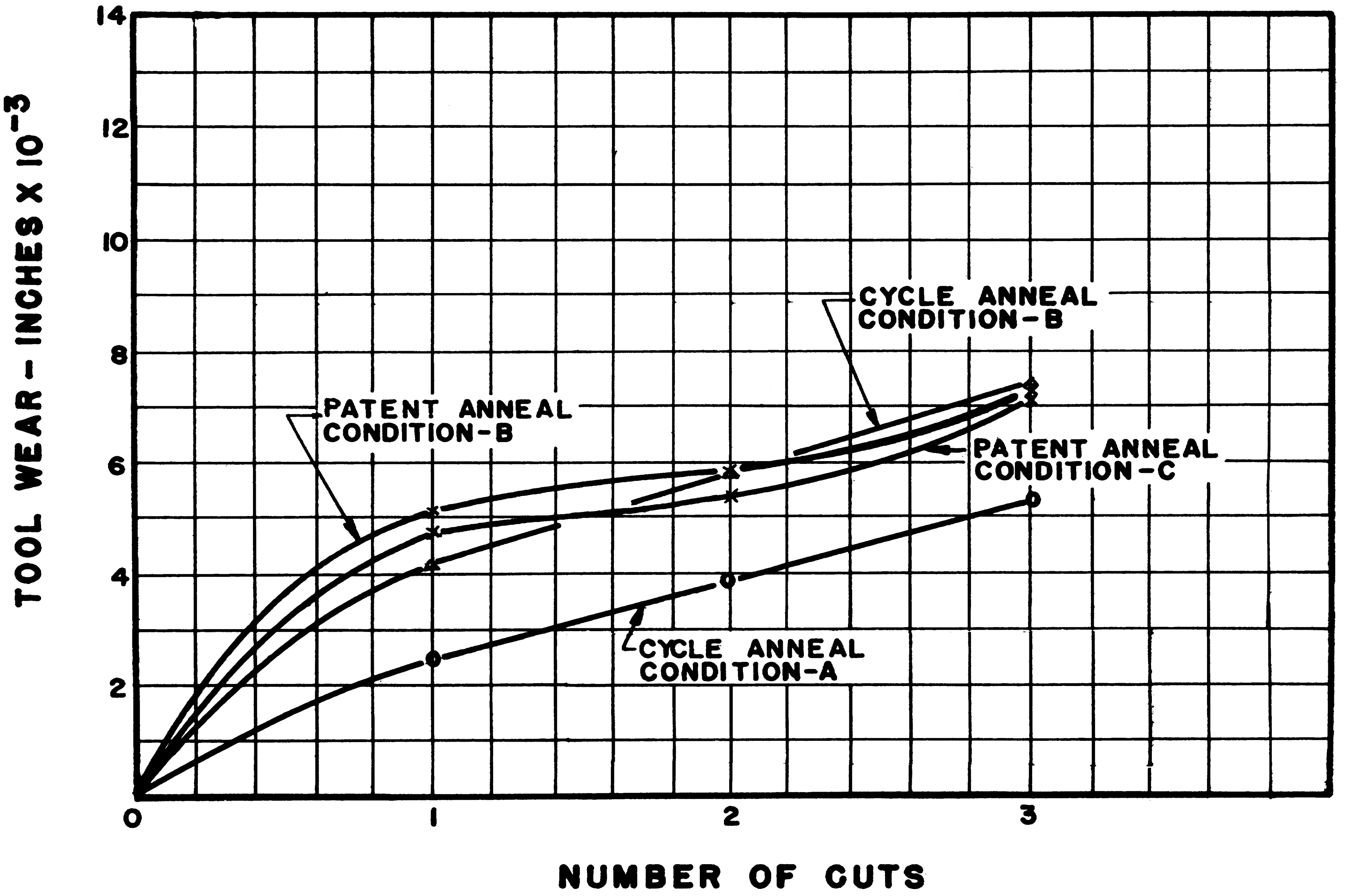
TOOL WEAR - INCHES X 10^-3
14
12
10
8
6
4
2
0
1
2
3
4
NUMBER OF CUTS
PATENT ANNEAL
CYCLE ANNEAL
180,000 PSI
CUTTER FAILED-FIRST CUT
CUTTER:
RADIAL RAKE = 10°
AXIAL RAKE:
CUT 1 = 15°
CUT 2 = 0°
CUT 3 = 15°
CORNER RADIUS = 0
FEED: .0033 IPT
CUTTING SPEED: 166.6 FPM

