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AN EVALUATION OF SURFACE ROUGHNESS AS MEASURED BY THE BRUSH SURFACE ANALYZER AND THE SCHMALTZ OPTICAL CUT

by
David Myles Huddart

A Thesis
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in Candidacy for the Degree of
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This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

May 24, 1967
Date

George E. Kane
Professor in Charge

C. J. Gould
Head of the Department

Acknowledgments

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The Zeiss microscope at the Homer Research Center was employed for data collection, and I am grateful to Mr. Paul Aylward of the Bethlehem Steel Corporation for his assistance in using this equipment.

I would also like to thank Mr. Gilbert Zambelli for his help in the machining of the test surfaces.

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Abstract

In order to gain an insight into the actual qualitative characteristics of a machined surface, it is necessary to view a profile microscopically. The setup may be difficult or impossible. A simple stylus trace instrument can yield a numerical description of a surface easily. This thesis attempted to relate a qualitative observation of surface roughness, obtained by means of an optical cut, to a quantitative measure recorded by the Brush Surface Analyzer. The qualitative description was reduced to a Roughness Parameter, and the arithmetic average roughness was correlated with it. For turning, shaping, and milling cuts, it was found that the average roughness could be used to estimate the Roughness Parameter with a high degree of significance.

Introduction

The concept of surface roughness has been investigated in many ways and defined with many terms. It would be to the manufacturing engineer's advantage to be able to fully describe the nature of the machined surfaces he is generating. The surface imparted to a workpiece during a metal cutting process is usually of some importance with respect to the function of the piece. For example, the fatigue strength and wear resistance are improved significantly by a smooth finish.

The type of finish rendered is also an indication of the characteristics of the metal removal process employed. A smooth finish reveals that basically the process is a mild cut, while a rough surface might indicate a relatively severe cutting operation. The nature of the finish can tell one if the forces on the tool were large or small, whether there was excessive tool wear, and even what type of tool wear.

Some basic definitions for describing and measuring surface roughness are presented by the American Standards Association (10). These will be established now and used throughout the paper.

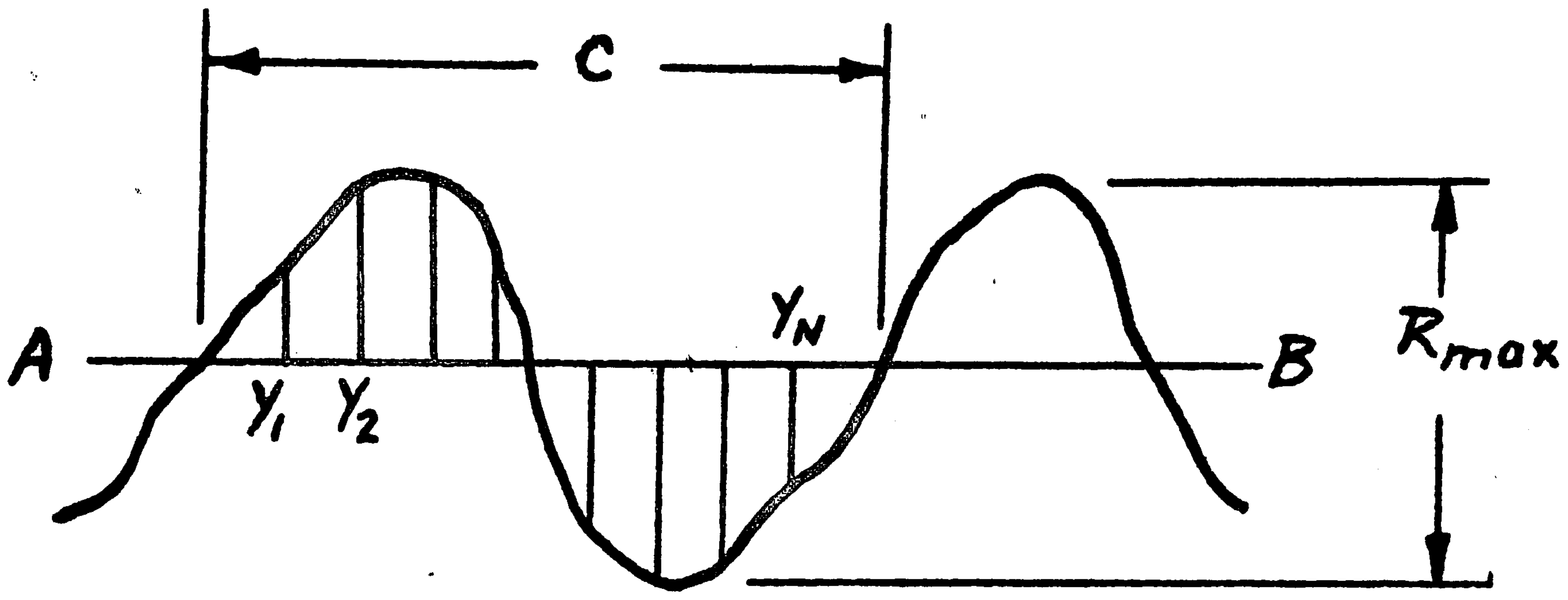

Fig. 1. Surface Profile

The following terms are of interest in Fig. 1.:

1. Profile - the contour of the surface in a plane perpendicular to the surface.
2. Roughness - the finer irregularities in the surface texture, usually resulting from the inherent action of the cutting process.
3. Waviness - the widely spaced component of surface texture resulting from machine and workpiece deflection or vibration.
4. Center line - a line parallel to the general direction of the surface, within the limits of the roughness width cutoff, such that the sums of the areas contained between it and those parts of the profile which lie on either side of it are equal. (line A-B)

5. Roughness width cutoff - that distance, along the center line, over which the average roughness is computed. (distance C)

6. Average Roughness (A.A.) - the arithmetic average deviation of the surface measured normal to the center line.

$$\text{A.A.} = \frac{y_1+y_2+ - - - +y_N}{N}$$

7. Profile Roughness - a graphical representation of the relative position and magnitude of the roughness along the profile of the surface.

8. R_{max} - the maximum peak to valley height of the roughness for a certain sampling length.

The average roughness is an important concept because it gives an indication of the relative magnitude of the surface roughness, and it is easy to measure. An observation of the actual surface profile, however, is required for a more complete definition of surface finish. The profile roughness may be thought of as a bridge between these two extremes of measurement. These, then, are the variables which will be investigated.

Previous Work in the Field

Quantitative measurement of surface finish has usually been evaluated in experimentation dealing with the effect of the cutting conditions on the roughness. Research at General Electric (9) may be considered a summary of the work in this area. The main independent variables studied were cutting speed, feed, and tool nose radius. It was found in machining the major ferrous alloys that increases in speed and nose radius resulted in a decrease in surface roughness, when measured as the root mean square (RMS) deviation from the center line. An increase in feed resulted in an increase in roughness. The data was obtained from a turning operation, but the results have been extended to other cutting processes.

Research at M.I.T. (8) emphasized the qualitative aspects of surface roughness on turning, grinding, and lapping operations. The Zeiss microscope and Brush Surface Analyzer, among other equipment, were used to measure RMS average roughness and R_{max} values. Surfaces were described by single parameters in a number of ways, one being the ratio R_{max}/RMS. It was noted that for fine finishes this ratio was as high as 20:1. For coarse finishes the value was between 5:1 and 3:1. Turning cuts on heat treated steel, which insured good shearing action, consistently yielded an R_{max}/RMS equal to 4:1. An explanation was given for the higher ratio when encountering finer finishes. The theory is that a few widely spaced irregularities present on a ground or lapped surface were usually not included during the averaging measurement but were included as the R_{max}.

Also reported in the M.I.T. paper were parameters suggested by Schmaltz[1] and Bodart[2]. The form factor of Schmaltz is a ratio of roughness valley to center line distance to maximum peak to valley distance (R_{max}). This is mainly a measure of the magnitude of the irregularities. Bodart's dimensionless quantity η includes a factor R_{max}/λ in which λ is the wave length of the irregularities. Therefore, η may be considered a measure of form as well as a measure of magnitude.

Reason (7) stated the importance of specifying what process produced the surface when designating the surface texture. A convex and a concave surface configuration may yield the same A.A. but could not have been produced by similar processes, he contends.

Keinzle and Heiss (5) used a stylus instrument to

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[1] Schmaltz, G., "Techische Oberflächenkunde", J. Springer, 1936.

[2] Bodart, E., "Les Etats de Surfaces", Standards, Genie Mecanique, vol. 6, 1939.

record surfaces of turning cuts. Tests were run on high carbon steel, and roughness was measured across and along the feed grooves. With low cutting speeds poor shearing action caused work hardened particles of workpiece material to periodically plough under the tool resulting in a jagged surface along the feed grooves. This surface yielded a characteristic readout of peaks and valleys on the stylus recording film. The authors state that the most important factors influencing surface texture are tool geometry and cutting conditions.

The Experiment

A. Instrumentation

The Brush Surface Analyzer consists of a hydraulically driven diamond tipped stylus which is suspended between two skids in a pickup head. As the stylus tip is moved over a surface, small deflections of the tip are transmitted through a viscous fluid coupler to an electromagnetic current generator inside the pickup. The current is amplified and converted into a graphical readout on heat sensitive paper. The arithmetic average roughness and the profile roughness are simultaneously recorded.

The Zeiss microscope utilizes the Schmaltz optical cut technique to reveal a section of a surface profile. A very narrow slit of light about .050 inches long is projected onto the surface at a 45 degree angle, the eyepiece views this slit at an opposing 45 degree angle. The surface is seen as a light band outlining the profile with the vertical axis (height of the irregularities) distorted by the factor $\sqrt{2}$. Fig. 2 on the following page illustrates the optical cut.

The microscope eyepiece is equipped with cross hairs on a micrometer so that vertical and horizontal measurements of the surface can be taken. The objectives available are 200X and 400X, and the microscope can resolve irregularities down to 30 microinches.

