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AN ANALYSIS OF THE NATURAL SHARPNESS RADIUS

OF

CUTTING TOOLS

A THESIS

Presented to

the Faculty of the Graduate Division

by

Roland Michael Toups

In Partial Fulfillment

of the Requirements for the Degree

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AN ANALYSIS OF THE NATURAL SHARPNESS RADIUS

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APPROVED

DATE APPROVED BY CHAIRMAN Sept. 6, 1961

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SUMMARY

Recent theoretical work in metal cutting demands more knowledge of the natural sharpness radius than is currently available. This radius is defined as the tiny rounding of the extreme edge of cutting tools. It is formed by chance during grinding of the cutting edge.

Finding a method of measuring the small radius was the first problem of this investigation. Photographs taken with a Unitron Metallograph and Universal Camera Microscope at 900X magnification provided the means. Templates were used to identify the exact size of the sharpness radius.

Variables appearing to affect the natural sharpness radius were then investigated. Six such variables appeared to exist: rake angle, tool material, grinding wheel type, direction of wheel application, type of grinding and operator experience, and honing. Each variable was studied for its contribution to radius size.

It was found that as the rake angle decreases the radius increases. Tool materials, Rex 95 HSS and Circle "C" HSS, were found to have little noticeable effect since the radius is a grinding function. As the grinding wheel gets finer the radius gets smaller, and a radius ground "with" the tool edge is smaller than that ground "against" the edge. "With" the edge means the wheel revolves in the direction from-- tool-to-edge, and "against" means that it revolves from-- edge-to-tool.

It was also shown that smaller radii are obtained with automatic grinders than with hand grinders. However, in comparing radii ground

by hand with experienced and inexperienced operators, no large difference is noticed providing each operator has used sufficient care. Honing the natural finish creates a larger radius and is perhaps the major contributor to radius size.

The natural radius range encompassing all variables was found to extend between 0.00010 - 0.00100 inches. Expressed mathematically the radius is:

$$r = a \tan^{n}\left(\frac{\delta}{2}\right)$$

where "r" is the radius, "δ" the lip angle, and "a" and "n" are constants defining the particular category. Albrecht's theory was used in deriving the formula. Constants for each radius category were determined.

CHAPTER I

INTRODUCTION

Definition of the natural sharpness radius.--One of the important variables affecting ease of cutting is correct tool geometry. It involves many problems, one being the natural sharpness radius. The radius forms during tool grinding, and is defined as the minute rounding on the extreme cutting edge of the tool.

As shown in Fig. 1, the cutting edge of the tool is the sharp corner formed by the clearance angle and the rake angle. A special single-point tool was needed in the two dimensional or orthogonal cutting process used. The cutting edge had to be on the side rather than on the front.

As the clearance and rake angles are ground, tiny particles break off at the very end because the material is thinnest here and cannot withstand the grinding force. This causes a rounded edge, illustrated in Fig. 2, which can be approximated by a portion of a circular arc. The radius of this portion is called the natural sharpness radius.

It should be remembered that the formation of this radius is actually a by-product of the grinding process. It is not purposely generated by the wheel, but forms naturally when the angles are being ground. As a result, its surface is rougher than the finish of the lip angle surfaces (1).*

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*Numbers in parentheses refer to Bibliography.

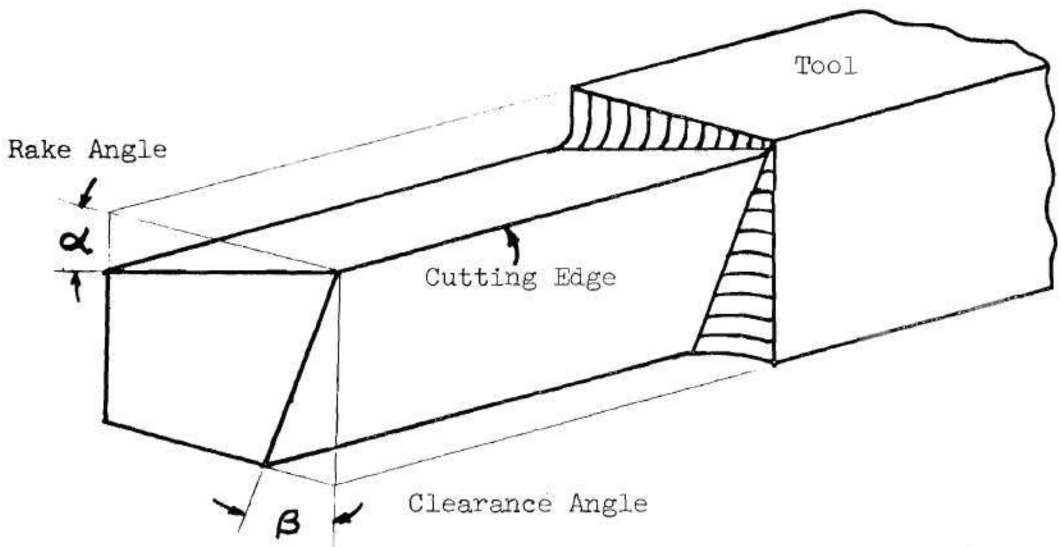


Fig. 1. Geometry of Special Single-Point Tool.

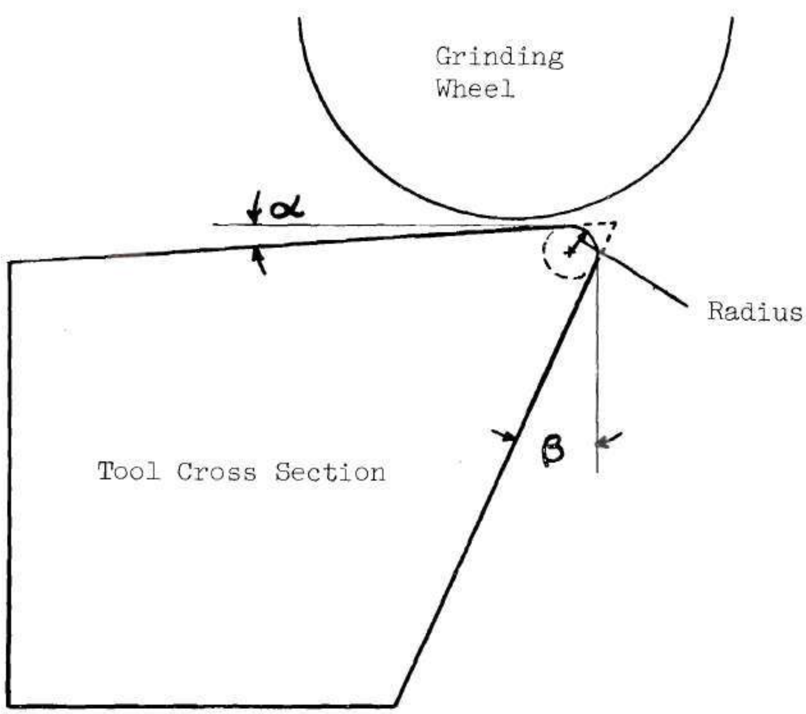


Fig. 2. Formation of Natural Sharpness Radius.

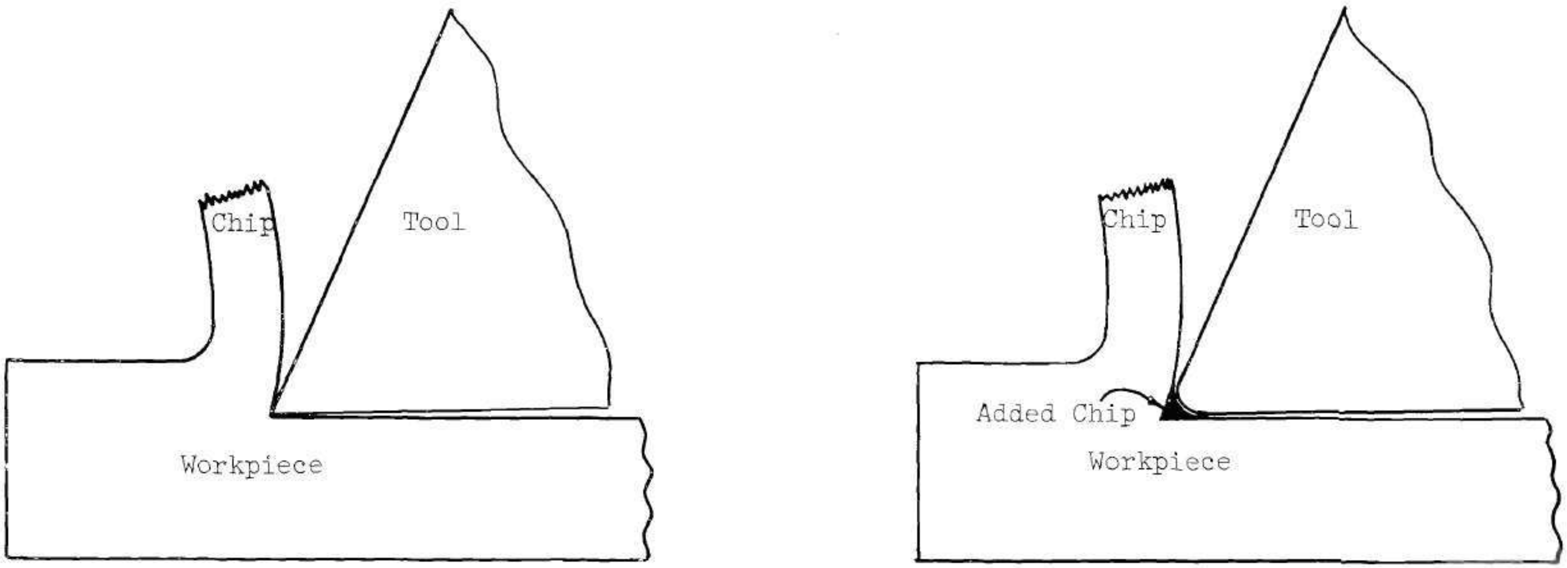
Purpose of the investigation.--The theory of metal cutting has been developed considerably in recent years. Experimenters such as Taylor (2), Boston (3), Shaw (4), Merchant (5), Ernst (6), P. Albrecht (7), and A. Albrecht (8) agree that the principal mechanism involved in the process is shearing action. The shearing action takes place along the shear plane, causing grain deformation and ultimate separation of chip from workpiece.

However in 1959, P. Albrecht (9) introduced a new concept to supplement the shearing process. Although shearing action clarifies the mechanics of metal cutting, he felt that experimental data does not completely coincide. Some questions stemming from the tool geometry appeared unanswered.

Albrecht found experimentally that a "ploughing" action is also involved. This is where the natural sharpness radius enters. It had been assumed the cutting edge is perfectly sharp. The sharp corner penetrates the workpiece at a specified depth and all the material above it becomes the chip as in Fig. 3(a). When the finite radius is taken into account, the small portion of workpiece material in front of the cutting edge must be considered. This is because the finite radius is really a "blunted" tool as seen in Fig. 3(b).

Albrecht maintains that this excess material is pressed into and becomes part of the regular chip. This action is called "ploughing." Thus, it appears the degree of sharpness, or size of the natural sharpness radius, may play an important role.

Furthermore, the introduction of this additional concept changes the forces at the cutting edge (10), and also becomes a factor in



(a) Without Radius

(b) With Radius

Fig. 3. Difference in Cutting Edge Geometry.

determining the life of the tool (11). For these many reasons, the analysis is undertaken to investigate variables affecting the natural sharpness radius.

Scope of the project.--A suitable method of measuring these tiny natural sharpness radii had to be found first. Many measurements of different radii were then taken and classified. Measurements were made of single-point tools only.

It is believed variables affecting the magnitude of the natural sharpness radii are:

1. Rake angle.
2. Tool material.
3. Type of grinding wheel used - fine, medium, coarse.
4. Direction of wheel application - "with" or "against" the cutting edge.
5. Type grinder and operator's experience.
6. Honing the tool after grinding.

Each of these variables will be examined in detail in later chapters. Radii categories will be set up and formulated mathematically and an attempt made to arrive at characteristics which cause and describe each category.

CHAPTER II

HISTORY OF RADIUS MEASURING DEVICES

Exact measurement of cutting edge sharpness presents the difficult problem of measuring a radius whose dimensions may be as small as one ten-thousandth of an inch. There is no prescribed way to measure the radii, although many solutions have been put forth. Kayser (12) says, "there have been many facetious efforts, but this [problem] has only been precisely answered three times during the last fifty years."

Kayser's three methods, along with other attempts at measuring the radius, will be described. In some cases the method may not have been used to measure the radius of cutting tools specifically, but all methods deal with calculating small radii of curvature, and may be further applied to cutting tools. The method used in this experiment will be explained last.

Mallock.--The first method referred to by Kayser was Mallock's in 1896 (13). The problem of studying the shape and nature of cutting edges appears to have first originated at this time. Mallock used interference fringes. He prepared two pieces of thin microscope cover slide glass about 1/2 in. long and 1/16 in. wide. They were pressed together by a small steel clip with the cutting edge inserted between them as shown in Fig. 4.

The setup was placed on the stage of a microscope and vertically illuminated with sodium light. Through the microscope, interference fringes

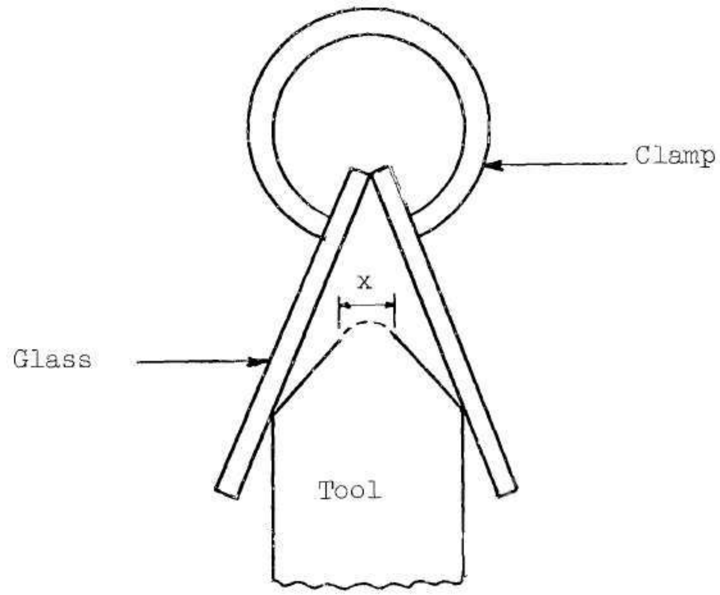


Fig. 4. Mallock's Setup For Measuring The Radius.

became visible between the two thin glasses. The number of fringes from the touching glass to cutting tip gave that distance in terms of the half wave-length of sodium light.

The method will not be examined in detail, but various other distances were measured, and Mallock derived a formula to fit the data. He found that the actual edge had a curved cross section, but was unable to directly measure this. From his data he saw that the radius could not be greater than $\frac{.125}{.25}x$, where the distance "x" is the value gotten from his formula.

Mallock's method does not entail touching the edge, and uses the smallest standard unit of measurement, the half wave-length of sodium vapor light.

Jentzsch.--Another method referred to by Kayser was Jentzsch's in 1926 (14). Jentzsch obtained accurate results by mounting the edge vertically on the table of a microscope, illuminating both sides of the edge at such angles that the reflected beams were picked up by the objective.

Through the microscope were seen two clearly lighted bands, one on each flank of the edge. Jentzsch measured the distance apart with a micrometer eyepiece. He then lowered or raised the microscope tube a known distance, again measuring the distance apart of the illuminated bands. As a result, he could construct the curve shown in Fig. 5, and arrive at the radius of curvature. Jentzsch worked at 175 diameters.

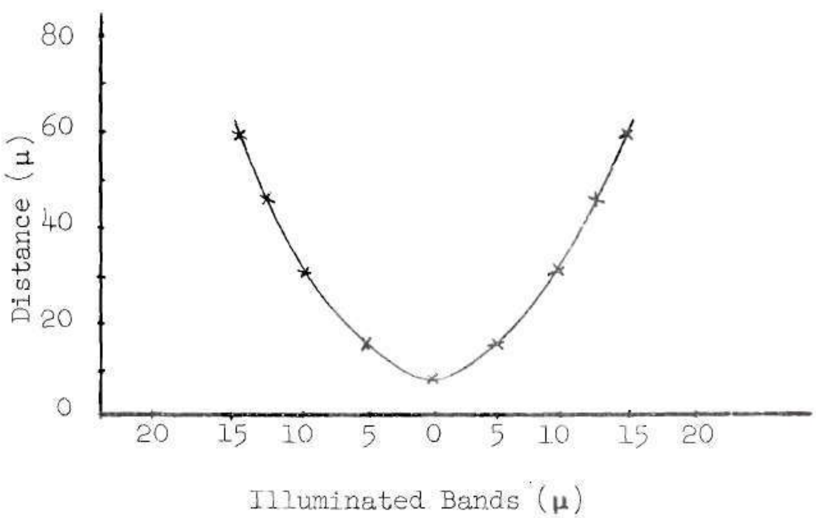


Fig. 5. Data Plotted By Jentsch To Obtain Radius.

He directed particular attention to the fact that the two lines which formed the edge deviated considerably from a straight line.

Schmerwitz.--The last method referred to by Kayser was the one Dr. G. Schmerwitz used in 1932 (15). Dr. Schmerwitz applied the method of

G. Guglielmo who in 1902 had determined the true form of bearing edges of balances.

Schmerwitz supported a cutting edge vertically as shown in the three sketches of Fig. 6.

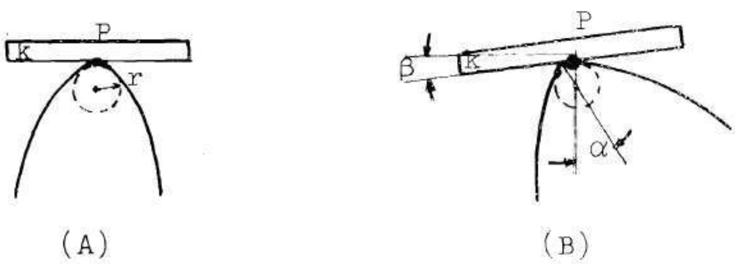


Fig. 6. Schmerwitz's Method Of Measuring The Radius.

A small beam k is carefully supported upon the edge so that its surface is horizontal. If the blade is rotated about its edge an angle α, the left side of the beam will be heavier than the right side as the supporting point P will have moved towards the right. Consequently, the beam k will be deflected from the horizontal, and the angle of inclination β can be determined.

If the cutting edge were absolutely sharp (C), the blade could be turned through any angle without disturbing the position on the beam. The supporting point would always remain at the same place.

The radius of curvature can be computed from the angle of inclination. With known radii giving known angles of inclination, the setup can be calibrated to give certain values when turned through given angles α.

