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Final Report - Part I

A STUDY OF COMPARATIVE MACHINING CHARACTERISTICS OF ALUMINUM AND MAGNESIUM BAR STOCK FOR AUTOMATIC SCREW MACHINES

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ABSTRACT

Tests made in an automatic screw machine indicated that magnesium bar stock generally machined better than did corresponding stock of 2011 T-3 aluminum. The aluminum provided slightly better finish and lower forces at light cuts. Some parameters, such as size control, chip formation, and power, favored magnesium for some operations but not for others. Increase in power requirements caused the machine to stall after producing only 1850 aluminum parts whereas a complete run of 4950 magnesium parts had not approached significantly close to the limit of the machine.

INTRODUCTION

Machinability studies on the basis of sharp tool tests have proved to be a valuable contribution to the evaluation of many materials. 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. Tests on a Brown and Sharpe automatic screw machine were made for this purpose in comparing aluminum and magnesium screw stock.

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. 1. The part was designed to reveal information on five basic machining operations: light- and heavy-forming, turning, drilling, reaming, 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;
2. forming an inner surface for the same thickness of cut, after rough-forming had reduced the original 1-in. bar diameter.

Specially designed single-component force dynamometers were mounted on the cross slides of the machine to measure form tool feeding forces. Also, turret-slide tool feeding forces were measured through strain gages mounted on the turret-slide follower arm. The forces were recorded on a Sanborn Recorder. In addition to the normal tool setup, a Hewlett-Packard electronic counter and an Esterline-Angus wattmeter were used to record spindle-speed fluctuations and power requirements, respectively, for the various machining operations.

OPERATING CONDITIONS

The test cutting conditions are summarized in Table I. Identical cutting conditions were used on both materials.

TEST PROCEDURE

By arbitrary definition, a test run was to consist of 5000 machined parts (approximately 40 12-ft. bars) unless the effects of tool wear were so pronounced that they led to stalling of the machine before the required number of parts was made. In the latter event, the run would terminate automatically.

The standard test procedure consisted of:

1) properly setting all tools to produce parts within specifications;
2) machining of parts, with collection and inspection of three consecutive pieces at intervals of 50 throughout the test run;
3) recording light-form, heavy-form and turn tool feeding forces, drilling thrust, and machine spindle speeds, and power requirements at intervals of 50 pieces; and
4) final inspection of cutting tools at the end of the test.

All surfaces on each of the collected parts were inspected visually for significant changes in surface appearance. 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. At the end of each run, a toolmaker's microscope was used for the final inspection of all tools.

TEST RESULTS

Table II gives a summary of the most important results on both materials. Tool wear and loading characteristics are given in Table III. The individual plots of surface roughness, feeding forces, dimensional variations, and power, in Figs. 1 through 11, serve to illustrate the effects of tool wear as it increases with the number of parts produced.

Under the test cutting conditions, the most obvious difference in results between the aluminum and magnesium alloys is reflected by the number of parts

produced from each material. The machine stalled at about 1850 pieces during machining of the aluminum alloy, but the magnesium alloy ran for practically 5000 pieces without any serious loss in machine efficiency. This difference in behavior indicates, of course, the difference in cutting horsepower requirements for the two materials. However, the length of the runs is not in itself a valid basis for evaluation of the two alloys and, therefore, further comparisons are made for each machining operation.

LIGHT-FORMING

Surface-roughness values, feeding forces, and diameter variations are plotted in Figs. 2, 5, and 7, respectively, for the light-forming operation on the oxide and inner surfaces.

Among all machining operations, the light-forming operation shows the 2011-T3 aluminum alloy to best advantage. Compared with the magnesium alloy for the same number of parts, the aluminum-based material gave better surface quality, better dimensional stability, and lower feeding forces. Both materials gave rather stable surface quality, and even though the surface-roughness values were higher on the magnesium alloy, the surface was still pleasing to the eye.

The effect of the bar oxide surface is most pronounced in terms of tool wear, the wear being 103% and 63% higher than was found on the inner surfaces of the magnesium and aluminum alloys, respectively. The increased wear apparently had little effect upon the results found on the aluminum alloy, for surface roughness, dimensional stability, and feeding forces were comparable between the two surfaces. There was also little difference in surface roughness between the oxide and inner surfaces of the magnesium alloy, although the results on the oxide surface were a little more erratic. However, the oxide surface produced a greater loss in dimensional stability which was probably brought about not only directly by the increased tool wear, but also by an accompanying increase in feeding force, as shown in Fig. 5. There was actually a slight decrease in the feeding forces on the aluminum as the run progressed.

HEAVY-FORMING

Figures 3, 5, and 8 represent the results of surface-roughness measurements, feeding forces, and dimensional variations, respectively, for the heavy-forming operation on each material.

While there are differences in surface quality between the aluminum— and magnesium-based materials, the most pronounced differences occur in diameter variations and in feeding forces. An increase in diameter of .0467 in. was accompanied by a force of 490 lb on the aluminum material, in contrast to an increase of .0187 in. at a force of 270 lb for the same num-

ber of pieces on the magnesium alloy. It is interesting to note that, with sharp tools, the heavy-form feeding forces on the 2011-T3 alloy were only 50% as high as those found on the magnesium material, and yet were over 80% higher at the end of 1850 pieces. Dimensional stability followed a similar pattern.

Only a very small amount of the excessive, formed diameter increases can be attributed to the wearing away of the cutting edge. The major portion of the increase in diameter comes as a result of deflections of the work and of the machine-tool components caused by the high feeding forces.

Tool wear appeared to be more severe on the aluminum alloy, with a rougher and more rounded cutting edge. This difference in wear could account for the reversal in relative feeding forces on the two materials. The AZ-31C-FS alloy gave heavier smear along the tool flank.

In general, the measured surface quality of the formed surfaces was similar on both materials for the first 500 pieces. However, the aluminum surface deteriorated much more rapidly as the run progressed. Visual inspection of the aluminum surface revealed that deeper markings and burnished rings began to show at about 350 pieces and the appearance got progressively worse to the end of the run, even though the Profilometer readings indicated some improvement in quality at about 1550 pieces. The magnesium surface, on the other hand, was relatively good to 1800 pieces before burnished areas made it less desirable in appearance. The surface looked better at the end of 4969 pieces, however, than the aluminum surface did at 1850 pieces.

TURNING

The turning results are shown in Figs. 4 and 7. As was true in most of the operations, the turned diameter variations and the turn-tool feeding forces were lower in the beginning and throughout the run on the 2011-T3 alloy. However, the AZ-31C-FS alloy had by far the better surface quality—an average surface roughness of 22-27 μ in. as compared with a value of 56-62 μ in. for the aluminum alloy. The feed marks were more pronounced on the aluminum material, but the surface was acceptable in appearance.

In spite of the good and consistent surface quality of the magnesium, the diameter variations were much more erratic and reached a peak range of .0048 in. in 1850 pieces, compared with a range of .0018 in. on the aluminum material. Turning feeding forces were about 60% higher on the magnesium over the same span of parts.

DRILLING

Drilling thrust forces are recorded in Fig. 6. Additional drilling characteristics involving power and machine spindle speeds are shown in Figs. 9, 10,

and 11, and will be discussed separately. Only visual observations and representative spot checks were made of surface finish and drilled diameters.

Observations of drill wear revealed two different wear patterns. The drill used on the aluminum alloy had a built-up edge of .0035 in., which kept the flank wear to less than .001 in. The corners, however, did not show any built-up edge and were badly worn and notched. The drill used on the magnesium alloy had only light smear over the cutting edges and showed fairly uniform flank wear of .0054 in. with only slight rounding of the corners even after 5000 pieces.

In turning and light- and heavy-forming, the initial feeding forces were always higher on the magnesium alloy. In drilling, however, this trend was reversed. As may be seen in Fig. 6, drilling thrust was consistently higher on the 2011-T3 alloy, although the difference between the thrust forces on the two materials diminished at about 1800 pieces.

