1962

Effects of surface roughness on the intensity distribution of light reflected from aluminum surfaces

Harvey N. Wingfield

EFFECTS OF SURFACE ROUGHNESS ON THE INTENSITY DISTRIBUTION OF LIGHT REFLECTED FROM ALUMINUM SURFACES

BY

HARVEY H. WINGFIELD, III

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

OF THE UNIVERSITY OF RICHMOND

IN CANDIDACY

FOR THE DEGREE OF

MASTER OF SCIENCE IN PHYSICS

MAY 1961

Addison D. Campbell

H. Pearce Atkins

Nolan E. Rice

James E. Worsham, Jr.

Billy W. Sloope

Jackson J. Taylor

ABSTRACT

An investigation was made in order to determine the effects of the roughness height of a surface of 99.99% aluminum metal on the intensity of the light reflected from this surface. The angular distribution of the reflected light was measured with a goniophotometer and measurements of the roughness height were made with the proficorder. These measurements showed that these surfaces could be divided into three regions. The first region consisted of specular reflection where the intensity decreased sharply as the roughness height increased from zero to $\lambda/3$ microinches. The second region, which extended over a roughness height range from $\lambda/3$ to 3λ microinches, was a transition region as the surface was changing from total specular reflection to almost total diffuse reflection. The third region found corresponded to almost total diffuse reflection and existed for values of roughness heights greater than 3λ.

TABLE OF CONTENTS

During the past few years, with the increased usefulness of aluminum metal in industry, the solving of some problems which have hampered its effectiveness has become necessary. One of these problems has been the fact that the incident light on some surfaces was scattered in such a manner that an observer saw a variance in the intensity of the reflected light as his position is changed with respect to the surface. One factor which contributed to such a phenomena was the topography of the surface. The topography of any surface is composed of many irregularities of various lengths, widths, directions, and heights including the possibility of having even smaller irregularities superimposed on the surface of the larger irregularities. Since these surfaces consisted of a succession of peaks and valleys which vary widely in magnitude, a detailed study of the variation of the intensity with the surface topography would be difficult and very tedious and is impossible to include within the scope of this investigation. Even though the geometry of a surface is exceedingly complex and difficult to describe, it has been found by Hagen and Lindberg (1) and the American Standards Association (2) that it was quite adequate and correct to describe the surface topography by means of the average roughness height of the surface. The roughness height is defined as the average of the peak to valley distances of the irregularities which make up the surface.

In the past, only a few attempts have been made to find relationships which exist between the angular distribution of the reflected intensity and the surface roughness for different materials.

An attempt to find the reflection for single wave lengths from a ground glass surface was performed by Gorton [3] in an effort to determine which part of the spectrum gave the greatest amount of reflection from a rough surface. He found that the best reflection was obtained with the smoothest surface for the longer wave-length region of the spectrum. Chinmayanandam [3] performed an investigation to find a method of analysis for part of Gorton's work. He

to the normal distribution law and developed a relationship for the intensity as a function of the wave length of the incident light as given below:

$$I = e^{-(8\pi^2 \cos^2 \phi)/\lambda^2 a}$$

where λ is the wave length of the incident light, ϕ is the angle of incidence, a is a constant, and I is the ratio of reflected intensity to the incident intensity.

Only over the past few years have investigations of the intensity distribution of the light reflected from materials been attempted. Most of these investigations have been done by personnel at the National Bureau of Standards on matt surfaces, and acid etched black glass. It should be noted that separate investigations in the two fields, the methods of analysis of a surface's topography and the intensity distribution of reflected light from different materials have been and still are being performed. However, most correlations which exist between a surface's topography and its optical effects such as reflectance, intensity, absorption, and transmission are generally unknown.

The <u>purpose</u> of this investigation is an attempt to correlate the roughness height and the intensity of the light reflected from 99.99% aluminum metal, hereafter simply referred to as aluminum metal, and to try to explain their meaning.

Apparatus

The geometric manner in which the incident light on a surface is reflected in different directions is measured with an instrument called the goniophotometer [5]. The invention of the goniophotometer was brought about by the need for information on the angular distribution of reflected light from different surfaces. The earliest known goniophotometer was built by Bouguer [6] in an attempt to verify Lambert's law experimentally. Several types of goniophotometers have been developed since. A visual goniophotometer has been developed by McNicholas [7] mainly to obtain intensity distribution curves for diffusing media. Westlanfer and Scott [8] have described a photoelectric goniophotometer used to obtain information concerning the variation of intensity for different materials exhibiting reflected intensities ranging from nearly completely specular to nearly completely diffuse. Their studies were made in the region near the angle of view equal to the angle of incidence of forty-five degrees. Hammond and Nimeroff [9] have described the optics of a photoelectric monoplane goniophotometer which had high resolution as the major improvement over the previously mentioned goniophotometers. With this instrument, fractional reflectance curves were obtained for a series of different samples. Parry Moon and Jacques' Laurence [10] have discussed the construction and calibration of a general purpose goniophotometer using the photocell principle.

The goniophotometer consists of three essential components (see Figure 1): (1) a source arm which can be placed in a known angular relation to the sample and which contains a source lamp and collimating lens system for projecting a beam of nearly parallel light onto the

