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AN INVESTIGATION OF THE EFFECT OF NATURAL TOOL SHARPNESS UPON CUTTING FORCES

A THESIS

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AN INVESTIGATION OF THE EFFECT OF

NATURAL TOOL SHARPNESS UPON

CUTTING FORCES

Approved:

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Date Approved by Chairman: Sept. 5, 1961

ACKNOWLEDGMENTS

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SUMMARY

Three types of materials, varying from ductile to brittle, were turned in a lathe and the cutting and thrust forces recorded. A series of ten cuts on each material was made with feed as the variable. The natural sharpness radius of the cutting tool was then measured by optical and photographic means. Using the value r/t as a parameter, where r is the natural sharpness radius and t is the undeformed chip thickness or feed, the cutting and thrust forces were studied.

This investigation was undertaken to extend the work done by P. Albrecht, who developed a theory in which he introduced a new force into the cutting process. This force, called the "ploughing" force, is dependent on the size and shape of the natural sharpness radius of the cutting tool.

Due to the difficulties in measuring, it was not practical to vary the size of the sharpness radius. Instead the parameter r/t was selected to study the effect of the radius. The feed could then be varied while the radius was held constant. Both the cutting and thrust forces were shown to decrease as the parameter r/t increased.

The magnitude of the sharpness radius was found to have an effect on the cutting force. For the same cutting conditions, the tool with the larger radius had the higher cutting force and thrust force and, hence, used the most power. The radii ground for this experiment were in the range of 0.0001 - 0.001 in.

A value of the parameter r/t, where the best cutting conditions existed, was found for each material. This meant that for a certain radius there was a corresponding feed that would determine a best ratio for cutting. A value of the radius was also found where minimum power was obtained.

The sharpness radius did introduce a force into the cutting operation in addition to the shearing force. This investigation showed the ploughing concept could be a logical explanation for the new force.

CHAPTER I

INTRODUCTION

It has been said that industry is wasting as much as 3 billion dollars of the 12 billion it spends each year for cutting chips (1)*. This loss is attributed to machining inefficiency and to the gap between what is being done in production and what could be done.

Machining is an engineering process, utilizing materials and energy to produce useful goods. The understanding of such actions, and of the part they play in the metal cutting operation, holds the key to real engineering advances in machining technology. Thus, for metal cutting research to be truly efficient and productive, what is required is a unified attack, both basic and applied, employing all of the physical sciences and engineering.

When early engineers began development of the present theory of metal cutting, certain simplifying assumptions were made. This is usually the case when a complex problem is first attacked. Among these initial simplifications was one that neglected the size and effect of the natural sharpness radius of the tool and considered it perfectly sharp at all times. This dimension was said to be small and insignificant in comparison with the dimensions of the cutting mechanism. In the years that followed, researchers in the metal cutting field adopted this assumption as a matter of fact.

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*Numbers in parentheses refer to items in the bibliography.

P. Albrecht, however, backed by experimental evidence, departed from the customary way of accepting the assumption. He developed a modified theory, based on shear, but which introduced an additional force into the cutting process. This force he referred to as the ploughing force. The ploughing force, Albrecht claimed, is dependent on the size and shape of the natural sharpness radius of the tool.

The investigation reported was undertaken to extend the work done by Albrecht. In particular, the effect of the natural sharpness radius upon cutting forces was studied by means of the r/t parameter. Three materials, from ductile to brittle, were turned on a lathe during the study. Strain measurements were made with a tool dynamometer and a Sanborn strain recorder. Recordings were closely examined for the natural sharpness radius effect.

CHAPTER II

REVIEW OF THE LITERATURE

Before 1959, all of the work done in the field of metal cutting was based on the fact that the deformation of metal was due to the shearing phenomenon alone. Even as far back as 1895, when Albert Kingsbury described chip formation (2), this basic assumption was used. He found that a crack always preceded the point of the cutting tool. This circumferential crack develops along a straight line for a certain distance and then turns off at 45 degrees to the original direction, branching out toward the surface of the chip, thus permitting the chip to unwind from the stock and slide out along the top of the tool.

In 1909, E. G. Herbert defined the chip as that portion of a forging which is at the point of being cut away by a turning tool in a lathe as a jet or stream of steel impinging on the point of the tool and dissipating its energy in the form of heat (3). Bruce reported that Jones and Laughlin compared the action seen on a high speed film to a river containing considerable debris at flood time flowing past an island or possibly an ice breaker moving through a frozen stream (4).

Malcolm F. Judkins claimed the tool was more like a punch than a wedge because the material is not so much split as pushed (5). The tool compresses the material ahead of the point or nose, and escape of the material so compressed involves shearing stresses resulting in rupture, segmentation, or plastic deformation and flow in ductile metals.

All of these men and many others who looked at chip formation agreed on one point, that is, that force diagrams are to assume the tool perfectly sharp and the cutting action a shearing process. The shearing action plastically deforms the work material and so separates it from the workpiece. In order to produce such plastic deformation considerable force is required. Forces acting between the cutting tool and work material are shown in Figure 1. The theory (6), based on this diagram, has to a large extent clarified the mechanics of the metal cutting process.

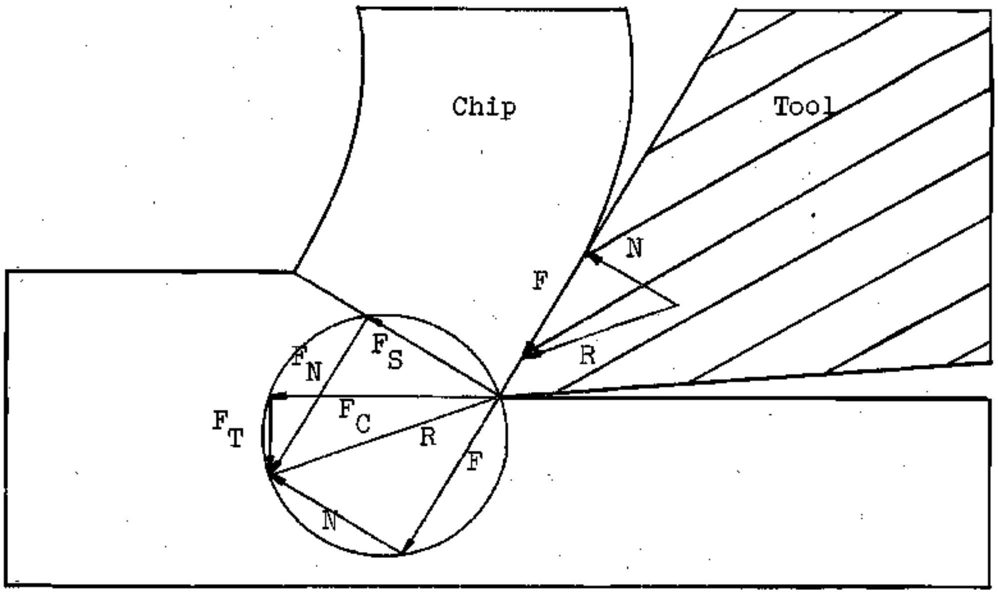


Figure 1. Conventional Force Diagram

P. Albrecht went beyond this basic idea and added an entirely new concept to the understanding of metal cutting (7). He claimed that the forces due to the shearing effect are present, but in addition, another force exists due to the finite sharpness of the cutting edge. He referred to this force as the "ploughing force." Thus, he claimed ploughing to be the number two mechanism in metal cutting. The introduction of it makes the analytical model of metal cutting more dependable and explanatory.

The major idea of the ploughing concept is that the shadowed area of metal in front of the "rounded" tool edge is displaced mainly into the chip (see Figure 2). The metal being pressed into the chip tends to

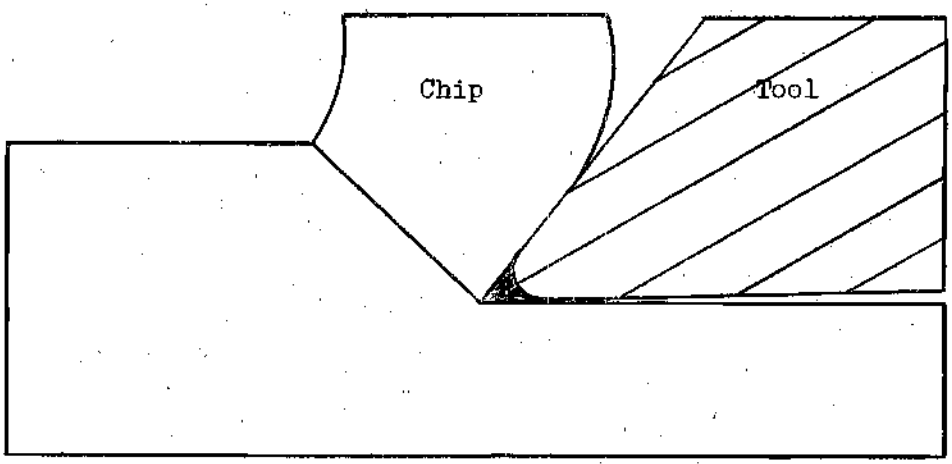


Figure 2. Ploughing Process

expand the layer adjacent to the tool face, contributing in this way, to chip curling. A minor portion of the metal will be pressed into the newly produced work surface causing residual compressive stresses, usually found after a machining operation. The development of a more complete force diagram which separates the ploughing force from the chip-tool interface force is shown in Figure 3.

In his development Albrecht used the term sharpness to define the very small rounding of the extreme cutting edge which is the tiny, approximately cylindrical surface connecting tool-flank and tool-face surfaces. This small cylindrical surface is developed on the cutting edge during grinding of cutting tool. As the grinding wheel works along the tool-face or tool-flank, tiny particles of tool material break off the extreme edge where the edge is so thin that the material cannot stand the impact of

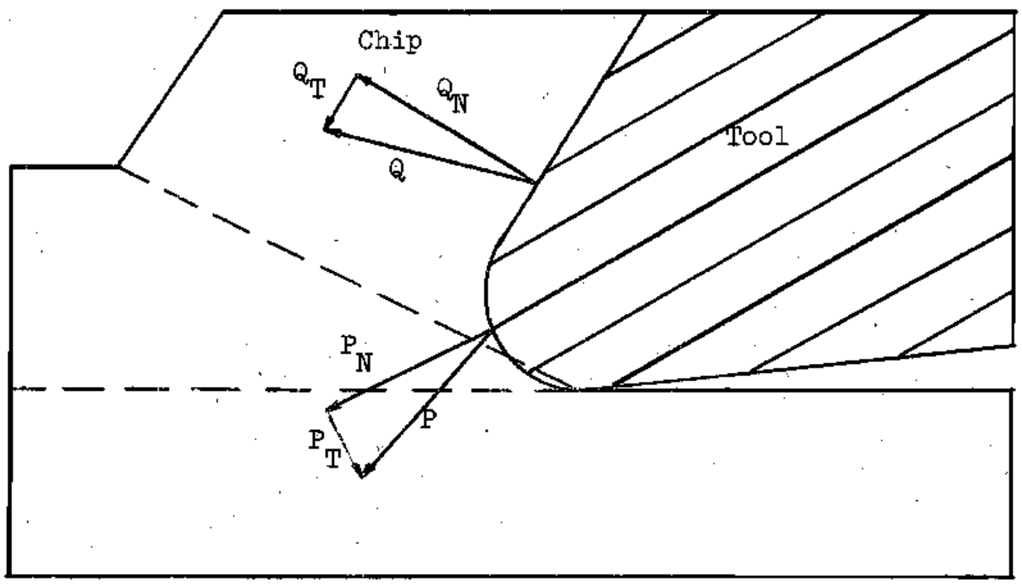


Figure 3. Force Diagram Containing Ploughing Force

grinding-wheel grains. It should be noted that the grinding wheel does not generate the rounded surface. Thus its surface finish can be expected to be much rougher than that of surfaces which were produced by the grinding wheel directly. The radius r of such a surface gives the magnitude of the rounding and thus can be adopted as a measure of the sharpness of the tool.

Methods of a mechanical-optical nature have been used to measure the radius. The magnitude of the sharpness radius was found to depend on several variables and usually to fall into the range between 0.0001 - 0.001 in. The higher values of this range were found to correspond to the negative range of rake angles and the smaller to high positive rake angles.

The sharpness concept can be usefully analyzed by way of the parameter r/t where r is the sharpness radius and t is the undeformed chip thickness. Albrecht undertook an investigation in which he attempted to see how the curling of the chip would react to a change in the ploughing force. This could have been done best by decreasing the sharpness radius until it becomes insignificant. However, this is not practical, and he therefore greatly increased the sharpness radius and kept the uncut chip thickness small instead. Albrecht found no ploughing when r/t becomes greater than unity. The tool face was out of range of chip-tool contact, and so the chip-tool contact ended in the rounded portion of the cutter. In this way the rounded portion served as the tool face. The chip obtained under these conditions showed no curl at all. It should be noted, however, that some of the straightening effect was due to the rounded tool face having a curvature in the opposite direction from usual chip curl.

For values of r/t less than unity, the curling started to appear at a value of t such that the rounded part of the surface ceased to function as a rounded tool face and started to act as a sharpness rounding producing a ploughing effect. In other words, when the uncut chip thickness is sufficient to provide chip-tool contact on the flat portion, chips curl.

Albrecht claimed that chip curling can be expected to become less and less pronounced with increasing thickness of the chip because of its higher rigidity. This is because the amount of metal ploughed remains essentially constant. Thus he states the ploughing force is independent of t, except at small values.

M. C. Shaw refuted the claim that the rounded nose on a tool has a significant effect (8). He claimed that practically all research work involving the analysis of cutting forces and stresses is conducted with sharp tools and values for undeformed chip thickness that are 0.005 in. or greater. Shaw claimed that it is not difficult to obtain and maintain a cutting edge having a radius of 0.0002 in. or less at low cutting speeds and hence that the size of the round nose is insignificant relative to the depth of layer removed. A very large nose would undoubtedly have a significant influence on cutting force results, but this would be poor practice. According to Shaw, only when cutting with a very dull tool or with a large built-up edge is the concept of ploughing a valid one.

In refuting this discussion by Shaw, Albrecht claimed his observations were based on actual figures and not on guesses or assumptions. He showed the ploughing force may attain a value in hundreds of pounds, equaling in magnitude other forces developed in metal cutting in the range of smaller t's.

Albrecht reasoned the validity of the ploughing force in this manner: he said that Shaw and others observed previously a change in the magnitude and direction of the resultant force on the tool when the chip-tool contact length is artificially decreased. This can only mean, then, that the resultant force associated with contact along the flat tool face is incomplete; that there must be a second force system contributing to the total force - namely a force system at the cutting edge - a ploughing force. Then, artificially decreasing the contact length on the tool face will change the relative magnitude of these two force systems, thus changing the observed magnitude and direction of the overall resultant force. This change in magnitude and direction of resultant force, that is, change in cutting force and apparent coefficient of friction, is predictable only when the two force systems are postulated. Thus Albrecht claimed his experimental work confirmed the existence of a ploughing force.

CHAPTER III

EQUIPMENT

The experimental runs were made using equipment pictured in Figure 4. A tool dynamometer was mounted on an engine lathe and the strain recorded on Sanborn equipment.

The tool dynamometer consists of a steel frame which houses strain gages on a round shaft (see Figure 5). The end of this shaft serves as the toolholder to which tools are firmly secured. The strain gages are attached so that they read the strain in both the cutting and thrust directions. The dynamometer is mounted on the lathe so that the tool can cut at the center of the workpiece at all times. A Tinius Olsen tension testing machine was used to calibrate the dynamometer.

The Sanborn recorder is a portable model with two panels, each having its own recording stylus (see Figure 6). The device consists of a full bridge element which acts to measure the resistance induced by the strain gages. The bridge is balanced by varying the resistance and capacitance quantities. Recordings of the strain are burned on a waxed recording sheet by a heated stylus (see Figure 20 in Appendix A for a sample record).

The engine lathe is one made by the Monarch Machine Tool Company. The carriage has a 14.5 inch swing and there is a 30 inch distance between centers.

The workpiece materials varied from brittle to ductile. Cast iron, aluminum, and steel were selected as the range. These materials were cut with high speed steel tools of the Firth Stirling brand. During the investigation workpiece hardness readings were taken on a Rockwell Hardness Tester.

The edges of the tool points were cut off by a Precision-Jarrett Abrasive Wheel and mounted in lucite. The sharpness radius was then measured by optical and photographic equipment.

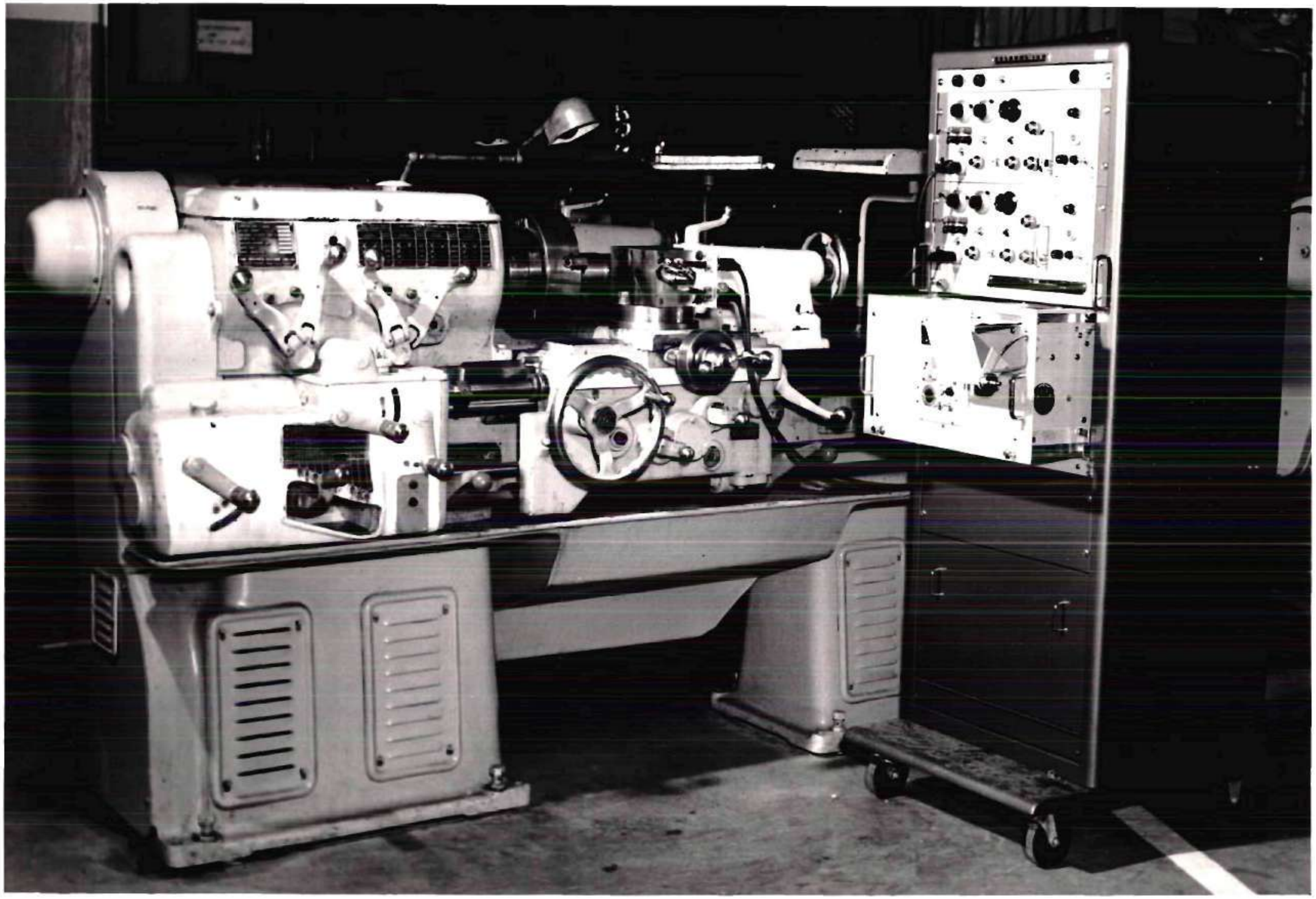


Figure 4. Test Equipment.