TOOL WEAR

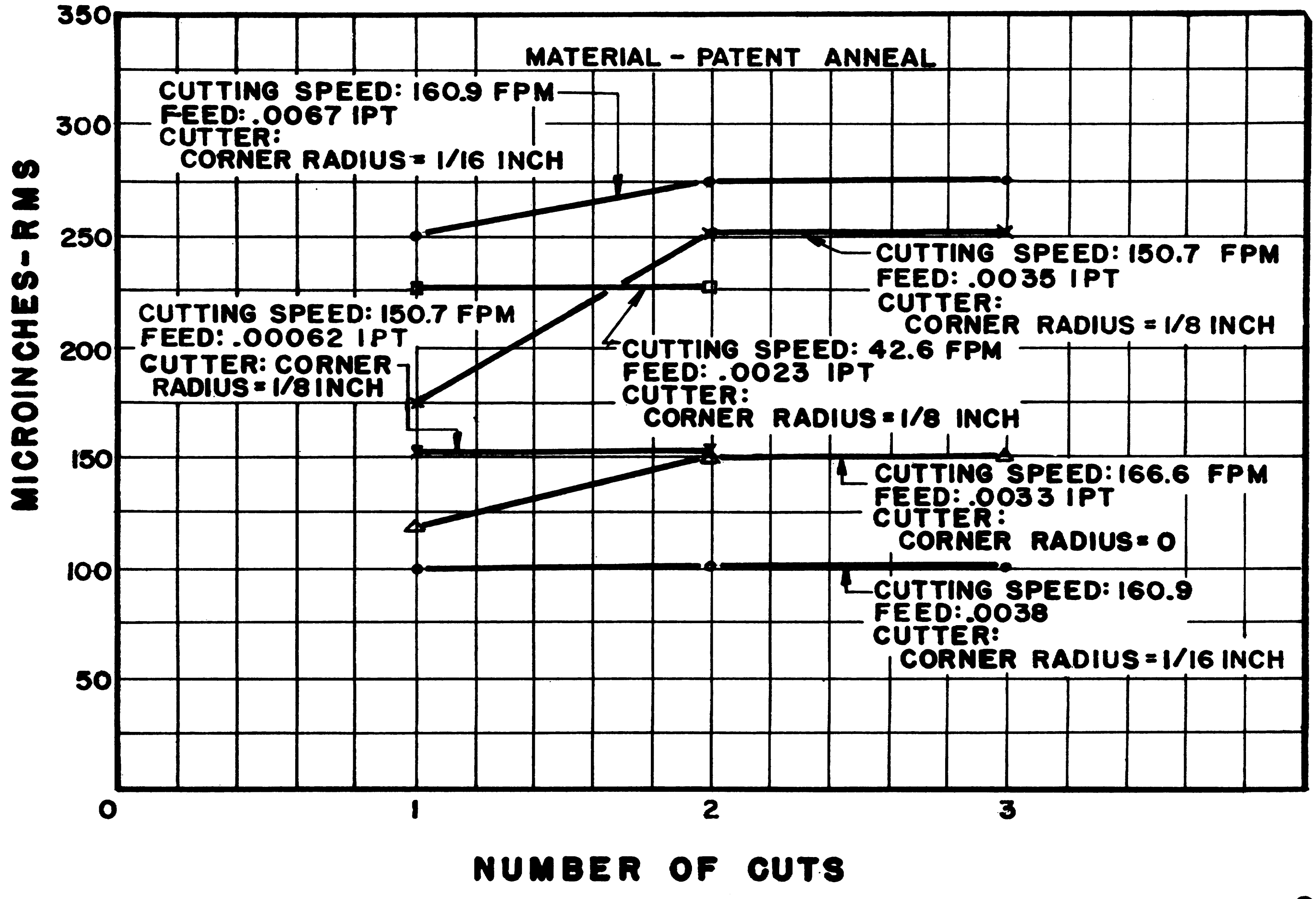


TOOL WEAR - INCHES X 10^-3
14
12
10
8
6
4
2
0
1
2
3
NUMBER OF CUTS
CUTTER:
RADIAL RAKE = 6°
AXIAL RAKE = 8°
CORNER RADIUS = 1/8 INCH
FEED: .0023 IPT
CUTTING SPEED: 42.6 FPM
180,000 PSI
PATENT ANNEAL & CYCLE ANNEAL

