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THE UNIVERSITY OF MICHIGAN
ANN ARBOR

Progress Report

MACHINABILITY STUDIES OF EIGHT PREPARED-VARIABLE COMBINATIONS OF 2011-T3 ALUMINUM ALLOY

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Project 2575

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ABSTRACT

Eight combinations of high and low values of copper content, solution temperature, and percent cold reduction in 2011-T3 aluminum rod were investigated as to relative machinability. Results showed that all the high values were bad, with copper being the most serious, solution temperature next, and cold reduction least effective. The effect of each property was intensified in combination with high values of the other variables. High copper was responsible for drift in machined dimensions. High solution temperature appeared to be responsible for excessive tool wear. High cold work affected surface finish and intensified the effects of the other variables.

OBJECTIVE

The objective of this investigation was to determine whether properties as they could vary in mill practice could be identified and evaluated in terms of machining performance.

PROGRAM OF INVESTIGATION

To meet the objective of the investigation, the program was planned to include eight different types of tests divided into two major groups. Seven short-time tests made up the first group. These involved measurements of torque in tapping, reaming, and drilling; cutting-force measurements in turning; cutting-temperature measurements in turning, chip formation; and friction-wear studies. A second major group was referred to as automatic screw-machine tests. It involved several typical automatic screw-machine operations such as turning, rough and finish forming, drilling, reaming, threading, and cutoff.

Eight combinations of three mill variables were prepared for study. These were copper content, solution temperature, and cold reduction. Although a contract was negotiated for only six of these combinations, all eight were studied in the first group of short-time tests and seven of the eight were processed through the automatic screw-machine tests.

SUMMARY CONCLUSIONS

The tests carried out in the automatic screw machine discriminated very sharply between the combinations of mill variables, resulting in overall machinability ratings ranging from acceptable to completely unacceptable. The poorest rating occurred with high copper, high solution temperature, and high cold reduction. The best machinability rating resulted from the opposite combination. Of the three variables, copper content seemed to be most important. Solution temperature affected both tool wear and type of chip formation, while cold reduction affected surface finish. Each of the three properties seemed to intensify or augment the effects of the other two at the upper limits. Several types of information were obtained from the screw machine and all of them support the final machinability ratings. Further, some observations of undesirable behavior characteristics were identical with complaints received from customers. The fact that the mill has aimed its specifications at these same property combinations would seem to substantiate the validity of the field complaints.

The short-time tests, on the whole, failed to predict both the desirable and undesirable characteristics observed in the automatic screw-machine tests. It is believed that failure to predict these properties is due primarily to such tests being made with sharp tools. Subsequent developments indicate the feasibility of predicting performance from short-time tests providing a simulated dull tool can be produced with the necessary control.

PROGRAM DETAILS

All details of test procedure and the quantitative results are recorded in the Appendix to this report. Parts I through VIII of the Appendix deal with the eight different tests included in the overall program. Part IX records all pertinent information on preparation and properties of the materials submitted for investigation. A few of the more significant results are discussed in some detail in the main body of the report only to reveal the basis for the above conclusions.

MATERIALS

A materials code was developed for the sake of simplicity and to help identify the eight variables combinations in the discussion of results. The following table gives the code for all these materials along with the corresponding Reynolds lot numbers.

TABLE I

MATERIALS CODE

Code	Lot Number of 1-in. Rod	Lot Number of 1-1/2-in. Rod
111	E-737	E-748
112	E-741	E-752
121	E-736	E-747
122	E-740	E-751
211	E-739	E-750
212	E-743	E-754
221	E-738	E-749
222	E-742	E-753

The first number in the materials code refers to the copper level. No. 1 is low copper; No. 2 is high copper. The second number refers to solution temperature. No. 1 is low temperature; No. 2 is high temperature. The third number refers to amount of cold reduction. No. 1 is low reduction; No. 2 is high reduction. Thus material 121 means low copper, high solution temperature, and low cold reduction. This code will be used throughout the report to identify the materials.

SHORT-TIME TESTS

The fact that the short-time tests failed to predict the performance in the automatic screw machine does not merit further discussion except in the rather complete reports on the same tests in the Appendix. It will suffice at this juncture to say that information was obtained which provides a basis for further investigations into the development of a short-time test. The feasibility of a significant short-time test appears to be greater than before this program was started.

AUTOMATIC SCREW-MACHINE TESTS

Six of the eight materials combinations were studied in a Brown and Sharpe 2G Automatic Screw Machine at conditions designed to simulate those which a customer might be expected to use in machining Reynolds barstock. The details of procedure are recorded in Part VIII of the Appendix.

Observations were made of surface finish, the dimensions of surfaces, cutting forces, and overall power requirements. These, likewise, are summarized in detail in Part VIII of the Appendix. In general, a test run involved machining 2450 parts unless circumstances developed earlier which made it necessary to quit before this time. This did occur in several instances.

Sample parts were taken from each 50 parts produced. These sample parts were measured for surface finish on at least three surfaces, and the corresponding diameters were also measured. A force dynamometer mounted on the front slide of the machine made it possible to follow changes in feeding force resulting from wear of the two form tools carried by this slide. One of these cut through the original bar surface and was subject to wear by any oxides present. The other tool cut only on the inner surface. The thrust force measured could be expected to increase as a result of the development of a worn land on the front of the tool.

After machining two sets of bars, it became evident that the high copper content resulted in so much rubbing friction that the machine was loaded beyond its capacity. A moderate amount of tool wear resulted in significant slowing down of the spindle. After this experience, a recording wattmeter was hooked up along with an electronic counter to follow and evaluate this undesirable characteristic. Such information was obtained for five of the materials machined in the automatic.

SIGNIFICANCE OF AUTOMATIC SCREW-MACHINE TESTS

To demonstrate the significance of the automatic screw-machine tests, some of the results obtained for materials 121 and 222 are discussed and presented as representative of the extremes which occurred in this series. Figures 1 and 2 compare the information obtained from the rear or heavy form tool. Figures 3 and 4 present similar information for the light forming cuts performed by the front slide, while Fig. 5 shows the same type of information for the turning cut.

Figure 1 (Appendix Fig. 8.4) shows the variation of roughness and diameter of the surface machined by the rear form tool on material 121, representing low copper, high solution temperature, and low cold reduction. It will be noted that the part diameter increased 0.008 inch as a result of the tool wear in producing 2450 parts. The surface roughness started out just below 20 microinches and increased to a mean of about 34 microinches after 500 parts and remained reasonably steady for the remaining 2000 parts. Corresponding data in Fig. 2 (Appendix Fig. 8.7) for material 222 (representing high copper, high solution temperature, and high reduction) shows that the diameter of the work increased 0.025 inch, or more than three times as much in machining only 1550 parts. The test had to be stopped at 1550 parts because power requirements exceeded capacity and the machine stalled. Surface roughness started out at about 25 microinches, increased to 32 microinches in the first 1000 parts, then increased further to 53 microinches in the next 550 parts. Figures 1 and 2 are typical of the extreme differences in performance encountered in the prepared variables.

Figure 3 (Appendix Fig. 8.11) shows size variation, surface finish, and feeding force for both of the form tools operating from the front slide of the machine while machining material No. 121. It will be noted that there were no significant trends on the inner surface during the machining of 2450 parts. On the other hand, the tool which machined through the outside surface with oxides did wear appreciably, resulting in an increased feeding force of 100 percent during the run and an increase in surface roughness from 15 microinches up to 70 microinches.

Similar information for material 222 is shown in Fig. 4 (Appendix Fig. 8.14). Here it will be noted that feeding force increased by more than 100 percent with both tools. Surface roughness of the outer surface also increased with wear. Had the machine been able to continue, the tool wear and increase in feeding force with this material would have been considerably worse. It is believed significant that the diameter variations are much greater than with material 121. This was observed to vary from bar to bar of the same material, indicating the possibility of some variation due to differences in quenching.

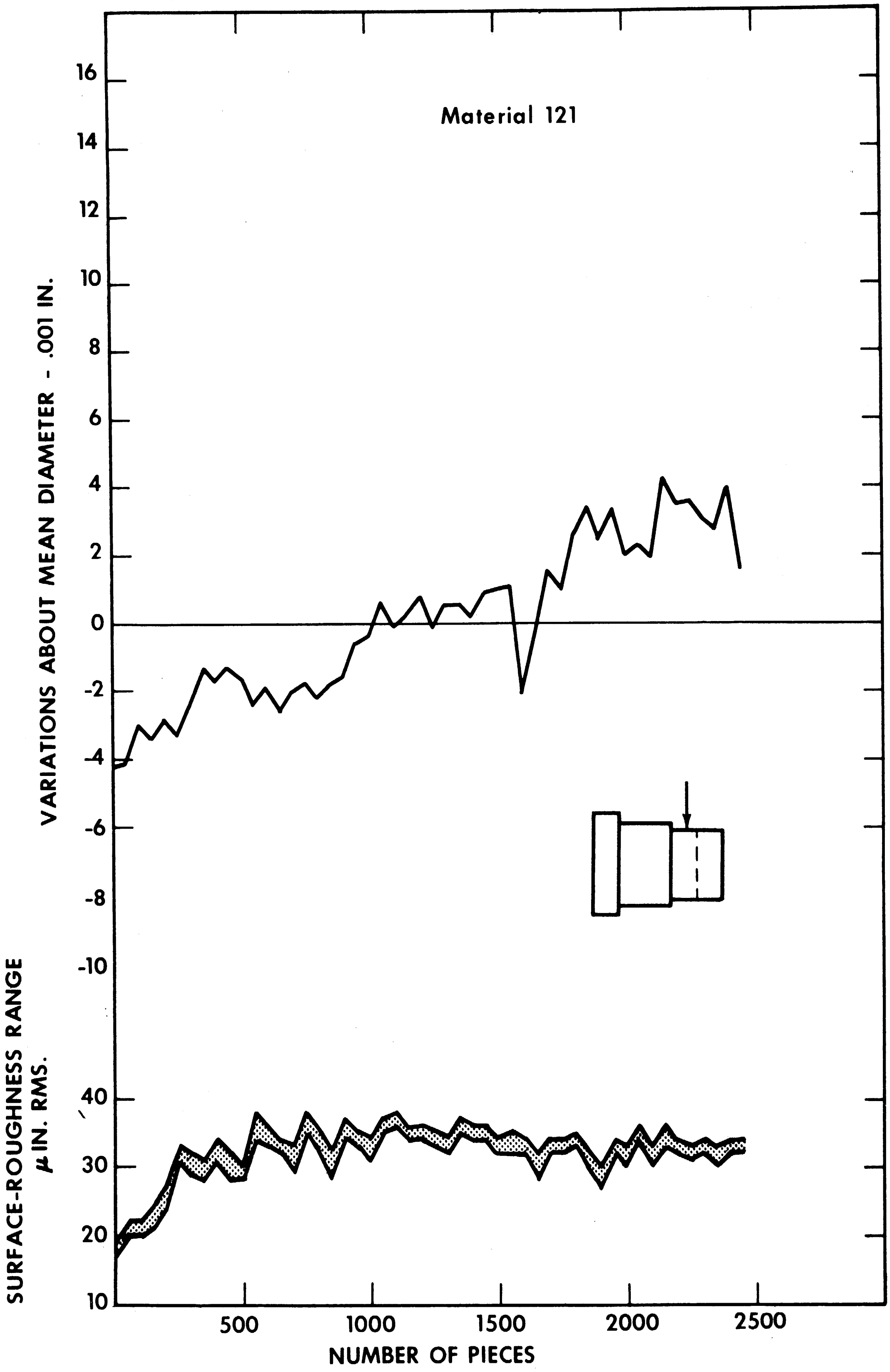


Fig. 1. Heavy forming - Surface-roughness range and diameter variations; material 121.

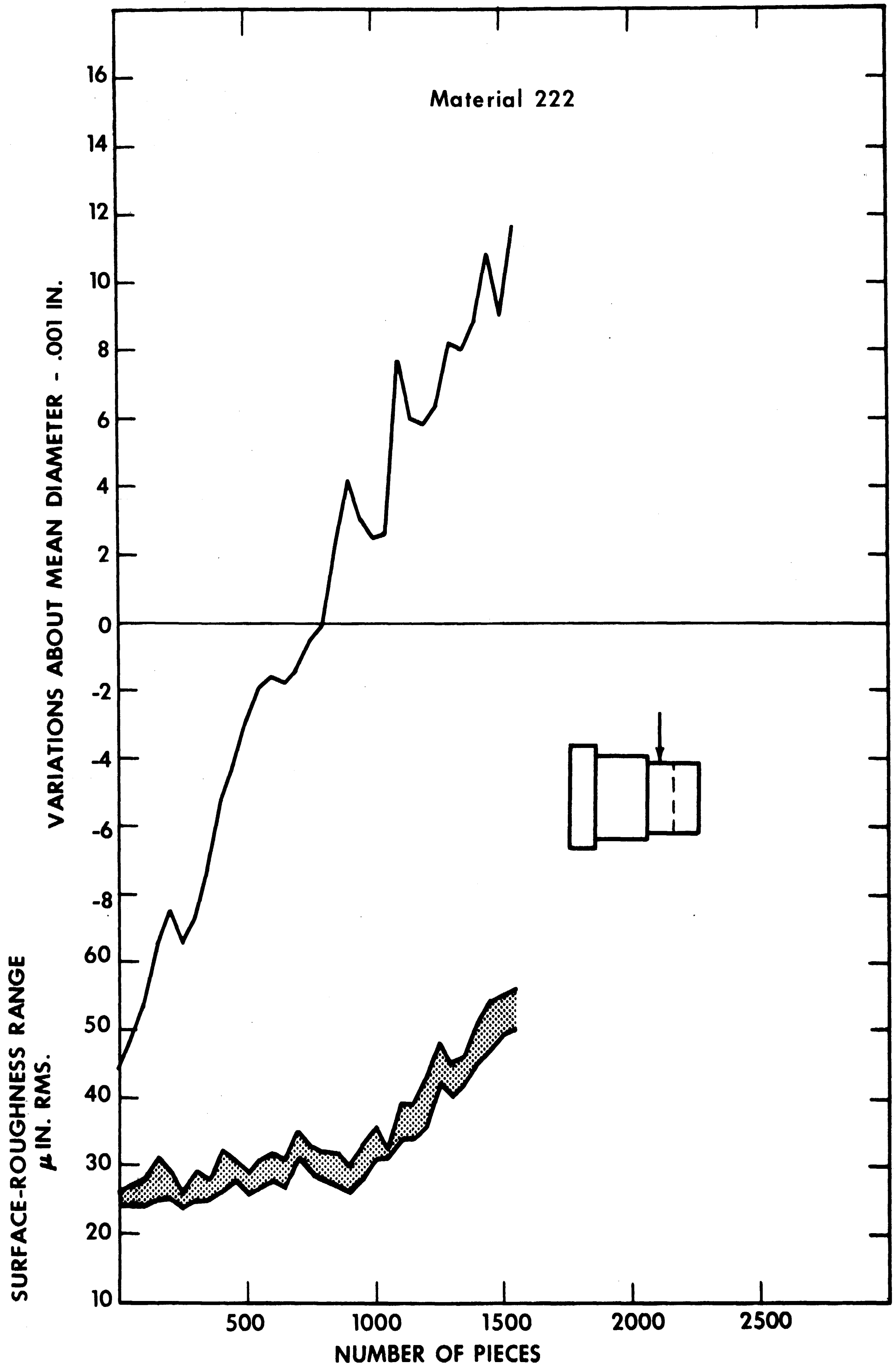


Fig. 2. Heavy forming - Surface-roughness range and diameter variations; material 222.

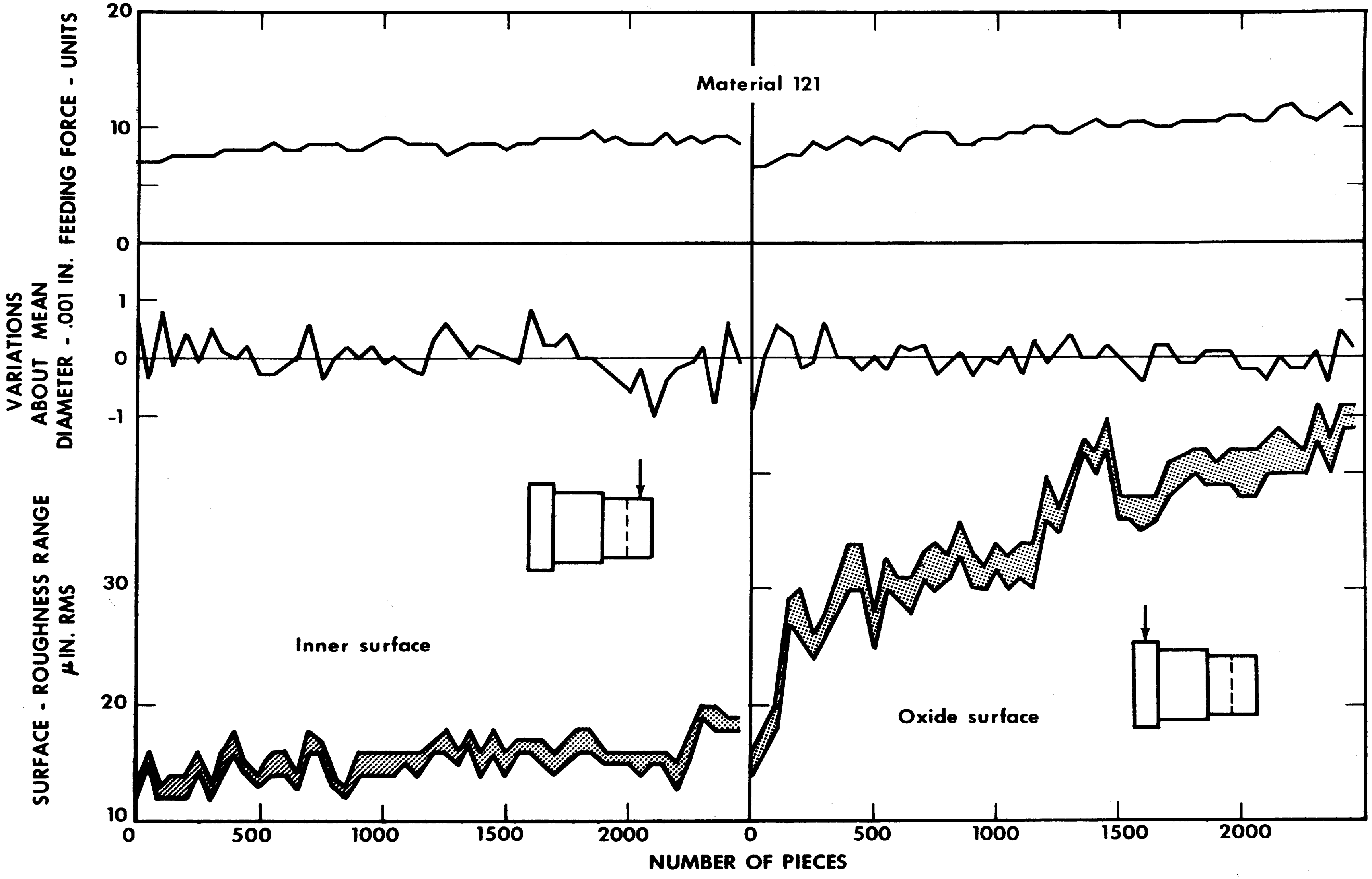


Fig. 3. Light forming - Surface-roughness range, dimensional stability, and feeding force; material 121.

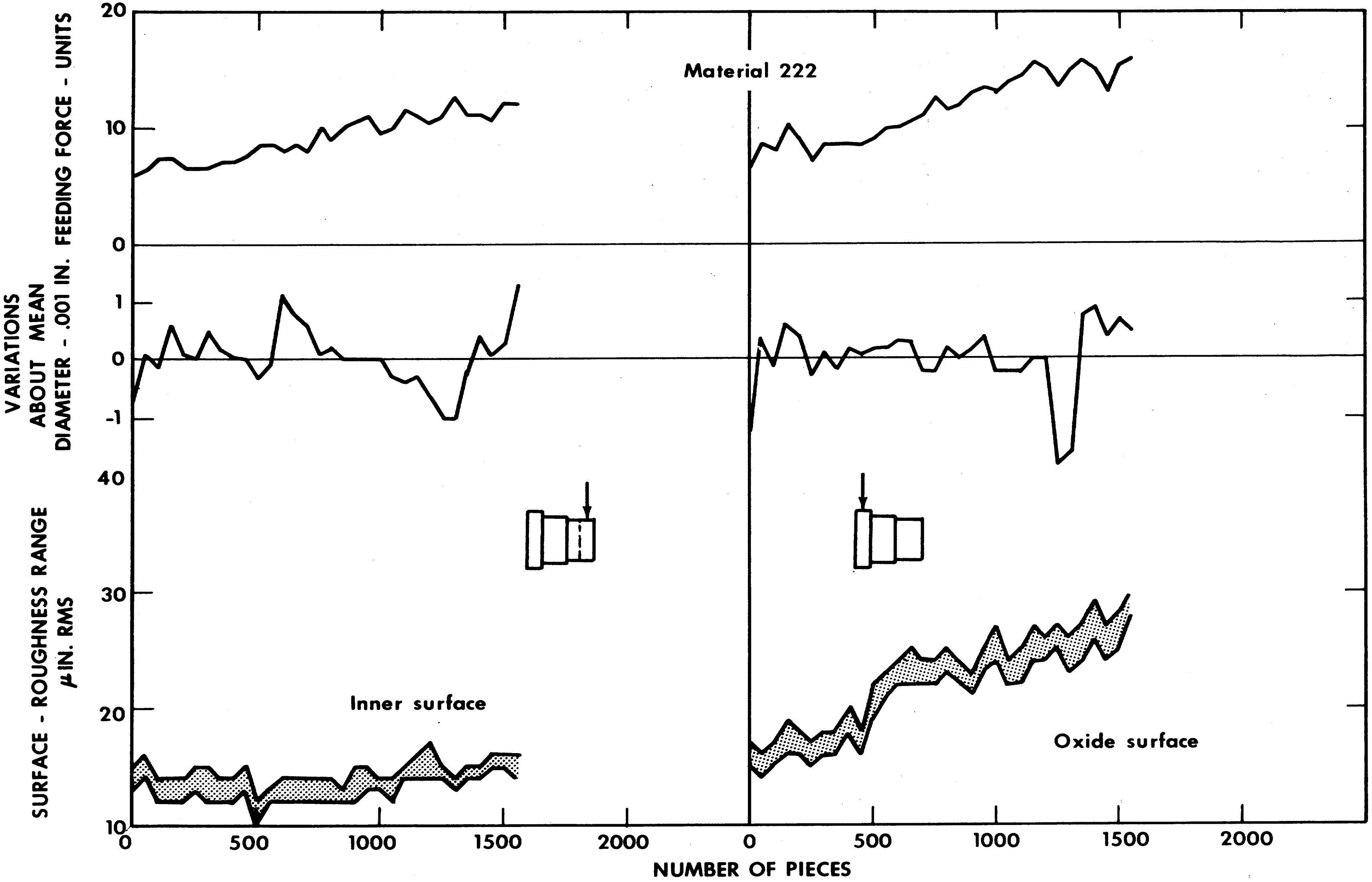


Fig. 4. Light forming - Surface-roughness range, dimensional stability, and feeding force; material 222.

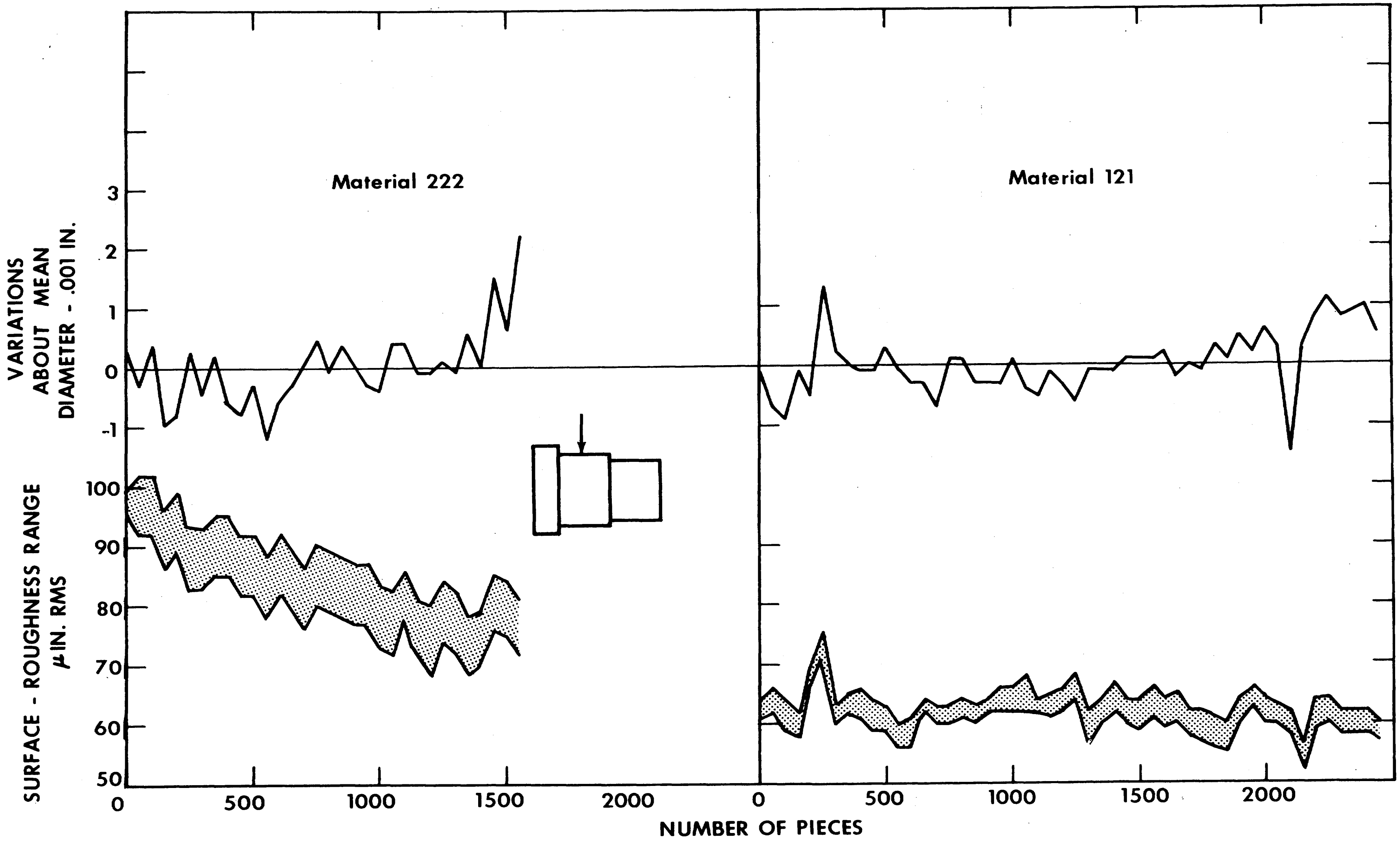


Fig. 5. Turning - Surface-roughness range and diameter variations.

Figure 5 (Appendix Fig. 8.15) shows the surface roughness and size variations in turning materials 222 and 121. It will be noted that the roughness of the turned surface improved with material 222 in spite of the fact that the diameter of that same surface increased with tool wear. There appear to be no significant trends of roughness in connection with material 121. Figure 6 (Appendix Fig. 8.17) shows pictures of four parts that have been sectioned to show the surface condition of the drilled hole both at the beginning and at the ends of the runs. These show that material 111 produces very poor finish in the drilled hole at the start of the run, but that it improves continually throughout the test, resulting in a very satisfactory appearing surface as shown for the last part. Material 222, on the other hand, produced a reasonably satisfactory finish at the start of the run and resulted in very unsatisfactory finish at the end of the run; this, likewise, was a continual process but in the opposite direction compared to material 111.

The most striking comparison of the materials machined is summarized in Table II, showing the diameter increase resulting from wear of the rear form tool.

TABLE II

DIAMETER INCREASE IN THE SURFACE
MACHINED BY THE REAR FORM TOOL

Code	Diameter Increase - Inches	Total Parts Produced
111	0.0065	2450
112	0.012	2400
121	0.008	2450
211	0.035	2400
212	0.022	2450
222	0.025	1550

The diameter increases for the rear form were substantially greater than those encountered in any other operation. This was due to two things: (1) the fact that a heavier feed rate was used with this tool, and (2) the mechanism which drives the rear slide is less rigid than the other tool supports in this particular machine design. The most significant conclusion from these measurements is that the diameter increases are consistently high for the high copper material and consistently lower for the low copper level.

All the high copper materials run through the automatic screw machine stalled the machine before the end of the run, whereas all twenty bars of the low copper materials were completed successfully. With material 222, the machine was stalled on the tenth bar. At this point, a new drill was put in the machine, making it possible to complete two more bars before the machine stalled in the thirteenth bar, at which time the test was discontinued. Both 211 and 212 stalled the machine, but in both cases it occurred in the nineteenth

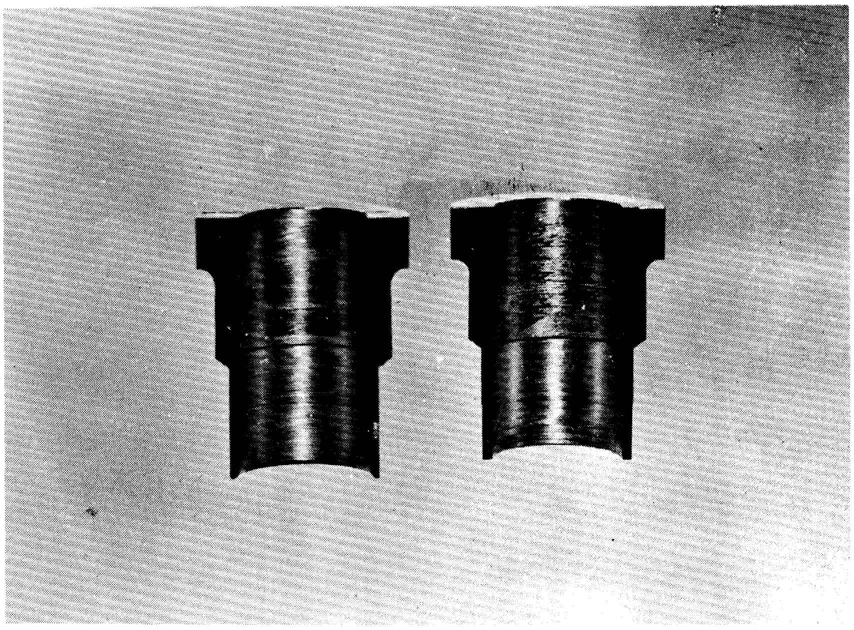


Fig. 6a. Material 222. View of drilled surface produced on piece No. 2 (left) and piece No. 1152 (right) before drill was replaced.

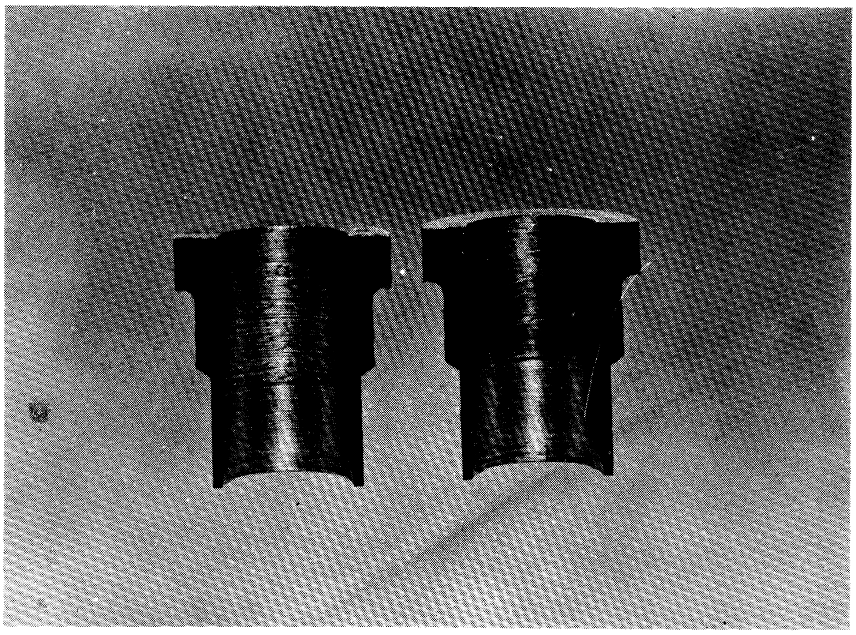


Fig. 6b. Material 111. View of drilled surface produced on piece No. 3 (left) and piece No. 2450 (right) at end of run.

bar and no attempt was made to carry the test farther in these instances.

An attempt was made to duplicate the initial experience with material 222 in the presence of representatives of the Reynolds Company. The test was carried out without threading tools since this operation had revealed no significant differences. In the rerun of 222 the machine stalled in the twelfth bar instead of the tenth as before. The diameter from the rear form tool had increased 0.026 inch compared to 0.025 in the first run. A bar of 111 material was inserted without any tool change. This resulted in no indication of machine stalling, and the increase in diameter from the rear form tool dropped to 0.016 inch. Following this, a bar of 221 material was inserted since no tests had been conducted on this material prior to this time. This resulted in the machine stalling after about 60 parts were machined and with an increase in diameter of 0.028 inch from the rear form. This experience is believed adequate to demonstrate the unsatisfactory performance contributed by high copper.

CONCLUSIONS

1. High values of copper, solution temperature, and cold reduction all tend to produce lower machinability.

2. A high solution temperature and high reduction are less undesirable when combined with low copper.

3. The best results obtained were with materials 121 and 111, although the high solution temperature represented by 121 appeared to be accompanied by and responsible for relatively high wear of the turning tool.

4. The general properties typical in materials 111 and 121 are highly desirable for machining purposes except for relatively poor finish with sharp tools. The latter is particularly evident in drilling and reaming.

RECOMMENDATIONS

Tentative recommendations can be made from the somewhat limited information obtained from this program. These are as follows.

MILL PRACTICE

It appears desirable to reduce the levels of all three variables below the higher limits represented by mill practice in the recent past. Disregarding industry specifications for 2011-T3 alloy, it appears desirable to aim toward the lower levels represented by the materials in this program, stopping at levels somewhat above these lower limits. Slight increases of solution temperature and cold reduction above the low limits might produce better surface finish.

NEED FOR FURTHER INVESTIGATION

The variables prepared for this program give no hint as to the rate of reaction to values between the extremes prepared. Therefore, it would be useful to study the effects of several different levels of these variables between the extremes and to explore possible variations caused by quenching practice. It is further recommended that some effort be made to develop a significant short-time test such as appears feasible with simulated dull tools. Such a test could then be used for routine machinability inspection of the mill product.

APPENDIX

DETAILED REPORTS

PART I. TAPPING

The eight work materials were subjected to a series of tapping tests in an attempt to indicate any differences that might exist for this type of cutting action. Each work material was given a code number as explained previously, and the following list shows the actual rods used:

Code Number	Rod Identification Number
121	11
111	65
221	96
211	117
122	25
112	63
222	122
212	113

PROCEDURE

Each work specimen was prepared in the form of a cylinder having a 1-inch outside diameter, 3/4 inch long, and drilled and bored to an inside diameter of 0.437 inch which gave a 62-percent thread depth after tapping.

A specimen was clamped in a dynamometer in line with the spindle of the tapping machine, and a thread was tapped through the full specimen length without the use of a cutting fluid. Torque required to cut the thread was recorded for the entire operation, and as the tap was withdrawn from the specimen by a reversal of spindle rotation, the "back-out" torque was recorded. This procedure was followed for each of the other materials, the same tap being used for each test.