Kayser.--Kayser himself in 1948 used an arrangement for determining the radius of curvature (16) of a cutting edge by means of interference fringes. He used the following setup:

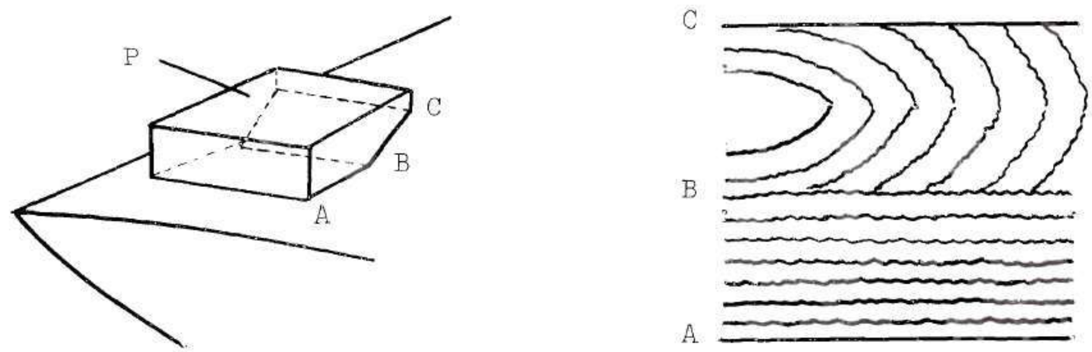


Fig. 7. Kayser's Method And Interferogram.

P is a bevelled transparent plate, preferably a diamond, which rests upon the blade at such an angle that the line of contact between the tool and object is approximately 0.01 mm. from the extreme edge.

Interference fringes obtained from the flat of the plate, with which the blade is in contact, extend from A to B. The interference fringes obtained between the blade and the inclined surface of the plate extend from B to C. One of the best defined of these is used to determine the contour of the slope up to the edge.

It is necessary to obtain interferograms from each side of the blade edge and to measure the respective angles of the blade to the diamond plate. The thickness of the object must also be known. It is best to photograph interferograms at 200 diameters, then project them on a screen. A tracing of the chosen fringe is made and the distance between adjacent fringes is determined. The trace of such a fringe represents the blade up to the extreme edge. From data thus accumulated an elementary knowledge of mathematics can be used to construct a blade cross section to get the radius.

Other methods.--Besides the methods set forth by Kayser, investigation reveals other important methods. One is the optical spherometer, an instrument based almost entirely on optics.

Guild (17) invented the optical spherometer in 1923. A microscope, fitted with a vertical illuminator, is lighted by a small lamp attached to the microscope for convenience. The radius to be measured is placed on the micrometer stage. On bringing the microscope up or down a circular disc will appear. This is focussed and the disc diameter measured on a micrometer scale in the focal lens of the eyepiece. The radius can be calculated by a formula, with calibration curves set up for each objective in the range it is to be used.

Gates, Habell, and Middleton (18) have since added many refinements to the spherometer. Its use was expanded even more by Jurek (19) and Wilson (20) in 1954.

The optical spherometer borders on the same principle of Arnulf used by Simonet and Bodart (21). They actually computed the radius of curvature of cutting tools using the method. A microscope and formulas are again used to compute the radius. This time, however, angles are measured to derive the formula, instead of the circular disc as used in the spherometer.

In 1958 two Russians, Omel'chenko and Mokhov (22), also came up with an optical device. It is based on the principle of the double microscope. Formulas are used to compute the radius of curvature.

An interesting and different method was set forth in 1957 by Taylor (23). It is used primarily to get tool wear, but could be adapted to the radius of curvature. Taylor reasoned that a planimeter could be used if the object were magnified enough to get a good picture. The tool is placed under a traveling microscope, and a trace of its greatly magnified radius is made at a large scale by a planimeter attached to the microscope. One feature of the instrument is the ease with which it can be calibrated and an estimate made of the overall accuracy.

Pure optics - method used in experiment.--Most recent emphasis on measuring small radii of curvature has been almost entirely on purely optical methods. Hemsley (24) says that optical instruments have a definite advantage over mechanical devices. In a mechanical device, levers, or their equivalents, do not act with complete geometrical accuracy. They suffer some slight distortion under their own weight, or their weight induces pivot friction which in turn causes distortion of various parts of the instrument. The greater the magnification of the instrument, the greater the effects become.

In an optical instrument, the light rays have no weight. Their direction can be changed without mechanical effort, and without setting up any tendency to distortion. Through a uniform medium they are always perfectly straight. The rays are directed by lenses, prisms, or mirrors, which can be made to limits of error that are very small by present day engineering standards. The essential elements in optical systems are not subject to wear or serious deterioration, thus having a distinct advantage over many measuring devices of a purely mechanical nature.

As many human variables as possible must be omitted during actual measuring. It is best to measure something like a photograph rather than the lens image directly because the image on the print is not subject to any variation while the measurement is being taken. Further, no computation is made by formulas, which decreases the number of variables. Keeping this in mind, a toolmaker's microscope, optical projector, optical comparator, and regular metallograph were investigated, but accurate results could not be obtained. In some cases sufficiently high magnification could not be gotten. In others reticules with marked divisions were not available, especially for the toolmaker's microscope. Albrecht says he used a purely optical method in 1960 (25), but he has not published a description of the method to date.

A completely new concept in instrumentation was turned to. A Unitron Metallograph and Universal Camera Microscope gave excellent results. Photographs are taken of the radius at high magnification. This eliminates all calculation by formula. Templates are used to get the exact size of the radius. A picture is shown in Fig. [illegible] of the Metallograph and Camera; a more detailed explanation of its workings will be given in later chapters.

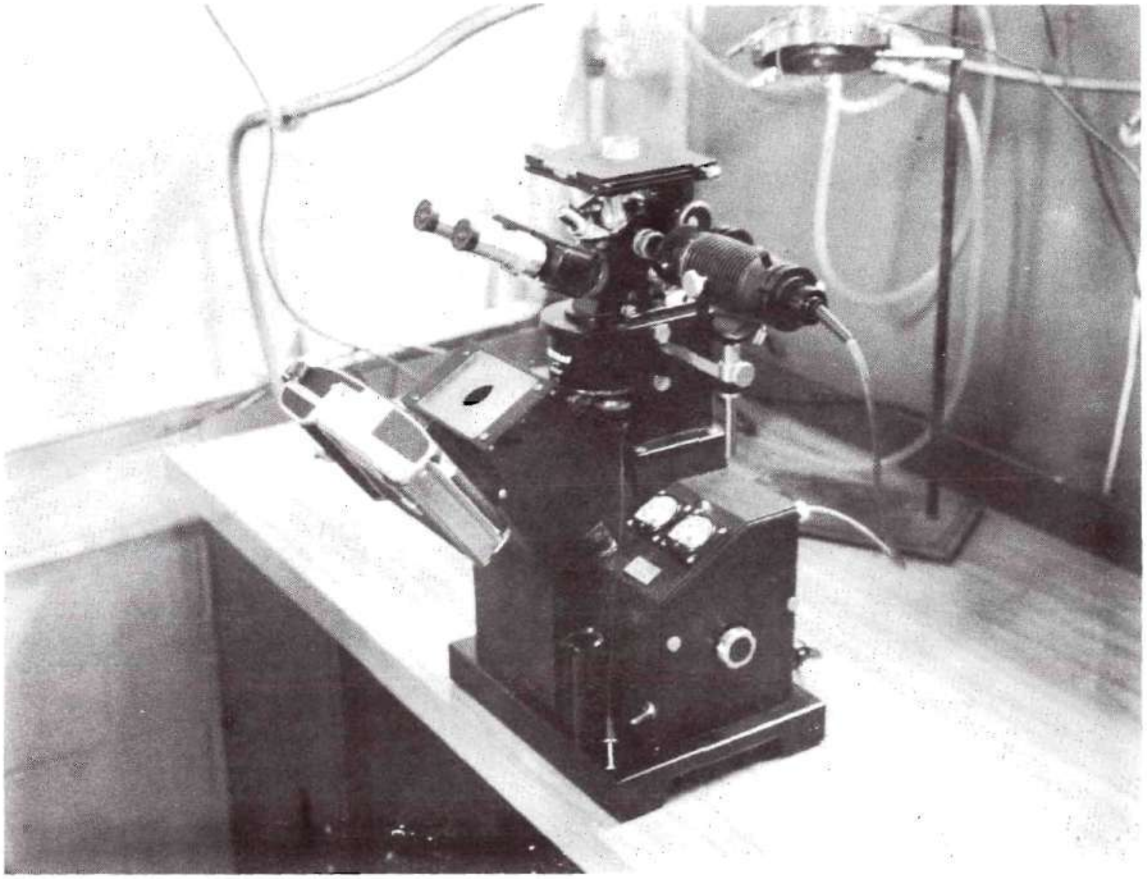


Figure 8. Unitron Metallograph and Universal Camera Microscope.

CHAPTER III

INSTRUMENTATION AND EQUIPMENT

Test specimens.--Two samples of high speed steel were used in the experiment. They are Rex 95 HSS and Circle "C" HSS, which have the following composition:

Rex 95 HSS	Circle "C" HSS
0.8 carbon	0.77 carbon
0.3 manganese	4.5 chromium
0.3 silicon	2.0 vanadium
4.0 chromium	18.5 tungsten
2.0 vanadium	1.0 molybdenum
14.0 tungsten	9.0 cobalt
0.75 molybdenum	
5.25 other elements	

Grinders.--Three grinders, two automatic and one hand grinder, were used in the operation. The automatic grinders, which operated at 3450 rpm, were made by the Walraven Company and the Cincinnati Tool Company. The hand grinder was a product of Black and Decker Company. It operated at 1500 - 1800 rpm.

Norton wheels of 60 and 120 grit were used on the automatic machine grinders. A Norton 46 grit wheel was used on the hand grinder. The coolant used was a soluble oil, water-based (1:10) compound. Honing of the steels was done with an Arkansas stone.

Abrasive cut-off wheel.--An abrasive cut-off wheel was used to cut the specimens. It is a product of the Precision-Jarrett Company and operates at 4000 rpm. All cutting is done while the specimen is submerged in a water-oil mixture.

Mounting setup.--A standard mounting device built by the Fisher Scientific Company was used. The specimen was mounted in 1385 AB Transoptic Powder manufactured by Buehler, Ltd. An aluminum jacket was provided to cool the specimen. A hand-operated press was used to release the specimens.

Polishing operations.--A Precision-Jarrett Twelve Specimen Automatic polishing machine was used in the initial operation with an alundum stone lap. The wheel operated at 96 rpm with standard No. 3 polishing powder. Remaining operations were performed by hand, using abrasive papers number 2, 1, 0, 00. The specimens were finished on a cloth wheel using Precisionite polishing powder.

Hardness Tester.--A Wilson "Rockwell" Hardness Tester was used with a diamond "BRALE" penetrator point and an applied load of 150 kg. The letter "C" is prefixed, as is customary, to denote the particular type reading.

Radius Measurement.--A model U-11 Unitron Metallograph and Universal Camera Microscope was used to measure the radius. It was calibrated for exact magnification by an objective micrometer glass slide. The camera used was a Polaroid Land Camera with type 47 film. The actual radii were measured using different size Rapidesign No. 140 circle templates, graduated from 1/16 in. diameter to 2-1/4 in. diameter.

CHAPTER IV

PROCEDURE

Preparing specimens.--All specimens were prepared in basically the same way. They were ground to the desired angle, and cut with the Abrasive Cut-Off Wheel. Different grinding methods will be given later. The cut-off wheel is a 1/16 in. thick abrasive wheel which cuts the specimen while held in a submerged chuck. Specimens were mounted in lucite.

They are put into a small cylindrical pipe filled with lucite, or 1385 AB Transoptic mounting powder. The powder is hydraulically pressed to a pressure of 3000 psi and heated to a temperature of 180° F. It is then brought up to a pressure of 5000 psi and a temperature of 320° F. After heating, a cooling jacket is put on the specimens and the heating element removed. They are finally allowed to cool naturally back to 180° F. The specimens, mounted solidly in the lucite, are manually pressed out of the small cylindrical pipe and are ready to be polished.

A Precision-Jarrett Twelve Specimen polisher was used for the initial polishing phase. Twelve lucite mountings are securely fastened in the machine and rotated on an alundum stone lap for approximately one hour. During this time a suitable paste is maintained on the wheel by mixing water with No. 3 polishing powder. The rough specimens are removed from the machine and washed. They are then polished manually on papers numbered 2, 1, 0, and 00, to get a fine finish. Care must be taken to keep the specimens clean and free from any grit. The polishing is done on a slab of plate glass. Next the specimens are polished on cloth with Precisionite polishing powder. A good finish, but not a perfect one, must be retained so the radius can be determined at high magnification.

Measuring the radius.--The specimens are now ready to be measured. The basic idea in using the Unitron Metallograph and Universal Camera Microscope is that after the specimen is focussed on the microscope, a picture is taken from which a direct measurement can be made. The following steps were necessary to get good results.

A magnification of 900 times was found to be a suitable choice. It is the largest magnification that can be used and still get all radii types on the same size film. The exact magnification is determined by an objective micrometer. A picture is taken of the micrometer at the unknown magnification. The lines are 0.01 mm. apart, and in the experiment they become magnified to 9 mm. To get 9 mm. from 0.01 mm., it is necessary to have a magnification of 900X.

The power on the microscope is turned on and amperage and voltage allowed to build up to 3.5 and 10 respectively. A green filter was chosen so sufficient contrast could be obtained. The specimen is attached to the microscope and brought into focus by use of hand levers. Then it is focussed again, this time on the ground glass lens at the base of the instrument.

The ground glass is turned back and the Polaroid Land Camera snapped into place. A shutter speed of one-half second and type 47 Polaroid film were used. The trigger is cocked and picture exposed. A developing time of 10 seconds was necessary with this type film. The developed picture was pulled from the camera and coated with a protective fluid to preserve its glossiness.

To determine the radius size the photograph was placed over a glass plate and templates used. Tiny and varied circle templates gave correct and accurate results. Whatever the size measured, it was divided by 900, the magnification factor, to get the actual radius.

Type of tests.--The type of grinding tests performed were correlated with the six natural sharpness radius variables set forth in the Introduction. They are rake angle, tool material, type of wheel used, direction of wheel application, type of grinding and operator experience, and honing.

Rake angles were varied from -30° to $+30^{\circ}$ in increments of 10°. The clearance angle was constant at 6°. Two different tool materials were used and radii values compared for all tests. Each material was hardness tested. It is believed hardness provides a basic reason for differences between tool materials.

Three different types of grinding wheels were used, fine, medium, and coarse. The fine is 120 grit, the medium 60, and the coarse 46 grit. Direction of wheel application was another variable incorporated and explained in Fig. 9. The wheel can either rotate "with" or "against" the edge. It was thought this would make a difference in the radius value.

The type of grinding and experience of the grinder is considered important. Radii were ground using both automatic and hand grinders. Automatic grinding should not vary with the grinder, but hand grinding may. Therefore, two machinists ground tools to compare with those a student ground. A commercial company also ground some automatically.

The last variable is the natural finish and honing. Honing consists in stroking the edge with an Arkansas oil stone, in a direction parallel to the edge; it is usually done before a tool is used on a lathe to remove all burrs. Thus, the radius value obtained could be considered a working value. The natural finish is the exact finish taken by the tool on the grinding wheel. The difference is shown in Fig. 10.

The difference each grinding variable makes was found by holding five factors constant while varying the sixth. Results of these readings are given in the appendix. Conditions are given for each table right above the values, and in each case radii are recorded for different rake angles.

Note that in Results and Discussion an average value from each table is used to show the extent of the variables upon the natural sharpness radius.

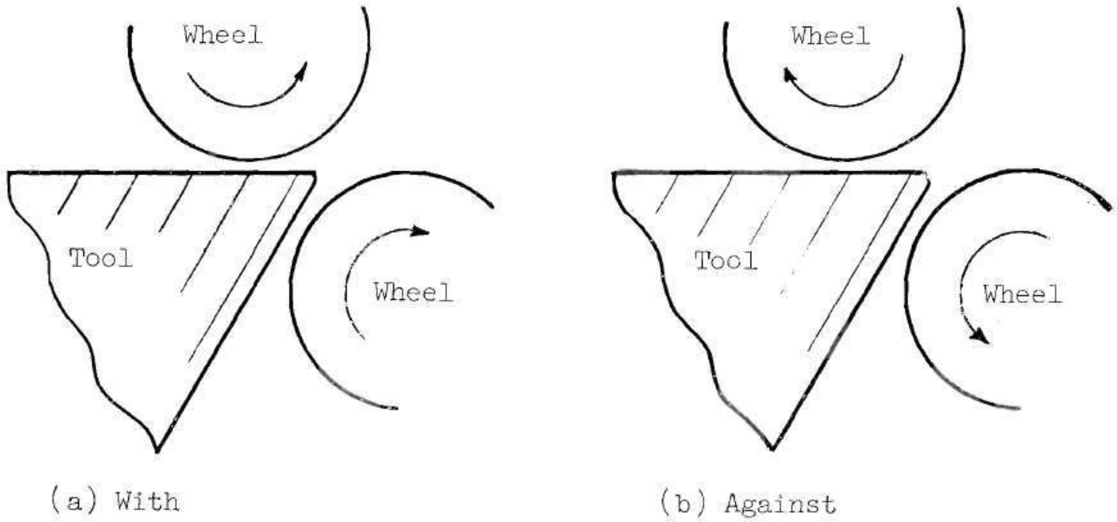


Fig. 9. Application of Grinding Wheel.

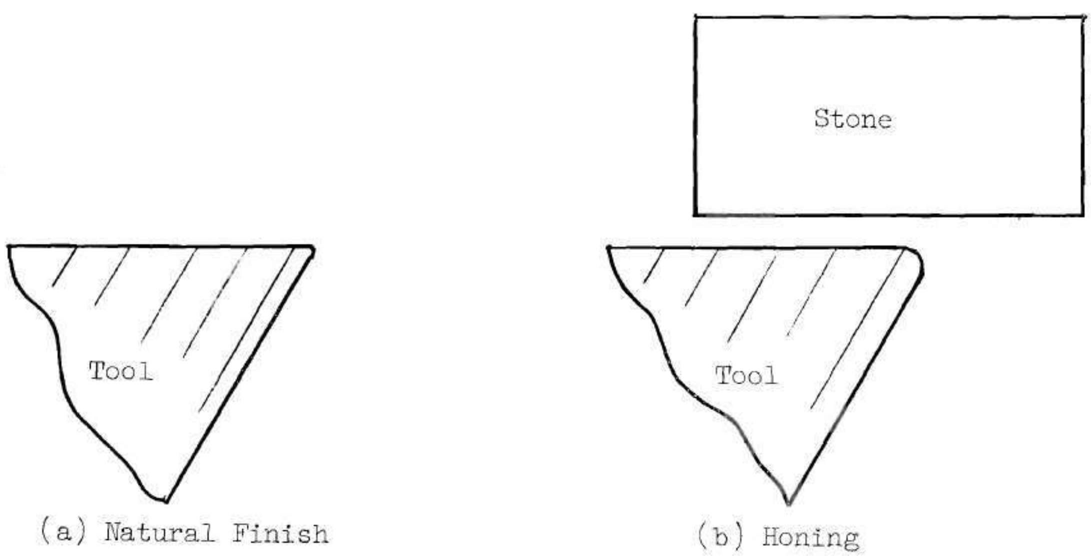


Fig. 10. Natural Finish and Honing Difference.

