THE UNIVERSITY OF MICHIGAN RESEARCH INSTITUTE
ANN ARBOR, MICHIGAN

Final Report

MACHINABILITY EVALUATIONS OF TEN LOTS OF 2011-T3 ALLOY

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UMRI Project 2575

REYNOLDS METALS COMPANY
RICHMOND, VIRGINIA

July 1958

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UMR6673

ABSTRACT

This study was a continuation of previous work performed in an automatic screw machine. Feeding-force transducers were added for all operations. These indicated that abnormal size variation was accompanied or caused by corresponding increases in feeding forces. Several prepared material variations plus two competitive alloys were studied in this manner.

INTRODUCTION

The desirability of evaluating materials on the basis of extensive machinability tests, such as might be performed on an automatic screw machine, was demonstrated rather convincingly in Machinability Studies of Eight Prepared-Variable Combinations of 2011-T3 Aluminum Alloy (Univ. of Mich. Eng. Res. Inst. Report 2575-1-P, Ann Arbor, June, 1957.) Several different sharp-tool tests were carried out in that program, but even though the tests did reveal some significant information, no evaluation of the variables could be made with any degree of consistency. The tests on the automatic screw machine, however, were very encouraging. Consistent trends were developed which divided, very sharply in many cases, the desirable from the undisirable variable combinations.

An analysis of the above investigation revealed a need for further study of the 2011-T3 alloy. In addition, it was advisable to make a comparison in machinability of the same alloy produced by other suppliers. This report presents the results of that study.

TEST MATERIALS

A brief description of the various 2011-T3 alloy variable combinations is given in Table I along with the identifying symbols which are used throughout the report. The two materials, 122 and 221, which were not tested in the first series of tests, have been included in this study.

TEST SETUP AND PROCEDURE

Except for improved and more complete instrumentation, the entire test program was basically identical to the one used in the first series of investigations. Reference is made to Univ. of Mich. Eng. Res. Inst. Report 2575-1-P for details of machine setup and test procedure.

Improved instrumentation permitted a much more complete study of tool feeding forces. Specially designed force dynamometers were mounted on the front and rear slides of the Brown and Sharpe screw machine to record the feeding forces on the light- and heavy-form tools. In addition, strain gages were mounted on the follower arm of the turret slide to measure, in particular, turning feeding force and drilling thrust. All forces were recorded on a 4-channel Sanborn recorder. Power and spindle-speed readings were recorded as before.

TABLE I

TEST MATERIALS* - VARIATIONS OF 2011-T3 ALUMINUM ALLOY

Identifying Symbol	Material Description	Lot Number
A	Alcoa, standard stock	-
G	German, standard stock	-
T_1	High silicon	E 807-A
T_2	Heat-treated, drawn (standard)	E 808-A
T_3	Heat-treated, centerless ground, drawn	E 809-A
T_4	Centerless ground, heat-treated, drawn	E 810-A
T_5	Poor spray quench	E 811-A
T_6	Good dip quench	E 812-A
122	Low copper, high heat-treat Temperature, high reduction	E 740
221	High copper, high heat-treat Temperature, low reduction	E 738

*All Reynolds materials except materials A and G.

One operation, chasing, and one inspection step, tool inspection on the machine at intervals during a test, were eliminated. It was felt that the threading operation did not reveal enough significant information to distinguish between the materials, and that the difficulty of making accurate tool-wear measurements on the machine gave rise to inconsistent results which had little value.

With the above exceptions, no other changes were made in the test procedure.

TEST RESULTS

The test results on all materials are summarized in Table III. Tables IV and V show the tool-wear and loading characteristics. Individual plots of surface roughness, diameter variations, feeding forces, cutting horsepower, and spindle speeds for each material are summarized in Figs. 1 through 24.

A comparison of the results indicates that the "T" materials, as a rule, did not behave as well as the others. They gave rise, generally, to greater tool wear, higher feeding forces, and higher power requirements. Surface quality, on the other hand, was comparable for all tools and in many cases was even better on the T materials, although not as many parts were produced. Of the eleven runs made on the ten materials (including a rerun on T_3), only materials A and 122 ran for 20 bars—approximately 2500 pieces—without stalling the machine. Material 122 gave the better overall results.

The three standard materials, A, G, and T_2, showed differences in behavior, but the differences were not consistent. Material A, for example, permitted the longest run but produced the poorest surface quality; material T_2 gave the best overall surface quality in spite of greater tool wear for 73% as many parts; material G had the most uniform surface quality, appeared to promote less tool wear, but required more power for forming and drilling, and produced only 64% as many pieces before stalling the machine. Additional observations are made in the brief summaries covering each operation.

LIGHT-FORMING

Figures 1 through 7 and Figs. 13 and 14 represent the results of the light-forming operation on the oxide and inner surfaces.

Light-forming on the inner surface produced the most consistent surface quality among all materials, although the materials can be grouped into two surface-behavior patterns. One group—materials T_1 through T_5—showed an improving surface quality in the early stages of a run until stable values were reached. The other materials started out with good surfaces which were maintained throughout the entire range of pieces produced with only slight increases in roughness.

Light-forming of the oxide surface produced much more erratic behavior, and in all but two cases resulted in much higher average surface roughness and feeding force values, even though the initial values were very similar to those produced on the inner surface. The difference in average levels can be attributed mainly to the higher rate of tool wear in this operation. It is interesting to note that the average surface quality of the T materials, with the exception of T_3, is as good or better than the average surface quality of the other materials even though the tool wear was as much as 250% higher. More burnishing was evident, however, on those materials, which gave rise to greater tool wear.

Materials T_2 and 221, with emulsion, gave the best average surface quality, comparable to that produced on the inner surface in each case. The effect of the oxide on the 221 material was more pronounced, however, when oil was used as the cutting fluid. The surface roughness more than doubled early in the run.

The generally poor results shown by materials T_3 and T_4 must, in some way, be attributed to the centerless grinding operation during fabrication. Apparently, not only the sequence of grinding is important, but the process itself appears to be undesirable because it contributes to a surface condition which promotes rough tool wear and gives rise to the poor results. In comparison with material T_4, material T_3, which was ground after heat treatment and before cold-drawing, had the most rapid changes in surface quality, dimensional stability, and feeding forces on the oxide surface, and gave an equivalent amount of tool wear for only half as many parts. Material T_4, which was ground before heat treatment, had the most erratic behavior on the oxide surface as well as the greatest diameter variations on the inner surface among all materials. The original bar surfaces were examined under a binocular microscope and compared with other bar surfaces, but no noticeable differences in appearance were noted. Several reasons could be given for the poor behavior of the ground materials, but further studies would have to be made to establish the cause definitely.

HEAVY-FORMING

The heavy-forming surface-roughness results are shown in Figs. 1 through 5. In general, those materials which gave poor and erratic surface quality in light-forming of the oxide surface also behaved badly in heavy-forming. In most cases, the surface got progressively worse with the number of pieces produced, with materials A, 122, 221 oil, and T_3 showing the greatest variations.

Some of the surface-roughness results, as measured with the profilometer, are rather misleading if taken entirely at their face value, for the profilometer does not always reveal the true character of a surface. It may be noted in Figs. 1 through 5 that some of the materials show an increasing surface roughness to a maximum, beyond which the surface appears to improve. Visual inspection, however, reveals that in practically all cases the sharp changes in surface roughness, predicted by the profilometer, were accompanied by the appearance of burnished rings, and that the burnishing became progressively worse as the test continued even though the surface-roughness values may have dropped. On some of the materials the burnished rings appeared after only a few hundred pieces, and only the surfaces of materials G and 122 appeared good throughout most of the run. These materials gave rise to the lowest feeding forces. On the other hand, material T_2 had the best average surface quality as recorded by the profilometer, but the visual appearance was inferior when compared with the surface produced on material G, for example. It was better than that produced on material A, however.

There did not appear to be a consistent relationship between tool wear and surface quality. For example, materials, G, T_1, and T_5 had the same surface roughness but the tool wear was .0029 in., .0107 in., and .0051 in., respectively. T_1 and T_5 produced about the same number of pieces, while 40% more pieces were produced from material G.

Tool wear had much more effect upon dimensional stability and feeding forces. Figures 8 and 9, Figs. 15 and 16, and Tables II and III show these effects.

In general, the greater the tool wear the higher the feeding forces, and the greater the variations in formed diameter. There were, however, some differences in behavior among the various materials. For example, T_6 gave rise to .0084-in. wear on the form tool, requiring a maximum feeding force of 505 lb. Material A, however, required a maximum feeding force of only 180 lb for the same amount of wear, even though the initial (sharp tool) force was 45% higher than the initial force recorded for the T_6 material.

TABLE II

SUMMARY OF TOOL WEAR, DIAMETER VARIATIONS, AND FEEDING FORCES FOR HEAVY-FORMING OPERATION

Material	No. of Pieces	Tool Wear, in.	Diameter Range, in.	Feeding Force Range, lb
A	2457	.0086	.0276	16-180
G	1577	.0029	.0143	34-86
122	2451	.0050	.0135	26-54
221 Oil	1964	.0105	.0368	23-399
221 Em	1218	.0033	.0172	21-116
T_1	1207	.0107	.0488	34-414
T_2	1793	.0098	.0445	17-286
T_3	1033	.0093	.0344	21-315
T_4	2080	.0090	.0445	15-253
T_5	1194	.0051	.0200	26-177
T_6	2002	.0084	.0496	11-505

These discrepancies in forces can be accounted for, at least partly by the condition of the cutting tool. Although two tools may have similar flank-wear values, one wear pattern may show much more severe breakdown of the contact area than the other. Rough wear was typical of the T materials. The differences are noted in Tables IV and V.

A very small part of the increase or growth in diameter is a result of the actual wearing away of the flank, but the greatest change, by far, is due to the deflections in machine components brought about by the increased feeding forces. As mentioned previously, the forces had little, if any, effect upon measured surface roughness, although burnishing was less pronounced when the forces were smaller.

TURNING

The turned-surface quality and the diameter and feeding-force variations are shown in Figs. 1 through 5, and Figs. 10 through 12, respectively.

With the exception of materials 221 oil and emulsion, T_3, and T_4, which gave very erratic results not only in measured values but in appearance, the turned-surface quality was fairly consistent throughout the runs on most of the materials, although there were some differences in levels as recorded by the profilometer. Materials G and T_1 gave excellent turned surface quality.

The use of oil as a cutting fluid on the 221 material produced a reversal in surface-finish behavior. With emulsion, the surface quality, though poor,

followed a trend similar to that displayed by most of the other materials: it improved with the number of pieces produced. With oil, however, the surface was generally bad and highly burnished, and got worse as the run progressed.

Loss of dimensional stability was more pronounced on the T materials, with material T_3 showing a growth in turned diameter of .008 in. in 1033 pieces. Tool wear and tool feeding forces were generally higher, and undoubtedly account for the rapid loss in accuracy. Materials A, G, 122, and 221 had the most consistent forces throughout the run, but the turned diameters were erratic even though there was no rapid growth in size. Some differences in behavior from one bar to the next were noted on material A, and this may account for the very pronounced turned-diameter variations between 500 and 1000 pieces.

DRILLING

In general, drilling performance was one of the important factors in determining the number of parts which could be produced before stalling of the machine occurred. This is discussed more fully in the section on Spindle Speeds and Power. The only other recorded results—drilling thrust—are shown plotted in Figs. 17 and 18.

The results show a considerable range in thrust-force behavior. Generally speaking, the initial thrust-force values were similar among the T materials, but the behavior patterns differed rather extensively. Material T_2 showed the most rapid and most drastic change in thrust force, rising from an initial value of approximately 180 lb to over 600 lb in a range of 200 pieces. The erratic force behavior on the T materials is undoubtedly associated with drill wear, for as can be noted in Tables IV and V, the wear was more severe on these materials, particularly with respect to corner and edge breakdown.

The two materials that ran for 20 bars, A and 122, had the lowest and most consistent thrust forces. The forces rose only 40 and 60%, respectively, in 2450 pieces. This compares with an increase of 285% in 1790 pieces on material T_2. Drill corner damage was much more severe on the latter material, however. On the other hand, material G, which actually showed the least severe drill wear, had the highest initial thrust forces. These were almost three times as high as those on the other materials, although there was an increase in force of only 30% in 1575 pieces.

Formal measurements of drilled-hole diameters and of surface roughness were not made, but random checks along with visual inspection of the surfaces did show some minor differences among the various materials, particularly in surface-finish behavior. Hole size was quite good and was fairly consistent from one material to the next with the exception of the early stages of the run on material A. Excessively oversize holes were produced for the first several hundred pieces before good dimensional stability was reached.

The drilled surface qualtiy was not exceptional on any of the materials. Material G had the best and most consistent surface over the entire range of parts, while material 122 had a rather rough and torn surface from beginning to end. Most of the other materials started out with fair to good surfaces in the beginning which got progressively worse as the run continued. The use of oil on material 221 produced a highly burnished surface in contrast to a dull, fairly rough surface produced with the emulsion.

REAMING

No formal measurements were made of the reaming operation. Feeding forces were recorded, but the changes, if any, were so small that they were difficult to pick up.

Like the drilled holes, the reamed holes in material A were oversize in the beginning of the run but improved with the number of pieces. All other materials produced holes which were tight on the reamers during spot checks for size.

Surface-finish behavior was, in some respects, just opposite to that shown in drilling. Material 122, which gave poor drilled surface quality, gave a good and a consistent reamed finish throughout the run of parts. Also, the materials which showed a continuous decrease in drilled surface quality exhibited just the reverse in reaming. The reamed surface improved as the number of pieces increased. Material G, which had the best and most consistent drilled finish, was very erratic in reaming and did not show as good a surface as most of the other materials.

The reamers were inspected for wear, but no significant differences were found among the results. Generally, only some rounding of the chamfered corners was noted.

CUTOFF

Outside of measurements of tool wear, the only observations of the cutoff operation were made visually. As may be seen in Tables IV and V, tool wear was most severe on the T materials, with much more pronounced edge and corner breakdown. The surface quality was similar in appearance among all materials, although there were slight differences in behavior. With the exception of 221 emulsion and T_2, all materials produced fair to good surfaces in the beginning. However, these surfaces got worse as the runs progressed and then began to improve near the end. The cutoff surfaces on material 221 emulsion and T_2 were consistently bad throughout the range of parts produced.

SPINDLE SPEEDS AND POWER

The curves plotted in Figs. 19 through 24 represent the horsepower requirements and the spindle speeds as they change with tool wear on two critical operations—drilling and forming. Turning horsepower is also plotted in Figs. 19 through 21. The drilling results represent the values of horsepower and spindle speed at the point where the drill has just reached the full length of the hole, or, in the case of forming, the results represent the horsepower and spindle speed during heavy-forming to size.

The drilling results are of particular interest, since this operation contributed most to the stalling of the machine on the short runs. Drilling behavior fell into two general categories. In one case, the drilling horsepower increased as the length of the hole increased, while in the other there was little, if any, increase in power from the start to the end of the drilling operation. Most of the materials fell somewhere in between these two extremes. Materials A and 122 required the least power and had the lowest rate of increase. Material A was also the only material which required less horsepower for drilling than for forming under the given cutting conditions. Both of these materials ran for the full test of 20 bars.

To illustrate differences in material behavior, a fourth power curve is plotted in Fig. 19 for material T_1 and in Fig. 20 for material A. In addition actual traces of the power curves as recorded by the wattmeter are shown in Fig. 28. The extra curve in Figs. 19 and 20 represents the power consumed during a combination cut including the beginning of drilling and partial forming. Therefore, the horsepower for the combination cut should be greater than the horsepower for the end of drilling as long as there is no great increase in drilling power requirements with an increase in hole length. It may be noted in Figs. 20 and 28, that, for material A, the end of drilling horsepower is lower than the horsepower for the combination cut over the entire range of parts. This was also a typical pattern on materials 122 and T_6. The speed curves in Figs. 23 and 24 also substantiate that drilling was less critical on these materials, because the greatest drop in speed was contributed by the combined cut. (Materials A and 122 have a speed curve plotted only for that operation which contributed most to spindle speed slowdown.)

The power and speed curves for material T_1 in Figs. 19 and 22, and the wattmeter traces in Fig. 28, represent the second type of behavior into which most of the materials fell. Initially the end of drilling horsepower was lower than the horsepower for the combined cut. However, as the test progressed, the drilling horsepower increased more and more with the length of the hole until the end of drilling horsepower was greater than that required for the combined cut at the start of the hole. The speed curves illustrate the same type of behavior. Whether the changes occurred as a result of tool wear or whether they occurred as a result of residual stresses (Table VII) induced during fabrication or by the form tools requires further study. In any event, the increase in horsepower, coupled with the drive-motor characteristics, was sufficient either to stall the machine, or to slow it down so much that continued running was inpractical.

CHIP FORMATION

The chip ratings given in Table VI are based upon arbitrary ratings assigned to chips of certain shape and size as described at the bottom of the table. The ratings given for every fifth bar are average values for the combined chips from all operations and should indicate the changes in behavior as tool wear increases. The composite rating for the material is an average of the individual bar ratings.

By far the best chips were produced from material G. All the chips were very finely broken up and usually of one coil or less in length. Most of the other materials had at least some tendency for long or stringy chips in drilling, turning, or cutoff. The forming chips were usually not troublesome.

RESIDUAL STRESSES IN MACHINED PARTS

Table VII is included in this report to indicate not only that residual stresses exist in the machined parts, but also that they can be either predominantly compressive or tensile in nature. No definite conclusions can be based upon this information, for the stress studies are far from complete. Additional work would be required before any real value can be placed upon the results, but it is believed that these stresses do have at least some significance in the machinability ratings of the various materials.