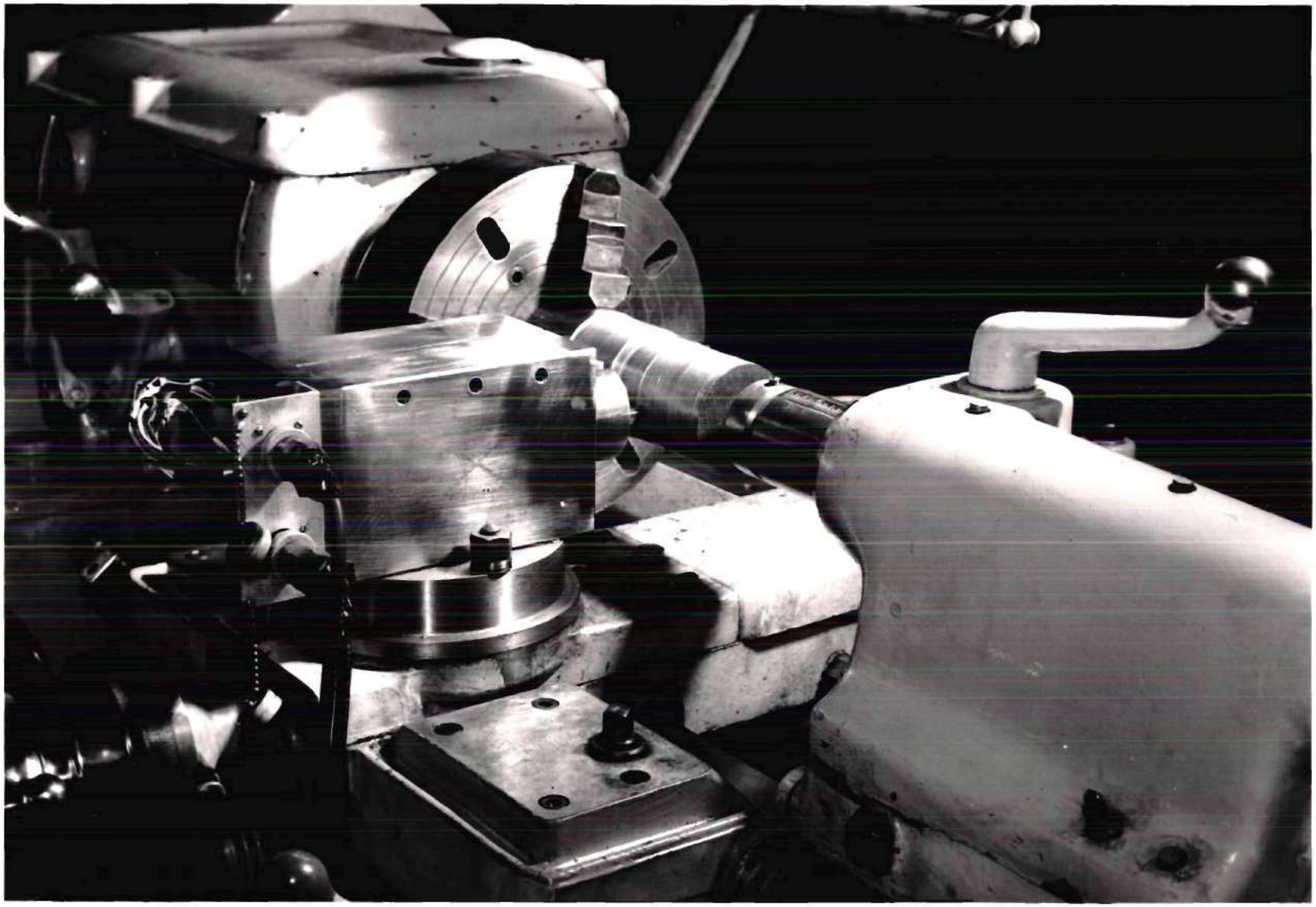


Figure 5. Lathe Dynamometer.

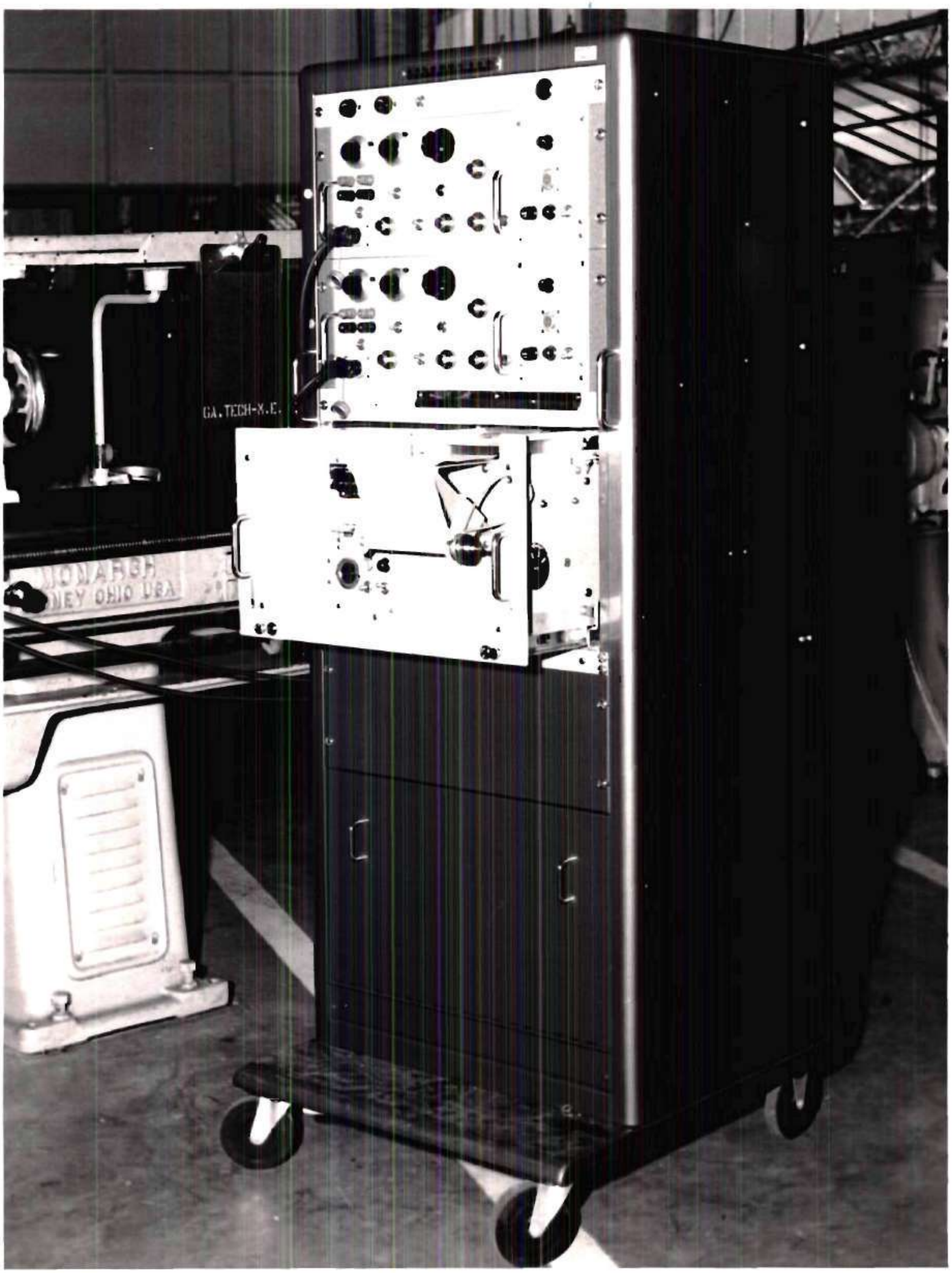


Figure 6. Sanborn Model.

CHAPTER IV

PROCEDURE

Preparation.--The piece of stock was first turned in the lathe so that the cylinder was of uniform diameter. The material was then taken out of the lathe and hardness readings taken with a Rockwell Hardness Tester. Several hardness readings were taken and an average obtained. The material was then put back in the lathe. The Sanborn bridge was balanced and the correct settings made on the machine.

Cutting.--The cutting tool was fastened in the dynamometer and the depth of cut set as a constant on the lathe. Cuts were taken with this tool varying the feed over a range of 0.0023 to 0.0260 inch per revolution. The speed of the machine and depth of cut remained constant over the range of feeds. At this point, the material was taken out of the lathe and again hardness tested.

Measuring the radius.--The cutting edge on the tool was carefully protected until it could be cut off with the abrasive wheel. This cut was made in one simple, fast operation. The small cutting edge was then mounted in lucite and the edge to be measured polished. By optical and photographic means the radius was magnified to many times its size and measured by a comparative process. Comparing the radius with known radii a definite dimension could be established.

CHAPTER V

DISCUSSION OF RESULTS

The three specimens used in these experiments varied from ductile to brittle. The Rockwell hardness readings shown below were taken before cutting. Due to work hardening, the surface became harder with each successive cut.

Material	Rockwell B hardness
Class 25 Cast Iron	92.0
C 1018 Steel	86.5
6061 - T6 Aluminum	40.0

Forces measured were the cutting force and the thrust force. The cutting force is the force exerted as the tool moves along the workpiece. The thrust force is due to the action of the tool perpendicular to the cutting direction.

Natural sharpness radius.--This radius, the very small rounding of the extreme cutting edge, is the approximately cylindrical surface connecting tool-flank and tool-face surfaces. The radii of the tools used are:

	Tool Rake Angle	Radius	Radius History
1.	-30	0.00100	natural
2.	-10	0.00083	natural
3.	0	0.00069	natural
4.	10	0.00049	natural
5.	10	0.00052	natural

	Tool Rake Angle	Radius	Radius History
6.	20	0.00040	natural
7.	30	0.00020	natural
8.	20	0.00220	intended
9.	20	0.00075	intended
10.	30	0.00037	intended

Tools 1-7 were ground and the radii formed were those formed in the process of grinding the tool-flank and tool-face surfaces. The negative rake angles have the largest values of radii and the higher positive rake angles have the smallest radii. The tools 8-10 do not fit in this category because a definite radius was ground on them. These radii are not due to the wearing of the edge alone.

Cutting force.--Comparing the materials used, Figure 7 shows that, for the same speed, feed, and tool, the steel specimen required the largest cutting force. The cast iron and the aluminum were next in that order. The least power is used in a cutting operation where the cutting force is a minimum.

In studying the cutting force versus r/t, the feed t could have been held constant and the sharpness radius r varied. However, this was not practical since the radius would have to be measured for each cut. Thus the value of the radius was held constant and the feed allowed to vary with each cut.

To preserve the experimental accuracy, the depth of cut was chosen at 0.010 in. and the speed of the workpiece held to 75 RPM. These values allowed as little pressure as possible to be exerted on the radius, and yet the magnitudes were large enough to obtain good results. The radius itself was measured before and after the series of ten cuts and the difference found negligible.

Figures 7-11 show that as the cutting force decreases the parameter r/t increases. For small values of r/t, where feed is large, the cutting force increases rapidly. For a given radius, a certain feed will determine an r/t at which minimum power will be expended and best cutting occur.

For aluminum, cutting at feeds low enough to maintain the parameter at 0.10 gives good results. Since cutting forces for cast iron are higher than for aluminum, a larger value of the parameter should be chosen. Cutting as close as possible to 0.50 gave good results in this case. The parameter value should closely approach 1.00 for cutting steel under these conditions. At above values, the power expended is minimum.

For example, in Figure 7, the best parameter value is 0.10 for aluminum. The measured radius of the tool is 0.00040 in. and, therefore, the best feed would be 0.004 inches per revolution. This condition is for least power when cutting at 75 RPM and a depth of 0.010 in.

Figures 12-14 are graphs of cutting force versus parameter r/t. In each figure three curves plotted for different size radii appear. The higher cutting forces are evidently associated with the larger radii. The feed varies the same for each curve, and therefore is a constant factor.

For a parameter value of 0.10, the corresponding cutting forces in Figures 12-14 are plotted in Figures 15-17. These graphs show how the cutting force increases with the sharpness radius. Thus, the cutting