CHAPTER V

RESULTS AND DISCUSSION

All radius readings are given in the appendix, Tables 11-20. In Results only average values from the tables in hundred thousandths of an inch will be used.

The first thing to consider is whether or not the readings are of any consistency and significance. There appears to be considerable agreement among the values for each rake angle. There are, of course, places where the grinder failed to do a perfect job, and at such magnification the reading is worthless and so omitted. This occurs only sporadically and is of no major consequence in the overall results. Such failure actually is to be expected in close and minute experimental work.

Rake Angle.--The first variable to be considered is the rake angle. Graphs of tabulations are plotted in Figs. 11-20. Curves show that in each case the radius value increases as the rake angle decreases. There is no deviation from this in any of the graphs. The reason for this is evident. As the rake angle decreases, the overall included angle of the tool increases, thus affording the grinder less and less of a point to grind. The edge will be blunter and a larger segment of a circle will appear on the tip.

It is also evident that negative rakes give greater change rates in radius values. The slope of the curve increases more than it does

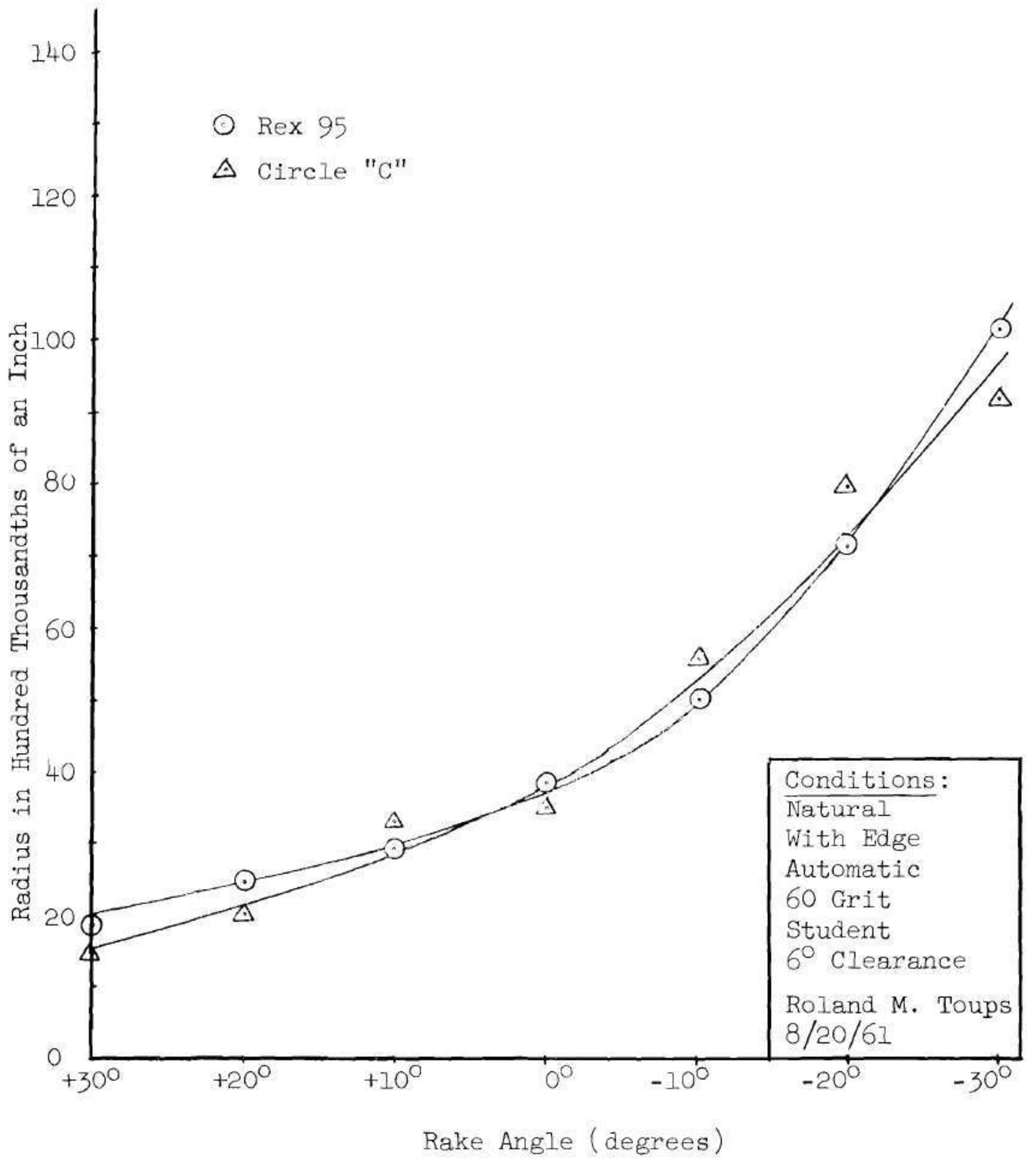


Fig. 11. Sharpness Radius vs. Rake Angle - No. 1.

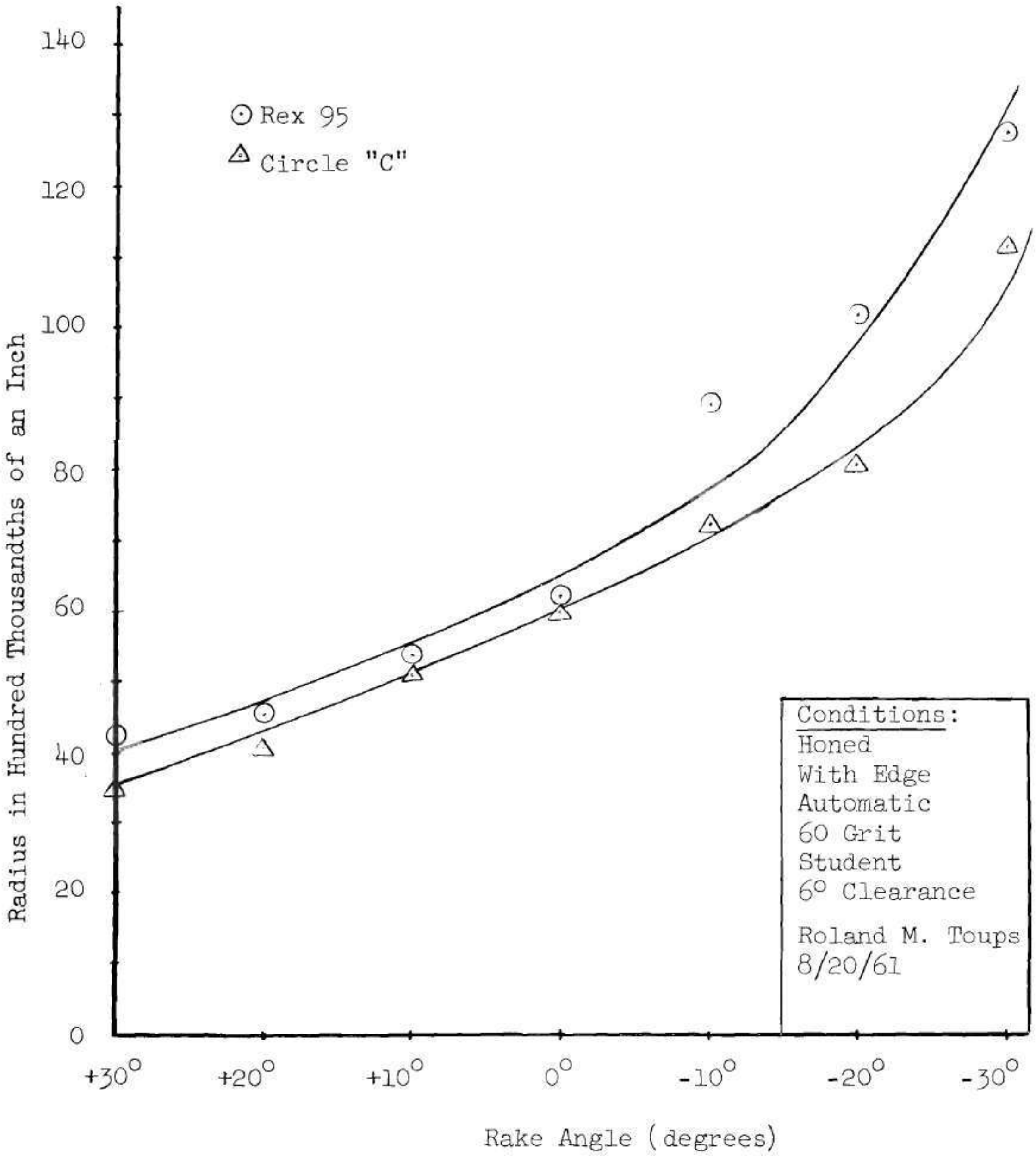


Fig. 12. Sharpness Radius vs. Rake Angle - No. 2.

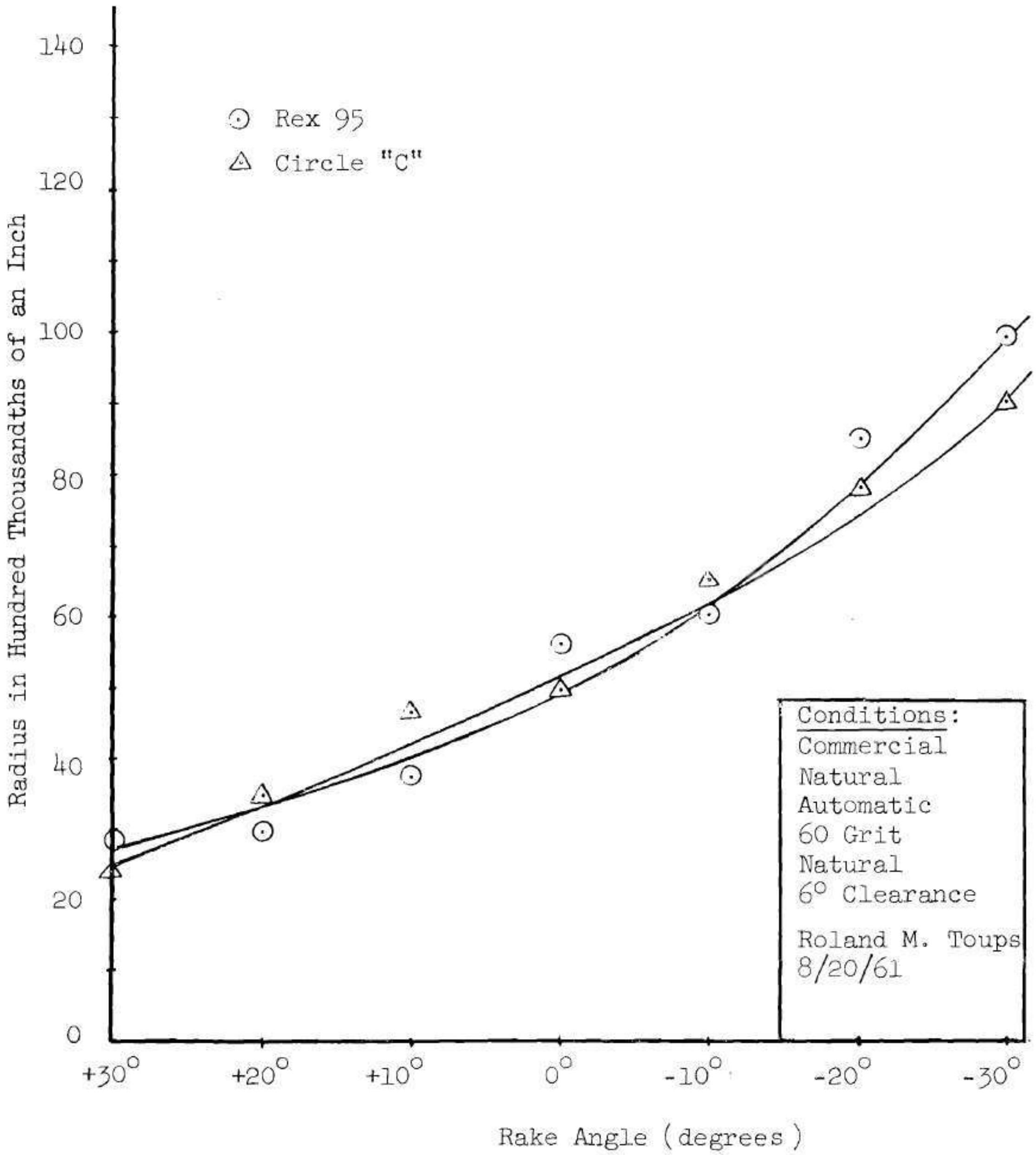


Fig. 13. Sharpness Radius vs. Rake Angle - No. 3.

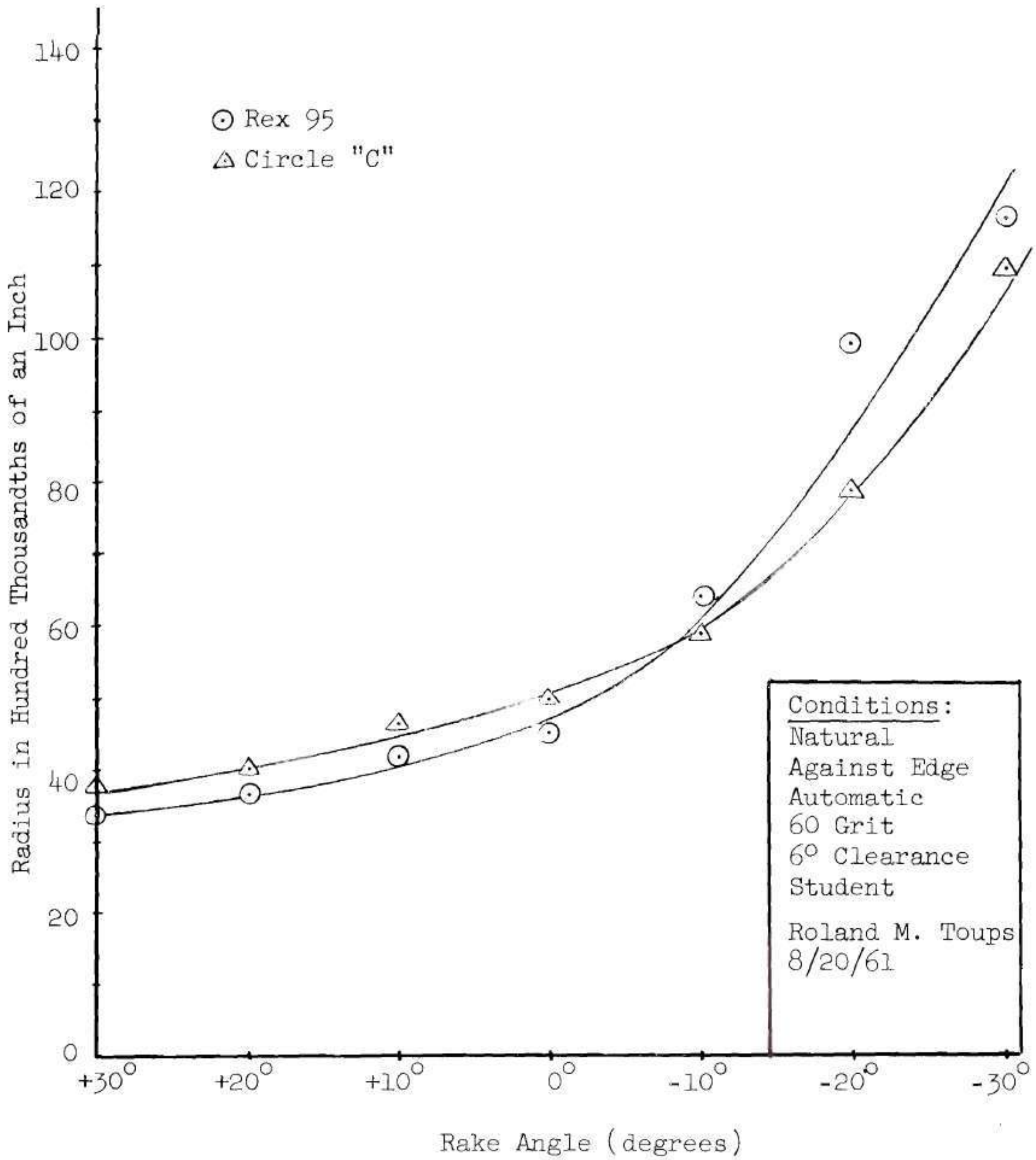


Fig. 14. Sharpness Radius vs. Rake Angle - No. 4.