The values in Table VII represent the difference between two scribed gage marks before and after axial and radial sawing of the two rings representing the light-formed and heavy-formed surfaces on the machined part. Some of the values are negative, indicating a closing of the part, while the positive values indicate that the rings opened up after sawing. The distribution of stresses is not known, however.

TRACES OF FEEDING AND THRUST FORCES

Figures 25, 26, and 27 show actual traces of the feeding forces on the turn and form tools, and drilling thrust. They serve to illustrate the changes that take place during a run, as well as the differences in behavior among the various materials. The effects of surface oxides can also be noted, particularly in the light-forming operation.

TABLE VI

CHIP-FORMATION SUMMARY

Material	Chip Ratings by Number of Bars* (120 pcs/bar)					Overall Rating, %
	Bar No. 1, %	Bar No. 5, %	Bar No. 10, %	Bar No. 15, %	Bar No. 20, %	
A	80	85	95	95	90	89
G	120	120	120			120
122	95	90	95	100	105	97
221 Oil	95	100	105	105		101
221 Em.	100	90	85			92
T_1	95	90	100			95
T_2	90	80	60			77
T_3	85	80				82
T_4	85	95	65			81
T_5	85	90	80			85
T_6	70	95	65	70		75

*Chip Ratings

More than 100% - very fine and well-broken chips.

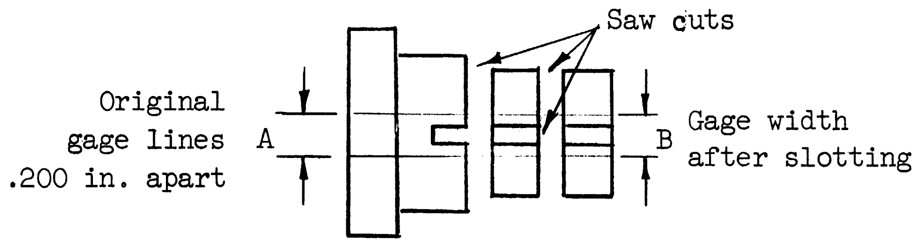
100% - tight coils to 1 in. long - very short open coils.

80% - tight coils to 6 in. long - short open coils to 3 in. long - very short loose coils - minor nuisance.

60% - tight coils to 12 in. long - open coils to 6 in. long - large loose coils to 3 in. long - moderate nuisance.

Less than 60% - very long tight coils - long open coils and stringy balled-up chips - major nuisance.

TABLE VII
RESIDUAL STRESSES IN TEST PARTS ON BASIS OF DEFORMATION
AFTER AXIAL AND RADIAL SLOTTING



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

Material, pieces	Light-Forming			Heavy-Forming		
	First Piece B-A, in.	Last Piece B-A, in.	Difference	First Piece B-A, in.	Last Piece B-A, in.	Difference
A, 2457	.0043	.0105	.0062	.0033	.0043	.0010
G, 1577	.0052	.0109	.0057	.0016	.0092	.0075
122, 2451	.0013	.0029	.0016	.0014	-.0063	-.0077
221 Oil, 1964	.0004	.0070	.0066	.0010	-.0092	-.0102
221 Em, 1218	.0028	.0121	.0093	.0053	.0119	.0066
T_1, 1207	.0010	.0236	.0226	.0002	.0044	.0042
T_2, 1793	.0004	.0184	.0180	-.0010	.0180	.0190
T_3, 1033	.0016	.0252	.0236	.0018	.0257	.0239
T_4, 2080	.0034	-.0090	-.0124	.0032	.0106	.0074
T_5, 1194	.0002	.0148	.0146	.0020	.0154	.0134
T_6, 2002	.0018	.0050	.0032	.0022	-.0076	-.0098

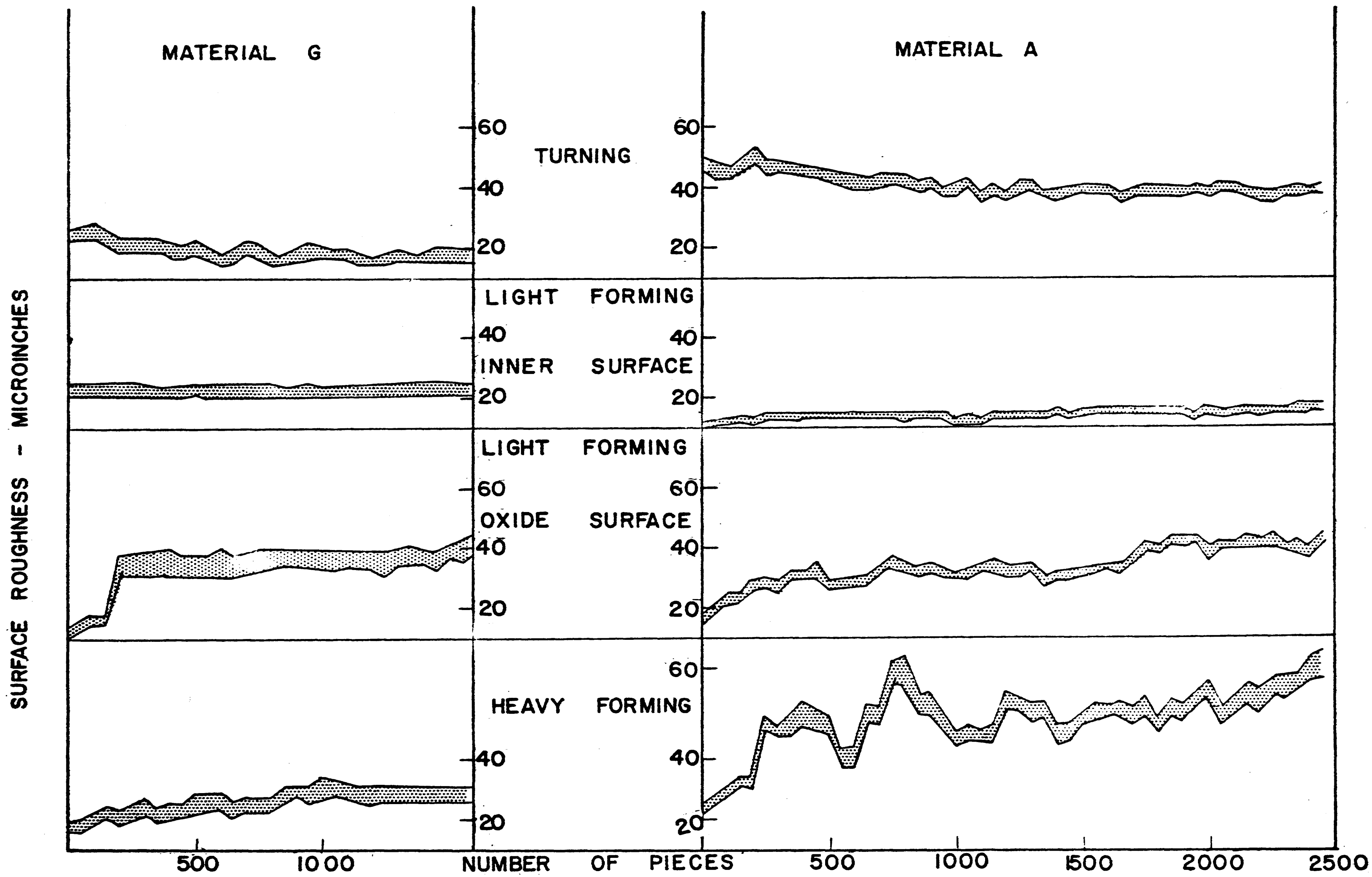


Fig. 1. Divisions for number of pieces under turning and light-forming.

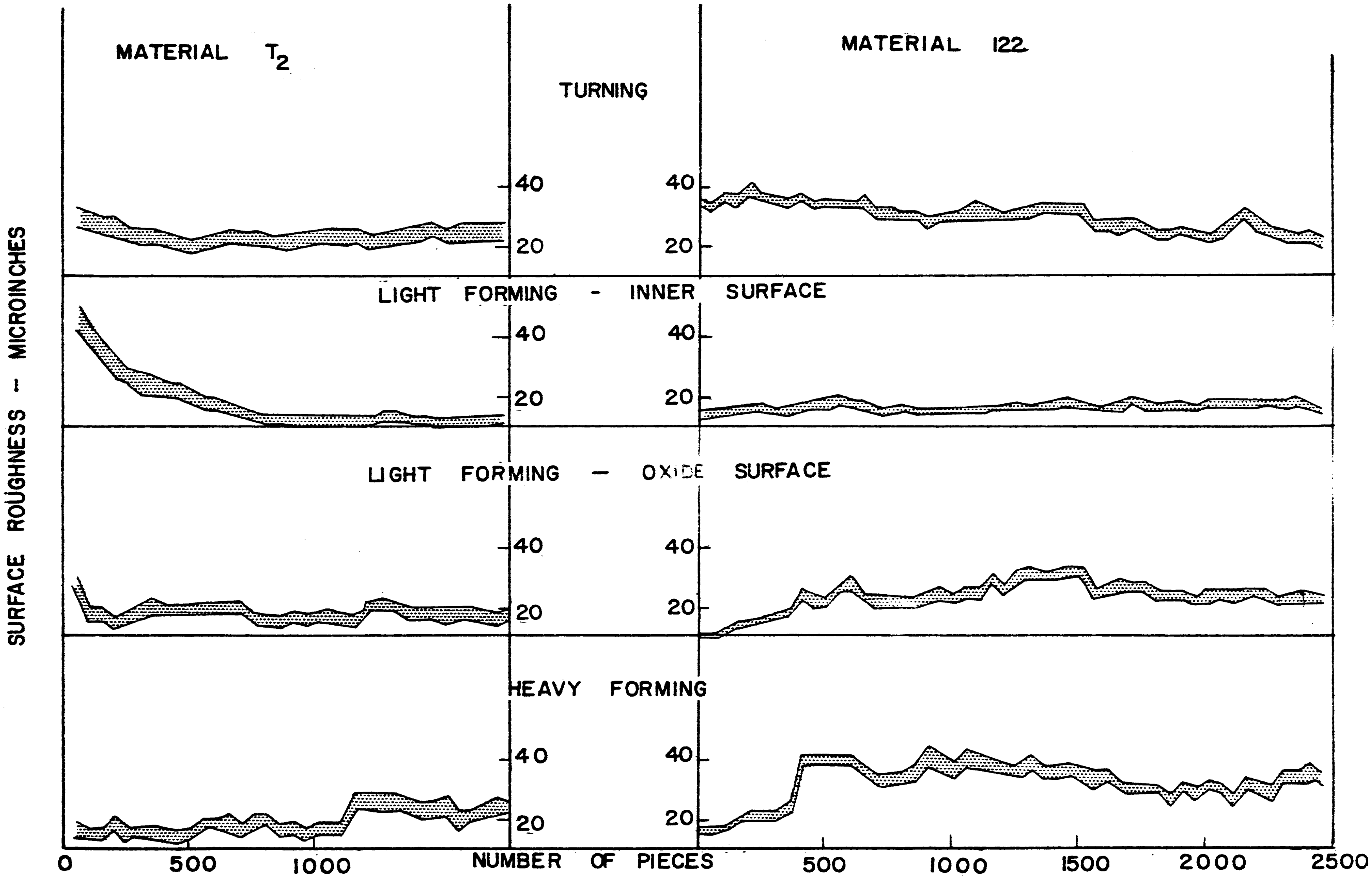


Fig. 3. Divisions for number of pieces under turning and light-forming.

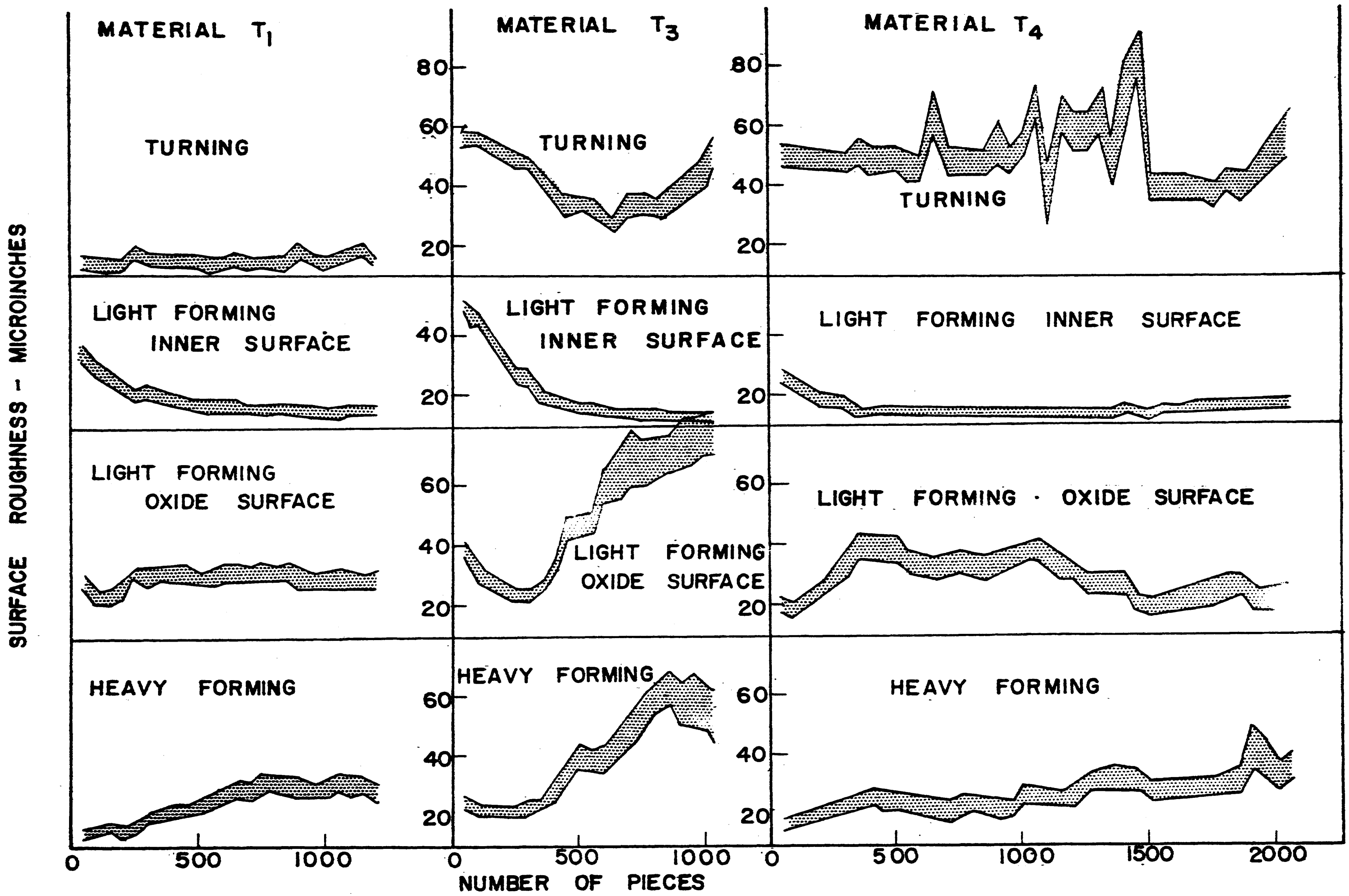


Fig. 4. Divisions for number of pieces under turning and light-forming.

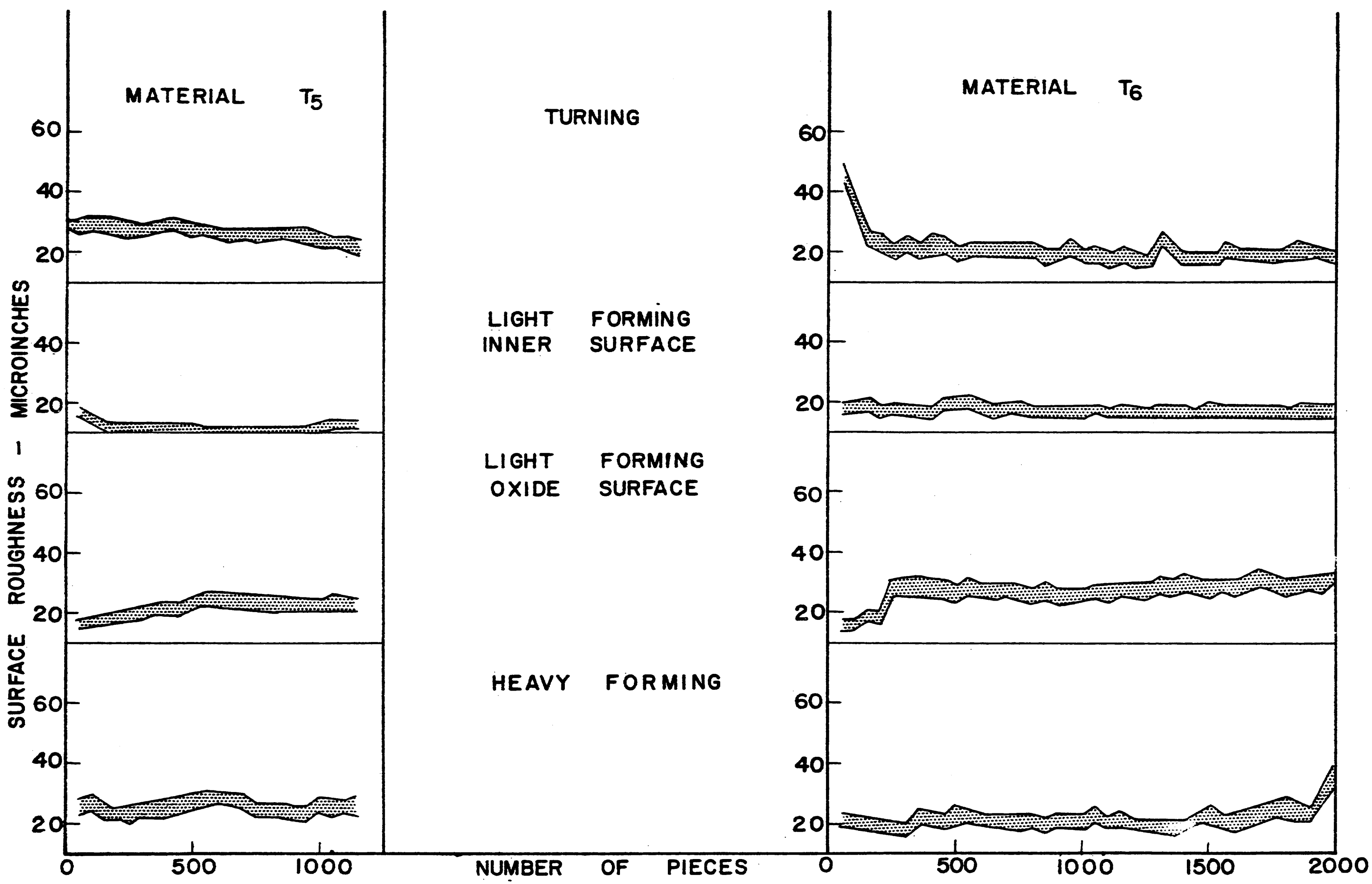


Fig. 5. Divisions for number of pieces under turning and light-forming.