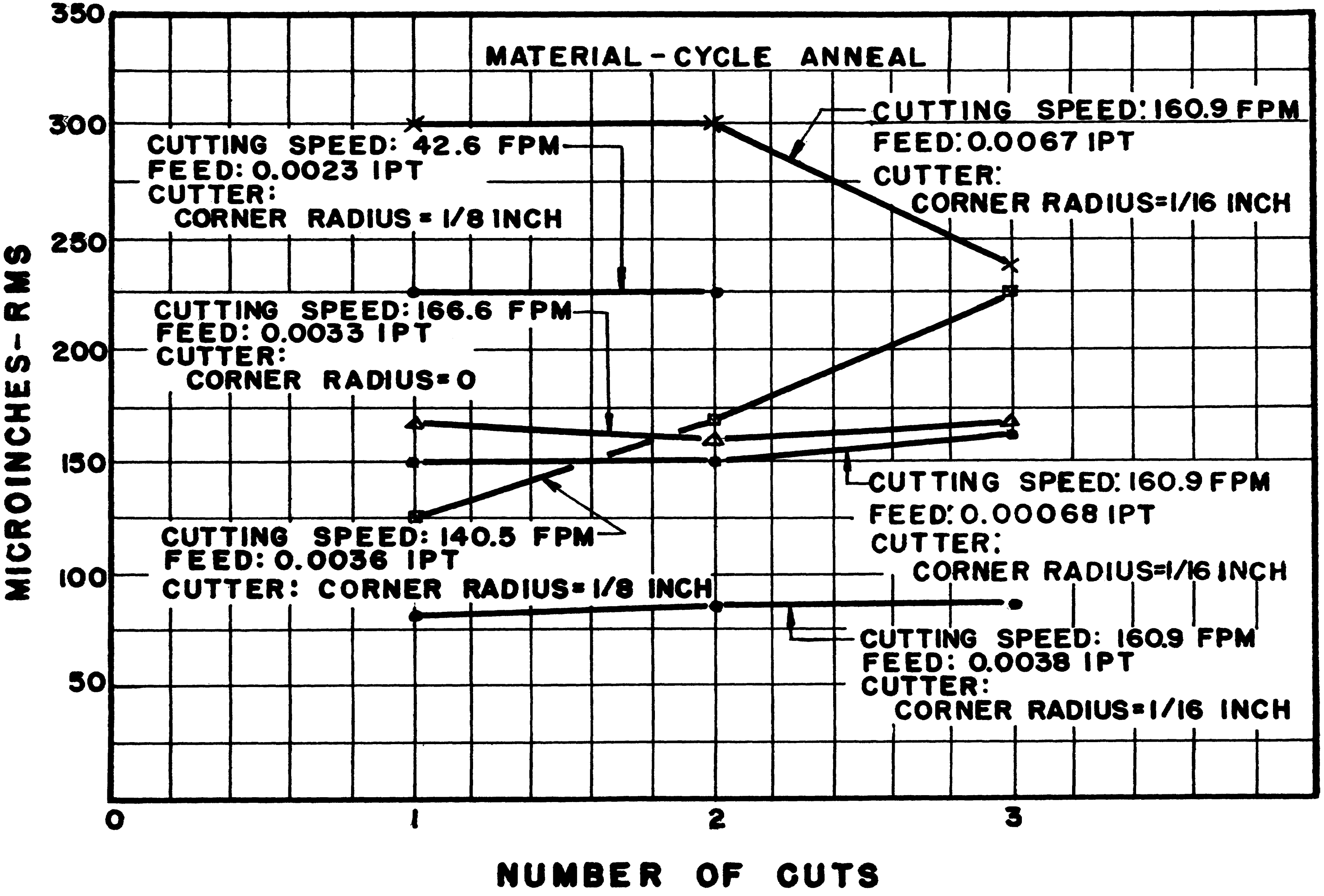
TOOL WEAR


TOOL WEAR - INCHES X 10^{-3}
14
12
10
8
6
4
2
0
1
2
3
PATENT ANNEAL CONDITION-B
CYCLE ANNEAL CONDITION-B
PATENT ANNEAL CONDITION-C
CYCLE ANNEAL CONDITION-A
NUMBER OF CUTS