Five other cutting-fluid conditions were used, and in each instance a new tap was used for each cutting fluid. Before the cutting commenced, each specimen was flooded with fluid, and the following list shows the number of tests conducted with each tap for the various fluid conditions:

Cutting-Fluid Description	Number of Tests per Tap
1. Dry	8 (1 per material)
2. "Superla" in water (1:20 by volume)	16 (2 per material)
3. 55 SSU Straight Mineral Oil plus 5% lard oil	32 (4 per material)
4. Trichlorethylene	8 (1 per material)
5. "Cimcool" concentrate (not mixed with water)	8 (1 per material)
6. Sun Circo XX Light 72 SSU Mineral Oil	8 (1 per material)

TEST CONDITIONS

A Detroit Precision Tapping Machine operating at a spindle speed of 74 revolutions per minute (cutting velocity about 10 feet per minute) was used for these tests. High-speed steel, 1/2 - 13 - NC, 4-fluted, straight-flute plug taps, commercially ground, served as cutting tools.

The dynamometer, used to analyze the torque requirements, contained wire-resistance strain gages connected in the form of a Wheatstone Bridge. Bridge output was fed to a Sanborn Recorder which provided the necessary signal amplification and recorded the torque readings on a tape oscillograph.

TEST RESULTS

Figures 1.1 through 1.6 show the test results of cutting and back-out torque versus work material, the fluid being the variable from one figure to the next. It should be noted that Figs. 1.2 and 1.3 show the results of more than one test.

Torque differences among materials are not very pronounced for a giv condition of cutting fluid, but the torque levels between fluids show a noticeable difference. This seems to indicate that the effect of cutting fluid is more pronounced than are the effects of material differences.

Figure 1.3 shows the results when using the fluid containing mineral and lard oils. Four tests were conducted with each work material to check the repeatability of results. Although the actual torques levels changed slightly, the relative levels of torque for each material remained in close order (i.e., 221 was highest and 121 lowest, the other materials falling between these extremes).

Class 2, go and no-go thread gages, were used to check the size of every specimen tested and all threads were acceptable.

Each specimen was viewed under a microscope and a visual inspection of the surface finish of the threads was made. Regardless of work material, all specimens tapped dry had the poorest finish. The best finish was obtained when using the 55 SSU Straight Mineral Oil plus 5-percent lard oil and the Sun Circo XX Light 72 SSU Mineral Oil. When using the remaining three fluids, the finish of the threads was rated intermediate between these two extremes.

It was observed that the chips produced when cutting the 111 and 121 materials were stringy, whereas the other materials produced broken chips. Chip loading appeared to be greatest with the 211 material.

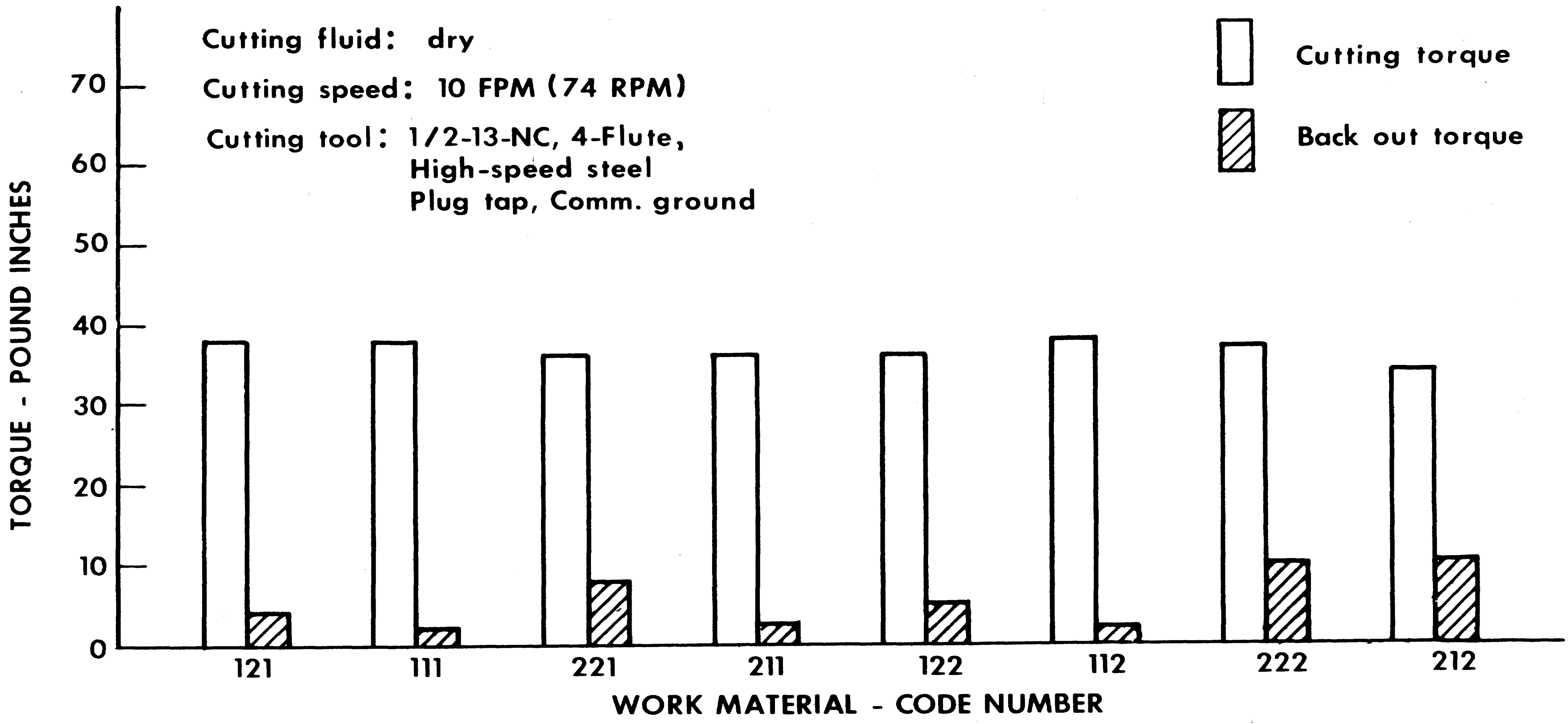


Fig. 1.1. Tapping torque vs work material.

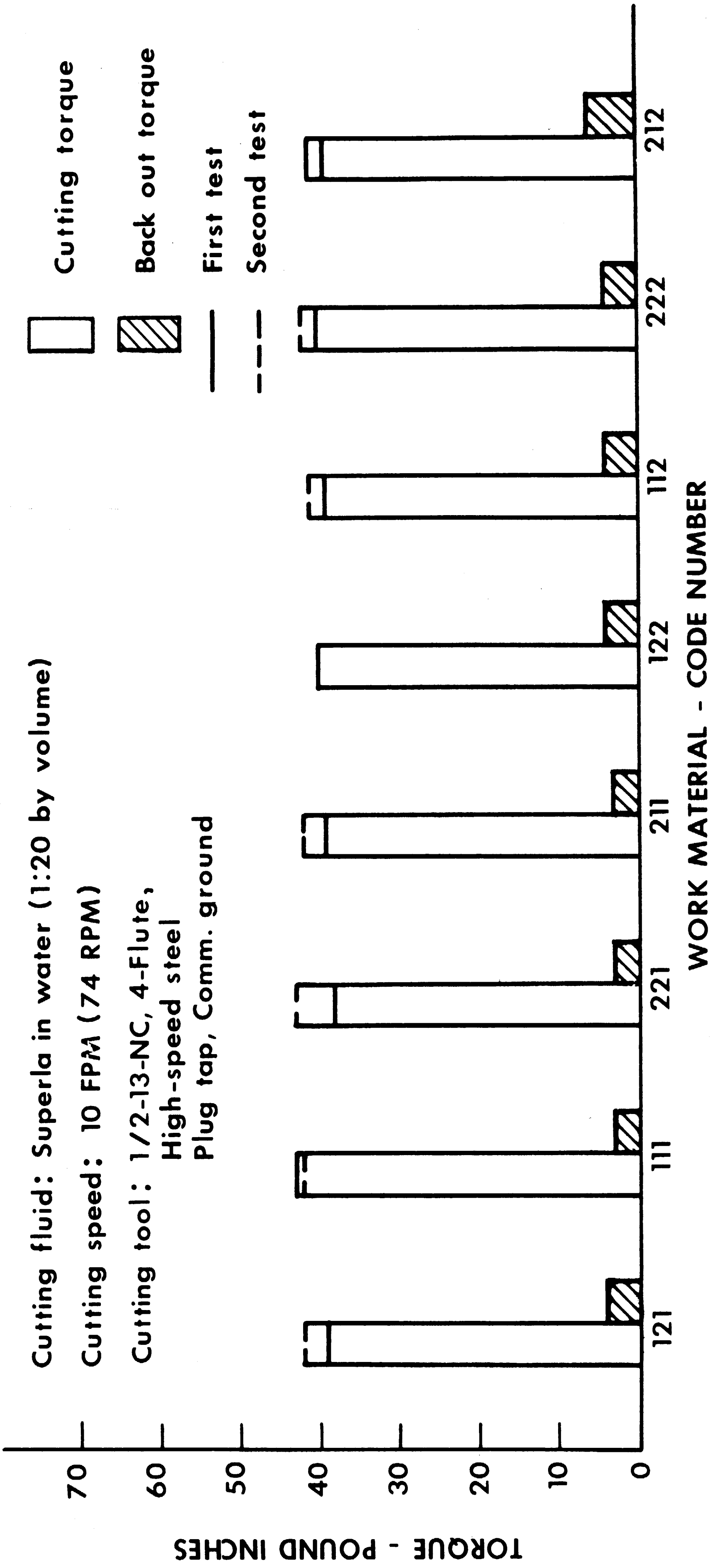


Fig. 1.2. Tapping torque vs work material.

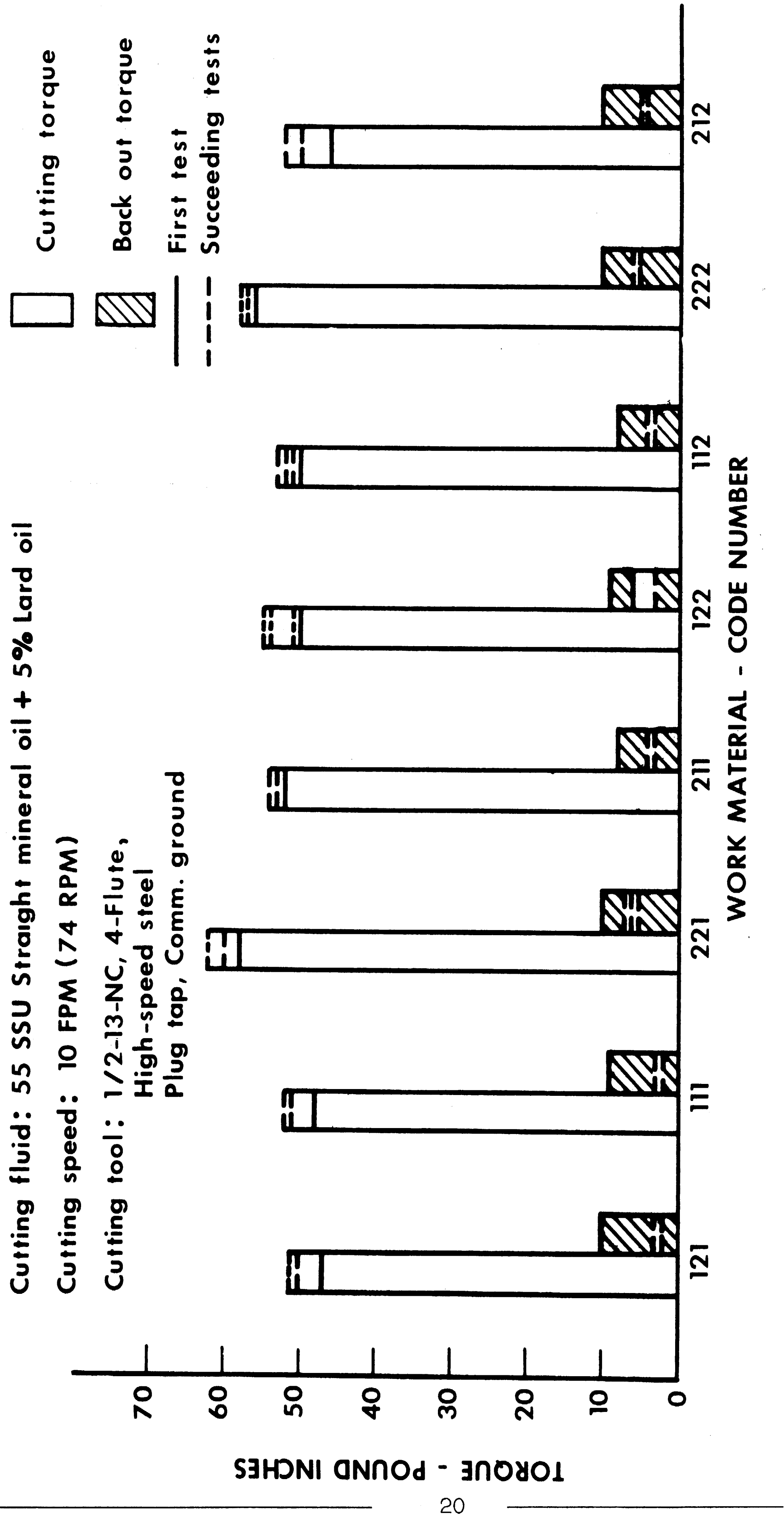


Fig 1.3. Tapping torque vs work material.

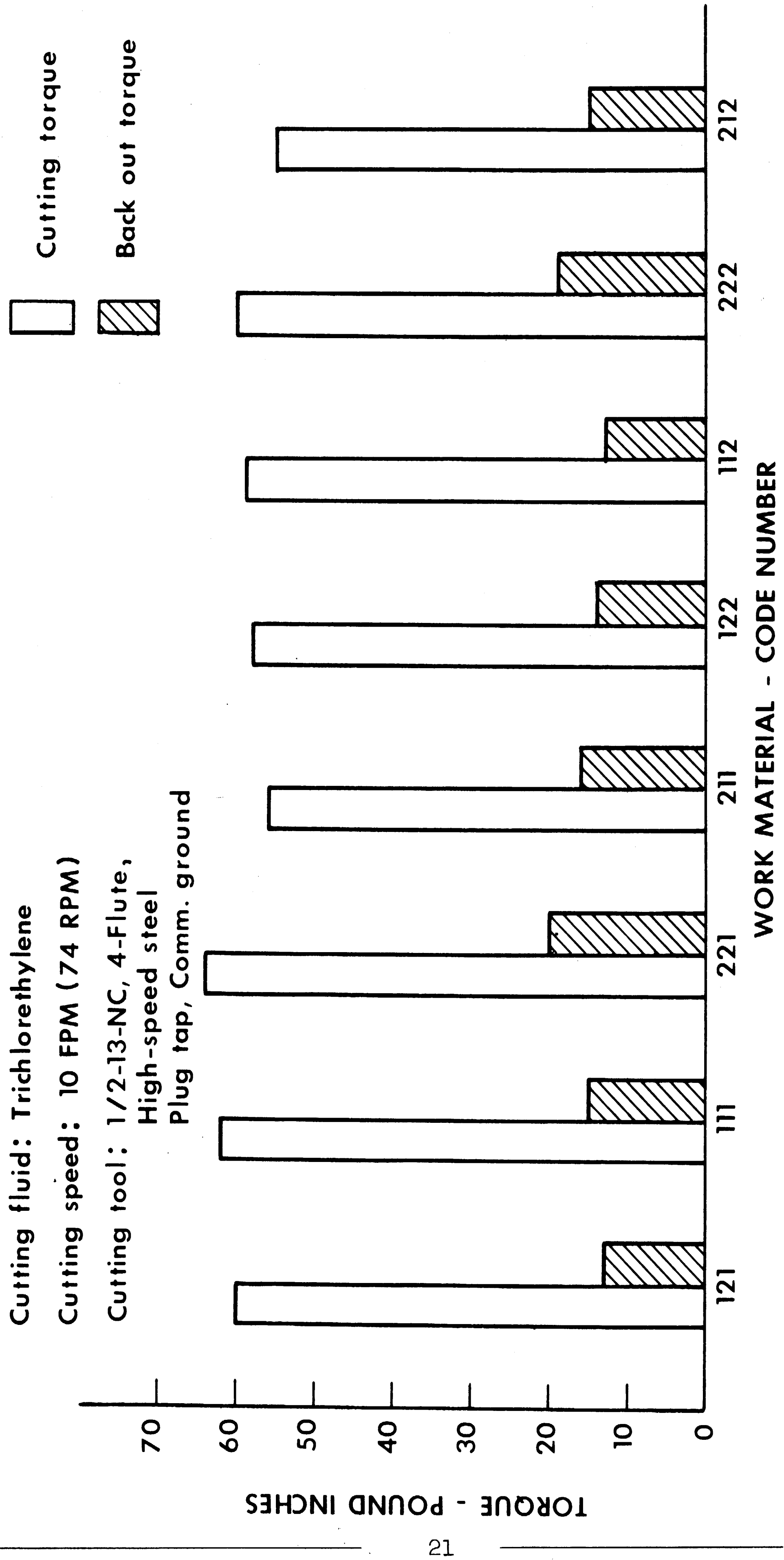


Fig. 1.4. Tapping torque vs work material.

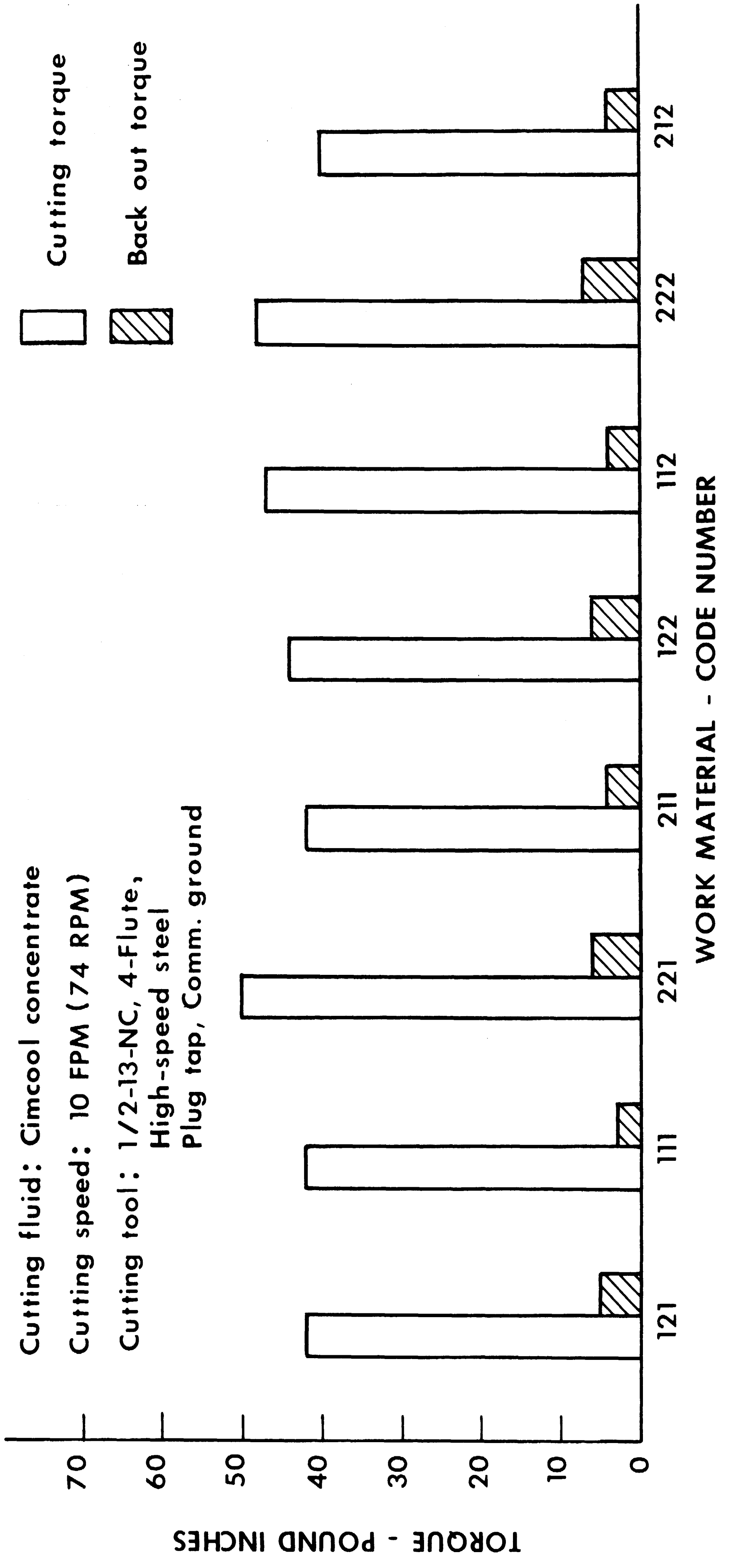


Fig. 1.5. Tapping torque vs work material.

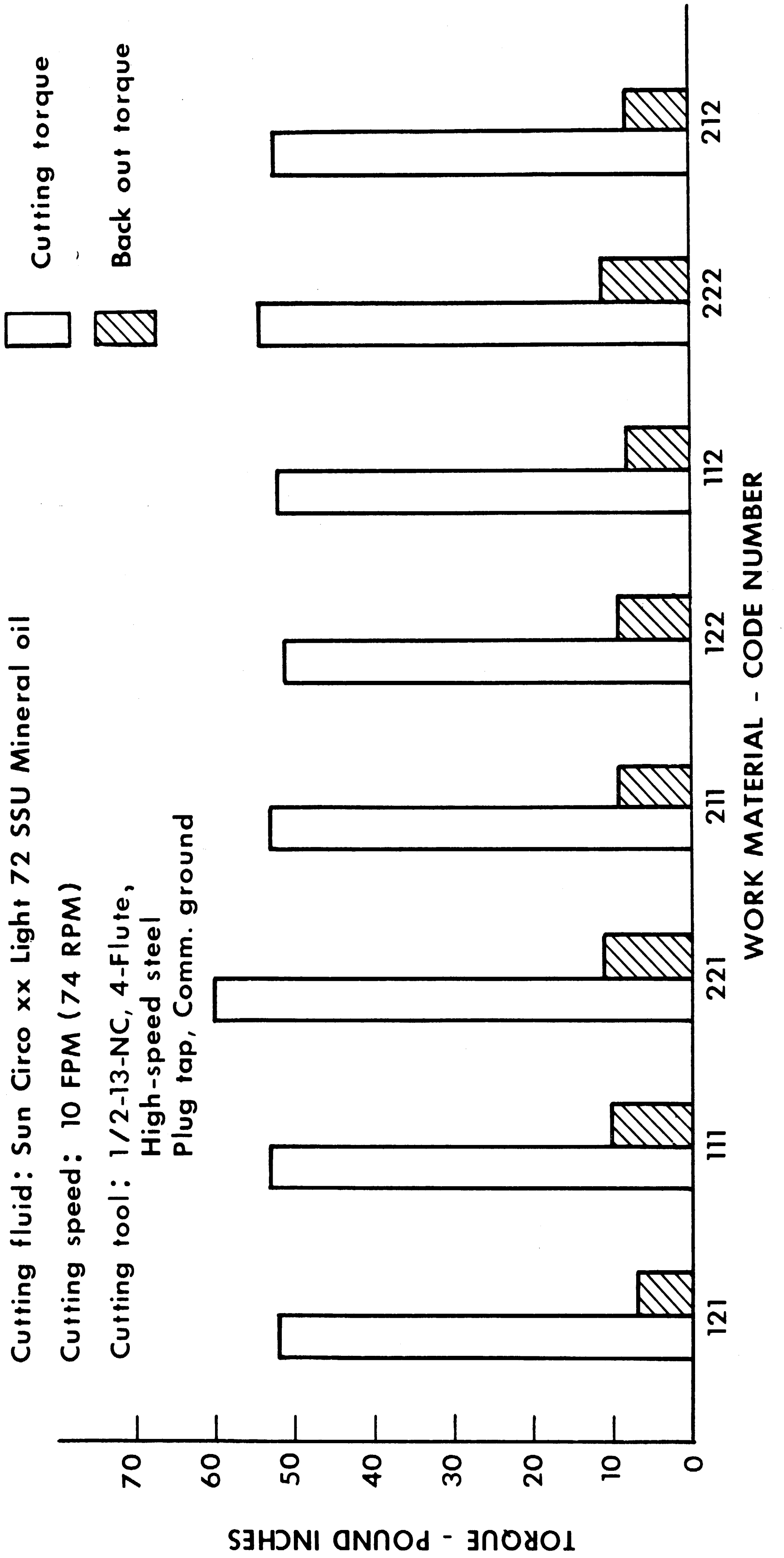


Fig. 1.6. Tapping torque vs work material.

PART II. REAMING

Specimens for these tests were made from the same rods listed under the section on Tapping. All eight work materials were used, the purpose being to determine if differences existed among the materials when they were reamed.

PROCEDURE

For each work material, specimens were prepared in the form of cylinders having a length of 3/4 inch and an outside diameter of 1 inch. The inside diameter was bored to three different preream sizes, 0.720 inch, 0.735 inch, and 0.745 inch, to permit the radial depth of cut (i.e., increase in radius after reaming) to be varied in steps of 0.015, 0.0075, and 0.0025 inches, respectively.

A specimen of one work material having an inside diameter of 0.745 inch was clamped in a dynamometer, the center of the specimen being aligned with the spindle of the drill press. The reamer was held in position by a floating holder which in turn was positioned in the spindle of the drill press. Using a feed rate of 0.025 inch per revolution and the 55 SSU Straight Mineral Oil plus 5-percent lard oil as a cutting fluid, the specimen was then reamed through its entire length. Torque readings were obtained both for cutting and backing out. Removal of the reamer was done by hand feed, and the amount of rubbing that occurred during this withdrawal was determined by the torque produced during this process of removal. The same procedure was followed using each of the other work materials.

A similar series of tests was conducted using "Superla" in water (one part Superla to twenty parts water by volume) as the cutting fluid.

A second comparison between these two cutting fluids was obtained by running tests where the feed rate remained at 0.025 inch per revolution and the preream hole diameter was 0.720 inch.

The last group of tests was conducted with one cutting fluid (55 SSU Straight Mineral Oil plus 5-percent lard oil), feed rates of 0.011 and 0.005 inch per revolution (preream hole size of 0.720 inch) and preream hole size of 0.730 inch (feed constant at 0.025 inch per revolution). These tests were run to determine the effects of feed rate and radial depth of cut on torque requirements. For the entire duration of each complete test, the specimen was flooded with cutting fluid.

TEST CONDITIONS

All tests were conducted on a Fosdick Upright Drill Press at a cutting velocity of 12 feet per minute (60 revolutions per minute). A 3/4-inch diameter, high-speed steel, spiral-fluted chucking reamer, having eight flutes at an 8-degree spiral, was used for all tests.

Torque readings were obtained with the dynamometer and electrical recording equipment described under the section on Tapping.

Since one reamer was used for all tests, it was necessary to check any possible effects of tool wear or smear on the cutting edges. This was accomplished by staggering the sequence of work materials and duplicating some earlier tests. For example, the test having conditions of 0.025-inch-per-revolution feed rate, 0.015-inch radial depth of cut, and the 55 SSU Straight Mineral Oil plus 5-percent lard oil as the cutting fluid, was repeated five times for each work material. Average values were used and it was noted that no trend indicating tool wear was apparent.

TEST RESULTS

Figures 2.1 through 2.7 show the results of these tests, each figure containing the work material versus three measured quantities.

The hole diameter of every specimen was measured with a Sheffield air gage. Readings were taken at each end of the specimen and the maximum and minimum hole sizes were recorded. These are plotted to show the range of hole-size variation. To attain a consistent degree of clamping pressure on each specimen placed in the collet of the dynamometer, the locking handles were always brought to the same relative position.

Readings of surface roughness in microinches, root mean square, were obtained with a Profilometer containing a type Q amplimeter. Each hole was checked at both ends and again the range of minimum to maximum was plotted.

The plots of torque actually show two things. Rubbing torque was obtained as the reamer was withdrawn from the specimen after the cut was completed. This item shows a point-to-point connection simply for the sake of clarity (i.e., the slope of any line has no significance). Cutting torque was measured at the start of the test and after 1/2 inch of the hole had been reamed. These values are also plotted as a range and show the increase in torque after a definite length of the hole was reamed for each material.

In cases where more than one test was run per set of test conditions, all limiting values were averaged but still plotted as ranges of maximum and minimum.

Figure 2.8 shows the effects of feed rate and radial depth of cut versus cutting torque for each work material. The values plotted are the extremes found for each condition, regardless of work material. For example, the plot of radial depth of cut for 0.0025 inch shows two points having 9 and 11 pound-inches of torque. All the work materials fell within this range, so to avoid cluttering the plot only the extreme values were used. It will be noted that neither curve intersects at the zero-zero point. This is indicative of rubbing between the reamer and hole.

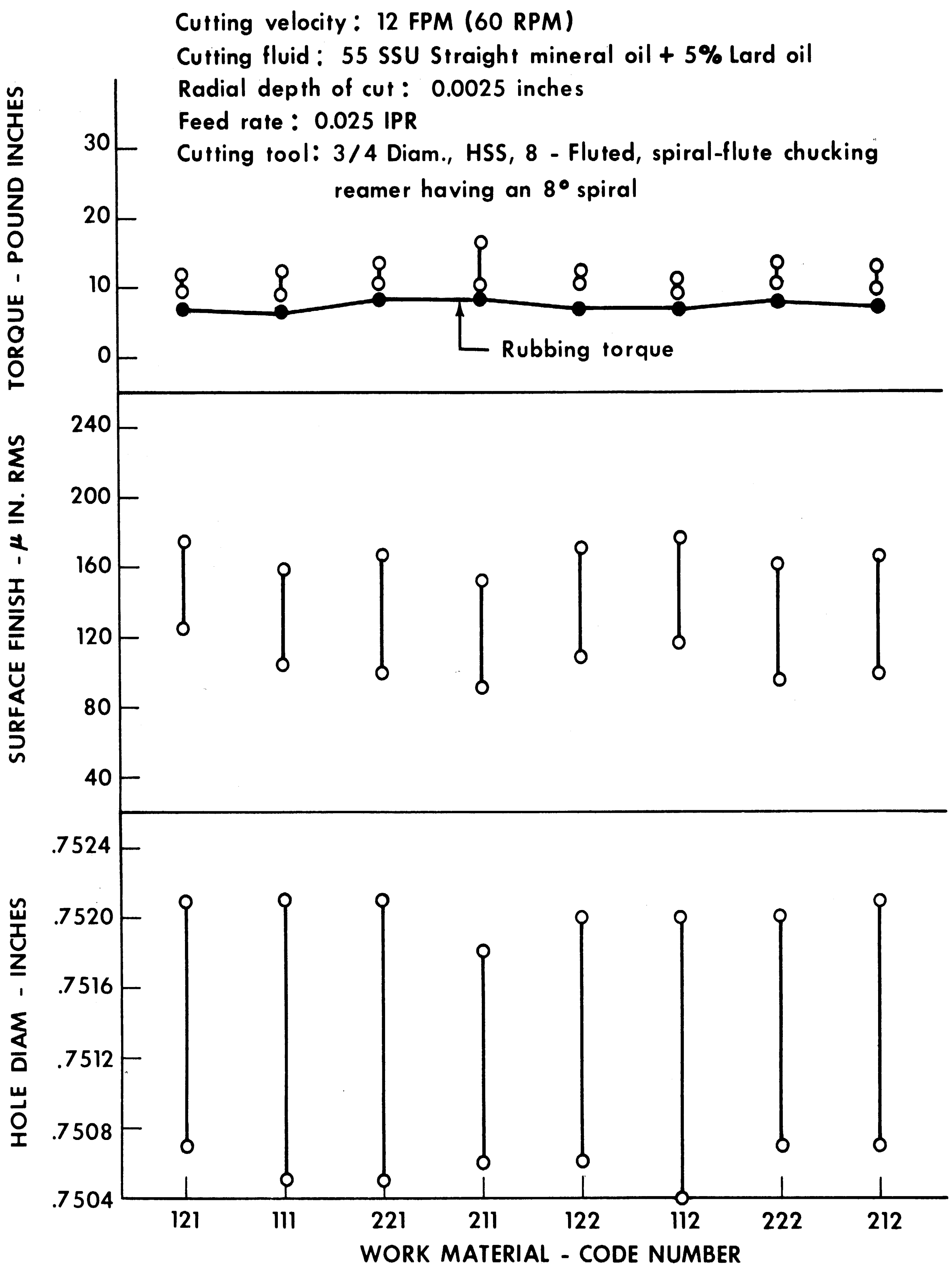


Fig. 2.1. Ranges of torque, hole size, and surface finish when reaming the work materials.