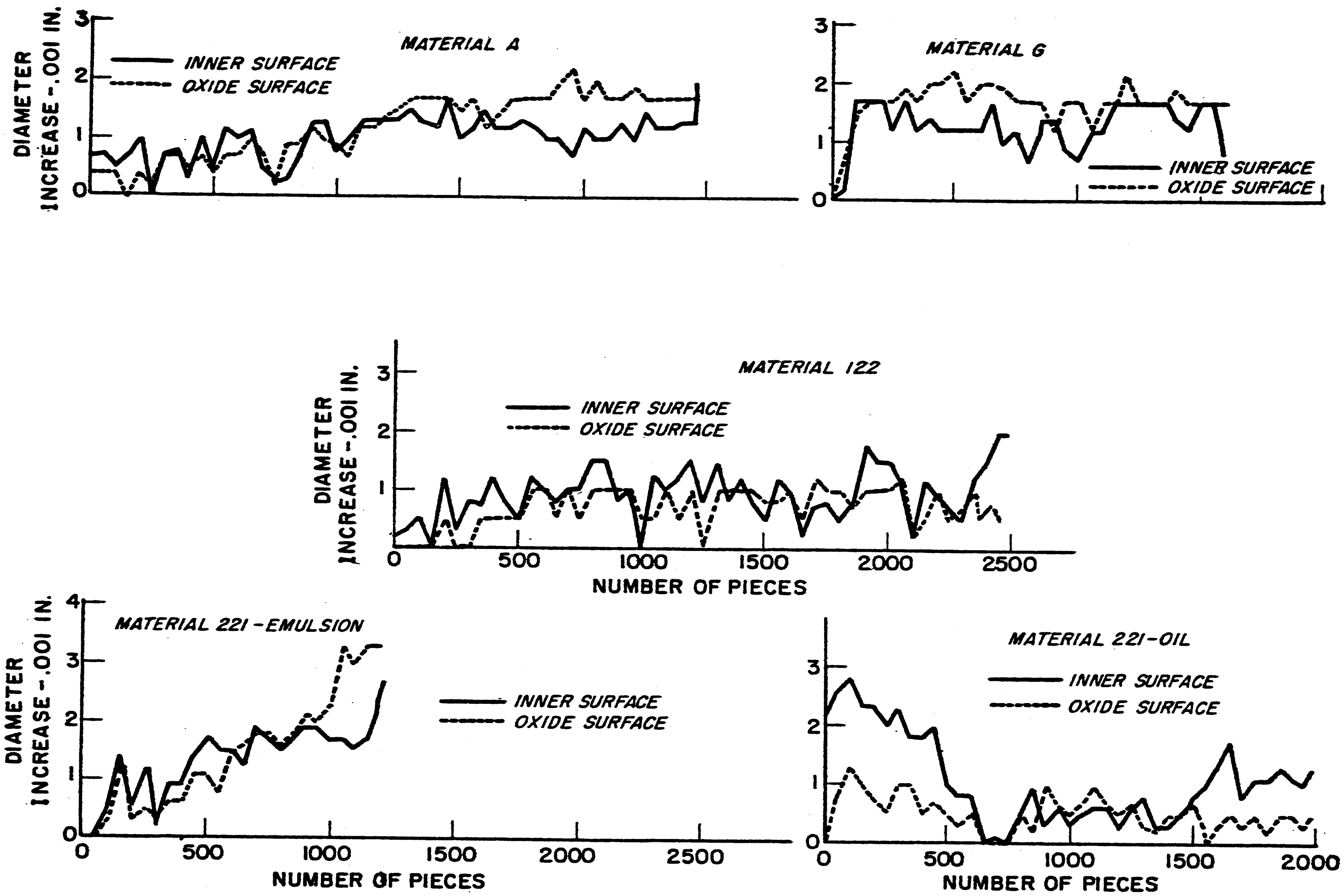


Fig. 6. Light-forming diameter variations vs. number of pieces.

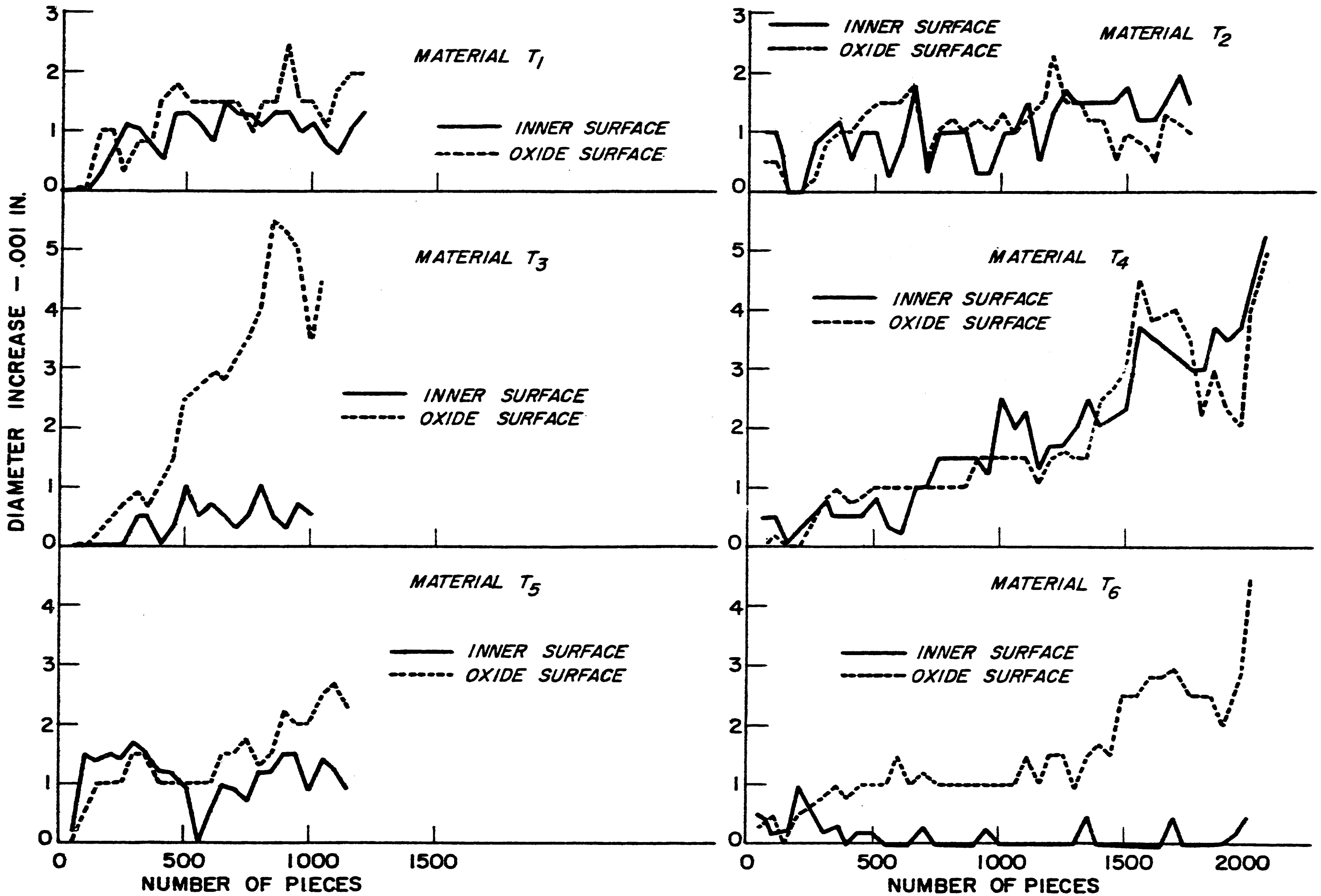


Fig. 7. Light-forming diameter variations vs. number of pieces.

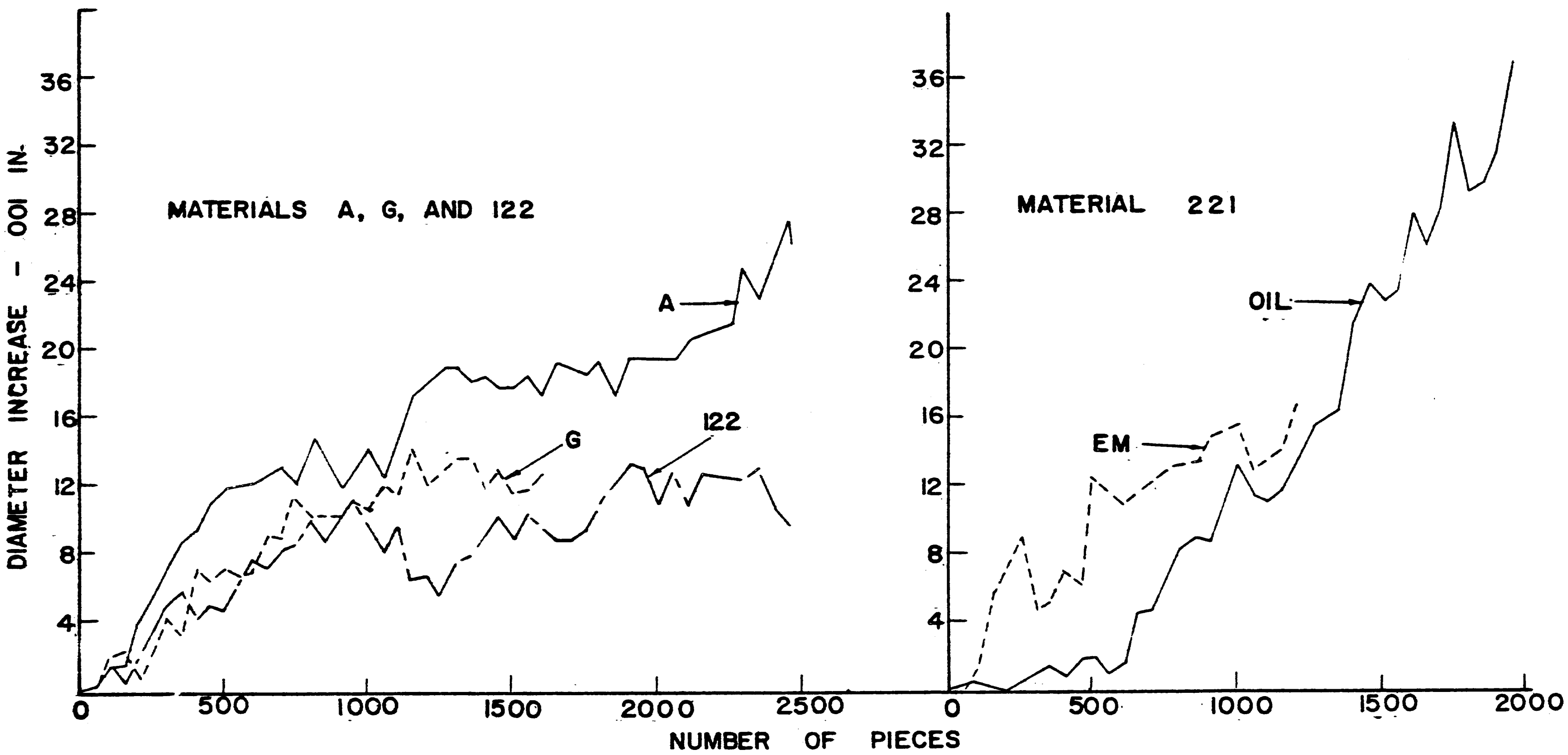


Fig. 8. Heavy-forming diameter variations vs. number of pieces.

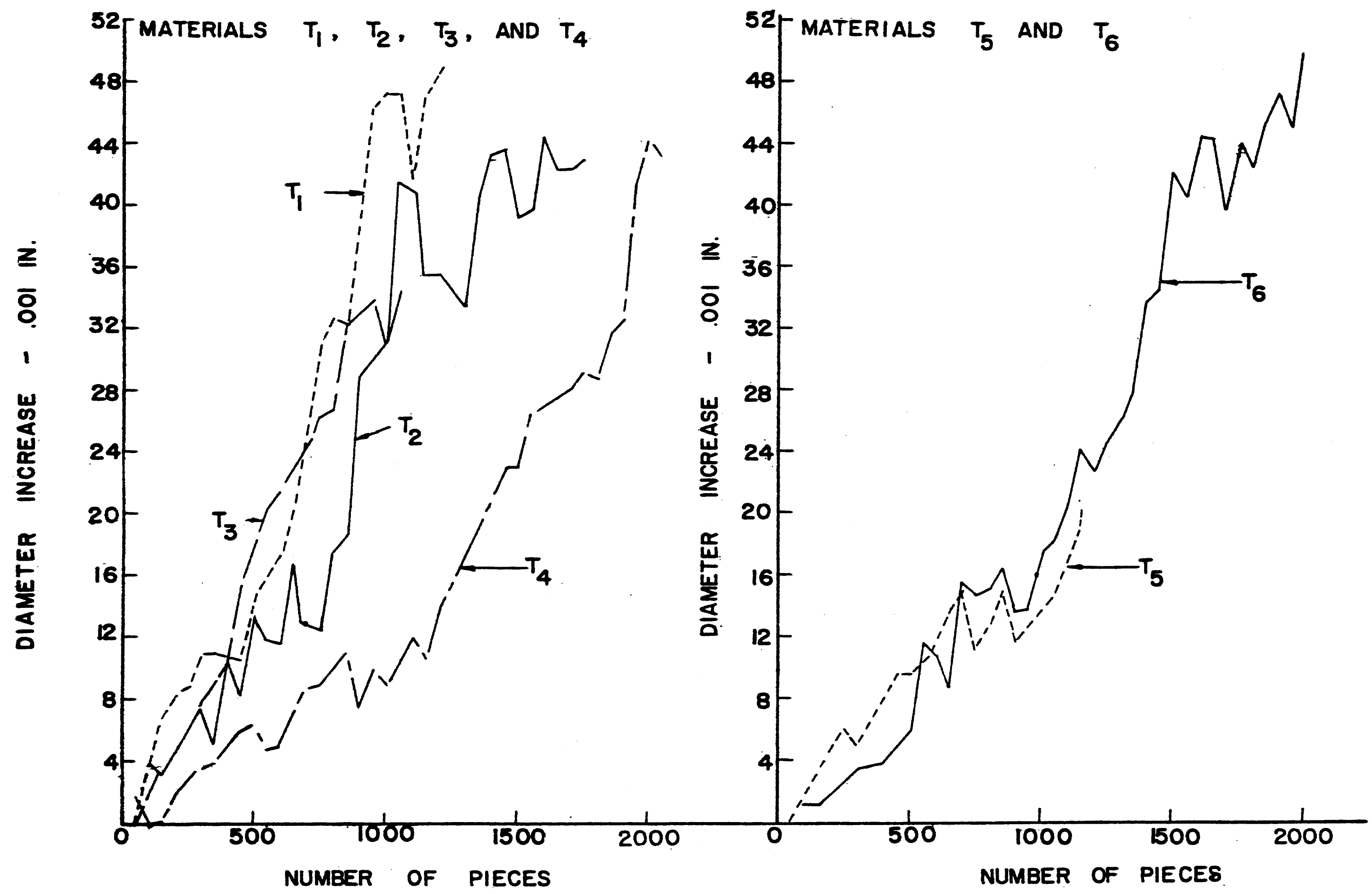


Fig. 9. Heavy-forming diameter variations vs. number of pieces.