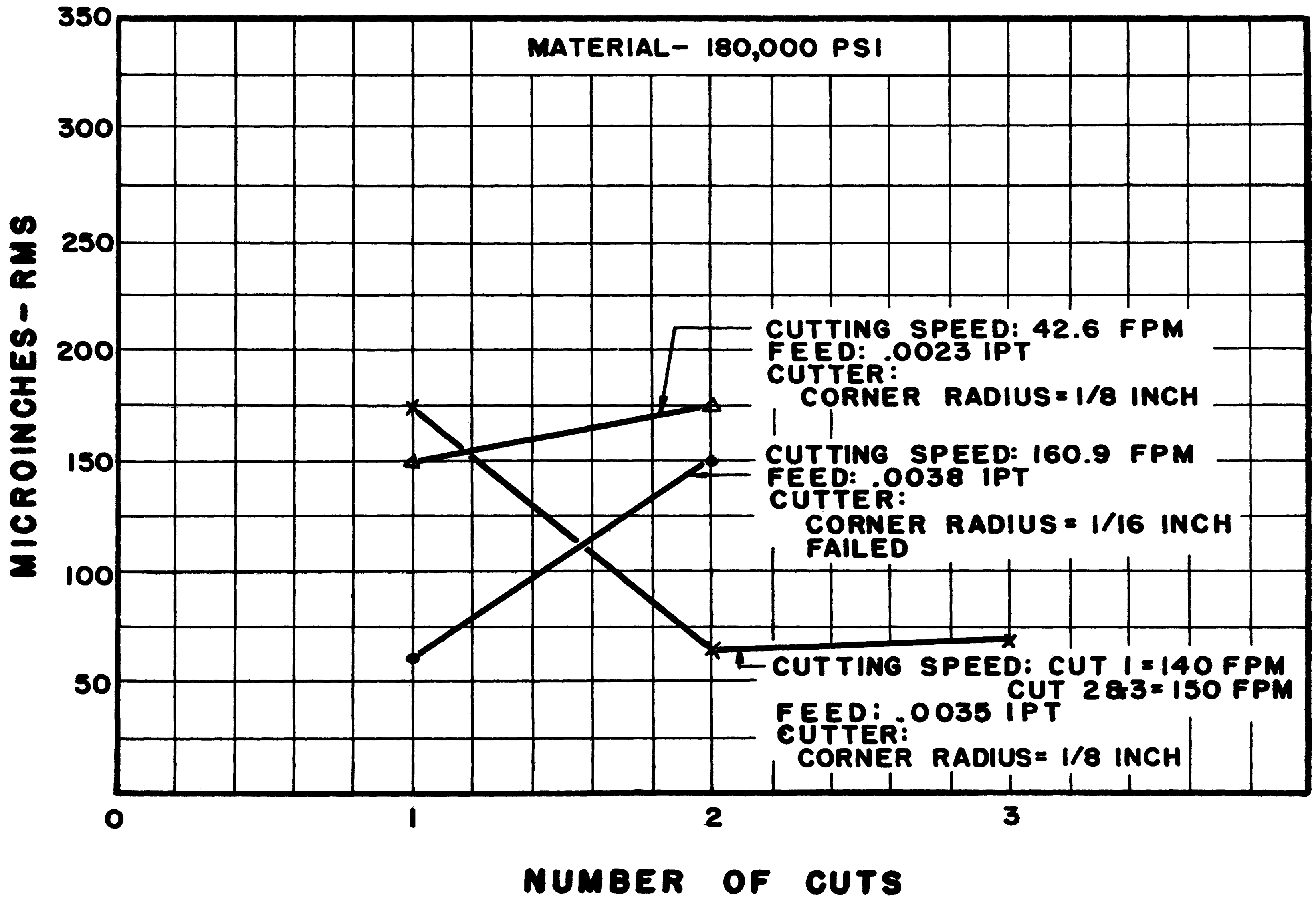
SURFACE ROUGHNESS



SURFACE ROUGHNESS