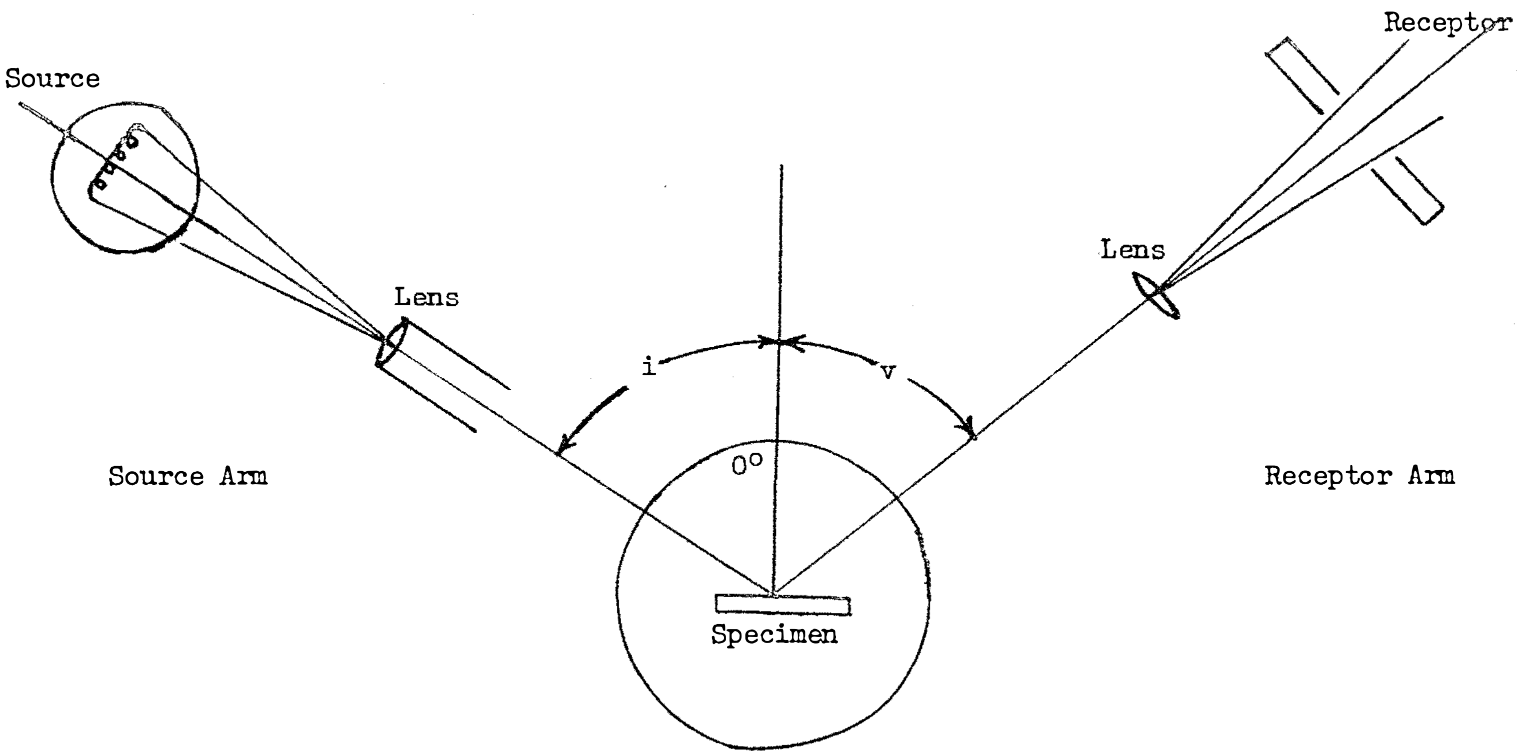


Fig. 1 -- Essential Components and Geometry of a Goniophotometer

sample; (2) a device, centrally located so that the axis of the source arm and the axis of the receptor arm intersect at the sample plane, for holding and rotating the sample to any desired position with respect to the source arm; and (3) a light sensitive detector, which is a stationary photocell, for receiving the rays reflected from the sample. It is to be noted that two of the three components are free to rotate about the centrally located pivotal point so that the angles of the incident beam and viewing beam may be varied as desired. The angle of incidence, denoted as $\angle i$, is the angle between the normal to the sample and the direction of the incident light. The angle of view, denoted as $\angle v$, is the angle between the normal to the surface and the photocell receptor.

The source arm contains a normal white light lamp which has a wavelength range of 3700A° to 7700A° with an average wavelength about 5700A° and with a maximum energy wavelength at 5560A°. Power to the lamp is supplied by a constant voltage source in the measurement unit. The converging lens projects an image of the filament to a correction lens which projects a beam of light onto the sample. Also in the source arm are two comparison photocells which are constantly lighted by the source lamp in order to provide a reference current for measuring the output of the first photocell. The comparison photocell current is adjusted electrically.

A photocell is contained in the receptor which receives the light reflected from the sample after it has passed through a receptor window and a converging lens. The current through this photocell is measured with respect to the reference current of the comparison photocells and the measuring mechanism indicates a value for the intensity which is the result of the ratio of the two currents. The intensity, denoted by I, is used as the ratio of the reflected intensity from the sample to the incident intensity on the sample and is measured as a percentage.

The sample holder, which holds the surface vertical, is located on on top of a circular table which rotates on the same central pivot as the source arm. Attached to the bottom of the table is a circle graduated in degrees in both directions from a normal to the sample. The inside of the goniophotometer is blackened completely so as to eliminate extraneous reflections. Measurements can be made to within five degrees of grazing incidence.

The proficorder [11] is one of several instruments which can be used to give a reproduction of the profile of the surface of the samples. The essential features of the proficorder, shown in Fig. 2, are: (1) a measuring head carrying a stylus mounted for motion perpendicular to the surface of the sample and an indicating device coupled to the stylus, (2) a means for moving the measuring head across the sample, and (3) a means for providing a trace, or record, representing the movements of the stylus.

The stylus is a conical diamond with a rounded tip which travels over the sample's surface. These tracer-type instruments measure the vertical deviation of the stylus with respect to some reference plane. On this instrument the reference plane is established by a skid attached to the measuring head and which rides over the surface. The skid has to be much larger than the irregularities of the surface so that its line of motion remains constant. The speed at which the stylus traverses