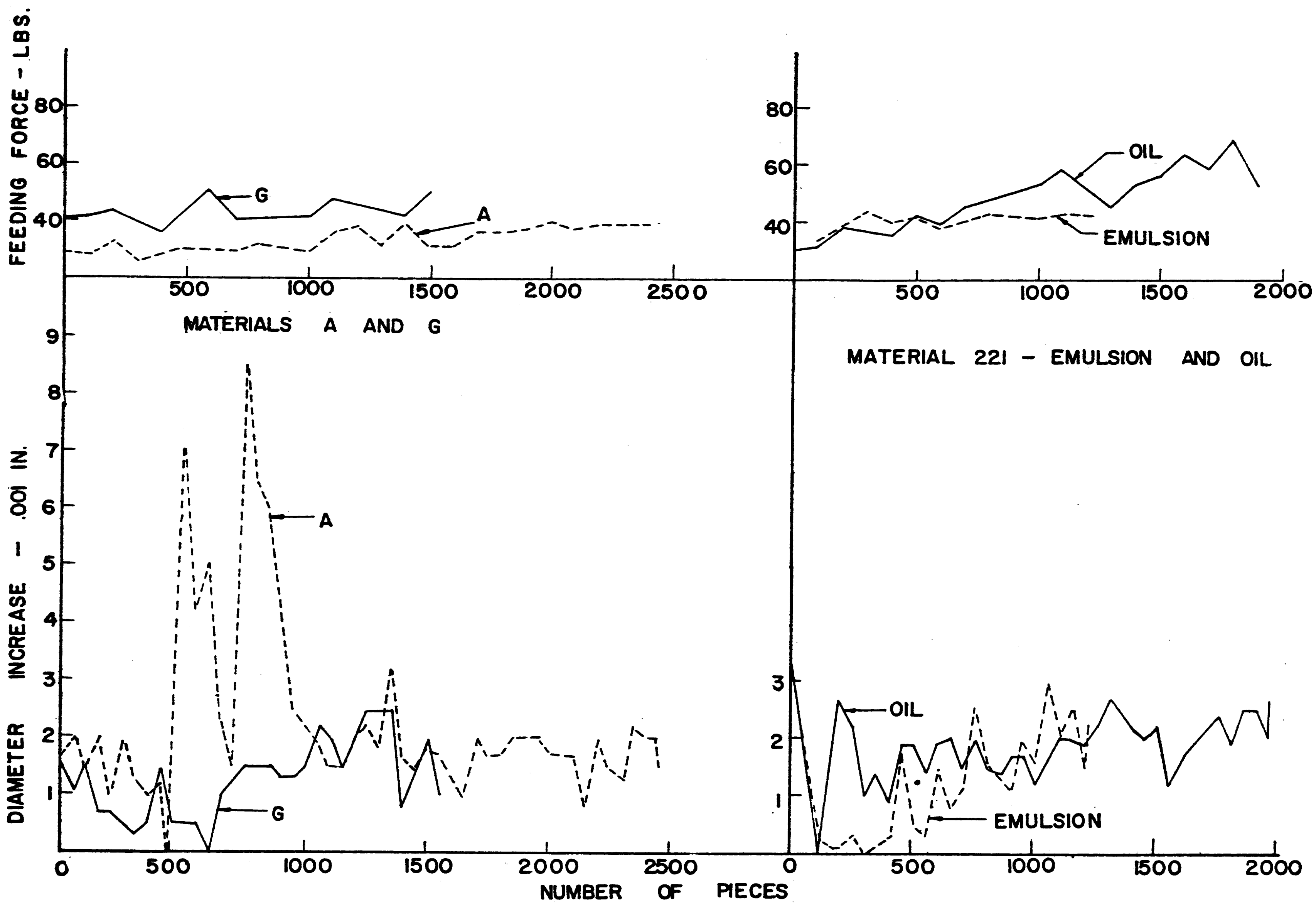


Fig. 10. Turning diameter and feeding-force variations vs. number of pieces.

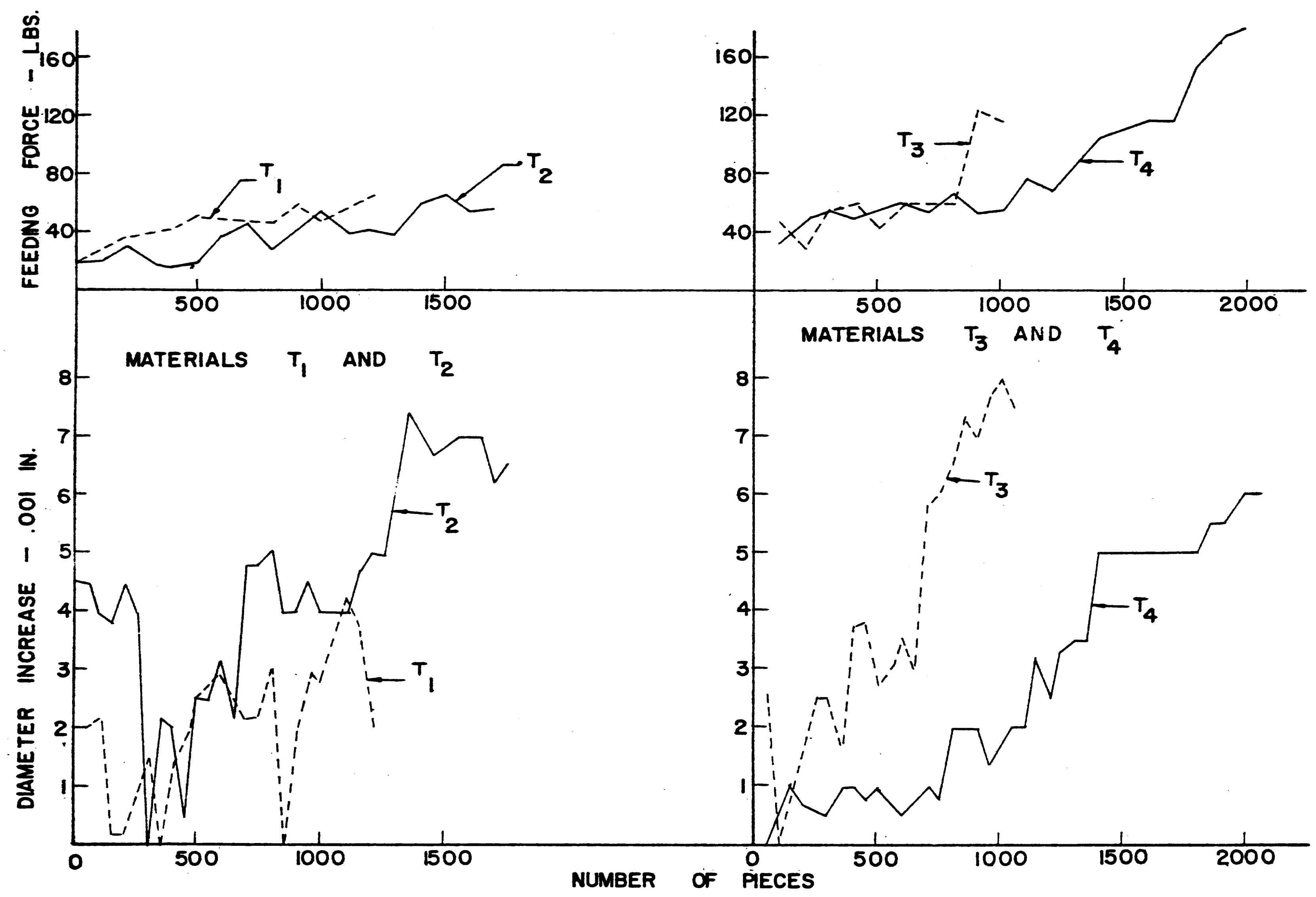


Fig. 11. Turning diameter and feeding-force variations vs. number of pieces.

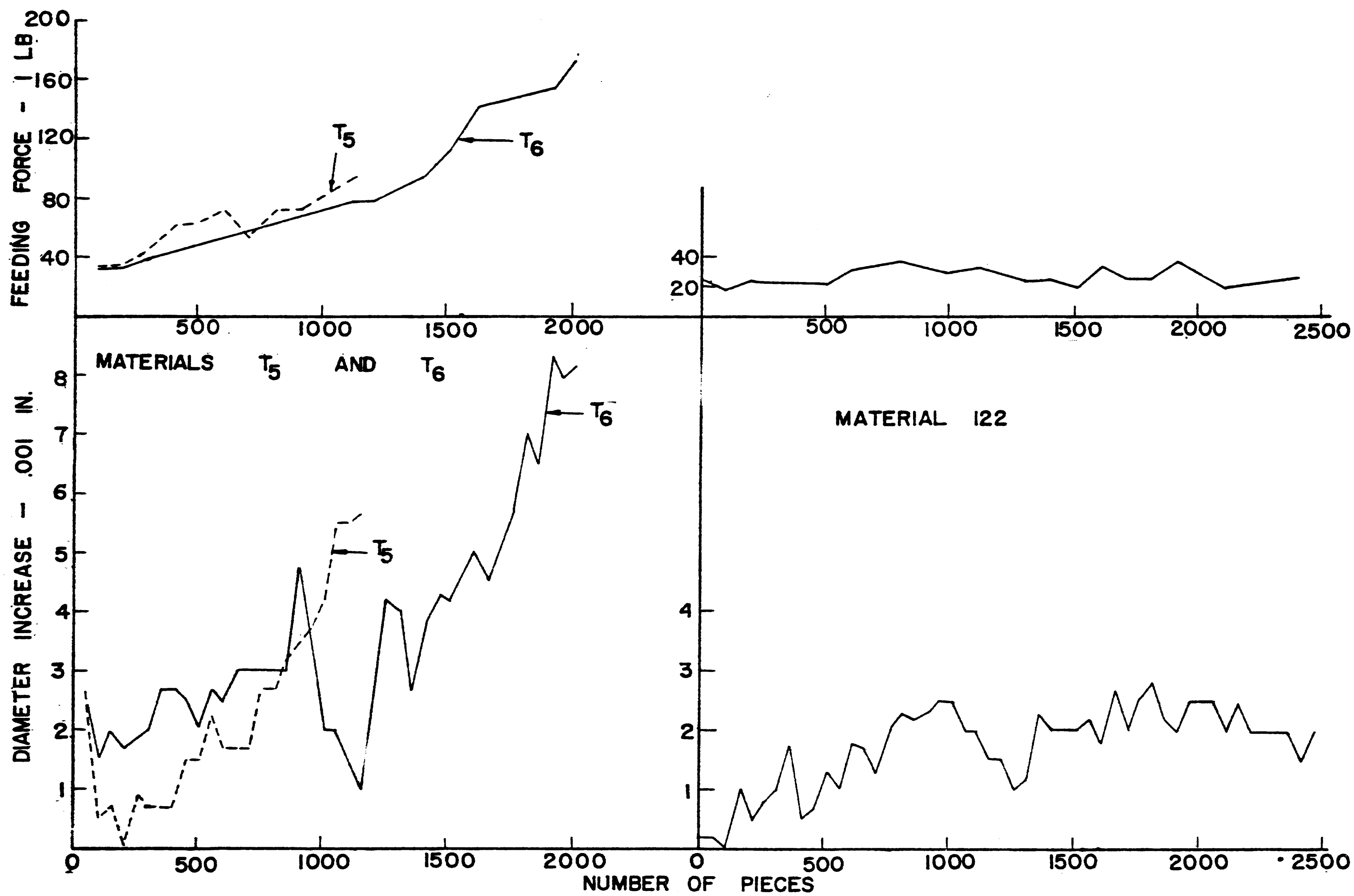


Fig. 12. Turning diameter and feeding-force variations vs. number of pieces.

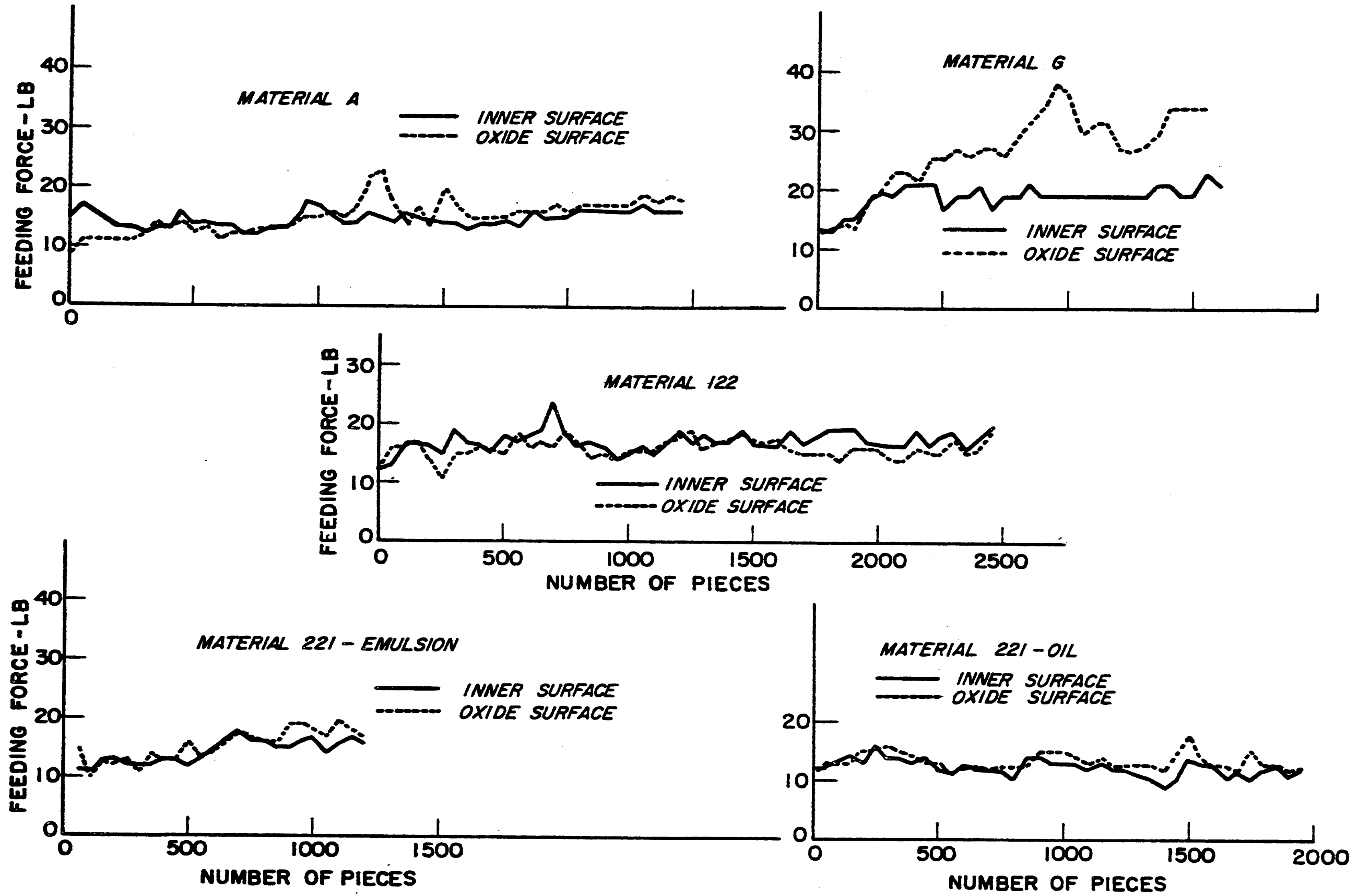


Fig. 13. Light-forming feeding forces vs. number of pieces.

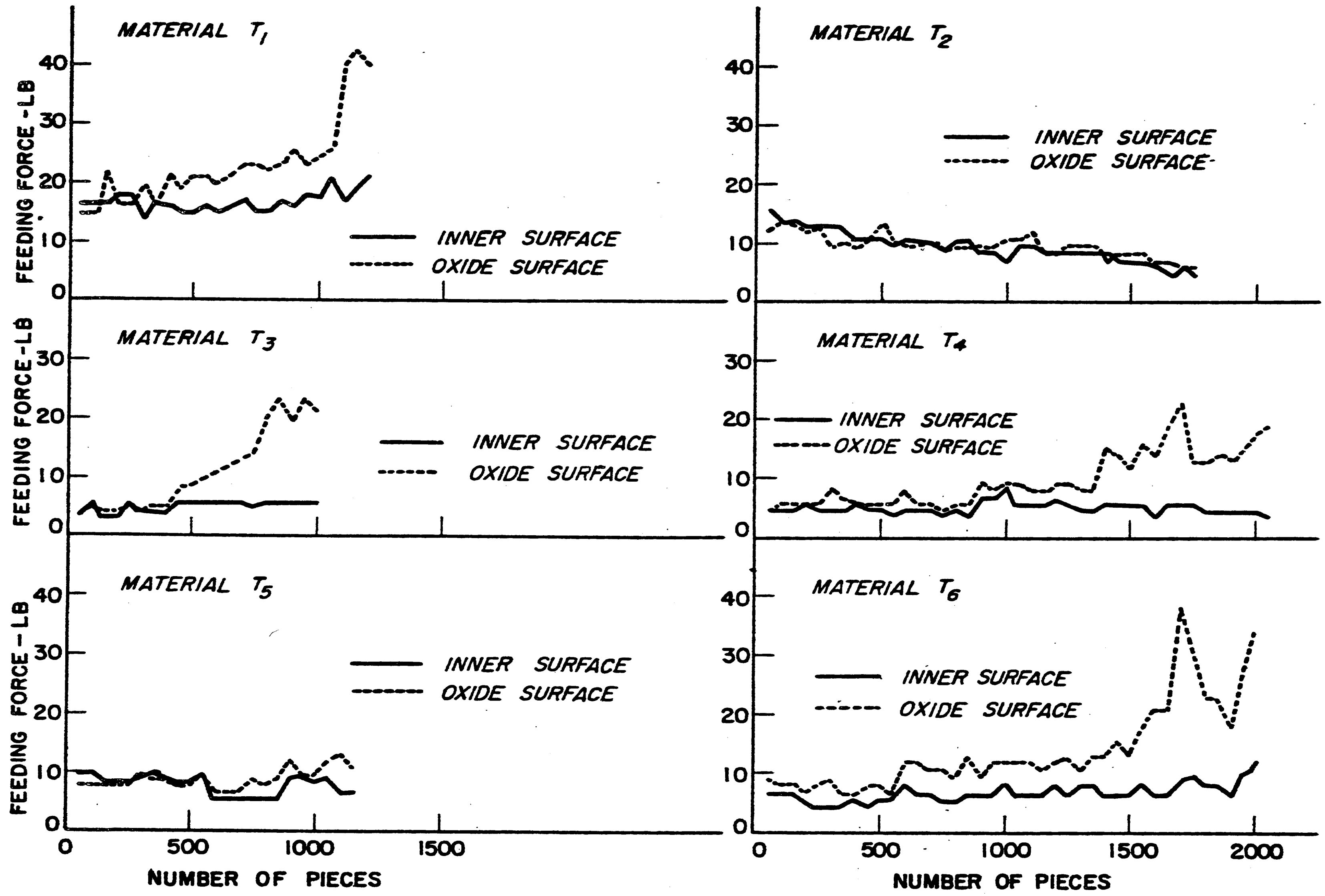


Fig. 14. Light-forming feeding forces vs. number of pieces.