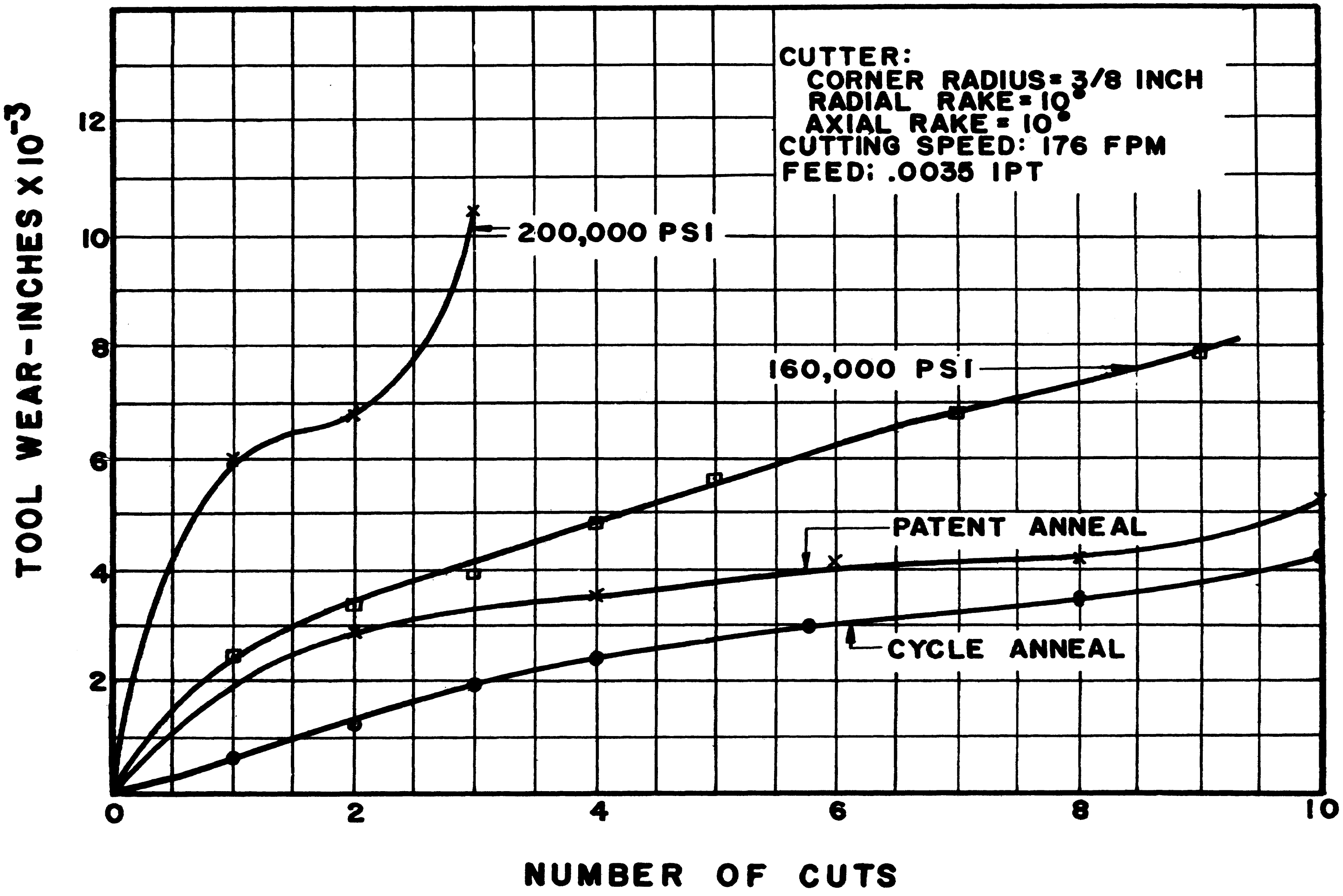


SURFACE ROUGHNESS



TOOL WEAR

BENDIX STRUT – BENDIX CUTTER