There were slight differences in drilled diameter stability and in drilled surface quality, but the results could be considered as excellent on both materials. The drilled finish on the aluminum progressed from a good dull surface in the beginning to an excellent polished surface at the end of the run. The hole diameter was about .002 in. oversize initially and decreased as the run progressed until it was about .0005 in. oversize at the end. The hole diameter on the magnesium was actually undersize throughout the entire run of parts, and the drill was literally a force fit into the hole. The hole actually got smaller to the end of the run. As might be expected, because of the tight hole, the drilled surface was burnished, but generally not of as good a quality as that found on the aluminum.

CUTOFF

Outside of tool wear, the only observations of the cutoff operation were made visually. Tool wear appeared to be severe on the aluminum alloy, particularly in terms of corner wear.

No difficulties were encountered in the cutoff operation, and the surface finish was generally satisfactory on both materials. Some tearing of the surface occurred during the first 100 pieces on the aluminum alloy, but the surface improved as the test progressed. Burnishing was very evident. The cutoff surface on the magnesium was quite consistent throughout the entire run and had a better overall quality than what was found on the aluminum.

REAMING

Only visual observations and a few spot checks of the reamed diameters were made of this operation. The results were similar to those exhibited in drilling. The surface quality was again better on the aluminum material, while the magne-

sium alloy produced the tighter holes. Feed and withdrawal marks were more prominent on the magnesium material.

The reamers were inspected for wear but only light smear was found on the chamfer.

CHIP FORMATION

Undoubtedly, the greatest disadvantage of the magnesium alloy found in this test program was in chip formation. The chips were very troublesome, and the machine had to be stopped at regular intervals and cleared of the chips that had wound around the moving parts. In the beginning of the run, the drill chips were generally about 2 ft long, and the turn chips were 1/2 in. in diameter and 20 in. long. The form chips were continuous and ranged from coils 1-1/2 in. in diameter to long stringy balled-up chips. As the run progressed, the turn and form chips became even more uncontrollable. The drill chips got shorter but began to pile up and bind in the drill flutes.

In contrast, the aluminum chips were very short, and for the most part were no more than 1/2 in. in length. The turn chips and the cutoff chips became longer at about 1700 pieces, but were never troublesome.

The chip ratings in Table IV, based upon arbitrary values assigned to chips of certain general size and shape, serve to compare the materials as well as to show the changes which occur in chip formation with the number of parts.

POWER AND SPINDLE-SPEED FLUCTUATIONS

Figures 9 and 10 represent the cutting horsepower and the spindle-speed values for three critical operations in the sequence necessary to machine the part. These three operations—(1) drill and form, a combined cut including the beginning of drilling and a partial heavy-forming operation; (2) end of drilling, when the drill has reached the full depth of hole; and (3) cutoff and finish form—require the greatest power and, therefore, would be most affected by tool wear. Normally, the combined cut would require the greatest power unless, during drilling, the horsepower requirements increased as the depth of hole increased. The curves in Fig. 11 are traces of actual power readings recorded by a wattmeter, and serve to show the differences in behavior between the two test materials, as well as to show the variations in power requirements for the three operations as tool wear increases.

It may be noted in Fig. 9 that the cutting horsepower requirements are higher for the aluminum alloy than they are for the magnesium alloy, even

though the initial feeding forces were lower on most of the operations. It may also be noted that the cutting horsepower for the aluminum material rises at an increasing rate with the number of parts, while the cutting horsepower for the magnesium alloy rises at a decreasing rate for the entire run.

The erratic behavior of the power curve for the end of drilling on the magnesium alloy reflects the effect of drill binding due to poor chip formation. The wattmeter traces in Fig. 11 show the points during the run at which the changes in behavior took place.

The power curves in Figs. 9 and 11 show that heavy-forming and the end of drilling contributed most to stalling the machine during the run of the aluminum material. The spindle-speed curves in Fig. 10 show also that drilling and forming contributed most to spindle-speed slowdown. For the most part the spindle-speed characteristics had the same general trends as the power curves—the greater the power requirements, the lower the spindle speed.

RESIDUAL STRESSES IN MACHINED PARTS

Table V is included merely to illustrate that residual stresses do exist in the machined parts, that these stresses can be of different signs and of different magnitudes, and that they can change as tool wear increases. It is believed that these residual stresses have an effect upon some of the results found in this study, and that further investigations would be desirable. The amount of opening or closing of the slotted rings gives some indication of the relative magnitude of the stress but does not reveal the stress distribution, nor does it indicate how much of the stress is induced by drilling, by forming, or by reaming.

TABLE I

TEST CUTTING CONDITIONS

Machine: Brown and Sharpe, No. 2G, single-spindle automatic screw machine
Cutting fluid: Sun Oil Company - Circle XXX oil with 10% lard
Materials tested: 2011-T3 aluminum alloy; AZ-31C-FS magnesium alloy

Operation	Cutting Conditions			Cutting Tools	
	Spindle Speed, rpm	Velocity, fpm	Feed, ipr	Material	Signature
Knee turn	2600	680	.0060	*T-1 H.S.S.	15,20,8,8,8,0,1/16
Light- or finish-form	2600		.0010	T-1 H.S.S.	20,0,8,0,0,0,0
Oxide surface		680			
Inner surface		490			
Heavy-form	2600	680	.0025	T-1 H.S.S.	20,0,8,8,0,35,0
Cutoff	2600	680	.0025	T-1 H.S.S.	20,0,8,2,20,-2,0
Drill	2600	370	.0069	Nat'l. Twist Drill H.S.S. std. screw machine drill, oxide-treated	118° point angle 10° relief angle
Ream	2600	380	.0330 (.0055/ blade)	Nat'l. Twist Drill H.S.S. std. machine reamer	6-blade spiral-fluted 45° chamfer

*T-1: 18% W, 4% Cr, 1% Va.

TABLE II

SUMMARY OF TEST RESULTS

		Materials	
		2011-T3 1847 pieces	AZ-31C-FS* 4969 pieces
Light-Forming			
Average tool wear, in.	oxide surface	.0025	.0061
	inner surface	.0016	.0030
Average surface roughness	oxide surface	15-18	29-35
	inner surface	12-14	29-36
Diameter range, in.	oxide surface	.0023	.0070 (.0049)
	inner surface	.0028	.0050 (.0044)
Feeding force range, lb	oxide surface	17-12	24-130 (88)
	inner surface	18-14	18-56 (45)
Heavy-Forming			
Average tool wear, in.		.0125	.0170
Average surface roughness, μin. rms		52-59	38-46
Diameter range, in.		.0467	.0255 (.0187)
Feeding-force range, lb		24-490	52-430 (270)
Turning			
Average tool wear, in.		.0032	.0050
Average surface roughness, μin. rms		56-62	22-27
Diameter range, in.		.0018	.0073 (.0048)
Feeding-force range, lb		15-58	24-95 (90)
Cutting horsepower range		1.07-1.40	.805-1.07 (.99)
Drilling			
Average drill wear, in.		.001 with severe corner wear	.0054
Thrust force range		214-357	167-410 (330)
Cutting Horsepower			
Start drill and form		2.06-2.90	1.73-2.70
End of drilling		1.75-3.00	1.63-2.61
Cutoff and form		1.85-3.02	1.62-2.62
Spindle-speed ranges			
Start drill and form		2230-1470	2250-1980
End of drilling		2330-1230	2310-2070
Cutoff and form		2230-1110	2280-2010

*Values in parentheses where included show comparison with 2011-T3 at 1850 pieces.