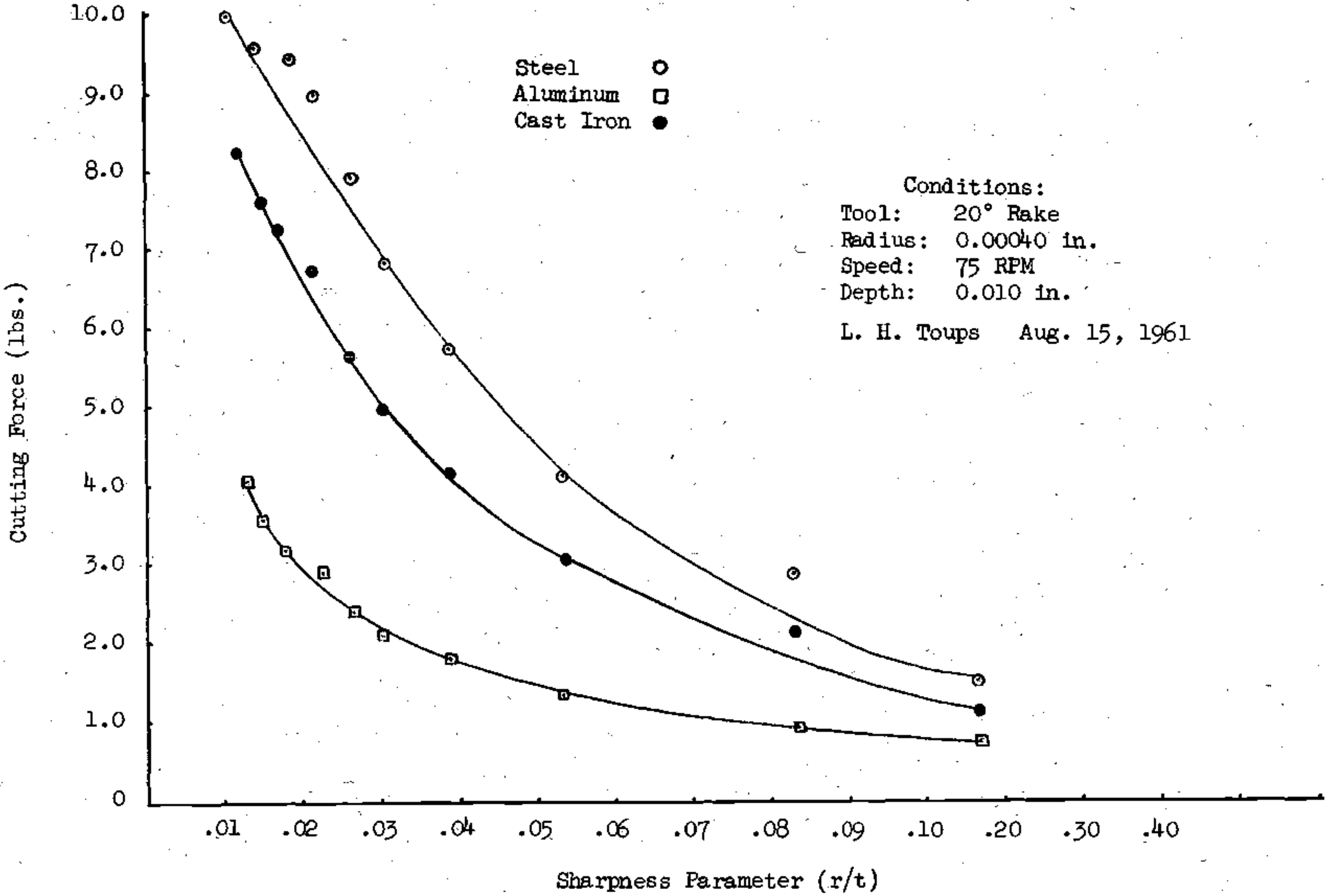


Figure 7. Cutting Force vs. Sharpness Parameter

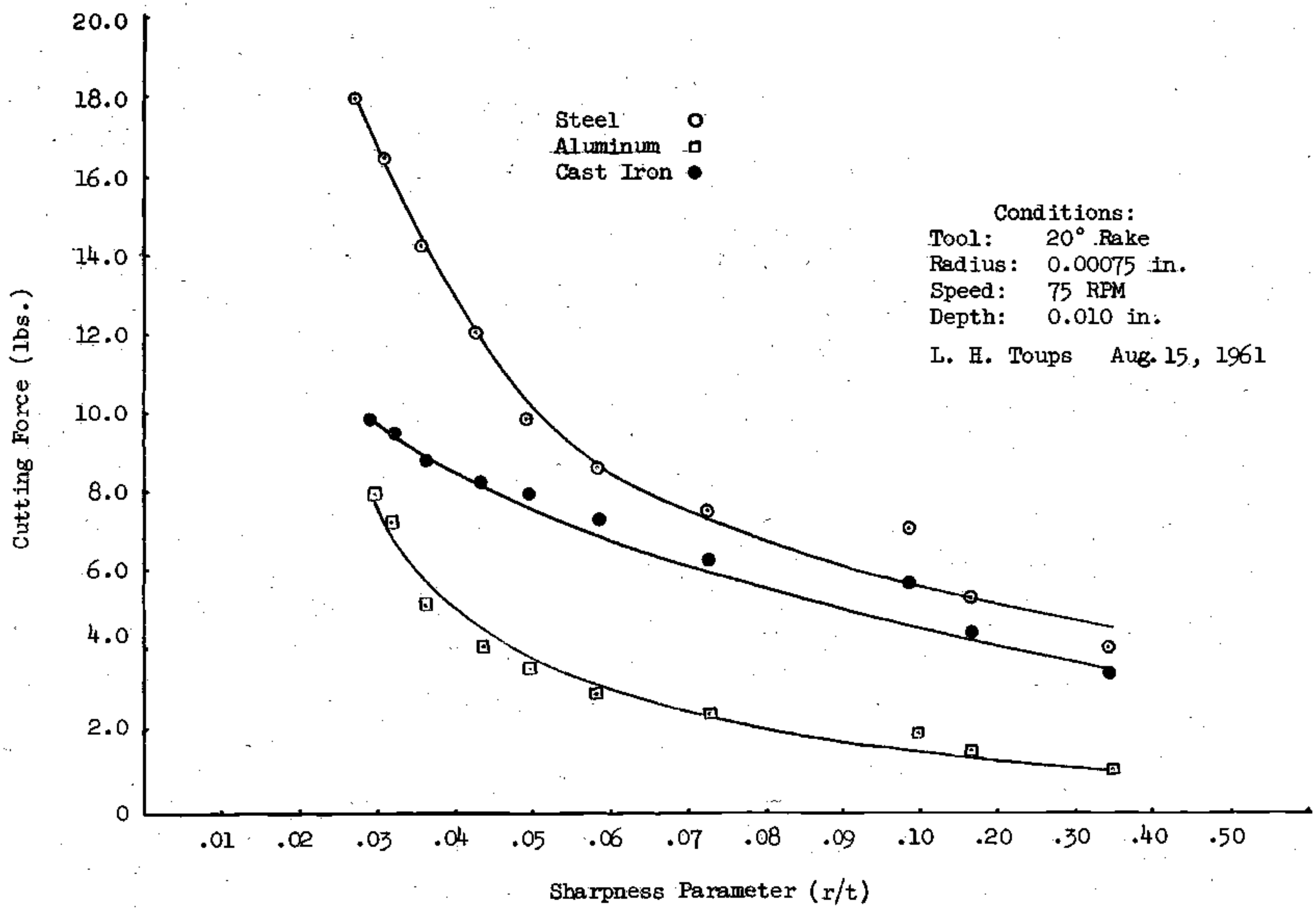


Figure 8. Cutting Force vs. Sharpness Parameter

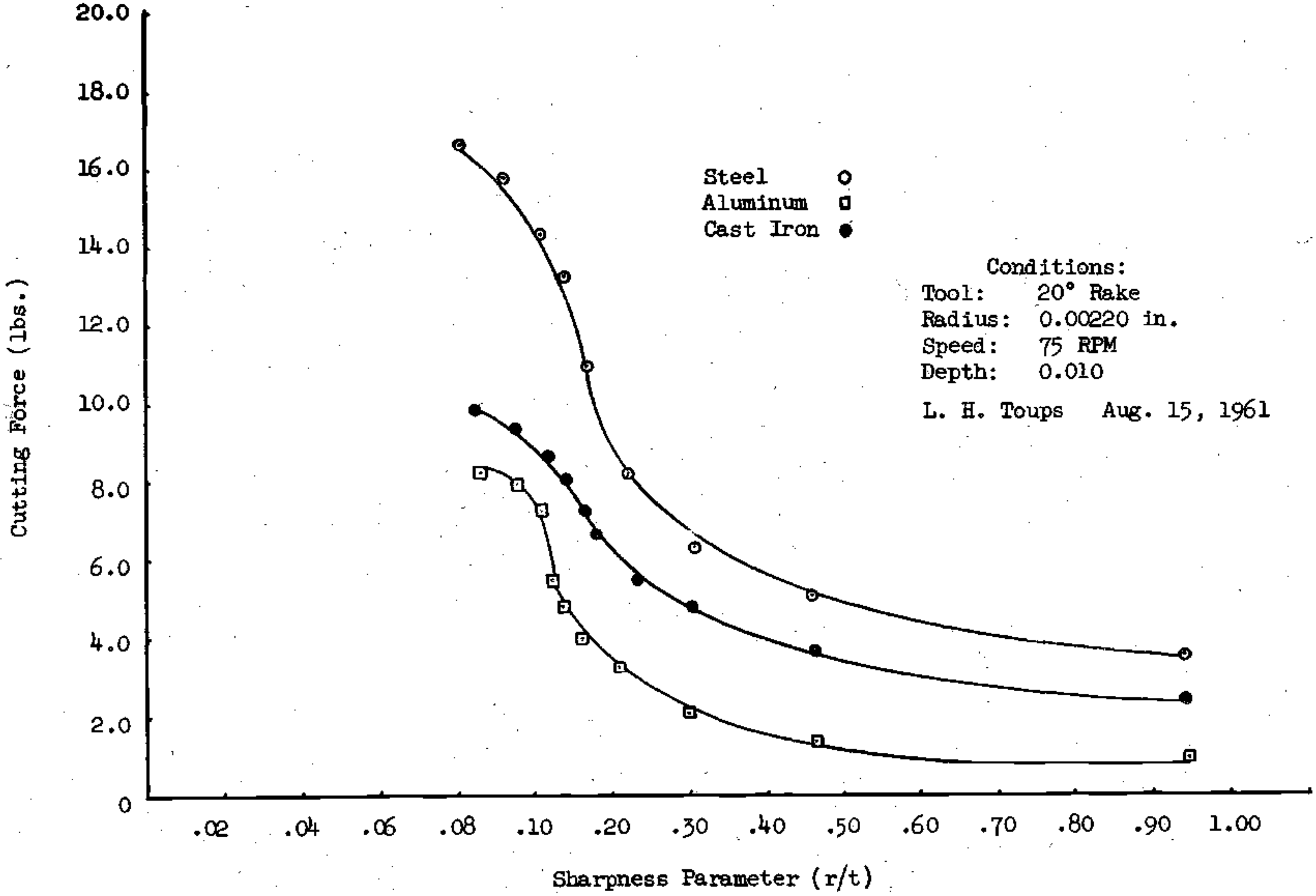
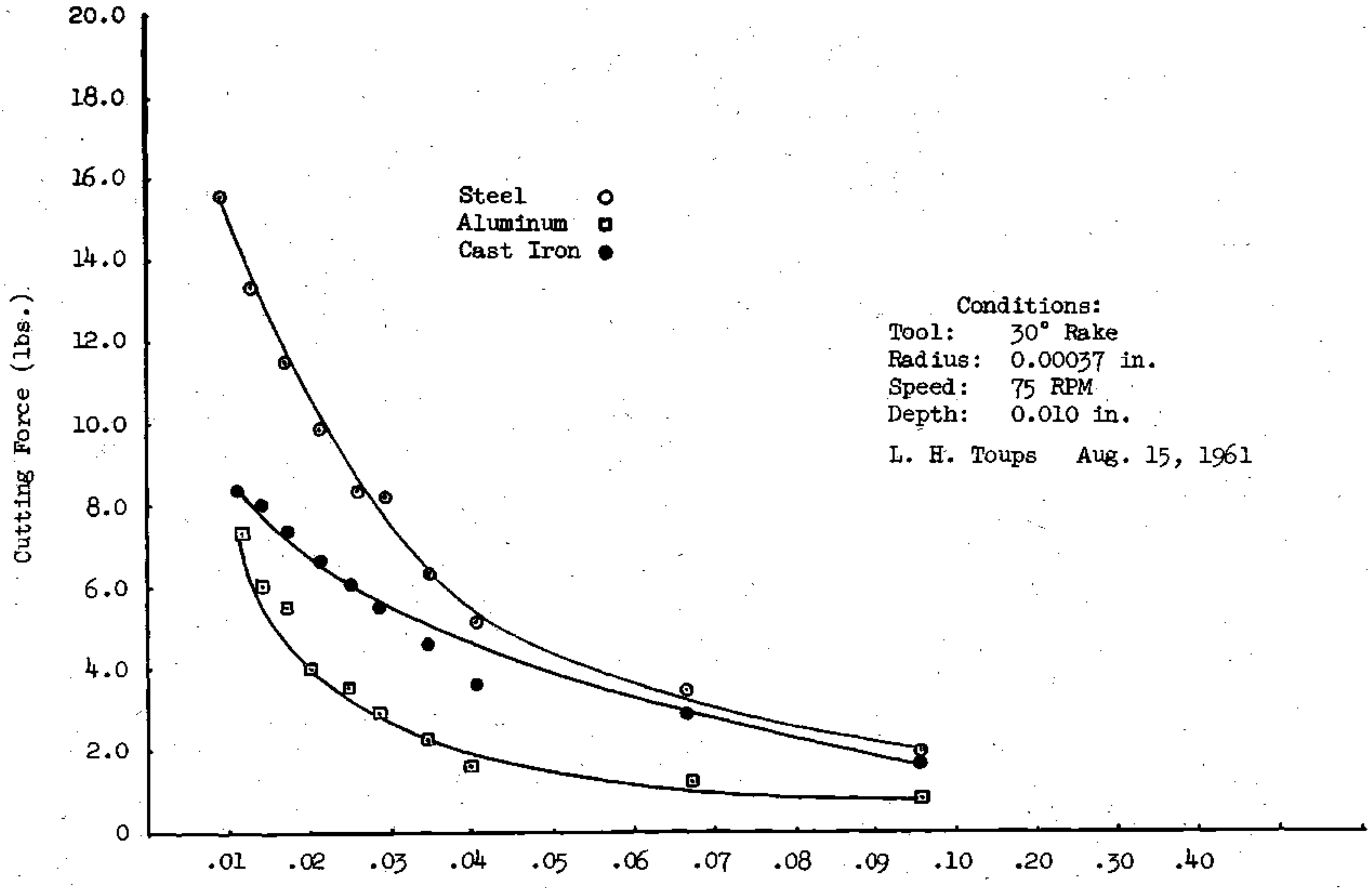


Figure 9. Cutting Force vs. Sharpness Parameter



20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
Cutting Force (lbs.)
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.20
.30
.40
Steel
Aluminum
Cast Iron
Conditions:
Tool: 30° Rake
Radius: 0.00037 in.
Speed: 75 RPM
Depth: 0.010 in.
L. H. Toups Aug. 15, 1961