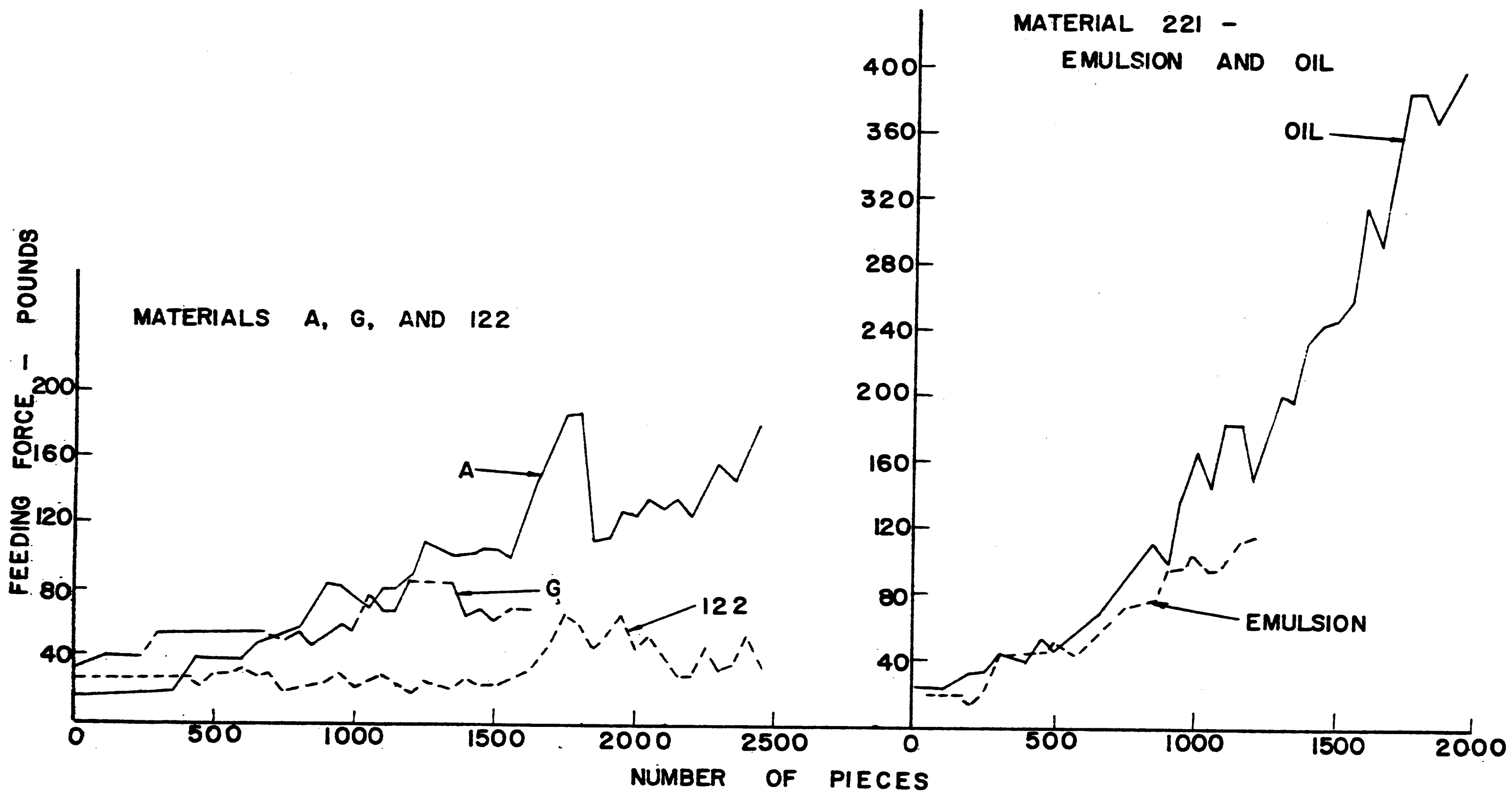


Fig. 15. Heavy-forming feeding forces vs. number of pieces.

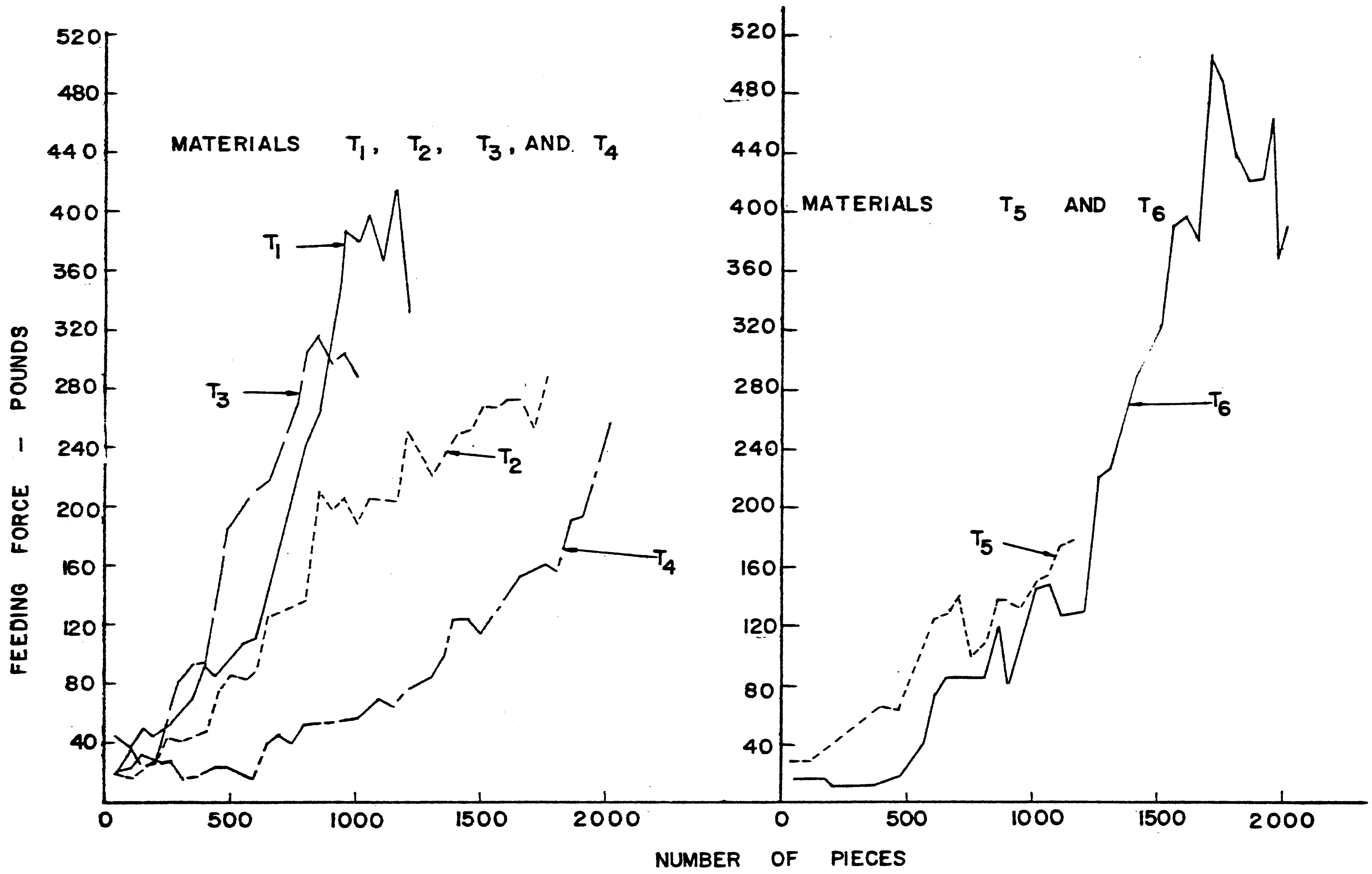


Fig. 16. Heavy-forming feeding forces vs. number of pieces.

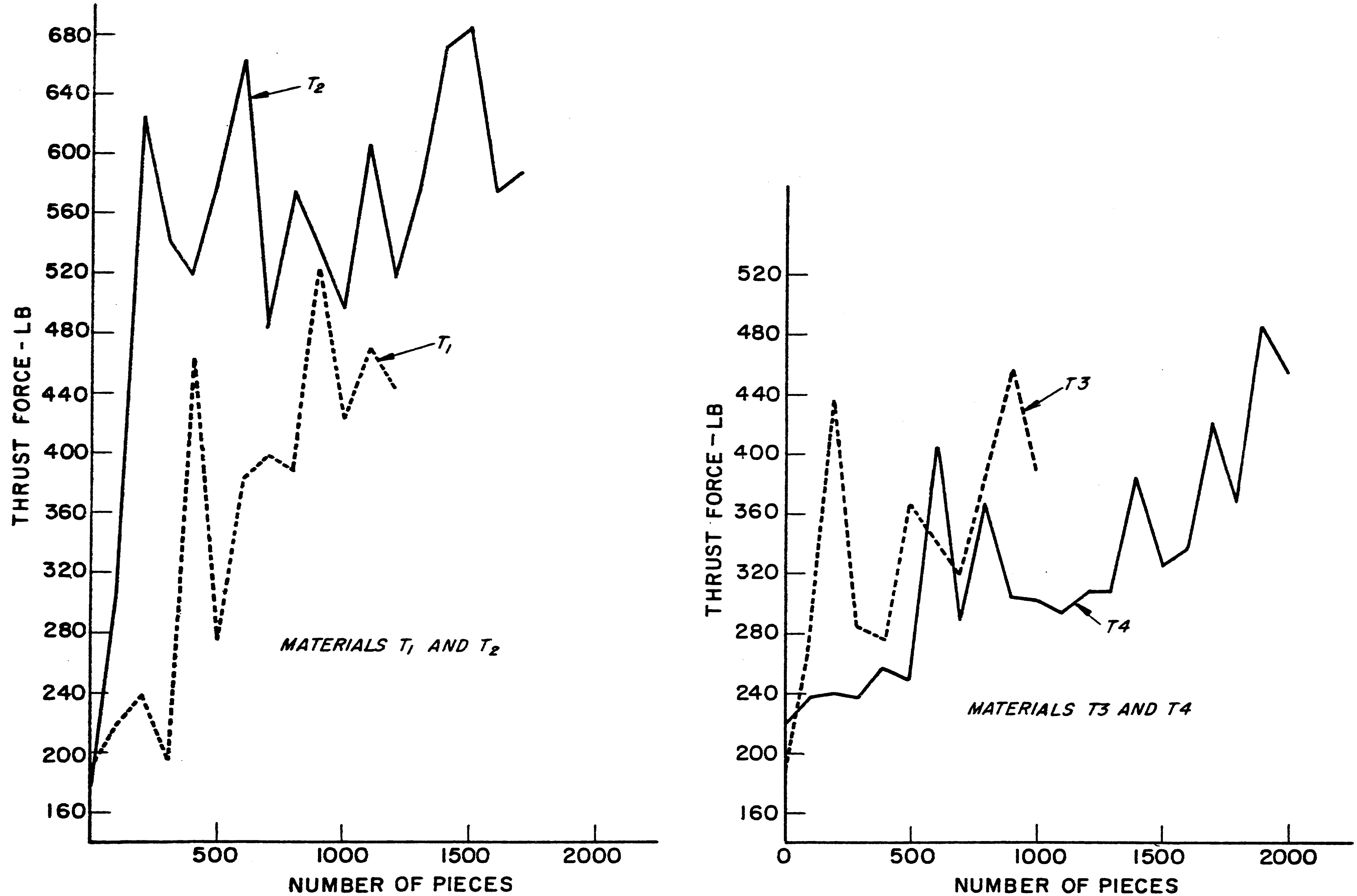


Fig. 17. Drilling—thrust forces vs. number of pieces.

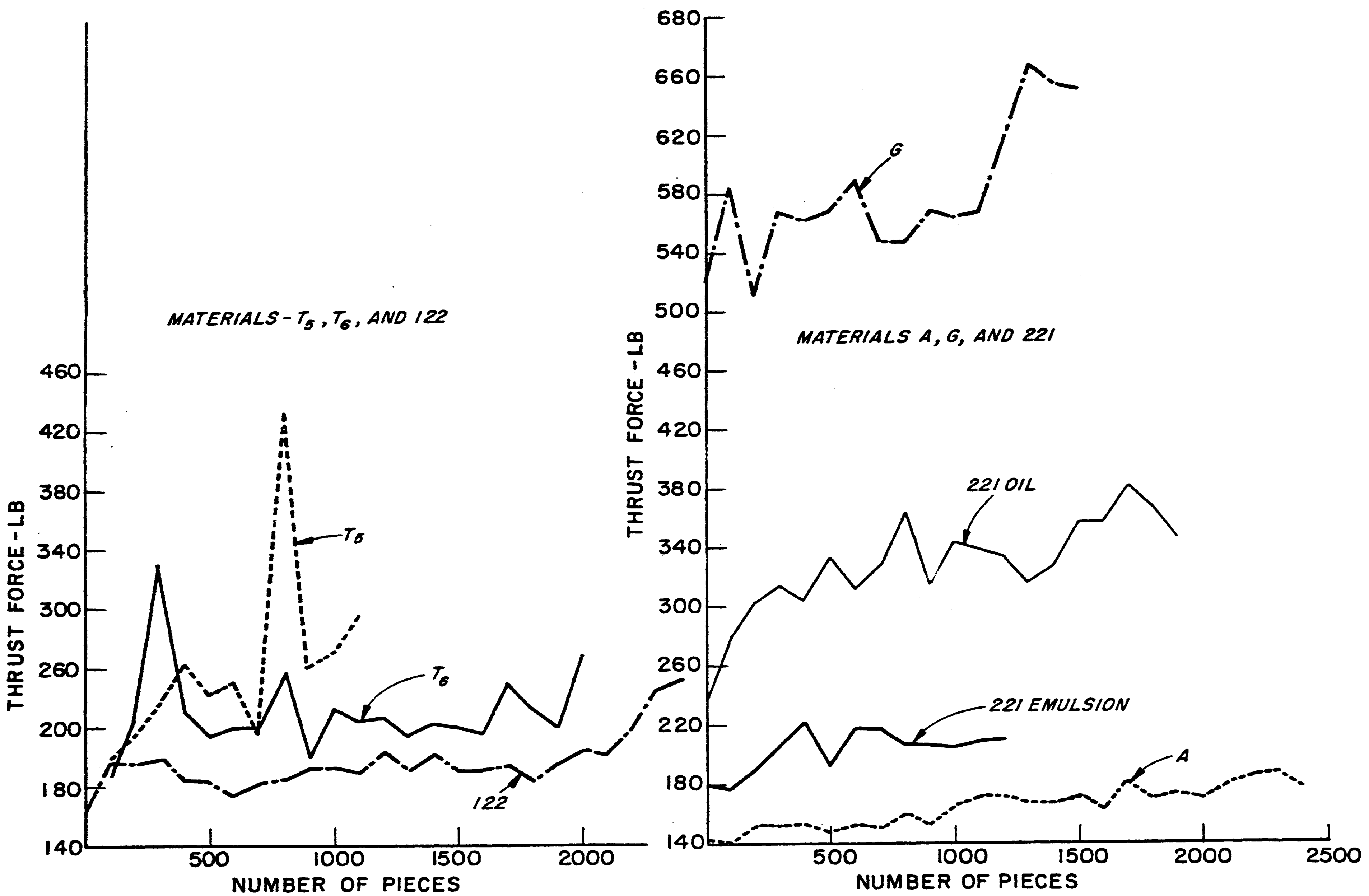


Fig. 18. Drilling—thrust forces vs. number of pieces.