TABLE III

TOOL-WEAR CHARACTERISTICS

Tool	Material 2011-T3 (1847 pieces)	Material AZ-31C-FS (4969 pieces)
Light-form oxide surface	.0025-in. flank wear; rough and appears to be hollowed out; shallow to deep notches; crater on face; .0005-in. B.U.E.	.0061-in. flank wear; uniform wear with slight notching; edge broken .001 in. back of original; smear along flank; no B.U.E.
Light-form inner surface	.0016-in. flank wear; uniform with a few shallow notches; .0004-in. B.U.E. over part of cutting edge.	.0030-in. flank wear; uniform in depth below face but rough along edge; edge broken .0005 in. back of original; some smear along flank.
Heavy-form	.0125-in. flank wear; not as uniform as on magnesium alloy; some notching; small very erratic B.U.E.	.0170-in. flank wear; fairly uniform; no apparent edge breakdown but flank is heavily smeared; small but erratic B.U.E.
Turn	.0032-in. wear; cutting edge broken .0012 in. back of original; some notching; slight, erratic B.U.E.; slight crater on face.	.0050-in. flank wear; fairly uniform; edge broken .001 in. back of original; very shallow crater on face; no B.U.E.
Cutoff	.0034-in. wear on one corner; both corners broken down; no appreciable cratering; smear on face had "washboard" appearance.	.0044-in. flank wear; worn in "washboard" pattern; corners rounded but not as severely as on aluminum alloy; no B.U.E.
Drill	Less than .001-in. wear but corners severely broken; .0035-in. B.U.E.; chisel edge intact.	.0054-in. uniform flank wear; smear over cutting edges; corners only slightly rounded.
Reamer	Both reamers similar in appearance; no appreciable wear; very slight B.U.E. on chamfer at end.	

TABLE IV

CHIP-FORMATION RATINGS*

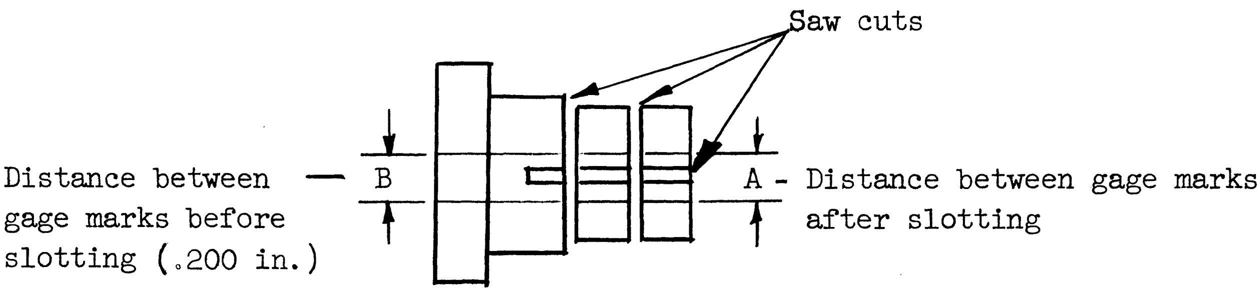
Material	Chip Ratings by Bars, % (about 125 pieces/bar)									Overall Rating
Bar No.	1	5	10	15	20	25	30	35	40	
2011-T3	120	110	110	85						106%
AZ-31C-FS	50	45	45	40	40	40	50	55	55	47%

*Arbitrary chip ratings:

More than 100% - Very fine chips ranging from less than a coil to 1/2 in. long.
100% - Small tight chips up to 2 in. in length.
80% - Tight chips up to 6 in. long; open chips to 3 in. long; mild nuisance.
60% - Tight chips up to 18 in. long; open chips to 9 in. long; small, irregular chip clusters; moderate nuisance
Less than 60% - Very long, tight chips: large diameters and long open coils; long, stringy, balled-up chips; major nuisance.

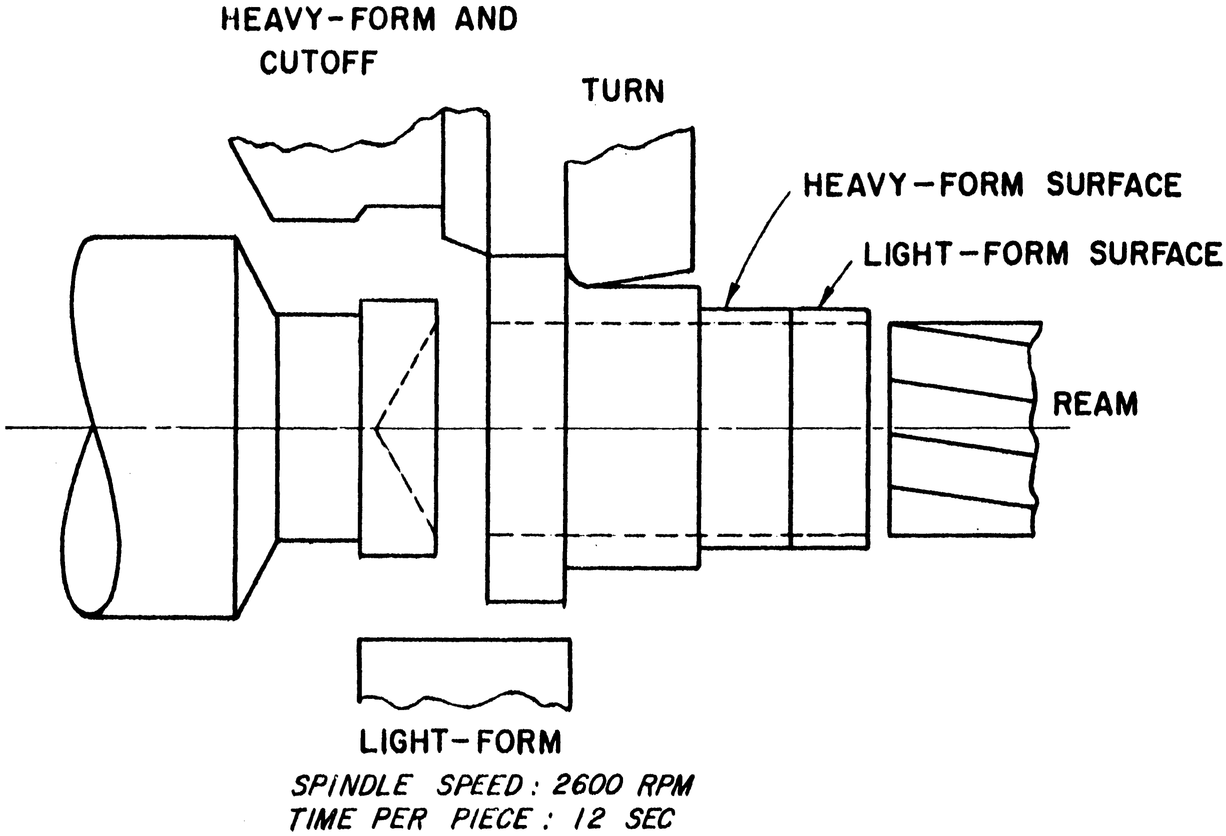
TABLE V

RESIDUAL STRESSES REPRESENTED BY PART DEFORMATION AFTER AXIAL AND RADIAL SLOTTING



Deformation equals A-B (Negative values indicate closing of the part.)

Material	Part No.	Light-Forming A-B	Light-Forming Difference	Heavy-Forming A-B	Heavy-Forming Difference
2011-T3	1	.0025	.0115	-.0016	.0041
	1846	.0140		.0025	
AZ-31C-FS	1	.0193	-.0067	.0165	-.0003
	4969	.0126		.0162	



OPERATIONAL SEQUENCE

1. TURN AND CENTER DRILL
2. DRILL
   PARTIAL CUTOFF AND HEAVY-FORM
   LIGHT-FORM (OUTSIDE SURFACE)
3. REAM
4. CUTOFF AND HEAVY-FORM
5. LIGHT-FORM (INNER SURFACE)
6. STOCK FEED

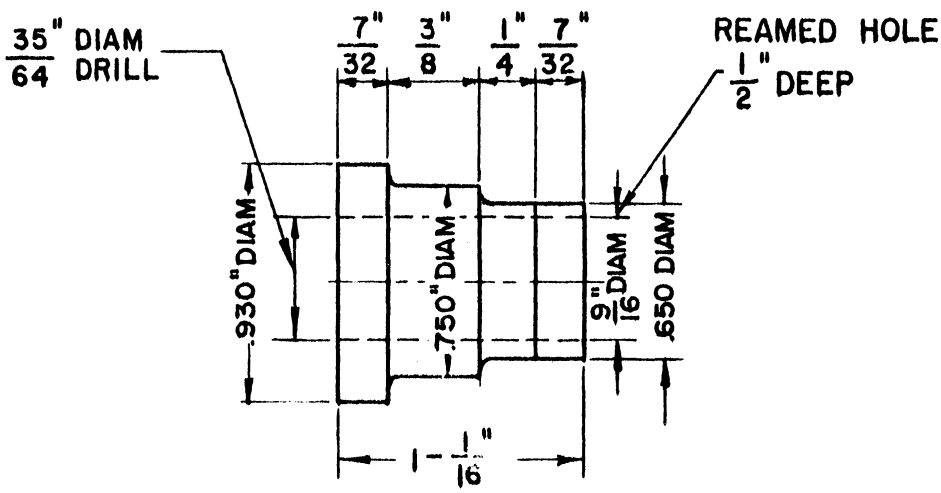


Fig. 1. Part specification and operational sequence on Brown and Sharpe No. 2G, single-spindle automatic screw machine.