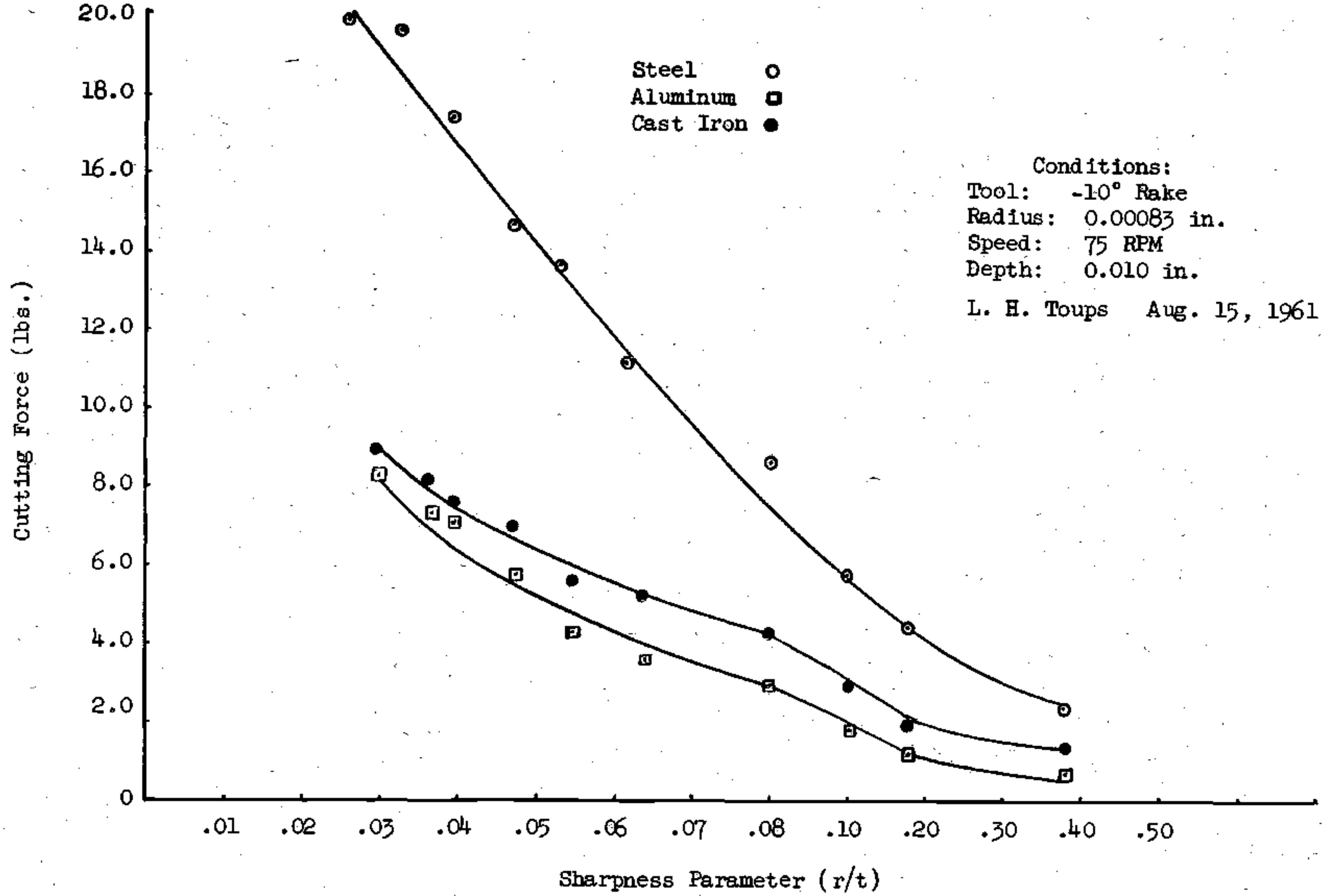


Figure 11. Cutting Force vs. Sharpness Parameter

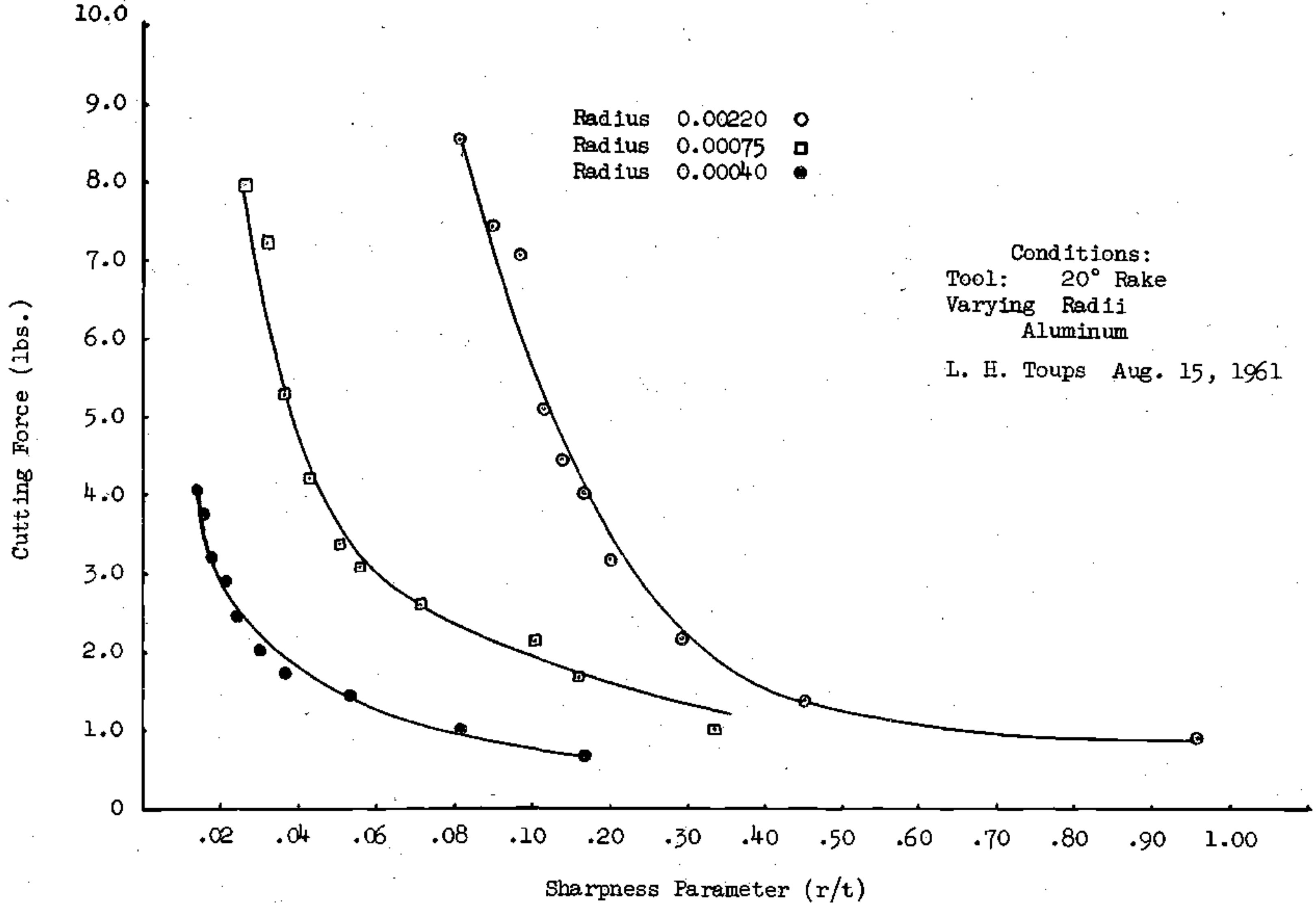


Figure 12. Cutting Force vs. Sharpness Parameter

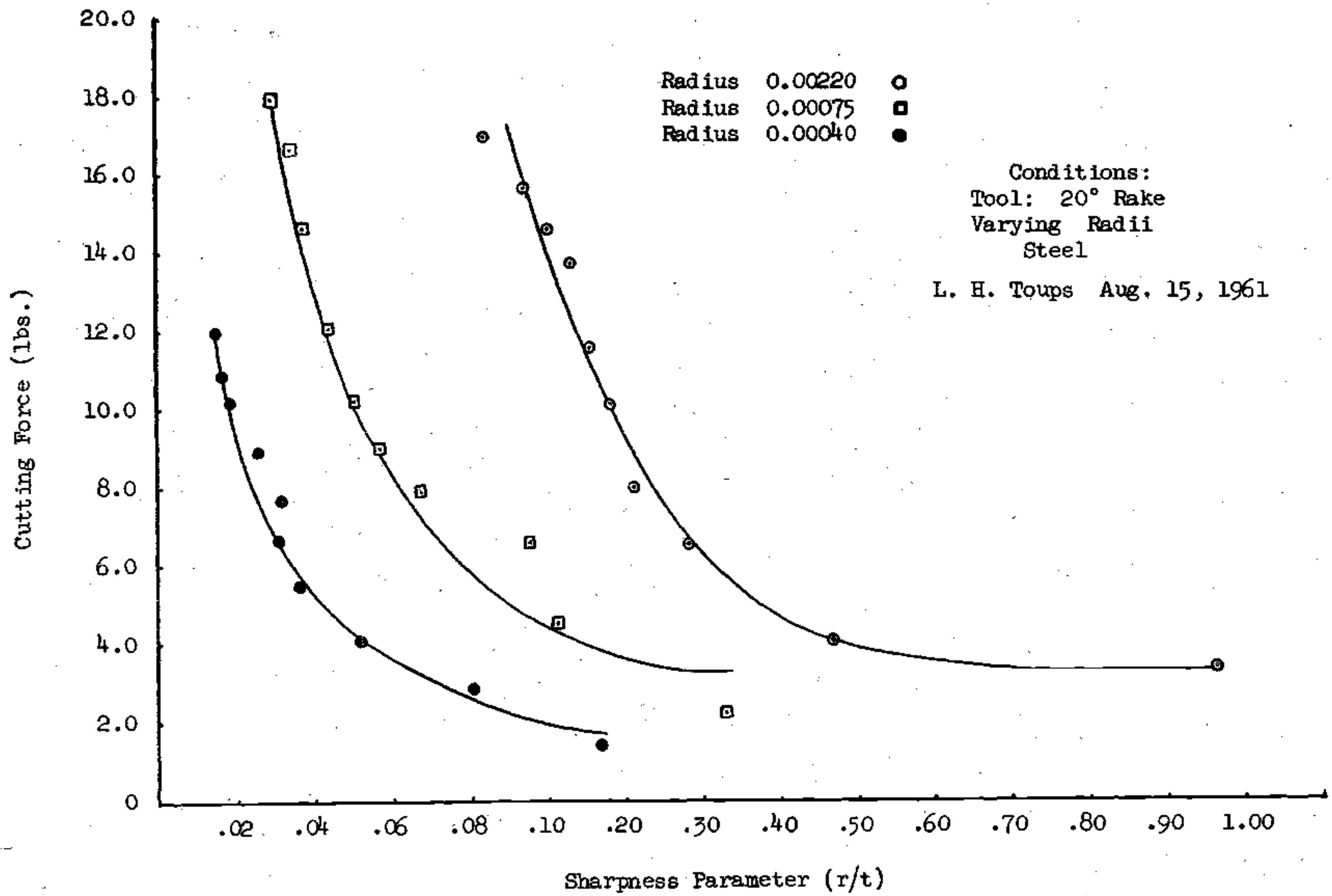


Figure 13. Cutting Force vs. Sharpness Parameter

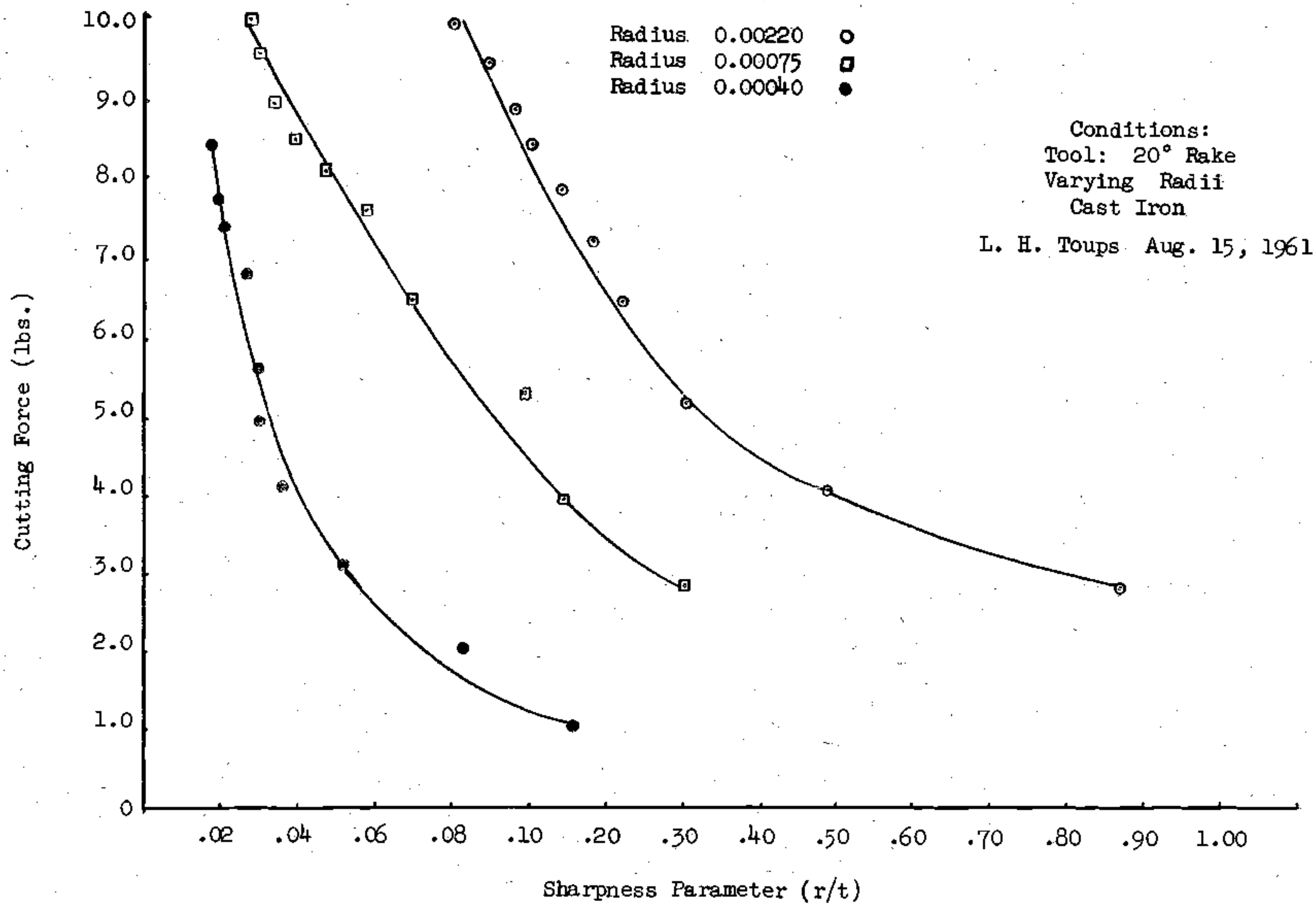


Figure 14. Cutting Force vs. Sharpness Parameter

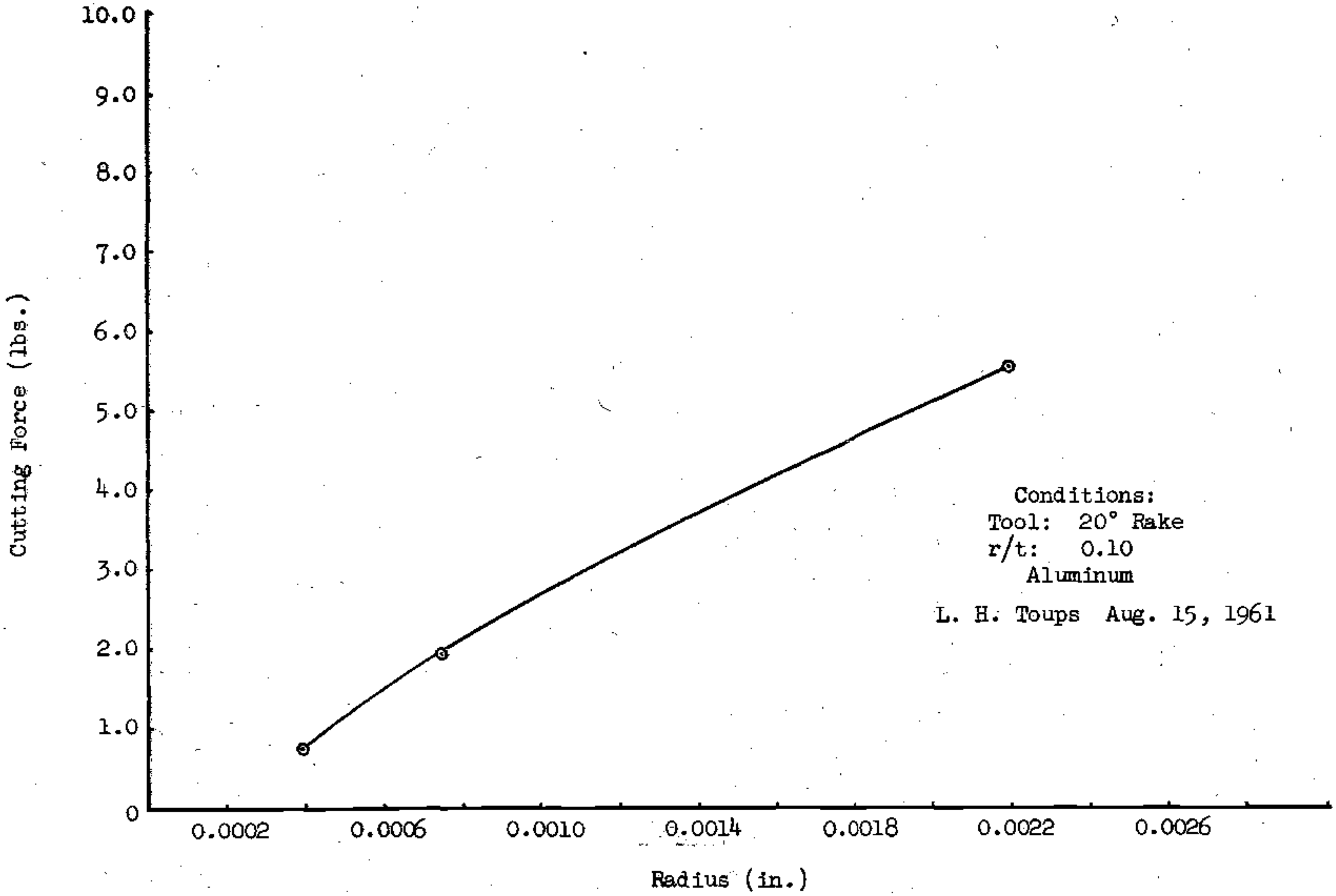


Figure 15. Cutting Force vs. Sharpness Radius

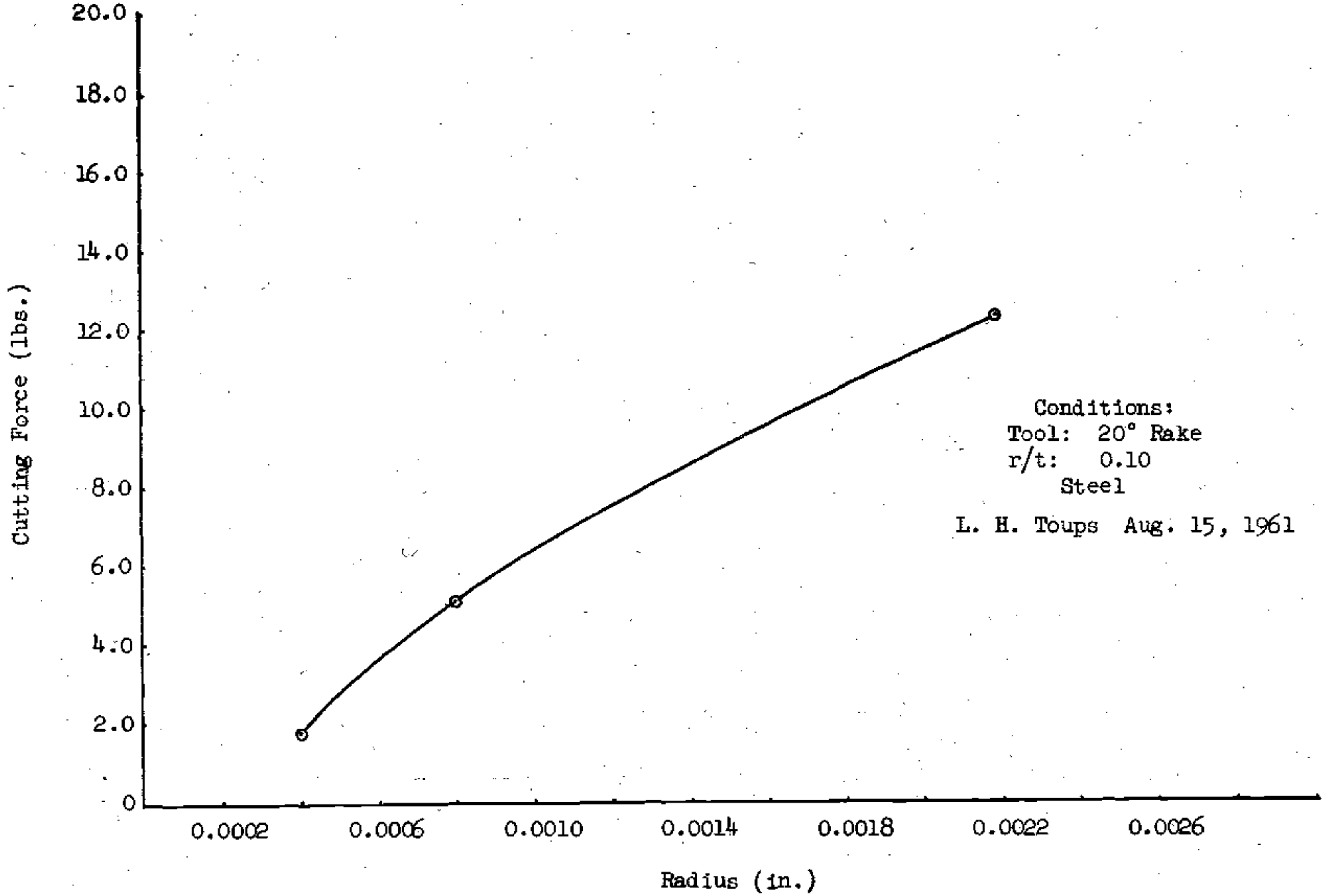


Figure 16. Cutting Force vs. Sharpness Radius

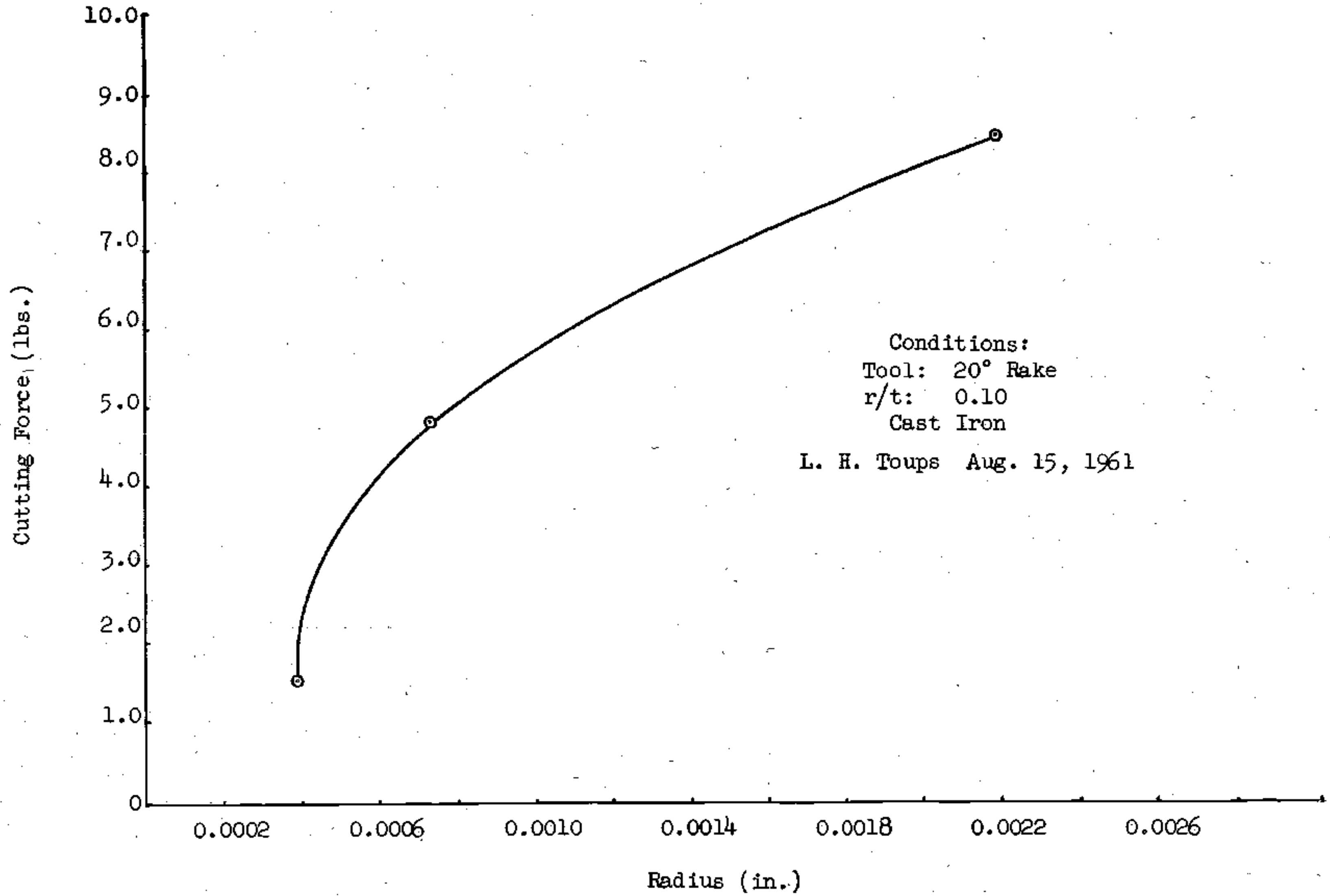


Figure 17. Cutting Force vs. Sharpness Radius

force increases for every parameter value.* This supports Albrecht's claim that the larger the sharpness radius the greater the cutting force. If the tool were perfectly sharp the cutting would be done by shearing only. However, with the sharpness radius present, the forces seem to be affected. The cutting force increases although feed and speed remain constant. Thus it might well be the additional force is due to the ploughing concept developed by Albrecht.