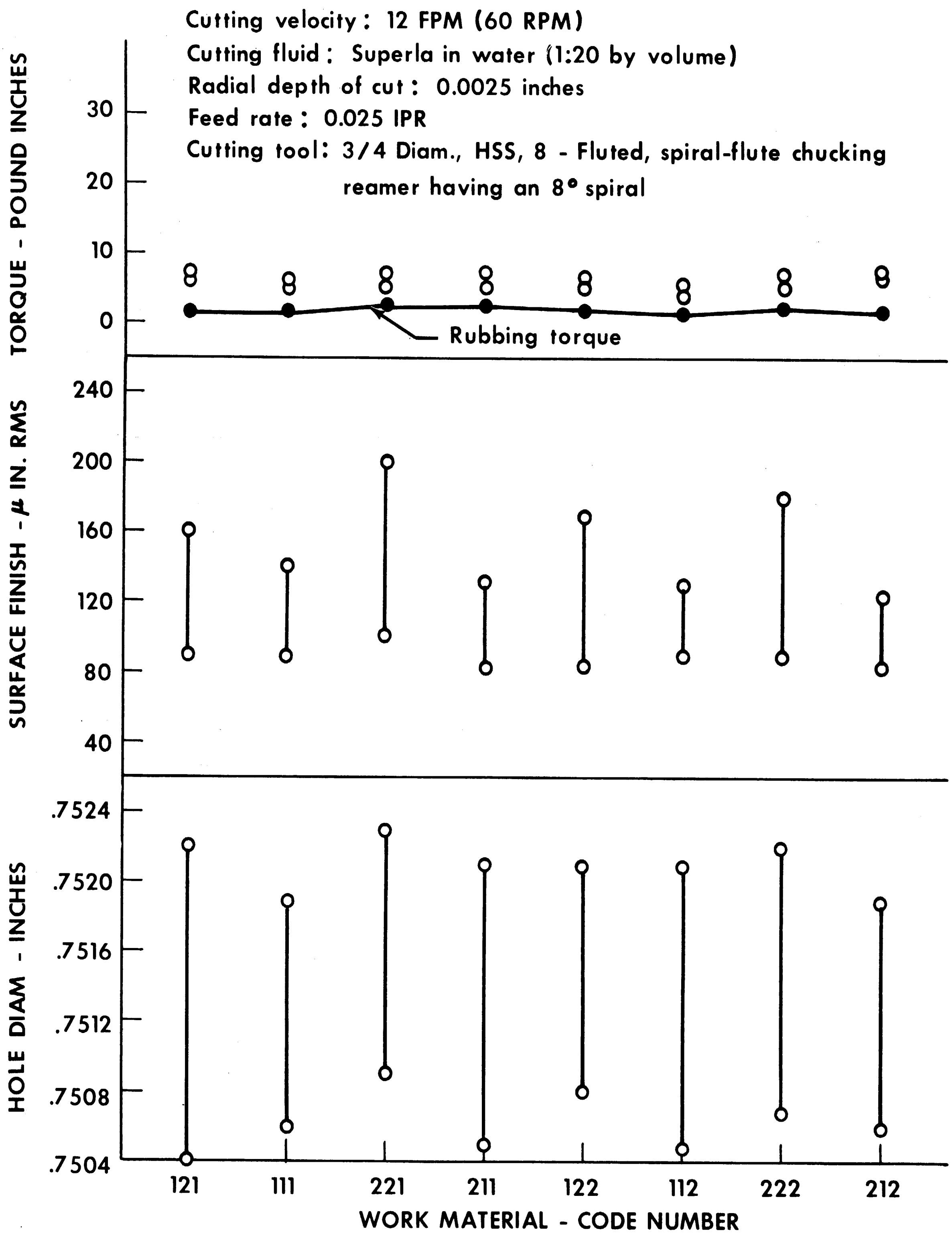
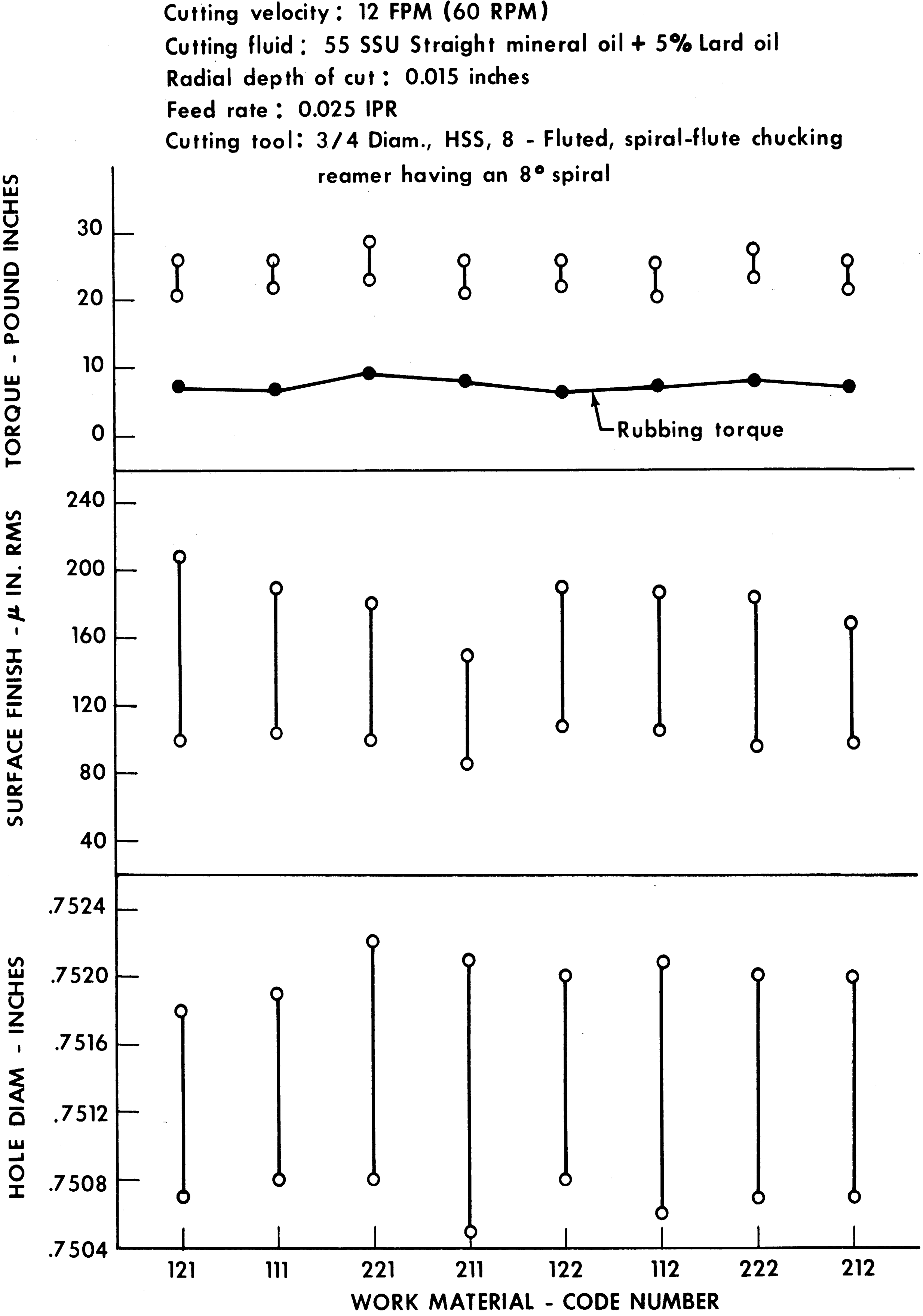


Fig. 2.2. Ranges of torque, hole size, and surface finish when reaming the work materials.



Cutting velocity: 12 FPM (60 RPM)
Cutting fluid: 55 SSU Straight mineral oil + 5% Lard oil
Radial depth of cut: 0.015 inches
Feed rate: 0.025 IPR
Cutting tool: 3/4 Diam., HSS, 8 - Fluted, spiral-flute chucking reamer having an 8° spiral

Fig. 2.3. Ranges of torque, hole size, and surface finish when reaming the work materials.

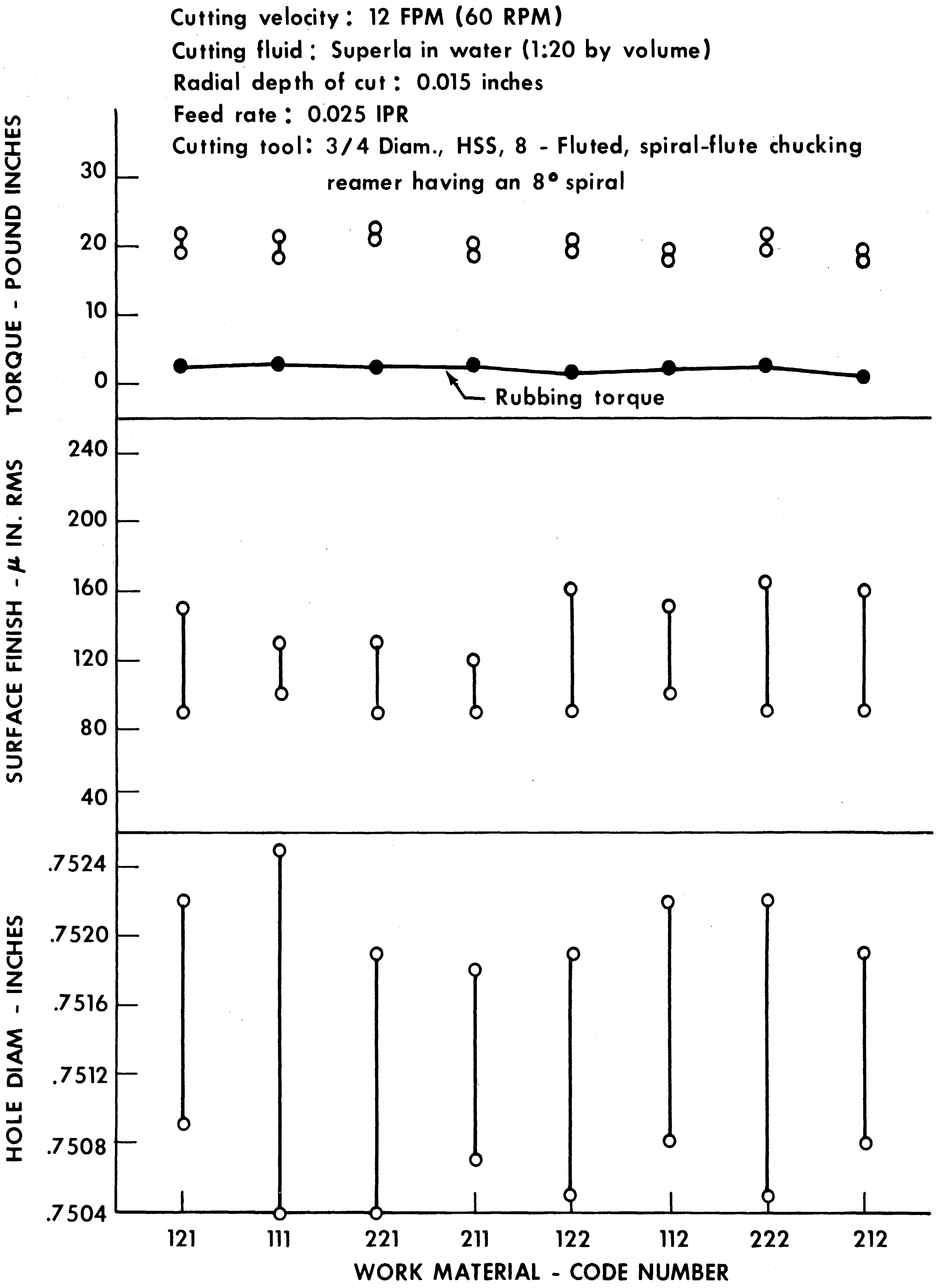


Fig. 2.4. Ranges of torque, hole size, and surface finish when reaming the work materials.

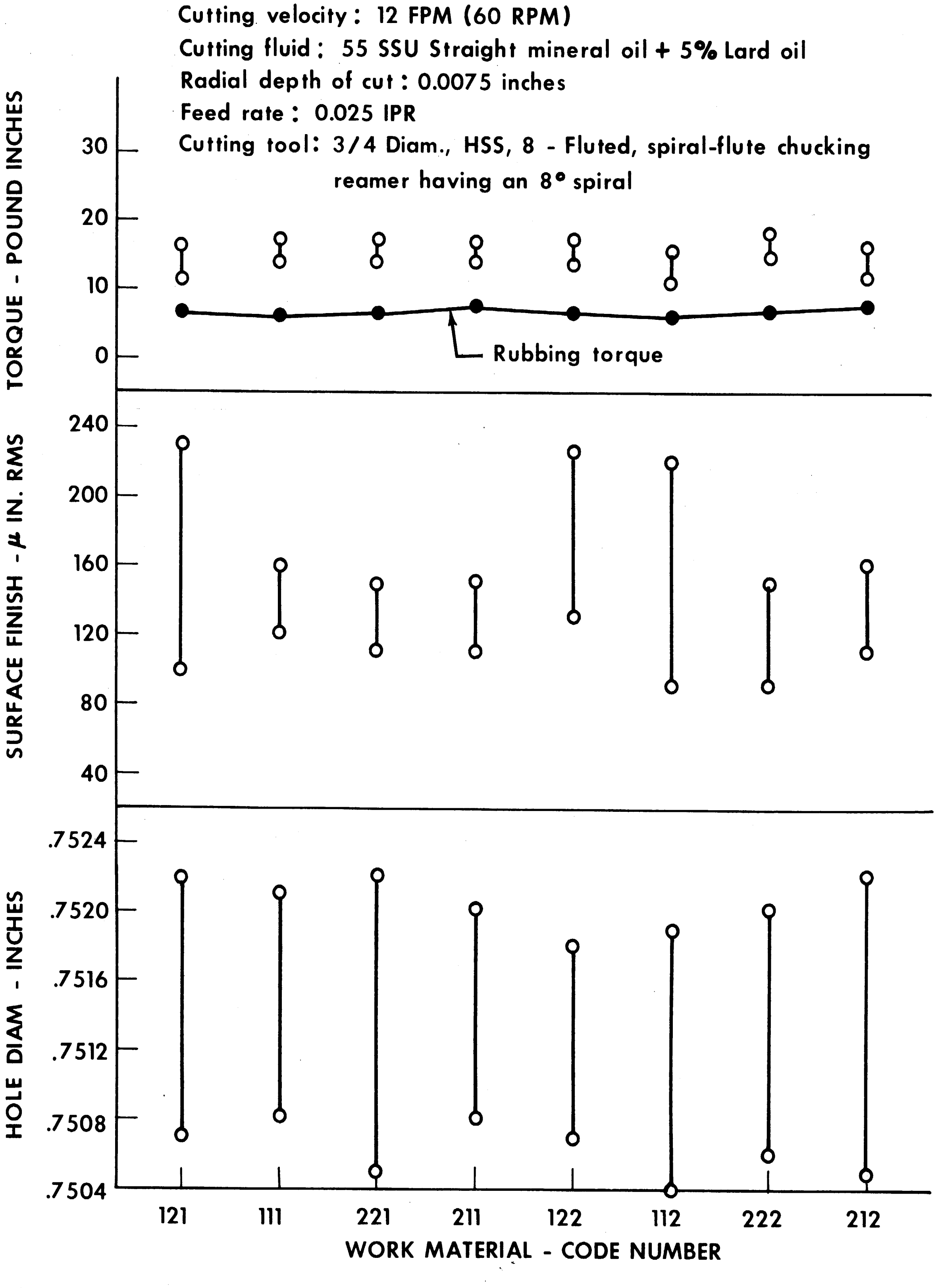


Fig. 2.5. Ranges of torque, hole size, and surface finish when reaming the work materials.

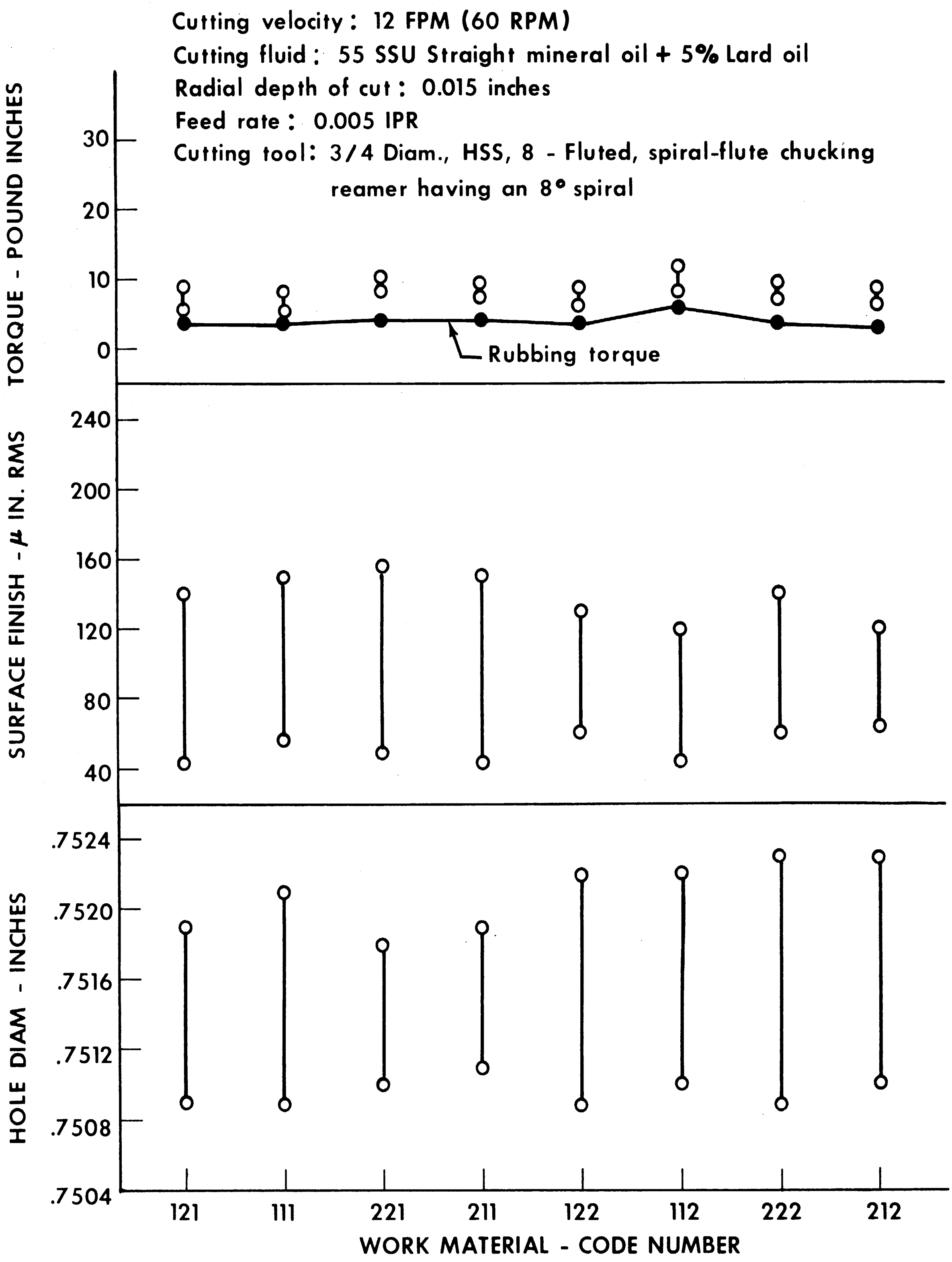
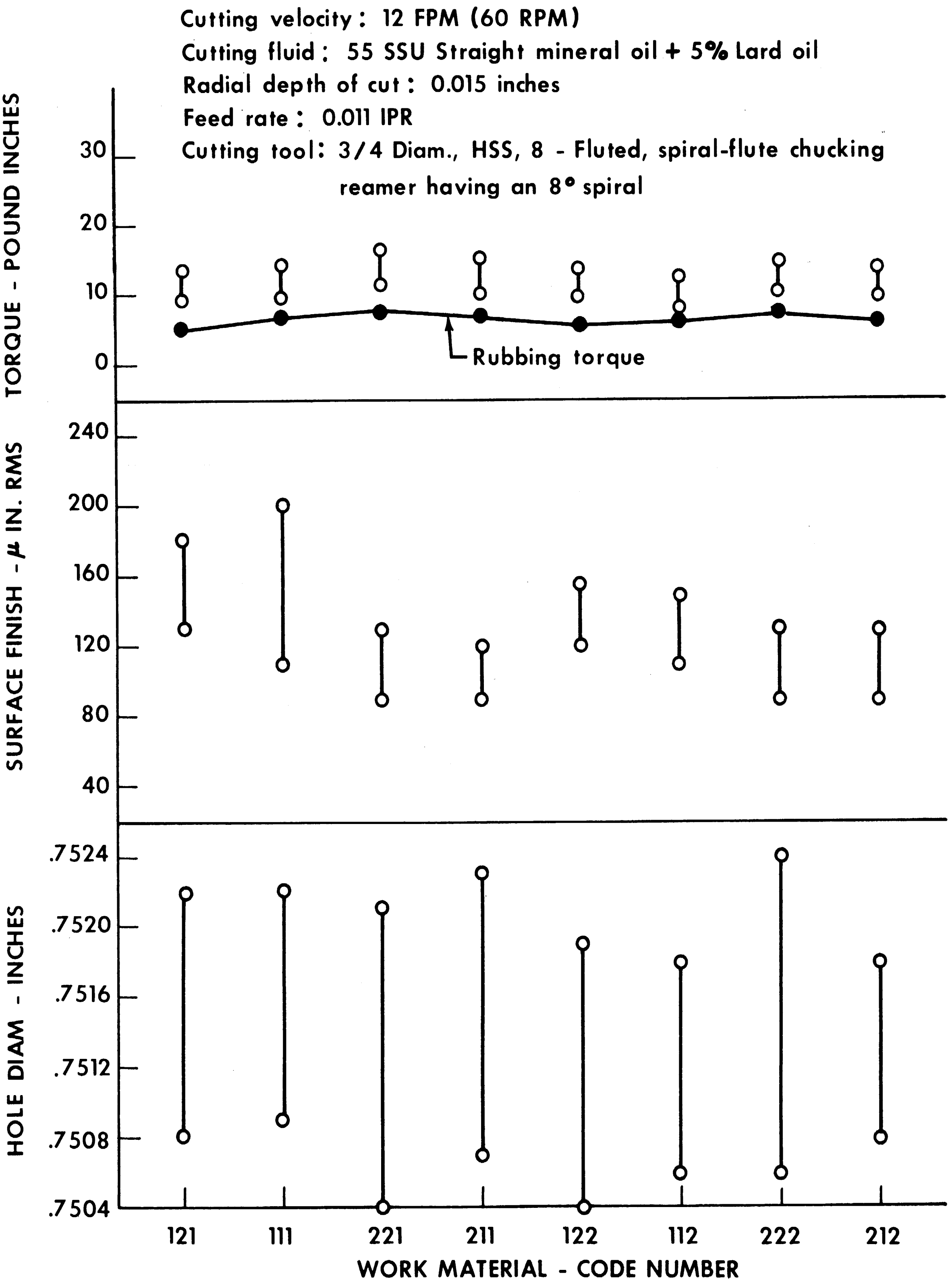


Fig. 2.6. Ranges of torque, hole size, and surface finish when reaming the work materials.



Cutting velocity: 12 FPM (60 RPM)
Cutting fluid: 55 SSU Straight mineral oil + 5% Lard oil
Radial depth of cut: 0.015 inches
Feed rate: 0.011 IPR
Cutting tool: 3/4 Diam., HSS, 8 - Fluted, spiral-flute chucking reamer having an 8° spiral

Fig. 2.7. Ranges of torque, hole size, and surface finish when reaming the work materials.

Cutting velocity: 12 FPM (60 RPM)
Cutting fluid: 55 SSU Straight mineral oil + 5% Lard oil
Cutting tool: 3/4 Diam., HSS, 8 - Fluted, spiral-flute chucking reamer having an 8° spiral

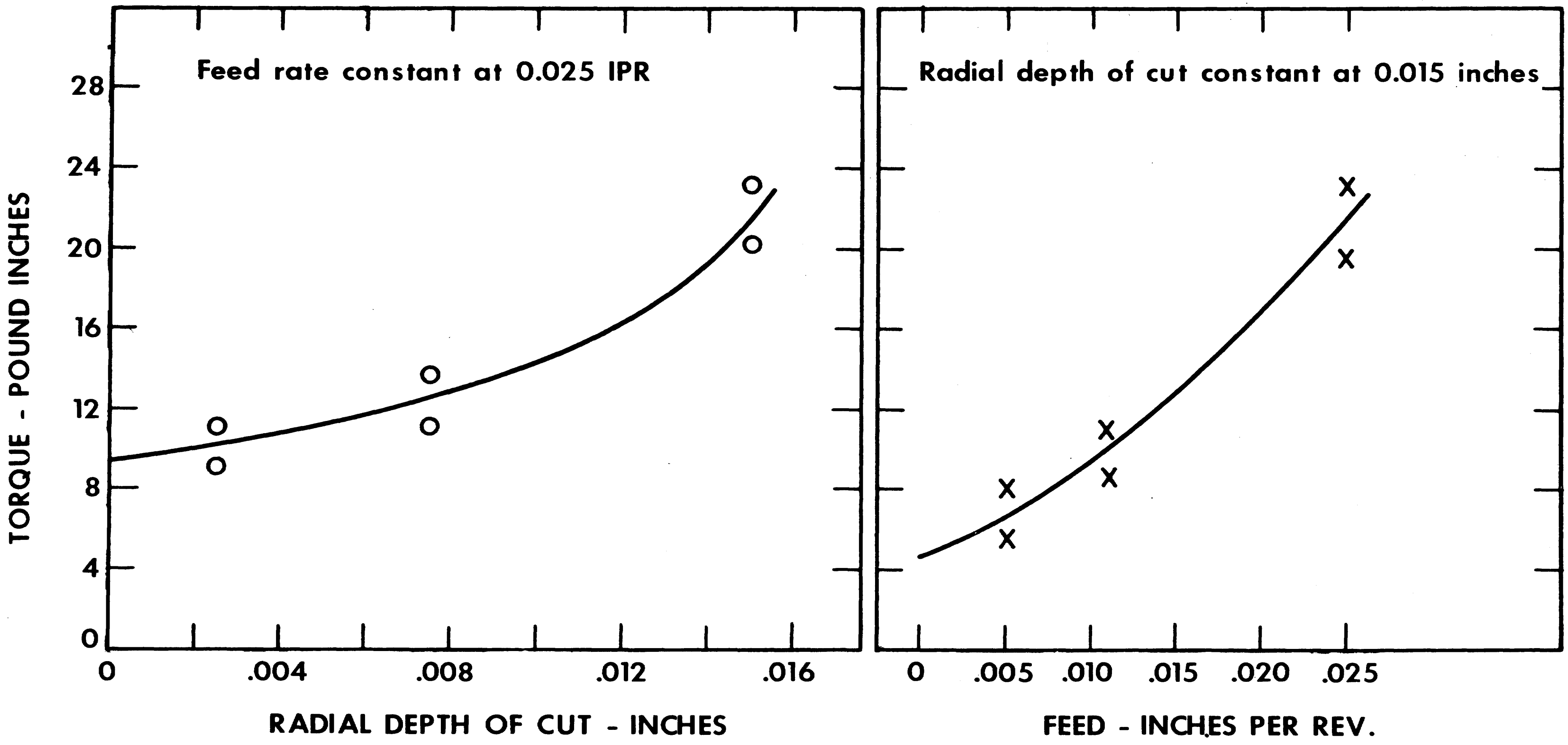


Fig. 2.8. Reaming torque vs depth of cut and feed rate.

PART III. DRILLING

The same rods used to produce specimens for tapping were used as work materials for these tests. Effects of drill diameter and feed rate on cutting torque were studied.

PROCEDURE

Test specimens were produced as solid cylindrical pieces, 1-inch outside diameter, about 3 inches long, and center-drilled in the ends. A 3/8-in.-diameter twist drill was chucked in the spindle of the drill press. The center of the specimen, held in a collet in the dynamometer, was aligned with the drill-press spindle. Torque readings were then obtained as the drill operated at a feed rate of 0.005 inch per revolution, cutting velocity of 35 feet per minute (360 revolutions per minute), and without the use of any cutting fluid. Feed rates of 0.009, 0.011, and 0.015 inch per revolution were then used in sequence with the same drill and work material. Following these tests, a feed rate of 0.005 inch per revolution and cutting velocity of about 35 feet per minute were maintained and drills of 1/4-, 1/2-, and 3/4-inch diameter were used in sequence to determine the effect of drill diameter on torque. Attempts were made to study the effect of cutting speed, but results were extremely erratic because of the occurrence of drill seizure in short periods of time; these tests were therefore abandoned. Isolated tests were conducted to attempt to ascertain which work materials could cause drill seizure in the shortest period of time, but after checking several combinations of cutting conditions such extreme reversals of results occurred that no definite correlation could be determined.

In a second attempt to define the tendency of drill seizure, a cutting fluid ("Superla" in water, 1 part to 20 parts by volume) was used, but once again there was a decided lack of correlation between drill seizure and work material.

Finally, the drills used in the phase of testing conducted on the automatic screw machine were subjected to tests to determine the magnitude of cutting torque. This was done because several of the work materials caused a slow-down of spindle speed during the drilling cut after tool wear reached a point of influence. The drill-work material combinations were maintained in accordance with their use on the screw machine. Besides testing these used drills, a new drill was used to determine the torque requirements with a sharp tool, thereby showing any effects of tool wear. All these tests were conducted at a feed rate of 0.007 inch per revolution, cutting velocity of 215 feet per minute (1500 revolutions per minute), with a drill diameter of 0.547 inch.

These test conditions were the closest approximation of conditions used on the screw machine that could be obtained with the drill press.

TEST CONDITIONS

All tests were conducted on a Fosdick Upright Drill Press using a cutting velocity of 35 feet per minute (revolutions per minute varied with changes in drill diameter). Each two-fluted twist drill had a helix angle of 30 degrees and point angle of 118 degrees.

Torque readings were obtained with the dynamometer and electrical recording equipment described under "Tapping."

TEST RESULTS

Figure 3.1 shows the results of cutting torque versus feed and drill diameter, using sharp tools. Each test condition is represented by two points, these being the extremes encountered within the eight work materials. For the sake of clarity, the six intermediate points, per test condition, have been omitted. Since the individual lines arising from the eight work materials overlapped quite closely, it was decided that one average line for all work materials would be quite representative. From these two lines, the following relationship has been derived:

$$\text{Torque} = 20{,}000\ f^{1.07}\ D^{1.8}$$

where:

Torque = cutting torque in pound inches (sharp tools)
20,000 = a proportionality constant
f = feed rate in inches per revolution
D = drill diameter in inches
1.07 and 1.8 = slopes of the lines showing effect of feed and drill diameter versus torque

The following table shows a comparison of torque versus work material for sharp and used drills (used drills had been employed on the screw machine).

TABLE III-1

COMPARISON OF TORQUE VERSUS WORK MATERIAL FOR SHARP AND USED DRILLS

Work Material Code No.	Torque-Pound Inches (Used Drill)	Torque-Pound Inches (New Drill)
*222 - 1	52	30
222 - 2	33	
212	38	30
211	32	30
111	30	30
112	30	30
121	31	30

*Two drills were used with this material, so both were checked. Drill 222 - 1 operated for a longer time than did 222 - 2, and because it had worn to a greater degree, the torque reading was higher.

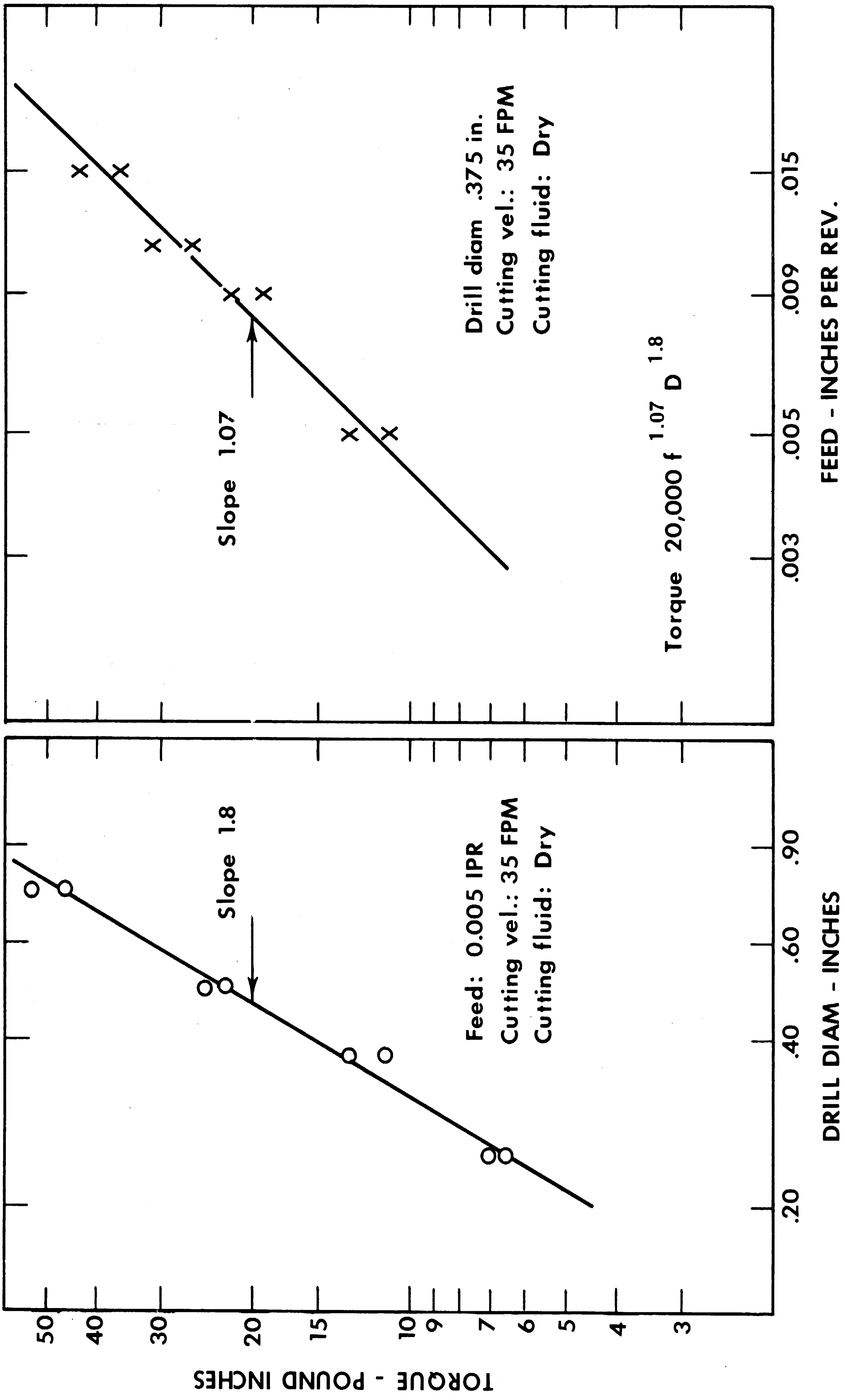


Fig. 3.1. Drilling torque vs feed and drill diameter.

PART IV. CUTTING FORCES

Two cutting-force components, the tangential or vertical force and the feeding or horizontal force, were measured with an electrical resistance strain-gage dynamometer and a Sanborn recorder system. The tests were performed on a 14-inch Monarch lathe. The material used was 1-1/2 by 30-inch bar stock of eight types identified by the code numbers 111, 121, 122, 211, 221, 222, 112, and 212. The depth of cut was maintained at .150 inch to make the cut as nearly orthogonal as possible. The cutting tools were Bethlehem 66 HSS ground to shape-0, variable, 6, 8, 3, 0, 0. The cutting was done dry because higher cutting forces are usually associated with dry cutting and the difference between several materials or conditions should be magnified.

Three conditions were varied, namely, the feed rate, the cutting velocity, and the side rake angle of the tool. The feeds were .003, .006, .012, and .024 inch per revolution of the work; the cutting velocities were 25, 50, 100, 200, and 400 surface feet per minute and the side rake angles were 0, 8, 16, 24, 32, and 40 degrees. The variable velocity and variable rake tests were run at a feed of .012 inch per revolution and the variable feed tests were run at 200 surface feet per minute at two rakes, 0 and 32 degrees.

The data obtained are summarized and plotted in Figs. 4.1 through 4.8 as Cutting Force versus Rake Angle, in Figs. 4.9 through 4.16 as Cutting Force versus Velocity, and in Fig. 4.17 as a representative curve of Cutting Force versus Feed.

In terms of the variables in the materials, the lowest forces are associated with the low cold reduction and high copper content. More specifically, the cutting forces, both vertical and horizontal, for low cold reduction material were from 10 to 15 percent lower than the forces for high cold work, with the higher percentages associated with higher rake angles. The cutting forces for high copper material were as much as 5 to 7 percent lower than the cutting forces for low copper material. Cutting velocity does not affect the magnitude of the difference between the cutting forces of the eight materials. There was no appreciable difference between the forces with high or low solution-treatment temperature material.

Table IV-1 shows the rank of the eight materials tested as to the cutting forces required, number 1 indicating the lowest cutting force.

In terms of cutting geometry, an appreciable difference was observed in the horizontal cutting forces between materials when using tools with a high rake angle and when cutting with large feeds.

TABLE IV-1

RANK OF EIGHT MATERIALS AS TO CUTTING FORCES REQUIRED
(Number 1 indicates lowest force)

Rank	Material (Code)
1	211, 221
2	212, 222
3	111, 121
4	112, 122

Cutting forces were measured while cutting material 222 at varying temperatures. A nearly continuous cut was made on a 1-1/2 x 18-inch bar which was heated to 212°F and immediately cut. At the end of the cutting time the temperature of the bar was about 100°F. The cutting forces were 102 pounds in the vertical direction and -3 pounds in the horizontal direction (when using a tool with 24-degree rake angle at a feed of .012 inch per revolution and a velocity of 100 surface feet per minute) from the beginning of the test to the end, indicating no noticeable temperature effects. There was a difference in chip formation, however. At the beginning and at the end of the cut the chip was short. Between the end points, which corresponded to a temperature in the range of about 150°F to 180°F the chip was longer (about 2 - 3 inches) and of larger radius (1 - 1-1/2 inches).