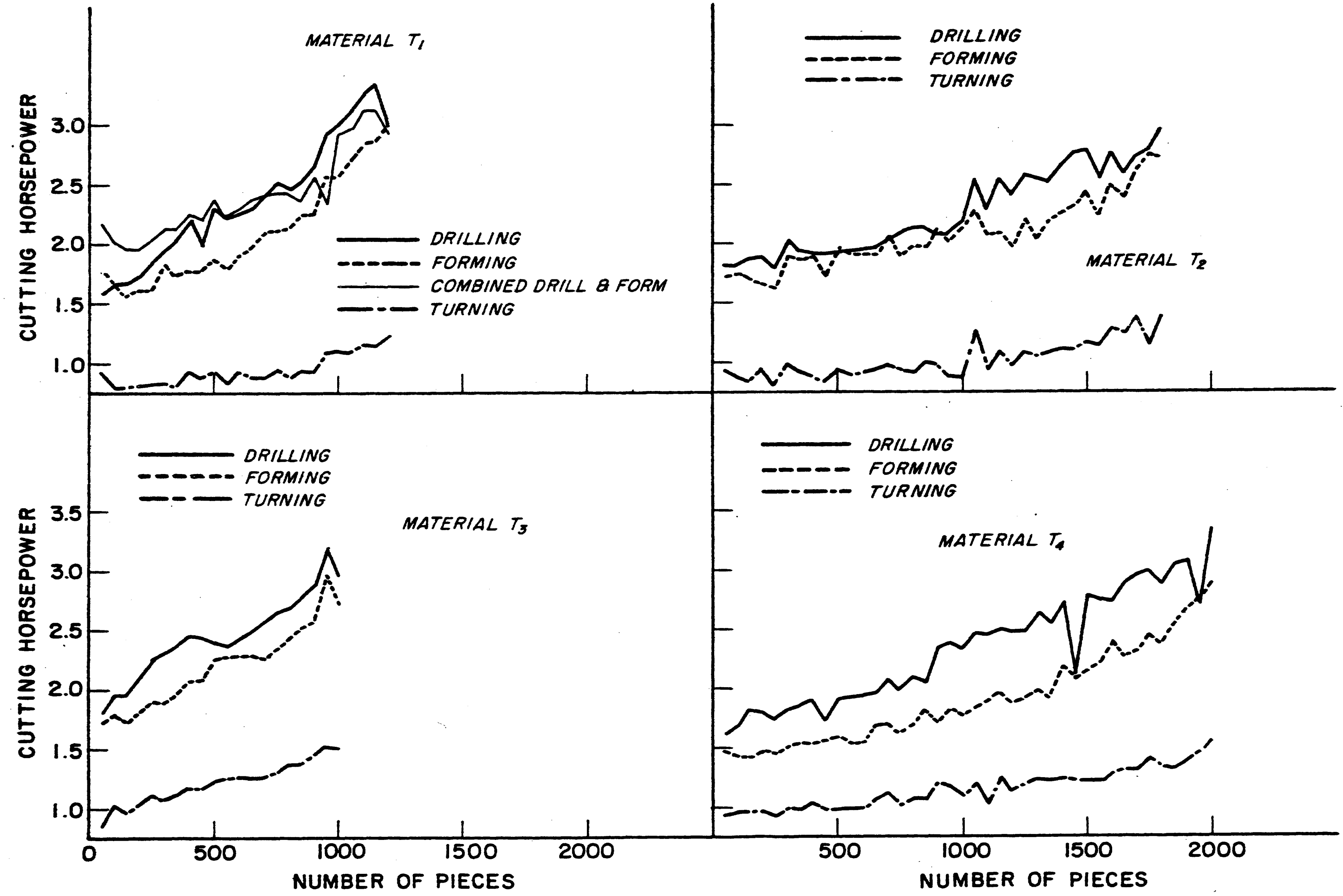


Fig. 19. Cutting horsepower vs. number of pieces.

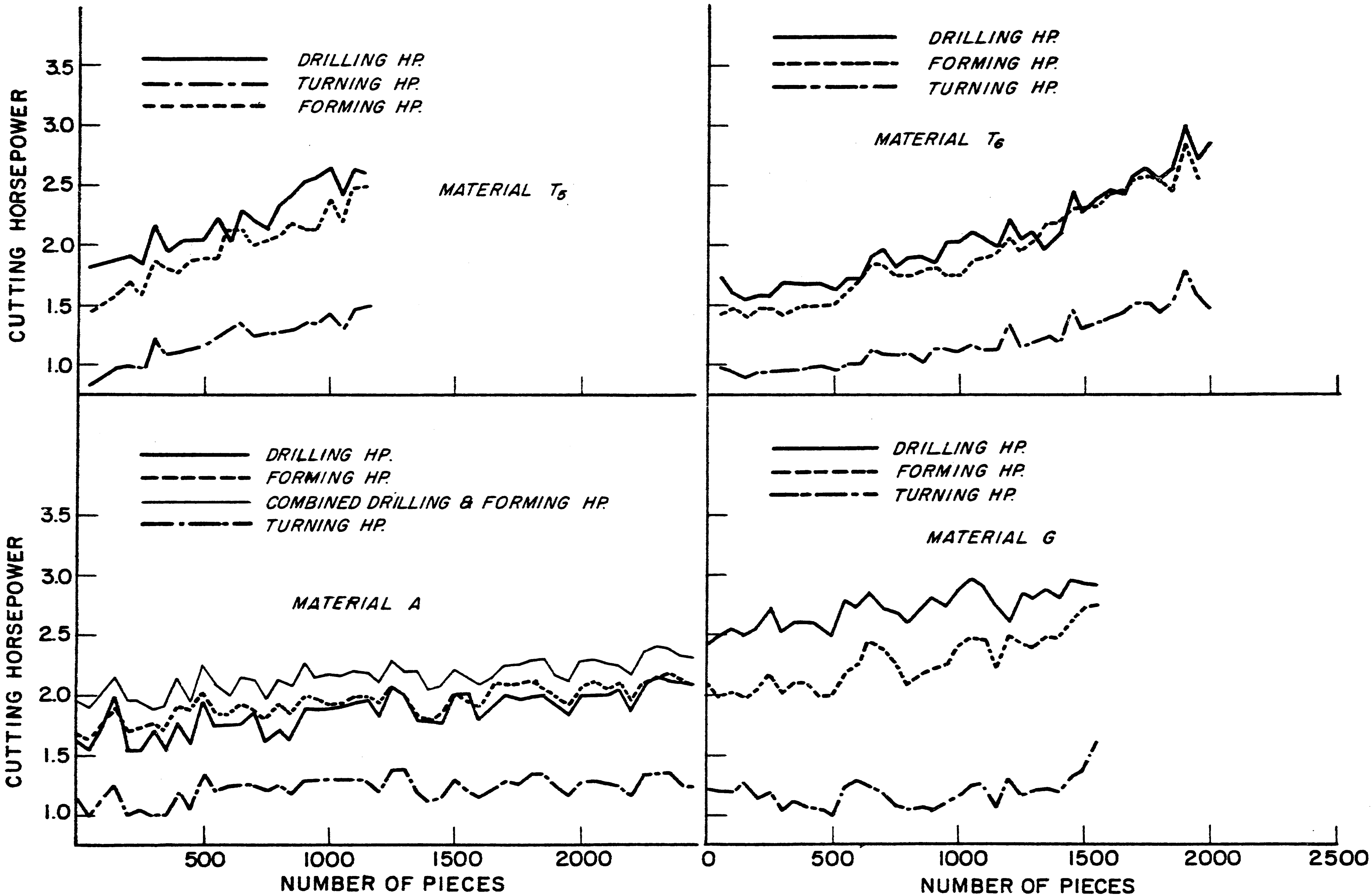


Fig. 20. Cutting horsepower vs. number of pieces.

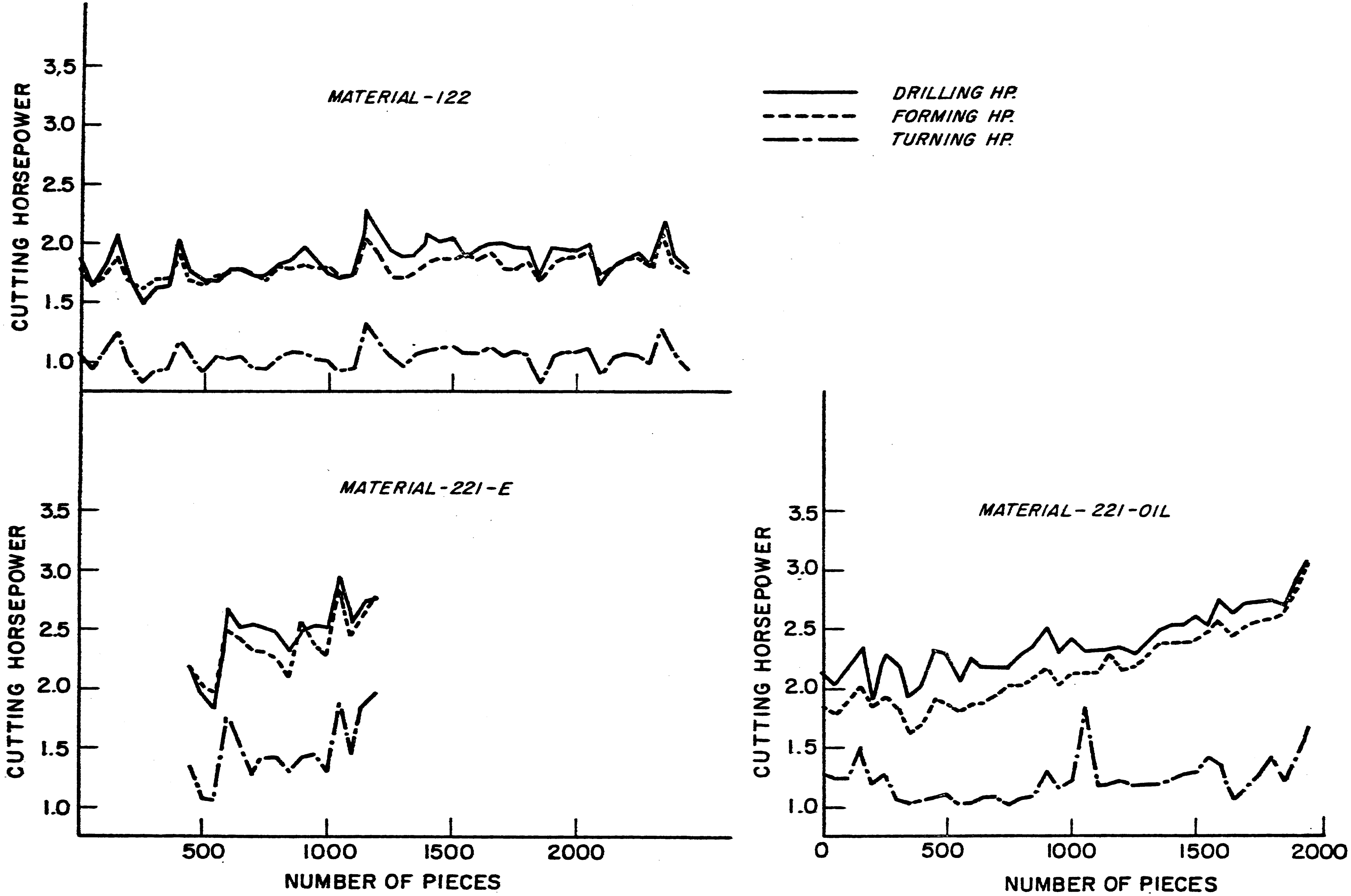


Fig. 21. Cutting horsepower vs. number of pieces.

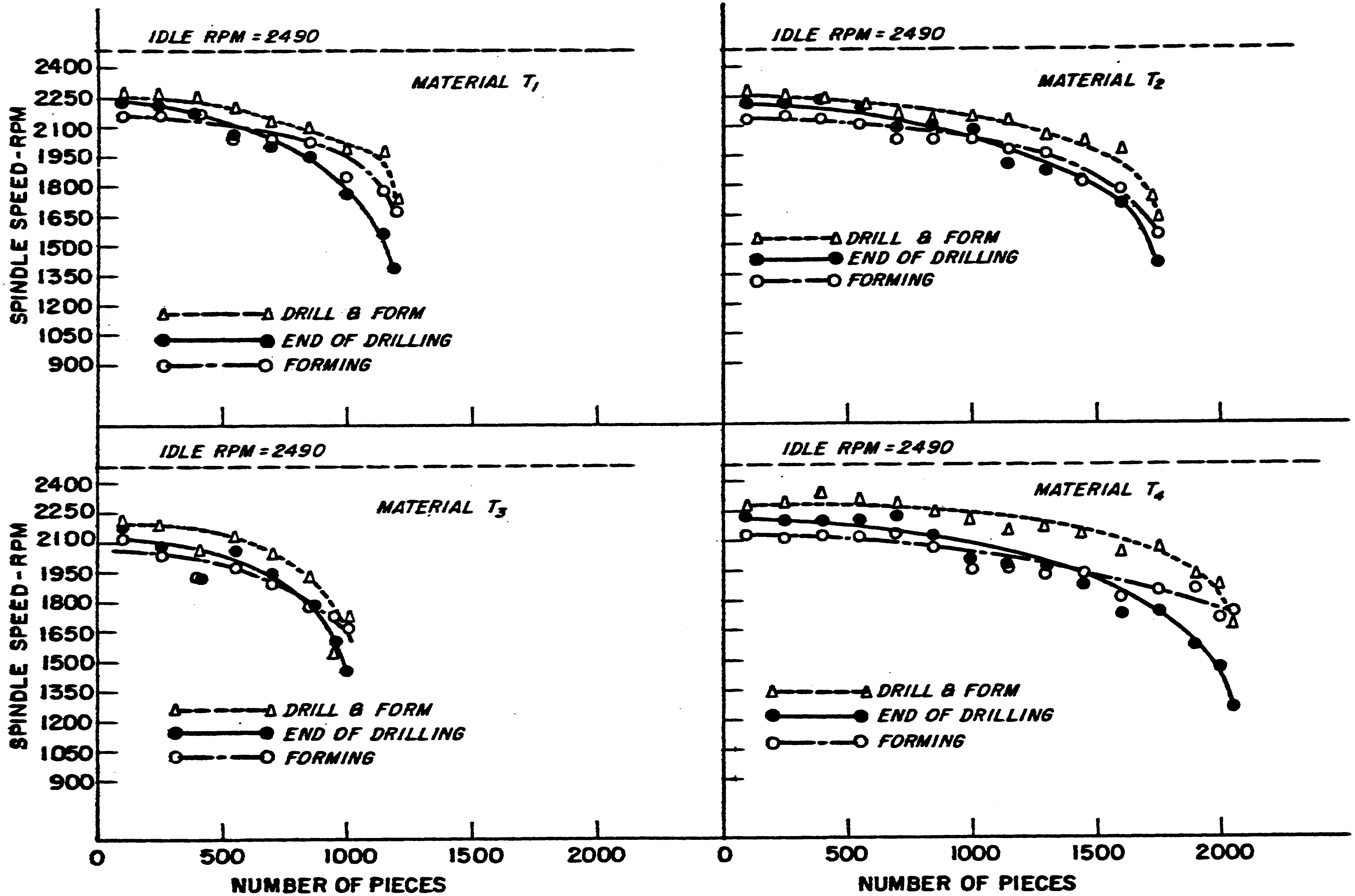


Fig. 22. Spindle rpm vs. number of pieces.

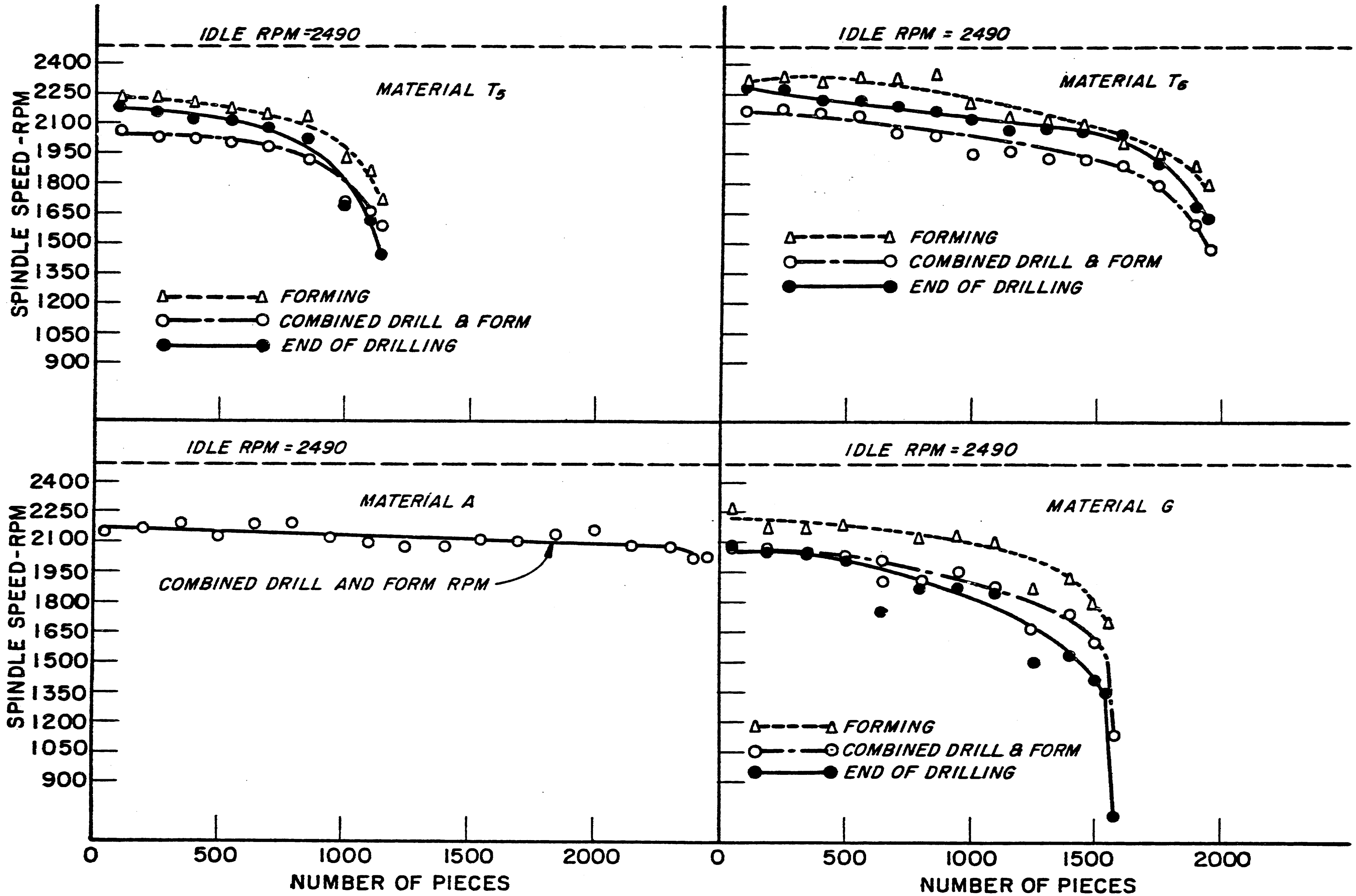


Fig. 23. Spindle rpm vs. number of pieces.