Albrecht found no ploughing when r/t was greater than unity. This is also evident. Figures 7-11 show the cutting forces approaching the abscissa asymptotically. At r/t greater than unity the cutting forces are very small and thus the ploughing force negligible. Albrecht's claim that shearing alone is present at r/t greater than unity seems correct, too.

In studying the cutting force, the parameter r/t was chosen because it was not practical to choose the variable r alone. While investigating this parameter, the radius is held constant and feed varied.

A sharpness radius can be chosen where cutting forces are a minimum. From Figures 15-17, radii less than 0.001 in. appear suitable. The ploughing force is still present. However, it will not be large enough to greatly increase the power used in cutting.

The thrust force, though smaller than the cutting force, acts in the same manner. It starts at a small value, increasing as the sharpness radius increases. However, the rate of increase is greater for the cutting force than the thrust force. Together with the cutting force, the

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*Only three values are used in obtaining the curves in Figures 15-17, because only three sharpness radii are available from Figures 12-14. Certainly more points are desirable. Nevertheless, the trend is evident.

thrust force constitutes the resultant cutting process force. Since the magnitude of the resultant is directly dependent on these forces, an increase in the components means an increase in the resultant force. Characteristics of the thrust forces are shown in Figures 21-31 in Appendix A.

The materials used rank in order of decreasing ductility as: aluminum, steel, and cast iron. This is of no consequence in the experimental data. In Figures 15-17 steel shows the greatest increase in cutting force with increasing radius. Cast iron and aluminum are next in that order. No classification, therefore, can be made at this stage with regard to material ductility.

CHAPTER VI

CONCLUSIONS

Certain conclusions appear possible as a result of the investigation. Certainly the natural sharpness radius falls somewhere in the range of 0.0001 - 0.001 in. Furthermore, Albrecht's claim of the cutting force increase with the sharpness radius, appears at least partly substantiated. Data are meager and not fully conclusive but a trend seems present. Thus, it may well be true that a ploughing force exists in cutting.

It also appears true that at r/t values beyond unity, the effect of the sharpness radius is no longer noticeably present.

Results also seem to show cutting should be done at sharpness radii below 0.001 in. because values above this become costly in power consumption.

A "best" r/t parameter is also an important consideration. For the materials used the values seem to be: 0.10 for aluminum, 0.50 for cast iron, and 1.00 for steel.

CHAPTER VII

RECOMMENDATIONS

Effect of built-up edge upon sharpness radii and cutting forces should be investigated. The ploughing force might depend upon the built-up edge by way of the radius.

Additional investigations could be conducted to determine what portion of the cutting force is due to ploughing.

A wider variety of materials ought to be chosen for an investigation of this sort. The ductility--ductile to brittle--might be found to have an effect on the cutting force or the sharpness radius.

APPENDICES

APPENDIX A

DYNAMOMETER CALIBRATION

To determine the load in pounds from the strain sensed by the dynamometer, the instrument had to be accurately calibrated. This was done by applying a known force to the cutting edge and recording the corresponding strain. A "tool" placed in the dynamometer was positioned so forces could be applied at the point where the cutting edge would be during cutting. Figures 18 and 19 are the calibration curves for the range of interest in this investigation.

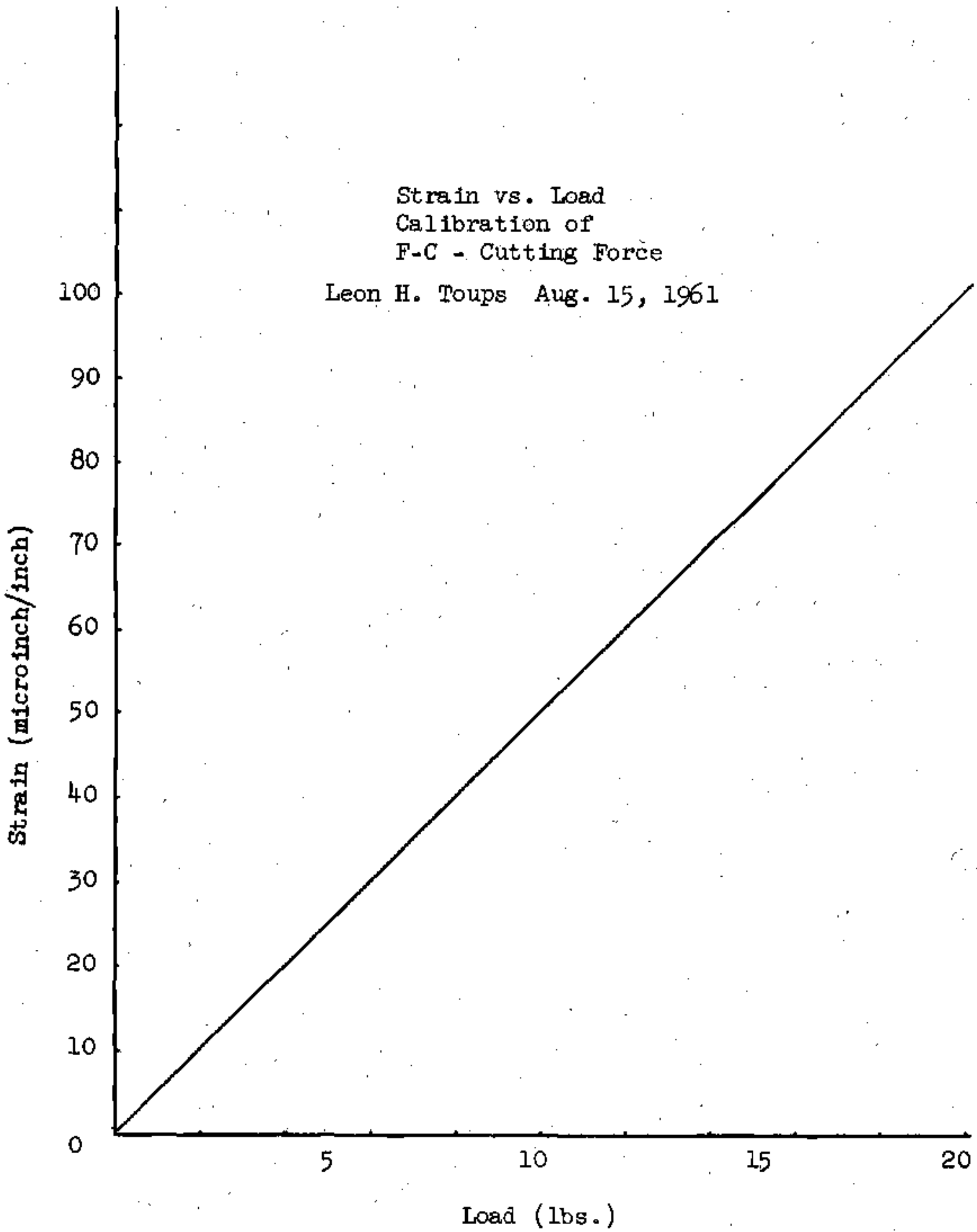

Figure 18. Calibration of Lathe Dynamometer

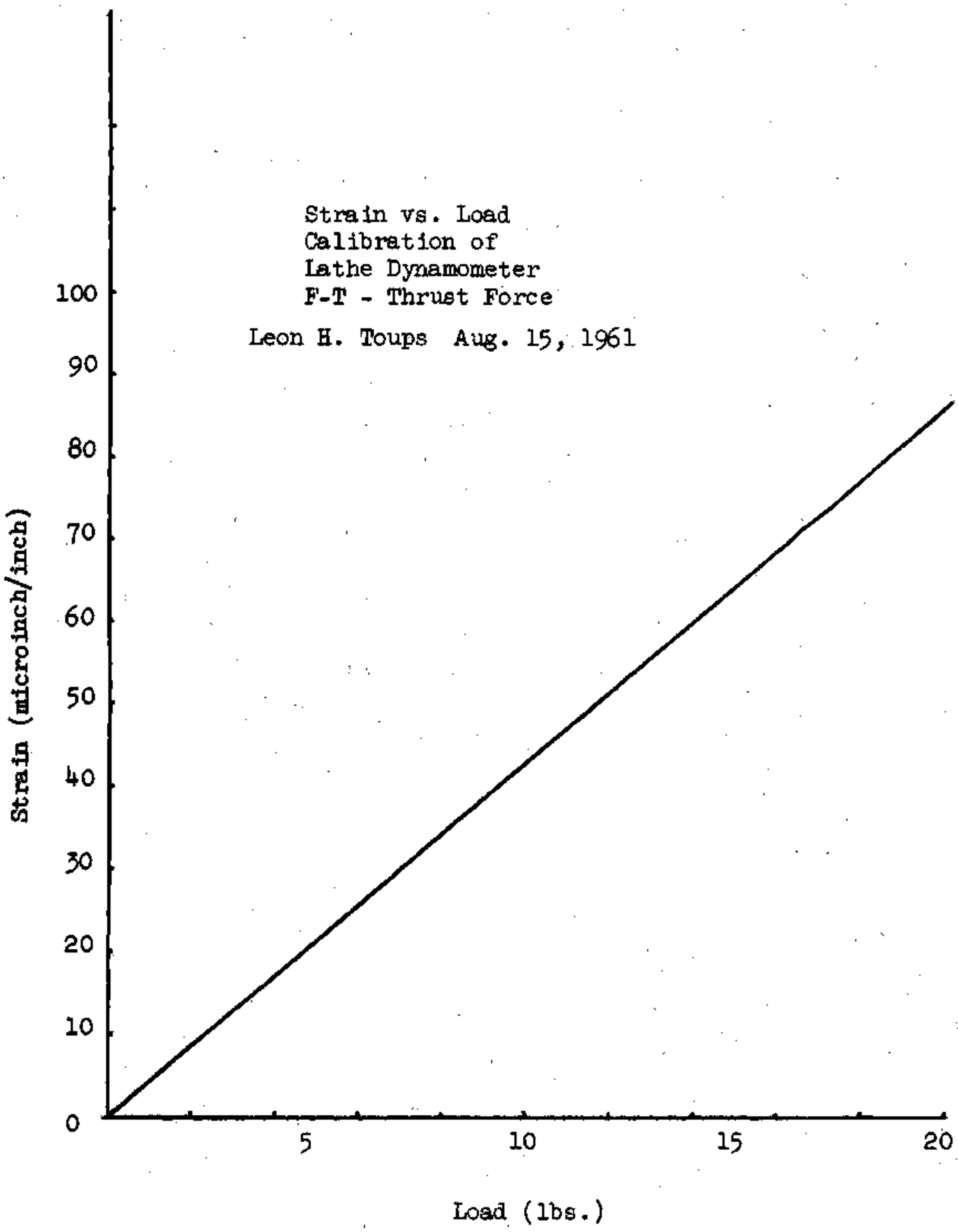

Figure 19. Calibration of Lathe Dynamometer

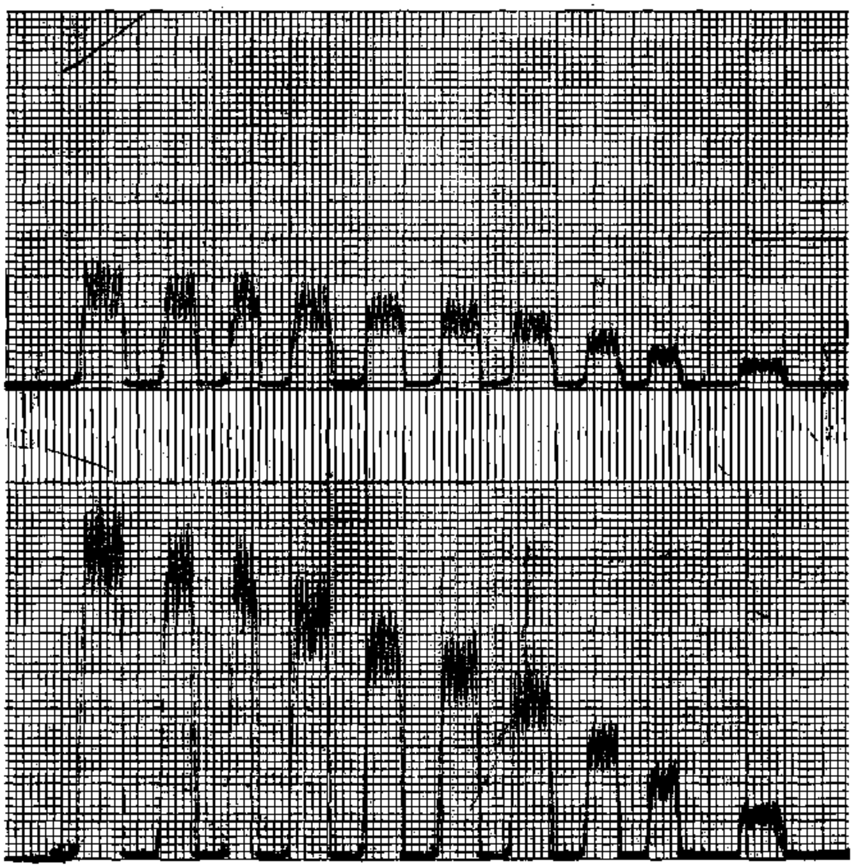

Figure 20. Sanborn Recording.