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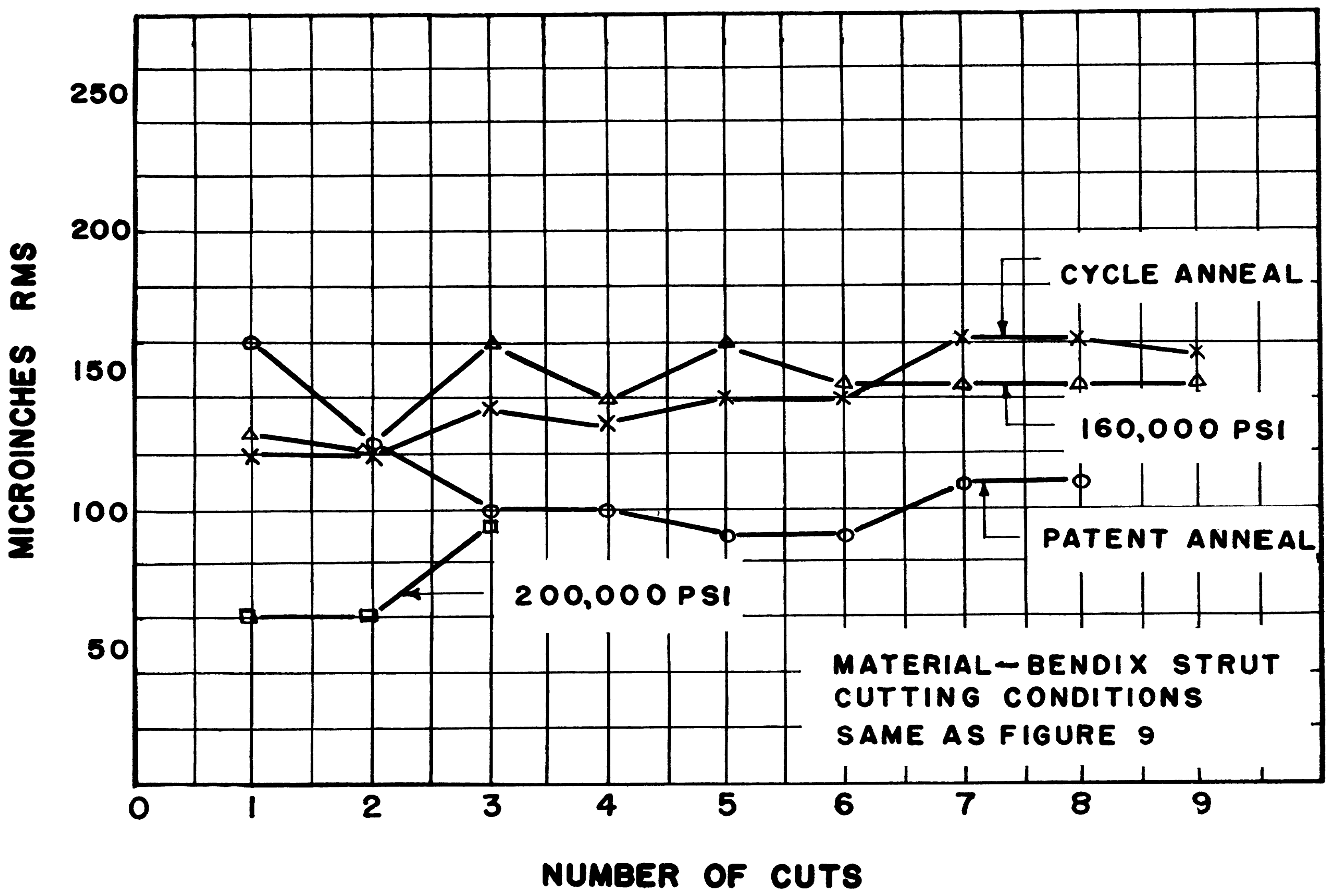