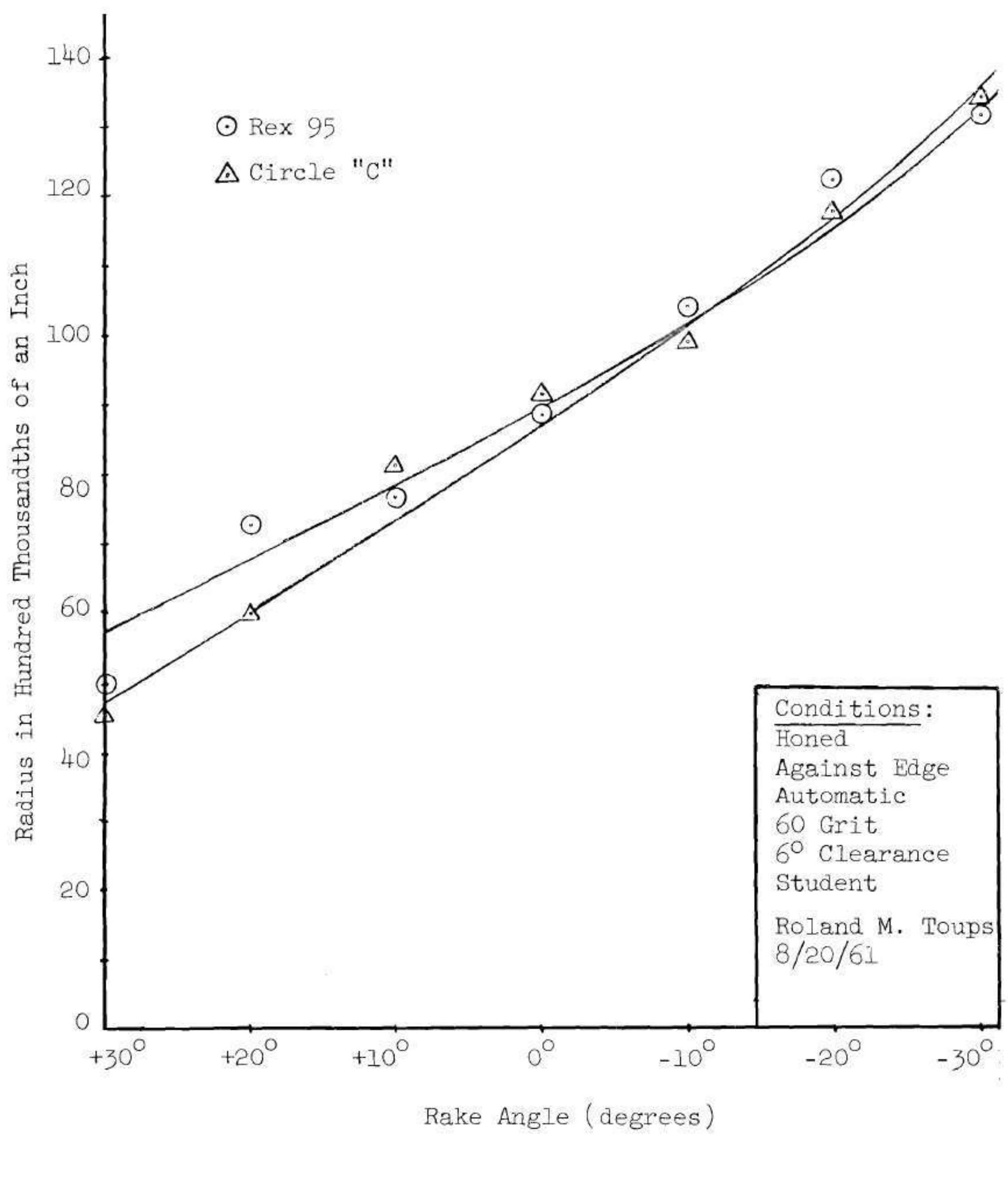


Fig. 15. Sharpness Radius vs. Rake Angle - No. 5.

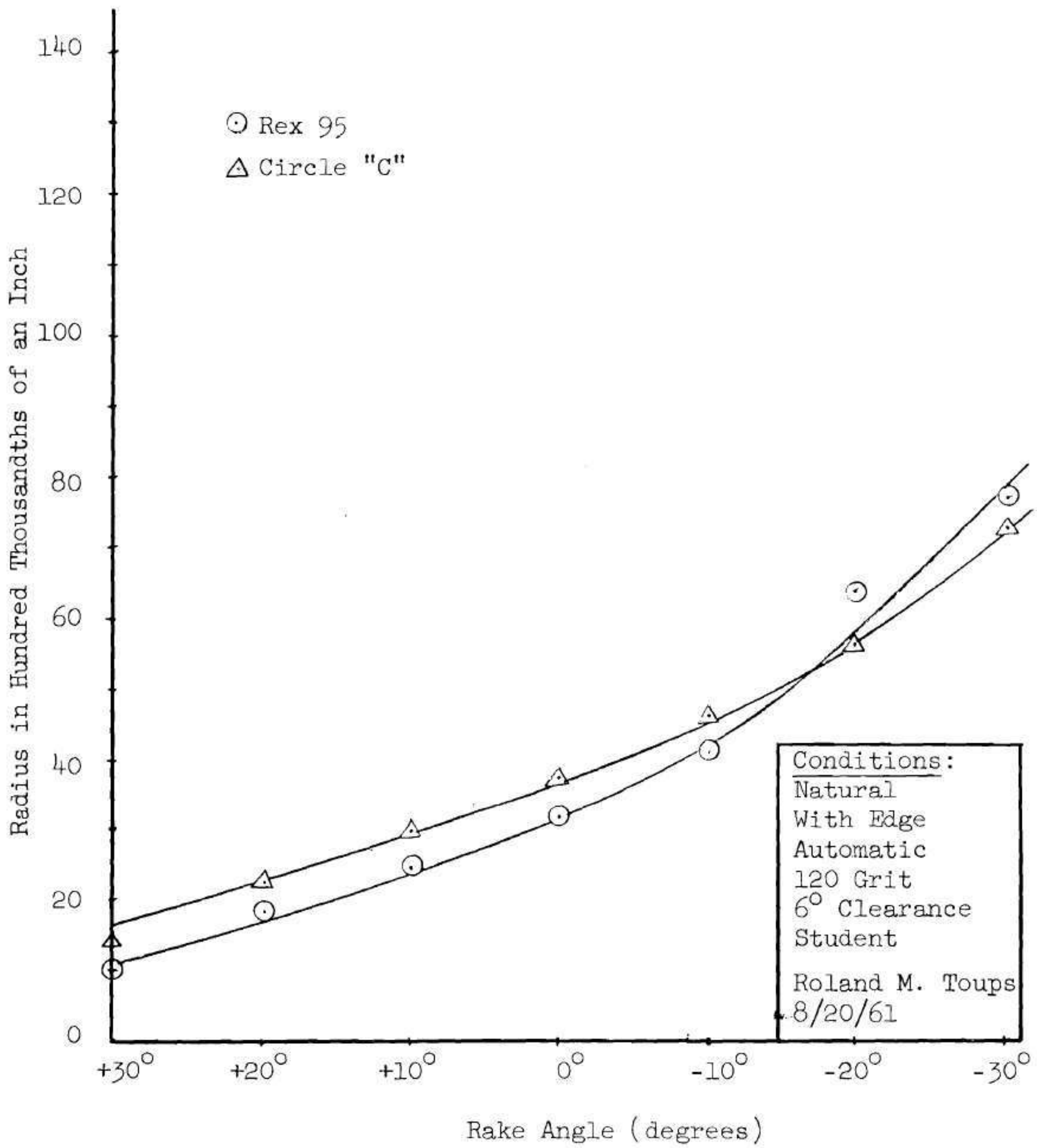


Fig. 16. Sharpness Radius vs. Rake Angle - No. 6.

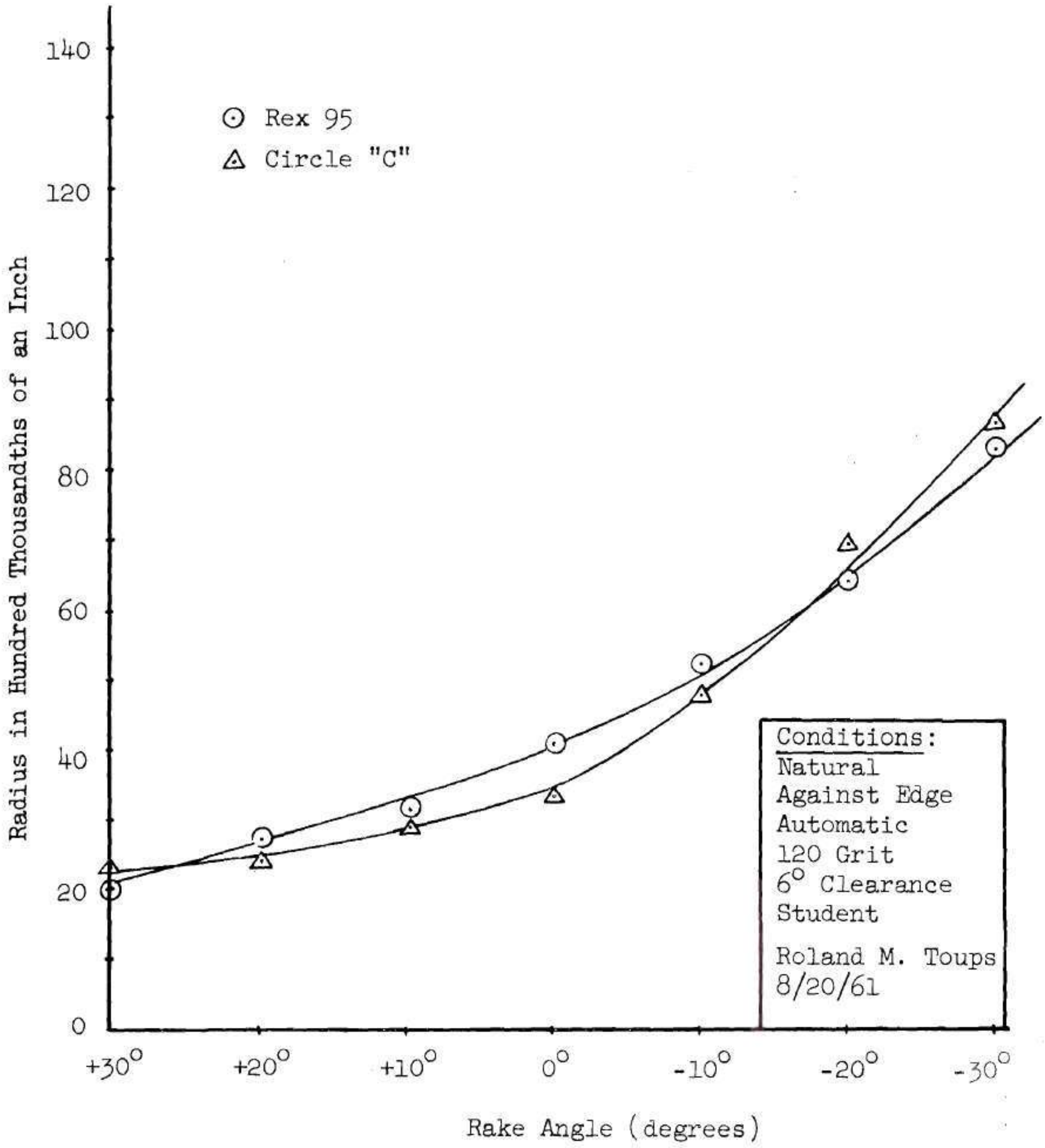


Fig. 17. Sharpness Radius vs. Rake Angle - No. 7.

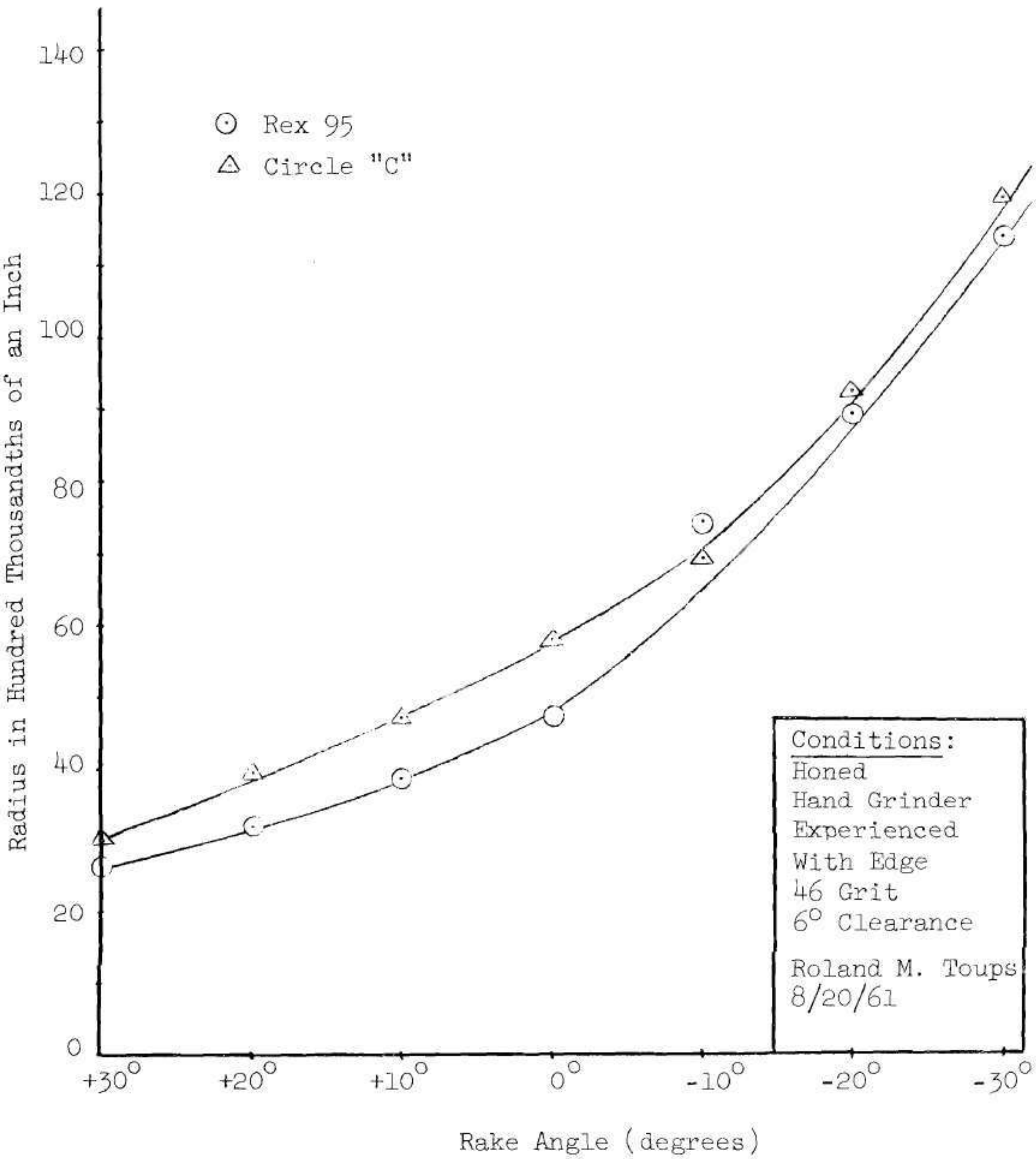


Fig. 18. Sharpness Radius vs. Rake Angle - No. 8.

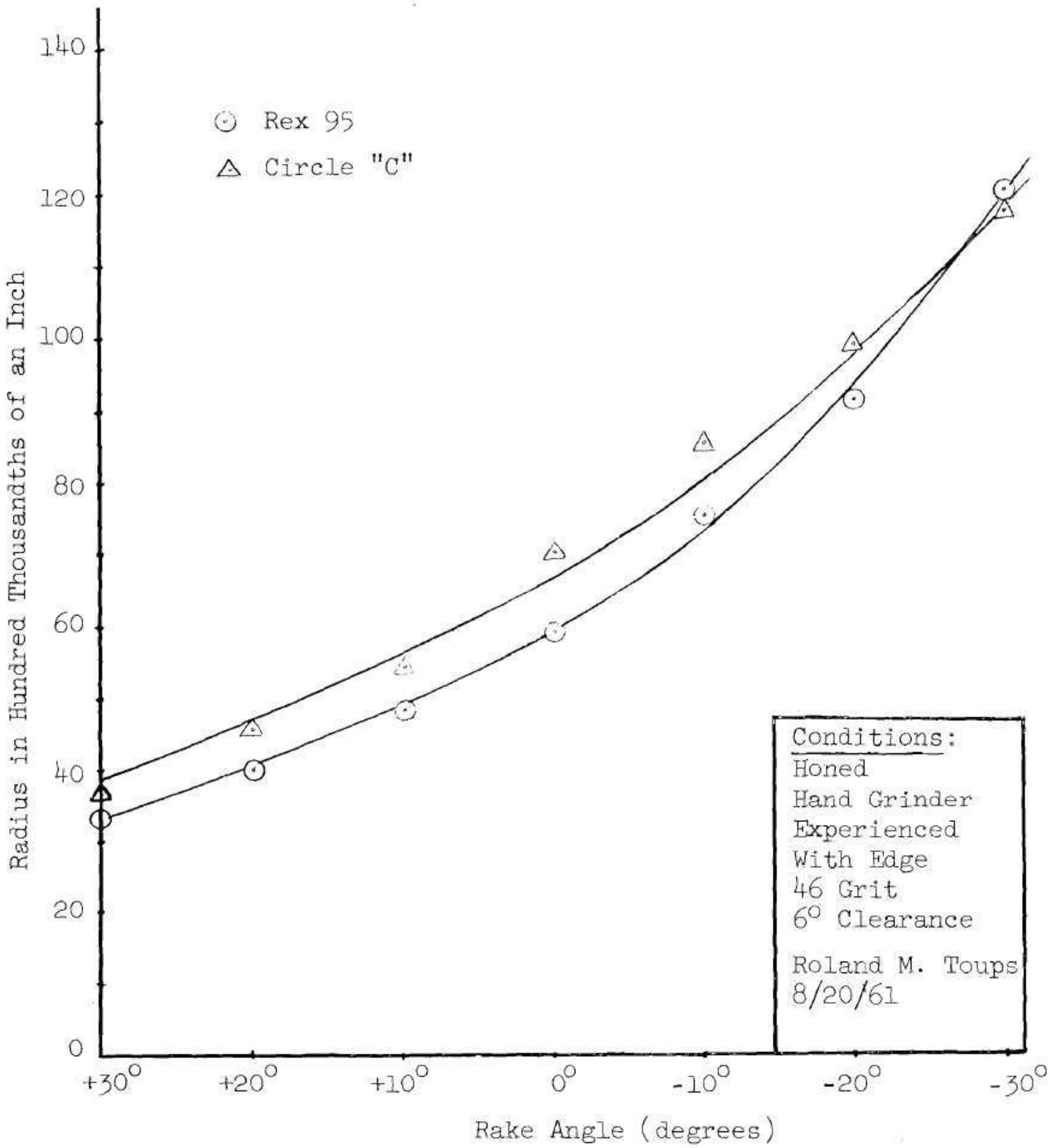


Fig. 19. Sharpness Radius vs. Rake Angle - No. 9.