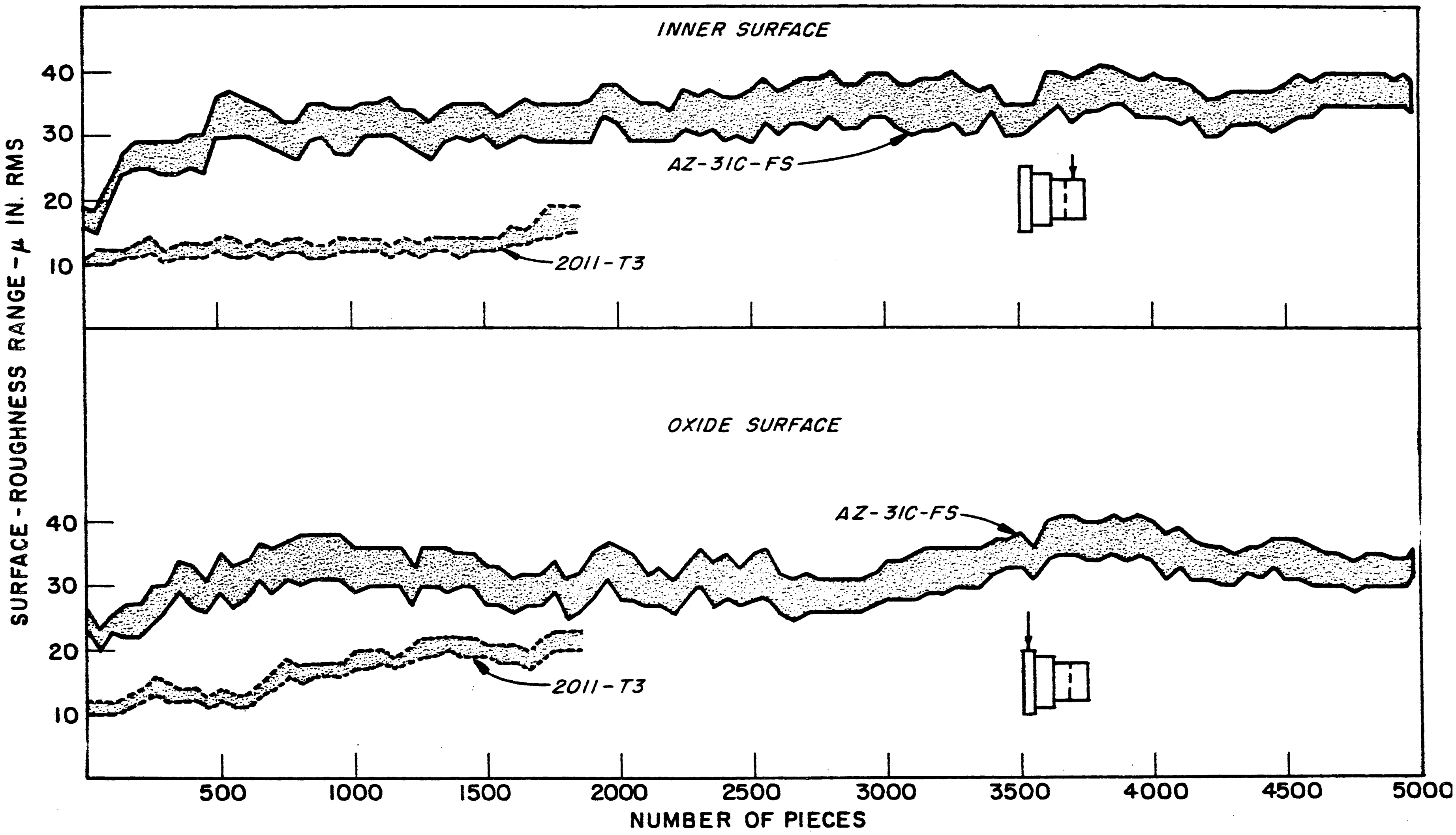


Fig. 2. Light-forming—surface-roughness range vs. number of pieces.

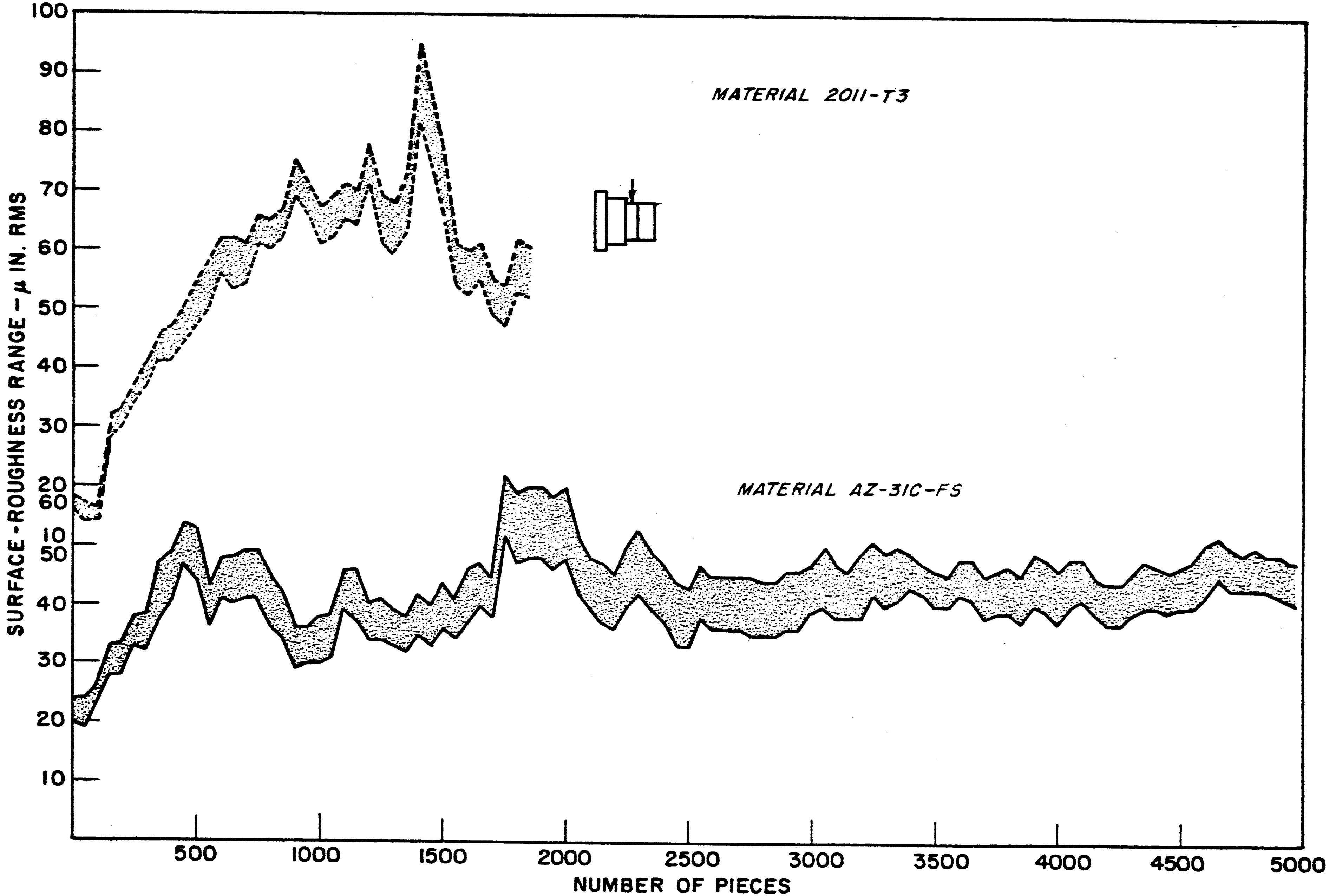


Fig. 3. Heavy-forming—surface-roughness range vs. number of pieces.