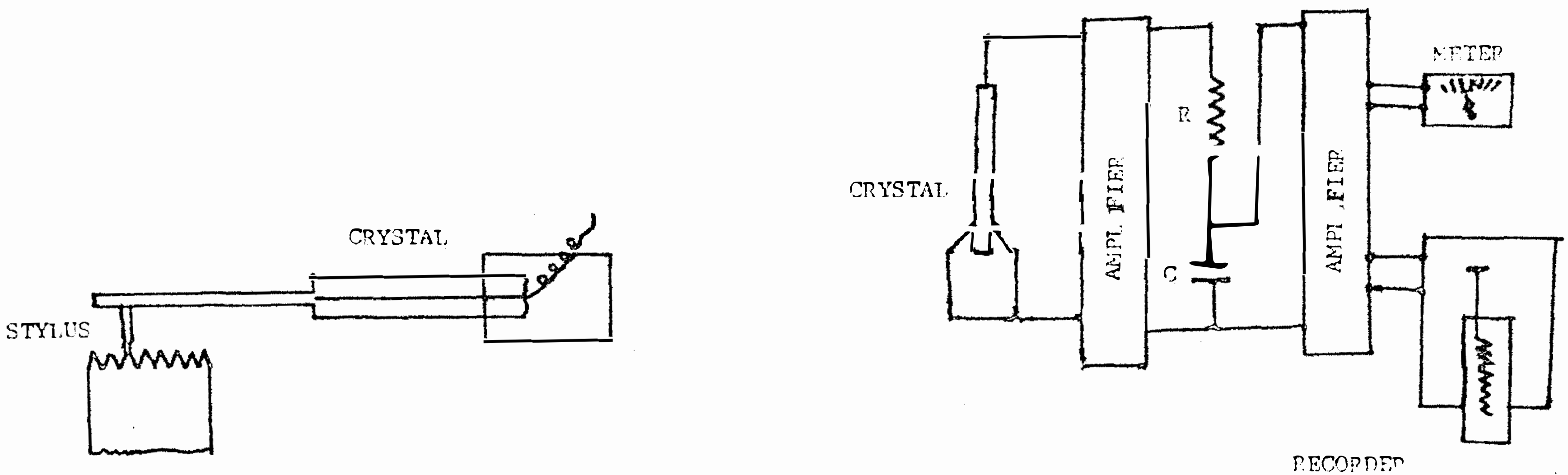


FIG. 2 ELECTRICAL PRINCIPLE OF PROFICORDER

across the surface should remain constant, and for this reason a motorized drive is used to move the stylus.

The up and down movements of the stylus are displayed on a graph which represented a cross section of the profile of the sample's surface. This was accomplished by sending the vibrations of the stylus to a prezoelectric crystal. The piezo device, which responded to the motion rather than to the position of the stylus, transformed the vibrations into an electric signal and sent them to an amplifier. A simple connecting circuit, consisting of resistance and capacitive reactance was inserted between two sections of the amplifier. In the range of frequancies for which the reactance of the capacitor was small compared with the resistance, the fraction of the output potential tapped off to feed the second section of the amplifier decreased linearly with the frequency and exactly compensated for the rise in the pickup. When the reactance becomes comparable with that of the resistance, the corrective action of the circuit ceased. This determined the low frequency limit of the instrument. The output from the amplifier must be independent of the frequency over the working range. After amplification, the signal was measured by a meter calibrated in units of surface roughness. As the stylus passed over the variations in the surface, the meter fluctuated over a range of valves. These <u>signals</u> were sent to the recorder which traced out a profile of the surface being traversed by the pick-up assembly.

In order to obtain a wide range of roughness height values, the samples used in these experiments were prepared by various methods as described below. However, at the same time it was desired to use surfaces which were similar in nature to those surfaces actually developed for industry. All samples were taken from the same sheet of 99.99% aluminum metal. This was done in order to eliminate, as far as possible, the effects of such variables as rolling direction, curvature of the surface, chemical composition, grain boundaries, and condition of the initial surface. When the samples were subjected to a chemical action, all were subjected to the same solution at the same time in order to minimize any variance in temperature, time limits, and any possible changes in the chemical solution's composition. The samples were prepared as follows:

Sample #1, average roughness height = 2.15u", where u" is used to denote microinch. This sample was given a thorough buffing sequence using a rough buffing compound. Afterward, it was subjected to a degreasing action and washed with distilled water.

Sample #2, average roughness height = 1.07u", and sample #3, average roughness height = 0.93u". These samples were treated alike with one exception. The process consisted of buffing the samples as before. Then, after subjecting them to the degreasing action and leaving them ten seconds in a three percent hydrofluoric acid, ten percent nitric acid solution, they were rinsed in distilled water and put into a five percent Alchemize [12], ninety-five percent phosphoric acid solution at a temperature of two hundred degrees Fahrenheit. Sample #2 was left in the phosphoric acid solution for two minutes while sample #3 was left in for five minutes.

Sample #4, average roughness height = 1.53u" and sample #5, average roughness height = 1.59u". These samples were subjected to the degreasing action and then put into twenty-five per cent sodium hydroxide solution at room temperature. Sample #4 was left in the solution for one minute while sample #5 was left in for three minutes. They were rinsed with distilled water after being taken out of the solution.

Sample #6, average roughness height = 176u". This sample was sanded along one direction with #180 grit paper, subjected to the degreasing solution, and rinsed with distilled water.

Samples #7 through #10, average roughness heights of 288u", 142u", 21u" and 11.2u" respectively. These samples were subjected to similar processes. All were sanded along one direction in varying amounts, degreases, and rinsed with distilled water. They were left for ten seconds in a three per cent hydrofluoric acid, ten per cent nitric acid solution and rinsed in distilled water. Samples #7 and #9 were left in a five per cent Alchemize, ninety-five per cent phosphoric acid solution at a temperature of two-hundred degrees Fahrenheit for two minutes. Samples #8 and #10 were left in the same solution for five minutes.

Sample #12, average roughness height = 0.95u". The sample was buffed, degreased, and rinsed in distilled water. After being left in the three per cent hydrofluoric acid, ten per cent nitric acid solution for ten seconds and being rinsed, it was left for seven minutes in the five per cent Alchemize, ninety-five per cent phosphoric acid solution at a temperature of two hundred degrees Fahrenheit.

After the samples had been prepared as described above, measurements of reflected intensity as a function of the angle of view were made with the goniophotometer as soon as possible in order to eliminate any other variables such as the surface being damaged by other materials in the area, pitting, and corrosion. To calibrate the goniophotometer, the light from the source lamp was allowed to fall directly on the receiver, and the measurement mechanism was set to read one-hundred percent or full scale deflection. The measuring device then expressed the intensity as the ratio of the reflected intensity to the incident intensity. The calibration of the instrument was checked before measurements were taken for each sample. The goniophotometric measurements were confined to a plane perpendicular to the sample plane.

After the sample was placed in the sample holder, measurements of the intensity were taken for a fixed angle of incidence while the angle of view was varied. These measurements of the intensity for different angles of view were taken at sufficiently small regular intervals to give a true rendition of the goniophotometric curve. In the region where the angle of view equalled the angle of reflection, measurements were taken at one degree intervals. Outside this region, measurements were taken at five degree intervals. Similar measurements were made for the three angles of incidence: 30°, 45°, and 60°.

The trace of the profile of the sample's surface was obtained from the proficorder. After the proper magnification had been chosen, both vertical and horizontal, the stylus was gently placed on the surface and allowed to traverse a one-half inch section of it. An attempt was made to make the trace for the same portion of the sample as was illuminated by the incident light.

Experimental Results and Discussion

From previous visual observations of rough surfaces, it has been known that as the roughness height of a surface increased, the reflected intensity decreased. It is not known in what manner this reflected intensity decreased with the increased roughness height. By finding the angular distribution of the reflected intensity for surfaces of known roughness heights the effects of the roughness height on the intensity can be examined.