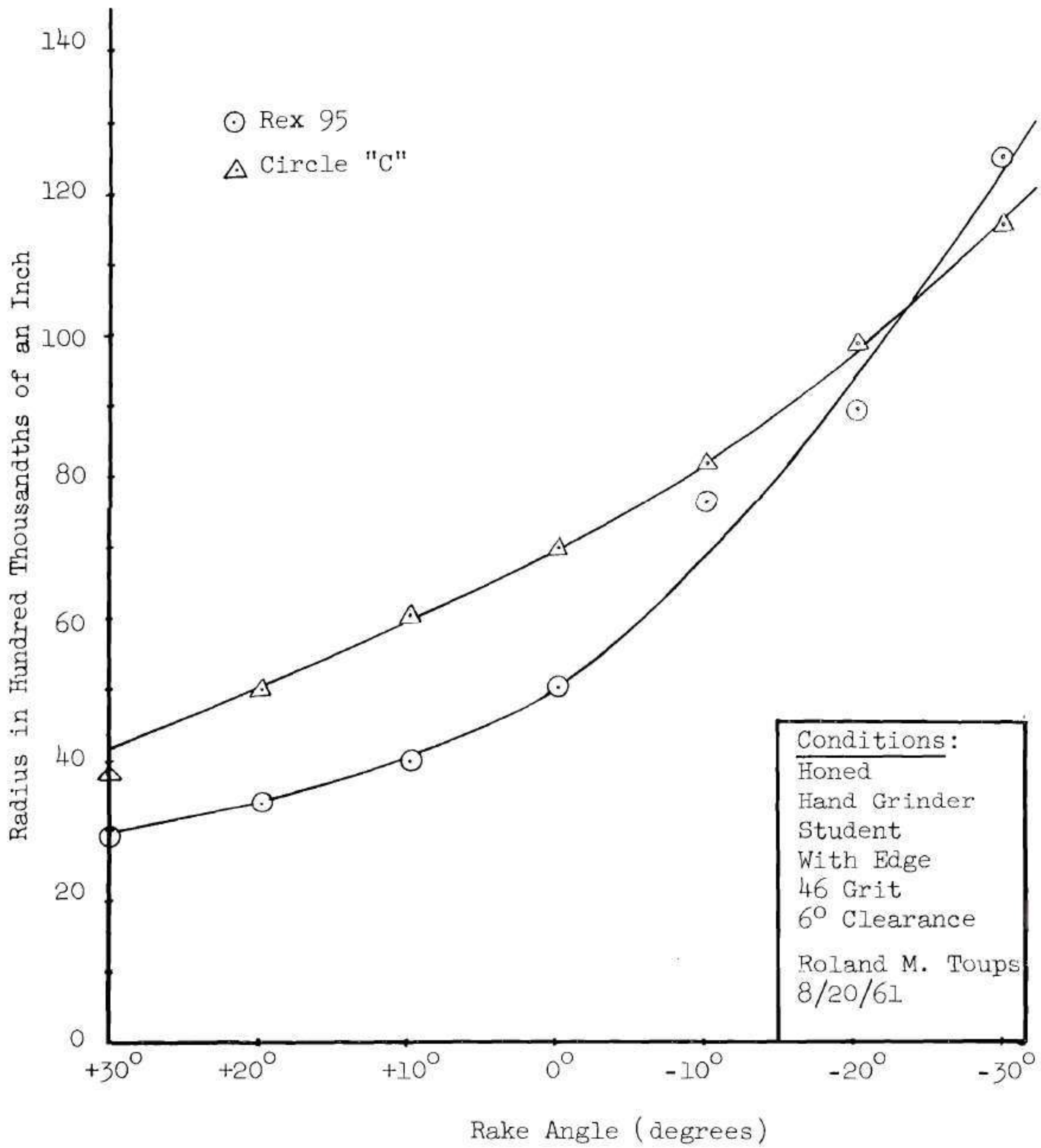


Fig. 20. Sharpness Radius vs. Rake Angle - No. 10.

at lower rakes. Again, the greater increase in lip angle is the reason. The difference in radii as the angle approaches values greater than 90°, or negative rakes, is quite large.

Tool material.--The thing to consider here is any deviation from similar behavior of Rex 95 HSS and Circle "C" HSS. Examining each graph, it is seen that no appreciable difference exists between the two steels. The two curves on each graph closely correspond. To show exactly how close, Table 1 was drawn up to give the exact values plotted. Numerical values are given in hundred thousandths of an inch.

Should the curves have been different, it is believed that the hardness of the two specimens would have been the chief reason. The whole process is based on grinding of the edges, and materials with different degrees of hardness would grind differently. For this reason a hardness test was run on the two specimens. Hardnesses were found to be almost identical as seen in Table 2. They substantiate why the two curves and hence, radii, are almost the same.

Fine, medium, coarse wheel.--Three different type wheels were used during the grinding operations. One was fine (120 grit), another medium (60 grit), and another coarse (46 grit). The difference the grit makes must be determined.

Two graphs, Figs. 21 and 22, and two Tables, 3 and 4, are set up to illustrate the difference. Table 3 and Fig. 21 show radii values for Rex 95 HSS in the three grit categories. The other table and graph give the radius variances for Circle "C" steel. Values are gotten from the tables in the appendix.

Table 1. Radius Values Plotted in Graphs No. 1-10.

Graph No. / Rake	Radius in hundred thousandths of an inch																			
	1		2		3		4		5		6		7		8		9		10	
	R	C	R	C	R	C	R	C	R	C	R	C	R	C	R	C	R	C	R	C
$+30^\circ$	19	15	42	36	27	26	35	38	50	48	10	13	20	22	27	30	34	37	30	39
$+20^\circ$	24	24	45	42	31	35	38	41	75	61	19	20	27	25	33	40	42	45	36	51
$+10^\circ$	29	31	52	52	40	45	45	47	80	82	25	27	32	29	40	49	52	56	42	60
0°	38	38	62	62	55	50	49	52	92	90	32	36	40	32	49	60	60	70	50	72
-10°	49	55	90	76	62	66	62	57	104	99	42	45	52	50	75	72	76	83	77	82
-20°	69	76	104	83	83	79	104	85	125	123	59	55	65	69	90	91	96	104	90	99
-30°	97	90	125	111	97	90	115	110	131	132	70	69	89	91	114	120	122	120	125	115

R - Rex 95 C - Circle "C"

Table 2. Specimen Hardness Test.

Rockwell "C" Hardness	
Rex 95 HSS	Circle "C" HSS
65.1	63.4
65.3	64.5
65.0	63.4
64.8	64.0
65.2	63.8
65.2	64.2
65.0	65.6
65.5	65.6
64.7	66.0
64.8	66.0
65.2	65.8
64.8	66.0
65.0 Avg.	64.8 Avg.

A definite trend exists in the graduation of radius values. The finer the grit the smaller the radius. This is because the finer wheel can better sharpen the point and make the segment smaller. In the coarse series, a honed value was used while in the medium and fine wheel natural radius values were used. There would be a slight absolute difference in the coarse values, natural and honed, but relative values of all the grits would remain the same. Hence the main point is still clearly illustrated. The plotted curves show this.

Application of the grinding wheel.--An explanation is given in the Procedure concerning "with" and "against" the cutting edge. In Table 5, which gives radius in hundred thousandths of an inch, there is a definite increase in radius size from "with" to "against" the edge. The values are taken from the tables in the appendix, in which the only variable is the application of the grinding wheel.

The effect can be explained in the following manner. When a point is to be put on a piece of wood with a knife, the blade is always moved toward the point, or "with" the edge. The same is true of cutting tools and grinding wheels. To get a smaller radius the grinding wheel is moved "with" the edge. It has a tendency to produce more burrs on the edge, but this will be dealt with further in the honing section.

Type of grinding process and operator's experience.--There are two factors to consider here. One is a comparison of radii ground with different automatic grinders. The other is a comparison of radii ground by experienced and inexperienced personnel using a hand grinder.

Table 3. Rex 95 HSS - Fine, Medium, Coarse Wheel.

	Radius in Hundred Thousandth of an Inch		
Rake	Fine Wheel	Medium Wheel	Coarse Wheel
$+30^{\circ}$	13	19	27
$+20^{\circ}$	20	24	33
$+10^{\circ}$	27	29	40
0°	36	38	49
-10°	45	49	75
-20°	55	69	90
-30°	69	97	114

Table 4. Circle "C" HSS - Fine, Medium, Coarse Wheel.

	Radius in Hundred Thousandth of an Inch		
Rake	Fine Wheel	Medium Wheel	Coarse Wheel
$+30^{\circ}$	10	15	30
$+20^{\circ}$	19	24	40
$+10^{\circ}$	25	31	49
0°	32	38	60
-10°	42	55	72
-20°	59	76	91
-30°	70	90	120

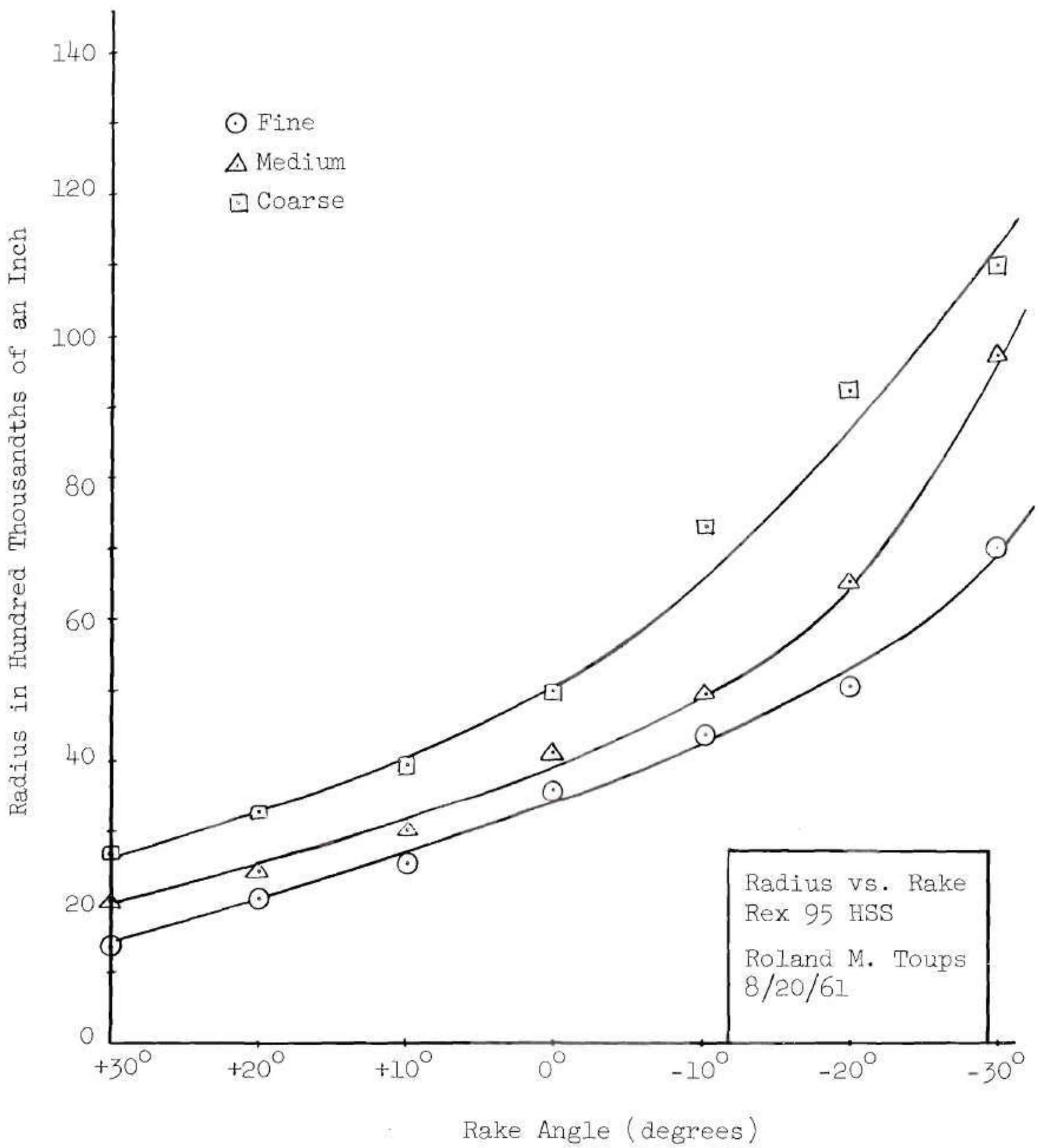


Fig. 21. Radius Values For Different Wheels.

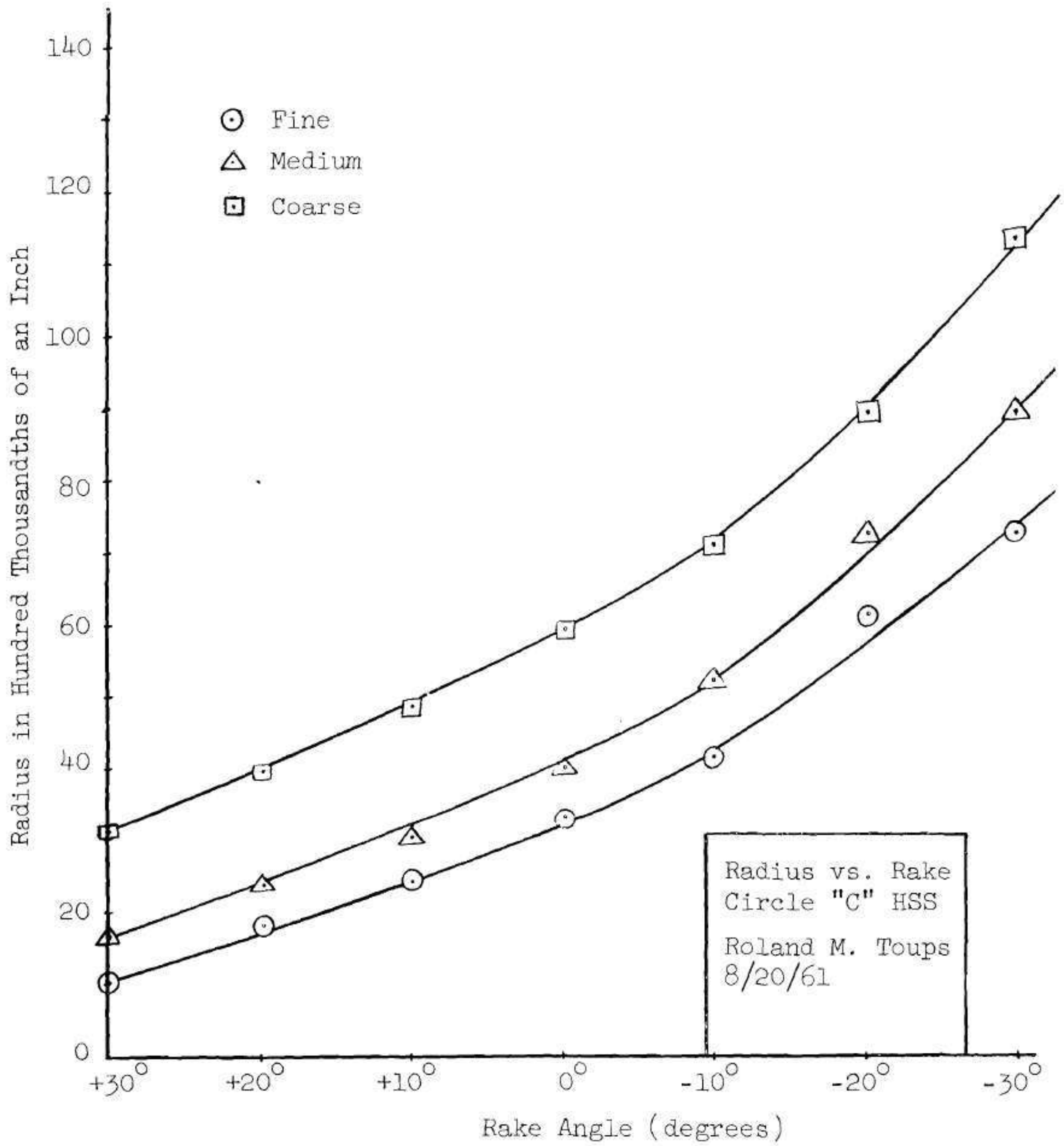


Fig. 22. Radius Values for Different Wheels.

Table 5. Radius Values Due to Wheel Application.

Type / Rake	Radius in Hundred Thousandths of an Inch											
	Medium Natural Rex 95		Medium Honed Rex 95		Medium Natural Circle "C"		Medium Honed Circle "C"		Fine Natural Rex 95		Fine Natural Circle "C"	
	W	A	W	A	W	A	W	A	W	A	W	A
$+30^{\circ}$	19	35	42	50	15	38	36	48	10	20	13	22
$+20^{\circ}$	24	38	45	75	24	41	42	61	19	27	20	25
$+10^{\circ}$	29	45	52	80	31	47	52	82	25	32	27	29
0°	38	49	62	92	38	52	62	90	32	40	36	32
-10°	49	62	90	104	55	57	76	99	42	52	45	50
-20°	69	104	104	125	76	85	83	123	59	65	55	69
-30°	97	115	125	131	90	110	111	132	70	89	69	91

W - with A - against

In the first case a commercial company ground tools on an automatic grinder and a student ground tools on an automatic grinder. Results are given in Table 6, and are seen graphically in Figs. 23 and 24.

There is no major difference is results obtained from those expected. Since the actual grinding is not a function of the operator but only of the condition of the wheel and machine, the two values should be fairly close. There is somewhat of an initial difference, but as the rake increases the differences diminish and both reach their peak at approximately 0.00090-0.00097 inches. Values are given in the tables in hundred thousandths of an inch.

It is surprising to see that hand ground values correlate so closely. Extreme care was taken by the operators and this could be the reason why. The whole idea is to measure the angles carefully with a bevel protractor as they are being ground and to grind a sharp edge. This gives good results, thereby showing it is not always necessary for the operator to be experienced if utmost care is taken. However, the operator must have sufficient knowledge of what is being done.

The magnitude of the coarse hand ground radii is much greater than the finer automatic grinder. That is to be expected.

Natural and honing finish.--The natural finish is the exact way in which the tool comes off the grinding wheel. By honing the natural finish the tiny burrs are disposed of and the edge is blunted to withstand the initial cutting shock on a lathe.

As can be seen from Table 8 and the curves in Figs. 27, 28, 29, and 30, honing greatly affects the natural sharpness radius. Of the variables examined, it appears to affect the radius most. As much as

Table 6. Automatic Grinding Radius Values.

Rake	Radius in Hundred Thousandths of an Inch			
	Commercial		Machine Shop	
	R	C	R	C
$+30^{\circ}$	27	26	19	15
$+20^{\circ}$	31	35	24	24
$+10^{\circ}$	40	45	29	31
0°	55	50	38	38
-10°	62	66	49	55
-20°	83	79	69	76
-30°	97	90	97	90

R - Rex 95 C - Circle "C"

Table 7. Hand Grinding Radius Values.