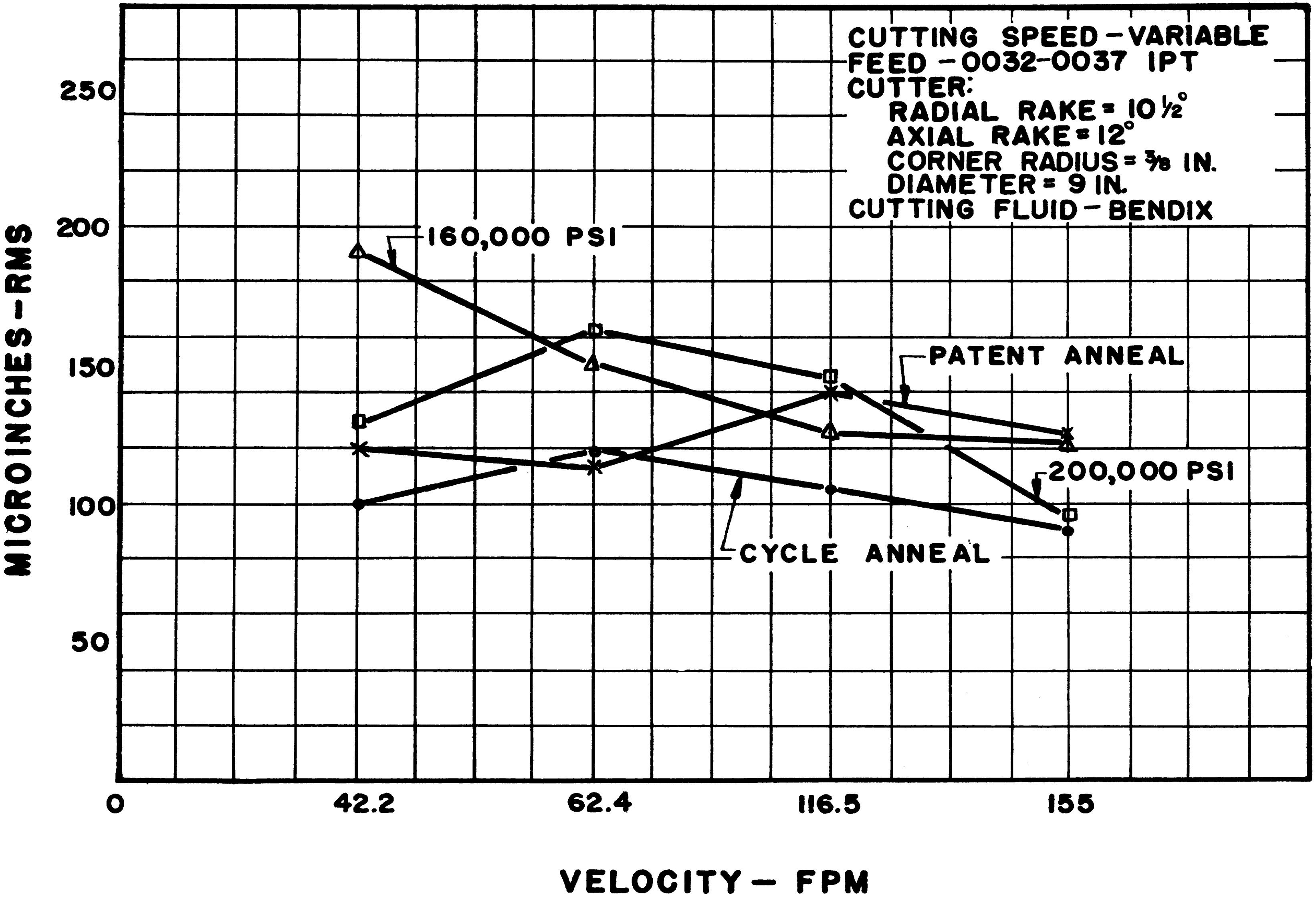
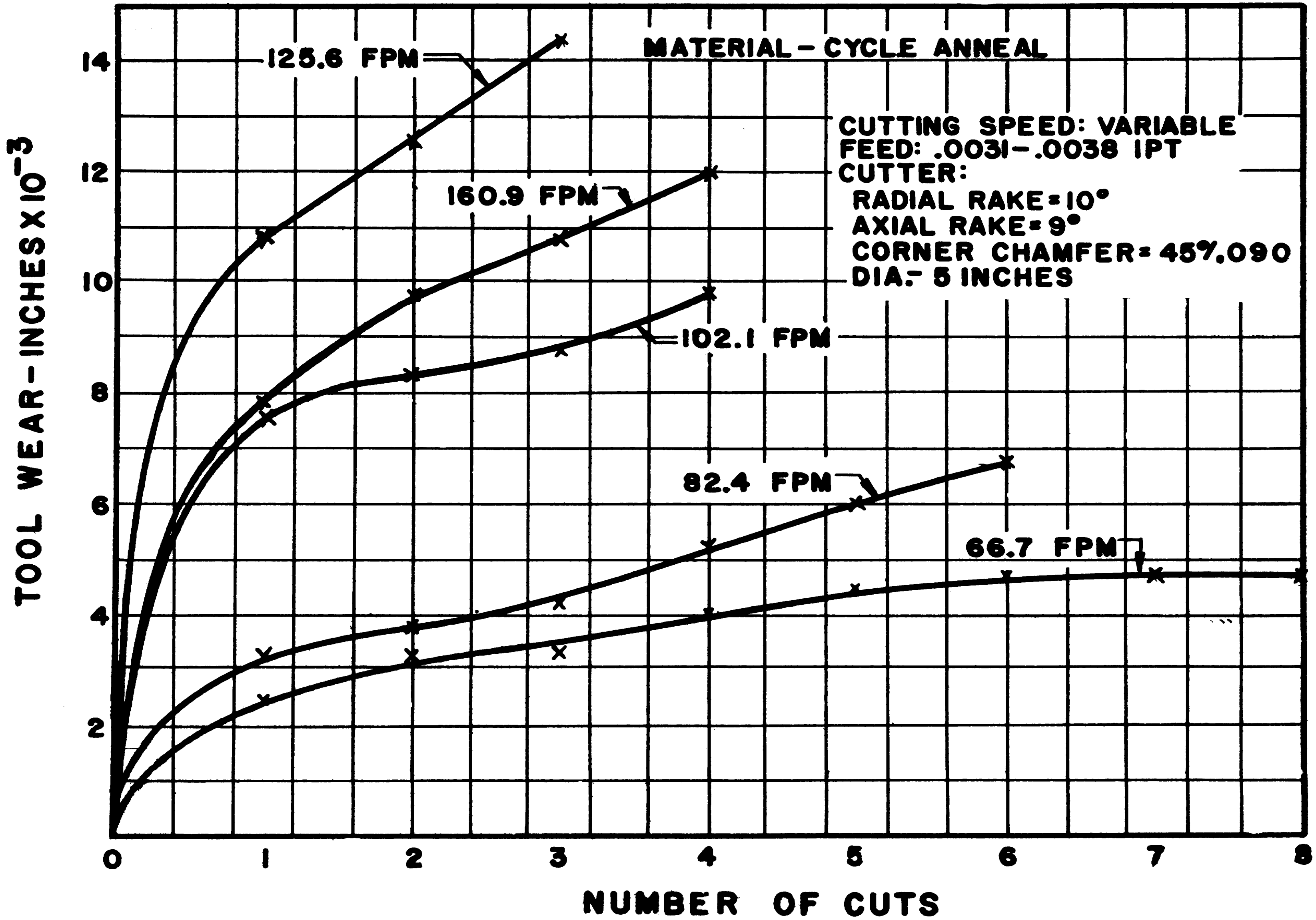