Since the material of the surface was the same for each sample, the assumption was made that the intensity of a rough surface depended only on the surface's topography. It was also assumed that the elements of the rough surface are equally illuminated by the incident light. It was assumed that the angles of incidence of the light with the surface were 60°, 45°, and 30° although actually the shape of the irregularities could cause the angle to vary from its assumed value.

The goniophotometric measurements of the intensity as a function of the angle of view for the three angles of incidence have been tabulated for each of the samples in Appendix I. It is observed that none of the samples had a peak intensity of one hundred percent as would be anticipated since this would occur only for a theoretically perfect surface. Two samples, #3 and #12 had the highest intensity observed, a value of ninety-four percent. Two factors which resulted in the intensity value being below the theoretical value of one-hundred per cent were the occurence of pits in the surface which deviated from the average roughness height, and also the fact that the general shape of the sample surface on which the irregularities were imposed was not perfectly flat but possessed some curvature, however slight. Further examination of this data indicated that as the angle of incidence was increased, the intensity also increased. This increase in intensity was found to be approximately constant for each particular sample, but the value varied from sample to sample. For example, referring to the tables in Appendix I, the constant for sample #1 is approximately 4 units as evidenced by the intensity increases from a value of 62.2 for 30° incidence, to 66.8 for 45° incidence, to a value of 70.5 for 60° incidence. However, for sample #5 this constant was approximately 8 units as shown by intensity increases from a value of 59.3 for 30° incidence, to 66.5 for 45° incidence, to a value of 74.6 for 60° incidence.

Goniophotometric curves, which are plots of the log of the intensity as a function of the angle of view for a constant angle of incidence, are drawn for the samples from the data in Appendix I. The surfaces of these samples are found to have reflections which ranged in nature from very specular to very diffuse. Figures 3-5 are goniophotometric curves for some typical surfaces for a 60° angle of incidance. Figure 3 is representative of a very high specular surface, sample #3, while Figure 4 represents a medium specular surface, sample #10, and Figure 5 is typical for a very diffuse surface, sample #7. From Figure 3, it is noted that the specular portion of the curve occurs at the angle of view equal to the angle of incidence. In Figure 3, the intensity decreased rapidly over a region of five degrees on either side of the specular angle, 60°, before leveling off to a value dependent upon the amount of diffuse reflections by the surface. By comparison, Figure 5 showed that the intensity for a surface with a large amount of diffuse reflection has a small peak value, 8.4 as a result of the wide scattering of the reflected light. Also, in contrast to the curve for the specular surface, Figure 5 showed that the intensity for a diffusely reflecting surface changed slowly with changes in the angle of view in a region of about twenty degrees on either side of the angle of view equal to the angle of incidence. Figure 4 represented a surface which was intermediate in nature in that it is less specular than the sample of Figure 3 and less diffuse than the sample represented by Figure 5. It had a value of 40.7 for the peak intensity and a value for the diffuse reflection of approximately 1 as compared to a peak intensity value of 94.2 and a diffuseness value of 1 for the specular reflecting surface and a peak intensity value of 8.5 and a diffuseness value of 3 for the extreme diffuse reflecting surface. When the three goniophotometric curves are compared with one another, the angular half-width, defined as the angular width at one-half the maximum intensity for the intensity distribution about the angle of reflection equaled to the angle of incidence, is noted to vary greatly from the specular surface to the diffuse surface. The value of the angular half-width is dependent on the amount of reflected light scattered and increased as the reflected light became scattered more and more; that is for reflection from rougher and rougher surfaces. For example, the angular half-width for the surface for which Figure 3 is drawn is 4.1 degrees while the angular half-width for the surface which figure 4 represents is 5.5 degrees, and the angular half-width for the surface shown in Figure 5 was 19°. The angular half-width was found to be practically a constant for the smoother surfaces of roughness height less than ten microinches, as these samples had small diffuse components and large specular components. The diffuse compo-