Rake	Radius in Hundred Thousandths of an Inch					
	Inexperienced		Experienced		Experienced	
	R	C	R	C	R	C
$+30^{\circ}$	30	39	34	37	27	30
$+20^{\circ}$	36	51	42	45	33	40
$+10^{\circ}$	42	60	52	56	40	49
0°	50	72	60	70	49	60
-10°	77	82	76	83	75	72
-20°	90	99	96	104	90	91
-30°	125	115	122	120	114	120

R - Rex 95 C - Circle "C"

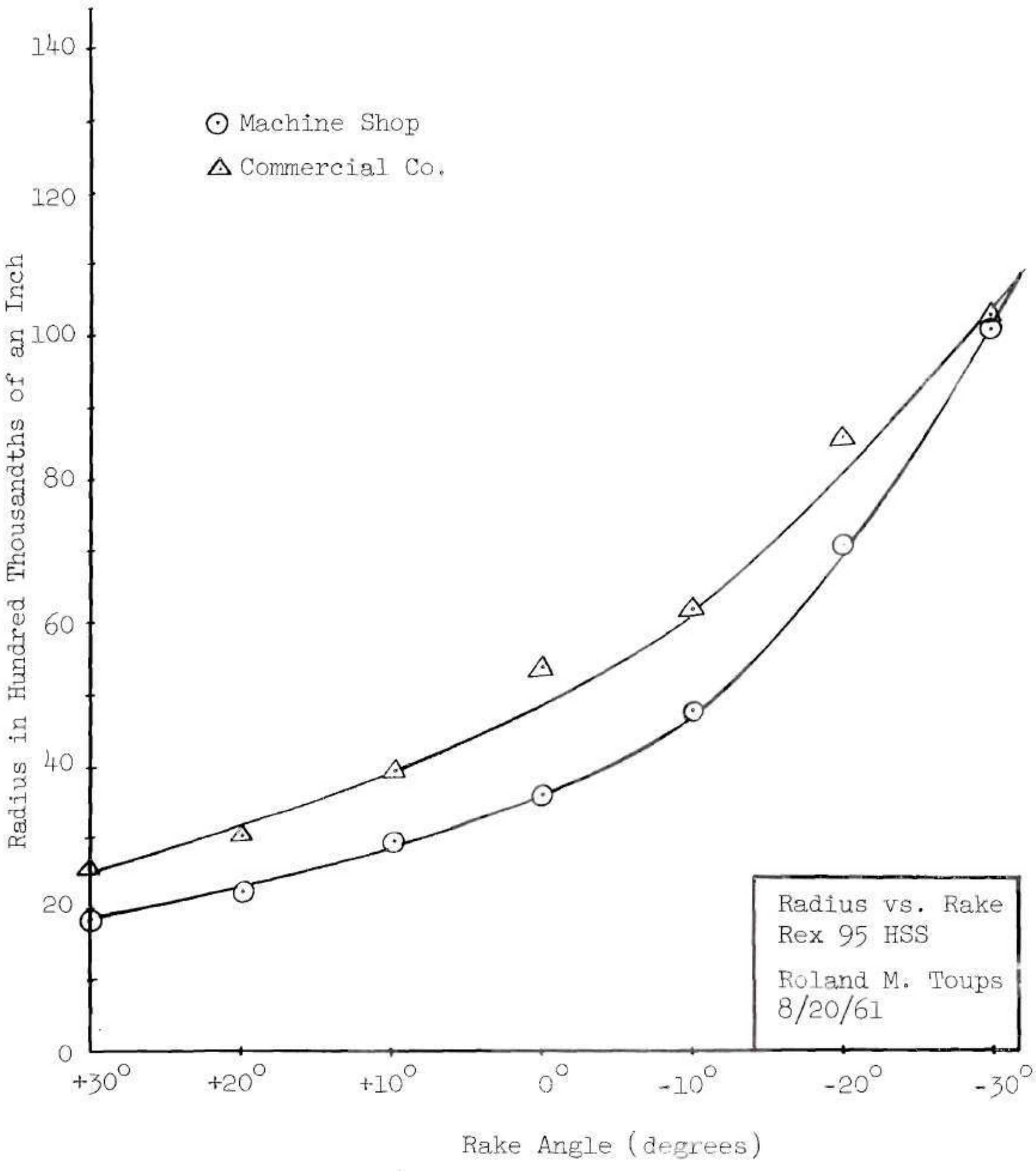


Fig. 23. Automatic Grinding Radius Values.

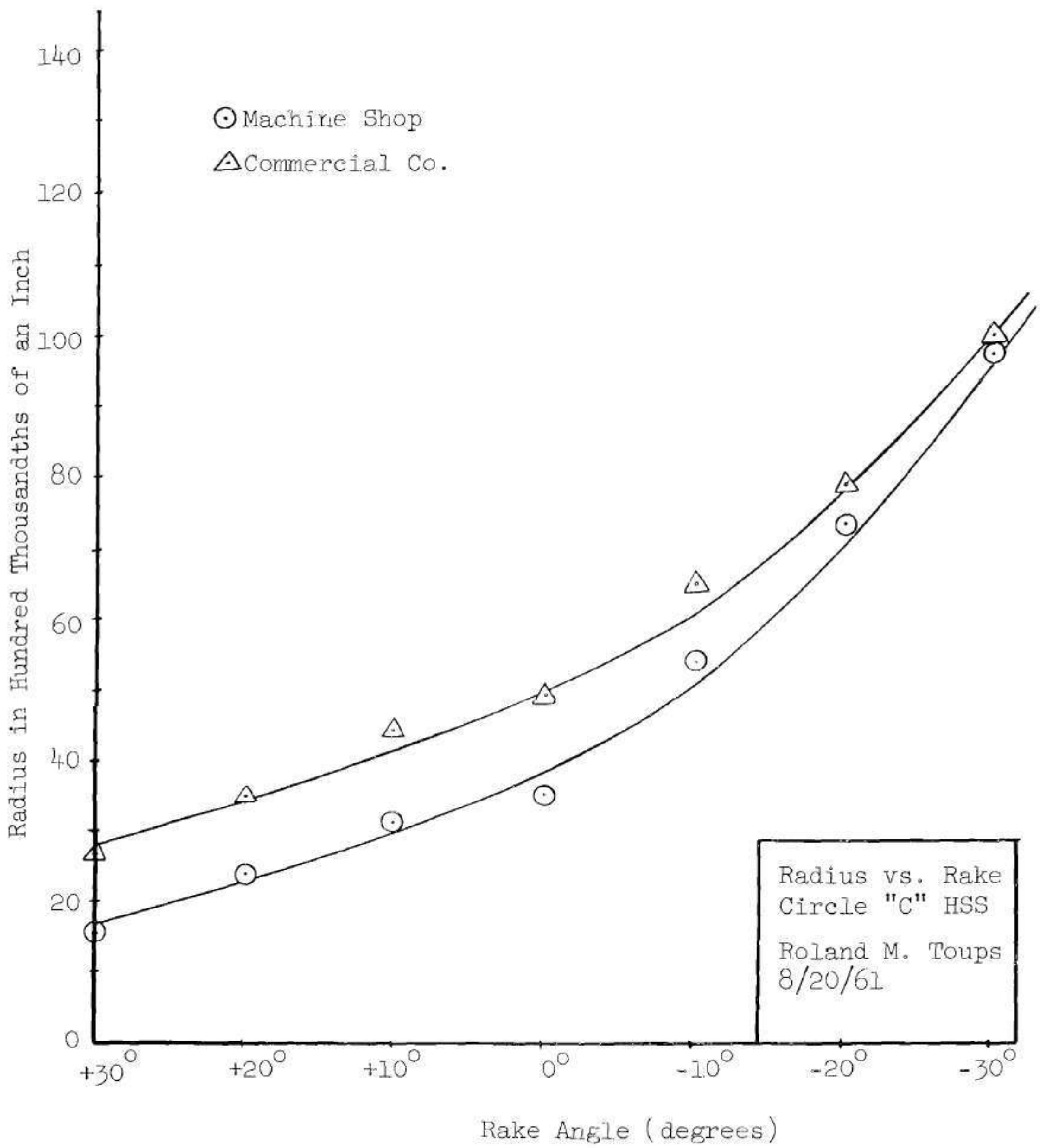


Fig. 24. Automatic Grinding Radius Values.

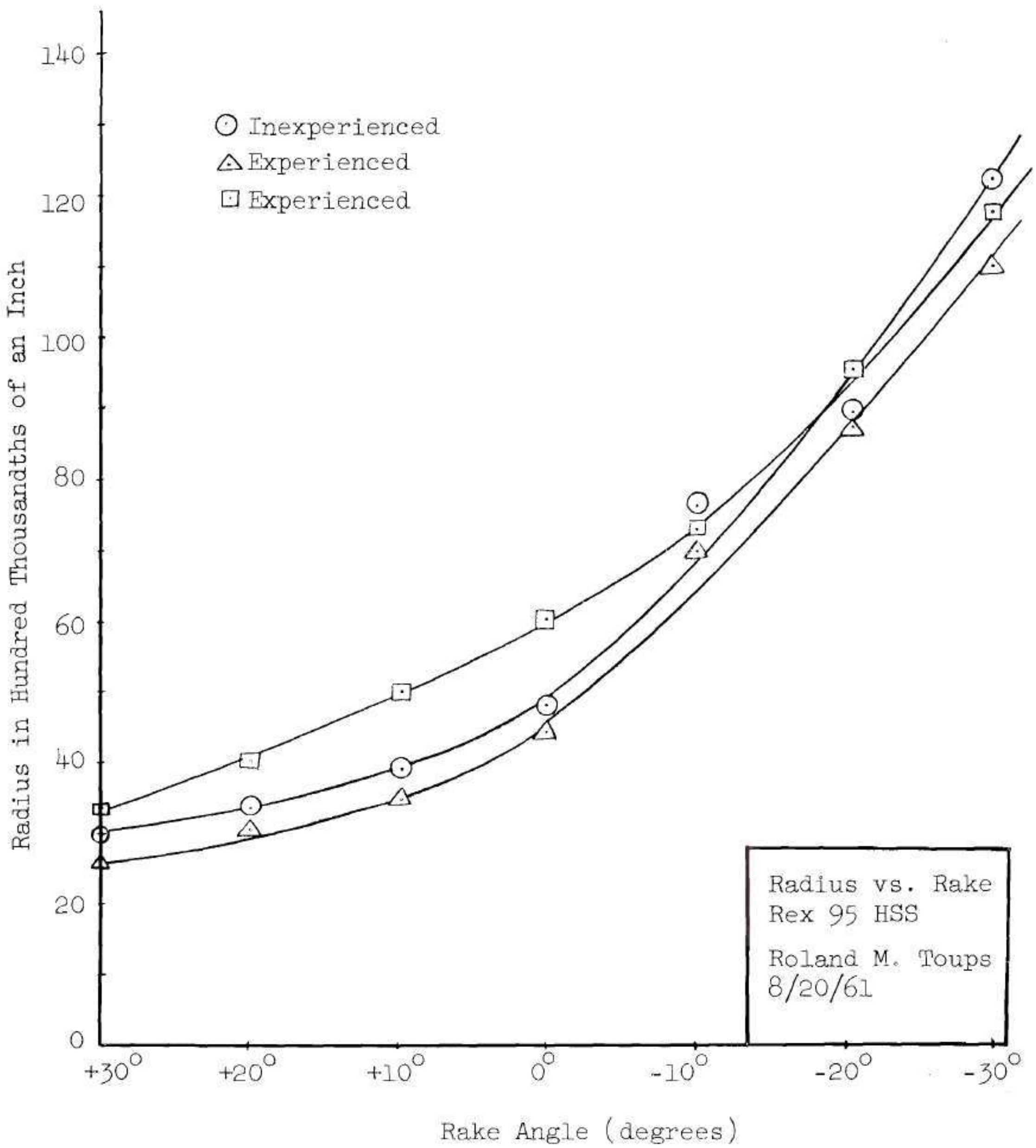


Fig. 25. Hand Grinding Radius Values.

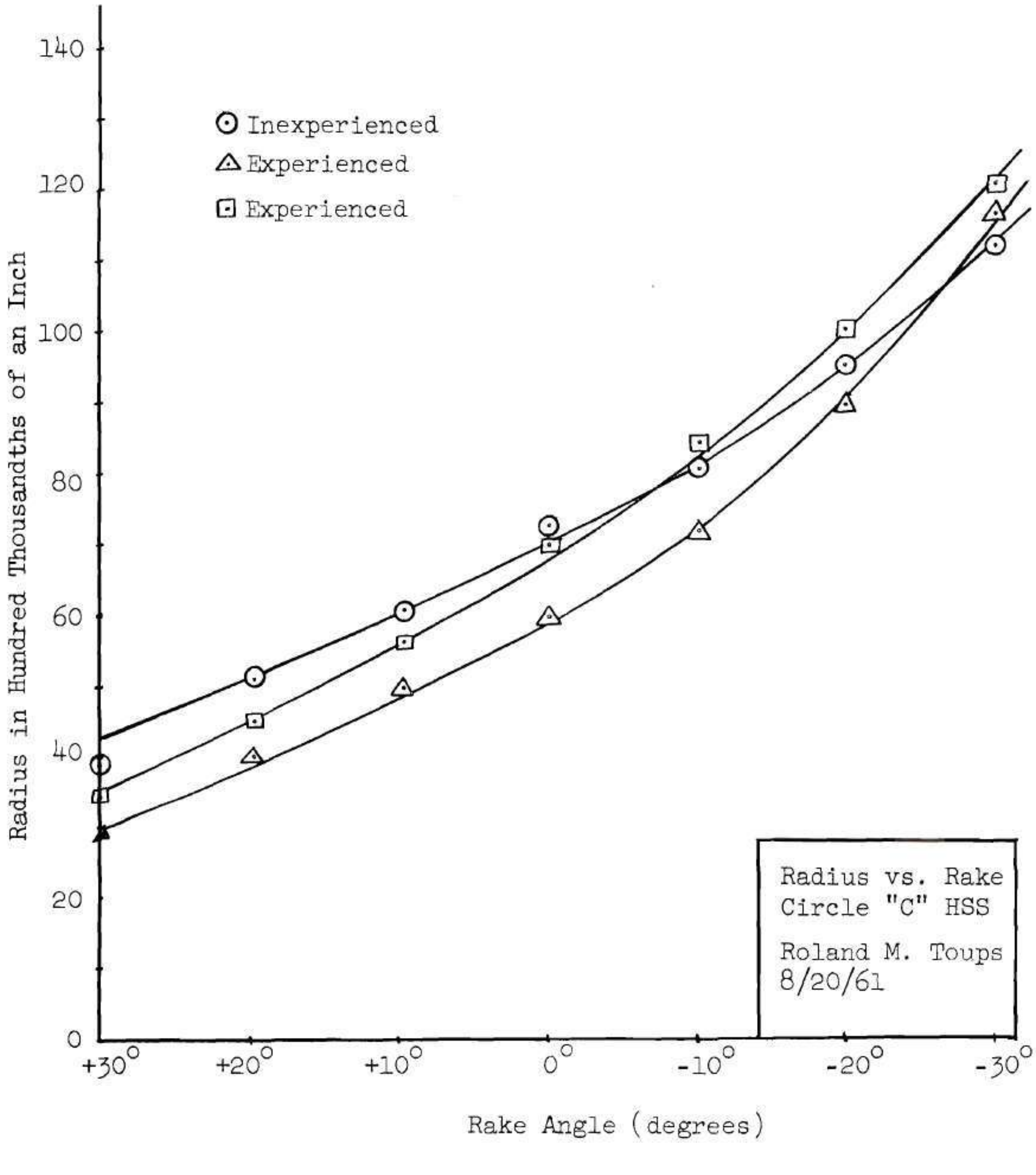


Fig. 26. Hand Grinding Radius Values.

Table 8. Difference in Honing and Natural Finish.

Type / Rake	Radius in Hundred Thousandths of an Inch: Medium With Edge Rex 95		Medium Against Edge Rex 95		Medium With Edge Circle C		Medium Against Edge Circle C	
	N	H	N	H	N	H	N	H
$+30^{\circ}$	19	44	35	55	15	36	38	48
$+20^{\circ}$	24	45	38	76	24	42	41	61
$+10^{\circ}$	29	60	45	80	31	52	47	82
0°	38	65	49	92	38	62	52	90
-10°	49	80	62	104	55	76	57	99
-20°	69	108	104	121	76	83	85	123
-30°	97	126	115	129	90	111	110	132

N - Natural H - Honed

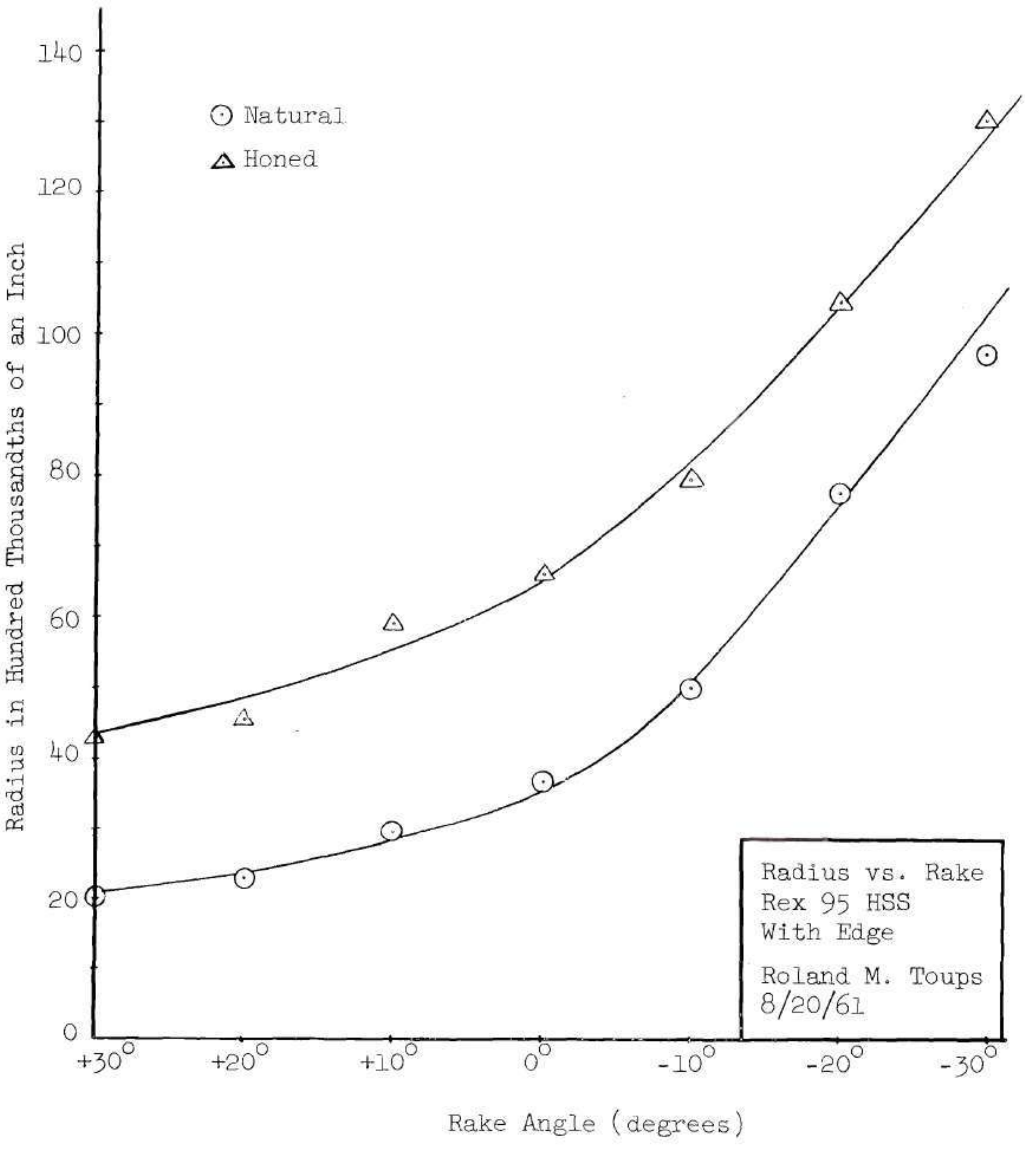


Fig. 27. Effect of Honing.