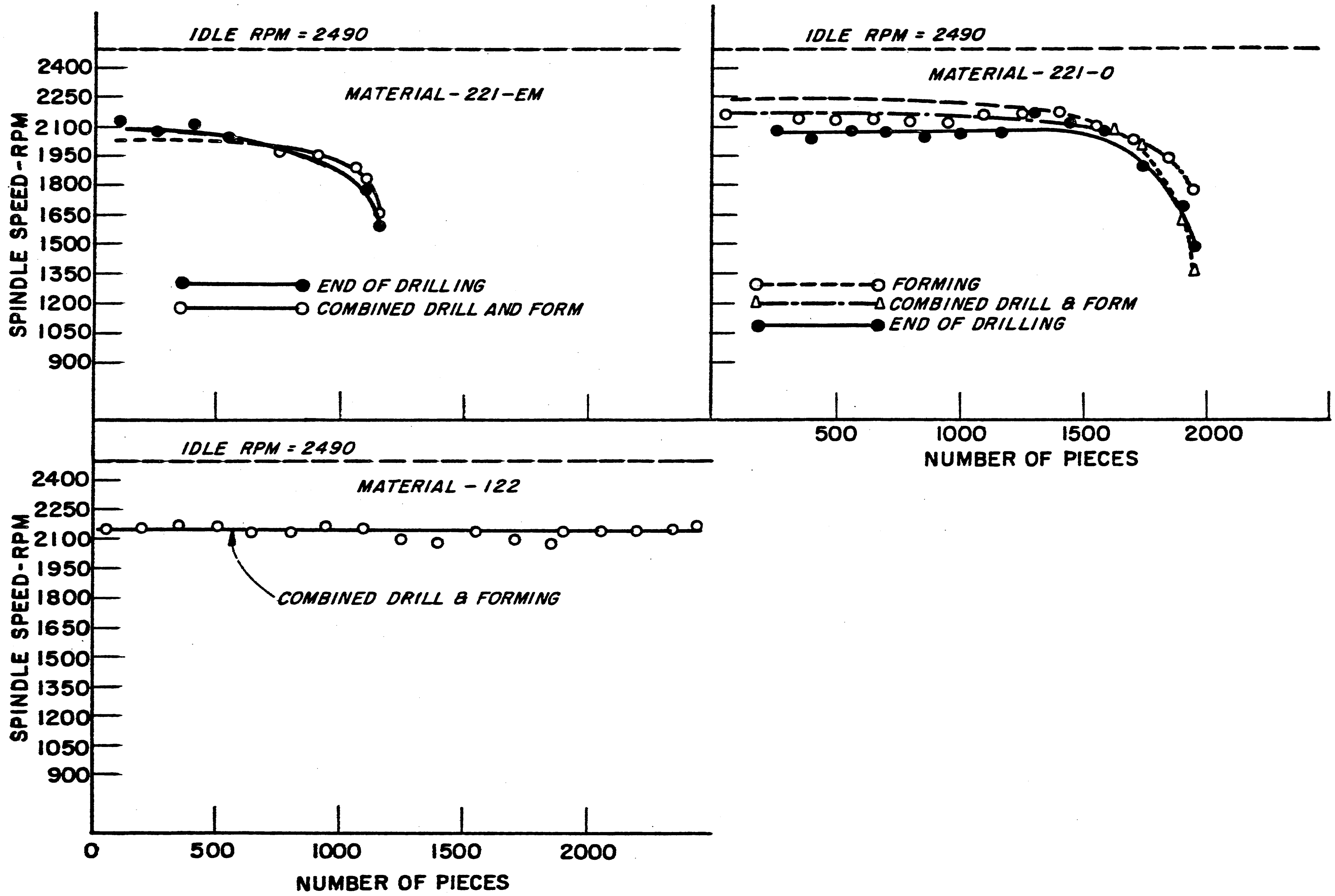
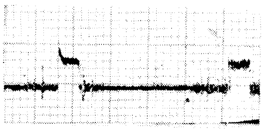


Fig. 24. Spindle rpm vs. number of pieces.

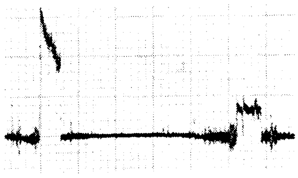
Material - T_1 - 1207 pieces

Trace of force on oxide surface.



Trace of force on inner surface.

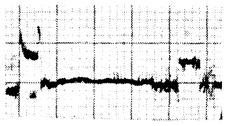
Beginning, ATT-2X



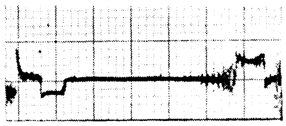
End, ATT-2X

Material - T_2 - 1793 pieces.

Beginning, ATT-1X

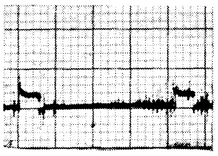


1000 pcs., ATT-1X

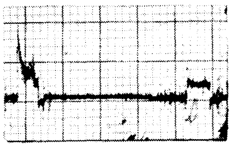


End, ATT-1X

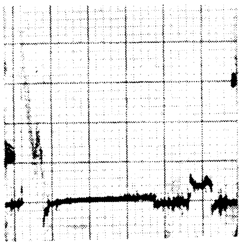
Material - T_3 - 1033 pieces.



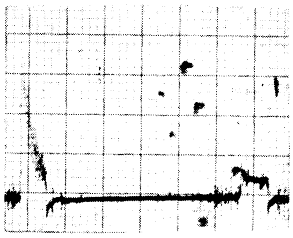
Beginning, ATT-1X



450 pcs., ATT-1X

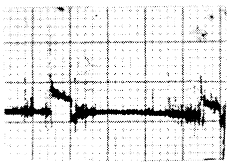


800 pcs., ATT-1X



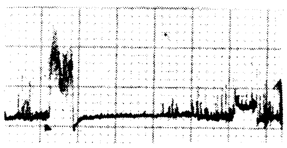
End, ATT-1X

Material - T_4 - 2080 pieces.



Beginning, ATT-1X

1650 pcs., ATT-1X

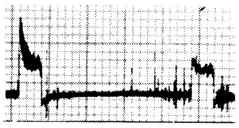


End, ATT-1X

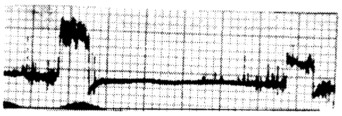
Fig. 25. Light-forming traces of feeding forces on oxide and inner surfaces. Forces are traced from left to right.

Material - T_5 - 1194 pieces

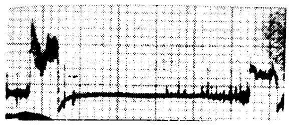
Beginning, ATT-1X



900 pcs., ATT-1X

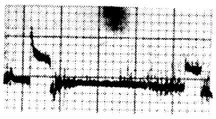


1100 pcs., ATT-1X

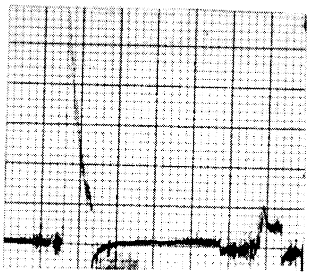


End, ATT-1X

Material - T_6 - 2002 pieces



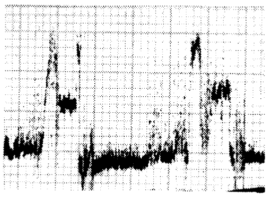
Beginning, ATT-1X



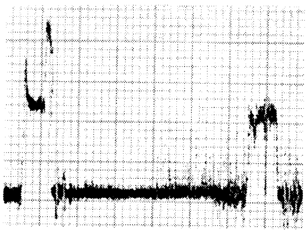
1850 pcs., ATT-1X

End, ATT-1X

Material - 221 emulsion - 1218 pieces

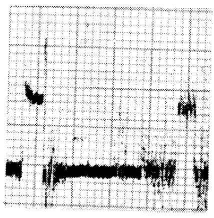


Beginning, ATT-1X

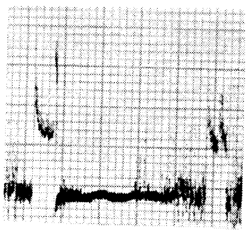


End, ATT-1X

Material - 221 oil - 1964 pieces



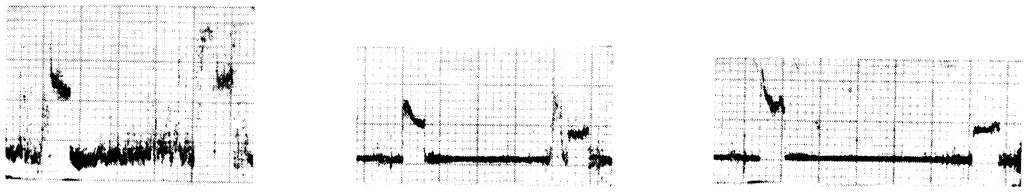
Beginning, ATT-1X



End, ATT-1X

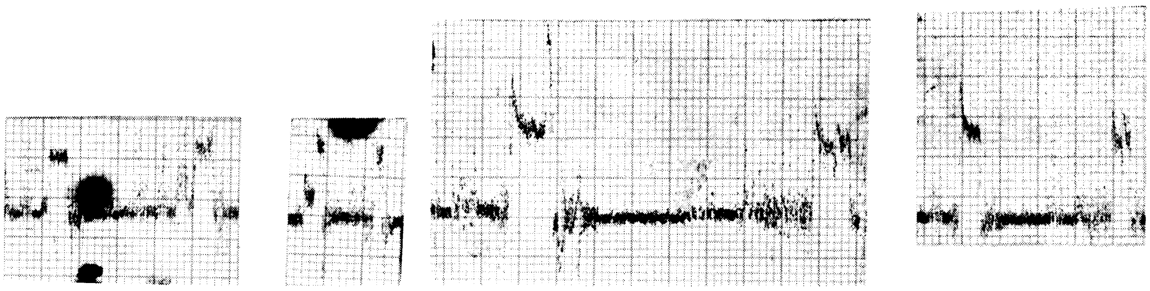
Fig. 25. Continued.

Material - G - 1577 pieces



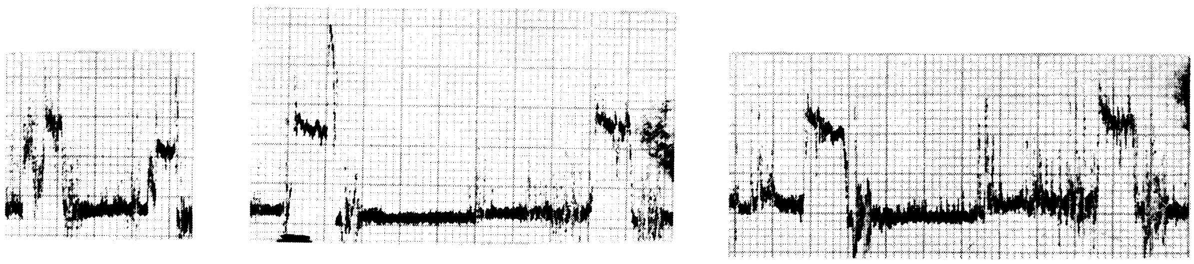
Beginning, ATT-1X 450 pcs., ATT-2X End, ATT-2X

Material - A - 2457 pieces



Beginning ATT-1X 650 pcs. ATT-1X 2000 pcs. ATT-1X End ATT-1X

Material - 122 - 2451 pieces

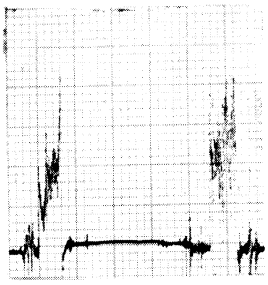


Beginning ATT-1X 650 pcs. ATT-1X End ATT-1X

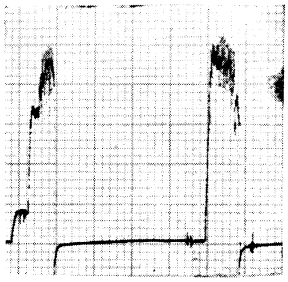
Fig. 25. Concluded.

Material - T_1 - 1207 pieces

Trace of forces for partial cutoff and partial form



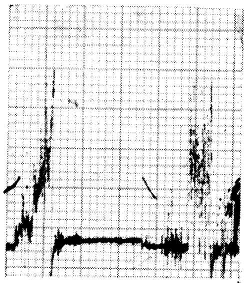
Trace of forces for finish cutoff and finish form



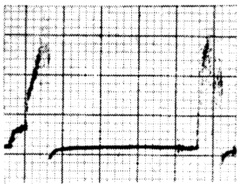
Beginning, ATT-2X

End, ATT-10X

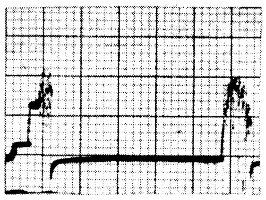
Material - T_2 - 1793 pieces



Beginning, ATT-1X

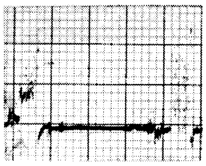


1150 pcs., ATT-10X

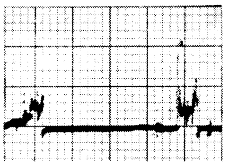


End, ATT-20X

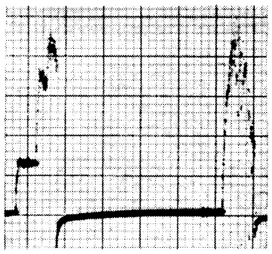
Material - T_3 - 1033 pieces



Beginning, ATT-2X

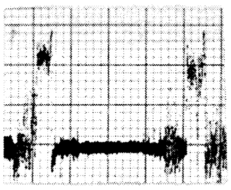


150 pcs., ATT-5X

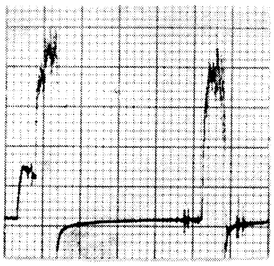


End, ATT-10X

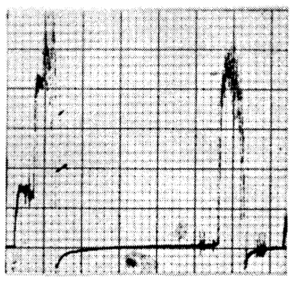
Material - T_4 - 2080 pieces



Beginning, ATT-2X



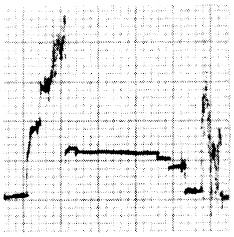
1650 pcs., ATT-5X



End, ATT-5X

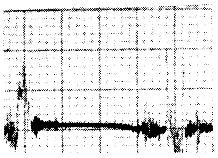
Fig. 26. Heavy-forming traces of feeding forces. Forces are traced from left to right.

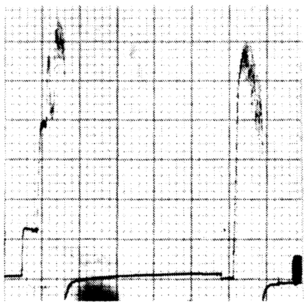
Material - T_5 - 1194 pieces


Beginning, ATT-2X


End, ATT-5X

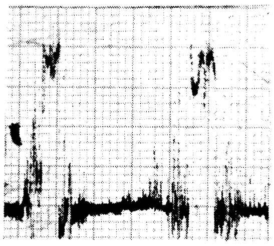
Material - T_6 - 2002 pieces

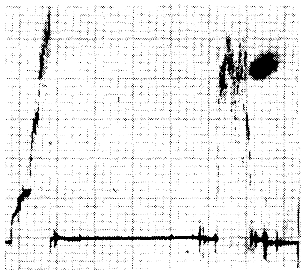

Beginning, ATT-2X


1850 pcs., ATT-10X

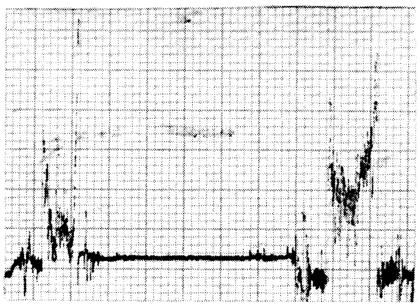

End, ATT-10X

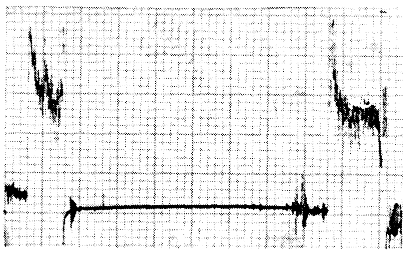
Material - 221 emulsion - 1218 pieces

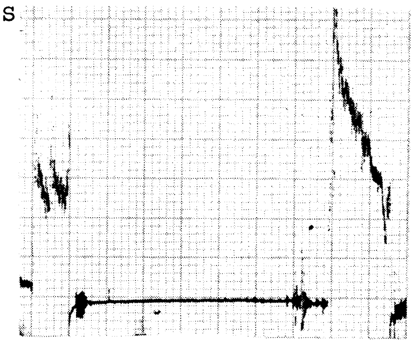

Beginning, ATT-1X


End, ATT-5X

Material - 221 oil - 1964 pieces


Beginning, ATT-2X


800 pcs., ATT-5X


1100 pcs., ATT-5X

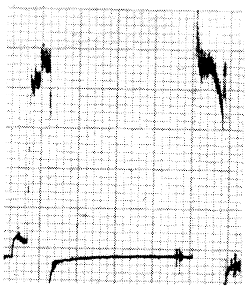
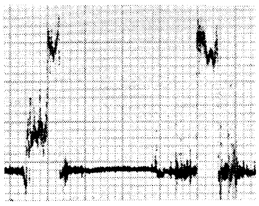
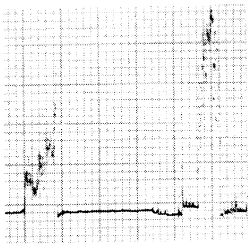

End—ATT-10X

Fig. 26. Continued.