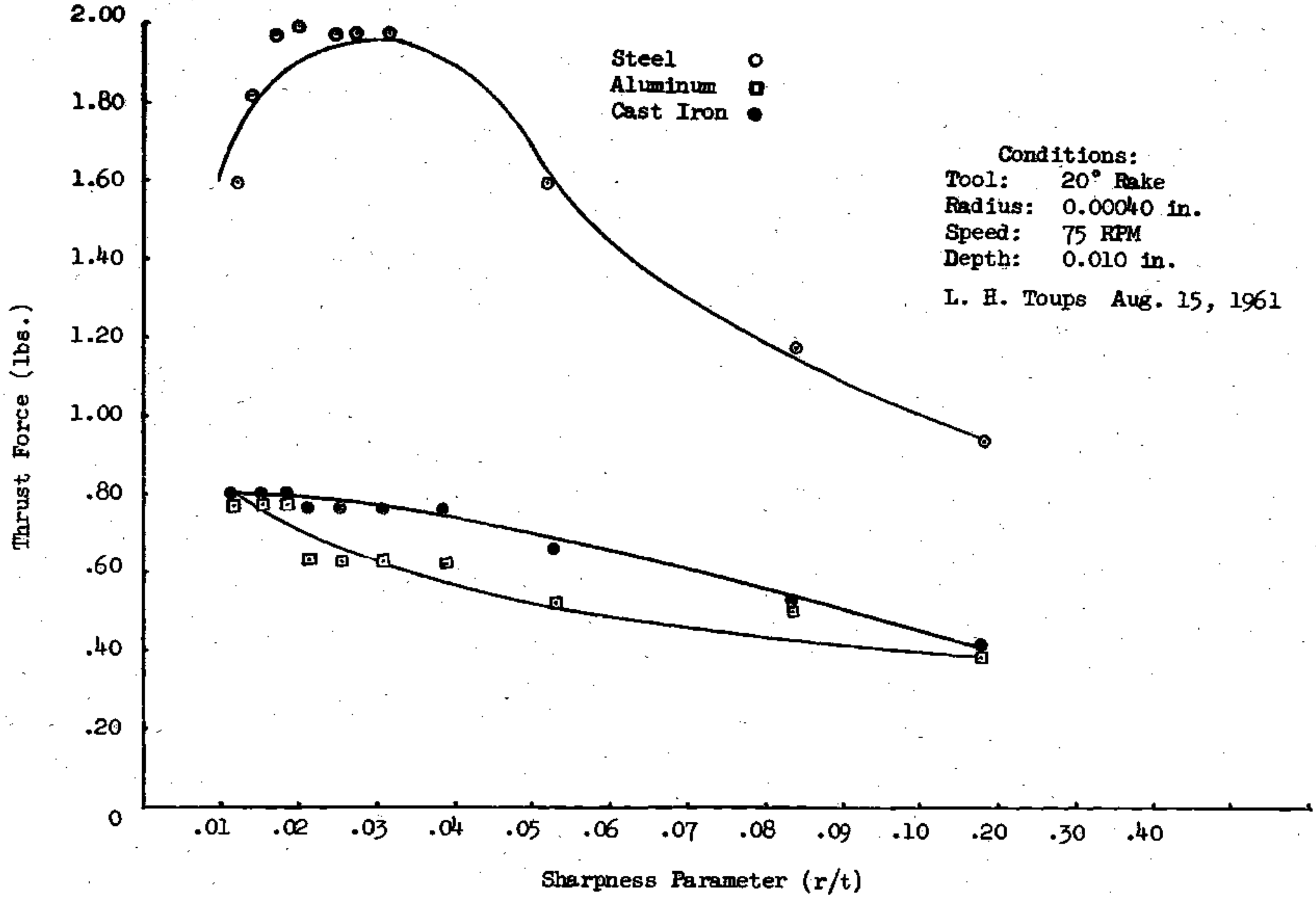

Figure 21. Thrust Force vs. Sharpness Parameter

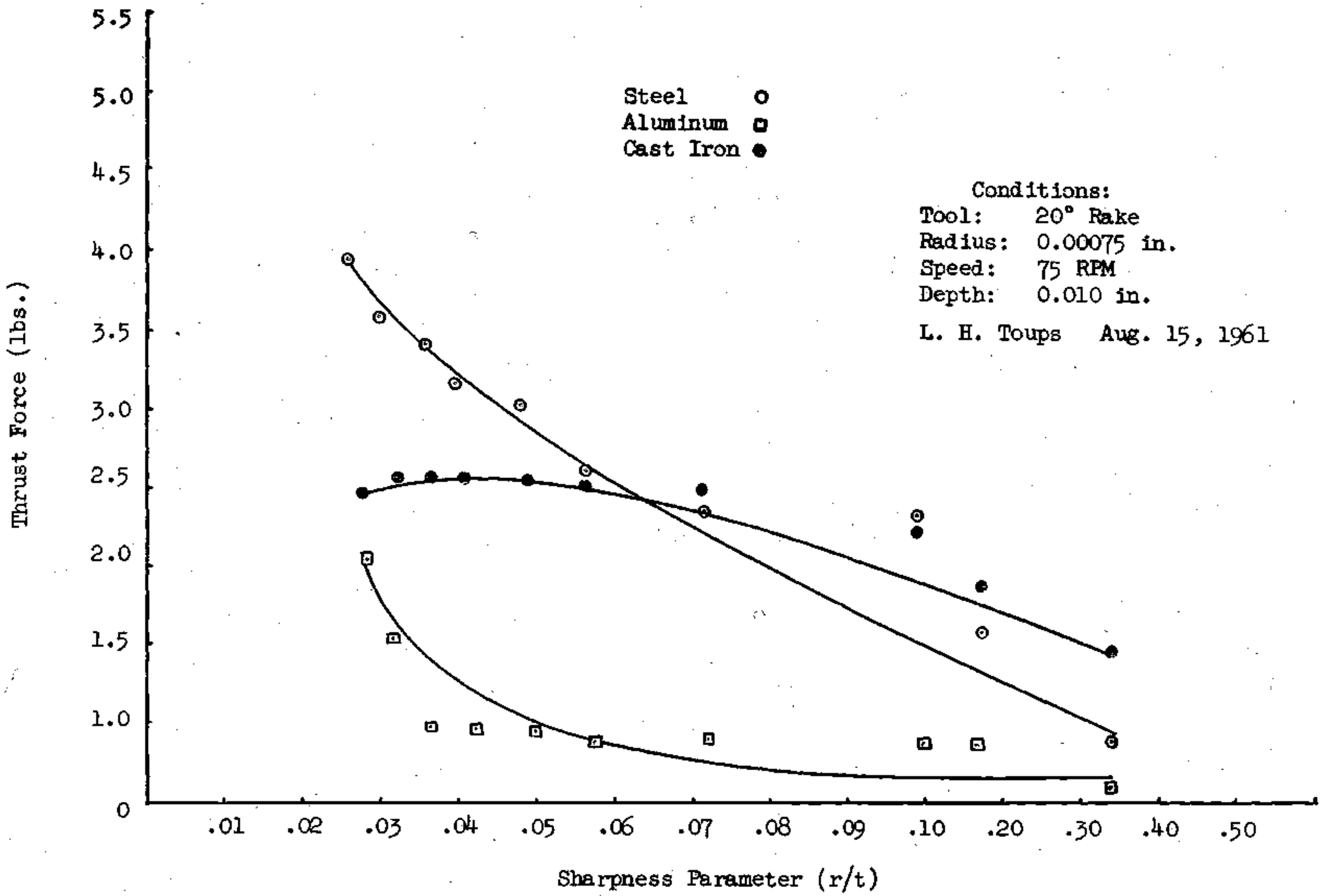

Figure 22. Thrust Force vs. Sharpness Parameter

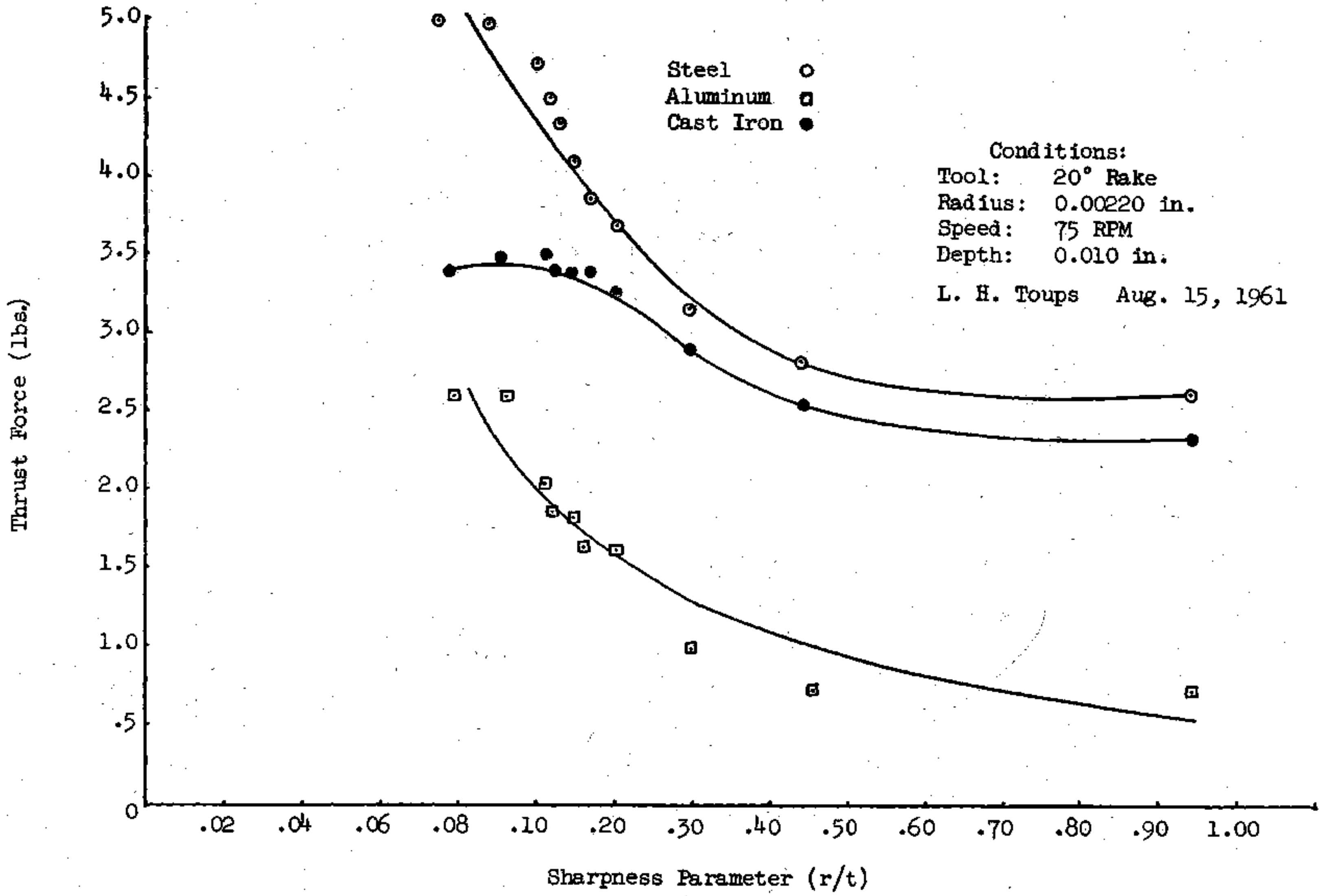

Figure 23. Thrust Force vs. Sharpness Parameter

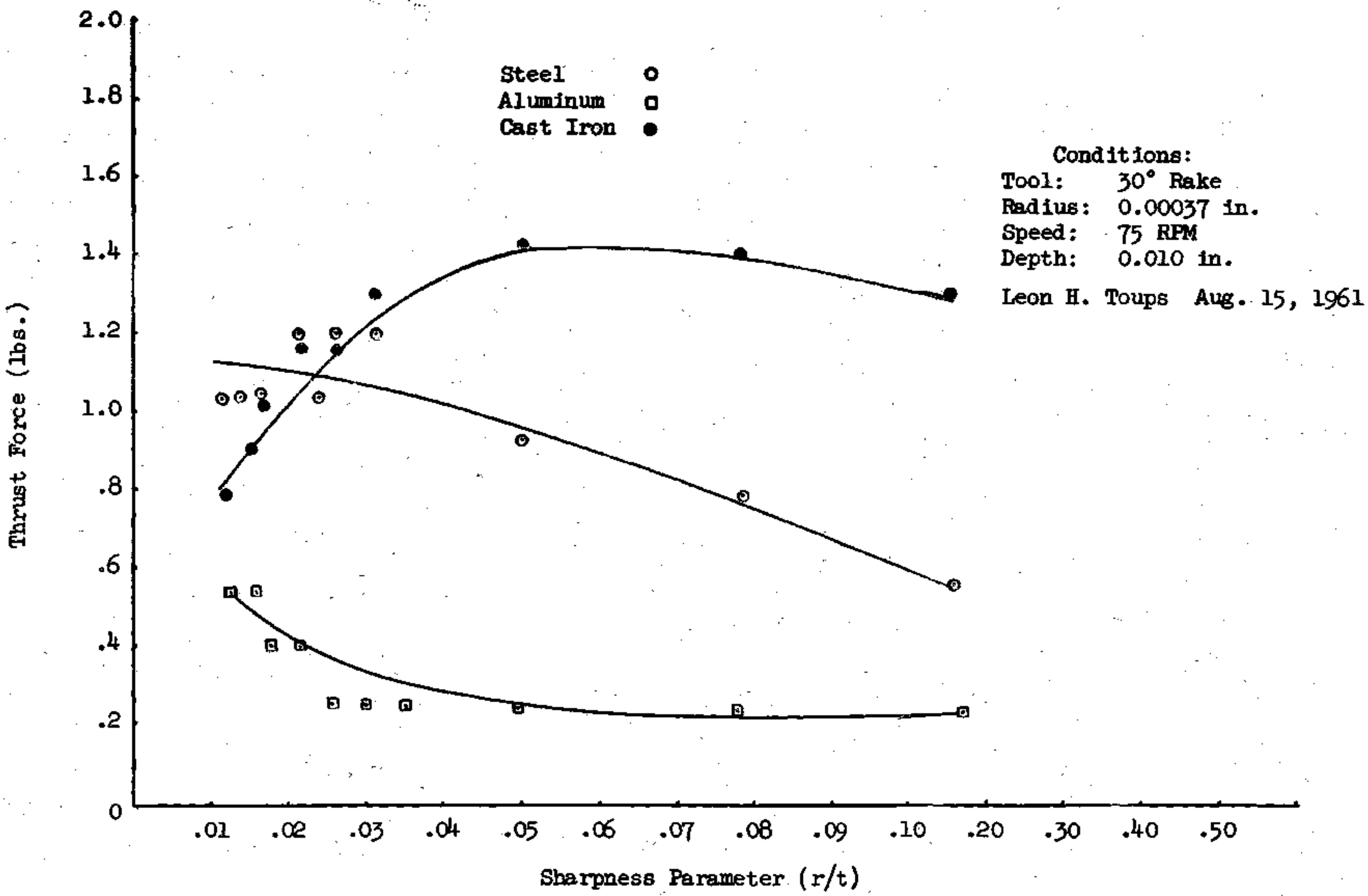

Figure 24. Thrust Force vs. Sharpness Parameter

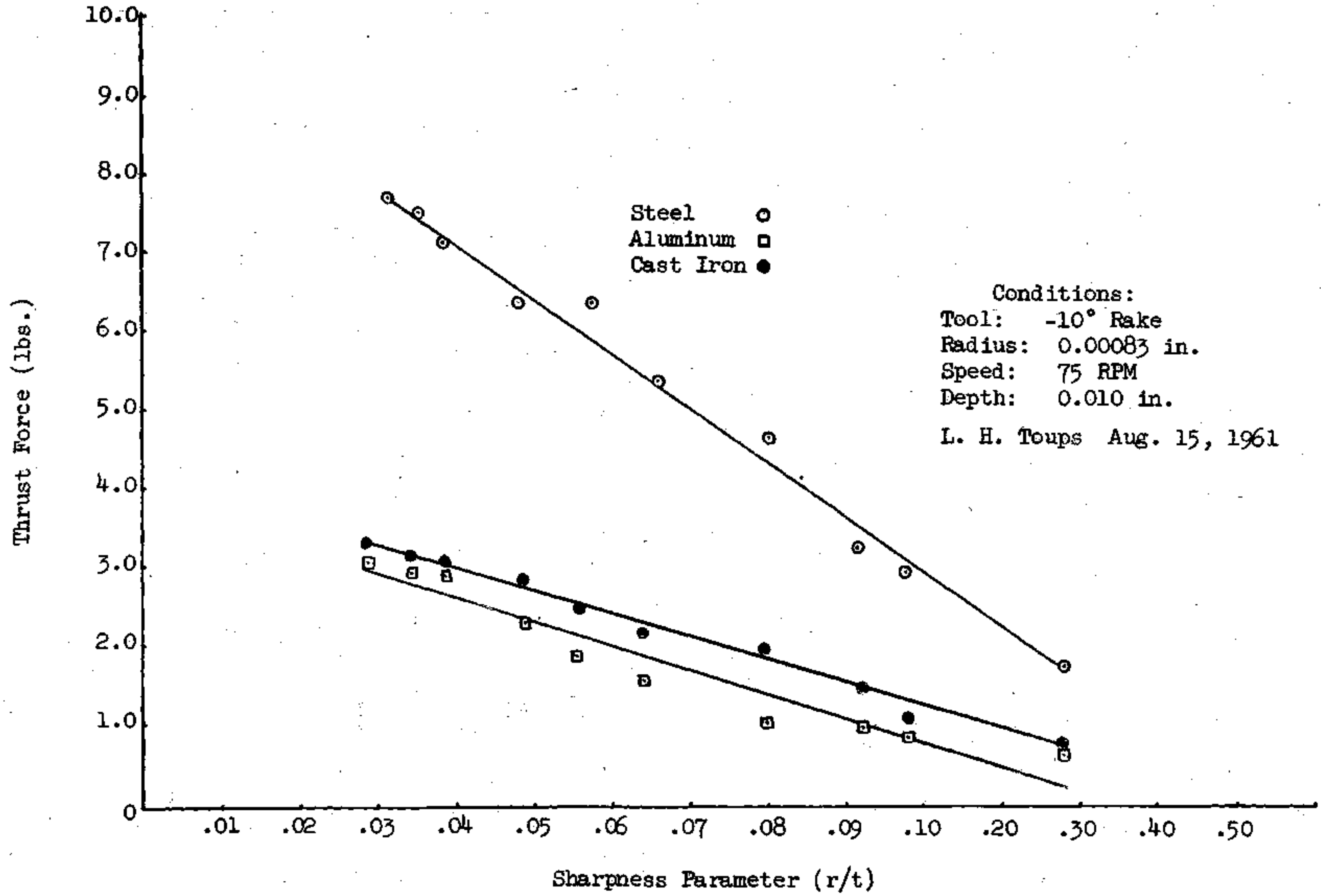

Figure 25. Thrust Force vs. Sharpness Parameter

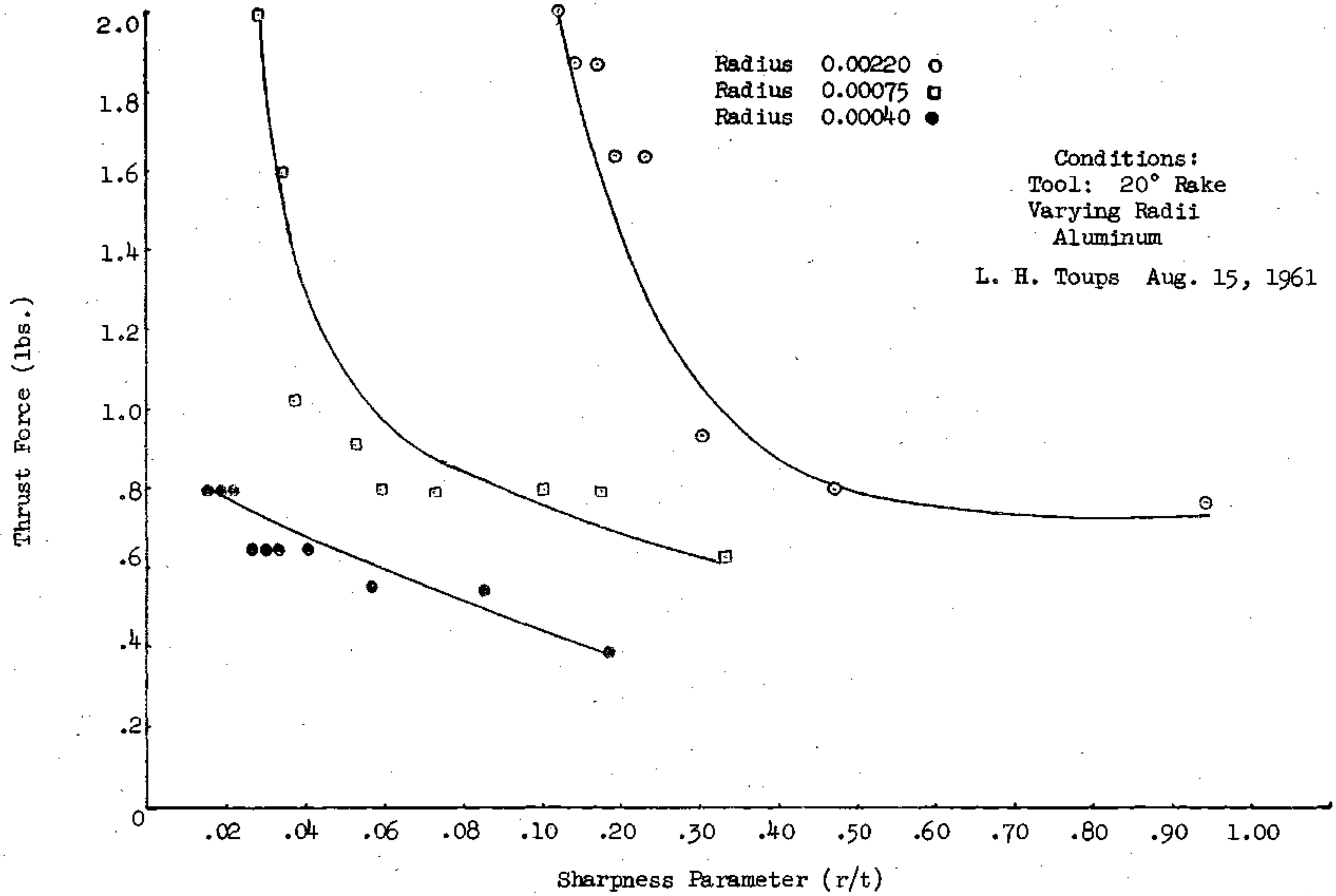

Figure 26. Thrust Force vs. Sharpness Parameter

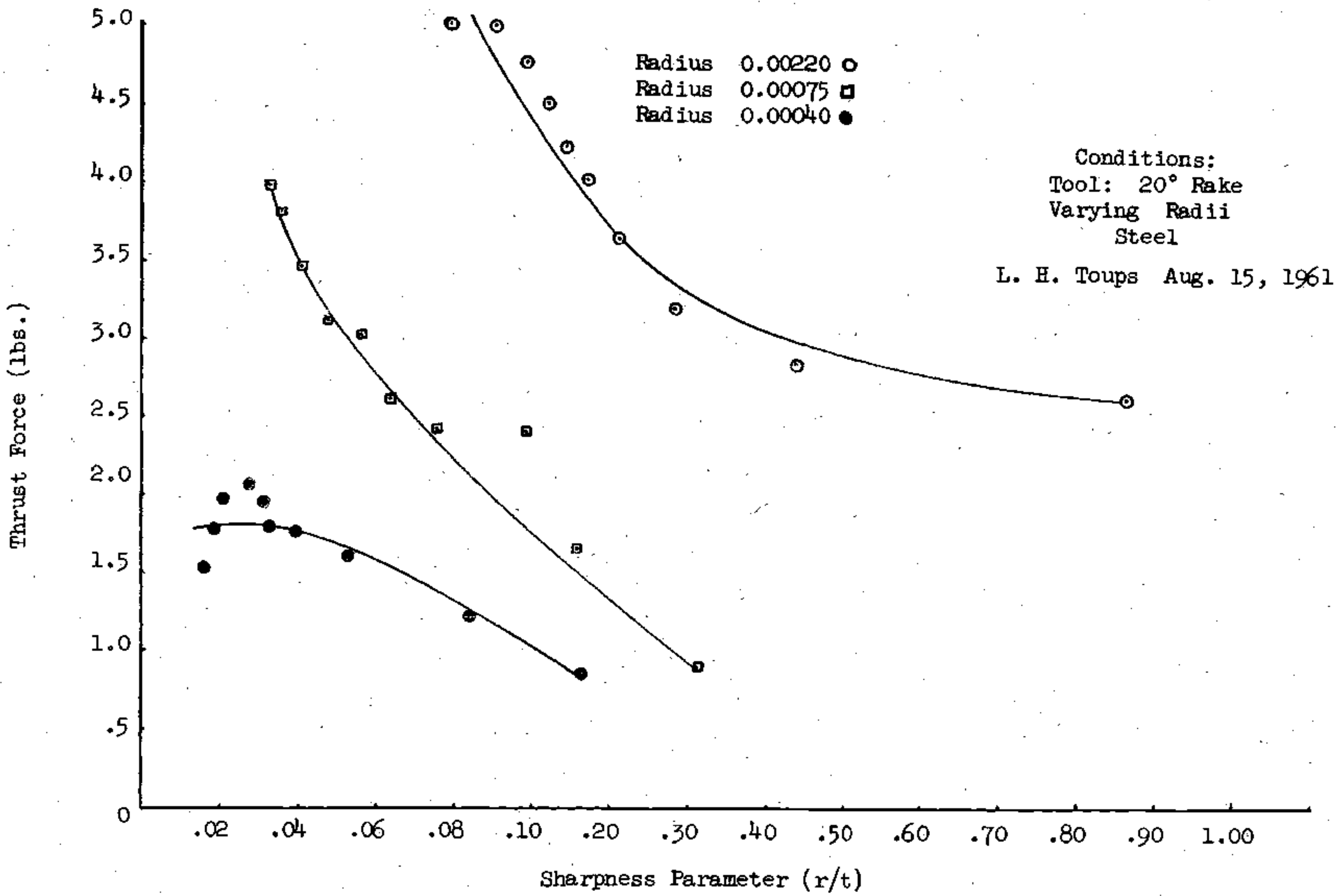

Figure 27. Thrust Force vs. Sharpness Parameter

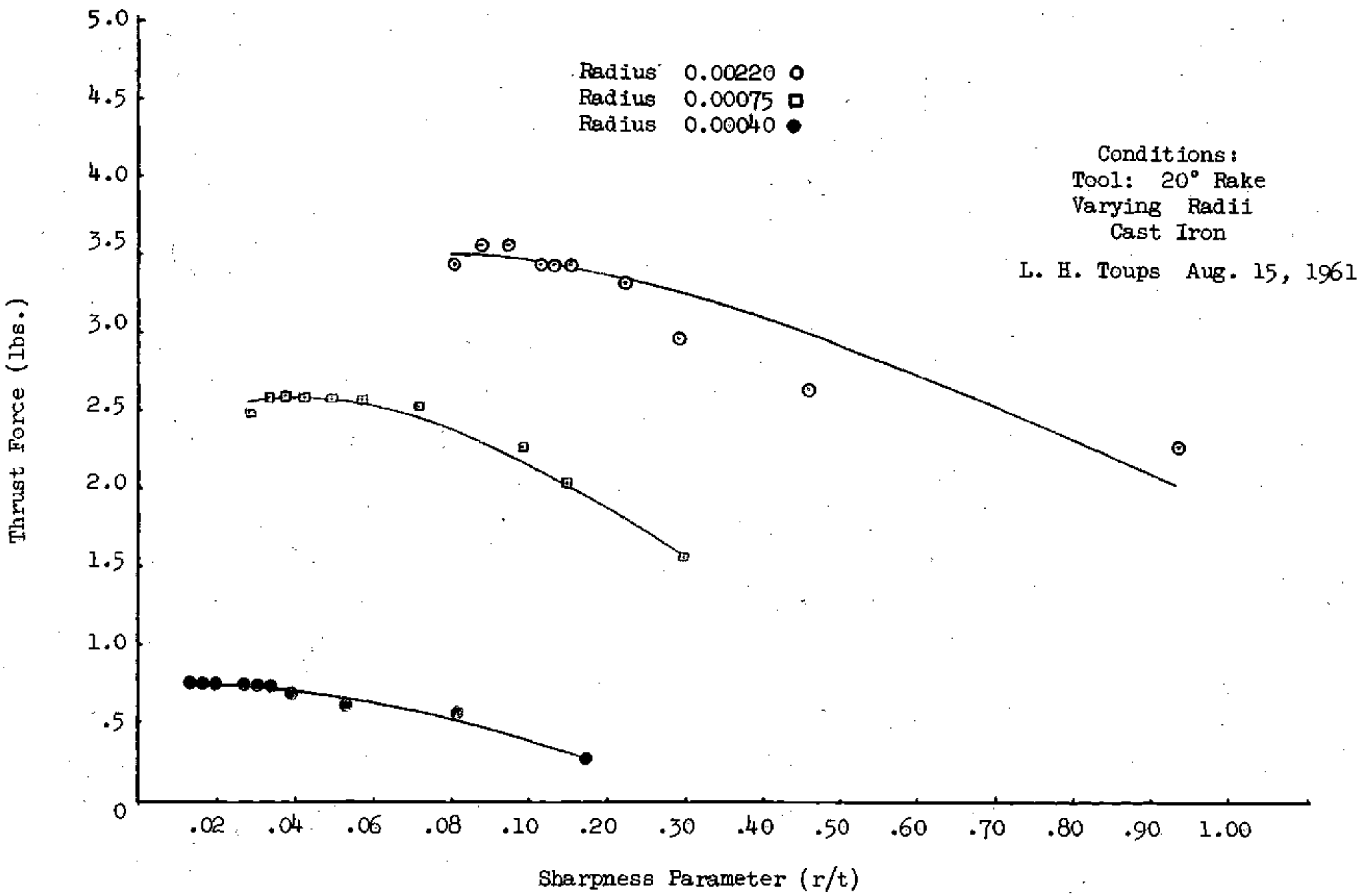

Figure 28. Thrust Force vs. Sharpness Parameter

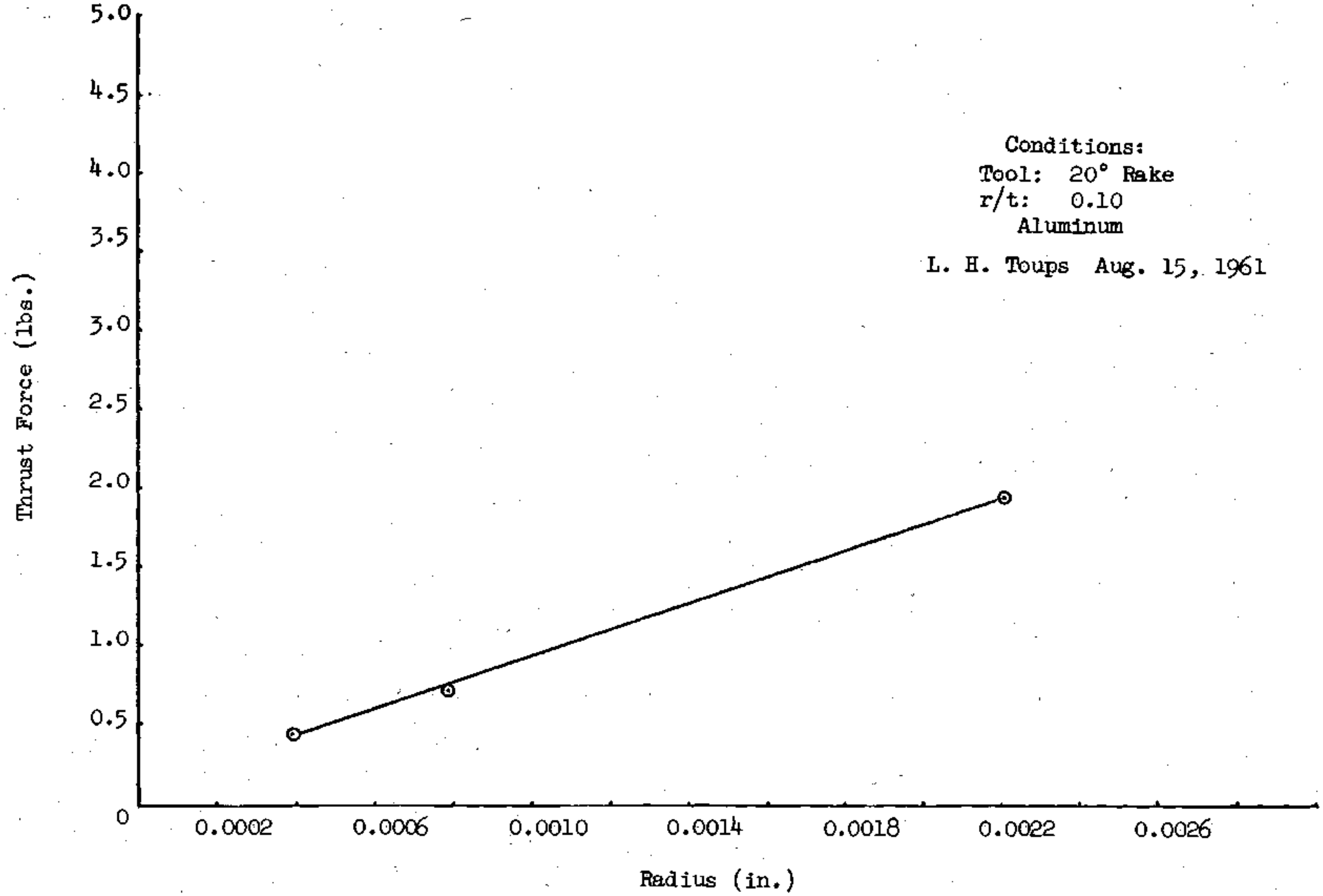

Figure 29. Thrust Force vs. Sharpness Radius