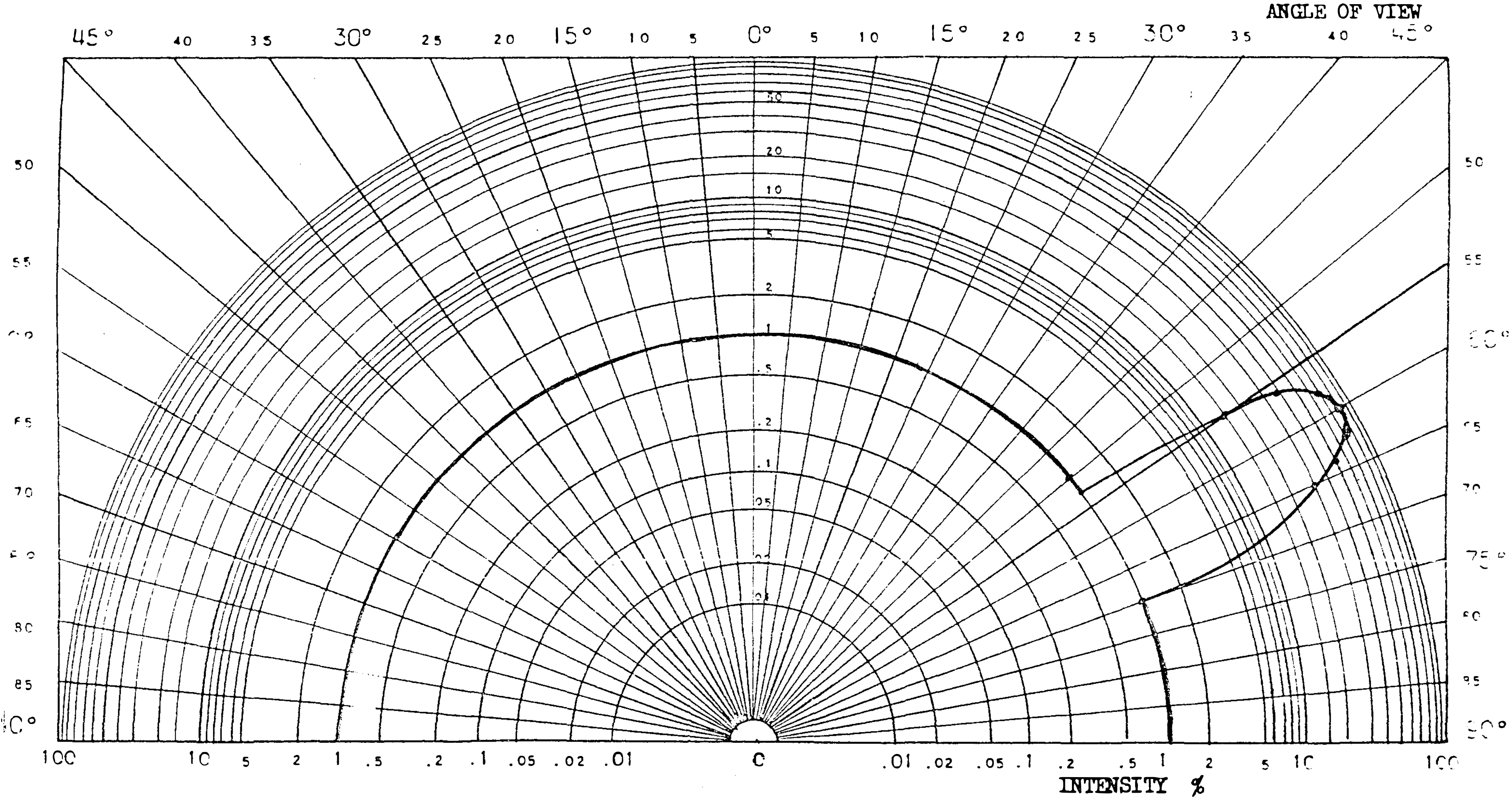


FIG. 3 A GONIOPHOTOMETRIC CURVE OF A HIGH SPECULAR SURFACE

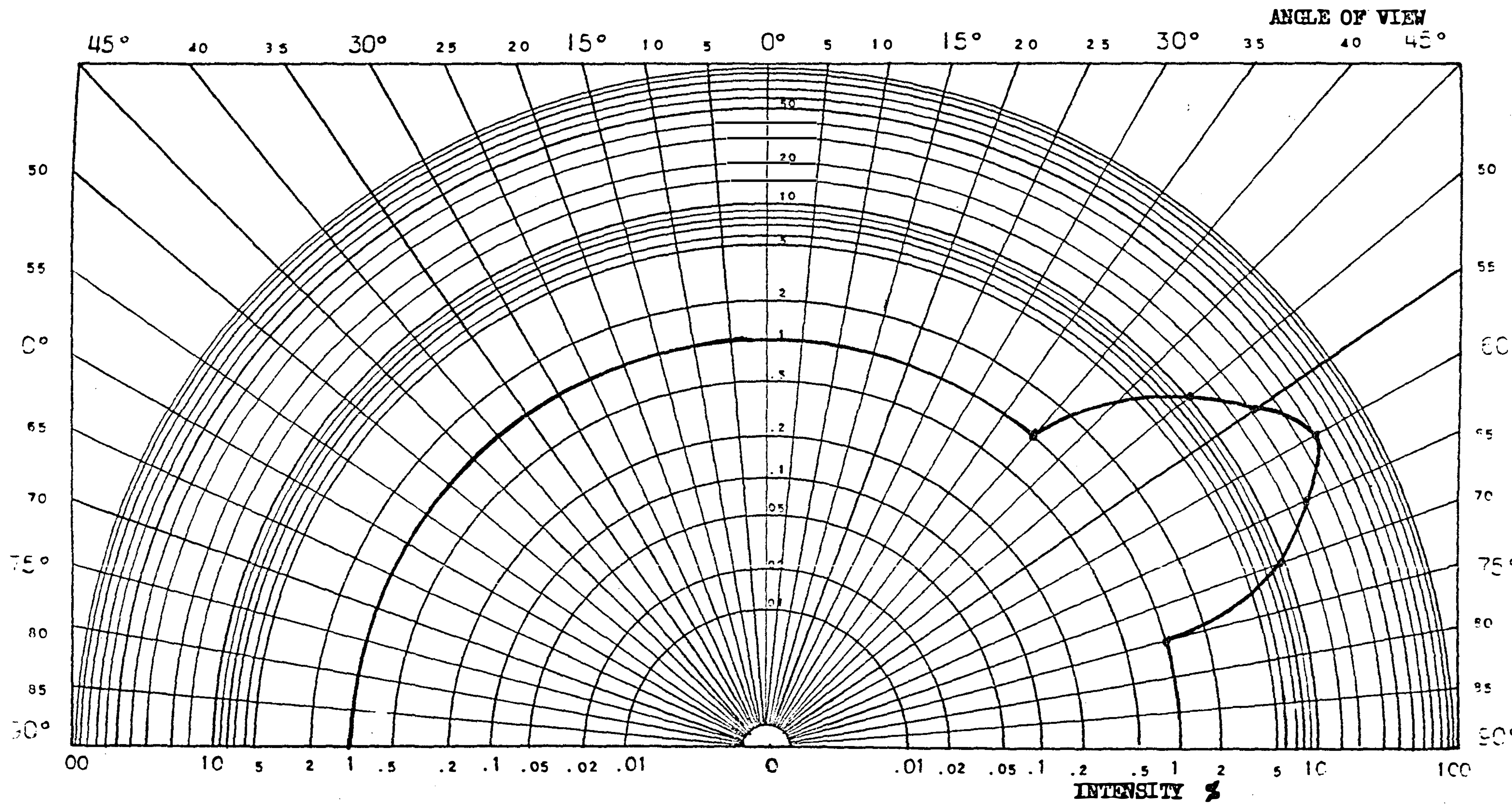


FIG. 4 A GONIOPHOTOMETRIC CURVE OF A MEDIUM SPECULAR SURFACE

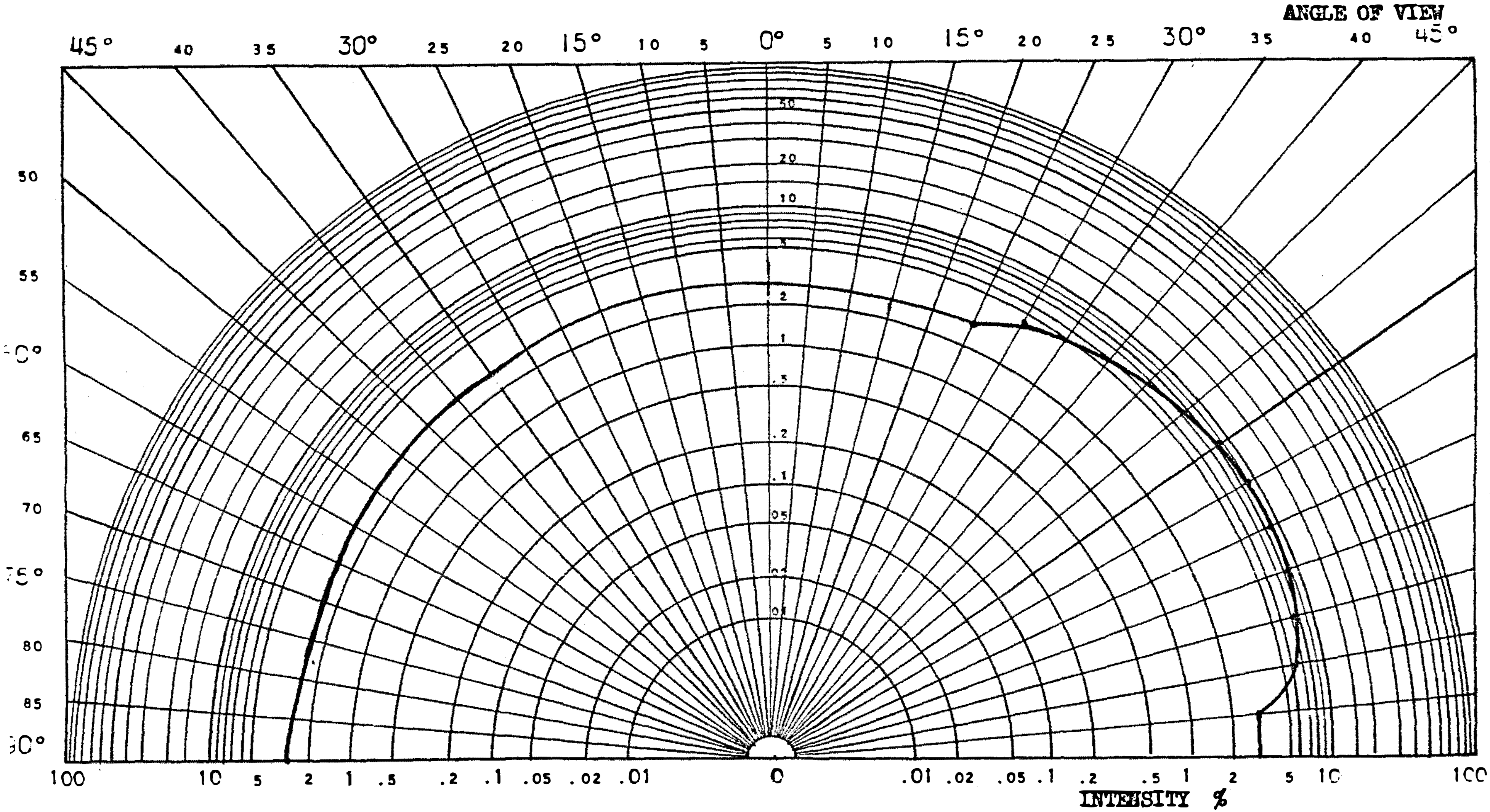


FIG. 5 A GONIOPHOTOMETRIC CURVE OF A VERY DIFFUSE SURFACE

ment for the samples with roughness height values greater than ten microinches increased, the angular half-width also increased very rapidly, and the peak intensity value became correspondingly smaller.

The traces recorded with the proficorder are reproduced in Appendix II. The average peak to valley distance as determined from these traces are used as a measure of the roughness height of the surface. This method of determining the roughness heights is used as it has been found by experiment [13] to give the truest value of several methods [14] attempted. It is noted from the traces that a wide range of roughness heights resulted from the different methods of sample preparation; for example, 0.93u" for sample #3 and 288u" for sample #7.

From the tables of Appendix I and roughness heights as determined from Appendix II, the peak intensities are plotted as a function of the roughness height for each of the angles of incidence. These curves are shown in Figures 6-8 for 30°, 45°, and 60° angles of incidence, respectively. All indicated a sharp decrease in the intensity as the roughness height increased from zero to twenty-one microinches after which the decrease became more and more gradual as the roughness height was increased further. Therefore, the intensity approaches a constant as very high roughness height values were reached. It was expected that the curves would approach a constant intensity, other than a value of zero, as some light always will be reflected from the surfaces although the amount might be small; this constant amount corresponding to the intensity