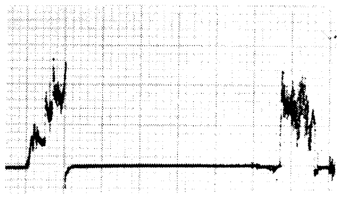
Material - G - 1577 pieces



Beginning, ATT-2X

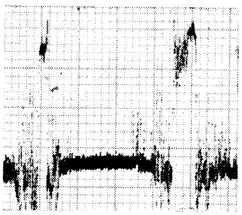


450 pcs., ATT-2X

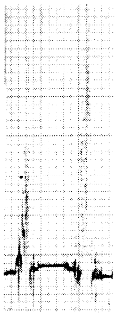


End, ATT-5X

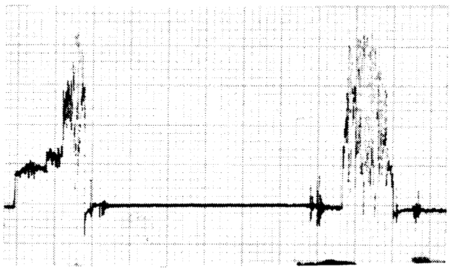
Material - A - 2457 pieces



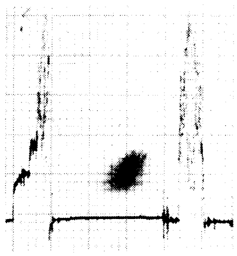
Beginning
ATT-2X



650 pcs.
ATT-2X

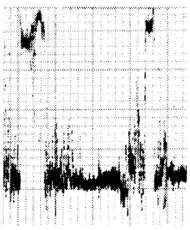


2000 pcs.
ATT-10X

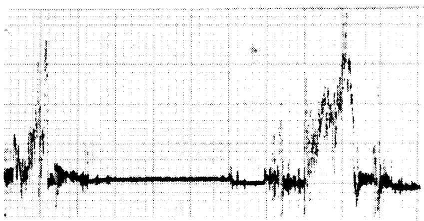


End
ATT-10X

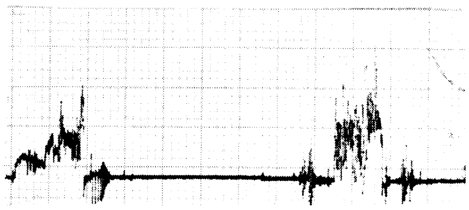
Material - 122 - 2451 pieces



Beginning
ATT-1X



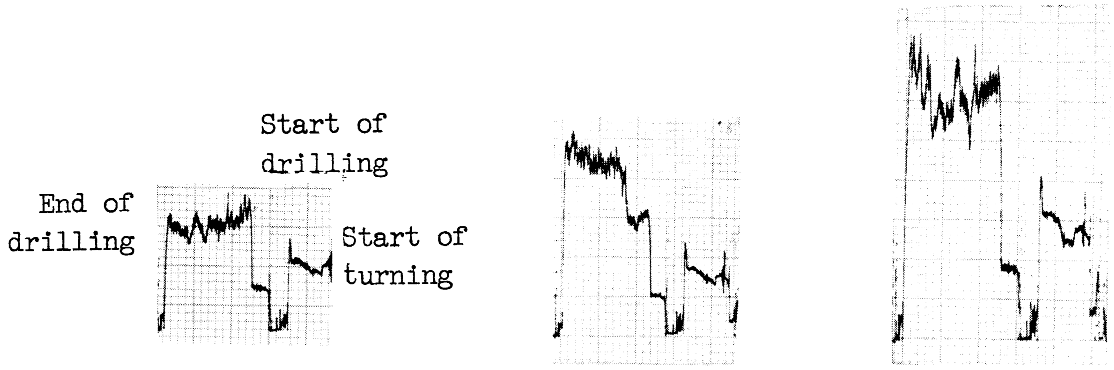
650 pcs., ATT-2X



End, ATT-5X

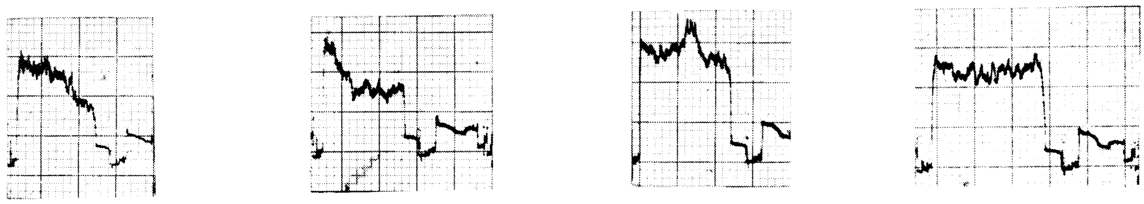
Fig. 26. Concluded.

Material - T_1 - 1207 pieces



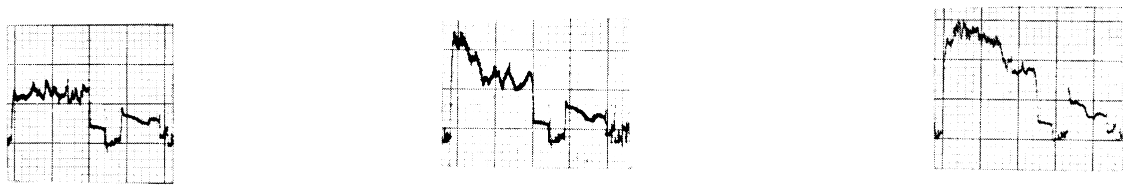
Beginning, ATT-5X   350 pcs., ATT-5X   End, ATT-5X

Material - T_2 - 1793 pieces



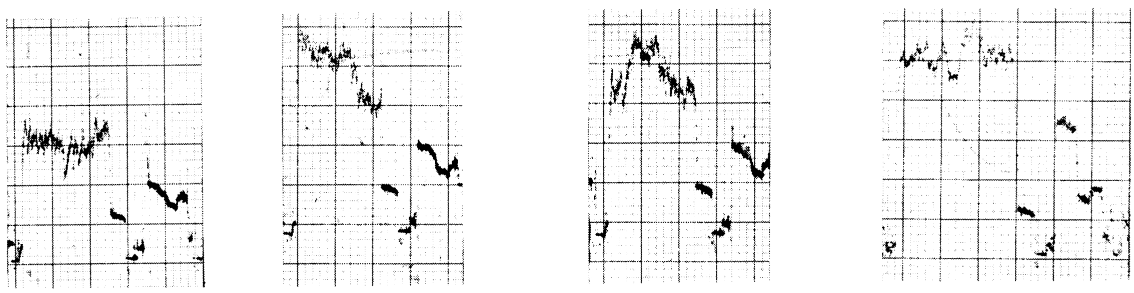
Beginning, ATT-20X   650 pcs., ATT-20X   1500 pcs., ATT-20X   End, ATT-20X

Material - T_3 - 1033 pieces



Beginning, ATT-20X   650 pcs., ATT-20X   End, ATT-20X

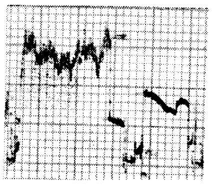
Material - T_4 - 2080 pieces



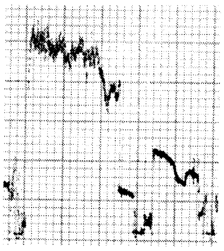
Beginning ATT-5X   600 pcs. ATT-5X   850 pcs. ATT-5X   End ATT-5X

Fig. 27. Turning and drilling traces of feeding and thrust forces. Forces are traced from right to left.

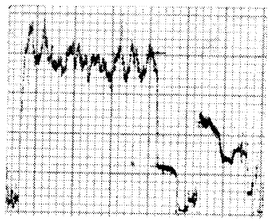
Material - T_5 - 1194 pieces



Beginning, ATT-5X

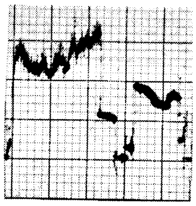


750 pcs., ATT-5X

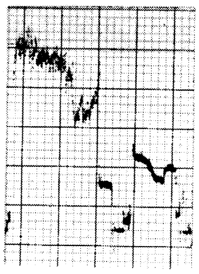


End, ATT-5X

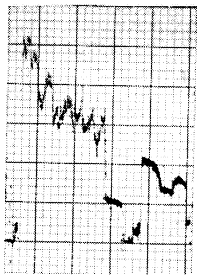
Material - T_6 - 2002 pieces



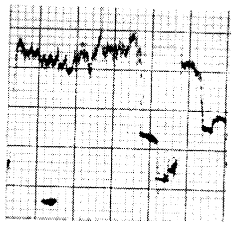
Beginning, ATT-5X



300 pcs., ATT-5X

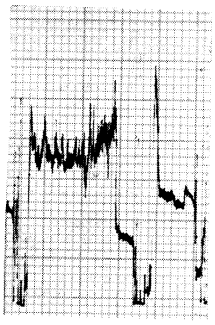


850 pcs., ATT-5X

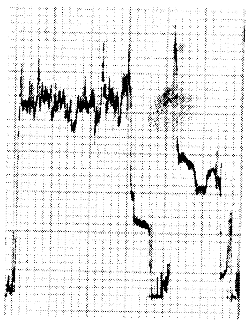


End, ATT-5X

Material - 221 emulsion - 1218 pieces

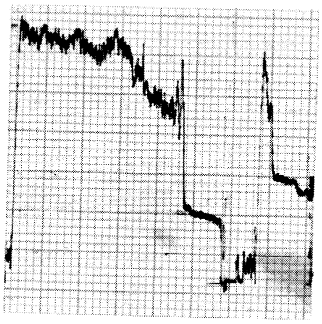


Beginning, ATT-2X

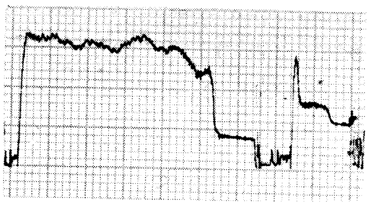


End, ATT-2X

Material - 221 oil - 1964 pieces



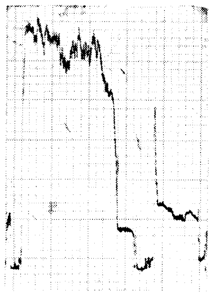
Beginning, ATT-2X



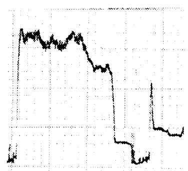
End, ATT-5X

Fig. 27. Continued.

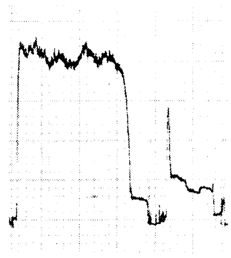
Material - G - 1577 pieces



Beginning, ATT-5X

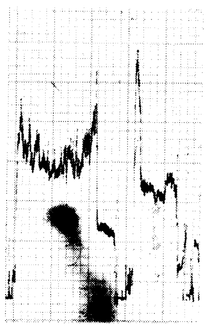


400 pcs., ATT-10X

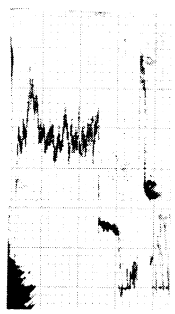


End, ATT-10X

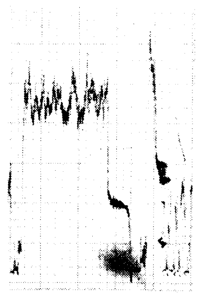
Material - A - 2457 pieces



Beginning, ATT-2X

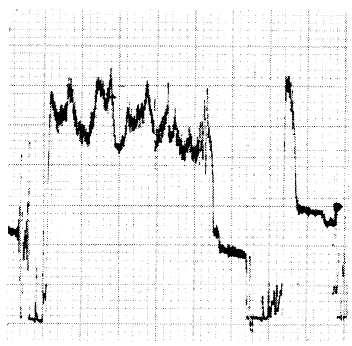


1350 pcs., ATT-2X

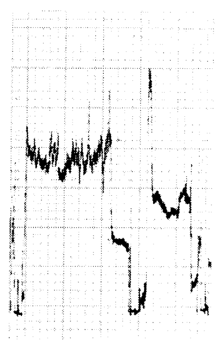


End, ATT-2X

Material - 122 - 2451 pieces



Beginning, ATT-2X



End, ATT-2X

Fig. 27. Concluded.

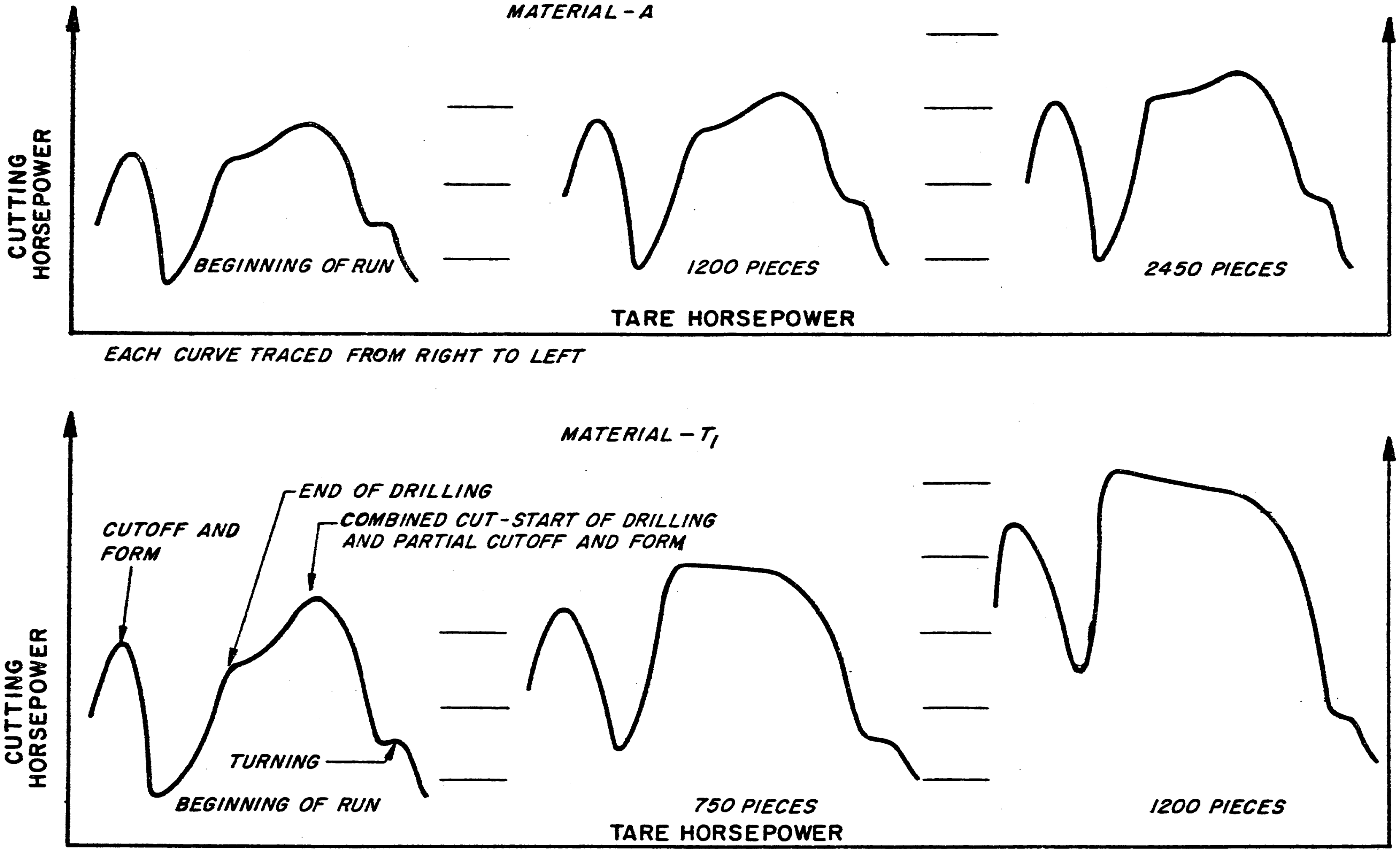


Fig. 28. Typical wattmeter-power curves showing power consumed for several machining operations. The curves show two drilling-behavior patterns exhibited by the materials used in the test program. All but one of the materials gave beginning patterns similar to those shown on the left above, but only materials A, 122, and T_6 maintained the pattern for the entire run. All other materials showed a change in drilling-power characteristics similar to the change represented above for material T_1. Material 221, with oil, was the only material to show a beginning pattern similar to the center pattern under T_1 above.