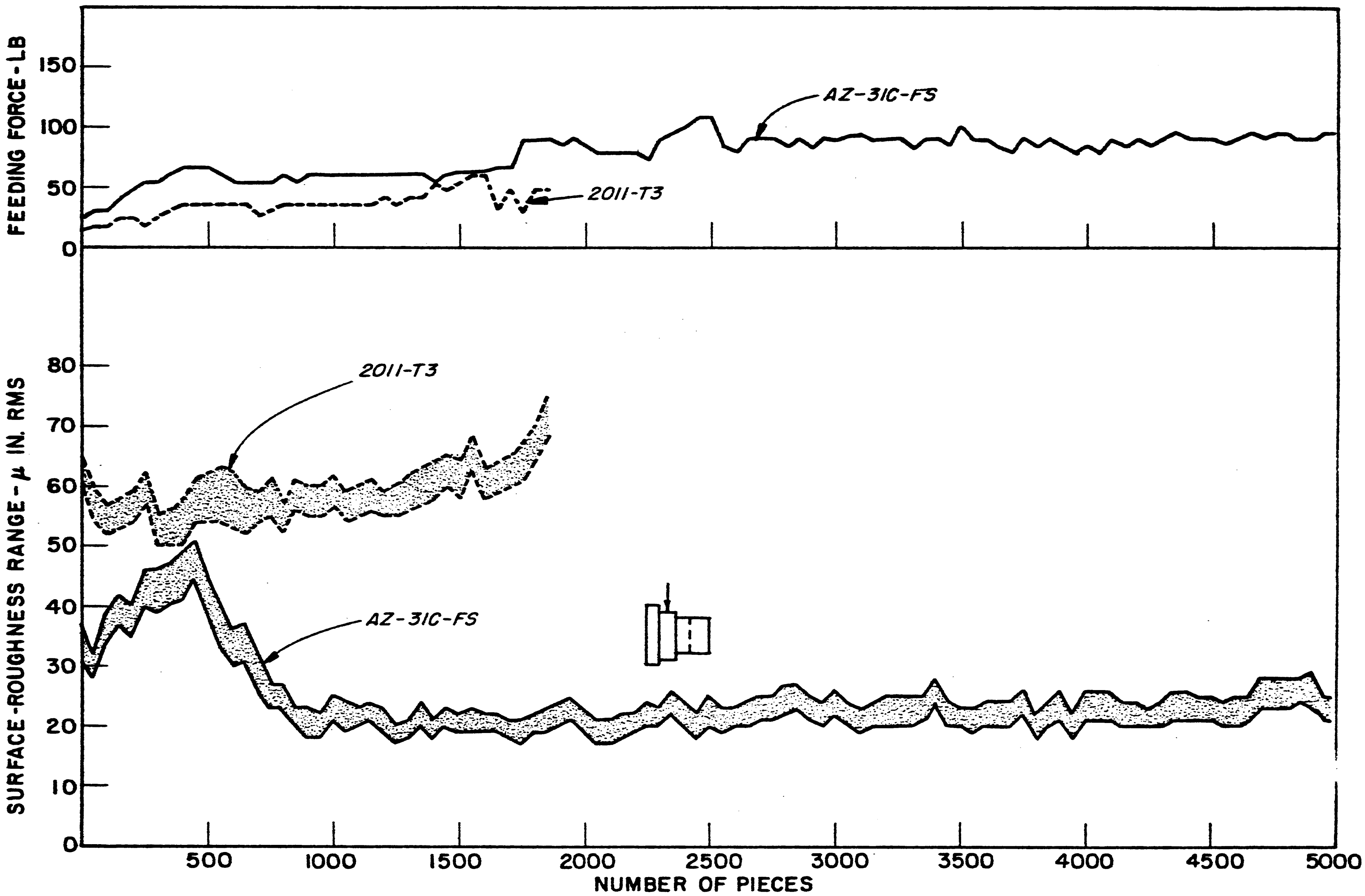


Fig. 4. Turning—surface-roughness range and feeding force vs. number of pieces.

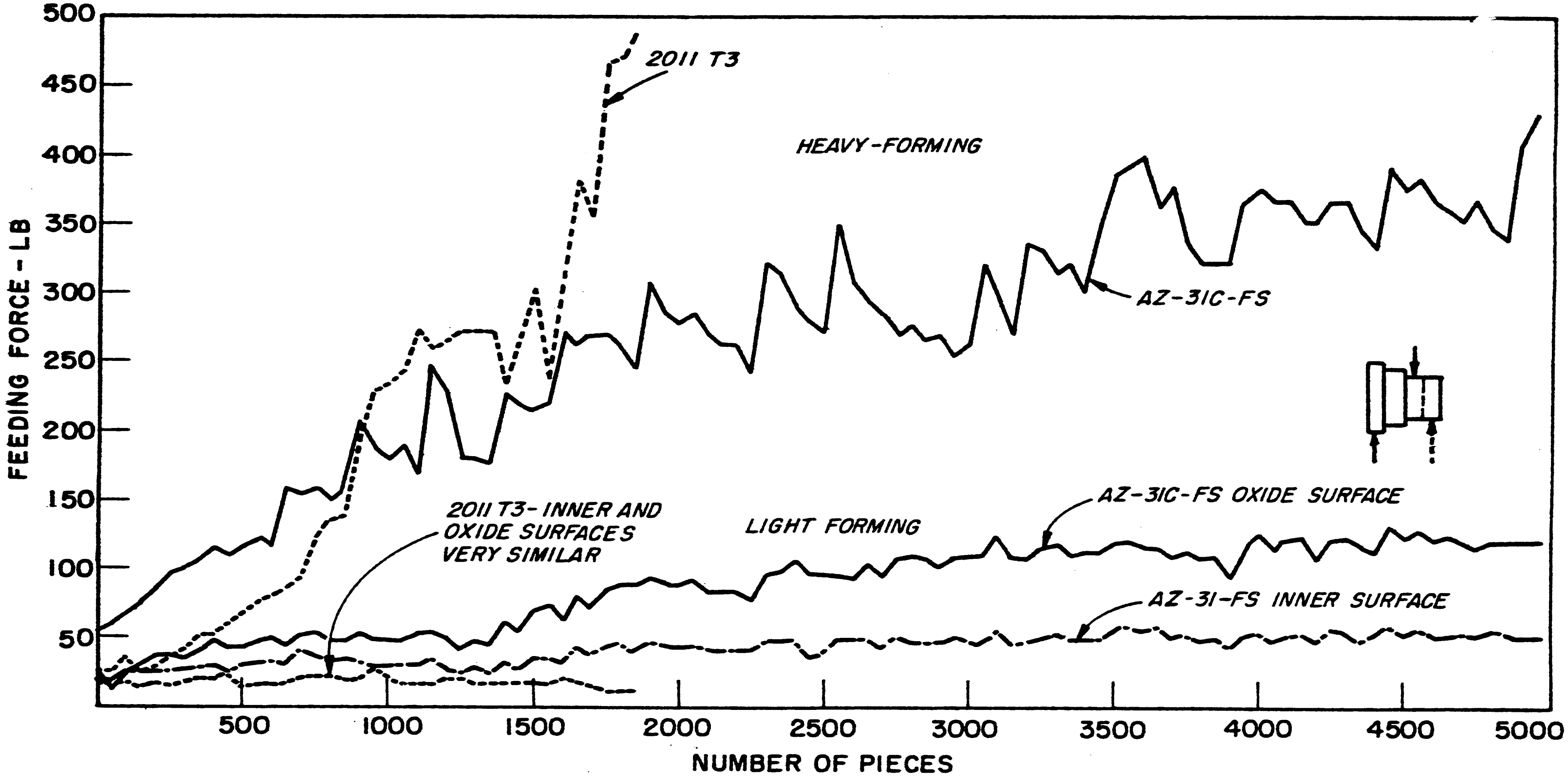


Fig. 5. Light- and heavy-forming—average feeding forces vs. number of pieces.