reflected from a perfectly diffuse surface. The constant which the intensity approached was noted to decrease as the angle of incidence decreased and, at the same time, the curve approached this constant value more rapidly for smaller angles of incidence than for larger angles of incidence.

Also, from these curves, it is seen that increasing the angle of incidence increased the slope of the curve in the range of roughness height values from zero to ten microinches. The smoother the surface, the greater was the increase in the slope. The intensity curves with the largest slopes are found for the smoothest surfaces for large angles of incidence.

Figures 6-8 also showed that the curves consisted of three regions regarding the intensity. The first region is characterized by high specularity and extended over a roughness height range from zero to about seven microinches, or $\lambda/3$ microinches where λ is the average wavelength of the incident light. At the upper limit of this region, the intensity decreased very rapidly with the increase in roughness height. A surface which has such a high specularity is represented by the goniophotometric curve in Figure 3.

The second region shows a transition occuring as both specular and diffuse components are present. This region, which is featured by the sharp change in the slope from almost vertical to one almost horizontal, extended over a roughness height range from about seven to seventy-five microinches, or $\lambda/3$ to 3λ. A surface, which this transition region represents, has an intensity distribution as shown by the goniophotometric curve in Figure 4.

The third region, consisting of almost all diffuse reflection shows the intensity decrease becoming more and more gradual and slowly approaching a constant as the roughness height value increased from about 3λ to very large values. The intensity distribution for a surface in this