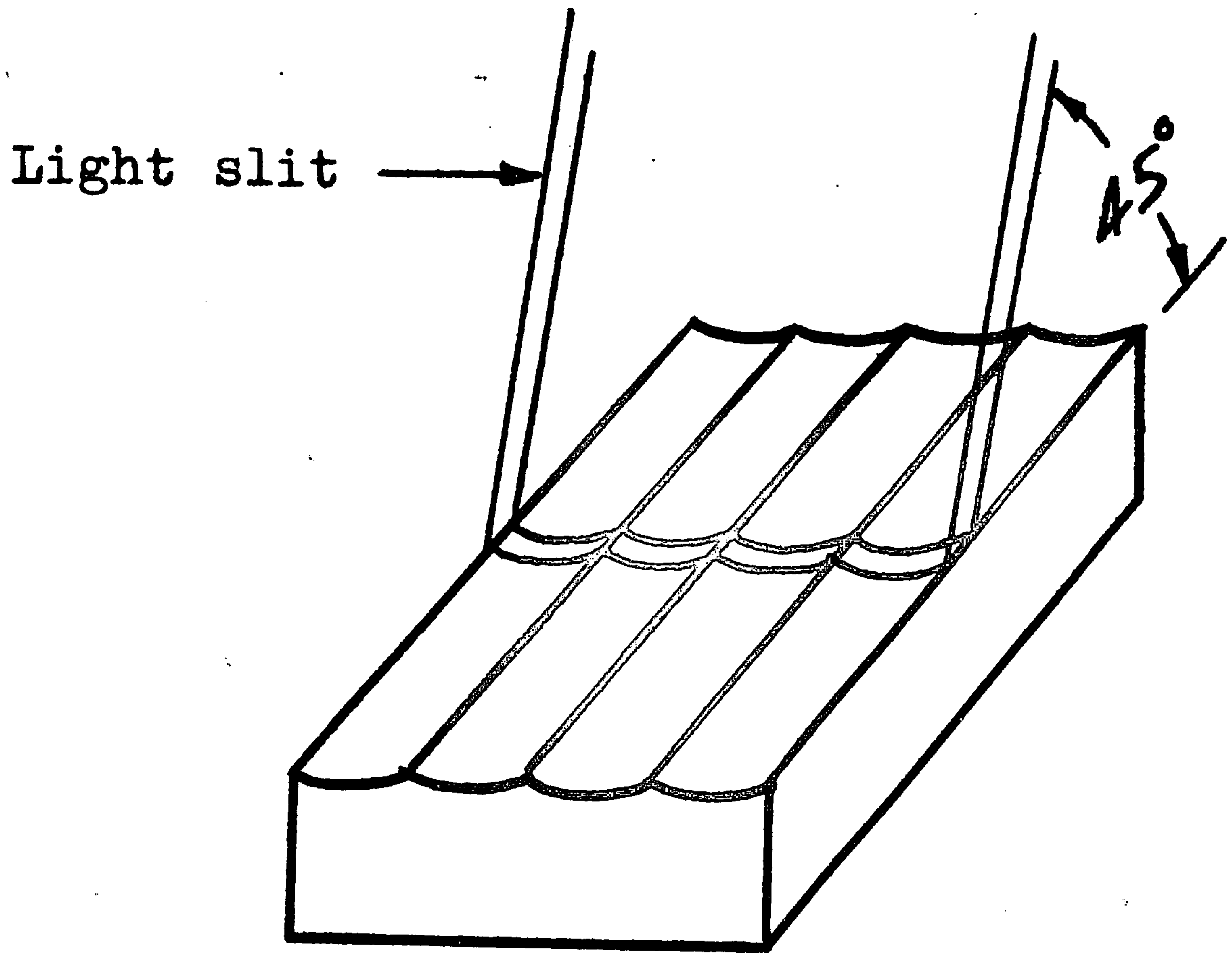


Fig. 2. Optical Cut Technique

B. Experimental Procedure

The tooling and cutting conditions are listed in Appendixes A and B. The objective in selecting these independent variables was to generate surfaces with a range of roughness magnitudes and forms. The four machining processes chosen were turning and shaping with single point tools and milling with an end mill and a side mill. With the side mill the generated surface is parallel to the cutter axis, with the end mill it is perpendicular to it.

The turning cuts were taken from 1.45 inch diameter bar stock on a Warner and Swasey turret lathe. The length of each cut was just long enough, about three-fourths of an inch, to make surface roughness measurement convenient. The small area cut insured constant cutting conditions and therefore a homogeneous surface for each data point.

The shaper and milling cuts were taken across narrow blocks, so that the areas of each were about one square inch. For the side milling cuts, even with these small areas, the texture of the surface was observed to be disrupted in spots. Therefore, it was necessary to outline those areas in which measurements by the two methods were to be made.

Surface roughness readings with the Brush Surface

Analyzer were recorded by tracing across the feed marks for each specimen, except the side milled surfaces. It was discovered that tracing along the feed resulted in a higher A.A. value with this type of cut. This is the roughness that is of interest in accordance with the American Standards Association specification. The tracing direction for all four types of cuts was perpendicular to the direction of cutting.

Fig. 3 shows the chart readout from the Analyzer. It represents a stylus trace length of about .300 inches, which is ten times the roughness width cutoff. A scale

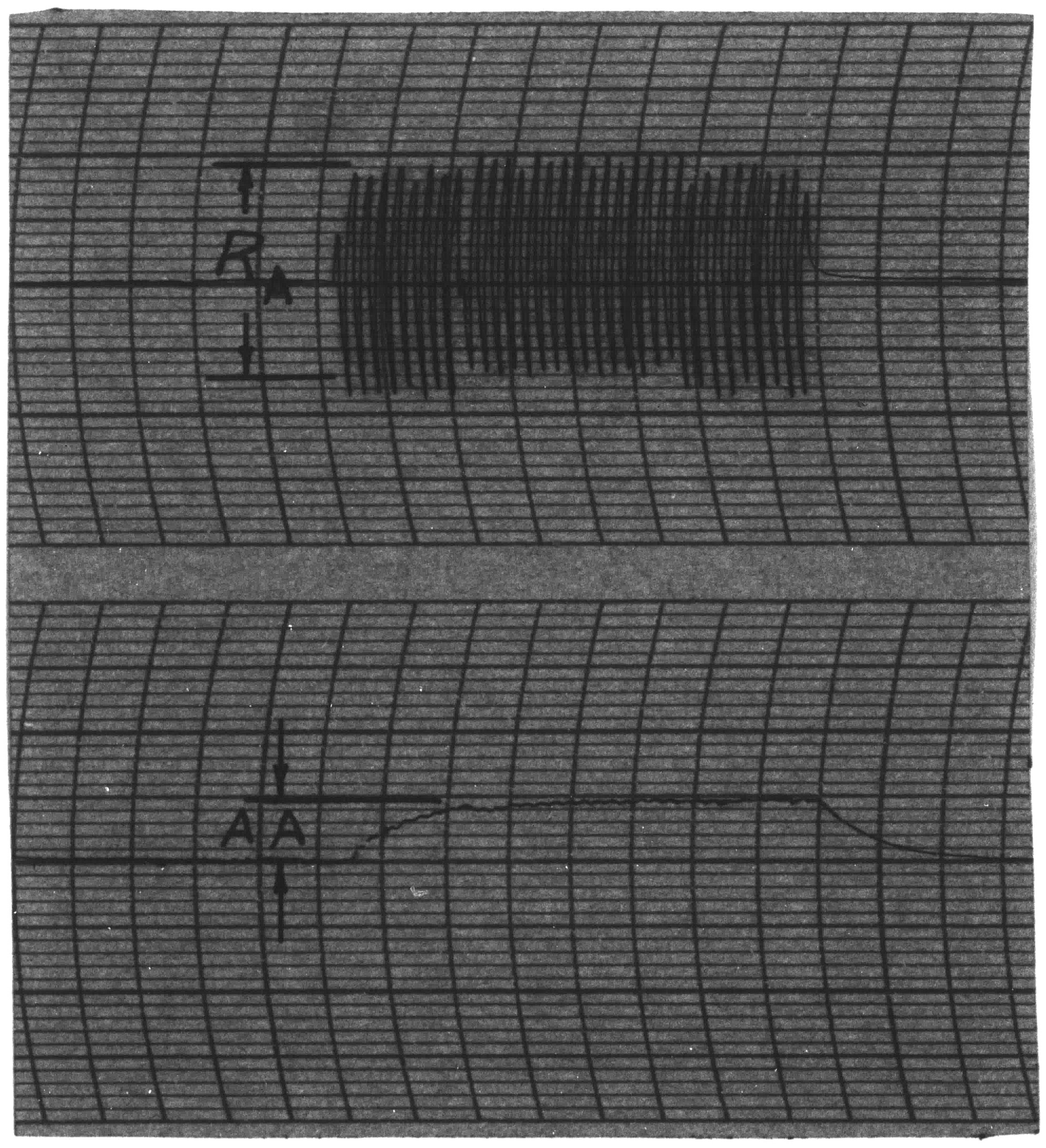


Fig. 3. Analyzer Chart Readout

selector is used to calibrate the chart in "x" microinches per chart division. The Analyzer measures A.A. and profile roughness. As a profile roughness parameter, the maximum peak to valley height of the irregularities was recorded and designated R_a. The R_a value is an estimate in the case of a very nonuniform surface. It was sometimes a matter of judgment as to which irregularities to consider for the measurement. The data for the Analyzer, A.A. and R_a, in Appendix C is an average of four readings taken at random positions on each surface.

In order to describe the actual surface texture as observed with the Zeiss microscope, two measurements were employed: the peak to valley roughness height and the peak to peak roughness width. The roughness height was called R_s and the roughness width L. These two quantities were chosen to be measured for two reasons. First, they are the most easily measured characteristics of the surface seen with the Zeiss microscope; and second, they can be combined to yield a parameter that is an indication of the relative roughness of the surface. This Roughness Parameter is expressed as R_s/L. An increase in R_s and/or a decrease in L is defined as an increase in surface roughness. Therefore, relatively high values of the parameter indicate relatively rough surfaces.

Fig. 4 illustrates the concept of the Roughness Parameter.