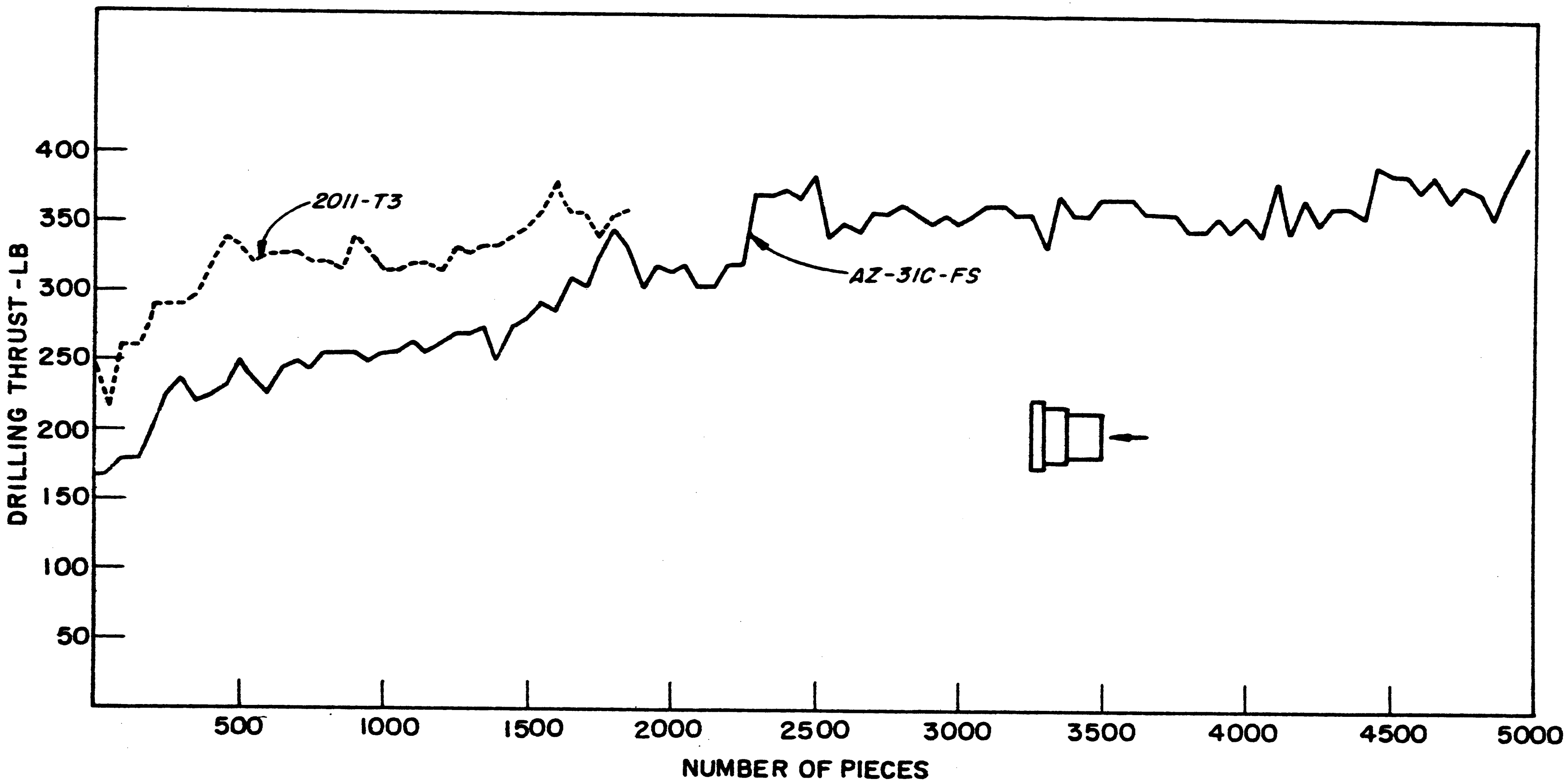


Fig. 6. Drilling thrust forces vs. number of pieces.

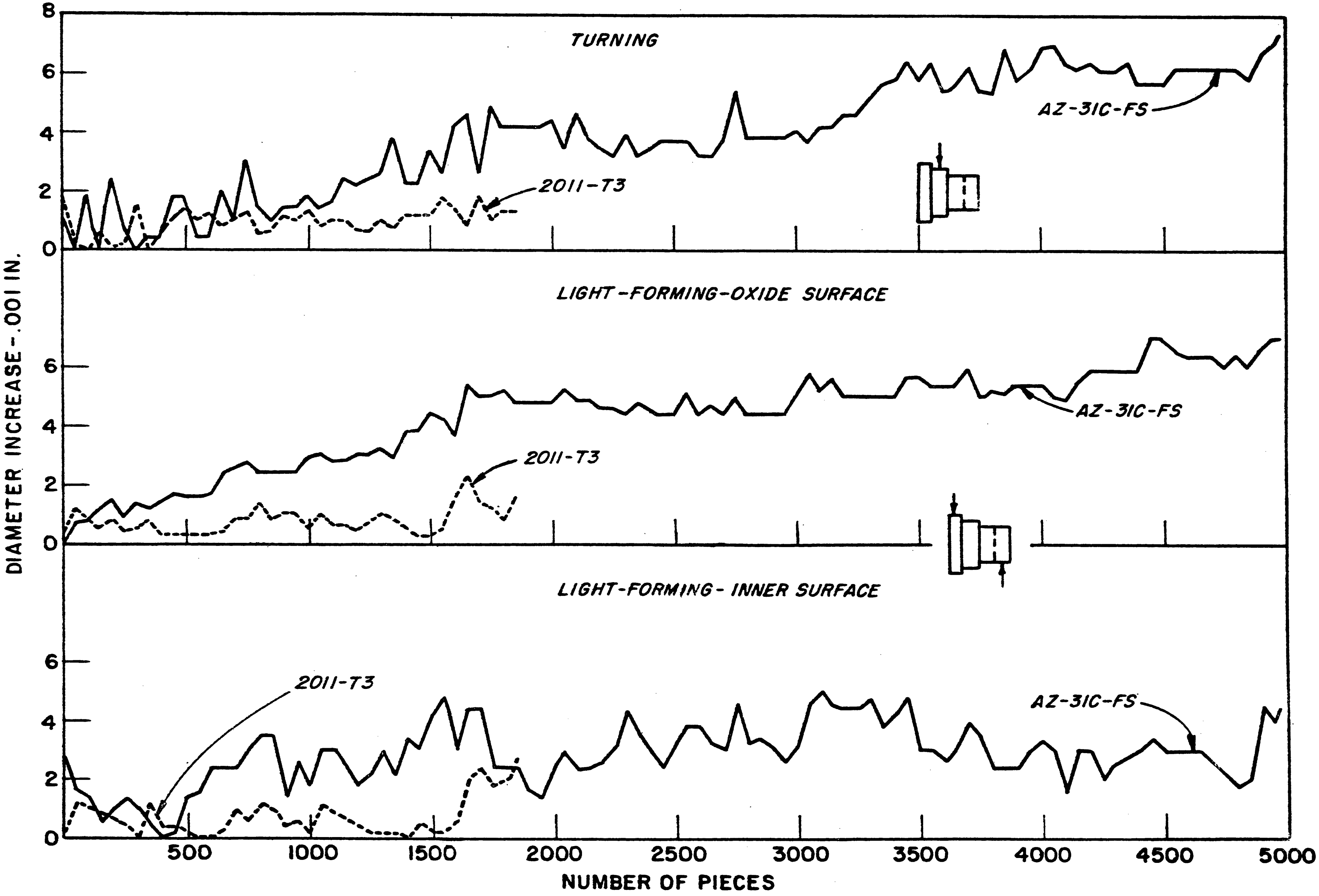


Fig. 7. Light-forming and turning—diameter variations vs. number of pieces.