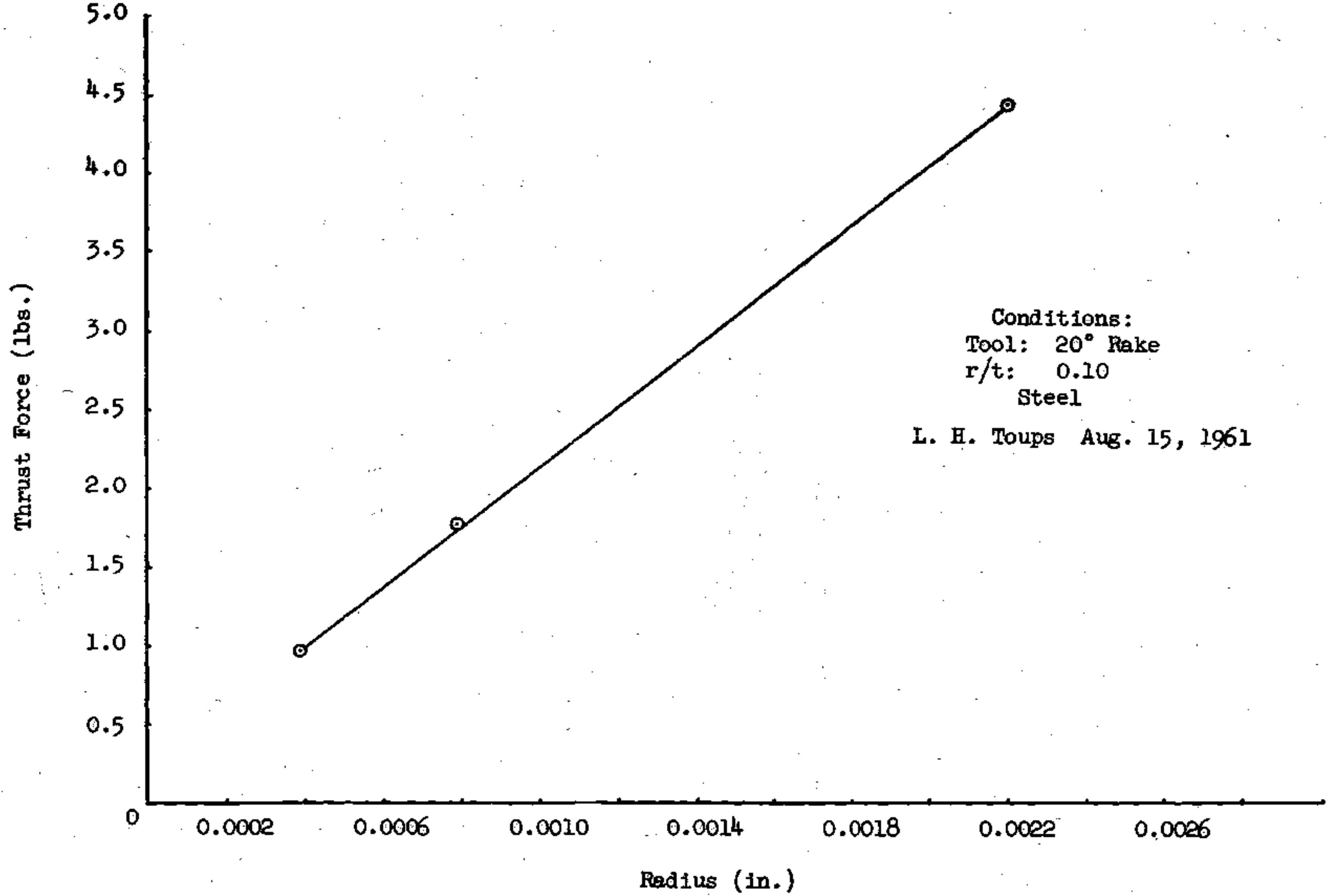

Figure 30. Thrust Force vs. Sharpness Radius

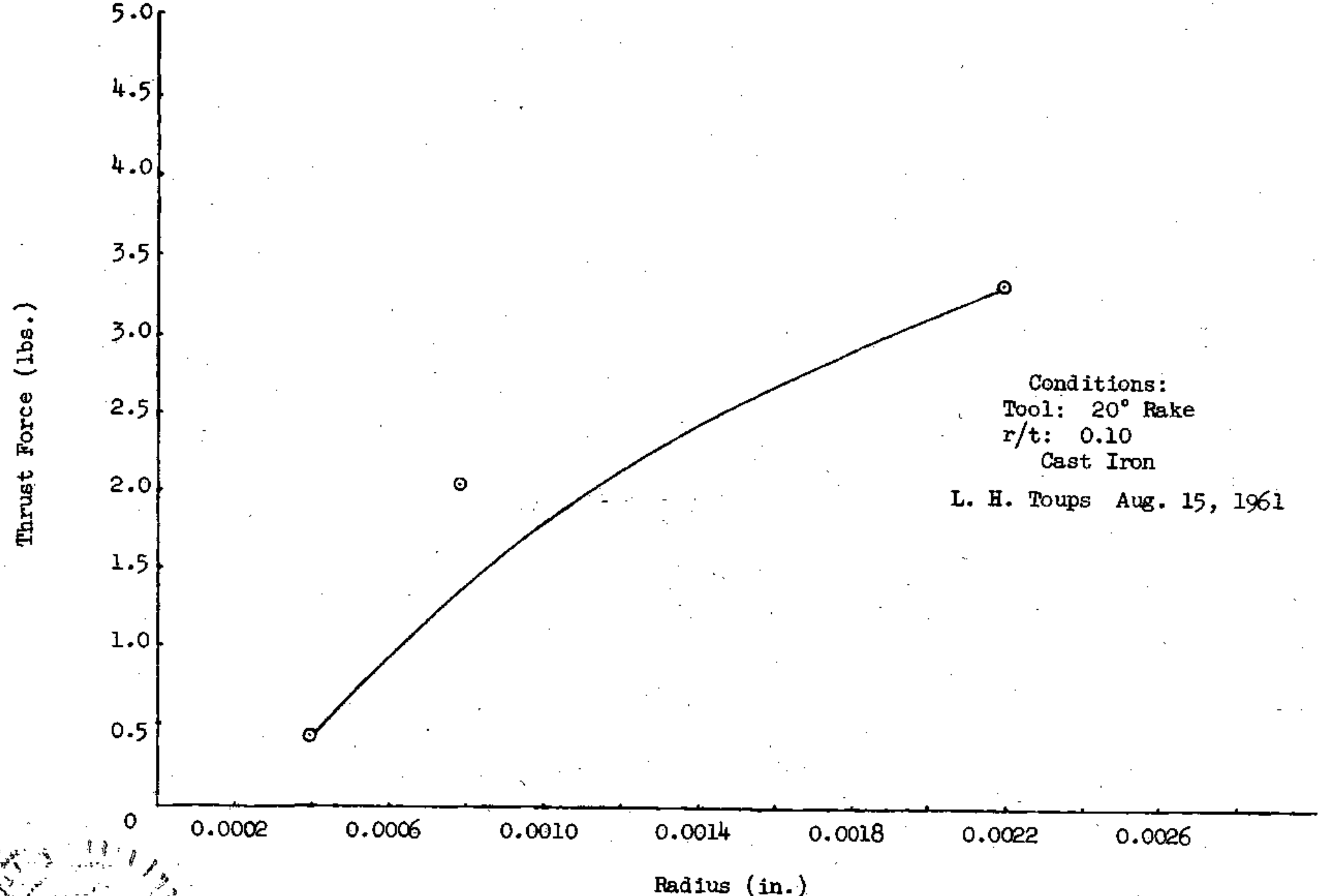

Figure 31. Thrust Force vs. Sharpness Radius

APPENDIX B

EXPERIMENTAL DATA

Table 1. Data for 0° Rake Angle Tool

Material: 6061 - T6 Aluminum

Diameter: 2.852 inch

Depth: 0.010 inch

Radius: 0.00069 inch

196 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	2.5	0.66	5.0	1.12	146	0.00496
0.0048	2.5	0.66	7.0	1.57	146	0.00694
0.0075	3.5	0.92	10.0	2.25	146	0.00997
0.0104	4.0	1.05	15.0	3.37	146	0.01490
0.0130	5.0	1.31	20.0	4.50	146	0.01990
0.0150	9.0	2.37	28.0	6.30	146	0.02790
0.0174	11.0	2.90	35.0	7.86	146	0.03480
0.0208	13.0	3.42	43.0	9.66	146	0.04280
0.0232	13.5	3.55	46.0	10.30	146	0.04560
0.0260	14.5	3.82	48.0	10.80	146	0.04780