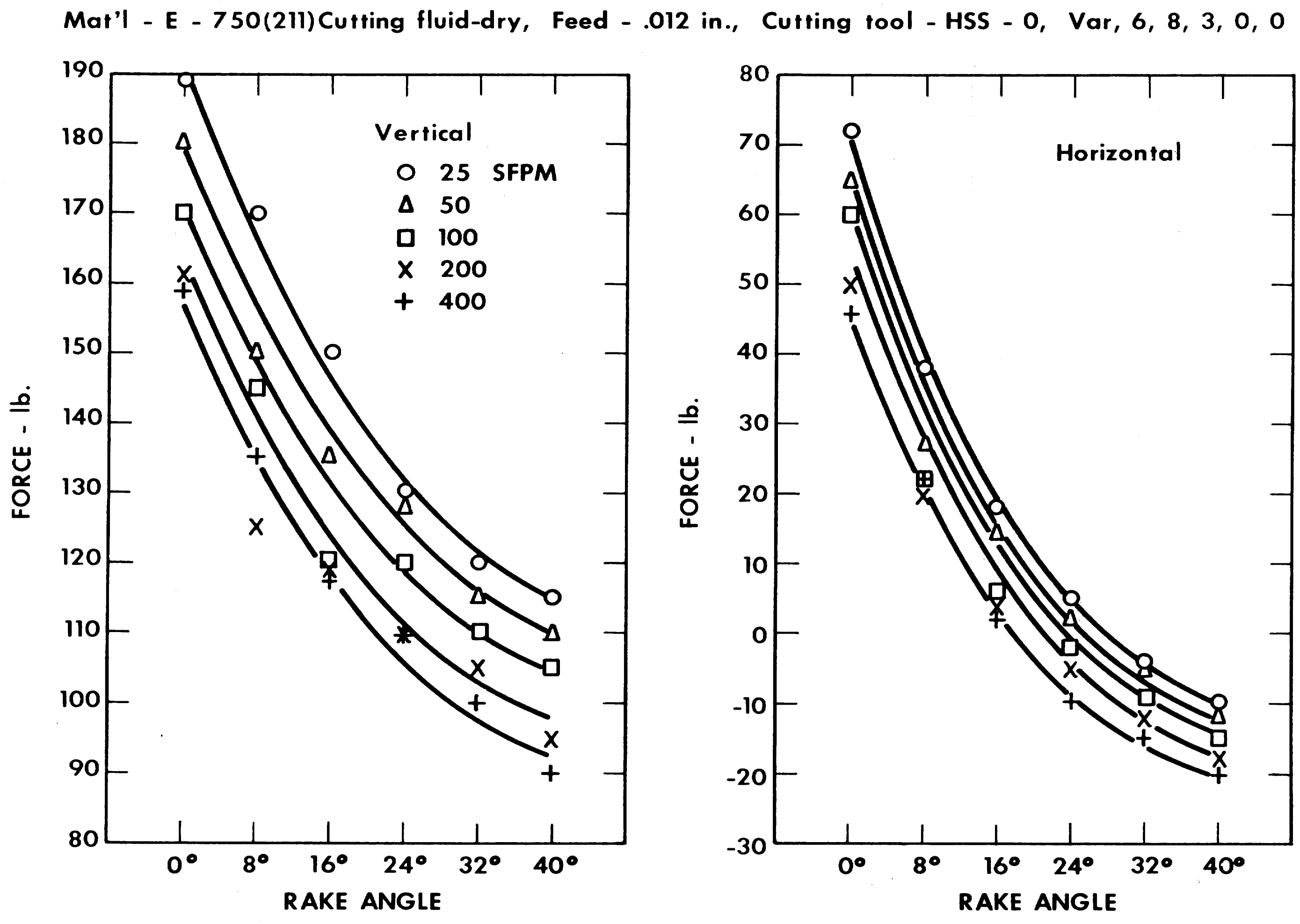

Mat'l - E - 750(211)Cutting fluid-dry, Feed - .012 in., Cutting tool - HSS - 0, Var, 6, 8, 3, 0, 0

Fig. 4.1. Cutting forces vs rake angle.

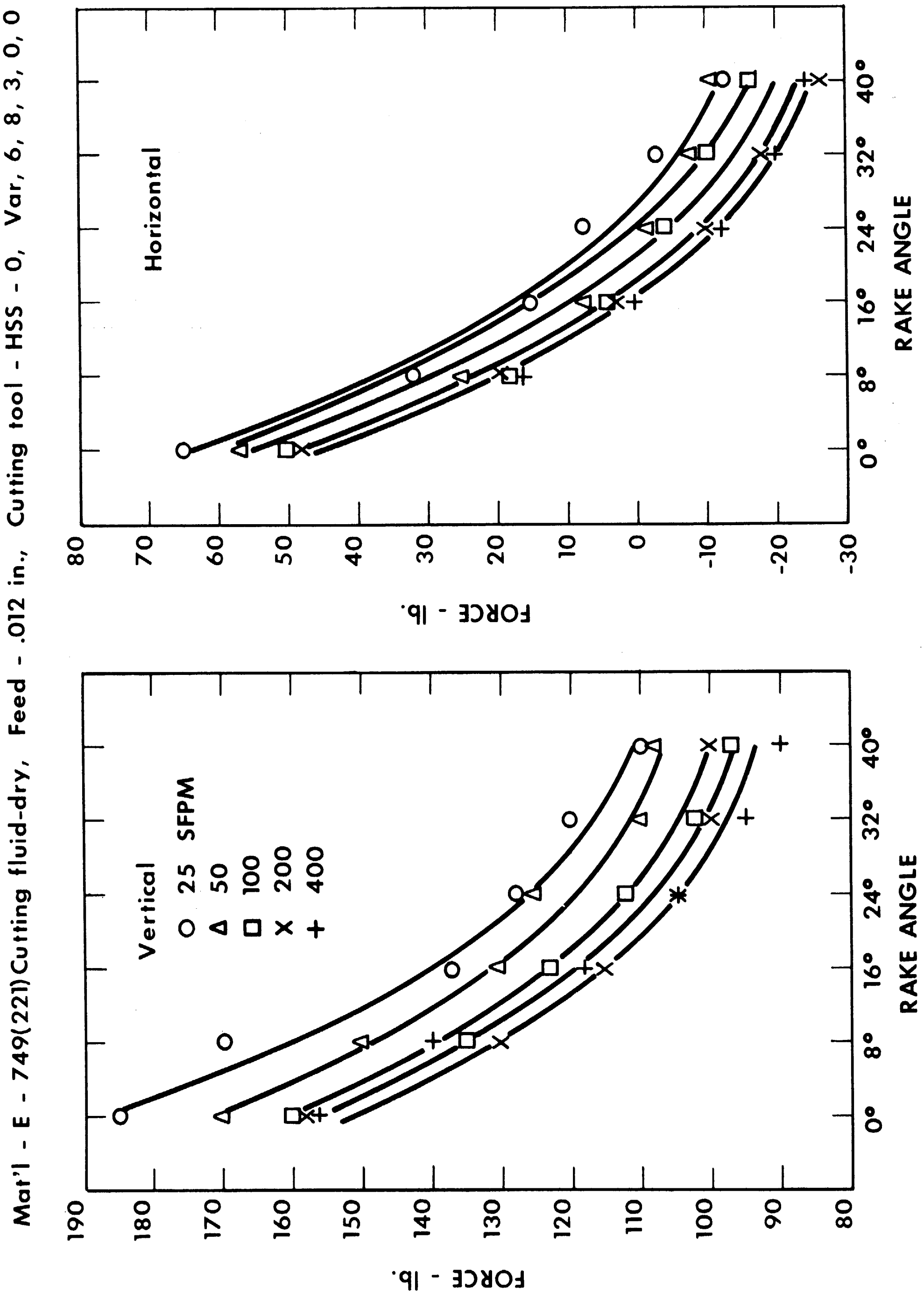


Fig. 4.2. Cutting forces vs rake angle

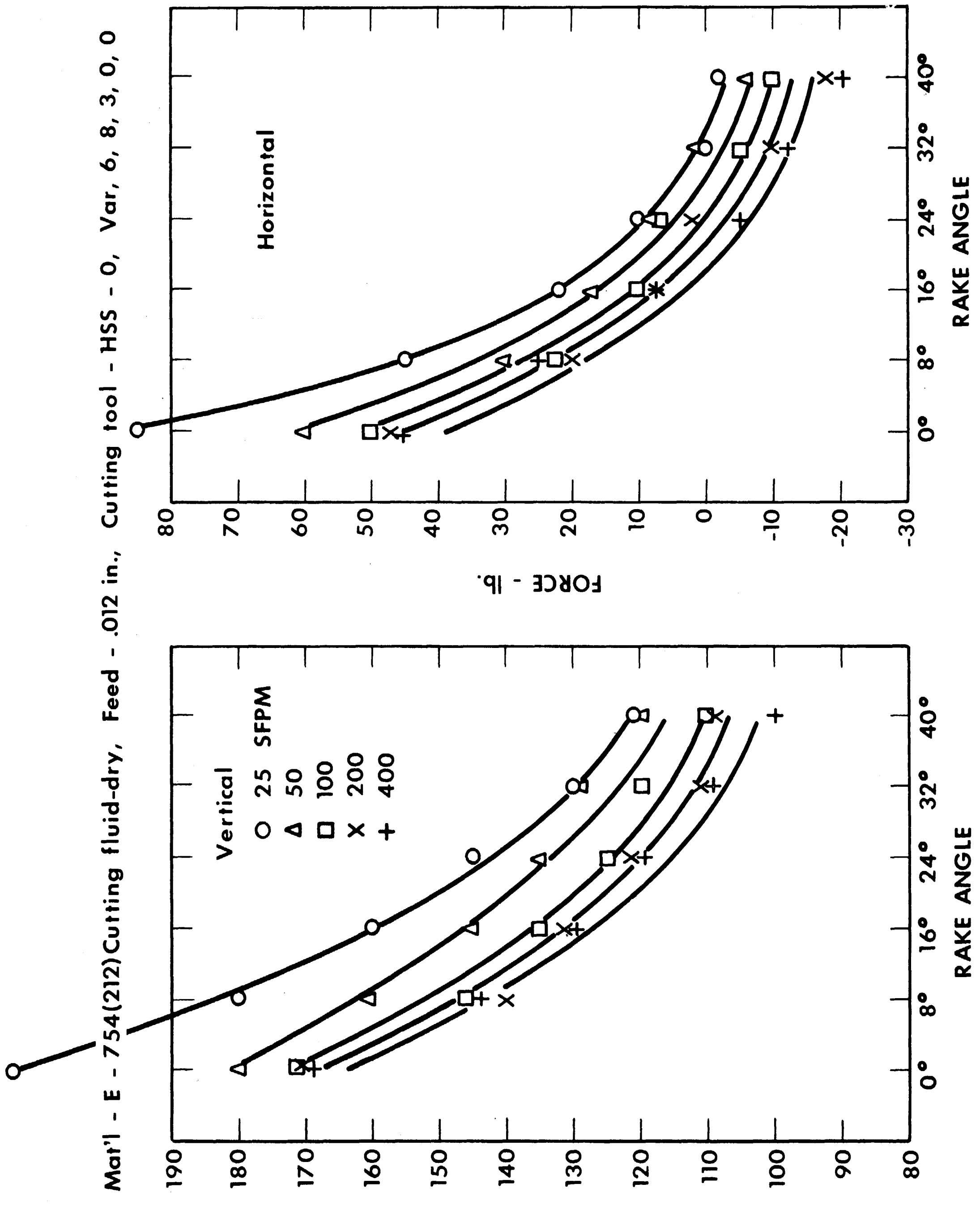

Mat'l - E - 754(212)Cutting fluid-dry, Feed - .012 in., Cutting tool - HSS - 0, Var, 6, 8, 3, 0, 0

Fig. 4.3. Cutting forces vs rake angle.

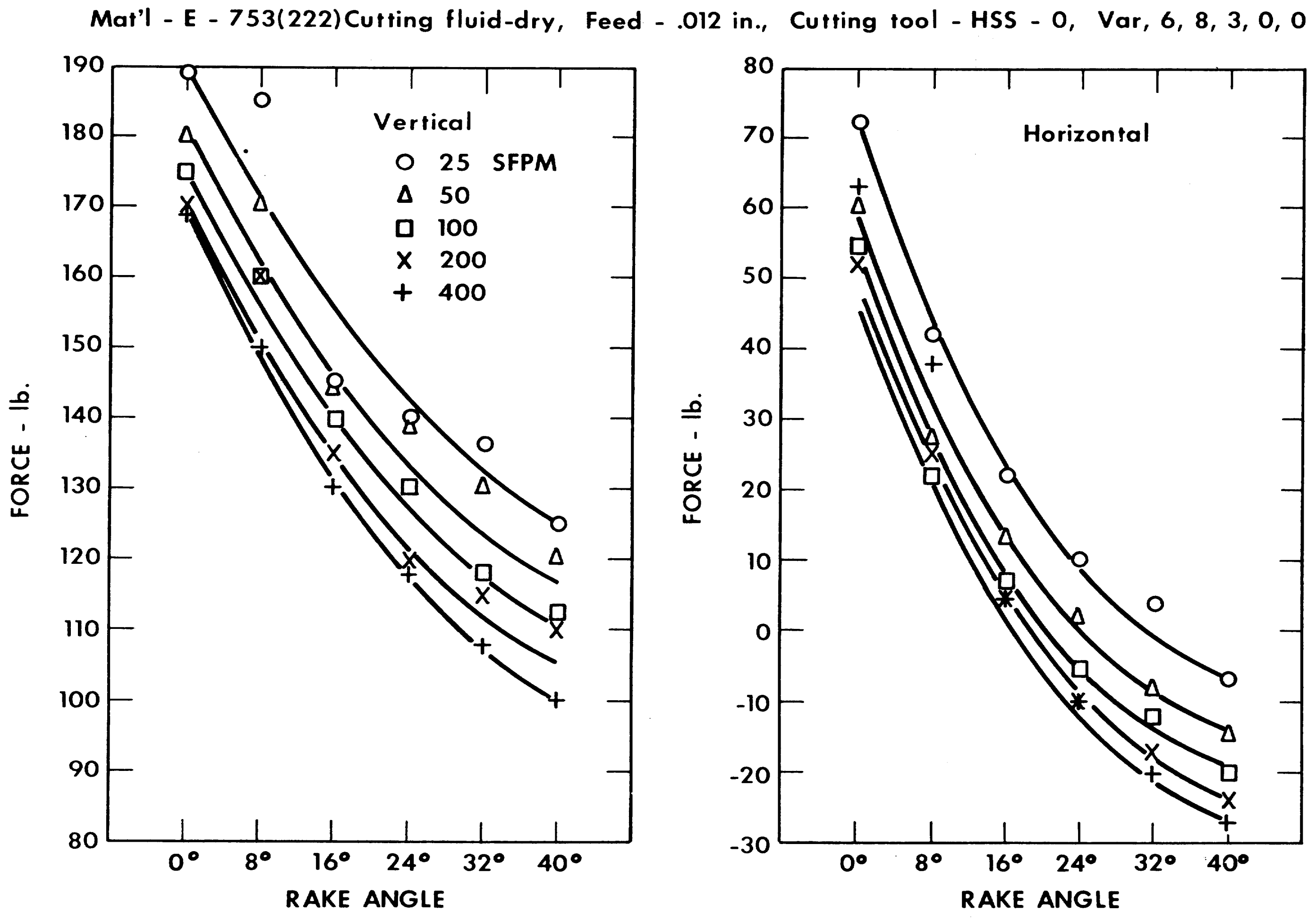


Fig. 4.4. Cutting forces vs rake angle.

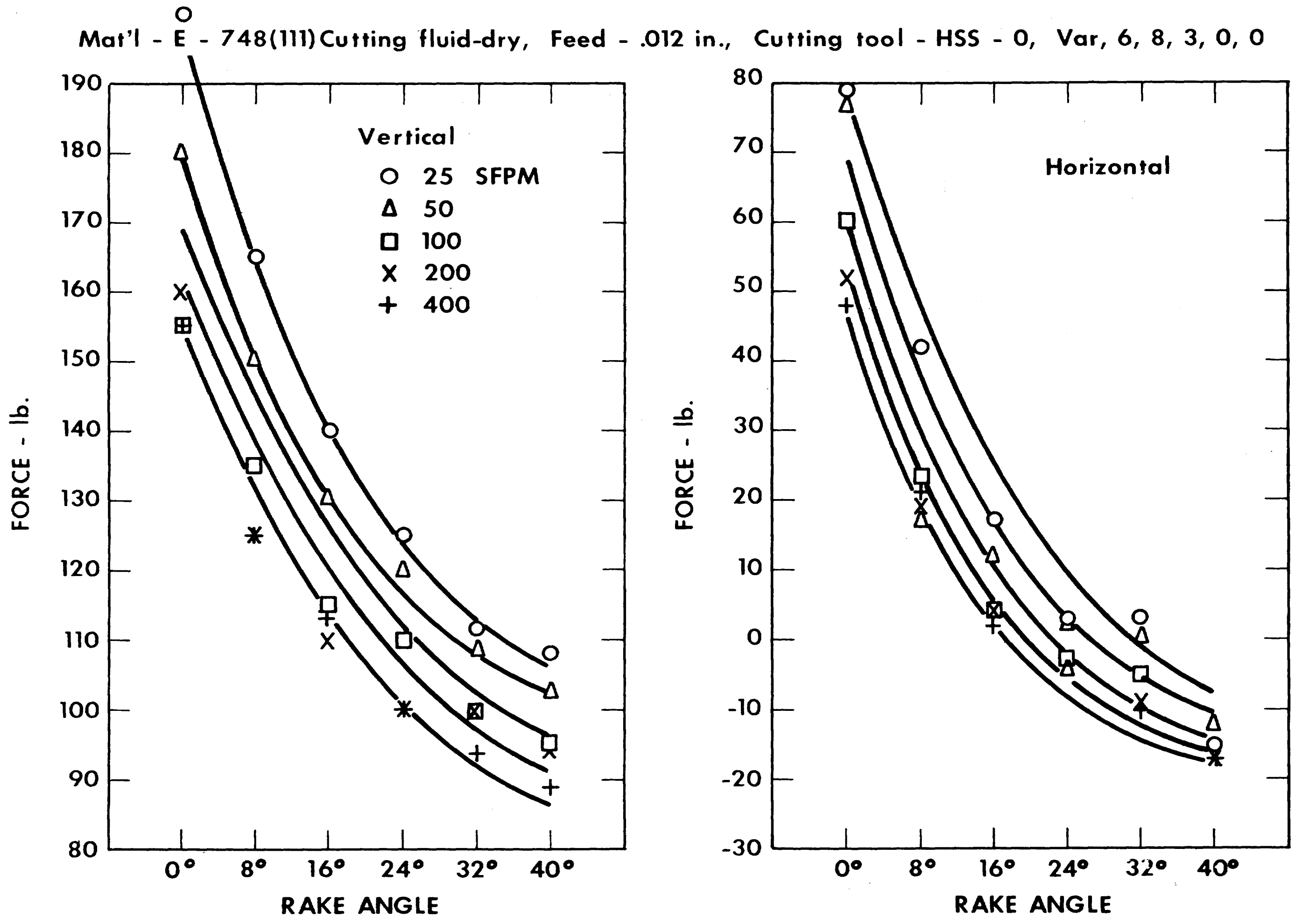


Fig. 4.5. Cutting forces vs rake angle.

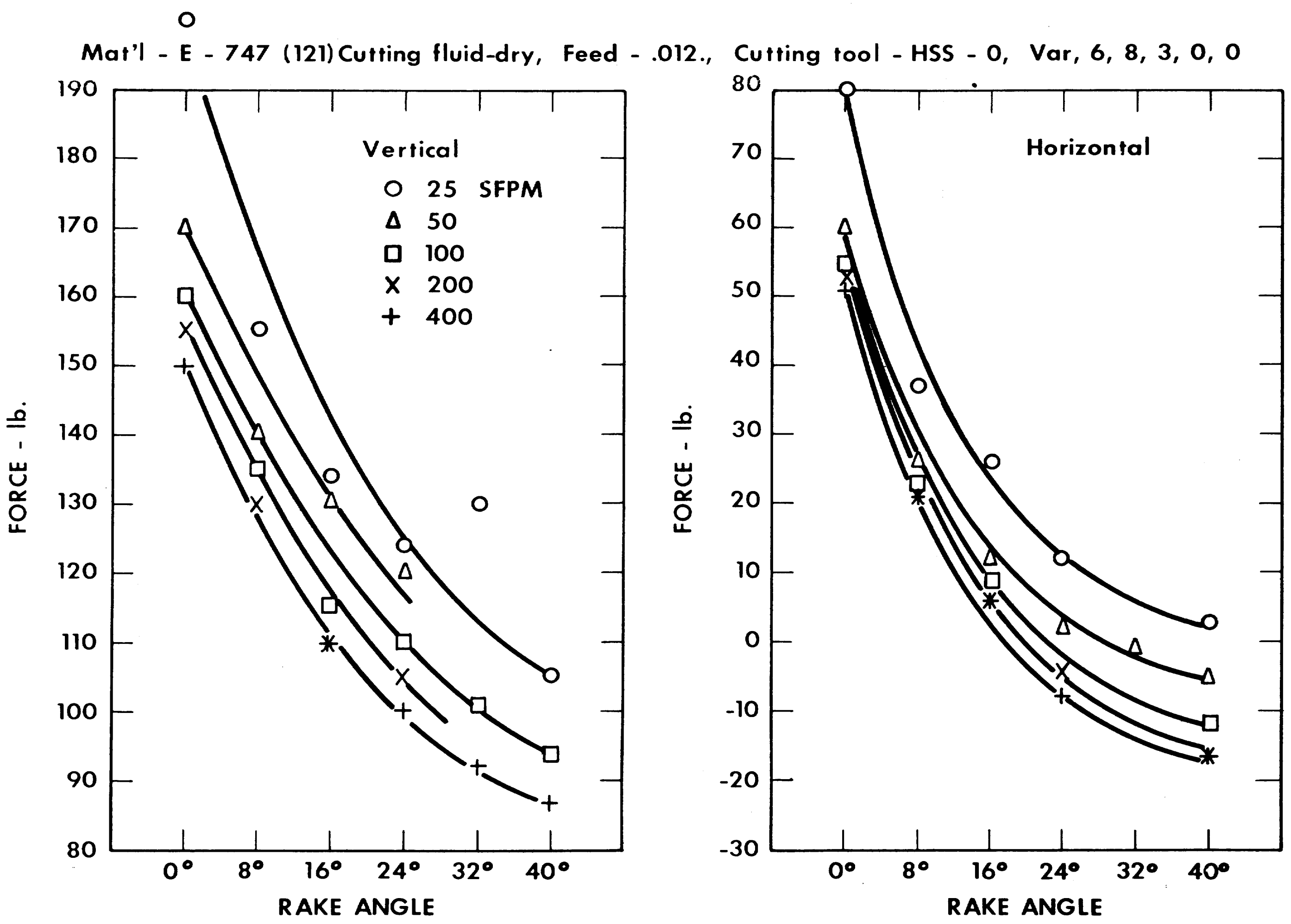
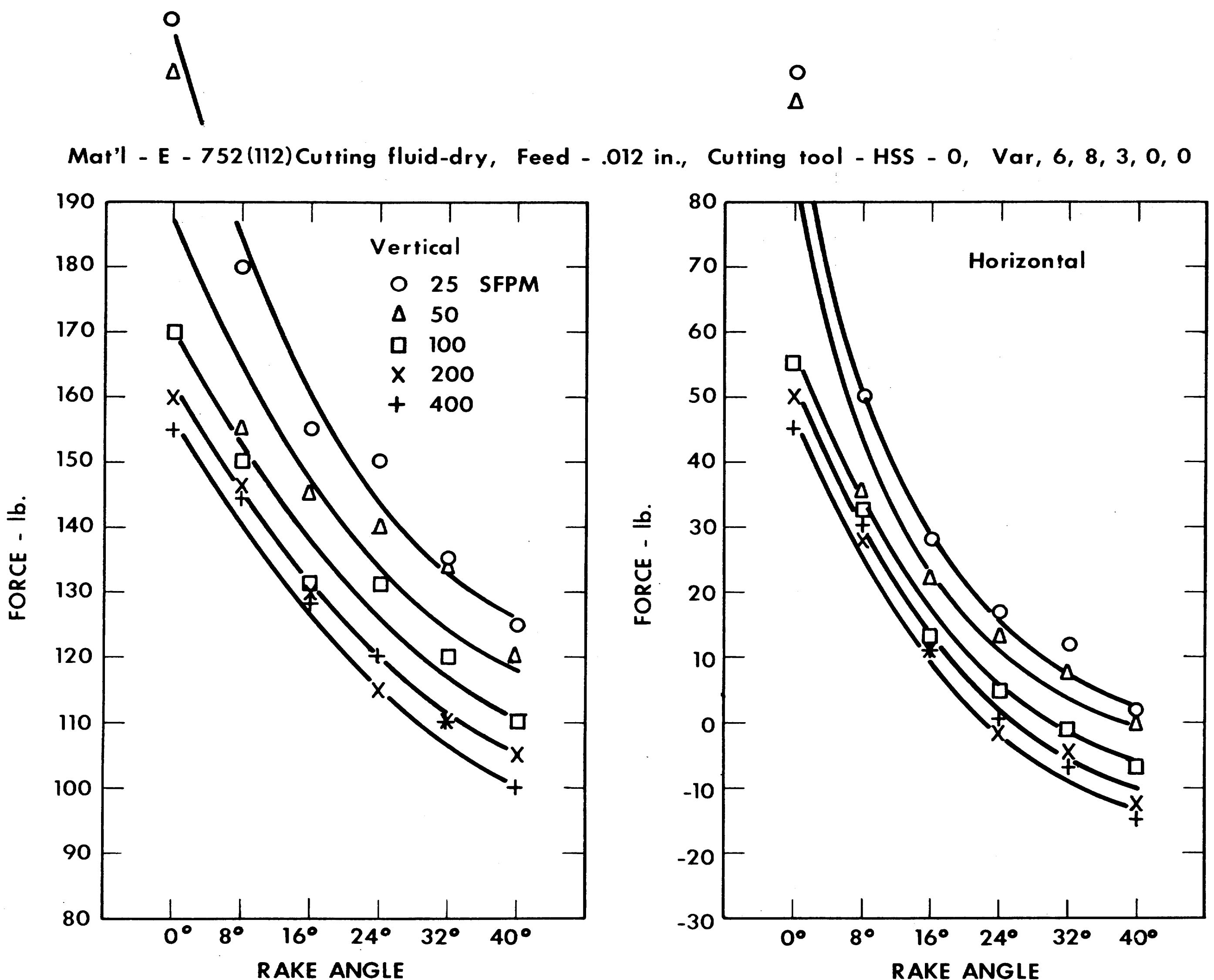


Fig. 4.6. Cutting forces vs rake angle.



Mat'l - E - 752(112)Cutting fluid-dry, Feed - .012 in., Cutting tool - HSS - 0, Var, 6, 8, 3, 0, 0

Fig. 4.7. Cutting forces vs rake angle.

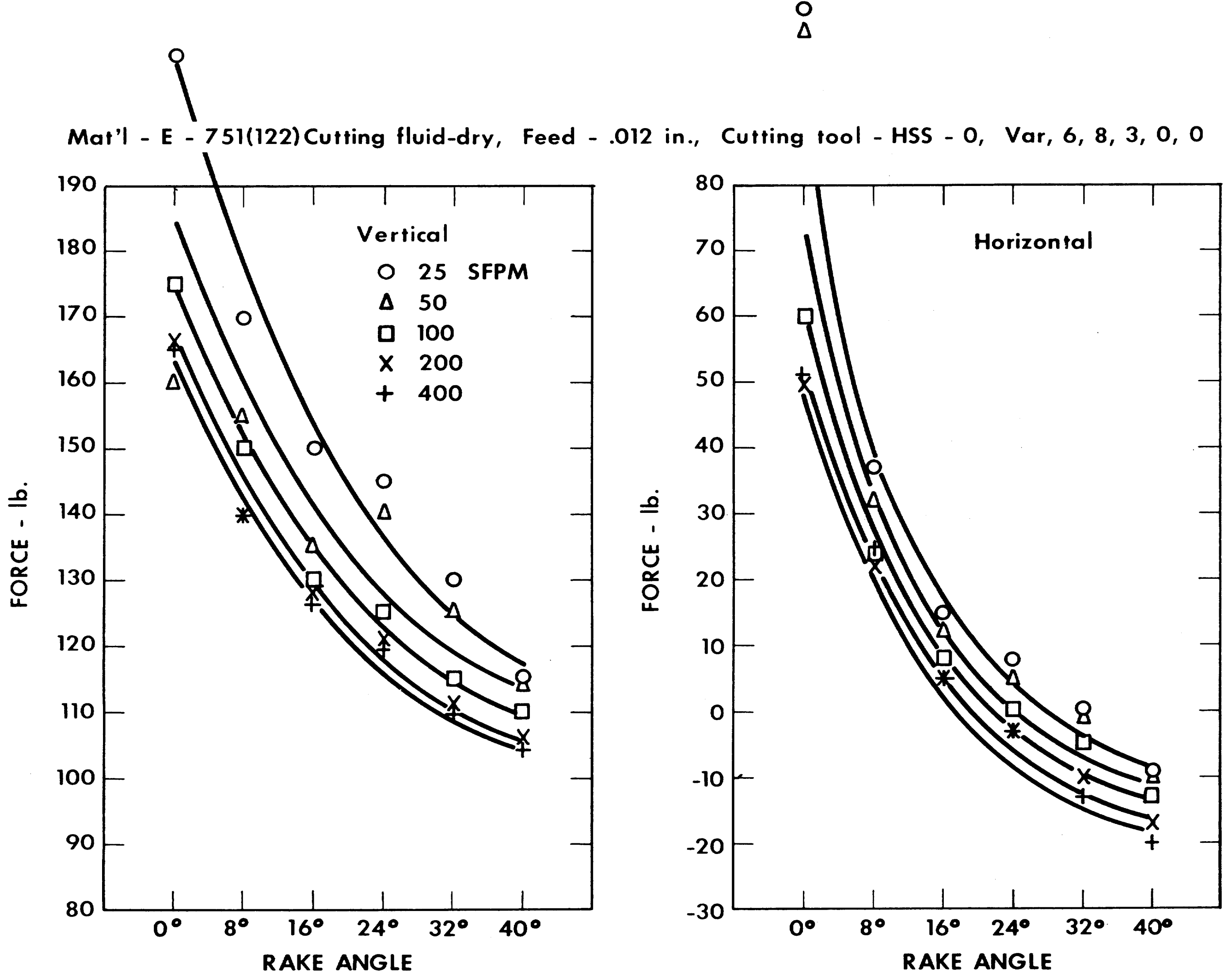


Fig. 4.8. Cutting forces vs rake angle.

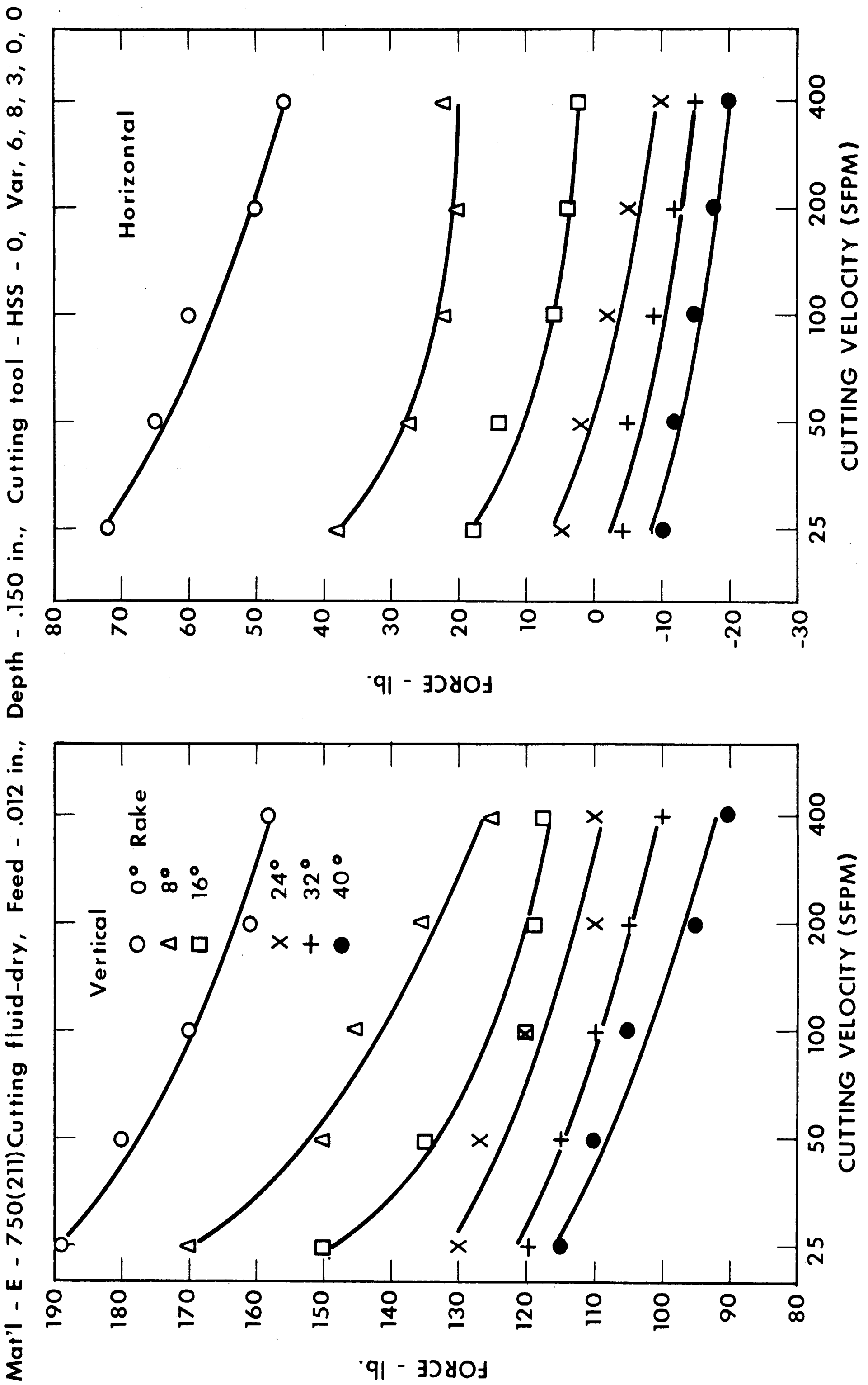


Fig. 4.9. Cutting forces vs velocity.