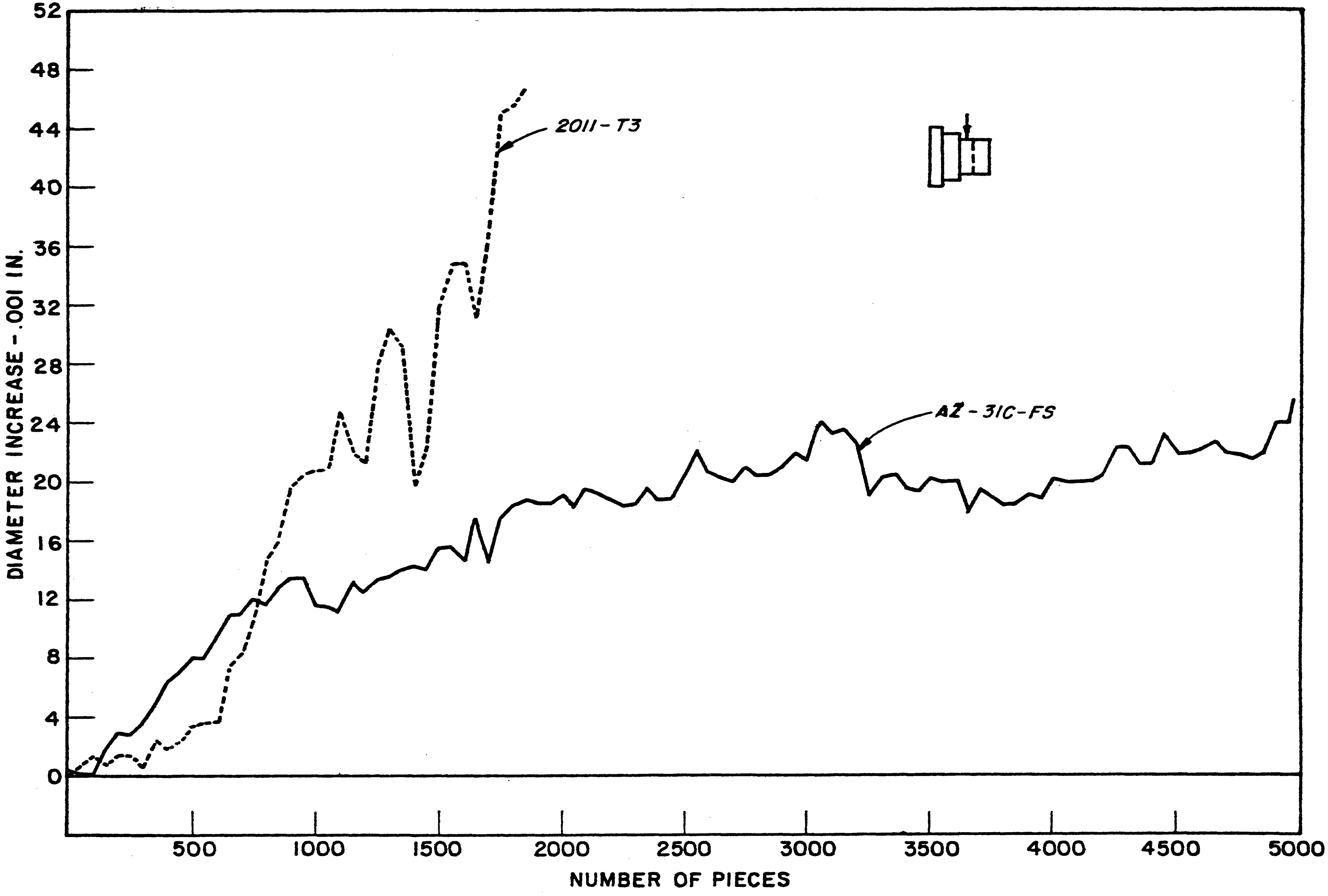


Fig. 8. Heavy-forming—diameter variations vs. number of pieces.

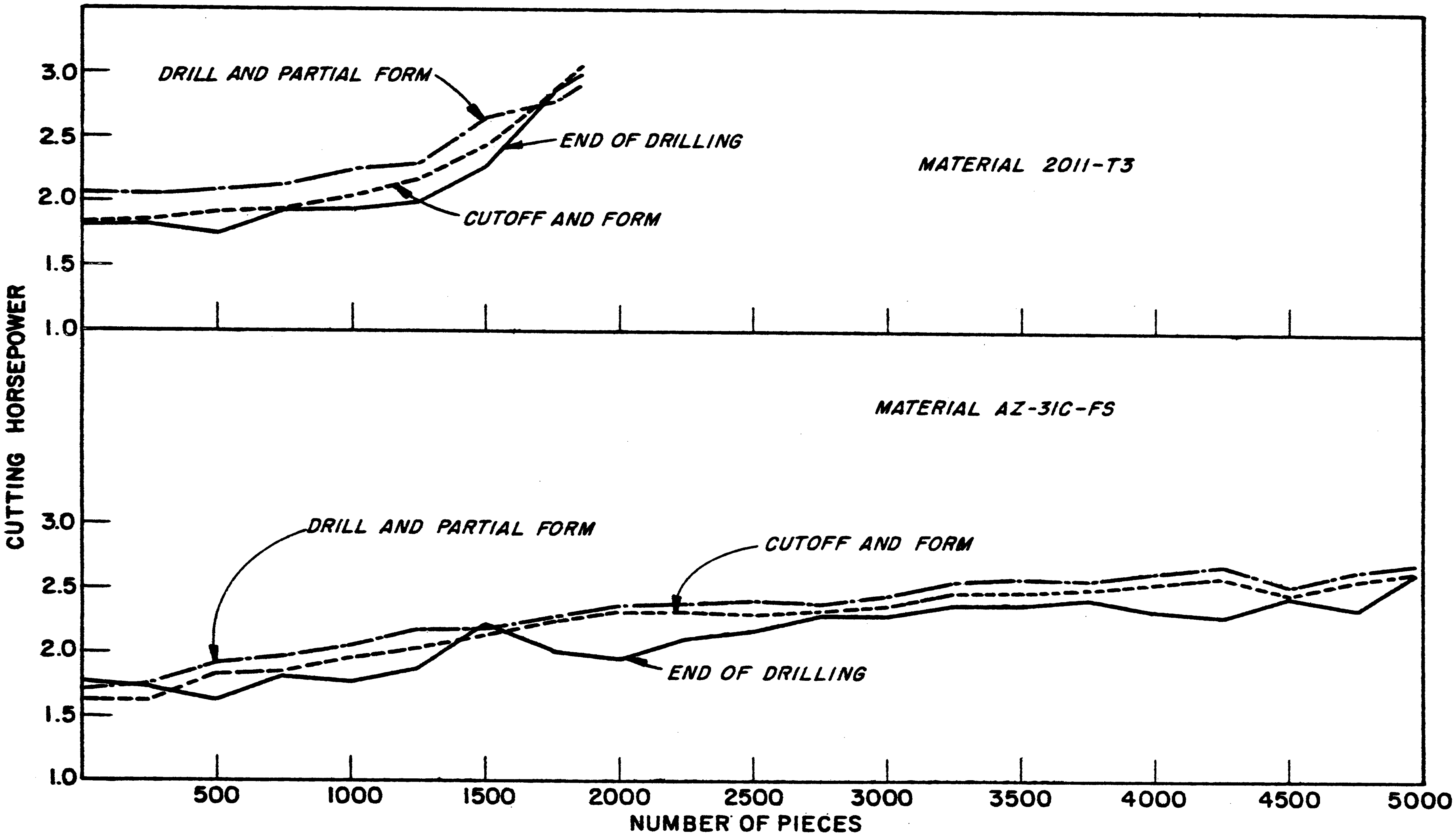


Fig. 9. Cutting horsepower vs. number of pieces.