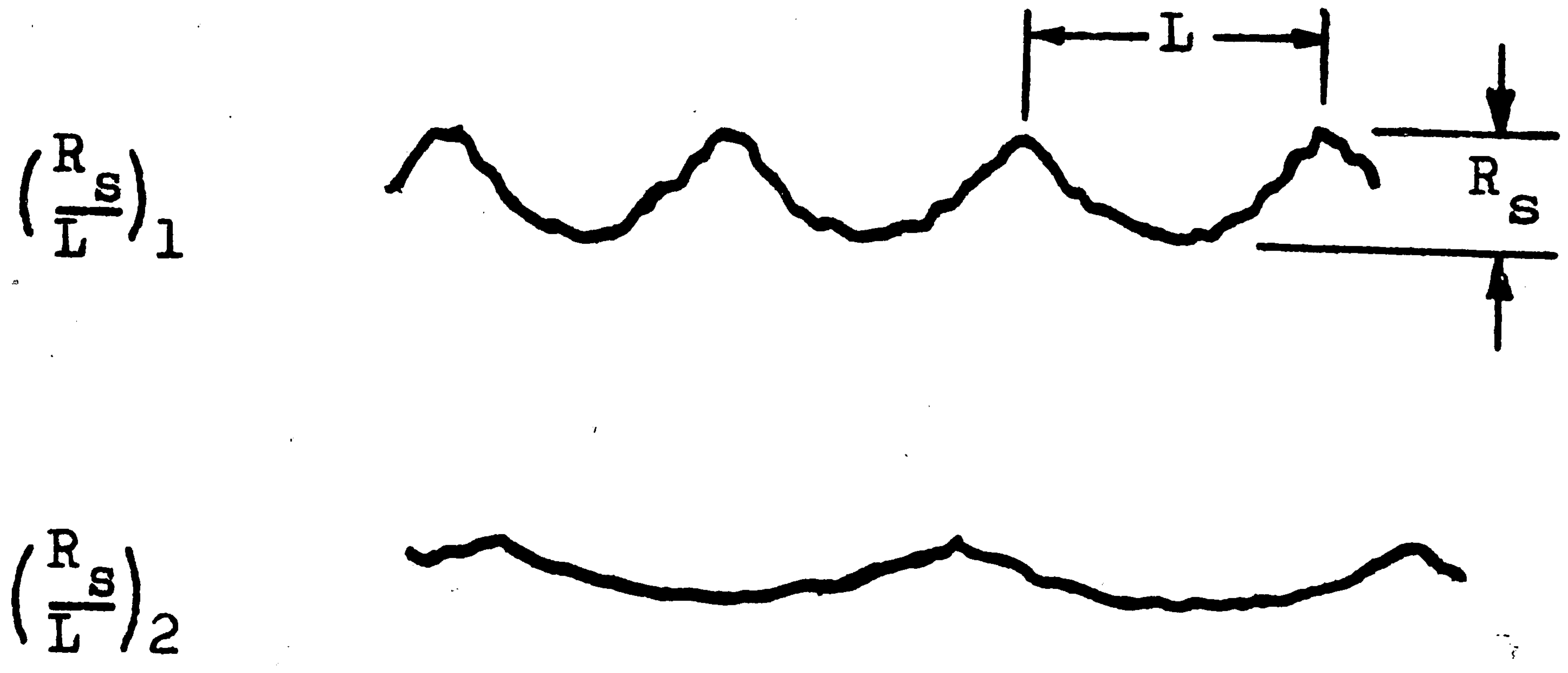


Fig. 4 Roughness Parameter

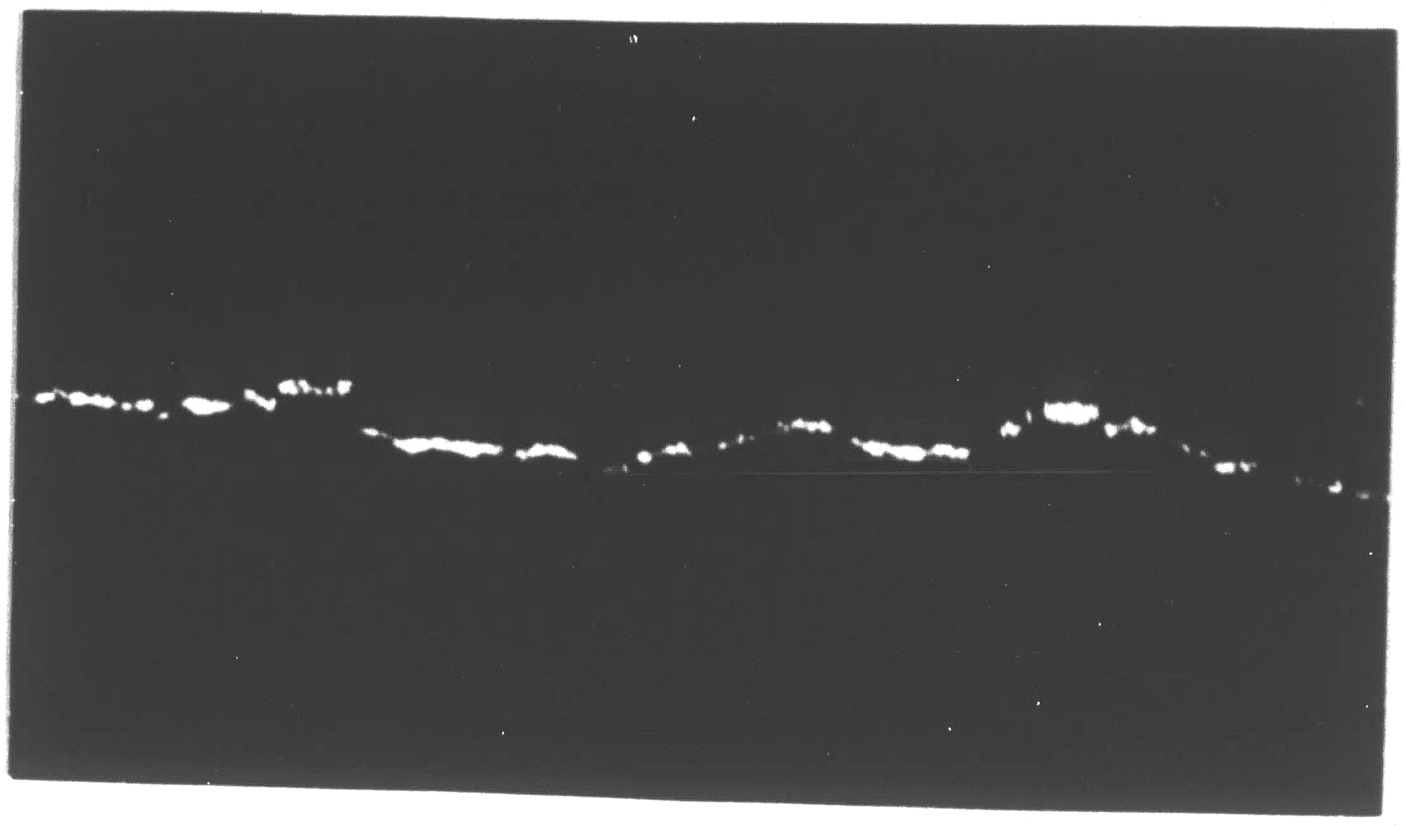
$$\left(\frac{R_s}{L}\right)_1 > \left(\frac{R_s}{L}\right)_2$$

Three types of surfaces, as seen by the optical cut, are shown in Fig. 5 on the following page. The R_s and L values can most easily be determined from the turned surface. The shaped surface is slightly more irregular, and the milled surface is the most irregular.

The R_s and L in the data table (Appendix C) are averages of four readings taken at random on each surface. Even though the cuts were designed to yield a uniform roughness pattern, the R_s and L measurements varied considerably, especially on the milled surfaces.