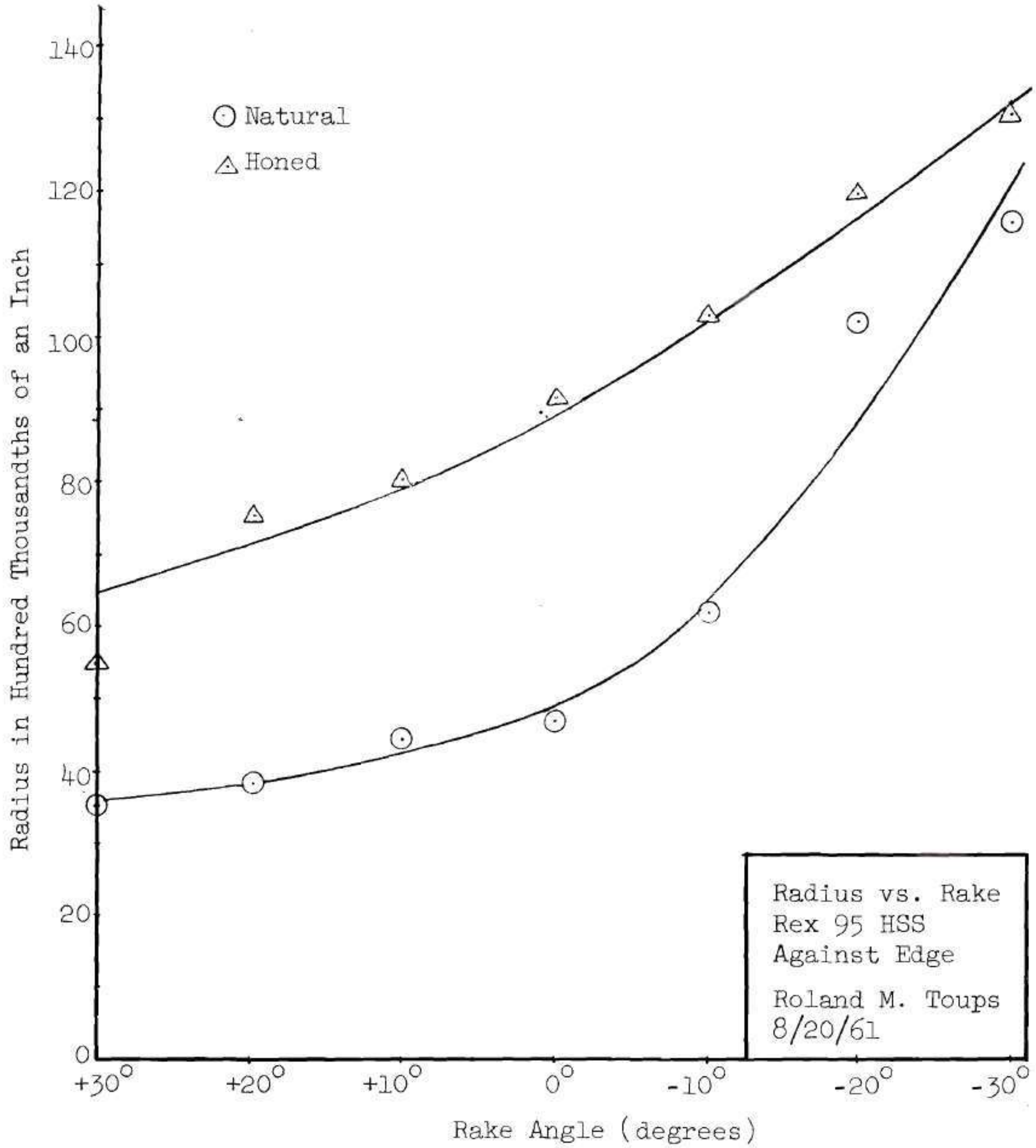


Fig. 28. Effect of Honing.

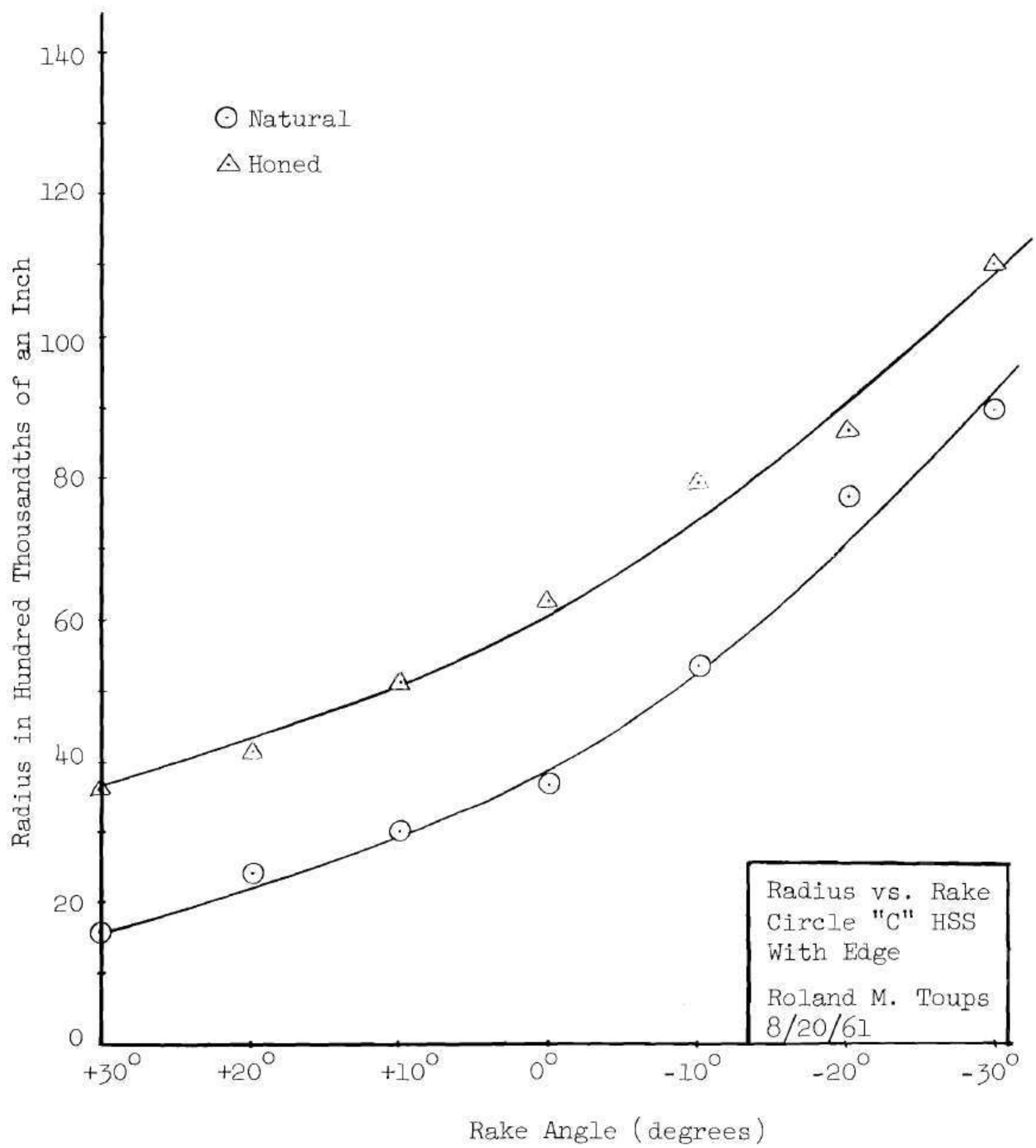


Fig. 29. Effect of Honing.

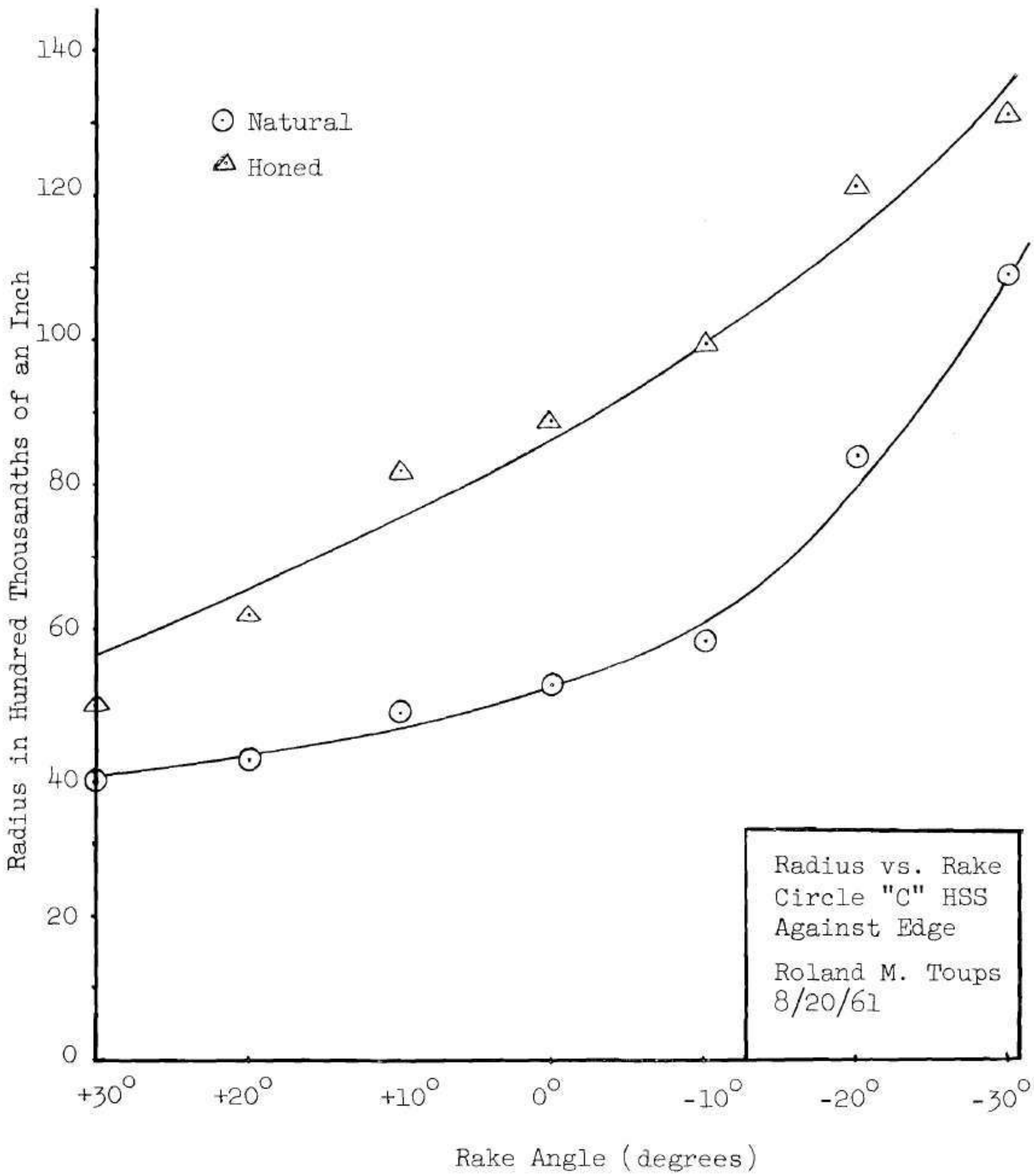


Fig. 30. Effect of Honing.

0.00030 in. in some cases is added to the radius after it is honed, as compared to the natural radius.

The radii were probably honed a little more than necessary, but were satisfactory for the purposes of this investigation. Honing is an operation that must be done before the tool can be put on a lathe. It must be carefully done with oil to get a uniform surface. Usually the deeper the cut, the more the tool edge is honed.

Overall results.--All variables have been separately analyzed as to whether or not they affect the natural sharpness radius. Table 9 contains a summary.

A series of pictures is included in the appendix to show the relative size and configuration of the natural sharpness radius for rake angles from -30° to $+30^{\circ}$.

Table 9. Overall Results.

Variable	Radius Change - Extent
Rake Angle	Radius increases as rake angle decreases.
Tool Material	Tools were similar, but different hardness should give different size radii.
Type of Wheel	Radius increases as the wheel gets coarser.
Application of Wheel	Radius ground with edge is less than against edge.
Grinder and Machinists' Experience	Hand grinding radius larger than in automatic grinding. Machinists' experience not of much consequence.
Natural or Honing Finish	Honed radii much larger than natural finish.

CHAPTER VI

MATHEMATICAL FORMULATION OF RADII

Albrecht's theory.--A formula will be derived to arrive at the natural sharpness radius mathematically. The method of Paul Albrecht (26) will be used.

Albrecht says the natural sharpness radius "r" depends on many variables. It can be shown mathematically to be a function of the lip angle "δ". With this in mind the formula can be written:

$$r = f(\delta)$$

There are only two known boundary conditions which apply. At one extreme $\delta = 0^\circ$, it can be seen that physically there is no radius at all, and hence $r = 0$. At $\delta = 180^\circ$ the included angle becomes a straight line and the radius is infinite.

Therefore the curve in Fig. 31 can be drawn, and it can likewise be extended into the region of negative sharpness, that is for values of included angle greater than 180°. Note where the rake angles of $+30^\circ$, $+20^\circ$, $+10^\circ$, 0°, -10°, -20°, -30° fall on the graph.

The shape of the graph can be approximated by the analytical expression,

$$r = a \tan^{n}\left(\frac{\delta}{2}\right)$$

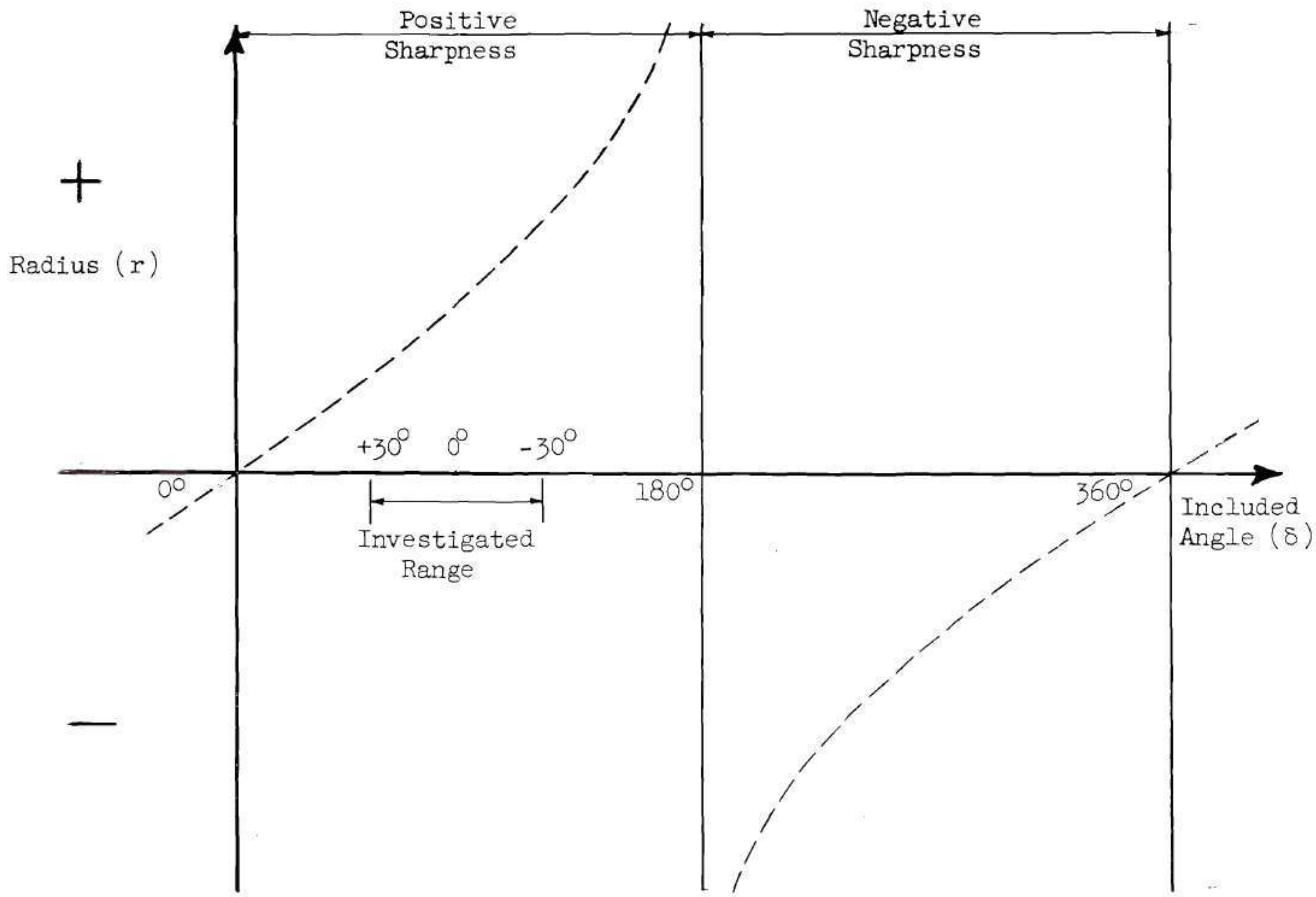


Fig. 31. Radius Sharpness vs. Included Angle.

since it behaves like the tangent curve. The letters "a" and "n" are parameters chosen so they will determine the vertical position of the curve. Points from these known curves will be substituted for "r" and "δ", leaving only two unknowns "a" and "n". Two points are sufficient to determine the parameters. Thus, the unknowns solved for, a formula for the radius is obtained.

Formulation.--Radius vs. rake angle graphs are available. Ten sets were plotted from the ten tables of recorded data in the appendix. They are Figs. 11-20 located in the "Different Rake Angle" portion of Results and Discussion.

Each set of graphs is different. From this it is readily seen that "a" and "n" will involve all the variables. To get a value of "r" and "δ" from the graph an average value will be taken from the two curves. To get "δ" add the rake plus the side relief and subtract from 90°. For example, $+30^\circ$ rake plus $+6^\circ$ clearance = 36°; $90^\circ - 36^\circ = 54^\circ$ included angle.

The first value will be found step by step. The remaining nine will be shown in tabular form.

For the first graph (Fig. 11 on page 23):
At $\alpha = 0^\circ$, $\delta = 84^\circ$:

$$0.00038 = a \tan^n 42^\circ$$

Likewise at $\alpha = -30^\circ$, $\delta = 114^\circ$:

$$0.00095 = a \tan^n 57^\circ$$

Table 10. Values For Radius Formula.