SURFACE ROUGHNESS

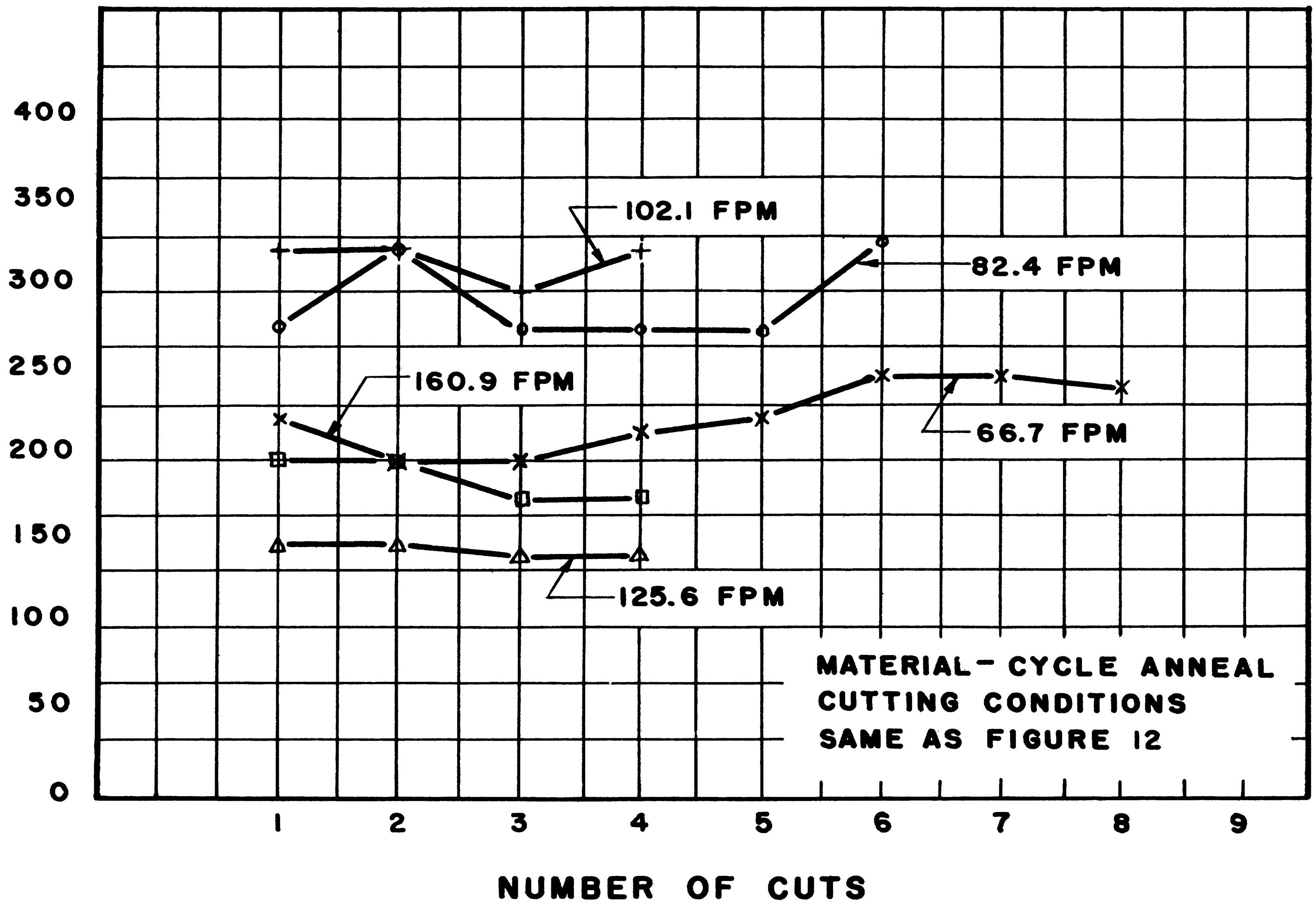


TOOL WEAR

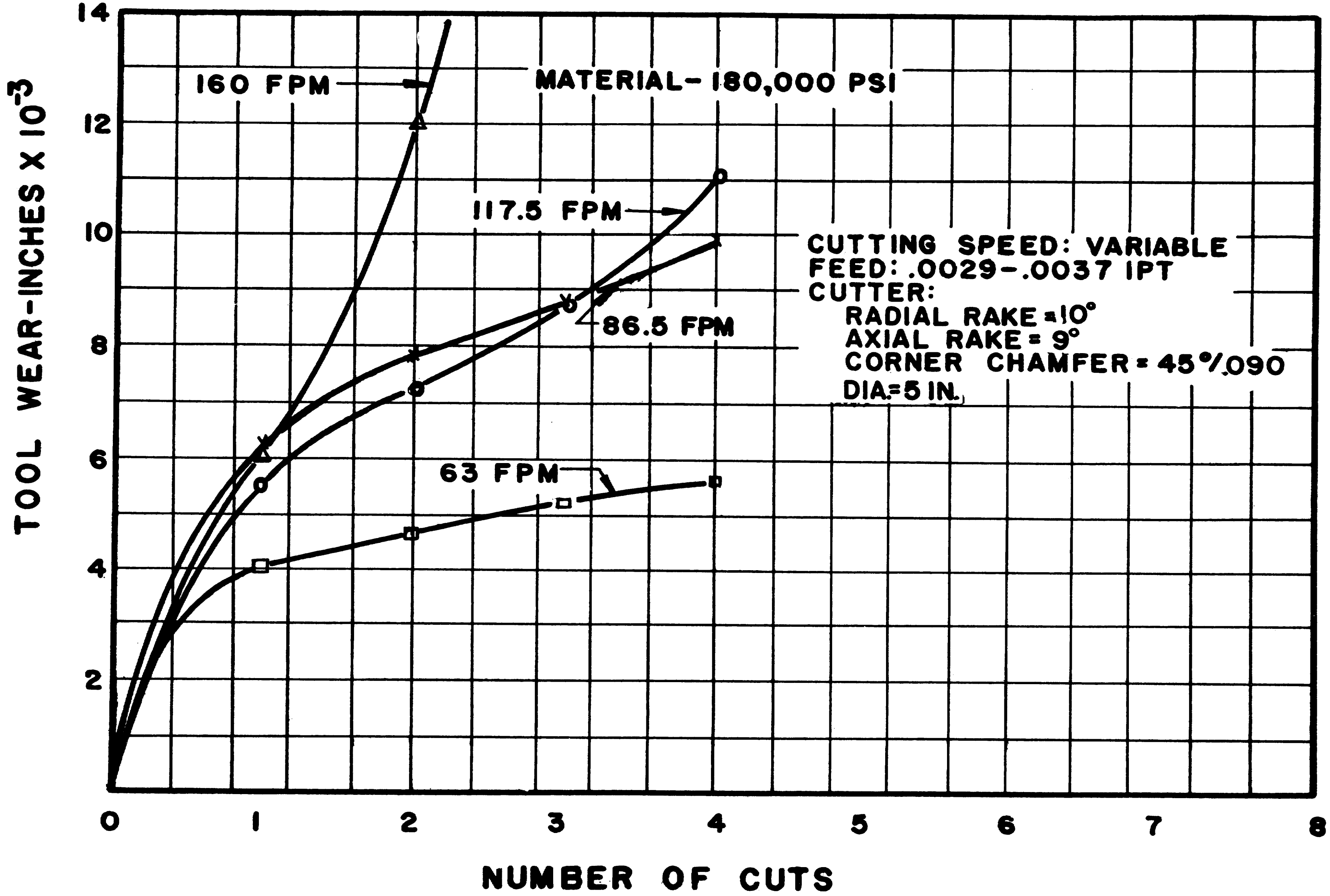


MATERIAL - CYCLE ANNEAL
CUTTING SPEED: VARIABLE
FEED: .0031 - .0038 IPT
CUTTER:
RADIAL RAKE = 10°
AXIAL RAKE = 9°
CORNER CHAMFER = 45°/.090
DIA.- 5 INCHES
125.6 FPM
160.9 FPM
102.1 FPM
82.4 FPM
66.7 FPM
TOOL WEAR - INCHES X 10^-3
NUMBER OF CUTS
0
1
2
3
4
5
6
7
8
2
4
6
8
10
12
14

SURFACE ROUGHNESS



TOOL WEAR



TOOL WEAR-INCHES X 10^{-3}
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
NUMBER OF CUTS
160 FPM
MATERIAL- 180,000 PSI
117.5 FPM
86.5 FPM
63 FPM
CUTTING SPEED: VARIABLE
FEED: .0029-.0037 IPT
CUTTER:
RADIAL RAKE = 10°
AXIAL RAKE = 9°
CORNER CHAMFER = 45°/.090
DIA.=5 IN.

SURFACE ROUGHNESS