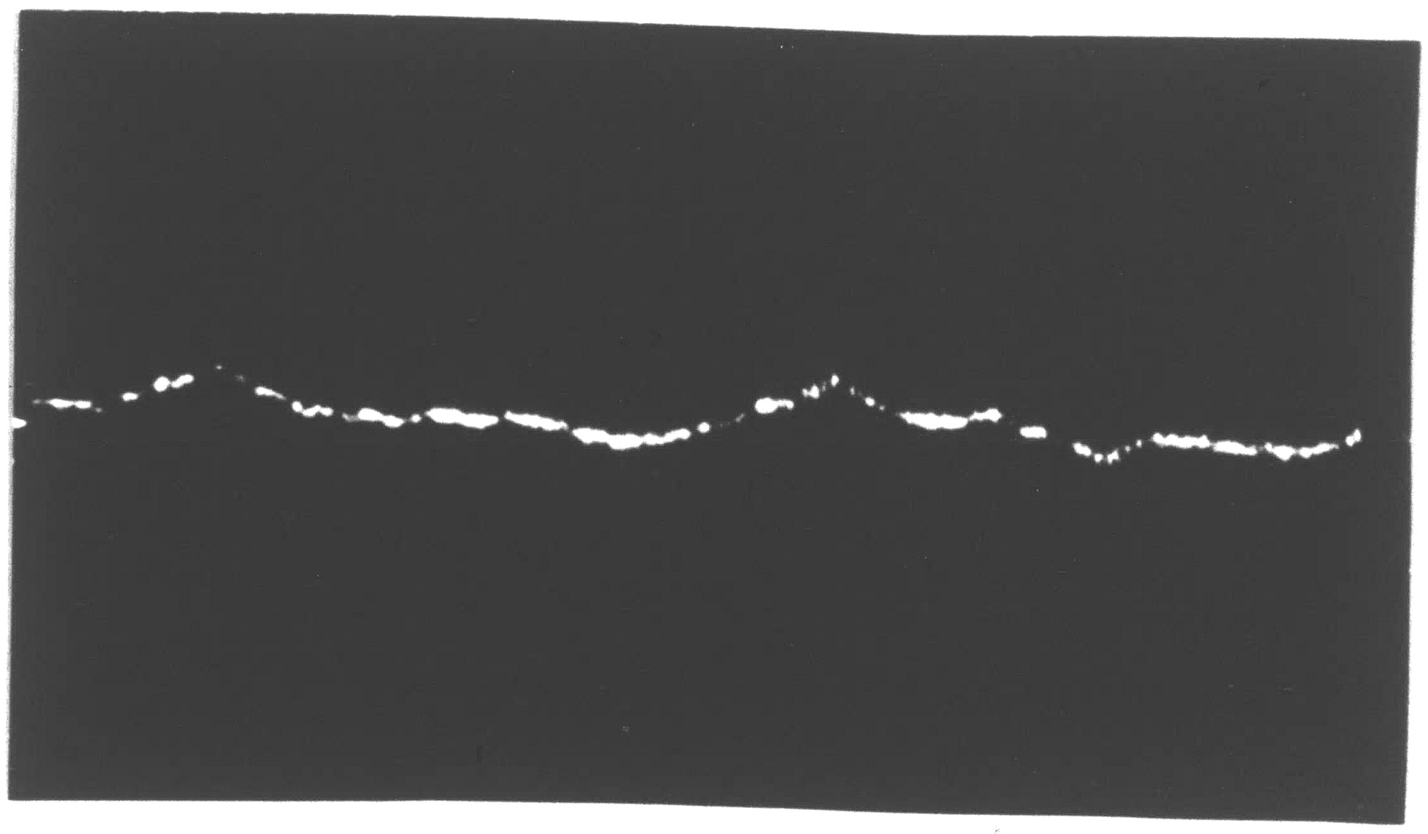
End Milled Surface

A.A.= 250 μin.
$R_s/L \times 100 = 6.57$



Shaped Surface

A.A.= 250 μin.
$R_s/L \times 100 = 7.56$



Turned Surface

A.A.= 225 μin.
$R_s/L \times 100 = 7.41$

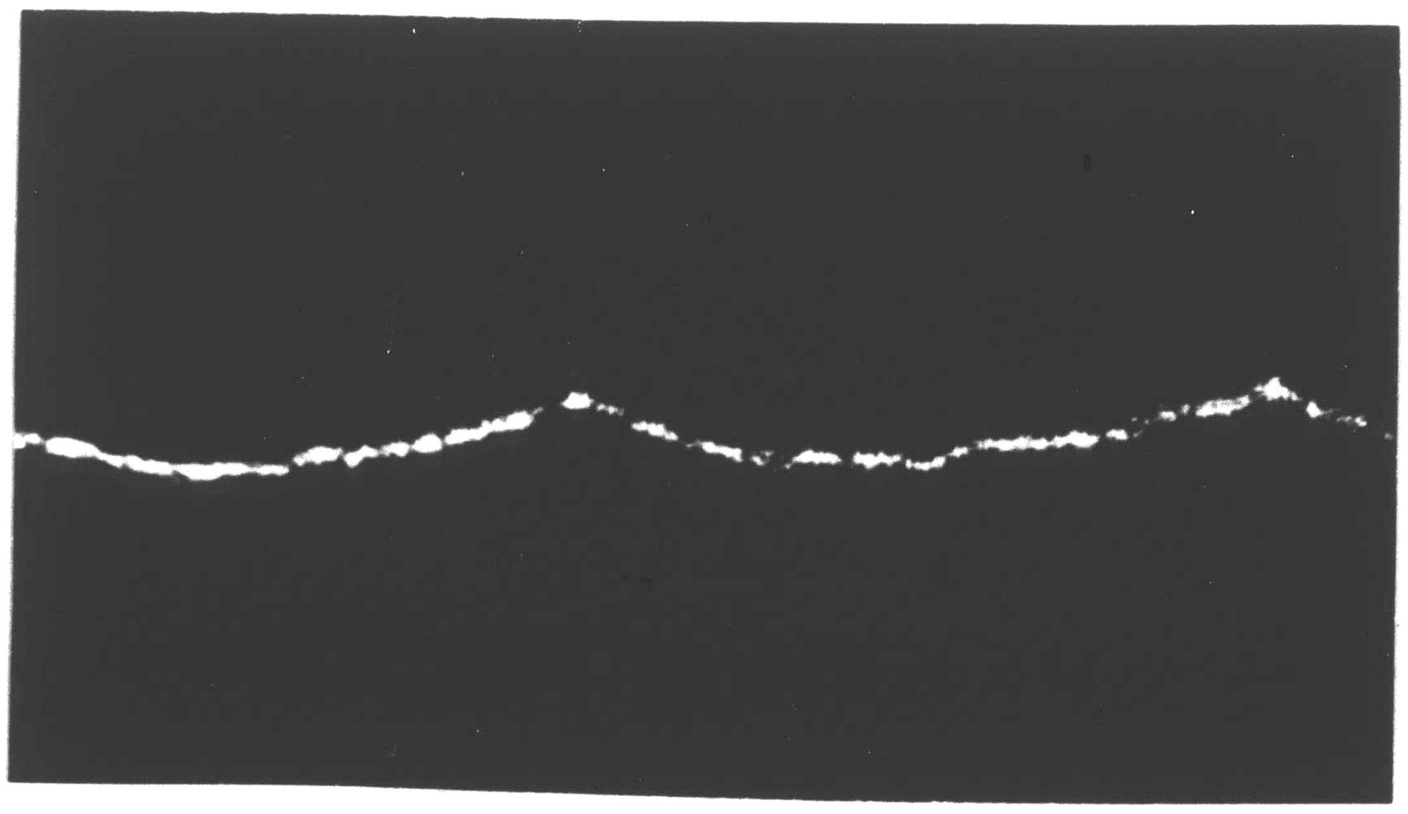


Fig. 5 Surface Profile Photographs

Taking more than four readings would result in an average closer to the true value. However, since the setup and alignment with the microscope were critical, special attention and time were devoted to this aspect in an effort to have these measurements representative of the surface.

Results

The surface roughness determinations are best observed and analyzed by means of graphing. The most significant plots are shown in Appendix D. Straight line fits were computed by the Multiple Linear Regression Program on the General Electric 225. A summary of the statistical analysis for the regressions is in Appendix E.

For testing the validity of the regression line as an estimate of the relationship between two variables, A.A. and R_s/L in graph 1 for example, the F statistic is used. The F is a ratio of the regression mean square to the residual mean square. The regression mean square is a measure of the deviation of the calculated line from the average value of the Roughness Parameter. The residual mean square is a measure of the deviation of the calculated line from each individual parameter value at each A.A. value. A relatively large F, considering the number of degrees of freedom, means that the line is a good fit to the data. Under these circumstances the regression is said to be significant. For the turning cuts in graph 1 the regression is significant at the 99 per cent confidence level.

Graph 2 attempts to relate increasing A.A. with increasing R_{max} measured by the optical cut. The regression is also significant at 99 per cent, but the F value is lower than that of the A.A. vs Roughness Parameter fit indicating a greater degree of scatter.

To investigate the relationship between the Analyzer R_{max} and the Roughness Parameter for the lathe, the data was plotted in graph 3. The regression is significant at 99 per cent, but again the F ratio is below that for A.A. vs R_s/L.

An indication of the Analyzer reading for A.A. and R_{max} is plotted in graph 4. As expected, an increase in R_{max} values is accompanied by an increase in A.A. This correlation is explained by the fact that as the stylus traces over larger peak to valley heights (R_{max}), its average displacement from the center line (A.A.) must be greater.

For the milling and shaping cuts an attempt was made to correlate the average roughness with the Roughness Parameter in graphs 5 and 6. The milled surface data exhibits wide scatter. Regression is not significant for either the side or end milled surfaces. The shaped surfaces show increasing trends for A.A. vs R_s/L. The regression is significant at the 99 per cent level.

A combination of the turning and shaping cuts and a combination of all four types of machining processes were investigated in graphs 7 and 8. The trend of increasing R_s/L with increasing A.A. is evident. The regressions yield a highly significant (99%) F value in both cases.

To investigate some measure of the effects of the cutting conditions on surface roughness, an analysis of variance was performed on data points 7,8,9,19,20, and 21 for the lathe. The summary of the results is in Appendix E. For all four variables used as a measure of roughness, the tool nose radius is the most significant factor in influencing a change in roughness. Graph 9 shows the effect of the nose radius on surface roughness as measured by the average roughness value.

Discussion

As previously seen in Fig. 5, the texture of the machined surfaces varies from uniform in the turning cut to irregular in the milling cut. This trend may be explained by referring to tool geometry. Obviously, during the metal cutting process, the tool is in intimate contact with the surface and cannot help but impose an element of its shape to the finished surface. In the case of the single point turning tool, that element is the nose radius. A broad nose will produce flat feed grooves, whereas a sharp nose will tend to cut a threaded configuration with large peak to valley roughness heights.

While the turning and shaping tools have their cutting edges at a rounded corner, the milling cutter offers a broad flat tooth for shearing the work. The teeth of both the side mill and shell end mill are at right angles to the direction of cut. This results in a gouging action rather than a clean shear of the metal. Particles of work material are prone to remain on the cutting edge of the tool under these conditions. Upon subsequent cuts by the tooth, these particles are caught between the tooth and the machined surface. They plough into the surface leaving small grooves. This "built up edge" phenomenon was observed for both milling cuts in this experiment, and this is the likely reason for the character of those surfaces.

All of the surfaces seem to be characterized by a concave profile of some arrangement of peaks and valleys. Therefore, it was assumed that the four processes could be lumped into one analysis for the correlation of A.A. and Roughness Parameter. The regression line for this (graph 8) was, indeed, very significant.

The most important aspect of this regression is its ability to predict a value of R_s/L from a given A.A. An interval is constructed in which R_s/L can be expected to lie with a 95 per cent probability when some value of A.A. is chosen. The interval is indicated by dashed lines on the A.A. vs R_s/L plots, and the formulas for these limits are in Appendix E.

A prediction of the Roughness Parameter has the least variance (±1.50) for the turned surfaces (graph 1). When the shaped surfaces are included with the turned (graph 7), the prediction limits are slightly wider; and when all four types of surfaces are combined (graph 8), the limits are wider still (±2.50). The reason for this is that the Roughness Parameter error at each A.A. point is based on the residual mean square of the regression. As indicated before, as the surface roughness became more irregular, the R_s and L measurements exhibited greater variation. This resulted in a larger residual mean square.

When describing machined surfaces, the manufacturer should have more information than the average roughness can convey. The peak to valley roughness height and spacing will determine, for example, the bearing area for contacting parts and will dictate how the parts will wear. The surface finish especially influences the nature of the "break in" wear.

Surface texture also effects the lubricating characteristics of a machined part since capillary action is a function of the roughness of mating surfaces.

The Roughness Parameter R_s/L is used as a measure of form and gives an idea as to what the surface actually looks like, whereas the A.A. is only a relative measure of roughness. For uniform surfaces such as the turning and shaping cuts, the individual R_s and L values of the parameter can be determined. From the data it is evident that the L is the feed of the tool in each case. Once the A.A. has been measured, the parameter is predicted. Then L is found from the cutting conditions, and R_s is known.

The R_s/L seems to be sensitive to changes in surface characteristics, but much information is lost when a three dimensional surface is described by one number. This parameter does tell more than the average roughness, but it yields a picture in two dimensions only. The surface finish will change in the third dimension, and so one value or one profile cannot be fully representative of the surface texture.

Another factor that complicates surface identification is waviness. Waviness is neglected by the A.A. and R_s/L for two reasons. First, these measurements are averages from various points on the surface; and second, the measurements are samples from a very small area of the total surface. The fact that certain waviness patterns exist on a surface is important in determining the functional characteristics of the part and in gaining information about the process that produced the part. Therefore, any complete theory concerning the identification of surface roughness should account for any waviness present. This leads to a description by more than one parameter.

Conclusions

1. When grouping surface measurements from turning, shaping, and milling processes, the ratio of roughness height to roughness width can be estimated, within a certain range, from the arithmetic average roughness. The relationship is linear.
2. For turning and shaping cuts the roughness height and roughness width can be estimated from the A.A. In the height to width ratio, the width is equal to the feed of the tool.
3. As the distribution of roughness irregularities becomes more nonuniform, such as in a milled surface, it becomes more difficult to correlate the roughness height and width with the A.A.
4. The tool nose radius has a highly significant effect on the surface roughness.
5. For complete identification of the nature of a machined surface, more than one parameter is necessary.

Areas for Future Study

1. In this experiment the profile roughness reading from the Brush Analyzer was converted to a number R_{max}. Possibly, some parameter or equation can be devised for this readout to more accurately describe the character of the surface it represents.

   A new parameter or equation to represent the Zeiss microscope interpretation might be important also.

2. Surface finishes that are of great interest in many applications are those below 100 microinches A.A. Processes connected with these finishes are grinding, lapping, polishing, etc. It would be interesting to investigate the nature of this group of surfaces with stylus equipment and optical techniques.

3. The standard roughness width cutoff length is .030 inches, which was used in this experiment. It is known that different cutoff lengths interact with the waviness pattern of a surface to yield an average roughness. Research into the exact relationship between these two variables is an area for future study.