ANGLE OF INCIDENCE = 30°

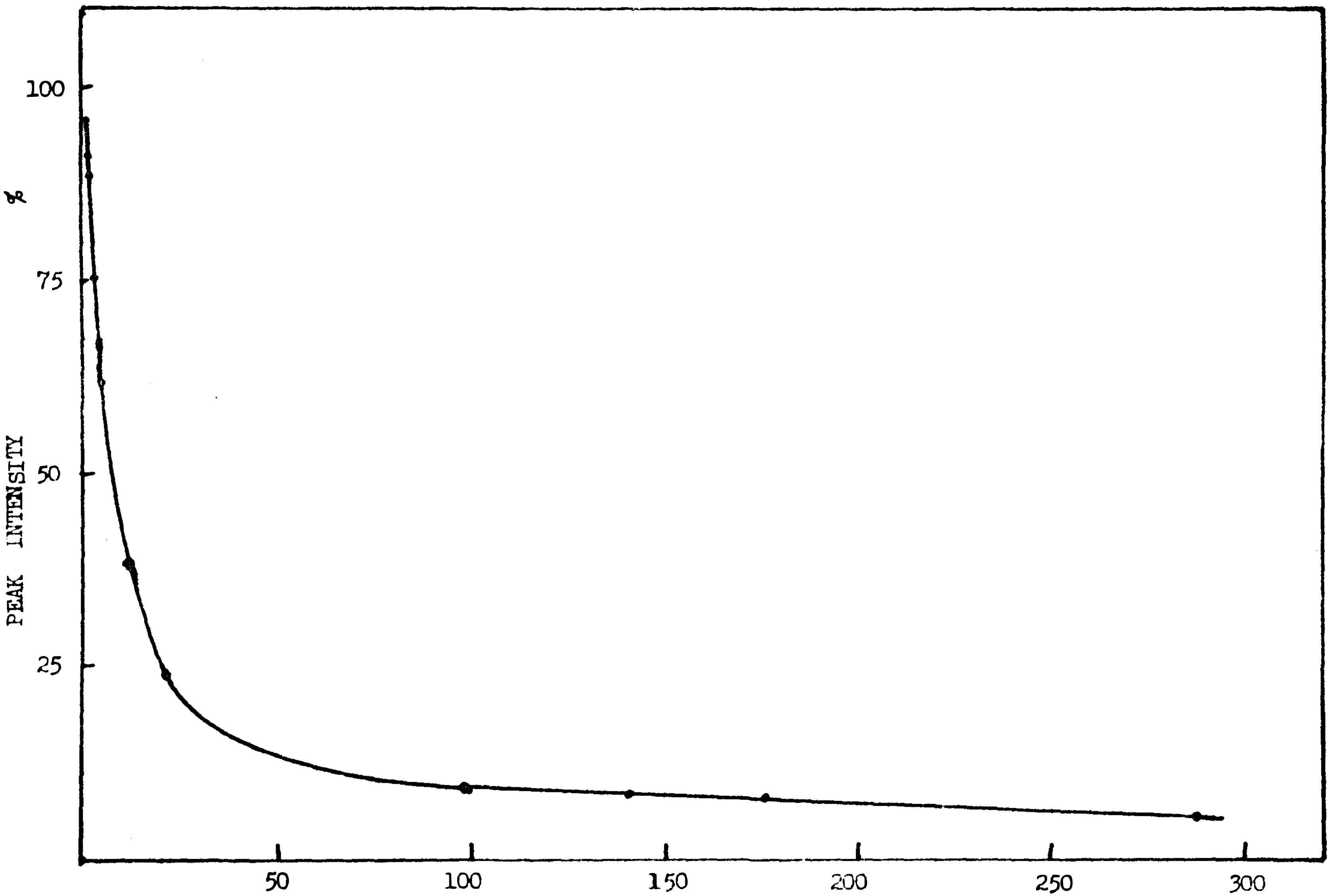


FIG. 6 ROUGHNESS HEIGHT MICROINCHES

ANGLE OF INCIDENCE = 45°

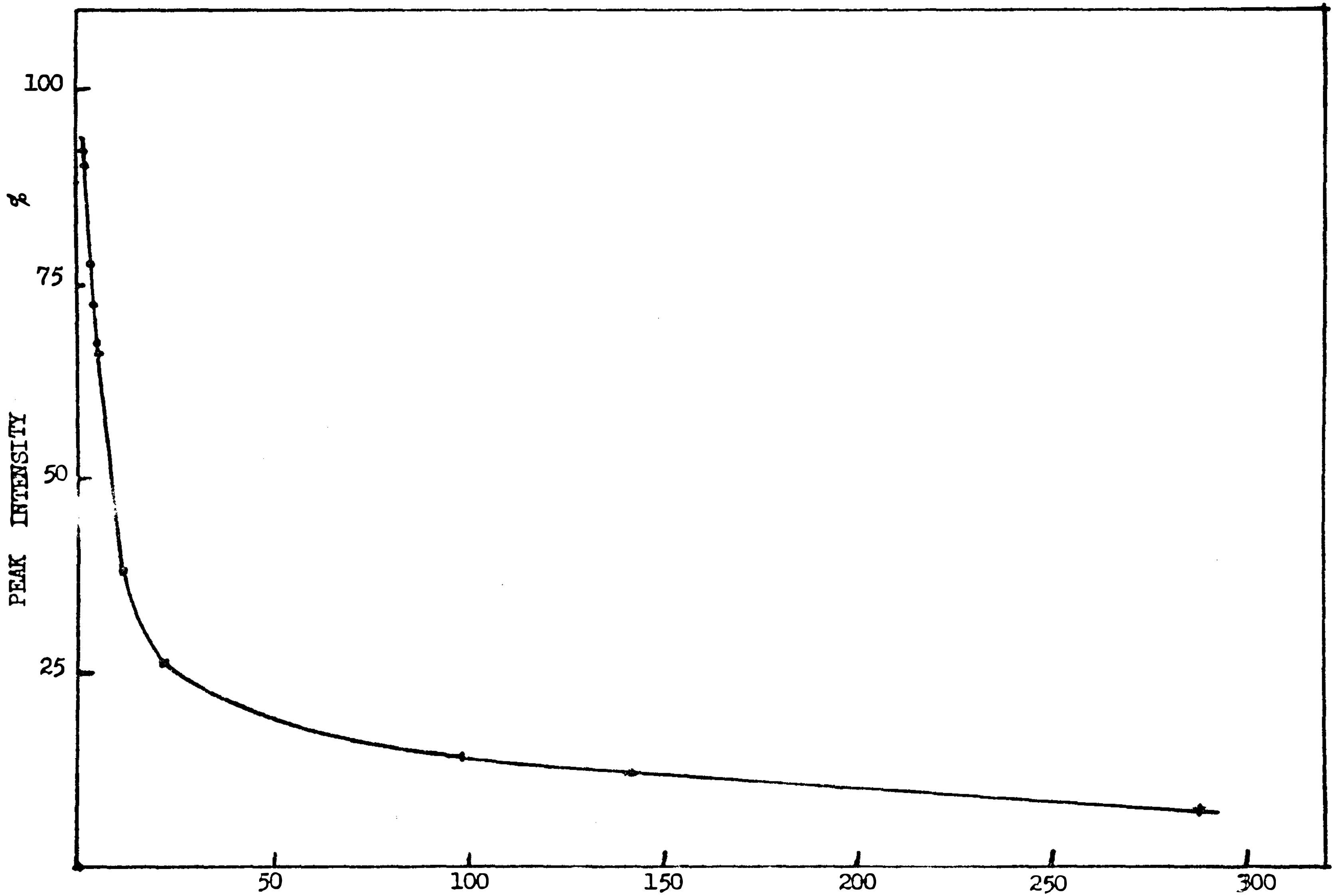


FIG. 7 ROUGHNESS HEIGHT MICROINCHES

ANGLE OF INCIDENCE = 60°

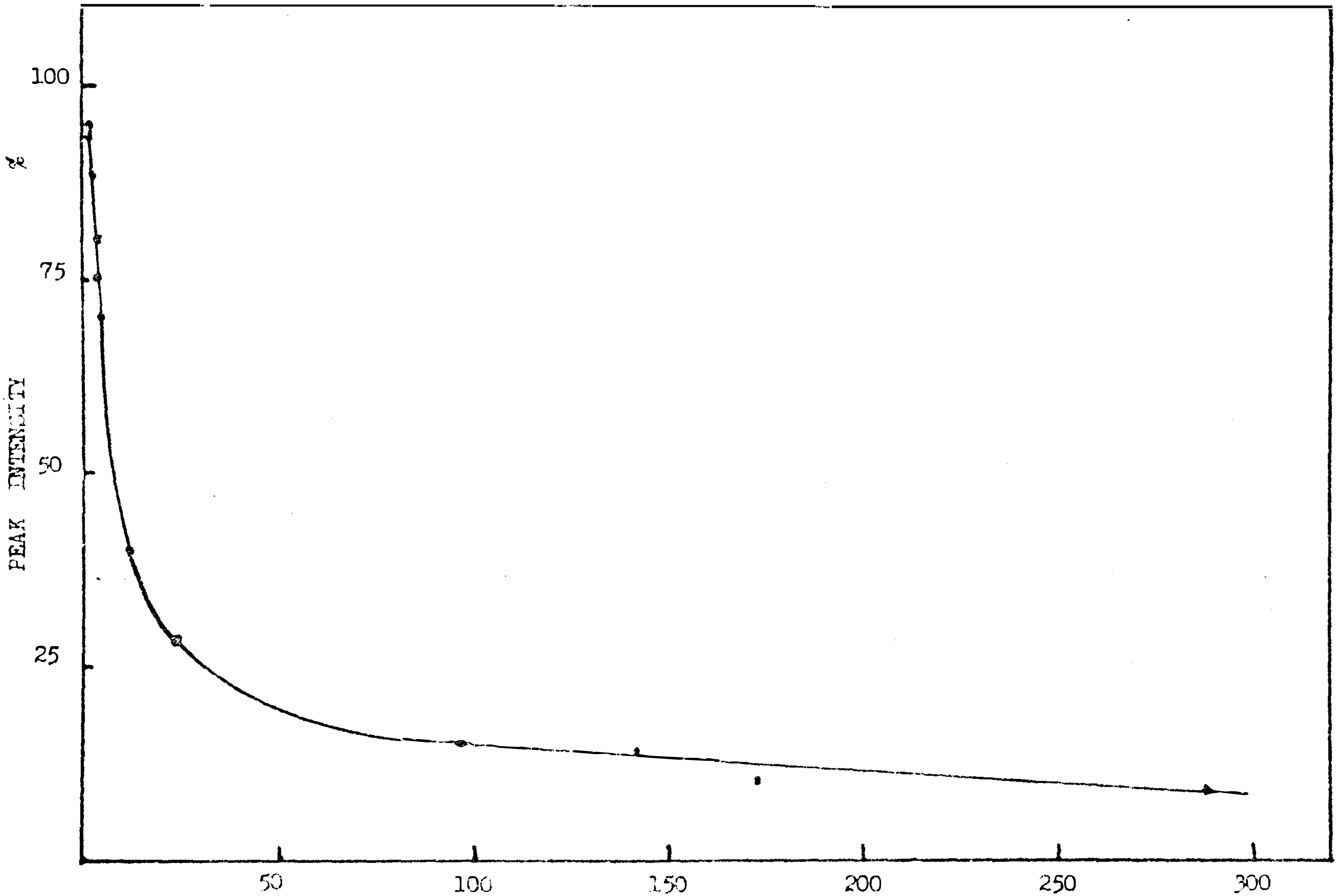


FIG. 8 ROUGHNESS HEIGHT MICROINCHES

region which has a large diffuse reflection is shown in Figure 5.

The occurence of these regions can be explained by a comparison of the average wavelength of the incident light and the roughness height values. For roughness heights less than $\lambda/3$ the surface reflected specularly almost all of the incident light. The transition region occurred where the wavelength of the incident light is the same order of magnitude as the roughness height. In this region, the light was both specularly and diffusely reflected, but the scattering of the light increased as the roughness height increased resulting in a continued lowering of the specular component of the intensity. In the third region, where the roughness height is greater than the average wavelength of the incident light, the reflected light became more and more scattered as the roughness height increased which was a result of pits and other abnormal irregularities in the surface topography, causing the light to be subjected to many multiple reflections.

Also observed from these intensity curves is the absence of interference maxima and minima. Such phenomena are found in the intensity curves for a surface of regular topography, an example of which would be a plane reflection grating placed with the grooves perpendicular to the plane of the incident and reflected