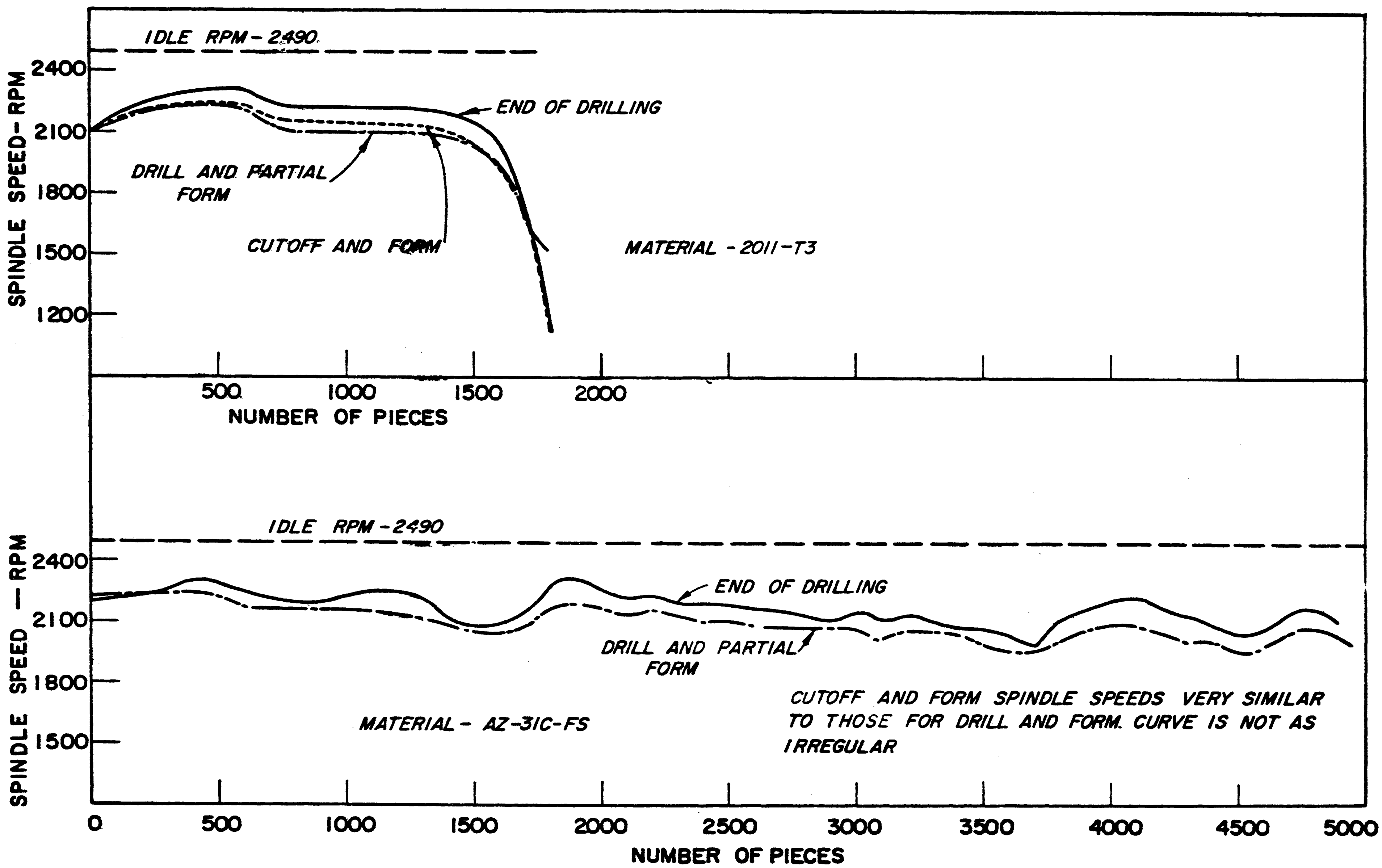


Fig. 10. Spindle-speed variation vs. number of pieces.

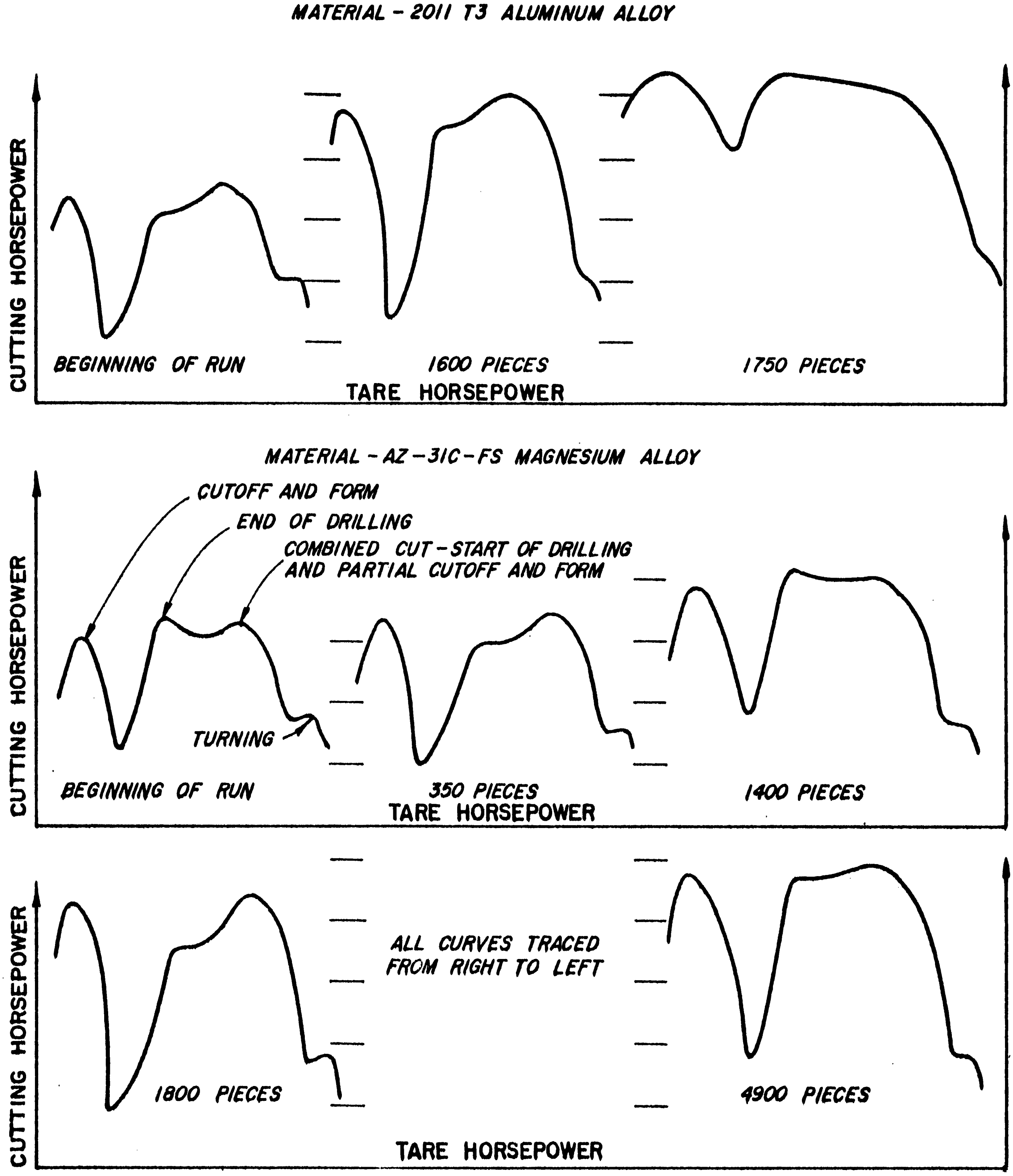


Fig. 11. Typical wattmeter power curves showing power consumed for several machining operations. One full machining cycle is represented. Curves show the effect of form tool and drill wear as power increases with the number of parts. The erratic drilling power requirements shown by the magnesium alloy were caused by chips packing in the flutes of the drill and binding in the hole. The increase in length of the curve in the upper right is due to an increase in cycle time caused by high cutting forces which reduced the spindle speed and eventually stalled the machine.