Appendix A

Tooling

A. Lathe - Holder: TGTR-16
Inserts: TBT 163 U-2, U-3, U-4
Geometry: -5, -5, 5, 5, 30, 0

B. Shaper - Holder: SBPR-20
Insert: T-15, 1/16 N.R.
Geometry: 6, 6, 5, 5, 15, 15

C. Shell End Mill - no. 671, 3.00 diam., Cleveland Twist Drill Co.

D. Side Mill - no. S-44-3, 6.00 diam., Brown and Sharpe Mfg. Co.

Material

A. 1018 cold rolled

B. 1020 annealed

C. 4140 hot rolled, heat treated

D. 1144 hot rolled

Instrumentation

A. Brush Surfindicator MS-1000
Brush Surface Analyzer MS-5000
Brush Electro-Hydraulic Drive MS-1400
Brush Recorder Mark II

Manufactured by Clevite, Brush Instrument Division, Cleveland, Ohio.

B. Zeiss Microscope

Manufactured by Carl Zeiss Co., Oberkochen, Germany

Appendix B

Cutting Conditions

		Mat'l	Speed (FPM)	Feed (in/rev)	Depth (in.)	Tool
Lathe	1.	1018	320	.029	.050	U-2
	2.	"	320	"	"	U-3
	3.	"	320	"	"	U-4
	4.	"	170	"	"	U-4
	5.	"	170	"	"	U-3
	6.	"	170	"	"	U-2
	7.	"	430	.019	.030	U-2
	8.	"	430	"	"	U-3
	9.	"	430	"	"	U-4
	10.	"	170	"	"	U-2
	11.	"	170	"	"	U-3
	12.	"	170	"	"	U-4
	13.	1144	320	.029	.050	U-2
	14.	"	320	"	"	U-3
	15.	"	320	"	"	U-4
	16.	"	170	"	"	U-4
	17.	"	170	"	"	U-3
	18.	"	170	"	"	U-2
	19.	"	430	.019	.030	U-2
	20.	"	430	"	"	U-3
	21.	"	430	"	"	U-4
	22.	"	170	"	"	U-2
	23.	"	170	"	"	U-3
	24.	"	170	"	"	U-4
Shaper	1.	1020	60	.025	.040	T-15
	2.	"	30	.025	"	"
	3.	"	60	.015	"	"
	4.	"	30	.015	"	"
	5.	4140	60	.025	"	"
	6.	"	30	.025	"	"
	7.	"	60	.015	"	"
	8.	"	30	.015	"	"

		Mat'l	Speed (FPM)	Feed (in/tth)	Depth (in.)
Shell End Mill	1.	1020	130	.0035	.020
	2.	"	55	.0032	"
	3.	"	130	.0016	"
	4.	"	55	.0020	"
	5.	4140	130	.0035	"
	6.	"	55	.0032	"
	7.	"	130	.0016	"
	8.	"	55	.0020	"
Side Mill	1.	1020	93	.0015	.010
	2.	"	62	.0015	"
	3.	"	93	.0044	"
	4.	"	62	.0055	"
	5.	4140	93	.0015	"
	6.	"	62	.0015	"
	7.	"	93	.0044	"
	8.	"	62	.0055	"

Appendix C

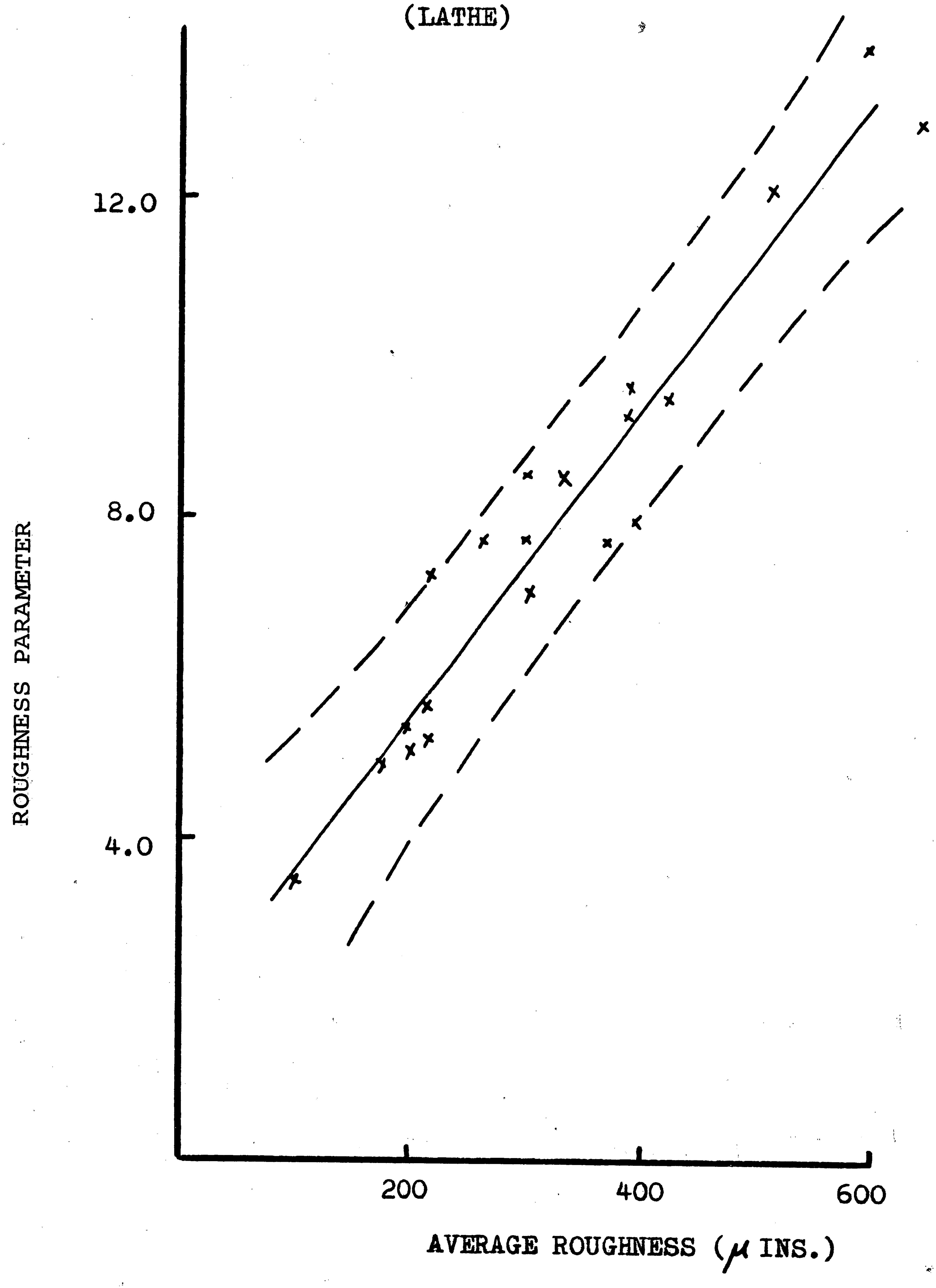
Data

	A.A.(μin)	R_a(μin)	R_s(μin)	L (in)	$R_s/L \times 100$
Lathe					
1.	540	2280	3530	.0292	12.09
2.	300	1200	2380	.0289	8.24
3.	210	900	1610	.0282	5.71
4.	650	2800	3720	.0291	12.78
5.	400	1700	2690	.0282	9.54
6.	300	1500	2090	.0278	7.51
7.	375	1500	1400	.0186	7.52
8.	225	1100	1030	.0188	5.48
9.	100	700	660	.0188	3.46
10.	400	1650	1720	.0189	9.10
11.	225	1000	1370	.0185	7.41
12.	175	850	910	.0187	4.87
13.	600	2500	3970	.0288	13.78
14.	275	1200	2160	.0288	7.50
15.	225	1100	1660	.0285	5.82
16.	650	3000	3680	.0288	12.78
17.	400	1600	2250	.0285	7.89
18.	300	1450	1870	.0275	6.80
19.	325	1400	1570	.0190	8.27
20.	225	1000	1050	.0192	5.47
21.	200	1000	980	.0188	5.21
22.	425	1600	1770	.0189	9.37
23.	250	1100	1180	.0185	6.38
24.	200	1000	1010	.0189	5.34
Shaper					
1.	325	1600	1960	.0242	8.10
2.	400	1800	2280	.0250	9.12
3.	225	1100	1260	.0160	7.88
4.	250	1150	1210	.0160	7.56
5.	475	2100	2490	.0276	9.02
6.	425	2000	2420	.0250	9.68
7.	275	1300	1270	.0156	8.14
8.	225	1000	1300	.0160	8.13

	A.A.(μin)	R_a(μin)	R_s(μin)	L (in)	R_s/L x 100
Shell End Mill					
1.	325	1500	2200	.0402	5.47
2.	275	1300	1500	.0307	4.89
3.	250	1450	1150	.0175	6.57
4.	225	1350	1170	.0190	6.16
5.	175	1000	1180	.0387	3.05
6.	200	1200	1320	.0372	3.55
7.	350	1500	1180	.0257	4.59
8.	175	1200	1130	.0322	3.51
Side Mill					
1.	160	680	780	.0225	3.47
2.	100	440	710	.0252	2.82
3.	120	600	610	.0210	2.90
4.	140	600	660	.0260	2.54
5.	75	360	600	.0147	4.08
6.	110	520	710	.0185	3.84
7.	120	480	470	.0287	1.64
8.	110	480	450	.0292	1.54