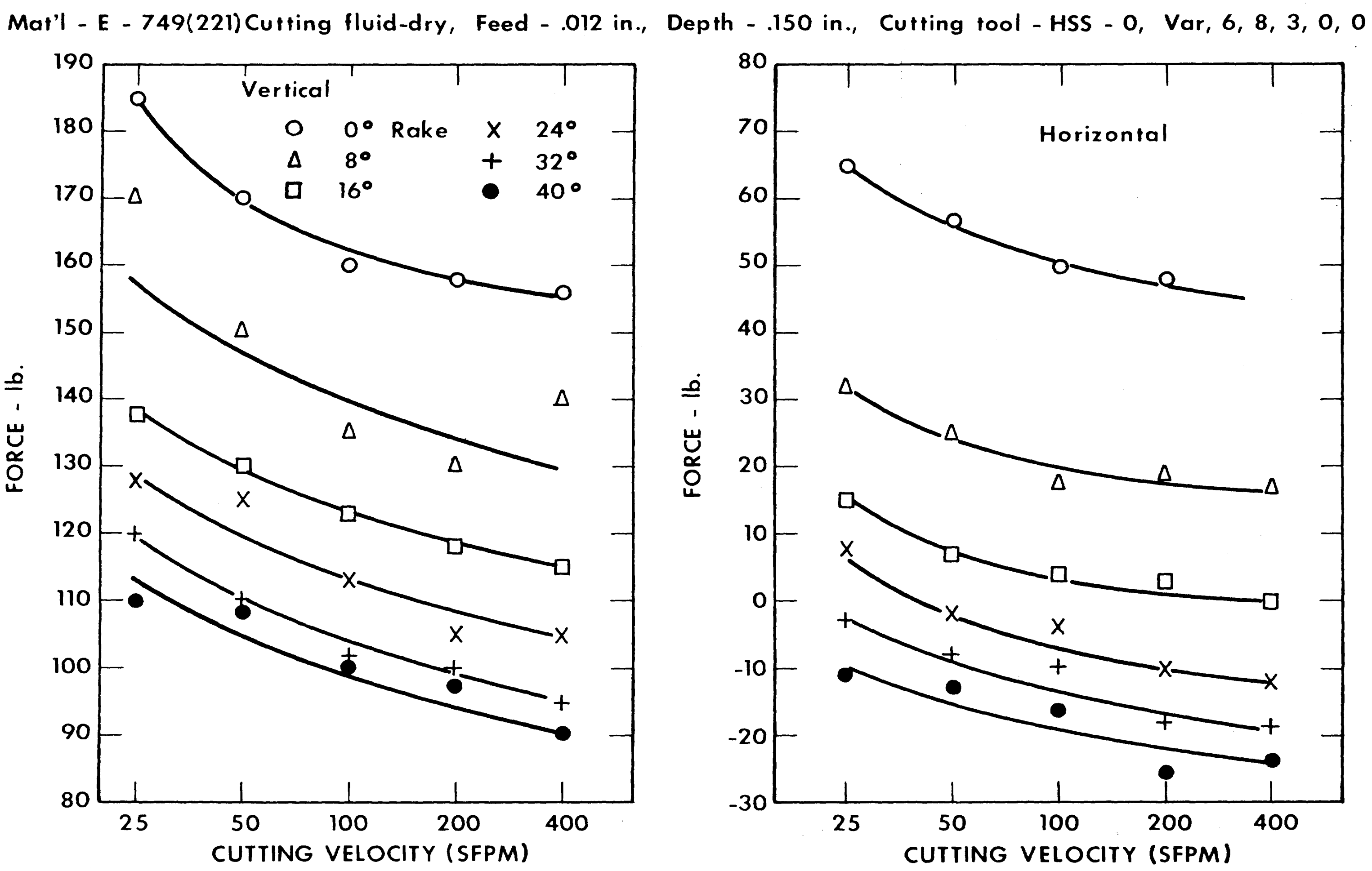


Fig. 4.10. Cutting forces vs velocity.

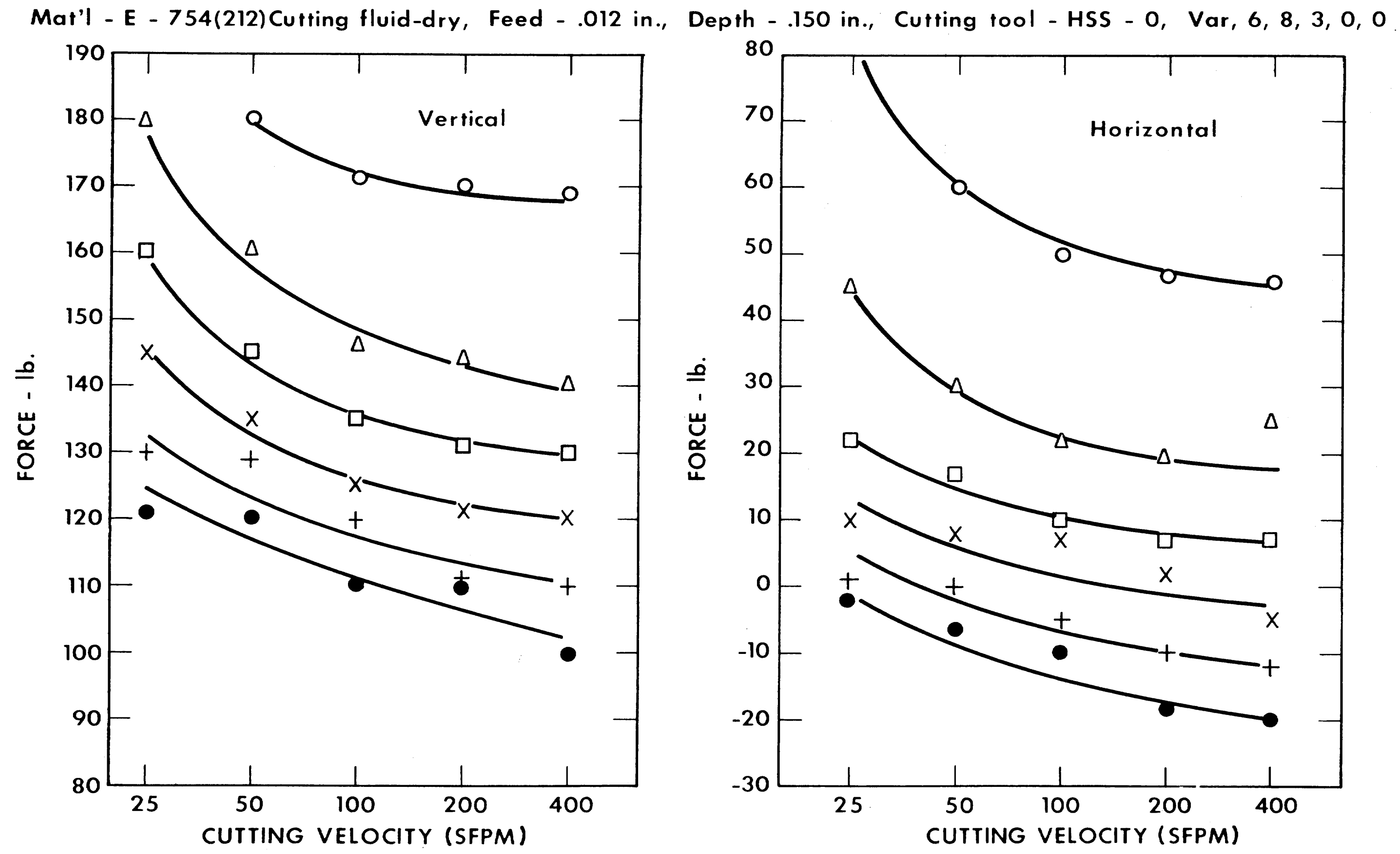


Fig. 4.11. Cutting forces vs velocity.

Mat'l - E - 753(222)Cutting fluid-dry, Feed - .012 in., Depth - .150 in., Cutting tool - HSS - 0, Var, 6, 8, 3, 0, 0

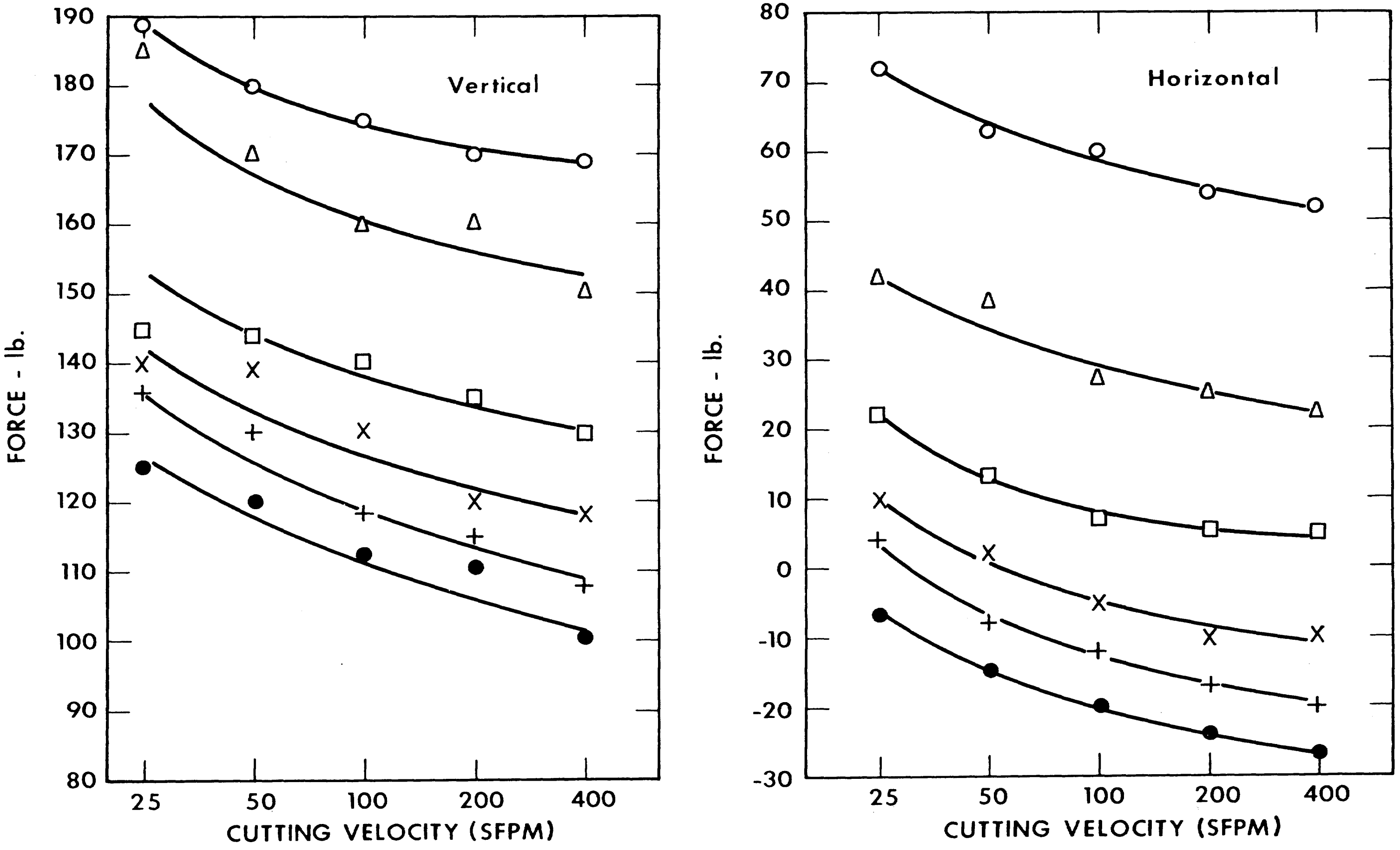
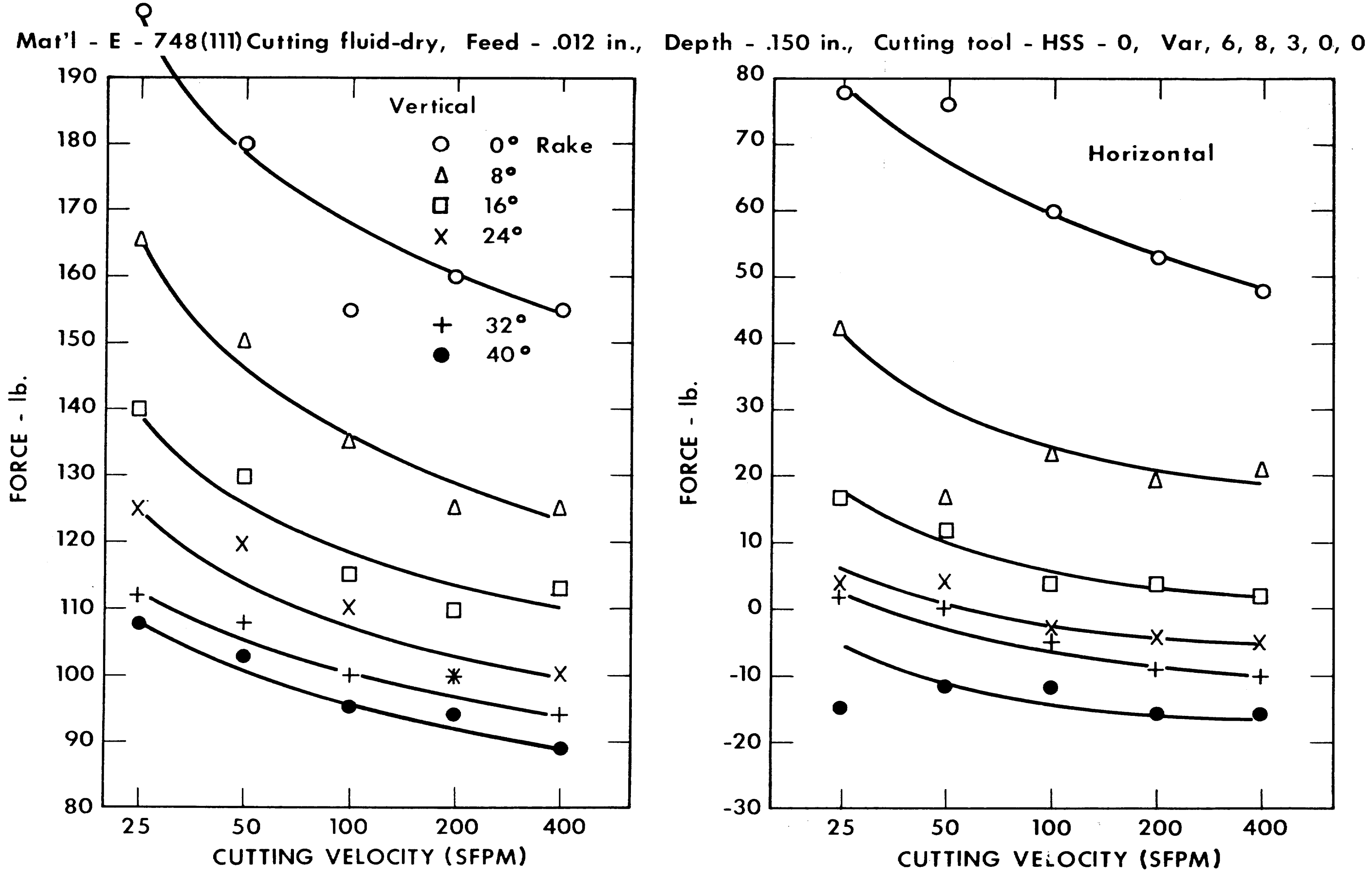


Fig. 4.12. Cutting forces vs velocity.



Mat'l - E - 748(111) Cutting fluid-dry, Feed - .012 in., Depth - .150 in., Cutting tool - HSS - 0, Var, 6, 8, 3, 0, 0

Fig. 4.13. Cutting forces vs velocity.

Mat'l - E - 747(121) Cutting fluid-dry, Feed - .012 in., Depth - .150 in., Cutting tool - HSS - 0, Var, 6, 8, 3, 0, 0

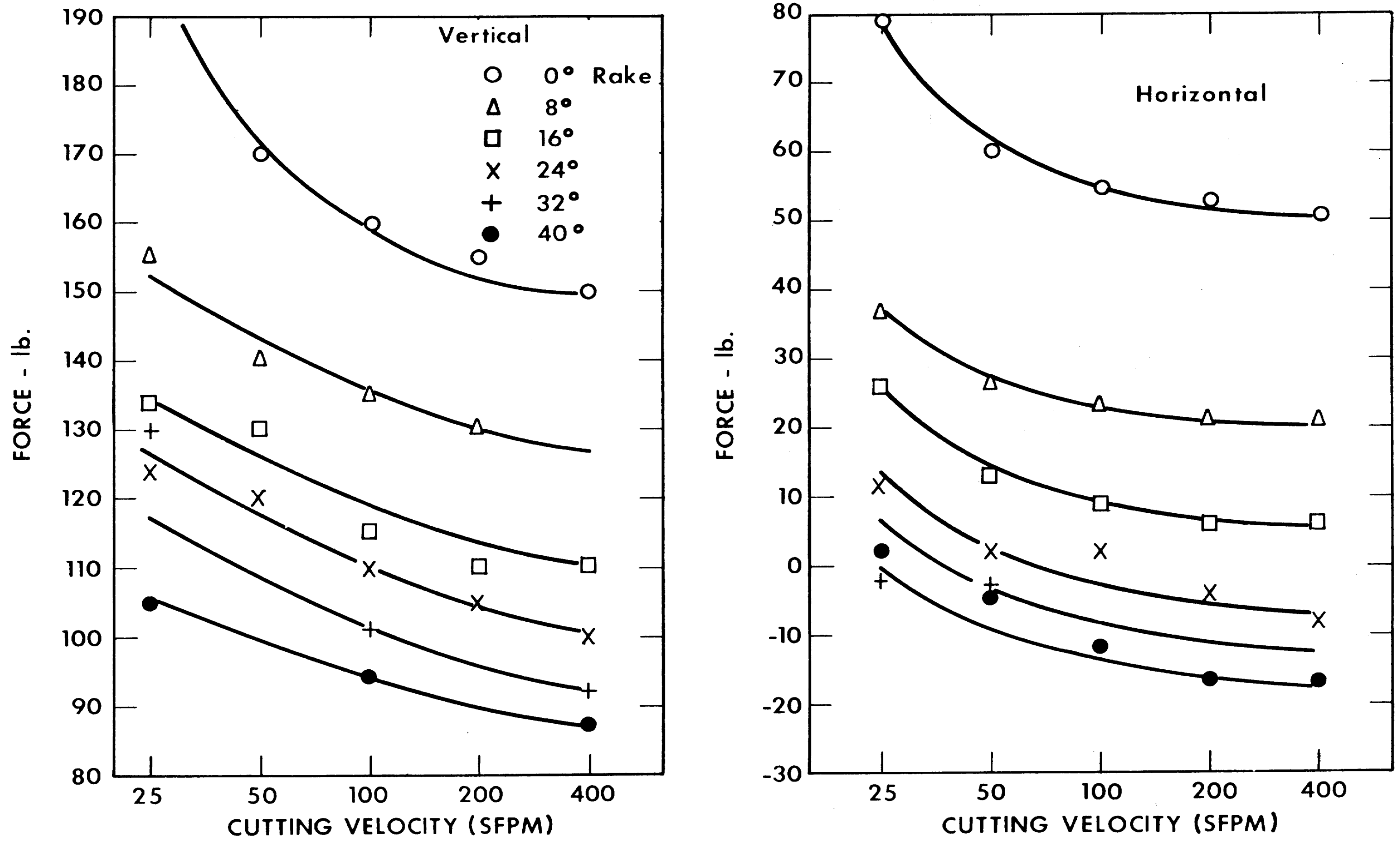
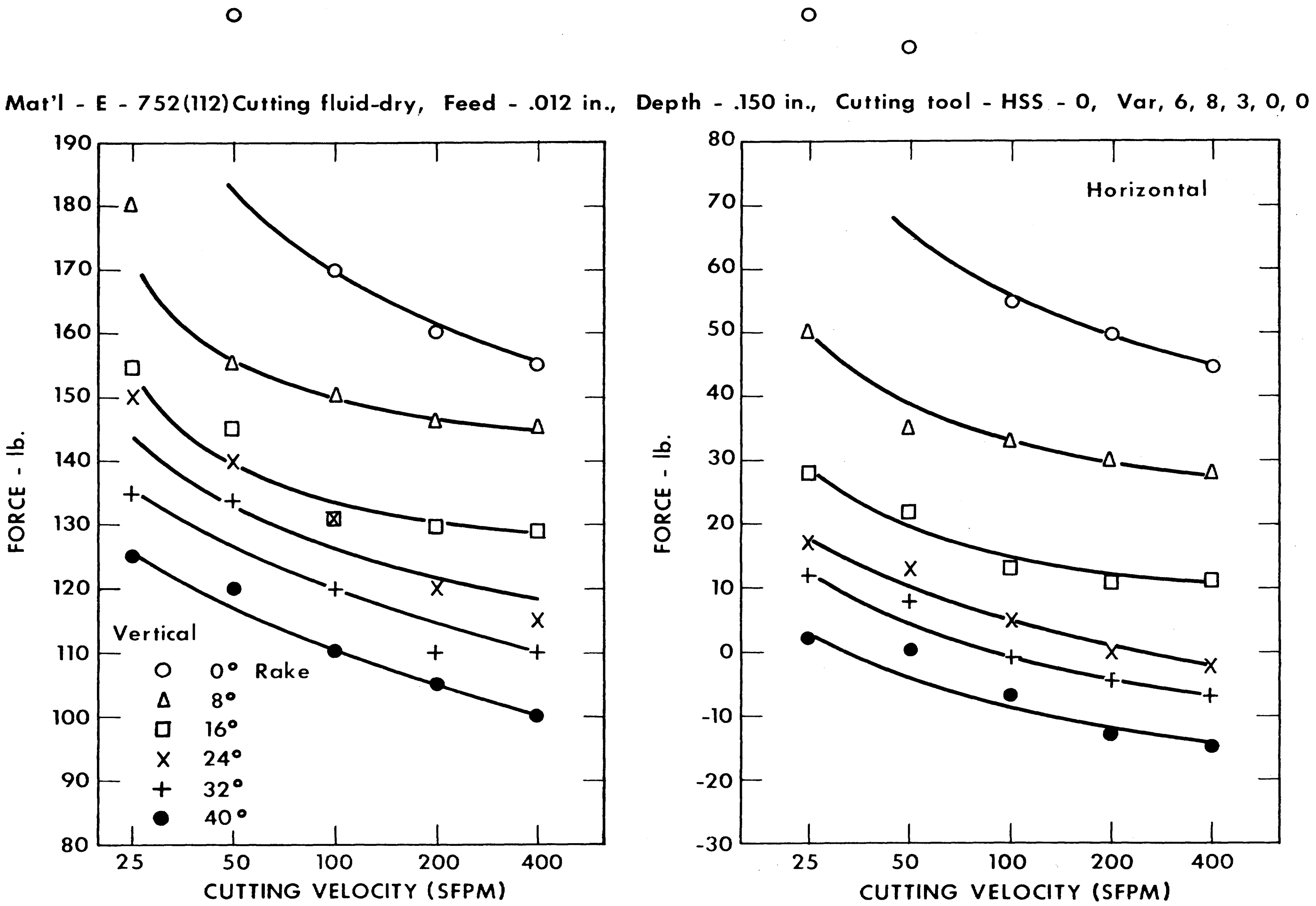


Fig. 4.14. Cutting forces vs velocity.



Mat'l - E - 752(112)Cutting fluid-dry, Feed - .012 in., Depth - .150 in., Cutting tool - HSS - 0, Var, 6, 8, 3, 0, 0

Fig. 4.15. Cutting forces vs velocity.

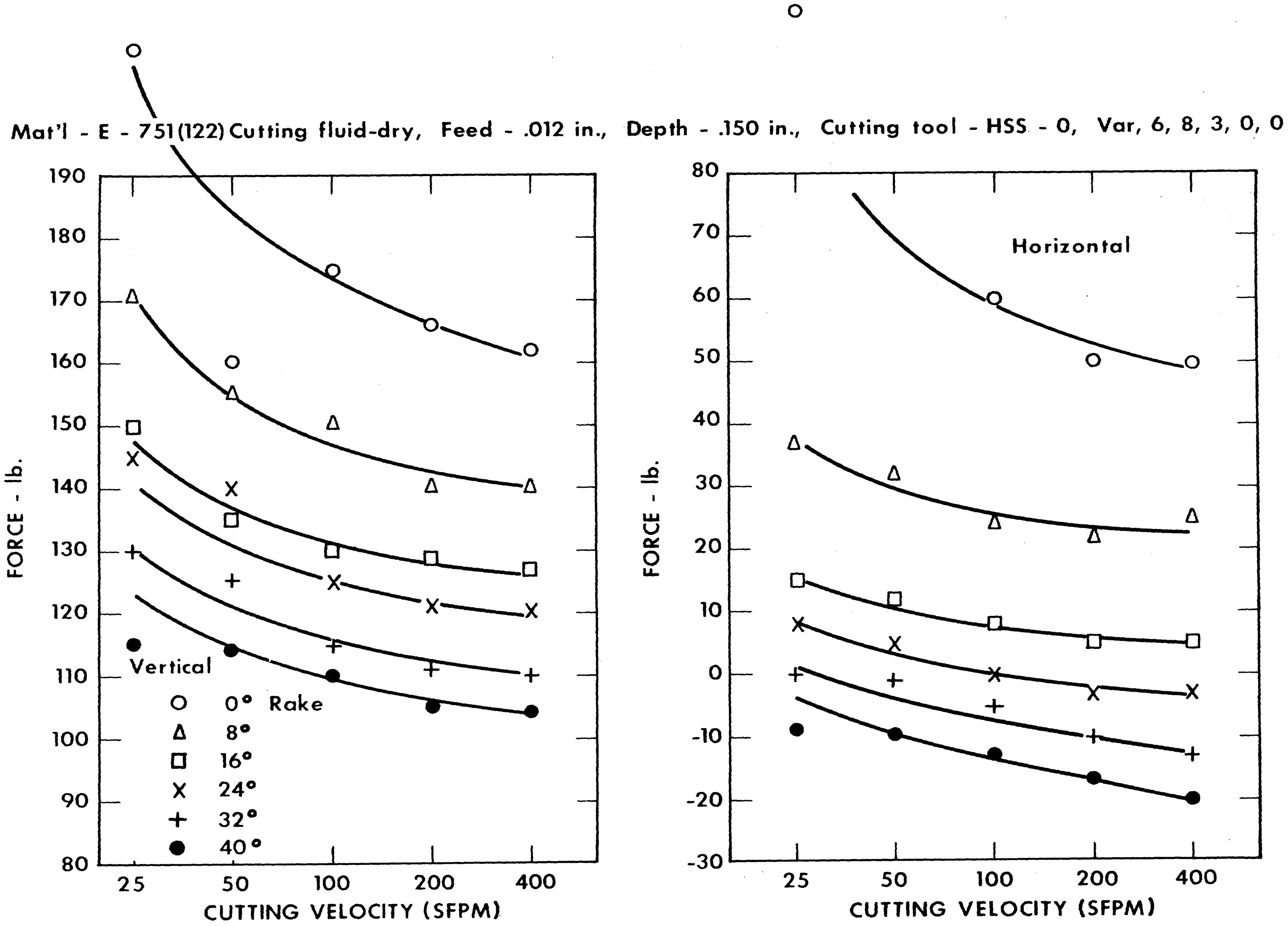


Fig. 4.16. Cutting forces vs velocity.

Mat'l - E - 753(222)Cutting fluid-dry, Depth - .150 in., Velocity - 200 FPM Tool - HSS - 0, Var, 6, 8, 3, 0, 0

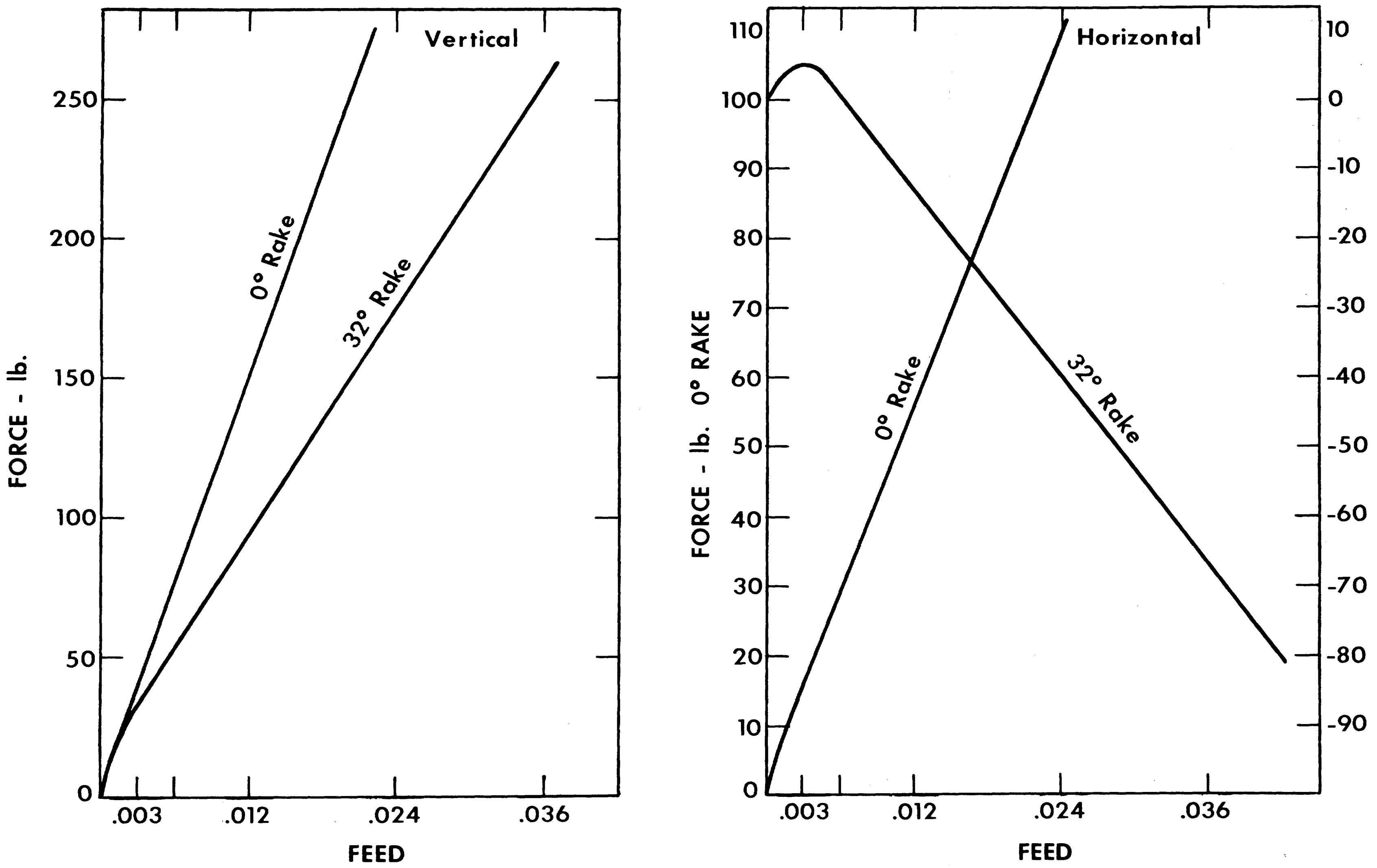


Fig. 4.17. Cutting forces vs feed.

PART V. CHIP FORMATION

Chips from many cutting conditions were collected and compared. The entire range of chips included discontinuous chips as shown in Fig. 5.1, and the continuous type, depending on the feed, depth, rake angle, and velocity. An interesting difference appears for the condition of a feed of .006 inch per revolution, side rake angle of 0 degrees, a depth of cut of .150 inch and a cutting velocity of 200 surface feet per minute.

Figures 5.1 and 5.2 show chips ranging from the very discontinuous type, as obtained when cutting material 121, to the more continuous type associated with material 222. Materials treated at a low solution temperature yielded more discontinuous chips than materials treated at a high solution temperature, except in the case of the low copper content and low cold-reduction materials (111 to 121). Low copper-content materials have the same type of chips as the high copper-content material except in the case of a more continuous chip with high copper content, high solution temperature and low cold-reduction material (121 to 221). Low cold-reduction material and high cold-reduction material have the same type of chip except that more continuous chips are associated with low copper content and high solution-treatment materials (121 to 122). In summary, the tendency toward a more continuous type of chip is associated with either high cold-reduction or high copper-content materials, or both (121 to 222), provided the material has been solution-treated at the high temperature.

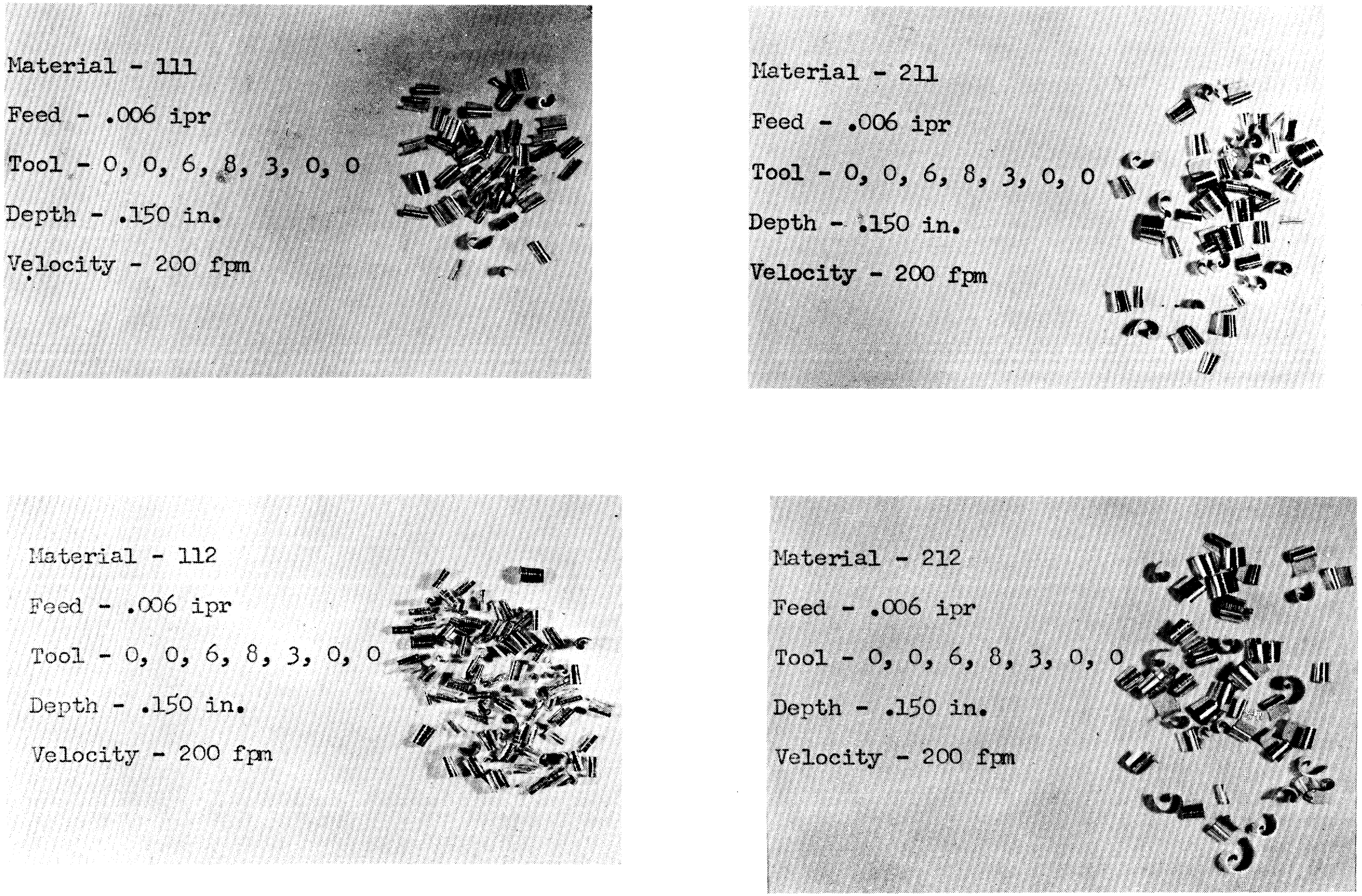


Fig. 5.1. Discontinuous chips.