Graphs	Constants	
Fig. No.	"n"	"a"
11	1.7	0.00053
12	1.1	0.00070
13	1.3	0.00057
14	1.2	0.00069
15	1.0	0.00092
16	1.5	0.00040
17	1.4	0.00050
18	1.3	0.00065
19	1.2	0.00073
20	1.1	0.00070

Solving these two equations simultaneously:

$$\log 0.00038 = \log a + n \log (\tan 42^{\circ})$$

$$\log 0.00095 = \log a + n \log (\tan 57^{\circ})$$

$$-3.42022 = \log a - n\ (0.04556)$$

$$\underline{-3.02228 = \log a + n\ (0.18748)}$$

$$0.39794 = 0.23304\ n$$

$$\underline{n = 1.7}$$

Solving for "a":

$$0.00095 = a \tan^{1.7} 57^{\circ}$$

$$\underline{a = 0.00044}$$

Two separate groups must be considered. Graphs no. 1, 3, 4, 6, 7, concern the natural sharpness radius, while graphs no. 2, 5, 8, 9, 10, correspond to the honed values.

For the natural sharpness group the average values for the two quantities are $n = 1.4$ and $a = 0.00053$. For these two values the radius formula becomes:

$$r = 0.00053 \tan^{1.4}\left(\frac{\delta}{2}\right)$$

If the values of the seven rake angles used are substituted in the formula, the overall range of the natural sharpness radii can be obtained. The following values correspond to the prescribed rake angles:

$+30^{\circ}$	---	0.00019 inch
$+20^{\circ}$	---	0.00027 "
$+10^{\circ}$	---	0.00035 "
0°	---	0.00045 "
-10°	---	0.00057 "
-20°	---	0.00074 "
-30°	---	0.00084 "

For the honed group the average values of the two unknown quantities are $n = 1.1$ and $a = 0.00074$. The radius expression becomes:

$$r = 0.00074 \tan^{1.1} \left(\frac{\delta}{2}\right)$$

If the seven rake angles are substituted as above the following values are gotten:

$+30^{\circ}$	---	0.00034 inch
$+20^{\circ}$	---	0.00039 "
$+10^{\circ}$	---	0.00054 "
0°	---	0.00066 "
-10°	---	0.00080 "
-20°	---	0.00097 "
-30°	---	0.00118 "

If both of these groups are put together to get an average working value for the radius, the two unknown quantities become $n = 1.3$ and $a = 0.00064$. The radius formula now becomes:

$$r = 0.00064 \tan^{1.3} \left(\frac{\delta}{2}\right)$$

If the seven rake angles are substituted the radius values are determined to be:

$+30^{\circ}$	---	0.00027 inch
$+20^{\circ}$	---	0.00035 "
$+10^{\circ}$	---	0.00044 "
0°	---	0.00056 "
-10°	---	0.00070 "
-20°	---	0.00088 "
-30°	---	0.00110 "

The range for these three groups computed by formula is as follows:

Natural	0.00019 - 0.00084 inch
Honed	0.00034 - 0.00118 "
Overall	0.00027 - 0.00110 "

A check of this is made by taking the mean of all readings in the respective groups. This gives the following range:

Natural	0.00020 - 0.00089 inch
Honed	0.00038 - 0.00120 "
Overall	0.00029 - 0.00105 "

The values for the respective categories are sufficiently close to justify the use of the formula.

CHAPTER VII

CONCLUSIONS

The Unitron Metallograph and Universal Camera Microscope is a suitable device for measuring natural sharpness radii of cutting tools. The method gives consistent results, but the specimen must be polished and mounted so it can be accurately photographed.

The six variables studied give a good indication of the behavior of the radius. It definitely varies with rake angle, type of grinding wheel, type of grinder, and finish. Experimental data shows that the tools chosen were too much alike to illustrate a difference in tool material. In these tests the experience of the grinder had no real significance when appropriate care was taken.

Formulation of results shows good reliability for the empirical data selected, and the formula

$$r = a \tan^{n}\left(\frac{\delta}{2}\right)$$

is accurate. Albrecht's theory is shown to apply in all cases and give good results when compared with actual averaged data.

The natural sharpness radius ranges between 0.00010-0.00100 inches. For all values, including the honing finish, the overall range is from 0.00029-0.00105 inches. This is perhaps a better working value and one to base further work on.

CHAPTER VIII

RECOMMENDATIONS

As shown by this investigation, extreme care in honing a tool is recommended. This is a delicate operation and one that requires careful attention, because it has an important effect on the sharpness radius. For practical usage it is a necessary operation, since tiny burrs may occur on the tool edge.

In future investigations of sharpness radii, tool material hardness should be investigated. Though the author believes this factor must affect the radius, no evidence of this fact was obtained in the present investigation.

APPENDICES

APPENDIX A

Seven pictures of natural sharpness radii corresponding to the seven rake angles used in the experiment are included as typical.

Figure 32. Natural Sharpness Radius.
Rake Angle +30°, Radius 0.00020 in.

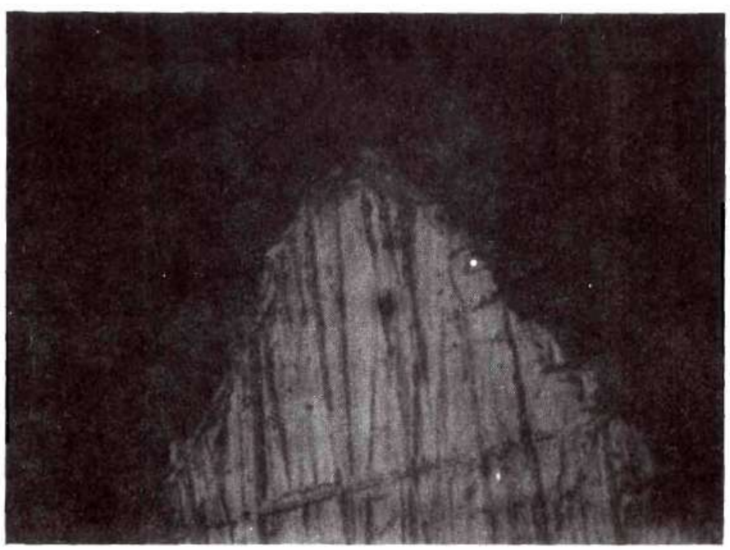


Figure 33. Natural Sharpness Radius.
Rake Angle +20°, Radius 0.00035 in.

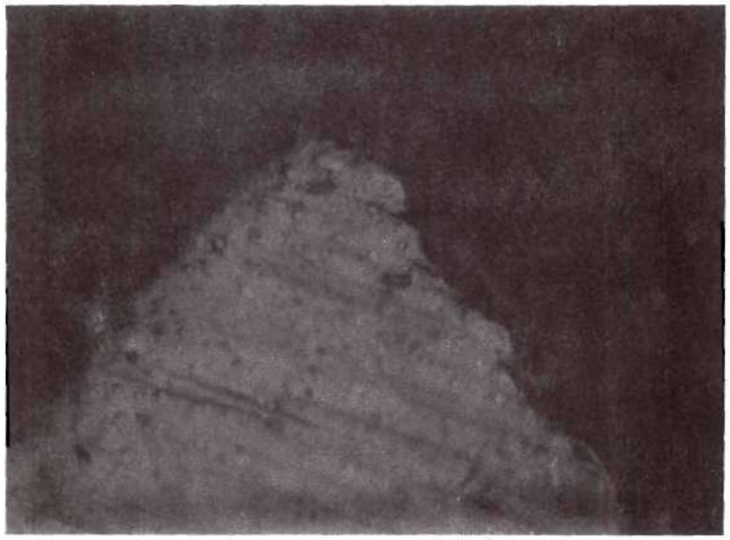


Figure 34. Natural Sharpness Radius.
Rake Angle +10°, Radius 0.00045 in.

Figure 35. Natural Sharpness Radius.
Rake Angle 0°, Radius 0.00056 in.

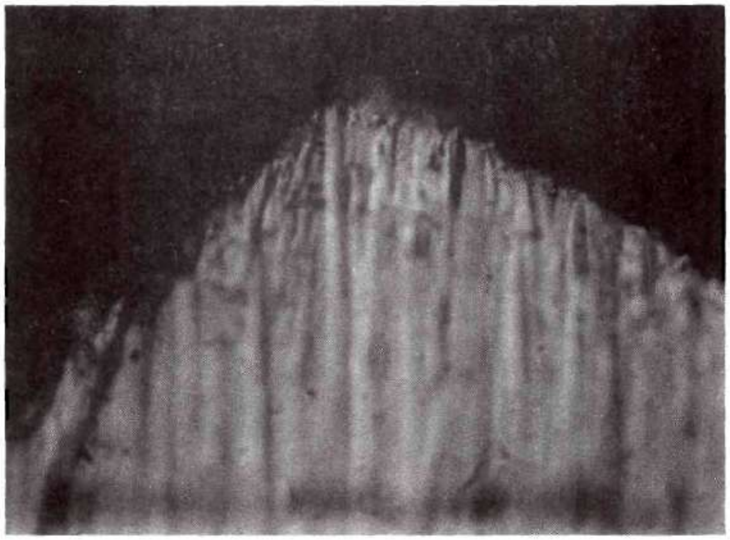


Figure 36. Natural Sharpness Radius.
Rake Angle -10°, Radius 0.00069 in.

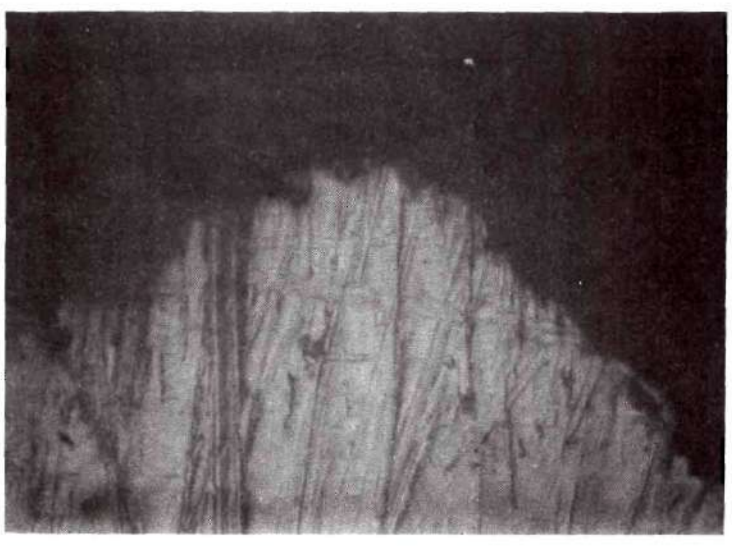


Figure 37. Natural Sharpness Radius.
Rake Angle -20°, Radius 0.00083 in.

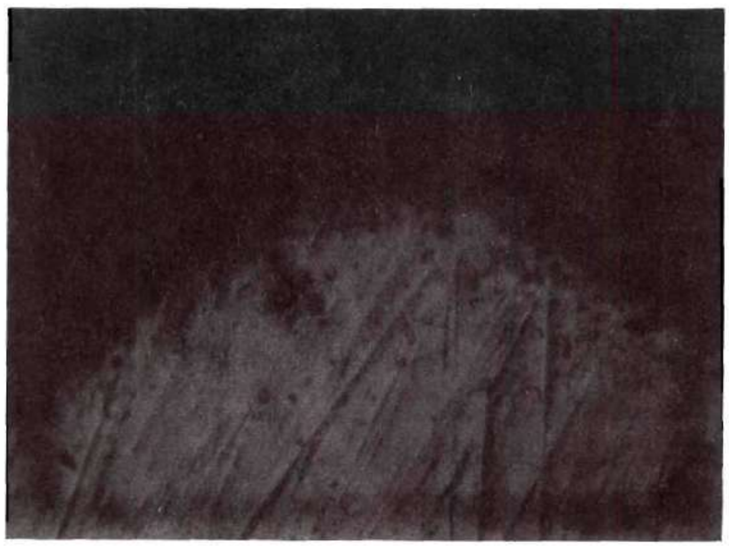


Figure 38. Natural Sharpness Radius.
Rake Angle -30°, Radius 0.00102 in.

APPENDIX B

Recorded data obtained during investigation.

Table 11. Record of Radius Values - No. 1.

Conditions: 6° Clearance
Automatic Grinder
60 Grit - Medium
With Edge
Natural
Student

	Radius in Hundred Thousandths of an Inch							
	Rex 95				Circle C			
Rake	1	2	3	Avg.	1	2	3	Avg.
+30°	16	22	18	19	15	15	14	15
+20°	20	26	25	24	22	26	25	24
+10°	29	27	30	29	-	31	31	31
0°	37	-	39	38	38	36	40	38
-10°	49	49	50	49	59	51	55	55
-20°	72	66	68	69	82	70	72	76
-30°	100	92	95	97	90	94	86	90

Table 12. Record of Radius Values - No. 2.

Conditions: 6° Clearance
Automatic Grinder
60 Grit - Medium
With Edge
Honed
Student

	Radius in Hundred Thousandths of an Inch							
	Rex 95				Circle C			
Rake	1	2	3	Avg.	1	2	3	Avg.
$+30^\circ$	42	38	44	42	-	37	35	36
$+20^\circ$	45	-	45	45	40	42	42	42
$+10^\circ$	50	46	60	52	56	53	47	52
0°	58	66	65	62	56	66	67	62
-10°	94	96	80	90	79	73	75	76
-20°	104	106	108	104	92	80	78	83
-30°	120	130	126	125	110	111	111	111

Table 13. Record of Radius Values - No. 3.

Conditions: 6° Clearance
Automatic Grinder
60 Grit - Medium
With Edge
Natural
Commercial Co.

	Radius in Hundred Thousandths of an Inch							
	Rex 95				Circle C			
Rake	1	2	3	Avg.	1	2	3	Avg.
$+30^{\circ}$	25	29	28	27	26	24	26	26
$+20^{\circ}$	-	33	30	31	38	33	36	35
$+10^{\circ}$	40	38	40	40	48	42	44	45
0°	55	60	50	55	50	51	50	50
-10°	60	64	63	62	68	64	65	66
-20°	90	76	82	83	82	81	74	79
-30°	94	100	-	97	82	98	90	90

Table 14. Record of Radius Values - No. 4.

Conditions: 6° Clearance
Automatic Grinder
60 Grit - Medium
Against Edge
Natural
Student

	Radius in Hundred Thousandths of an Inch							
	Rex 95				Circle C			
Rake	1	2	3	Avg.	1	2	3	Avg.
$+30^{\circ}$	37	36	32	35	37	39	38	38
$+20^{\circ}$	38	39	38	38	40	38	45	41
$+10^{\circ}$	45	49	41	45	47	47	47	47
0°	49	52	46	49	53	55	48	52
-10°	-	62	62	62	60	54	56	57
-20°	104	109	99	104	88	82	84	85
-30°	120	113	112	115	110	111	110	110

Table 15. Record of Radius Values - No. 5.

Conditions: 6° Clearance
Automatic Grinder
60 Grit - Medium
Against Edge
Honed
Student

	Radius in Hundred Thousandths of an Inch							
	Rex 95				Circle C			
Rake	1	2	3	Avg.	1	2	3	Avg.
$+30^{\circ}$	50	45	55	50	48	-	49	48
$+20^{\circ}$	72	78	76	75	61	61	62	61
$+10^{\circ}$	80	81	80	80	84	80	82	82
0°	92	93	92	92	93	94	83	90
-10°	106	102	104	104	104	96	97	99
-20°	125	130	121	125	123	-	123	123
-30°	145	119	129	131	130	134	132	132

Table 16. Record of Radius Values - No. 6.

Conditions: 6° Clearance
Automatic Grinder
120 Grit - Fine
With Edge
Natural
Student

	Radius in Hundred Thousandths of an Inch							
	Rex 95				Circle C			
Rake	1	2	3	Avg.	1	2	3	Avg.
$+30^{\circ}$	10	12	9	10	14	15	10	13
$+20^{\circ}$	18	-	20	19	17	23	20	20
$+10^{\circ}$	25	27	23	25	-	28	26	27
0°	30	32	34	32	35	-	36	36
-10°	42	42	42	42	45	45	47	45
-20°	59	63	55	59	59	55	51	55
-30°	64	72	74	70	76	62	68	69

Table 17. Record of Radius Values - No. 7.

Conditions: 6° Clearance
Automatic Grinder
120 Grit - Fine
Against Edge
Natural
Student

	Radius in Hundred Thousandths of an Inch							
	Rex 95				Circle C			
Rake.	1	2	3	Avg.	1	2	3	Avg.
$+30^{\circ}$	20	18	20	20	21	22	22	22
$+20^{\circ}$	27	26	27	27	29	21	24	25
$+10^{\circ}$	32	33	31	32	33	28	27	29
0°	46	44	30	40	30	34	32	32
-10°	50	49	57	52	65	46	40	50
-20°	66	65	-	65	66	69	70	69
-30°	88	90	89	89	90	91	91	91

Table 18. Record of Radius Values - No. 8.

Conditions: 6° Clearance
Hand Grinder
46 Grit - Coarse
With Edge
Honed
Experienced Grinder

	Radius in Hundred Thousandths of an Inch							
	Rex 95				Circle C			
Rake	1	2	3	Avg.	1	2	3	Avg.
$+30^\circ$	27	28	27	27	32	31	27	30
$+20^\circ$	30	31	38	33	44	36	39	40
$+10^\circ$	40	45	35	40	49	50	49	49
0°	49	49	50	49	61	62	57	60
-10°	74	-	76	75	71	74	-	72
-20°	90	91	90	90	-	90	92	91
-30°	104	114	123	114	121	120	120	120

Table 19. Record of Radius Values - No. 9.

Conditions: 6° Clearance
Hand Grinder
46 Grit - Coarse
With Edge
Honed
Experienced Grinder

	Radius in Hundred Thousandths of an Inch							
	Rex 95				Circle C			
Rake	1	2	3	Avg.	1	2	3	Avg.
$+30^{\circ}$	39	33	30	34	34	32	45	37
$+20^{\circ}$	40	46	40	42	40	44	50	45
$+10^{\circ}$	-	50	54	52	56	57	56	56
0°	60	61	60	60	69	66	75	70
-10°	82	74	70	76	73	86	89	83
-20°	92	93	103	96	104	105	104	104
-30°	123	125	118	122	119	120	120	120

Table 20. Record of Radius Values - No. 10.

Conditions: 6° Clearance
Hand Grinder
46 Grit - Coarse
With Edge
Honed
Inexperienced Grinder

	Radius in Hundred Thousandths of an Inch							
	Rex 95				Circle C			
Rake	1	2	3	Avg.	1	2	3	Avg.
$+30^{\circ}$	30	33	27	30	36	42	-	39
$+20^{\circ}$	36	35	36	36	50	51	51	51
$+10^{\circ}$	40	44	43	42	52	63	65	60
0°	51	49	49	50	70	74	72	72
-10°	77	79	75	77	80	82	82	82
-20°	96	88	84	90	99	99	98	99
-30°	120	122	133	125	114	116	-	115

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