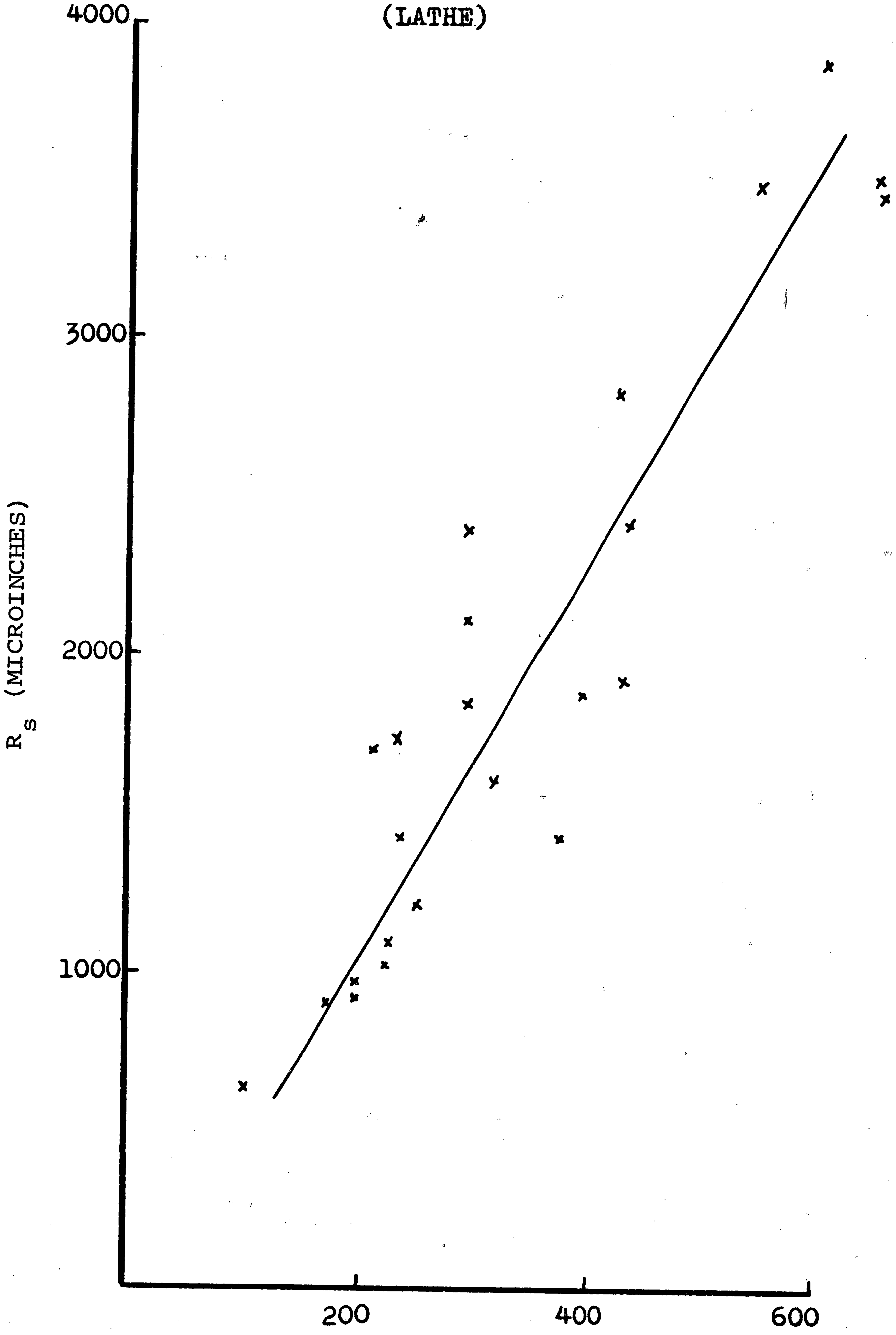
Appendix D

GRAPH 1 - ROUGHNESS PARAMETER VS AVERAGE ROUGHNESS (LATHE)



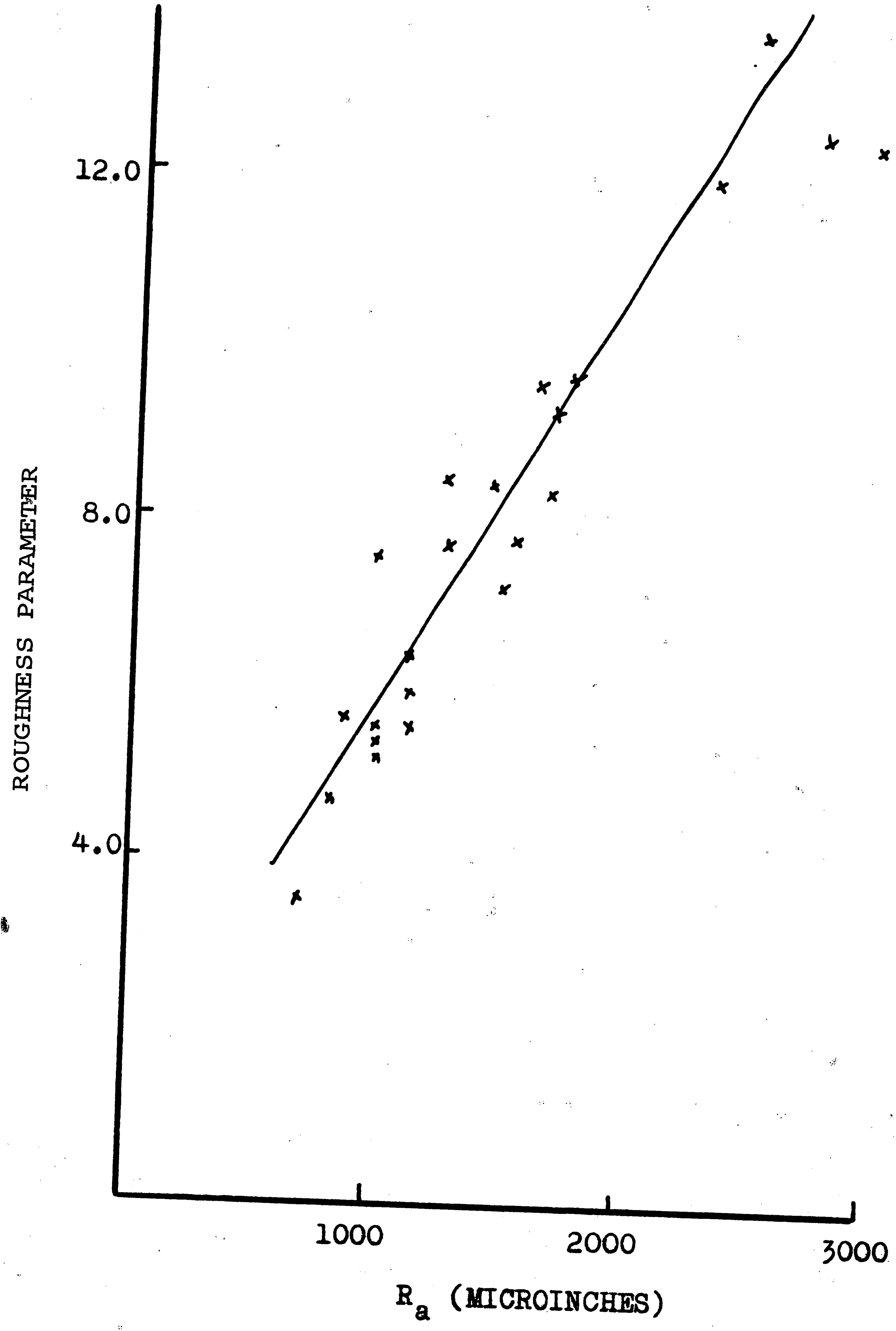
GRAPH 2 - SCHMALTZ R_{max} VS AVERAGE ROUGHNESS

(LATHE)



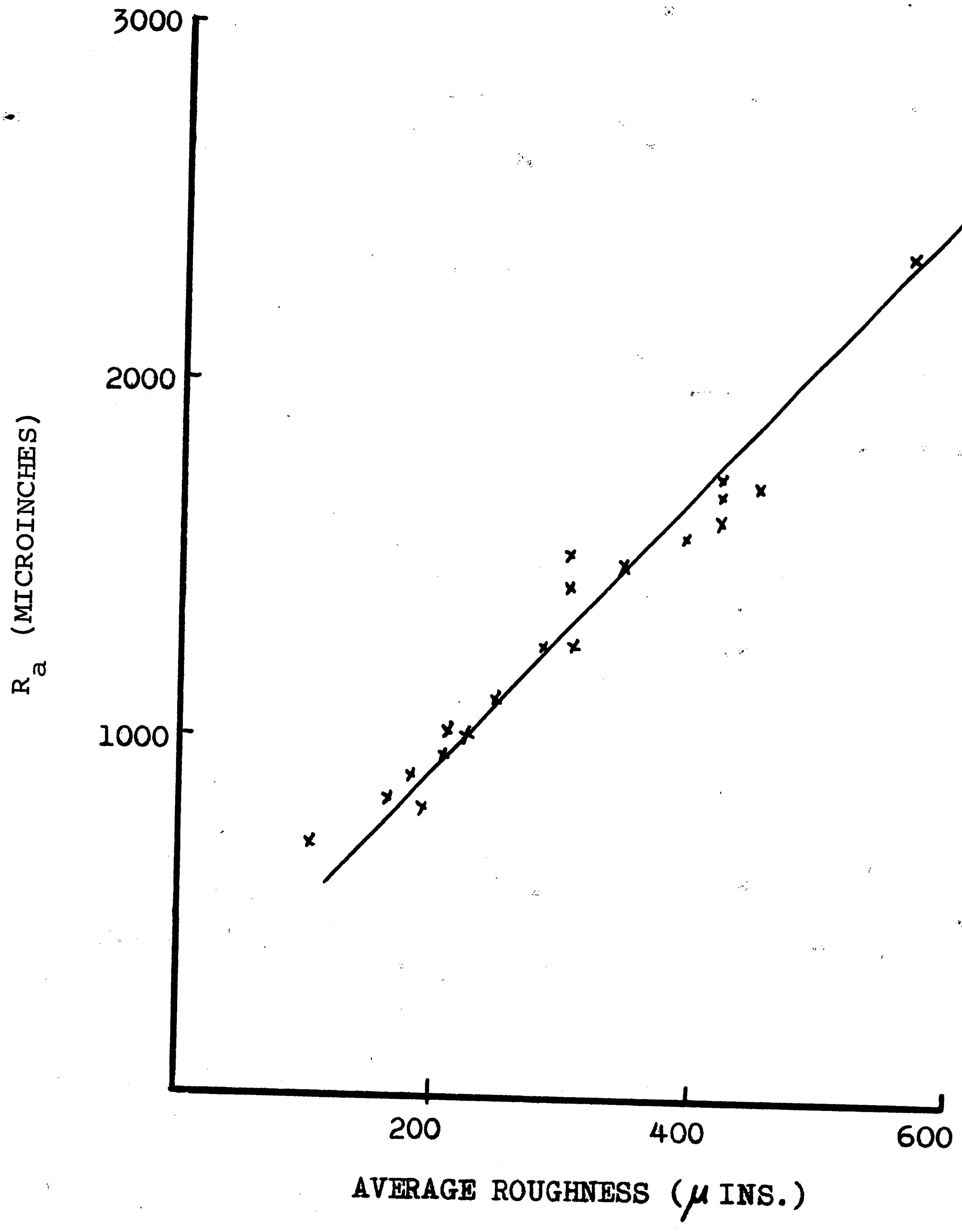
GRAPH 3 - ROUGHNESS PARAMETER VS ANALYZER R_{max}

(LATHE)