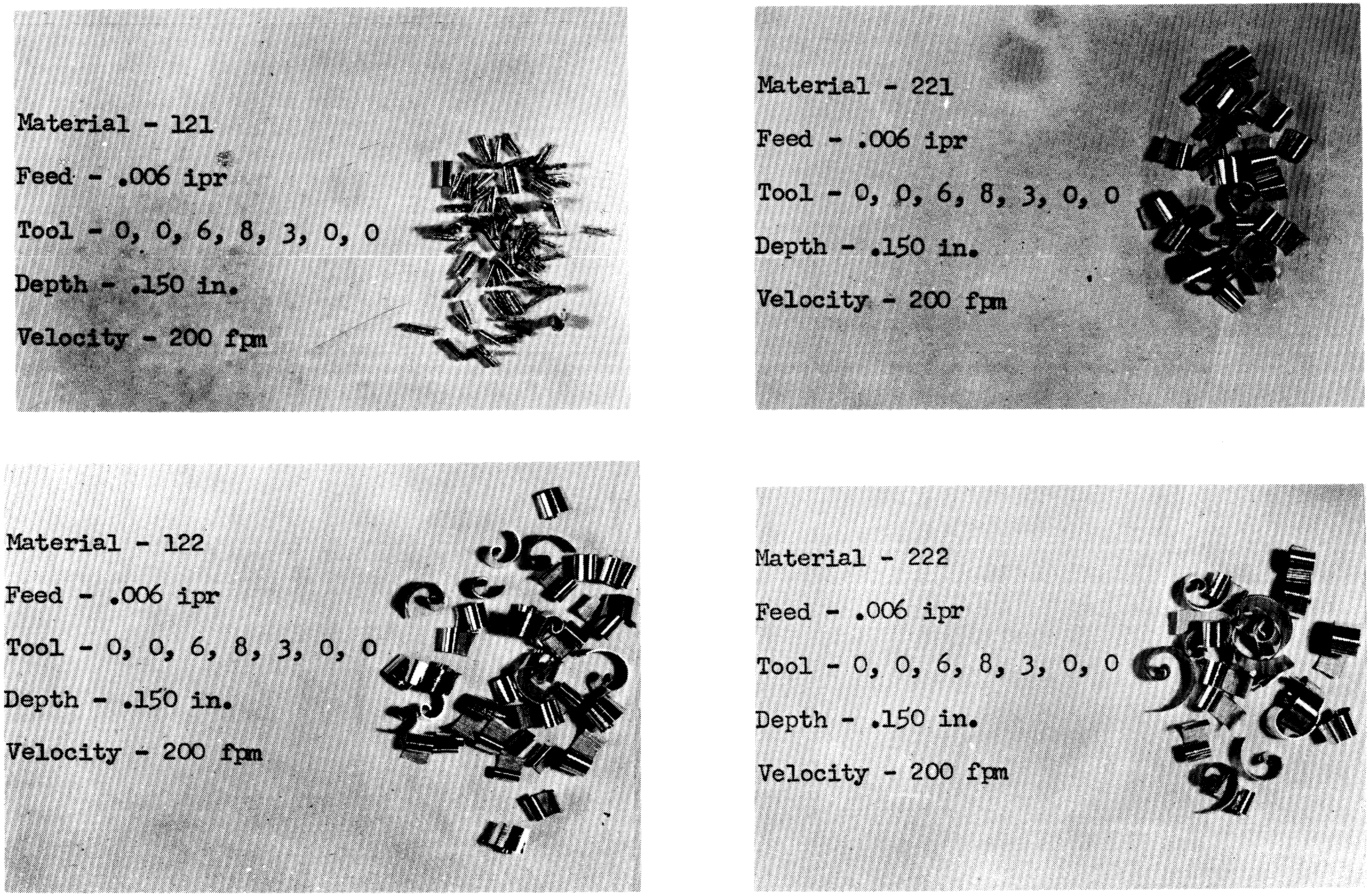


Fig. 5.2. Chips ranging from very discontinuous to more continuous types.

PART VI. CUTTING TEMPERATURES

Turning cuts were made on 1-1/2-inch-diameter bars of the materials designated by the code numbers 111, 121, 112, 122, 211, 221, 212, and 222 at a feed of .012 inch per revolution, and a depth of cut of .150 inch; with three speeds, 100, 300, and 500 surface feet per minute; and at 100 surface feet per minute with feeds of .003, .006, .012, and .024 inch per revolution. The tool was a Bethlehem 66 HSS of shape 0, 8, 6, 6, 6, 15, 0. No cutting fluids were used.

The temperature of the cutting tool was measured during the cut by a Chromel-Alumel thermocouple, of 30-gage wire inserted and butt-welded into a hole of .025-inch diameter, and drilled to within .010 to .015 inch of the top or rake surface of the tool and about 1/32 inch from the cutting edges of the tool. This technique does not measure the maximum temperature nor does it indicate temperature distribution, but it does give a relative indication of the effect of various materials and cutting conditions on cutting temperature.

During all cuts a built-up edge was formed on the tool. There was little difference in recorded temperatures as between materials. The maximum range was 5 percent, part of which could be attributed to experimental error. Figure 6.1 is a plot of recorded temperatures as functions of cutting velocity and feed, for the averages of all eight materials.

Figure 6.2 is a plot of the same data on log-log coordinates. Equations can be written for the relationship between cutting temperature and cutting velocity and feed as $T = C_1 V^n$ and $T = c_2 f^a$, when the data can be represented by straight lines. In this case the numerical relationships are T (°F) = $80\ V^{1/6}$ and T (°F) = $346\ f^{.149}$, where V is in feet per minute and f in inches per revolution. These can be combined to give $T = 156\ f^{.149}\ V^{1/6}$.

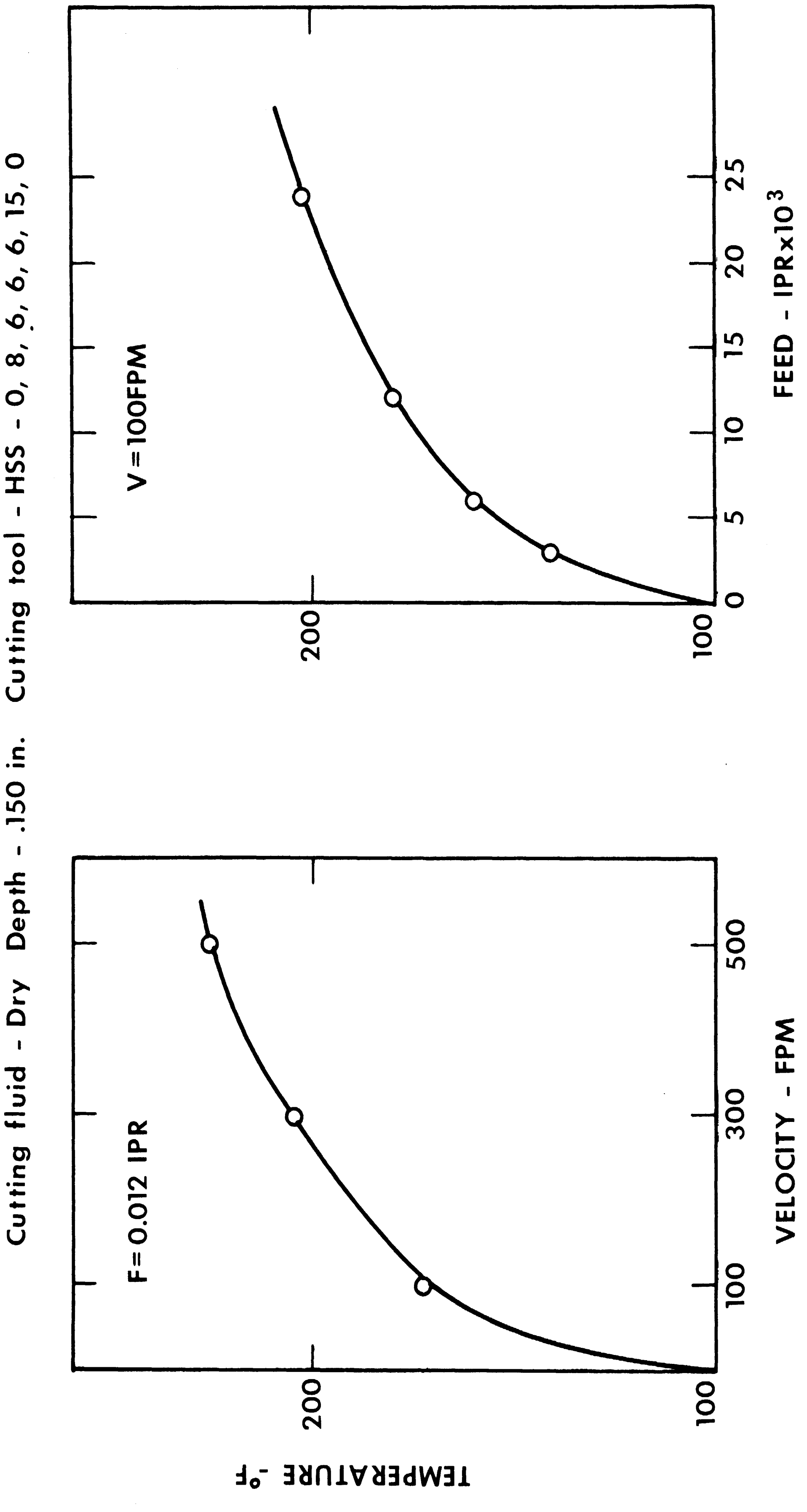
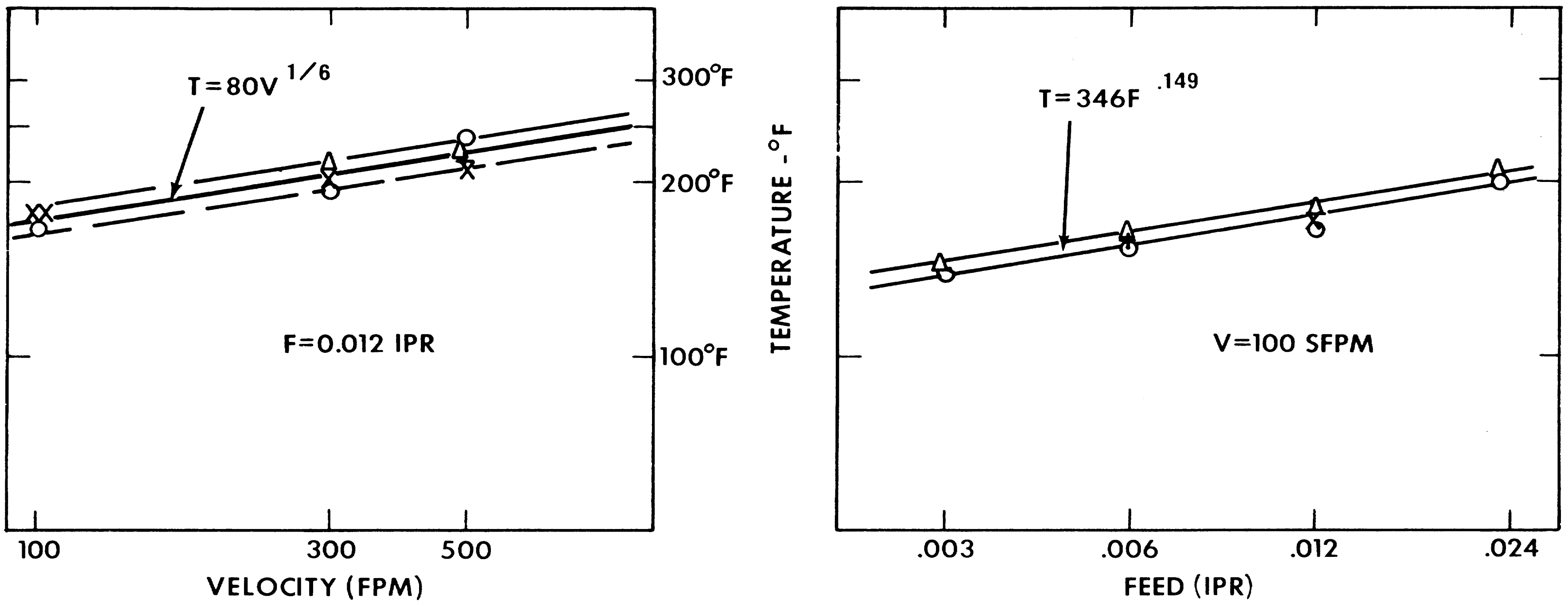


Fig. 6.1. Cutting temperatures vs velocity and feed (average of eight materials).



$T = C_1 V^n$ $T = C_2 F^a$

Fig. 6.2. Cutting temperatures vs velocity and feed cutting conditions (same as Fig. 6.1).

PART VII. FRICTION-WEAR TESTS

PROCEDURE

A special testing machine developed for studying the frictional, seizure, and wear characteristics of material-lubricant combinations was used in these tests. The tests consisted of rubbing a stationary specimen with a rotating, cylindrical specimen with controllable normal load applied. The normal load was increased from zero linearly with time for a given period, followed by a period of constant load; testing was terminated prior to completion of this cycle whenever seizure occurred.

Three criteria were used for evaluating the above characteristics: seizure time, wear, and coefficient of friction. To measure the latter, applied load and resultant torque were measured and recorded continuously throughout the tests by means of electrical resistance strain-gage transducers and a "Sanborn" amplifier-recorder unit.

To differentiate best between the friction and wear characteristics of aluminum caused by the extremes of mill tolerances on copper content, solution temperature, and degree of cold reduction, several combinations of variables were utilized in these tests. They were:

1) Two speed ranges - 200 and 500 feet per minute.
2) Three lubricating media - an oil, an emulsion, and carbon tetrachloride.
3) Two tool materials - SAE 1080 steel and the aluminum corresponding to the test specimen.
4) Two tool configurations.
5) Four specimen diameters, ranging from 1.240 to 1.500 inches.

In addition, of course, the eight possible combinations of extremes of the mill variables were all used in any given series of tests.

The first 32 test runs were of an exploratory nature to attempt to define the nature of the tests to follow. The test conditions were: low rubbing velocity; commercial 5/16-inch-diameter drill rod as tools oriented tangentially to the test specimen; and carbon tetrachloride as lubricant. Variations of specimen diameter were studied for possible "skin effect." After a minimum of ten minutes of testing the resulting scars on both test specimens and tools were visually studied under low-power magnification; the coefficient of friction was computed at several different loads within each test. It was concluded from the results of this series of tests that there existed no consistent difference in frictional characteristics between the surface and interior of the as-received bars. Since no clear distinction could be made between the eight extremes of mill conditions from these tests, it was determined to alter the test conditions radically to bring about mechanical seizure between tool and specimen.

Tests 33 through 58 were consequently run under the following conditions: rubbing velocities of approximately 500 feet per minute; a commercial emulsion "Superla" as lubricant; and one-inch-diameter aluminum rods as tools, oriented radially from the test specimen. The desired seizure occurred in every test; the arithmetic averages of the seizure times for each material code classification are given below in Tables VII-1 and VII-2. Tests 58 through 82 were run under identical conditions except that a mixture of 95 percent mineral oil and 5-percent lard oil was used as lubricant instead of the emulsion. A time plot of both applied load and resultant torque was recorded for all tests in both of these series, and the coefficient of friction computed therefrom for two points within each test. The significant results of these latter two series of tests are summarized below.

RESULTS

Decided differences in seizure characteristics between the two extremes of both cold reduction and solution temperature were demonstrated by these tests. The second series (numbers 33-58), using an emulsion, indicated in all cases that the high solution temperatures imparted increased seizure resistance to the material, with the average time required for seizure being 20 percent greater for this group as a whole than for the low-temperature group. In the third series of tests, using an oil, the greater percentage of cold work showed in all cases a greater resistance to seizure than did the lower degrees of cold reduction. For these test conditions it was also found that those materials heat-treated at the lower, rather than the higher, temperature were in general more seizure-resistant, although the results were not as consistent here as for the variation in cold work. The average time required for seizure to take place for all the highly worked materials taken as a group was 38 percent greater than the average time for all the lower reductions taken as a group, and the average seizure time was 16.5 percent greater for the low-temperature group than for the high-temperature group.

The opposite reactions to like variations in solution temperature noted in the second series using an emulsion compared to that noted in the third series with the oil would indicate a great difference in the degree, and probably mechanism, of lubrication between these two fluids. This conclusion appears to be supported by the results of the coefficient of friction computations where the average coefficient with the emulsion was found to be slightly over 50 percent greater than the average coefficient with the oil. These opposite reactions were not entirely unexpected, for past experience with cutting fluids has indicated that even small changes in fluid composition can bring about rather profound differences in their ability to reduce friction in a given cutting situation.

It becomes apparent from the test data, then, that no definite relationship can be established between variations in any one of the mill variables and seizure characteristics of the resulting metal unless the lubricating medium is specified. This is consistent with the theory that seizure is a function of both rubbing temperature and pressure, because changes in fluid composition can change markedly both the heat extractive and lubrication properties of the medium.

TABLE VII-1

SEIZURE TIMES FOR EACH MATERIAL

Code	Seizure Time (minutes) (Average of at least 3 Tests)	
	Series 1 (Emulsion)	Series 2 (Oil)
111	2.27	2.51
112	2.02	3.37
121	2.43	1.87
122	2.56	3.82
211	2.16	2.80
212	2.16	3.76
221	2.78	2.48
222	2.55	2.50

TABLE VII-2

AVERAGE SEIZURE TIMES COMPILED FROM TABLE VII-1

Code	Seizure Time (minutes)	
	Series 1 (Emulsion)	Series 2 (Oil)
XX1	2.41	2.42
XX2	2.32	3.36
X1X	2.15	3.11
X2X	2.58	2.67
1XX	2.32	2.89
2XX	2.39	2.88

TABLE VII-3

COEFFICIENTS OF FRICTION FOR EACH MATERIAL

Code	Coefficient of Friction (Average of at least 3 tests)	
	Series 1 (Emulsion)	Series 2 (Oil)
111	.168	.101
112	.156	.108
121	.158	.093
122	.140	.103
211	.165	.099
212	.147	.098
221	.162	.103
222	.157	.104

PART VIII. AUTOMATIC SCREW MACHINE

The short sharp-tool tests, which have been reported in the earlier parts, have revealed some significant facts about the relative performance of each class of material. However, tests of this nature do not always indicate how a material will behave under prolonged cutting conditions, where tool wear must be taken into account. Tool wear may give rise to changes in such important factors as surface quality, dimensional stability, cutting forces, and power requirements. Since any one or a combination of these factors may be used as a criterion of tool failure, depending on part specifications and tolerances, an extensive test which will permit a relative evaluation of the materials on the basis of the above factors becomes desirable. The tests on a Brown and Sharpe automatic screw machine were made for this purpose.

TEST SETUP

The shape and size of part, and the operational sequence used in a Brown and Sharpe, No. 2G, single spindle, automatic screw machine are shown in Fig. 8-1. The part was designed to reveal information on six basic machining operations—light and heavy forming, turning, drilling, reaming, chasing, and cutoff.

To find possible effects of the oxide surface on the original bar stock the light forming operation was divided into two distinct parts: (1) forming for a thickness of cut of .035 from the original bar surface, and (2) forming an inner surface for the same thickness of cut, after rough forming had reduced the original 1-inch bar diameter. A single-component force dynamometer was used with a Sanborn Recorder to record the feeding forces encountered in machining the two surfaces.

In addition to the normal tool setup, a Hewlett-Packard electronic counter and an Esterline-Angus wattmeter were used to record spindle revolutions per minute fluctuations and power requirements, respectively, for the various machining operations.

OPERATING CONDITIONS

All test conditions are summarized in Table VIII-1. They remained constant for all materials tested.

TABLE VIII-1

ALL CONDITIONS OF TEST

Machine:	Brown and Sharpe, No. 2G, single-spindle automatic
Cutting Fluid:	5% Emulsion, Sun Oil Co. "Superla" and water
Materials Tested:	111, 112, 121, 211, 212, 222

Operation	Cutting Conditions		Feed, in/rev.	Cutting Tools	
	Spindle Speed, rpm	Velocity, fpm		Material	Signature
Knee Turn	2600	680	.0060	*T-1 HSS	15,20,8,8,8,0,1/16
Light or Finish Form	2600		.0010	T-1 HSS	20,0,8,0,0,0,0
Oxide Surface		680			
Inner Surface		490			
Heavy Form	2600	680	.0025	T-1 HSS	20,0,8,8,0,35,0
Cutoff	2600	680	.0025	T-1 HSS	20,0,8,2,20,-2,0
Drill	2600	370	.0069	Nat'l Twist Drill-HSS Std. Screw machine drill, oxide treated	118° Point angle 10° Relief angle
Ream	2600	380	.0330 (.0055/blade)	Nat'l Twist Drill-HSS Std. machine reamer	6 Blade spiral fluted 45° Chamfer
Chase	1170	230	.0625	Geometric-HSS Style 3/4-D milled	3/4"-16 NF 15° Hook angle

*T-1 - 18% W - 4% Cr - 1% Va

TEST PROCEDURE

Each material was tested under identical tool setup and cutting conditions, and the length of a test was defined as twenty 12-foot bars, or approximately 2400 pieces. New tools were used on each material.

The standard test procedure consisted of (1) properly setting all tools to produce parts within specifications; (2) machining of parts, with collections and inspections of six consecutive pieces (including 3 unthreaded specimens) at intervals of 50 throughout the test run; (3) recording light form feeding forces, machine spindle speeds, and power requirements at intervals of 50 pieces; and (4) inspecting cutting tools every 2, 5, and 10 bars (approximately 240, 600, and 1200 pieces, respectively) during the run, with final inspection at the end of the test.

All surfaces on each of the collected parts were inspected visually for significant changes in surface appearance. In addition, surface-roughness measurements were made on the formed and turned surfaces with a Micrometrical Profilometer, and turned and formed diameters were measured with a super micrometer to record the degree of dimensional variation over the life of the test. Three surface-roughness readings and two diameter measurements were made of each surface on each of two unthreaded parts, and the plotted values under "Test Results" represent an average value for each 50th piece.

Visual inspection was the only observation made of the threads, cut-off surfaces, and the drilled and reamed holes.

All the running tool inspections for wear and loading characteristics were made right at the machine with a pocket comparator, with one exception. The light form tool was removed from the machine at the 2, 5, and 10 bar intervals, and inspected much more accurately under a toolmaker's microscope. At the end of a run, however, the toolmaker's microscope was used for the final inspection of all tools. The results of these inspections are given in Table VIII-3.

TEST RESULTS

Heavy Forming.—Figures 8.2 to 8.7, inclusive, represent the results of surface-roughness measurements in microinches, root mean square, and of diameter variations for the heavy forming operation on each of the materials tested. While there are some differences in surface-roughness values, the most pronounced or significant differences in performance appear in dimensional stability. All the high copper materials show a much greater range between the formed diameters at the beginning and at the end of each test. These differences are summarized in Table VIII-2.

TABLE VIII-2

HEAVY FORMING - DIAMETER RANGE

Material	No. of Pieces	Diameter Range
111	2450	.0065
112	2400	.0124
121	2450	.0084
211	2400	.0353
212	2450	.0217
222	1550	.0248

It is obvious that this magnitude of difference in diameter cannot be attributed to tool wear alone, but must be due primarily to the increase in forces which result from an increase in tool wear. Tool wear, shown in Table VIII-3, was much more severe on the high copper materials and, therefore, gave rise to higher cutting forces. Even in the low copper materials, it is seen that the greater the tool wear the steeper the slope of diameter variations.

The increase in forces due to tool wear was very evident during machining of the high copper materials. During the test on the 222 material, the machine actually stalled on the 10th bar. The drill was replaced at this point, and 3 more bars were run before the machine stalled again, leaving little doubt that the heavy form tool forces contributed to the stalling. The test was eventually repeated with practically the same results. When a bar of 221 material was put into the machine with the same tooling, stalling occurred again before the bar was completed. However, when the 111 material was inserted, the machine kept running for the full length of the bar although there was a noticeable drop in original spindle speed.

Stalling also occurred in the test on the 211 material, near the end of the 20th bar, while the test on the 212 material was completed with a very sharp decrease in machine spindle speed. No extreme changes in spindle speed were observed in any of the tests on the low copper materials.

Figure 8.8 shows typical results of power requirements and reductions of spindle speed for the heavy forming and cutoff operation as plotted for the 112 and 211 materials.

In general, the surface quality of the formed surface was similar at the beginning of each test run on all materials. However, there was a much more rapid deterioration of the surface on the high copper material as the run progressed, although the surface on the low copper materials was somwhat erratic. Noticeable changes in surface appearance—particularly in the form of polished or burnished rings—appeared much earlier in the high copper series of materials.

Light Forming.—Relative feeding force values, diameter variation, and surface-roughness readings are plotted in Figs. 8.9 to 8.14, inclusive, for the light forming operation on the oxide and inner surfaces.

The obvious difference in surface quality of these two surfaces is reflected in the type of tool wear which was encountered. The oxide surface gave rise to much more severe notching on the tool flanks.

On the low copper materials, the high heat-treat temperature—low reduction, and the low heat-treat temperature—low reduction gave the most erratic results. The high reduction (112) material had the most stable surface quality on both the oxide and inner surfaces, and the results were quite similar to those found on the 212 material. There was very little difference in the quality of the inner surface on either the high or low copper materials.

TABLE VIII-3

TOOL WEAR - ALL MATERIALS

Tool	111 2450 Pieces	112 2400 Pieces	121 2450 Pieces	211 2400 Pieces	212 2450 Pieces	222 1550 Pieces
Heavy Form	.0028 wear. No notching. Best of all tools. Very shallow cratering.	.0041 wear. Very slight notching and corner breakdown. Moderate crater.	.0030 wear. Medium notching. Shallow cratering.	.0084 wear. Washboard wear pattern. Loading on flank. Medium deep crater.	.0048 wear. Badly notched. Cratered flank with loading. Uneven, deep craters.	.0065 wear. Washboard wear. Broad notches with loading. Corners worn.
Light Form Oxide Surface	.0017 wear.* Prominent notching. Slight chipping of cutting edge.	.0020 wear. Notched, rather rough wear pattern.	.0021 wear. Notching fairly severe. Uneven wear.	.0024 wear. Moderately severe notching.	.0025-.0031 wear. Non-uniform and rough. Pronounced notching.	.0023 wear. Fairly uniform, but cutting edge chipped in several areas.
Light Form Inner Surface	.0008 wear.* Very uniform. No notching.	.0011 wear. Uniform. No notches visible.	.0011 wear. Uniform. Slight notching.	.0025 wear. Very uniform. No notching.	.0021 wear. Fairly uniform. No prominent notching.	.0013 wear. Uniform. Slight notching.
Turn	.0014 flank wear. Notch at periphery. Medium deep crater. Sound edge.	.0013 flank wear. .0025 notch at periphery. Crater extends to edge, but edge still sound.	.0012 flank wear. .0040 notch at periphery. Crater has just broken through edge.	.0048 flank wear. No notch at periphery. Deep crater. Edge breakdown most severe.	.0039 flank wear. No notch at periphery. Edge broken as on 211 material.	.0047 flank wear. No notch at periphery, but cutting edge broken because of deep crater.
Drill	.002 wear. No notching. Slight breakdown of one corner.	.0021 wear. No notching. Very slight corner damage.	.0025 wear. No notching, but cutting edge rough. Slight corner breakdown.	.002 wear, but cutting edges broken and notched near periphery. Corners broken.	.0019-.0039 wear. Cutting edges broken near periphery. Corners extensively damaged.	.001 wear,** but cutting edges extremely rough and broken. Flanks deeply notched.
Cutoff	.0021 wear. Fairly uniform. No notching. Slight corner roundness.	.0038 wear. Notched. Crater broken through portions of cutting edge, worn flat on both corners.	.0028 wear. Erratic but no severe notching. Shallow crater, edge sound. Corners worn.	.0052 wear. Notched. Extensive breakdown of both corners. Crater breakthrough along entire edge.	.0068 wear. Spalled flank with considerable loading. Crater broken through edge. Corners rounded.	.0077 wear. Uniform. No notching. Rough edge due to crater breakthrough.
Chasers	Similar results. All chasers have at least some breakdown of the leading edges on first two full threads, though not severe. More prominent in 112 material. 111 material has largest B.U.E. of .003.			Similar to low Cu results, but a little more severe on all materials. Dies still in good shape, however. Not much difference noted in B.U.E. or smear.		
Reamer	All reamers similar. Difficult to distinguish any wear. B.U.E. on chamfer. .0005. Light smear on margins.			All reamers similar. Evidence of cratering at corners of chamfer. Wear on chamfer from .0009-.0012. Light smear on margins for full length of hole.		

---

*Approximately 1800 pieces.

**Approximately 1150 pieces.

Tool wear (Table VIII-3) was again more severe on the high copper materials, and this is reflected in the steeper slopes of the feeding-force curves. Dimensional variations were about the same for all materials.

Turning.—Figures 8.15 and 8.16 show the results found in the turning operation in each material.

There appears to be very little difference between the 211 and 111 materials, and between the 212 and 112 materials, although there is a large difference in surface quality between these two groups. All the high percent reduction materials had comparable surface-roughness values which were considerably higher and wider in range than the values found on the low percent reduction group, particularly those with a combination of low heat-treat temperature. The high heat-treat temperature—low reduction material gave intermediate values of surface roughness. It may be observed, also, that the high percent reduction materials showed a decrease in surface-roughness values as the test progressed. This is somewhat misleading; generally an increase in burnished areas accompanied the indicated improvement in surface quality.

Most of the materials gave comparable dimensional stability, but the 211 and the 111 materials showed slightly greater variation. These two materials gave rise to the largest built-up edge on the turning tools, although it was no greater than .001 inch.

As was true of all tools, turn-tool wear was more severe on the high copper group, particularly in terms of cratering on the face. Deep craters caused the cutting edges to break down on the turn tools in each test. Some breakdown of the cutting edge was also encountered on the 121 material. Another significant observation in tool wear was that a peripheral notch appeared on the flanks of all turn tools used on the low copper materials but did not appear as predominantly on the high copper materials.

Cutoff.—Outside of tool wear, the only observations of the cutoff operation were made visually. Tool wear was much more severe on the high copper materials, as may be noted in Table VIII-3.

No real difficulties were encountered in the cutoff operation, but visual inspection showed that the surface started out quite well on the high copper materials and got worse as the test progressed. In the low copper series, however, the surface improved slightly after the start of a test, remained stable for most of the run, and in some cases began to get worse again as tool wear increased at the end.

Visual inspection of the surfaces indicated that the 222 and 112 material gave the best results, followed by 212 and 211 which were similar and finally by the 121 and 111, which gave the poorest finish. Only 1550 pieces of the 222 material were produced, however, as compared to 2450 pieces on the other tests.

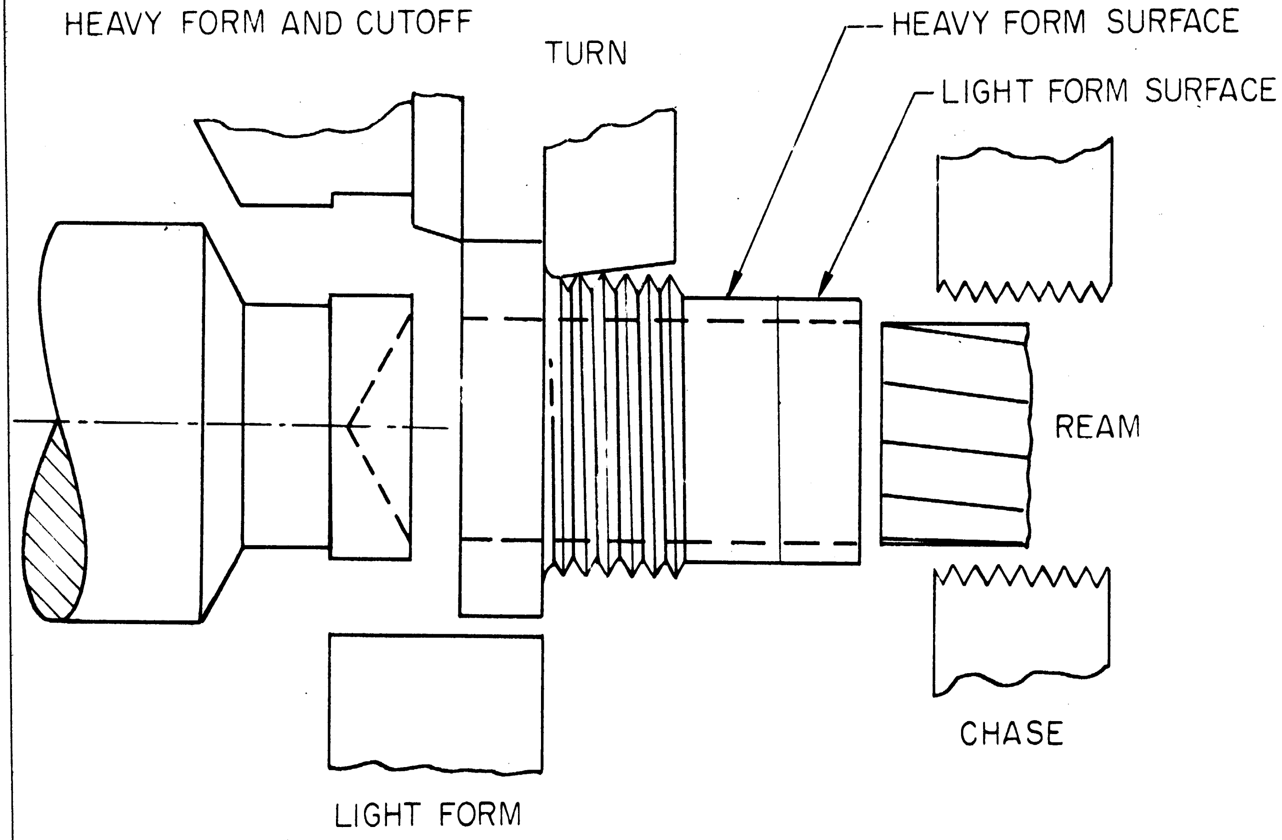
Drilling.—No actual readings were made either of drilled diameter or of surface roughness, but Fig. 8-17 shows typical surface behavior between the high and low copper materials.

The photographs show the first and last pieces produced in the test on the 222 and the 111 materials. The part on the left in each case is one of the first pieces machined. It may be noted that there is a complete reversal in behavior. The drilled surface quality on the 222 material was excellent in the first piece and deteriorated with the number of pieces made. On the other hand, the 111 material showed very poor surface quality, initially, which improved as the test progressed. Similar observations were made on the other materials in each class.

Observations of drill wear showed that there was very little difference in the size of the actual wear land produced in drilling the high and low copper materials, but the high copper series caused far greater notching and edge breakdown, particularly near the periphery, than did the low copper materials. Very extensive corner damage was also typical, and these drills contributed to the machine slowdown encountered in machining the high copper group.

Reaming.—There appeared to be very little difference between the classes of material in this operation, although no actual measurements were taken on the reamed holes. Some wear was found on the chamfer of the reamers used on the high copper materials, but the values were small, usually less than .001 inch. Very light smear on the margins was typical of all materials.

Chasing.—Thread-surface quality was comparable on all materials. Slight notching of the thread flanks was typical of all tests, although slightly more severe on the high copper group.