Table 2. Data for 0° Rake Angle Tool

Material: 6061 - T6 Aluminum

Diameter: 2.786 inch

Depth: 0.015 inch

Radius: 0.00069 inch

196 RPM

Feed ipr.	Strain microinch/inch	F-T lbs	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	3.5	0.92	5.0	1.12	143	0.00485
0.0048	4.5	1.18	9.0	2.02	143	0.00875
0.0075	7.5	1.97	14.0	3.14	143	0.01360
0.0104	11.0	2.90	22.5	5.06	143	0.02190
0.0130	16.0	4.21	27.0	6.06	143	0.02620
0.0150	17.0	4.49	30.0	6.75	143	0.02930
0.0174	18.0	4.74	35.0	7.87	143	0.03410
0.0208	17.0	4.49	40.0	9.00	143	0.03900
0.0232	16.0	4.21	45.0	10.10	143	0.04380
0.0260	16.5	4.34	48.0	10.80	143	0.04680

Table 3. Data for 20° Rake Angle Tool

Material: C 1018 Steel

Diameter: 2.810 inch

Depth: 0.010 inch

Radius: 0.00040 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	3.5	0.92	6.0	1.35	55.1	0.00226
0.0048	4.5	1.18	12.0	2.70	55.1	0.00450
0.0075	6.0	1.58	18.5	4.16	55.1	0.00694
0.0104	7.0	1.84	25.0	5.62	55.1	0.00939
0.0130	7.0	1.84	30.0	6.74	55.1	0.01120
0.0150	7.5	1.97	35.0	7.87	55.1	0.01310
0.0174	8.0	2.10	40.0	9.00	55.1	0.01500
0.0208	7.5	1.97	47.0	10.50	55.1	0.01750
0.0232	7.0	1.84	49.0	11.00	55.1	0.01830
0.0260	6.0	1.58	54.0	12.00	55.1	0.02000

Table 4. Data for 20° Rake Angle Tool

Material: Class 25 Cast Iron

Depth: 0.010 inch

Radius: 0.00040 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs
0.0023	1.5	0.395	4.5	1.01
0.0048	2.0	0.526	9.0	2.01
0.0075	2.5	0.658	14.0	3.15
0.0104	3.0	0.790	19.0	4.27
0.0130	3.0	0.790	22.5	5.06
0.0150	3.0	0.790	25.0	5.62
0.0174	3.0	0.790	30.0	6.74
0.0208	3.0	0.790	33.0	7.42
0.0232	3.0	0.790	34.0	7.65
0.0260	3.0	0.790	37.5	8.42

Table 5. Data for 20° Rake Angle Tool

Material: 6061 - T6 Aluminum

Diameter: 2.910 inch

Depth: 0.010 inch

Radius: 0.00040 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	1.5	0.395	4.5	1.01	149	0.00304
0.0048	2.0	0.526	9.0	2.01	149	0.00506
0.0075	2.5	0.658	14.0	3.15	149	0.00709
0.0104	3.0	0.790	19.0	4.27	149	0.01020
0.0130	3.0	0.790	22.5	5.06	149	0.01220
0.0150	3.0	0.790	25.0	5.62	149	0.01420
0.0174	3.0	0.790	30.0	6.74	149	0.01730
0.0208	3.0	0.790	33.0	7.42	149	0.01880
0.0232	3.0	0.790	34.0	7.65	149	0.02030
0.0260	3.0	0.790	37.5	8.42	149	0.02340

Table 6. Data for 20° Rake Angle Tool

Material: C 1018 Steel

Diameter: 2.760 inch

Depth: 0.010 inch

Radius 0.00220 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	10.0	2.63	15.0	3.37	54.0	0.00552
0.0048	11.0	2.90	20.0	4.50	54.0	0.00737
0.0075	12.0	3.16	30.0	6.75	54.0	0.01100
0.0104	14.0	3.69	35.0	7.86	54.0	0.01290
0.0130	15.0	3.95	42.5	9.55	54.0	0.01560
0.0150	16.0	4.21	50.0	11.20	54.0	0.01840
0.0174	17.0	4.48	60.0	13.40	54.0	0.02190
0.0208	18.0	4.74	64.0	14.40	54.0	0.02360
0.0232	19.0	5.00	70.0	15.70	54.0	0.02570
0.0260	20.0	5.26	75.0	16.80	54.0	0.02750

Table 7. Data for 20° Rake Angle Tool

Material: Class 25 Cast Iron

Diameter: 2.845 inch

Depth: 0.010 inch

Radius: 0.00075 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	6.0	1.58	12.0	2.70	55.8	0.00457
0.0048	7.5	1.97	17.5	3.93	55.8	0.00665
0.0075	8.5	2.24	23.0	5.16	55.8	0.00874
0.0104	10.0	2.63	29.0	6.52	55.8	0.01100
0.0130	10.0	2.63	34.0	7.64	55.8	0.01300
0.0150	10.0	2.63	36.5	8.20	55.8	0.01390
0.0174	10.0	2.63	38.5	8.66	55.8	0.01470
0.0208	10.0	2.63	40.0	9.00	55.8	0.01530
0.0232	10.0	2.63	43.0	9.65	55.8	0.01630
0.0260	9.5	2.50	44.0	9.89	55.8	0.01670

Table 8. Data for 20° Rake Angle Tool

Material: 6061 - T6 Aluminum

Diameter: 2.858 inch

Depth: 0.010 inch

Radius: 0.00075 inch

205 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	3.0	0.79	5.0	1.12	153.9	0.00522
0.0048	3.5	0.92	8.0	1.80	153.9	0.00840
0.0075	5.0	1.31	12.0	2.70	153.9	0.01260
0.0104	6.0	1.58	17.4	3.82	153.9	0.01780
0.0130	6.5	1.71	20.0	4.50	153.9	0.02100
0.0150	7.0	1.84	23.0	5.17	153.9	0.02410
0.0174	7.0	1.84	27.5	6.18	153.9	0.02880
0.0208	7.0	1.84	30.0	6.74	153.9	0.03150
0.0232	7.5	1.97	35.0	7.86	153.9	0.03670
0.0260	8.0	2.10	37.5	8.42	153.9	0.03930

Table 9. Data for 20° Rake Angle Tool

Material: 6061 - T6 Aluminum

Diameter: 2.858 inch

Depth: 0.010 inch

Radius: 0.00075 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	2.5	0.658	5.0	1.12	56.1	0.00190
0.0048	3.0	0.790	7.5	1.68	56.1	0.00285
0.0075	3.0	0.790	10.0	2.25	56.1	0.00382
0.0104	3.0	0.790	12.0	2.70	56.1	0.00458
0.0130	3.0	0.790	14.0	3.15	56.1	0.00534
0.0150	3.5	0.921	15.0	3.37	56.1	0.00572
0.0174	4.0	1.05	18.0	4.04	56.1	0.00686
0.0208	4.0	1.05	23.0	5.16	56.1	0.00876
0.0232	6.0	1.58	32.5	7.30	56.1	0.01240
0.0260	8.0	2.10	36.0	8.09	56.1	0.01380

Table 10. Data for 20° Rake Angle Tool

Material: Class 25 Cast Iron

Diameter: 2.846 inch

Depth: 0.010 inch

Radius: 0.00220 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	8.5	2.24	12.0	2.70	55.8	0.00457
0.0 48	10.0	2.64	17.5	3.93	55.8	0.00665
0.0075	11.0	2.89	22.5	5.06	55.8	0.00857
0.0104	12.5	3.29	28.0	6.30	55.8	0.01070
0.0130	13.0	3.42	32.5	7.31	55.8	0.01240
0.0150	13.0	3.42	35.0	7.86	55.8	0.01330
0.0174	13.0	3.42	37.5	8.44	55.8	0.01430
0.0208	13.5	3.56	40.0	8.98	55.8	0.01520
0.0232	13.5	3.56	42.5	9.54	55.8	0.01620
0.0260	13.0	3.42	45.0	10.10	55.8	0.01710

Table 11. Data for 20° Rake Angle Tool

Material: 6061 - T6 Aluminum

Diameter: 2.762 inch

Depth: 0.010 inch

Radius 0.00220 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	3.0	0.79	4.0	0.90	54.1	0.00148
0.0048	3.0	0.79	6.0	1.35	54.1	0.00221
0.0075	3.5	0.92	10.0	2.25	54.1	0.00369
0.0104	6.0	1.58	15.0	3.38	54.1	0.00554
0.0130	6.0	1.58	18.0	4.04	54.1	0.00661
0.0150	7.0	1.84	21.0	4.71	54.1	0.00770
0.0174	7.0	1.84	24.0	5.39	54.1	0.00884
0.0208	8.0	2.10	32.5	7.31	54.1	0.01190
0.0232	10.0	2.64	35.0	7.87	54.1	0.01290
0.0260	10.0	2.64	38.0	8.54	54.1	0.01400

Table 12. Data for +20° Rake Angle Tool

Material: C 1018 Steel

Diameter: 2.851 inch

Depth: 0.010 inch

Radius: 0.00075 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	3.5	0.922	11.5	2.59	56.0	0.00439
0.0048	6.0	1.58	20.0	4.50	56.0	0.00764
0.0075	9.0	2.37	30.0	6.74	56.0	0.01140
0.0104	9.0	2.37	35.0	7.86	56.0	0.01330
0.0130	10.0	2.63	40.0	9.00	56.0	0.01530
0.0150	11.5	3.03	45.0	10.10	56.0	0.01710
0.0174	12.0	3.16	54.0	12.10	56.0	0.02050
0.0208	13.0	3.42	64.0	14.40	56.0	0.02440
0.0232	14.0	3.68	74.0	16.60	56.0	0.02820
0.0260	15.0	3.95	80.0	18.00	56.0	0.03060

Table 13. Data for 30° Rake Angle Tool

Material: C 1018 Steel

Diameter: 2.938 inch

Depth: 0.010 inch

Radius: 0.00020 inch

91 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	1.5	0.395	5.0	1.12	70	0.00238
0.0048	2.5	0.658	10.0	2.25	70	0.00477
0.0075	4.0	1.05	17.5	3.94	70	0.00836
0.0104	9.5	2.50	23.5	5.28	70	0.01120
0.0130	7.5	1.97	31.0	6.97	70	0.01480
0.0150	7.5	1.97	34.5	7.76	70	0.01650
0.0174	5.0	1.32	45.5	10.20	70	0.02160
0.0208	5.0	1.32	43.0	9.67	70	0.02050
0.0232	1.5	.395	48.5	10.90	70	0.02310

Table 14. Data for 30° Rake Angle Tool

Material: C 1018 Steel

Diameter: 2.851 inch

Depth: 0.010 inch

Radius: 0.00037 inch

28 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	2.5	0.658	10.0	2.25	20.9	0.00143
0.0048	3.0	0.79	20.0	4.50	20.9	0.00285
0.0075	4.0	1.05	28.0	6.28	20.9	0.00398
0.0104	4.0	1.05	35.0	7.86	20.9	0.00497
0.0130	5.0	1.31	42.5	9.56	20.9	0.00606
0.0150	5.0	1.31	45.0	10.10	20.9	0.00640
0.0174	5.0	1.31	50.0	11.20	20.9	0.00709
0.0208	5.0	1.31	60.0	13.50	20.9	0.00856
0.0232	5.0	1.31	65.0	14.60	20.9	0.00926
0.0260	4.5	1.18	75.0	16.90	20.9	0.01070

Table 15. Data for 30° Rake Angle Tool

Material: C 1018 Steel

Diameter: 2.810 inch

Depth: 0.010 inch

Radius: 0.00037 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	2.0	0.53	8.0	1.80	55.1	0.00300
0.0048	3.0	0.79	15.0	3.37	55.1	0.00572
0.0075	3.5	0.92	23.0	5.16	55.1	0.00862
0.0104	4.5	1.18	29.0	6.52	55.1	0.01090
0.0130	4.5	1.18	37.5	8.43	55.1	0.01400
0.0150	4.0	1.05	39.0	8.76	55.1	0.01460
0.0174	4.5	1.18	45.0	10.10	55.1	0.01690
0.0708	4.0	1.05	53.0	11.90	55.1	0.01990
0.0232	4.0	1.05	60.0	13.50	55.1	0.02260
0.0260	4.0	1.05	70.0	15.70	55.1	0.02620

Table 16. Data for 30° Rake Angle Tool

Material: Class 25 Cast Iron

Diameter: 2.927 inch

Depth: 0.010 inch

Radius: 0.00037 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	5.0	1.31	8.5	1.91	57.4	0.00332
0.0048	5.0	1.31	13.0	2.92	57.4	0.00508
0.0075	5.5	1.45	17.5	3.94	57.4	0.00686
0.0104	5.5	1.45	22.0	4.94	57.4	0.00861
0.0130	5.0	1.31	25.0	5.62	57.4	0.00978
0.0150	4.5	1.18	27.0	6.06	57.4	0.01050
0.0174	4.5	1.18	30.0	6.74	57.4	0.01170
0.0208	4.0	1.05	34.0	7.64	57.4	0.01330
0.0232	3.5	0.92	35.0	7.86	57.4	0.01370
0.0260	3.0	0.79	38.0	8.54	57.4	0.01480

Table 17. Data for 30° Rake Angle Tool

Material: 6061 - T6 Aluminum

Depth: 0.010 inch

Radius: 0.00037 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.
0.0023	1.0	0.264	3.0	.674
0.0048	1.0	0.264	5.0	1.12
0.0075	1.0	0.264	7.0	1.57
0.0104	1.0	0.264	10.0	2.25
0.0130	1.0	0.264	13.0	2.92
0.0150	1.0	0.264	16.0	3.60
0.0174	1.5	0.395	18.0	4.04
0.0208	1.5	0.395	25.0	5.62
0.0232	2.0	0.526	27.0	6.06
0.0260	2.0	0.526	32.5	7.31

Table 18. Data for -10° Rake Angle Tool

Material: C 1018 Steel

Diameter: 2.760 inch

Depth: 0.010 inch

Radius: 0.00083 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	6.0	1.58	10.0	2.25	54.2	0.00370
0.0048	12.0	3.16	30.0	6.74	54.2	0.01110
0.0075	15.0	3.95	35.0	7.86	54.2	0.0.290
0.0104	17.0	4.48	40.0	9.00	54.2	0.01480
0.0130	20.0	5.26	50.0	11.10	54.2	0.01820
0.0150	24.0	6.31	60.0	13.50	54.2	0.02220
0.0174	24.0	6.31	66.0	14.80	54.2	0.02430
0.0208	27.0	7.10	78.0	17.50	54.2	0.02880
0.0232	28.0	7.37	88.0	19.70	54.2	0.03230
0.0260	29.0	7.63	92.0	20.60	54.2	0.03380

Table 19. Data for -10° Rake Angle Tool

Material: Class 25 Cast Iron

Diameter: 2.846 inch

Depth: 0.010 inch

Radius: 0.00083 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs	Velocity sfpm	Power hp.
0.0023	3.0	0.790	5.5	1.23	55.8	0.00208
0.0048	4.5	1.18	10.0	2.25	55.8	0.00381
0.0075	6.0	1.58	15.0	3.37	55.8	0.00572
0.0104	8.0	2.10	20.0	4.50	55.8	0.00763
0.0130	9.0	2.36	25.0	5.62	55.8	0.00952
0.0150	9.5	2.50	27.5	6.18	55.8	0.01050
0.0174	11.0	2.90	32.5	7.30	55.8	0.01240
0.0208	11.5	3.03	35.0	7.86	55.8	0.01330
0.0232	12.0	3.16	37.5	8.42	55.8	0.01430
0.0260	12.5	3.29	40.0	9.00	55.8	0.01520

Table 20. Data for -10° Rake Angle Tool

Material: 6061 - T6 Aluminum

Diameter: 2.714 inch

Depth: 0.010 inch

Radius: 0.00083 inch

75 RPM

Feed ipr.	Strain microinch/inch	F-T lbs.	Strain microinch/inch	F-C lbs.	Velocity sfpm	Power hp.
0.0023	3.0	0.790	3.5	.786	53.2	0.00126
0.0048	3.5	0.921	6.0	1.35	53.2	0.00218
0.0075	4.0	1.05	9.5	2.13	53.2	0.00343
0.0104	4.0	1.05	12.0	3.16	53.2	0.00509
0.0130	6.0	1.58	17.0	3.82	53.2	0.00615
0.0150	7.0	1.84	20.0	4.50	53.2	0.00725
0.0174	9.0	2.37	26.0	5.84	53.2	0.00942
0.0208	11.0	2.90	32.0	7.19	53.2	0.01160
0.0232	11.0	2.90	33.0	7.41	53.2	0.01190
0.0260	12.0	3.16	38.0	8.55	53.2	0.01380

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