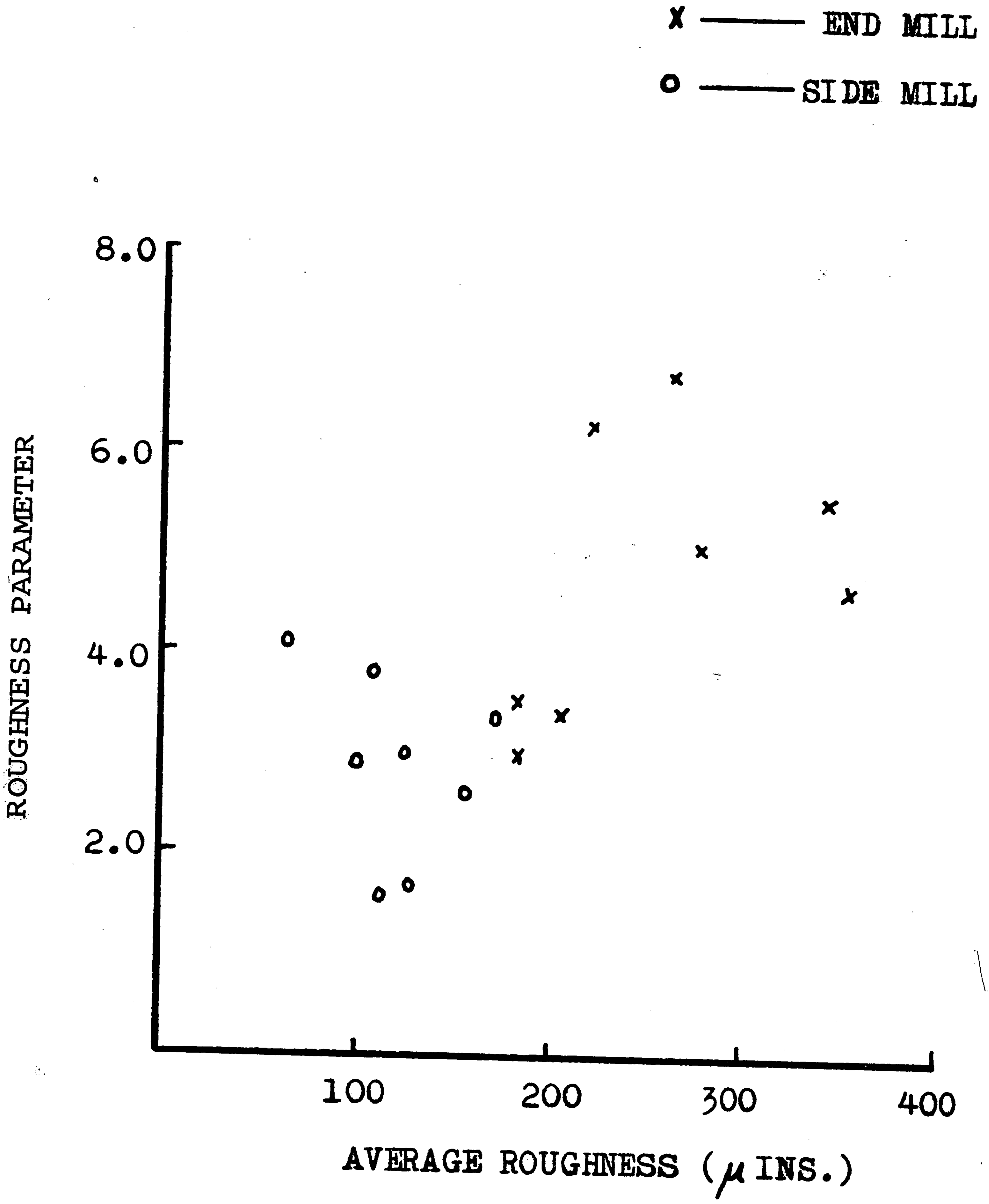
GRAPH 4 - ANALYZER R_{max} VS AVERAGE ROUGHNESS

(LATHE)



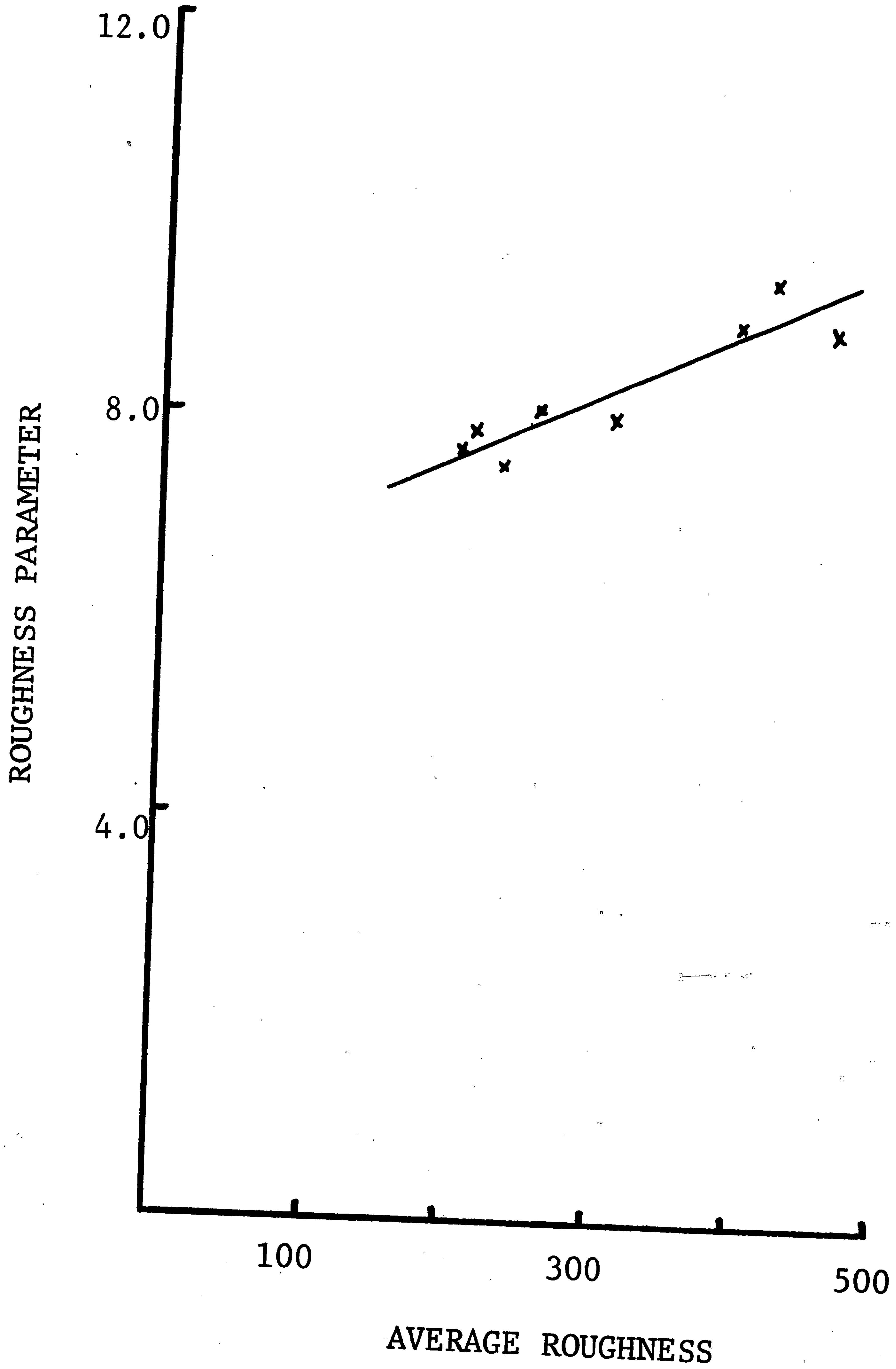
GRAPH 5 - ROUGHNESS PARAMETER VS AVERAGE ROUGHNESS

(MILLER)



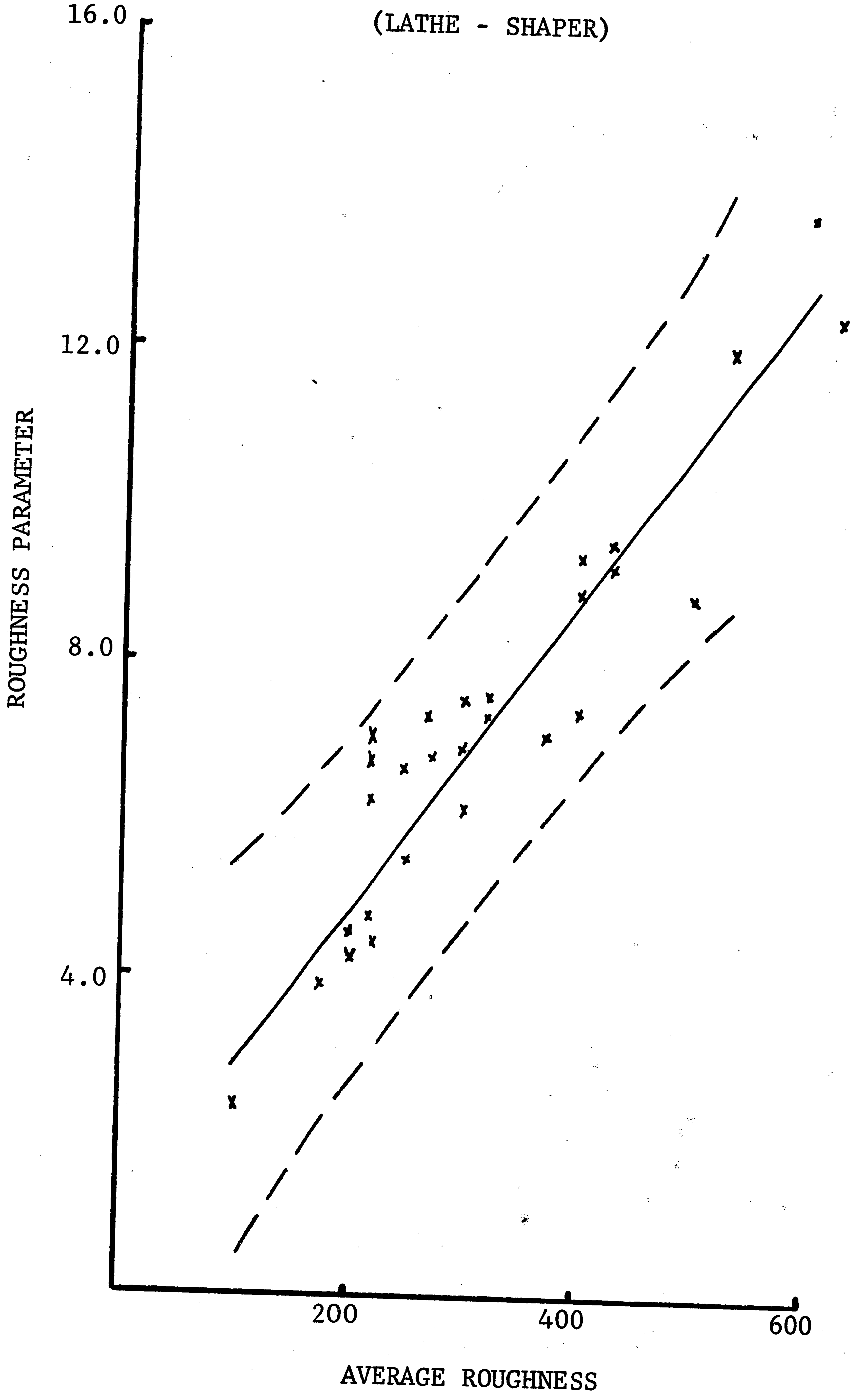
GRAPH 6 - ROUGHNESS PARAMETER VS AVERAGE ROUGHNESS

(SHAPER)