Spindle Speeds: 2600 rpm (high); 1170 (low-chasing only)
Time per Price: 12 seconds

Operational Sequence

1. Turn and Center Drill
2. Drill
   Partial Cutoff and Heavy Form
   Light Form (Oxide Surface)
3. Chase
4. Ream
5. Cutoff and Heavy Form
6. Light Form (Inner Surface)
7. Stock Feed

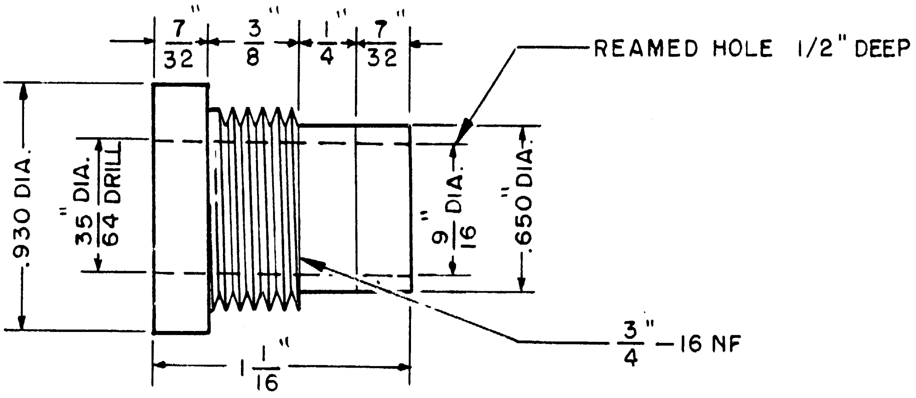


Fig 8.1. Part specifications and operational sequence on Brown and Sharpe, No. 2G, single-spindle automatic screw machine.

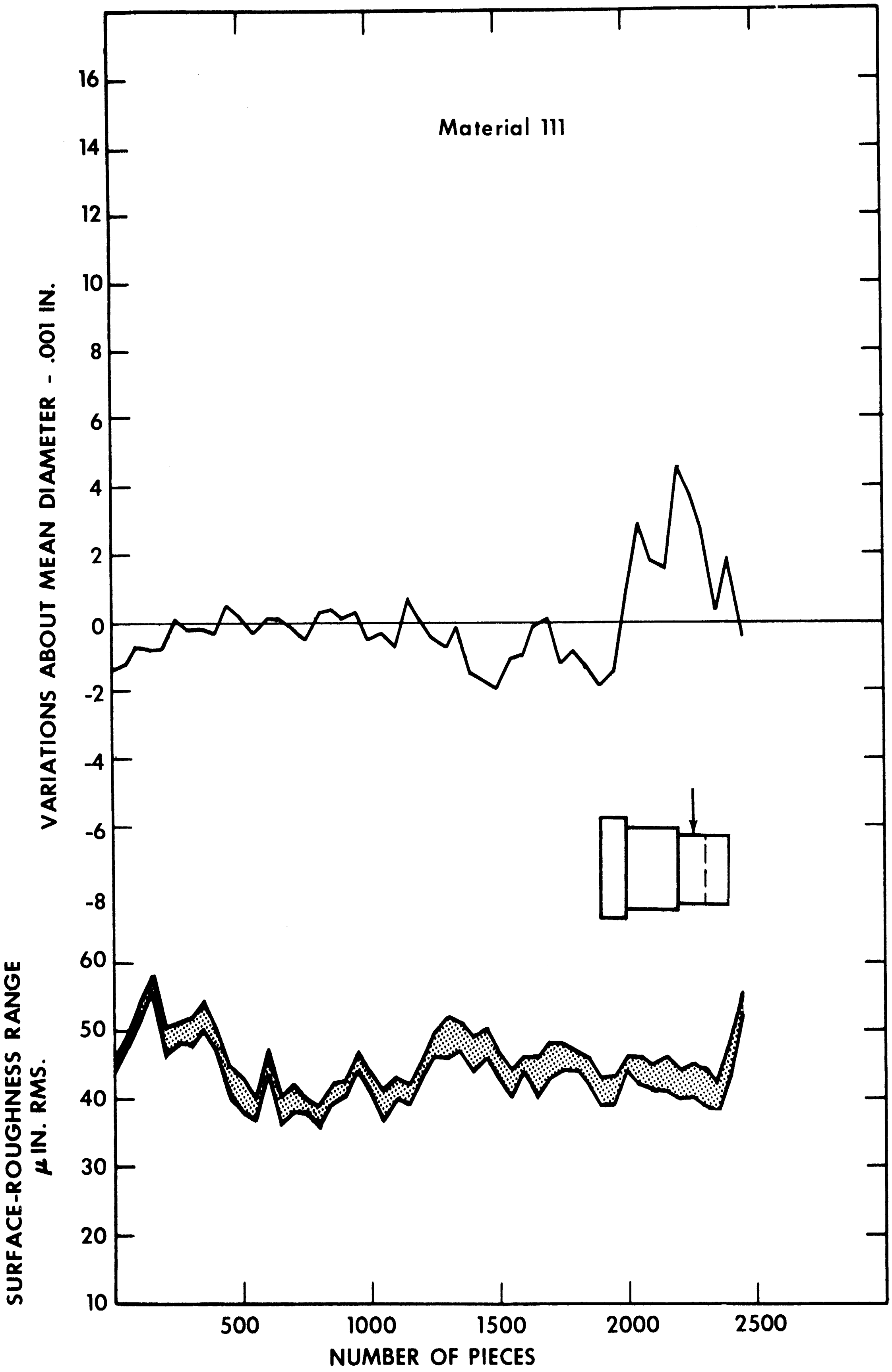


Fig. 8.2. Heavy forming - Surface-roughness range and diameter variations; material 111.

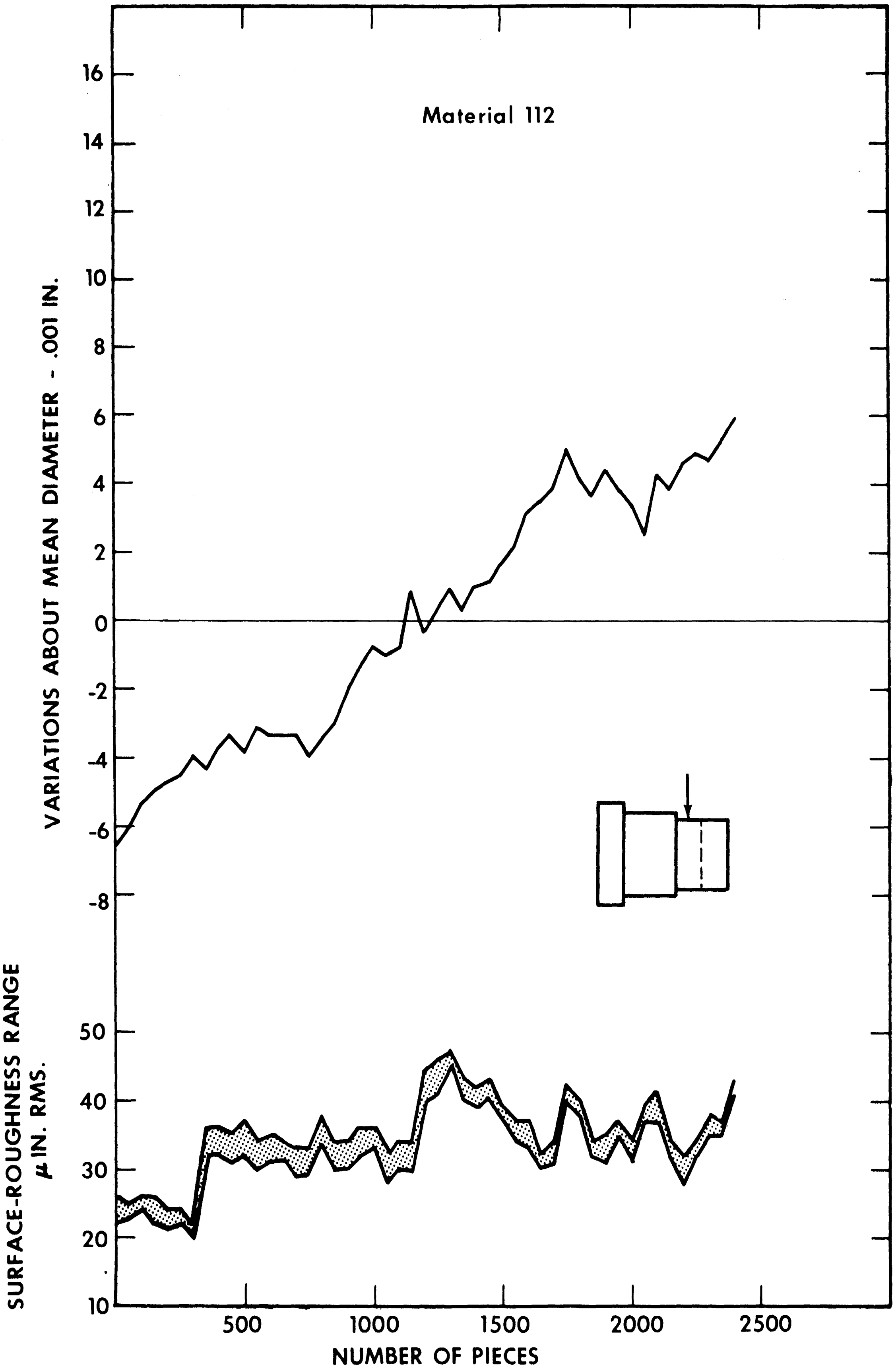


Fig. 8.3. Heavy forming - Surface-roughness range and diameter variations; material 112.

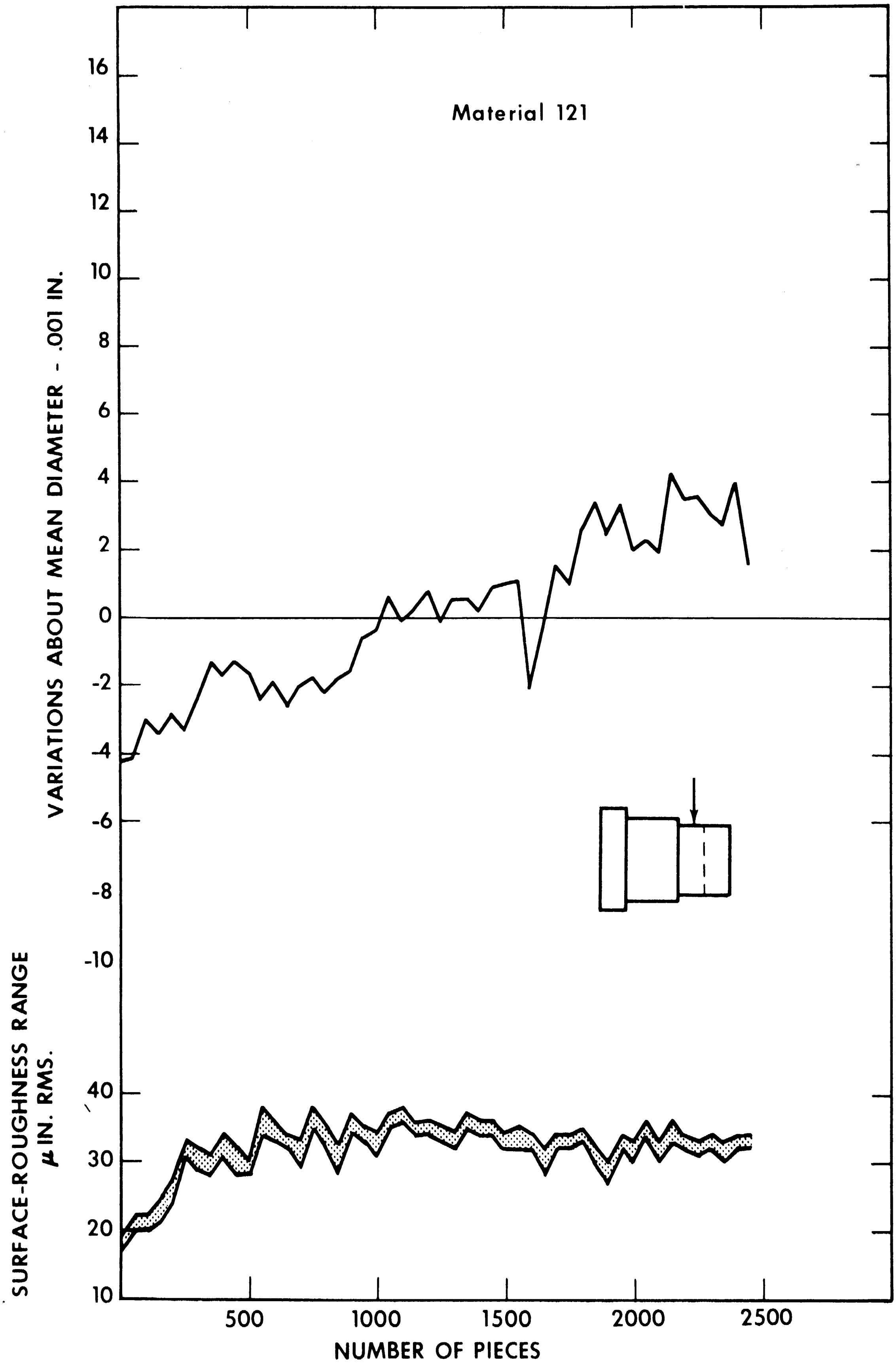


Fig. 8.4. Heavy forming - Surface-roughness range and diameter variations; material 121.

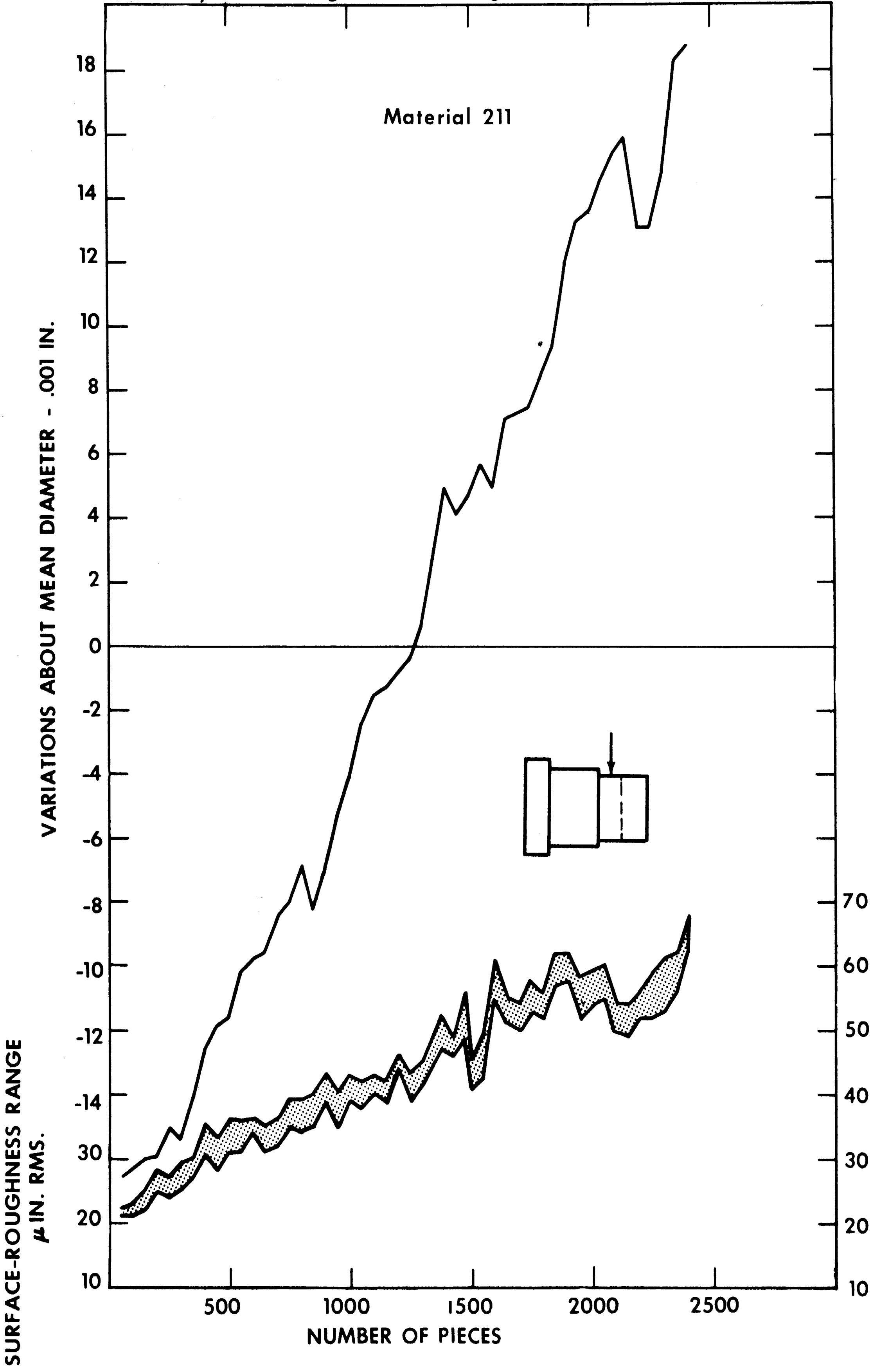


Fig. 8.5. Heavy forming - Surface-roughness range and diameter variations; material 211.

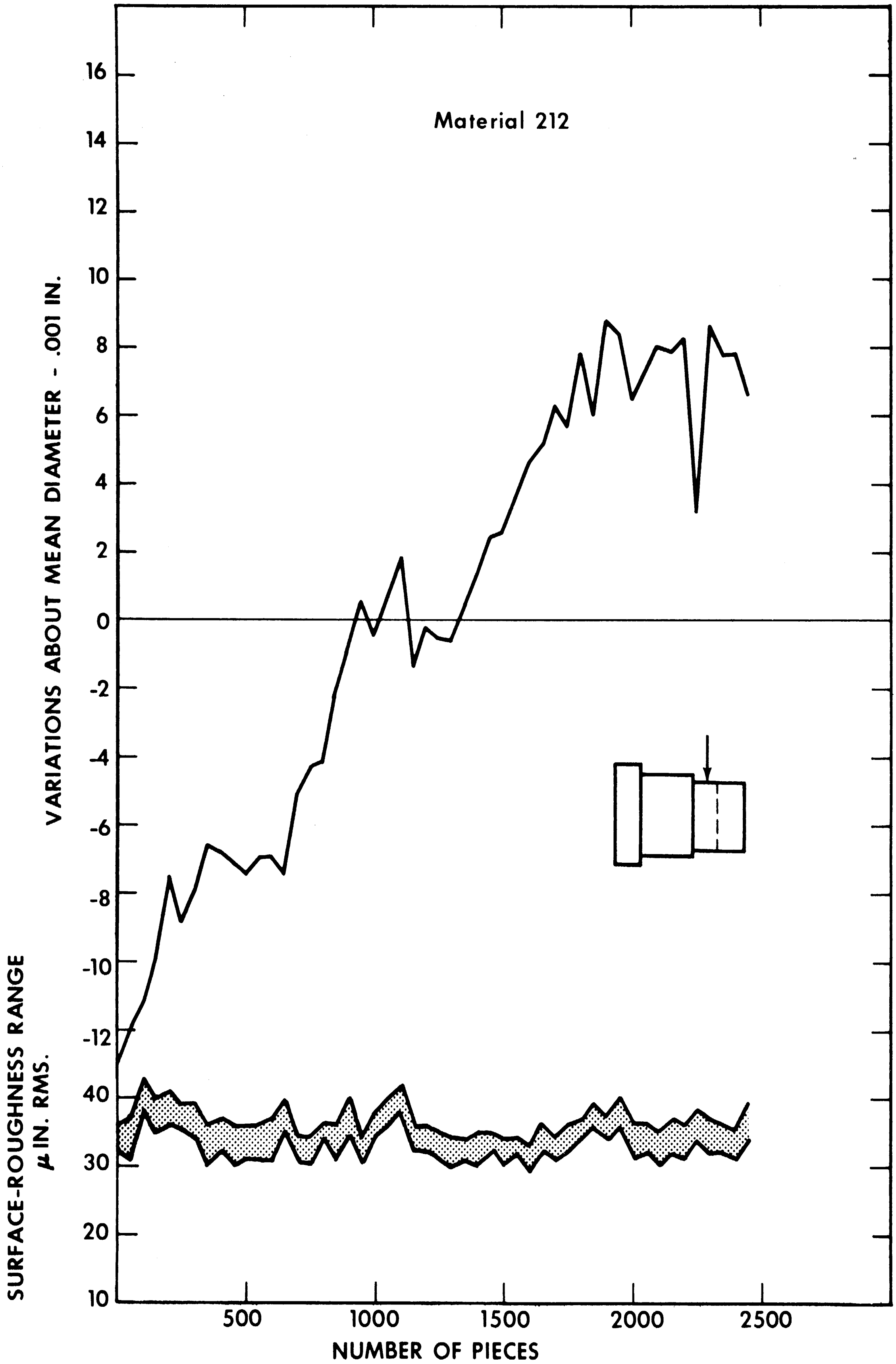


Fig. 8.6. Heavy forming - Surface-roughness range and diameter variations; material 212.

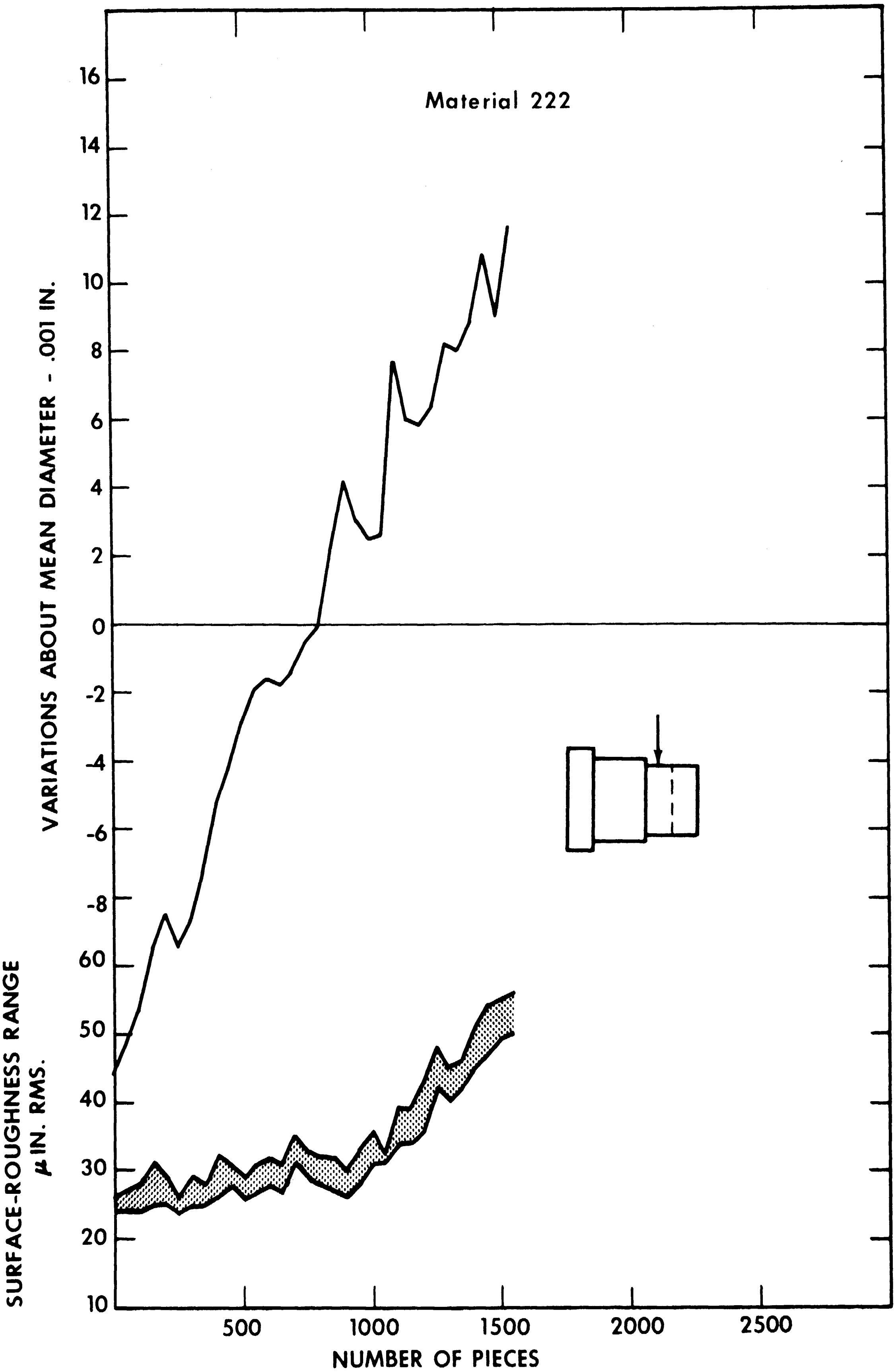


Fig. 8.7. Heavy forming - Surface-roughness range and diameter variations; material 222.

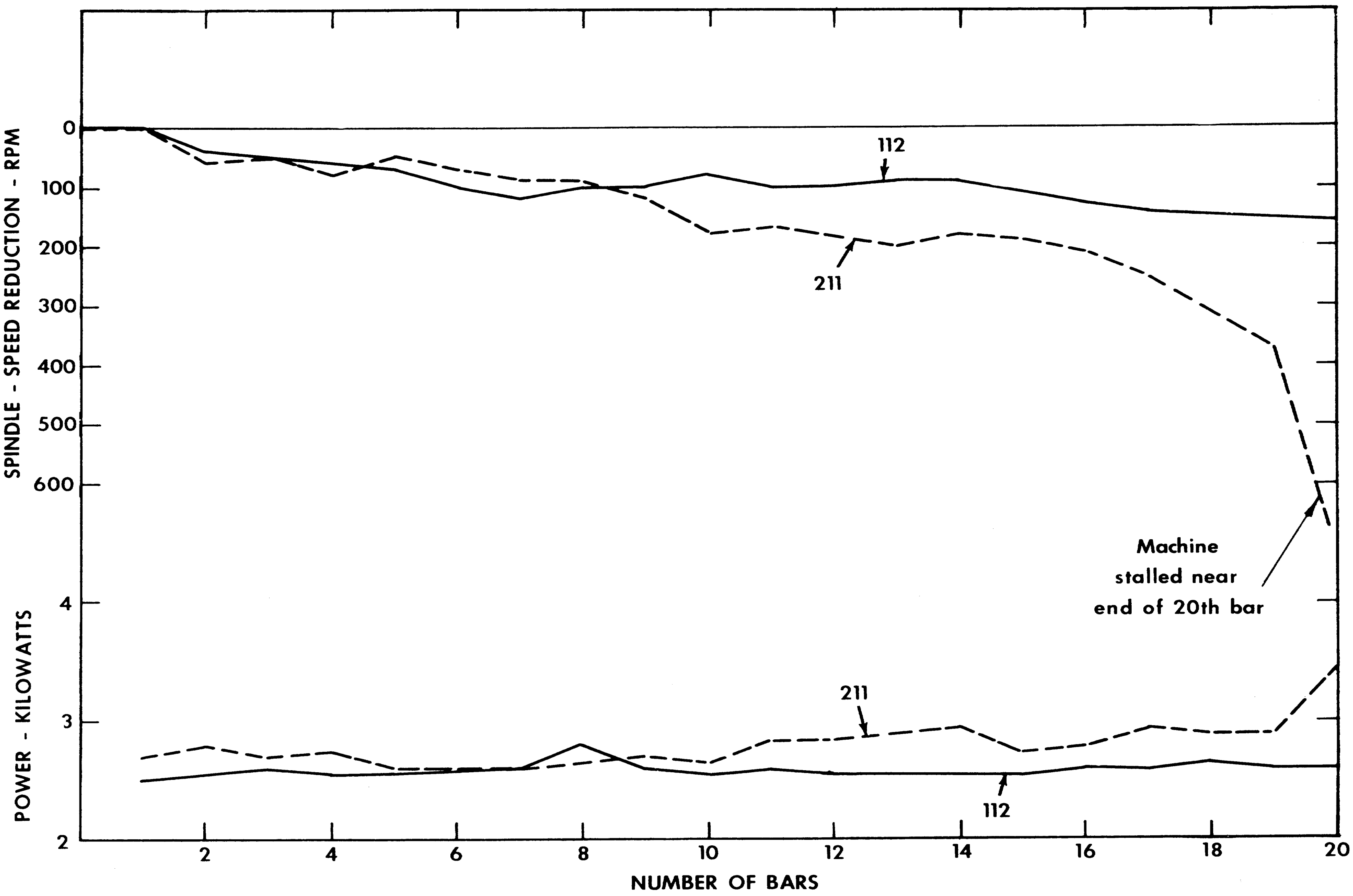


Fig. 8.8. Heavy forming - Typical values for power and spindle-speed reduction for high and low copper materials.

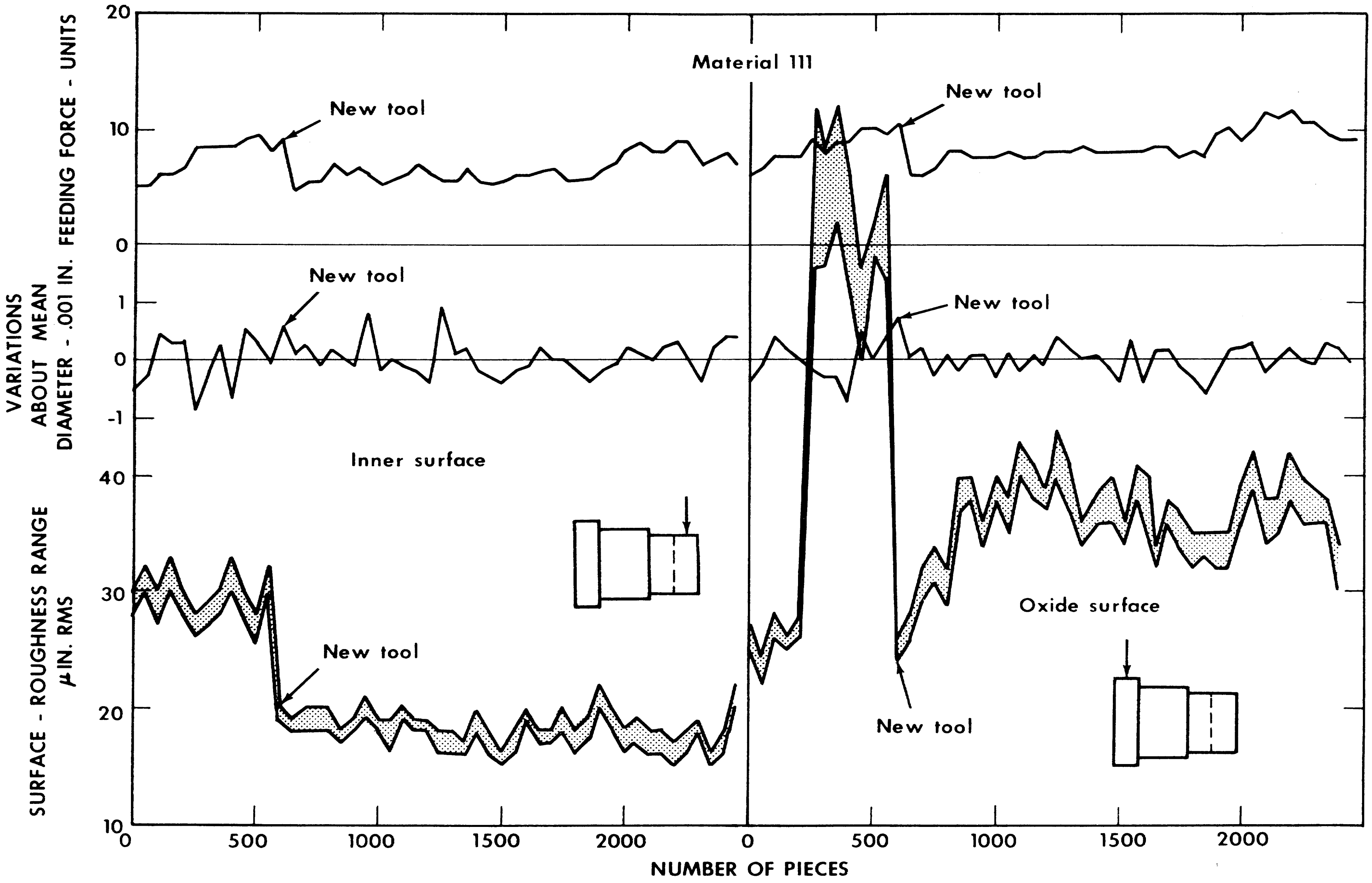


Fig. 8.9. Light forming - Surface-roughness range, dimensional stability, and feeding force; material 111.

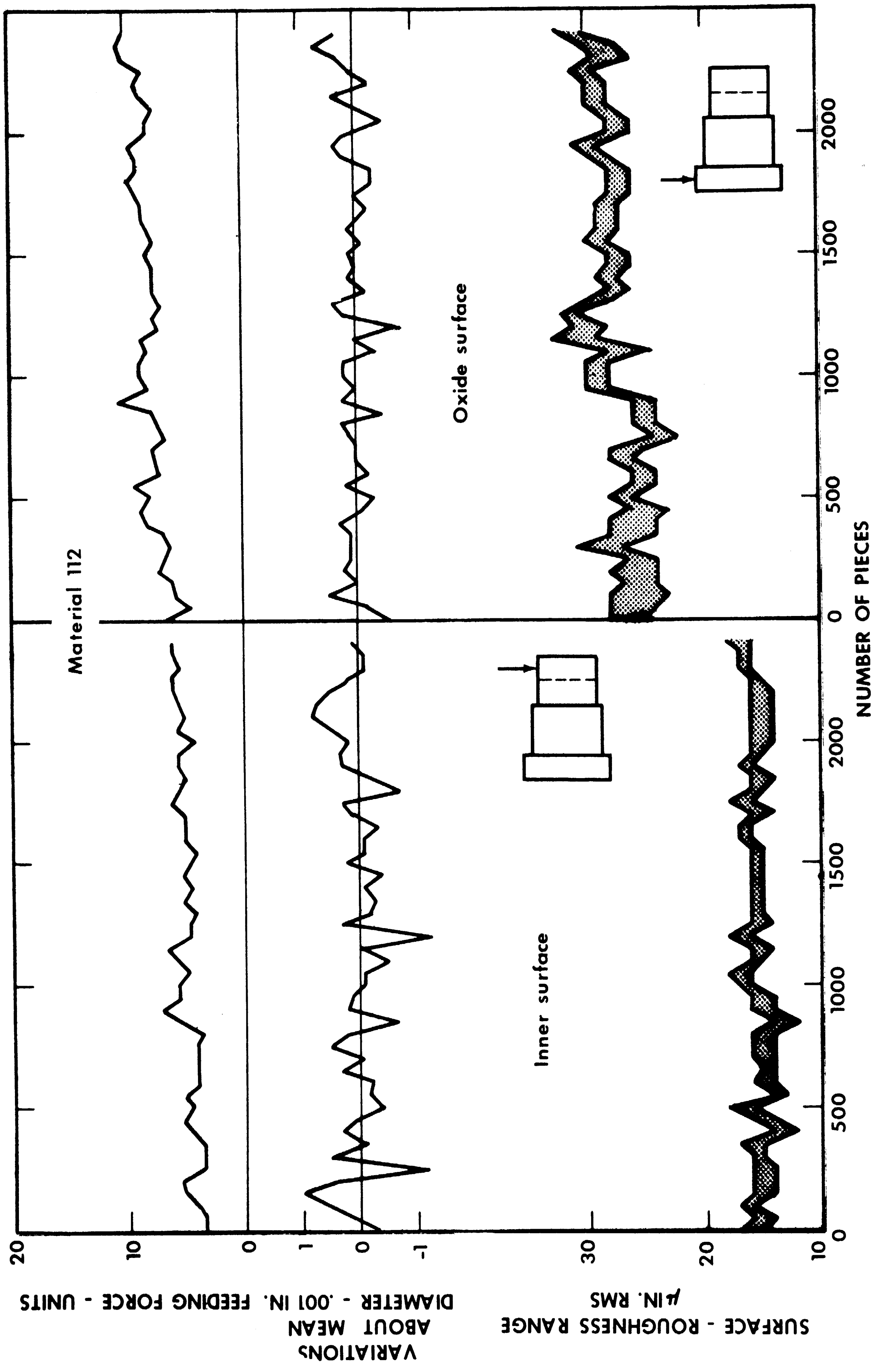


Fig. 8.10. Light forming - Surface-roughness range, dimensional stability, and feeding force; material 112.

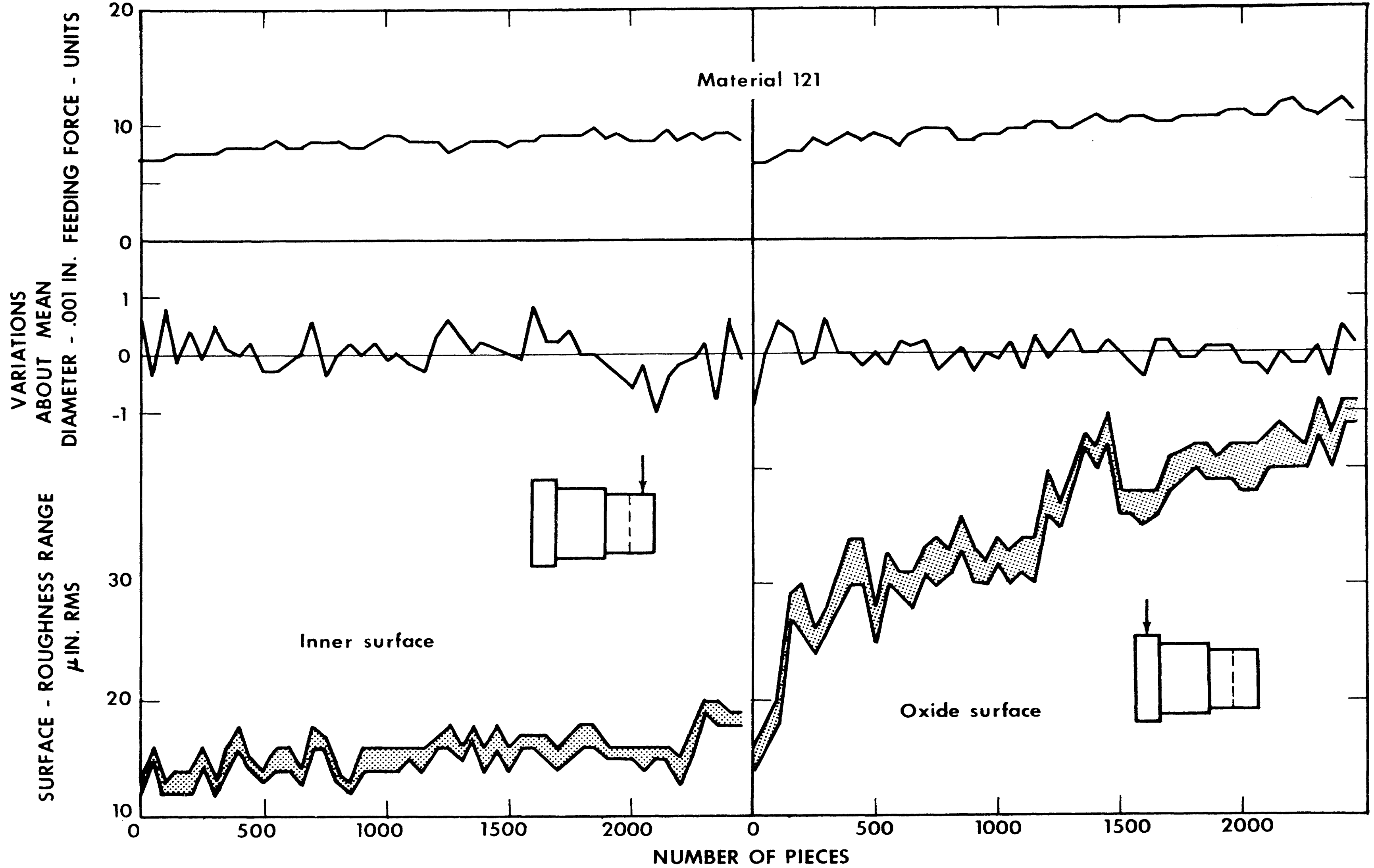


Fig. 8.11. Light forming - Surface-roughness range, dimensional stability, and feeding force; material 121.

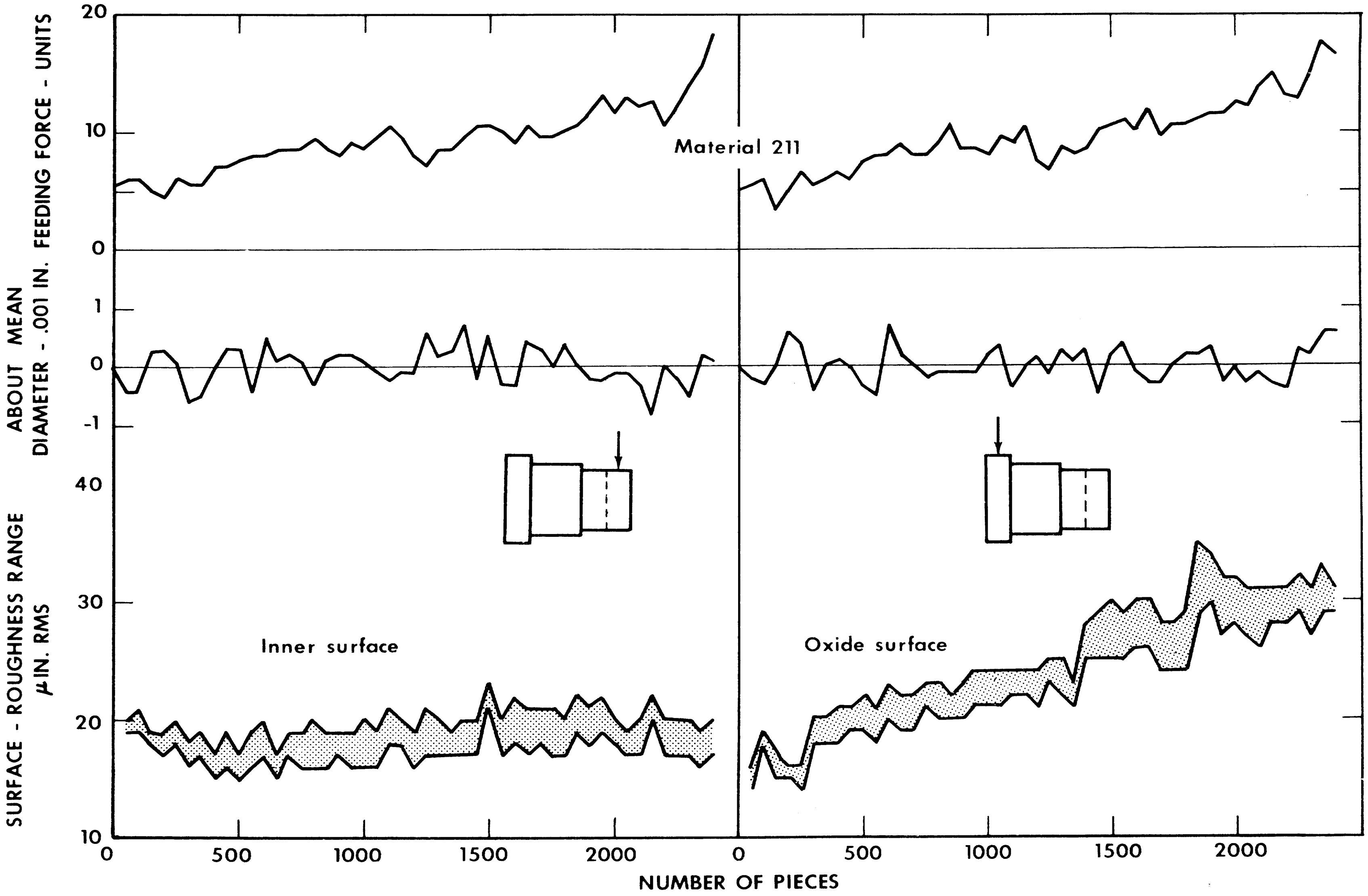


Fig. 8.12. Light forming - Surface-roughness range, dimensional stability, and feeding force; material 211.

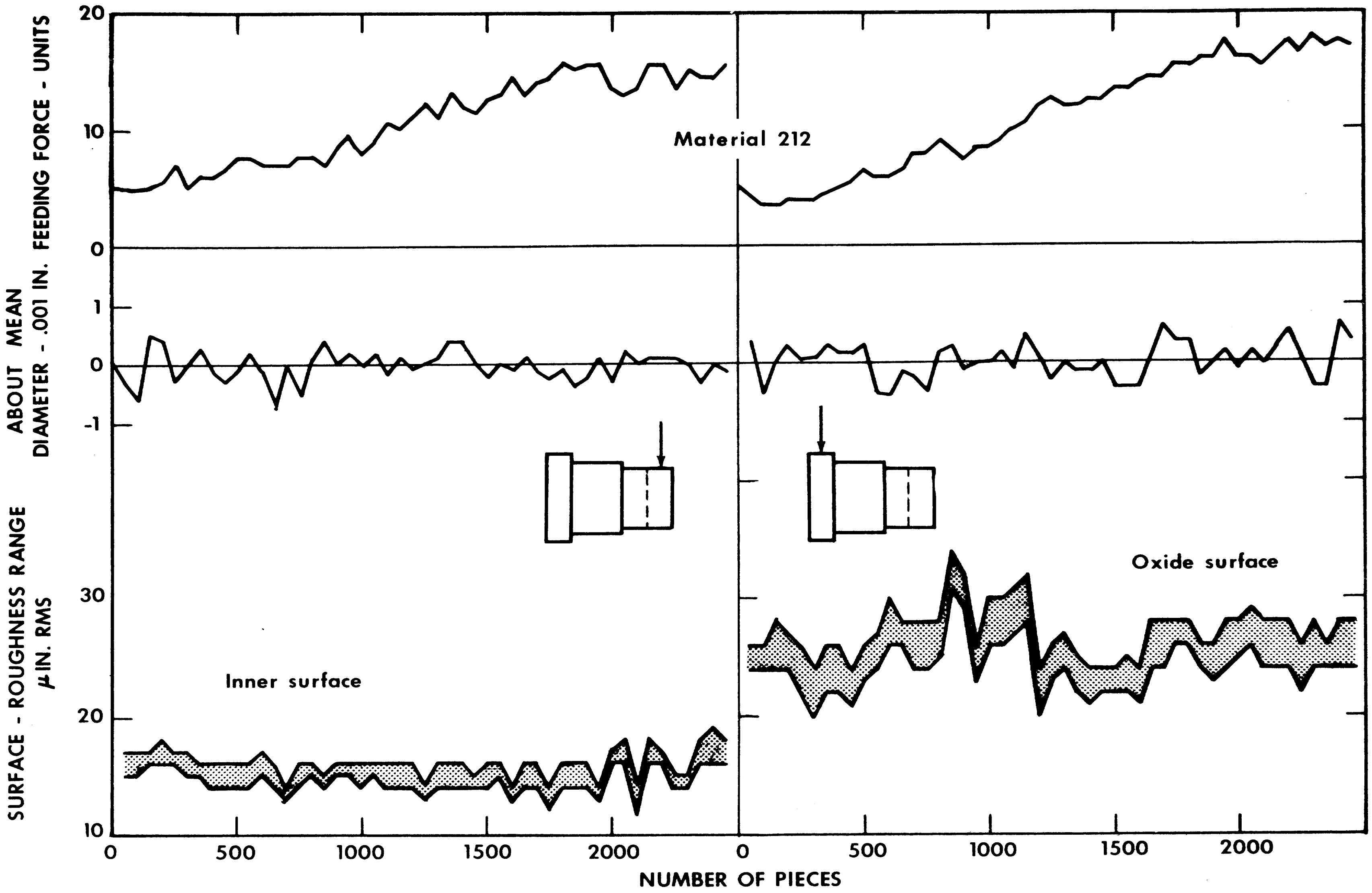


Fig 8.13. Light forming - Surface-roughness range, dimensional stability, and feeding force; material 212.

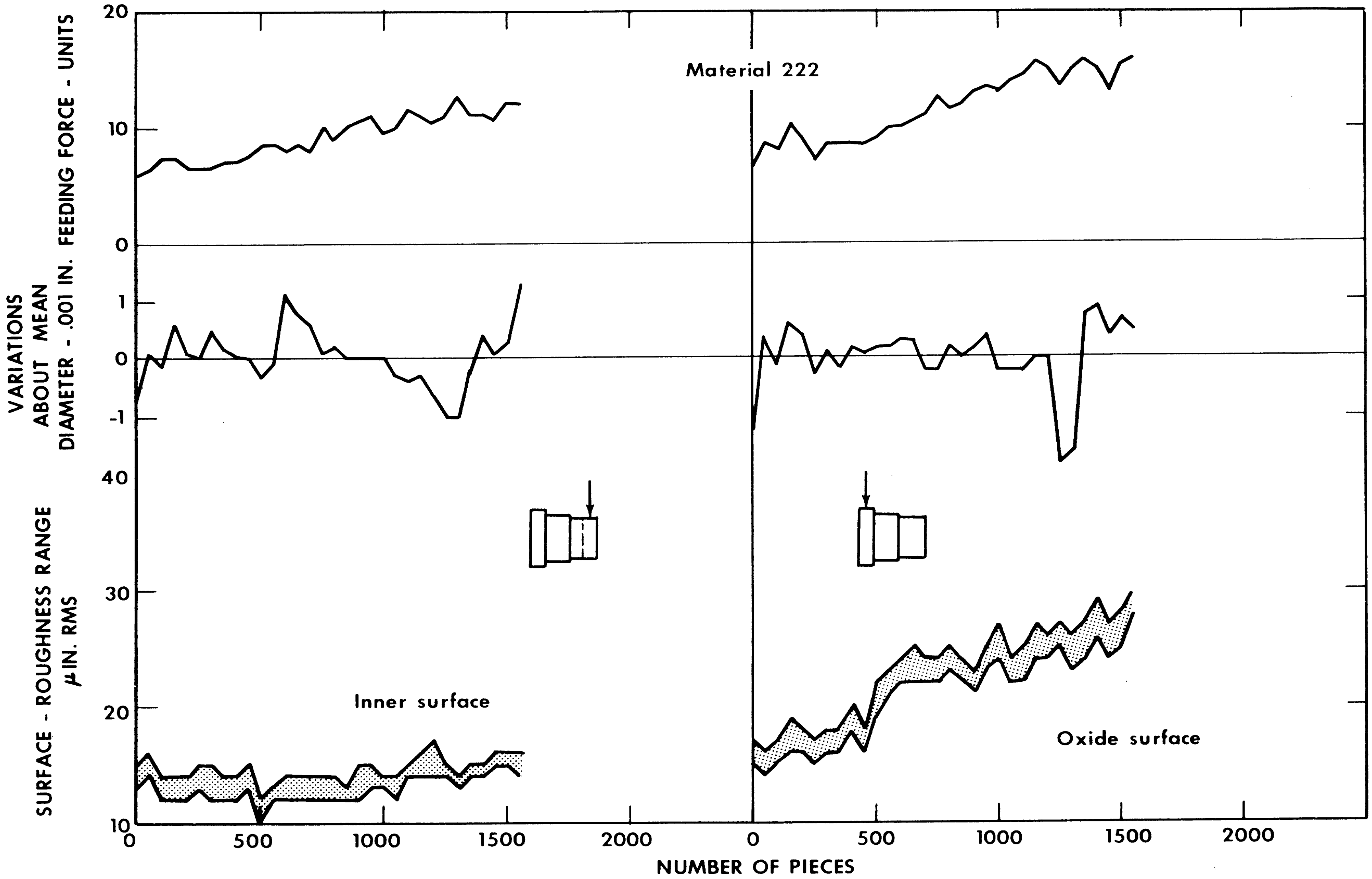


Fig. 8.14. Light forming - Surface-roughness range, dimensional stability, and feeding force; material 222.

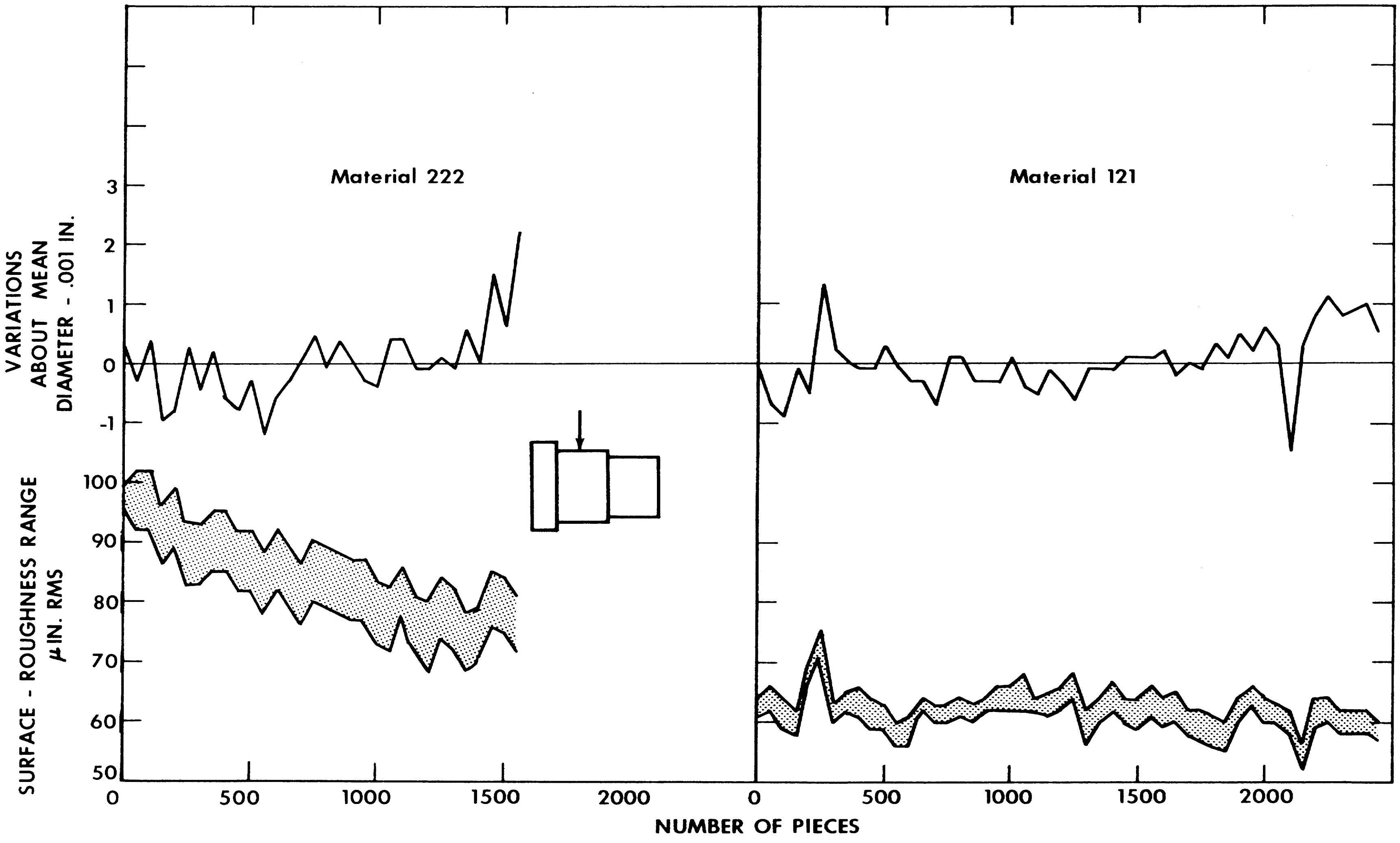


Fig. 8.15. Turning - Surface-roughness range and diameter variations.

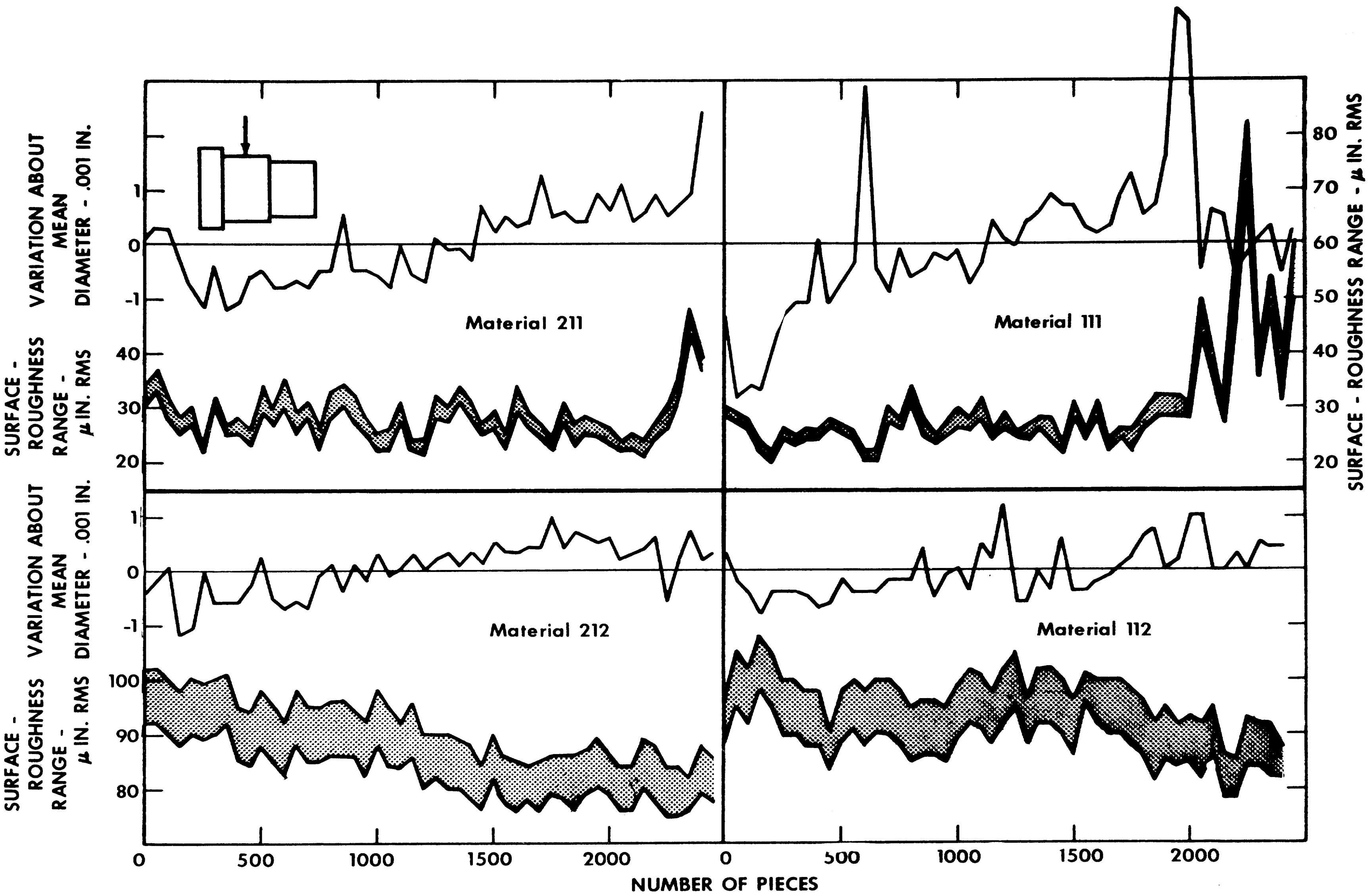


Fig. 8.16. Turning - Surface-roughness range and diameter variations.

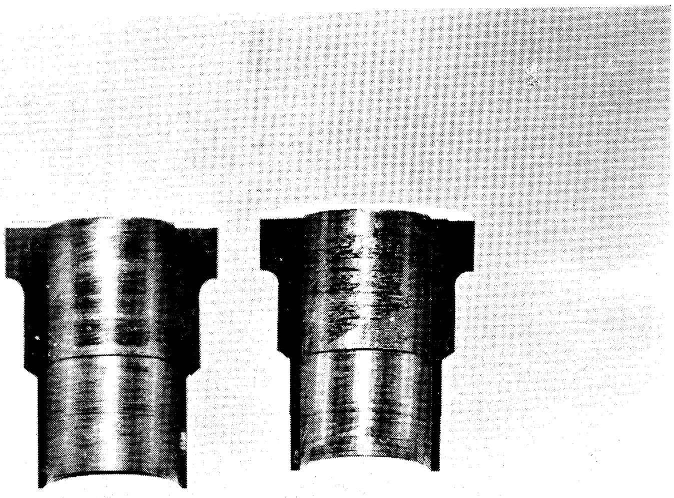


Fig. 8.17a. Material 222. View of drilled surface produced on piece No. 2 (left) and piece No. 1152 (right) before drill was replaced.

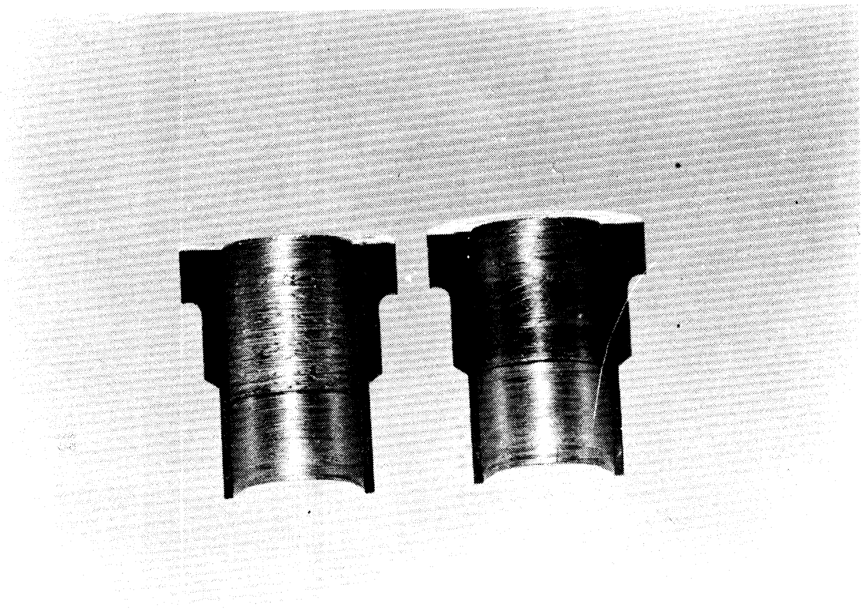


Fig. 8.17b. Material 111. View of drilled surface produced on piece No. 3 (left) and piece No. 2450 (right) at end of run.

PART IX. PRACTICE USED ON CONTROL MATERIAL FOR MACHINABILITY TESTING

Casting:

1. No. 15 Remelt furnace charged for 5.00% Cu content.
   24,000 pounds
   48% Scrap
   52% Virgin Pig

2. Furnace sample analyzed:
   4.99% Cu
   0.2% Pb
   0.2% Bi

3. Lead and bismuth added.

4. Furnace sample analyzed:
   5.25% Cu
   0.45% Pb
   0.50% Bi

5. 2500 pounds pigged and 2400 pounds of virgin added to dilute copper.

6. Furnace sample analyzed:
   5.05% Cu

7. Metal run-around to holding hearth, fluxed, and one drop of six ingots was cast through the continuous fluxer.

   Practice followed:

   Temperature - 1380°F
   Speed - 2 in. per minute
   Head - 4 in.
   Water - Top-Medium
   Bottom-Medium
   Chlorine Flow - 1 lb/hr

8. The next run-around to holding hearth froze in the run-around trough when solid 2011 scrap was added to the furnace in order to raise the level of the molten metal to have it flow into the holding hearth.

9. The run-around was completed by digging the solidifying metal out of the run-around trough, reheating the metal in the furnace, and adding more solid 2011 scrap to the furnace near the end of the run-around.

10. 110 pounds of pure copper scrap was added to the 11,000 pounds of metal in the holding hearth.

11. Metal was fluxed, skimmed and the second drop was cast through the continuous fluxer, using the same casting practice.

Preheating:

1. The metal was homogenized at a metal temperature range of about 970-995°F for a 12-hour soak.

2. Load was pulled and air cooled to room temperature.

Hot Rolling: (Breakdown)

1. Charged into reheat furnace and brought to rolling temperature.

2. Rolled from 12 x 12 ingots to 6 x 6 blooms at a temperature range of 770-800°F.

Sawing:

1. Ultrasonically tested for gross defects and sawed to 44-in.-long billets.

2. Each billet was identified according to the ingot from which it came and the location within that ingot.

Scalping:

Scalped from 6 x 6 to 5-1/2 x 5-1/2, removing 1/4 in. from the surface of the billets.

Inspection:

A few billets were caustic etched. No defects or irregularities were noted.

Reheating:

1. Billets were selected for each lot so that analysis would be correct for that item and so that a billet from each ingot would be represented in the lot and the location of the billets in respect to the ingot would be random.

2. Billets were charged into the reheat furnace and brought to rolling temperature.

3. The billets were rolled to either 1-1/8-in. diameter or 1-3/16-in. diameter for 1-in.-diameter rod or 1-5/8 in. or 1-11/16 in. for 1-1/2-in.-diameter rod, depending on the amount of cold work required after heat treatment. The rolling temperature range was about 730-755°F.

4. The identification was maintained on each rod so that its location in respect to the ingot from which it came would be known.

Drawing:

A 1/16-in. reduction was made on all rods in order to reduce the variation in cold working after heat treatment which would be due to variations in the hot rolled size of the rods. This drawing is not the normal practice for this size of rod.

Heat Treatment:

The furnace was set to give a heat-treat temperature range of 920-930°F or 970-980°F. The time the metal was in the furnace was three hours. This gives a minimum soak time at temperature of 30 minutes.

Drawing:

Either a 1/8-in. reduction or a 1/16-in. reduction was made on the rod for the final "T3" temper.

Sawing:

The rods were sawed to standard 12-ft lengths and stencilled with their correct identifying number. All rods from a particular billet have the same number as that billet.

Inspection:

The material was inspected and applied to the order.

Rod Identification:

Cast 1054-2 (Six ingots numbered 1 through 6)
Cast 1054-3 (Six ingots numbered 7 through 12)

Billets numbered 1 through 8 starting from top of ingot.

First number (s) is ingot number.
Last number is billet sequence number.

Example:

Rod No. 108 is a rod from ingot No. 10 and billet location No. 8. This ingot is from cast 1054-3 and the billet is located at the bottom of the ingot.

Chemical Analysis:

Cast 1054-2	Si	Fe	Cu	Mn	Mg	Pb	Bi	Ti
Buttons (Release Sample)	.11	.41	5.03	.03	.01	.40	.41	.02
Casting control-top			5.05					
-middle			5.01					
-bottom			5.03					

Billets	Si	Fe	Cu	Mn	Mg	Pb	Bi	Ti
No. 18 Center	.13	.41	4.99			.42	.52	
18 Surface	.12	.42	4.95			.42	.52	
25 Center	.13	.40	4.95			.42	.53	
25 Surface	.13	.42	4.99			.43	.54	
31 Center	.13	.42	4.95			.43	.54	
31 Surface	.12	.42	4.95			.43	.54	
49 Center	.11	.43	4.95			.43	.53	
49 Surface	.11	.40	4.87			.43	.53	
55 Center	.11	.41	4.95			.42	.50	
55 Surface	.11	.42	4.91			.42	.50	
61 Center	.12	.42	4.95			.43	.50	
61 Surface	.12	.43	4.99			.43	.50	
Cast 1054-3								
Buttons								
Release Sample								
Casting control								
Top	.13	.41	5.89	.03	.01	.46	.50	.02
Middle			5.81					
Bottom			5.77					
			5.85					
Billet slices								
No. 79 Center	.11	.45	5.60			.50	.57	
79 Surface	.12	.46	5.64			.50	.56	
89 Center	.12	.46	5.64			.49	.58	
89 Surface	.12	.45	5.64			.50	.55	
91 Center	.12	.47	5.68			.50	.56	
91 Surface	.12	.46	5.64			.50	.58	
101 Center	.11	.46	5.64			.49	.54	
101 Surface	.11	.47	5.72			.50	.54	
115 Center	.11	.47	5.77			.50	.54	
115 Surface	.12	.45	5.64			.49	.54	
125 Center	.11	.46	5.60			.49	.54	
125 Surface	.12	.46	5.64			.49	.54	

The buttons are samples taken from the molten metal and cast into a mold. The billet slices were cut at the time the billets were cut to length. All the analysis are wet analysis with the exception of the Si, Fe, Mg, Mn, and Ti in the release samples which were done spectrographically.

The billet slices were analyzed to determine the extent of segregation of alloying elements in the center and surface of the scalped material and variation of analysis from top to bottom of ingot. The variation in analysis of the buttons and billets is due to segregation on the surface of the ingot which is scalped off before the billets are rolled into rods.

Item No.	Lot No.	Size	Avg.Cu Anal. %	Heat-Treat Temp.	% Cold Work	T.S. (1000 psi)	Y.S. (1000 psi)	Elong. %	Rod Ident.	No. of Rods Applied of Each Ident.
1	E736	1" diam	4.95	280°F	11	50.1	45.2	15.0	11	5
						52.3	47.5	15.0	17	4
									21	4
									22	2
									31	5
									35	5
									45	5
									54	3
									56	4
									64	3
2	E737	1"	4.95	930	11	44.9	40.3	16.0	13	7
						45.8	41.1	15.5	27	6
									36	6
									37	5
									46	4
									57	5
									65	7
3	E738	1"	5.65	980	11	54.6	49.3	11.5	75	5
						49.5	44.1	12.5	85	4
									88	5
									96	7
									105	8
									112	6
									121	5
4	E739	1"	5.65	930	11	46.4	41.6	13.5	77	6
						46.5	41.3	13.5	84	6
									92	6
									103	5
									106	7
									117	8
									127	2
5	E740	1"	4.95	980	21	52.0	48.1	14.0	15	4
						52.5	48.6	13.5	25	5
									32	8
									48	4
									52	7
									62	5
									66	7
6	E741	1"	4.95	930	21	52.9	49.4	11.0	16	4
						48.0	44.4	12.5	23	5
									34	8
									42	5
									47	5
									55	2
									63	8

Item No.	Lot No.	Size	Avg. Cu Anal. %	Heat-Treat Temp.	% Cold Work	T.S. (1000 psi)	Y.S. (1000 psi)	Elong. %	Rod Ident.	No. of Rods Applied of Each Ident.
7	E742	1" diam	5.65	980°F	21	57.9	52.7	13.0	78	6
						56.2	51.6	13.0	86	6
									95	4
									108	6
									114	7
									122	7
									128	4
8	E743	1"	5.65	930	21	50.5	46.8	12.0	75	6
						49.5	45.6	12.0	82	7
									98	3
									107	5
									113	5
									123	8
									125	6
9	E747	1-1/2"	4.95	980	8	43.9	37.3	19.5	12	5
						44.4	37.6	18.5		
10	E748	1-1/2"	4.95	930	8	43.1	37.0	16.5	61	5
						43.6	36.7	20.0		
11	E749	1-1/2"	5.65	980	8	49.3	41.0	19.0	111	5
						49.0	41.5	18.5		
12	E750	1-1/2"	5.65	930	8	44.0	37.6	18.0	124	5
						43.8	38.8	16.5		
13	E751	1-1/2"	4.95	980	15	48.6	43.3	14.0	43	5
						48.3	42.7	14.5		
14	E752	1-1/2"	4.95	930	15	46.5	40.5	14.0	33	5
						45.6	41.1	14.0		
15	E753	1-1/2"	5.65	980	15	51.6	46.5	14.0	71	5
						52.0	45.8	13.0		
16	E754	1-1/2"	5.65	930	15	46.1	42.1	12.5	93	5
						47.0	42.5	12.5		

Submitted to the Production Laboratories of the Mechanical Engineering Department by John H. den Boer, Metallurgist, Reynolds Metals Company, Lister Hill, Alabama.