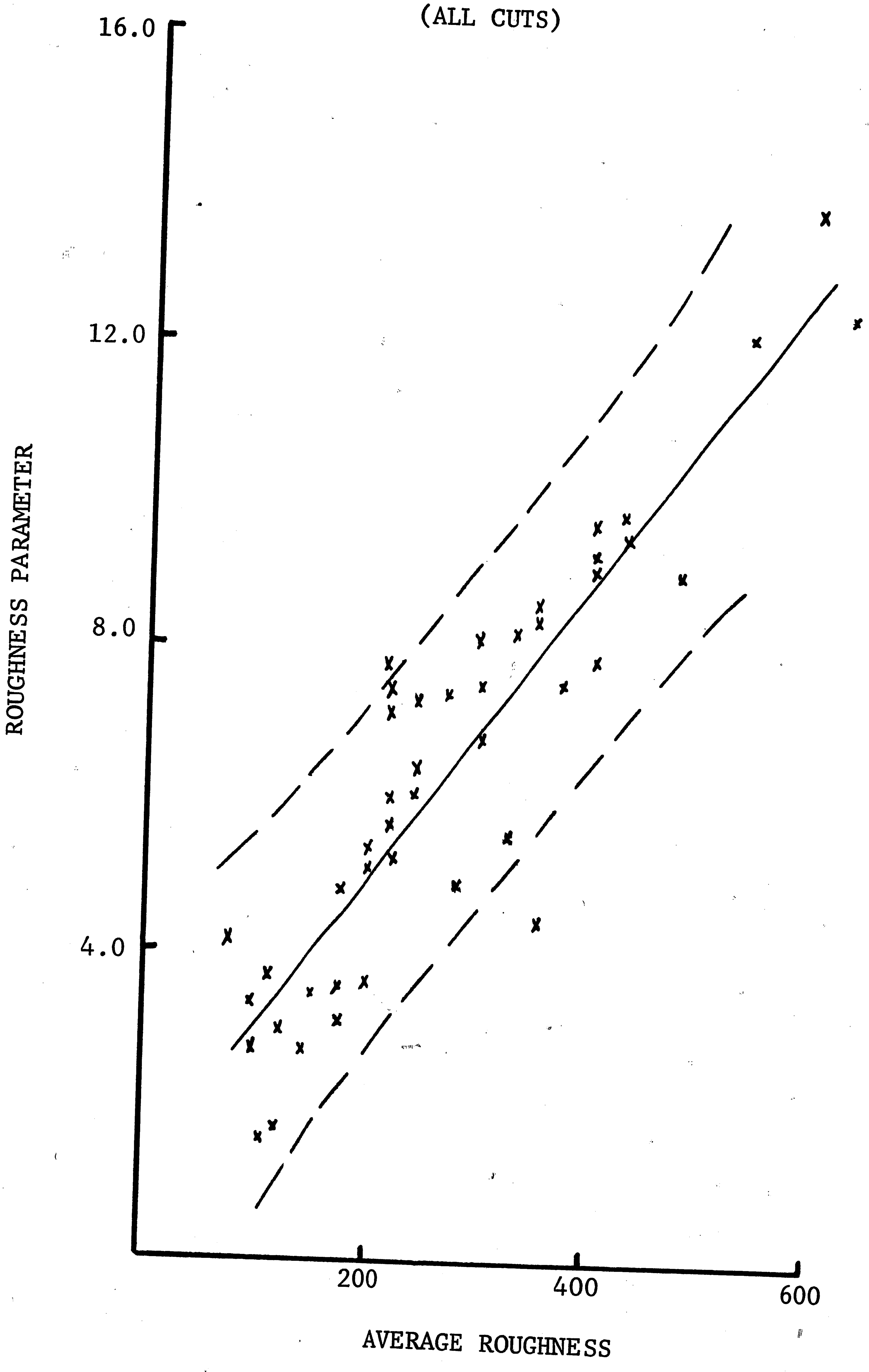
GRAPH 7 - ROUGHNESS PARAMETER VS AVERAGE ROUGHNESS

(LATHE - SHAPER)



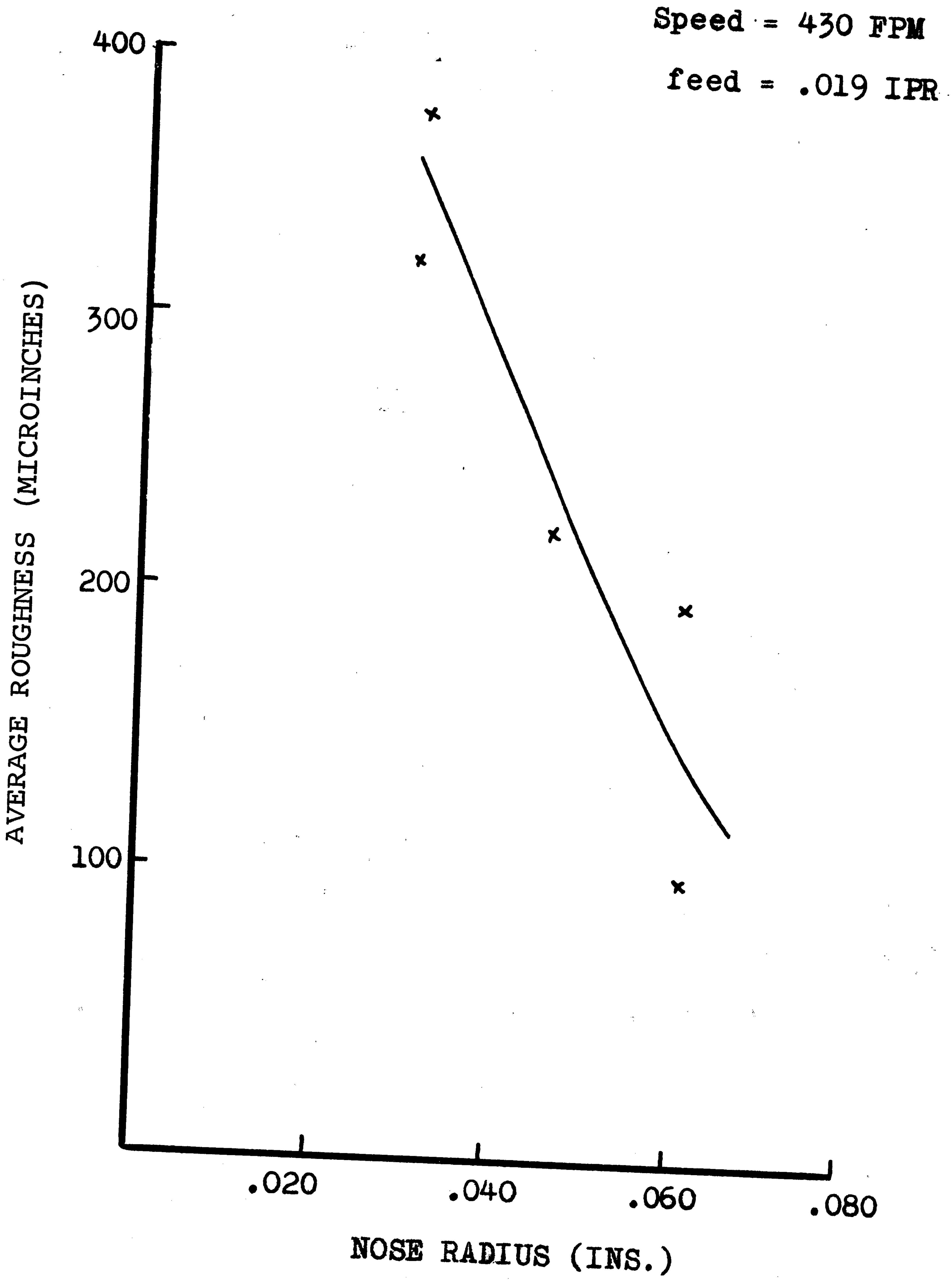
GRAPH 8 - ROUGHNESS PARAMETER VS AVERAGE ROUGHNESS

(ALL CUTS)



GRAPH 9 - AVERAGE ROUGHNESS VS TOOL NOSE RADIUS

(LATHE)



Appendix E

Analysis of Data

I. Multiple Linear Regression

A. Turning cuts

1. Roughness Parameter vs Average Roughness

$R_s/L = 1.9990 + .0176(A.A.)$

	Degrees of Freedom	Mean Square	F	Sig.
Regression	1	163.400	351.27	99
Residual	22	.466		

2. Schmaltz R_{max} vs Average Roughness

$R_s = -7.9315 + 5.8245(A.A.)$

Regression	1	17810000.	111.76	99
Residual	22	160521.		

3. Roughness Parameter vs Analyzer R_{max}

$R_s/L = 1.6538 + .0042(R_a)$

Regression	1	155.700	186.16	99
Residual	22	.836		

B. Shaping cuts

Roughness Parameter vs Average Roughness

$R_s/L = 6.3443 + .0065(A.A.)$

Regression	1	2.7870	17.94	99
Residual	6	.1556		

C. Milling cuts

1. Side Mill- Roughness Parameter vs Average Roughness

$R_s/L = 3.6983 - .0072(A.A.)$

Regression	1	.2362	.24	not
Residual	6	.9866		

2. End Mill- Roughness Parameter vs Average Roughness

$R_s/L = 2.4116 + .0094(A.A.)$

Regression	1	2.6820	1.78	not
Residual	6	1.5078		

D. Combined cuts

Roughness Parameter vs Average Roughness

$R_s/L = 1.2968 + .0189(A.A.)$

Regression	1	332.000	222.07	99
Residual	46	1.495		

II. Analysis of Variance

Average Roughness (A.A.) for Lathe data points 7, 8, 9, 19, 20, 21.

Effect	Degrees of Freedom	Mean Square	F	Sig.
Nose Radius	2	44827.08	152.40	99
Material	1	468.75	1.59	not
Interaction	2	4318.75	14.69	99
Error	6	293.75		

III. Prediction Limits for the Regressions (6)

$$R_s/L = a + b(\overline{AA}_o) + t_{\alpha/2} \cdot s_e \sqrt{1 + \frac{1}{n} + \frac{n(\overline{AA}_o - \overline{AA})^2}{S_{aa}(n-1)}}$$

Where:

$t_{\alpha/2}$ = value of the "t" statistic for n-2 degrees of freedom

s_e = square root of the residual mean square

S_{aa} = standard deviation of A.A.

$\overline{AA}$ = average value of A.A.

$\overline{AA}_o$ = value of A.A. for which the range of the Roughness Parameter is calculated

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Vita

David Myles Huddart was born on February 11, 1943, in Springfield, Illinois. He is the son of Mr. and Mrs. Harry Huddart. He attended Rensselaer Polytechnic Institute in Troy, New York, and graduated in 1965 with a Bachelor of Mechanical Engineering Degree.

He entered Lehigh University in September 1965 for graduate study in Industrial Engineering.

He married the former Mary Susan Fogarty on December 18, 1965, and has a son, Christian Andrew, born January 13, 1967.