beams of light. The fact that interference maxima and minima are absent from the intensity curves for the surfaces of samples used in this investigation is attributed to the fact that these surfaces, instead of being regular in nature, are extremely irregular in structure. It should be pointed out that although the samples used did not have a surface of regular topography, samples were not used which had deep gouges, scratches, or severe undercutting.

The path difference between the light beams reflected from two surfaces, one a distance r below the other, is given by the relation 2 r cos ϕ where ϕ is the angle of incidence and r is the roughness height. The value of r was found by taking the point where two lines, one a tangent to the nearly vertical slope and one a tangent to the nearly horizontal slope, intersect and finding the coordinate for the roughness height. In the specular region of the Figures 6-8, the path difference was found to be a constant approximately equaled to $\lambda/3$ microinches for each of the three angles of incidence. These values are shown below:

ϕ	r (u")	path difference (u")
60°	6.5	6.5
45°	4.5	6.4
30°	3.8	6.5

CONCLUSIONS

The experimental evidence indicated that the surfaces fitted into three categories regarding the peak intensity distribution of the reflected light as a function of the roughness height of the surface. The first region corresponded to the specular portion for a roughness height range of zero to approximately $\lambda/3$ microinches. In this region, for each of the three angles of incidence, the path difference 2r cos ϕ, was equaled to a constant whose value was approximately $\lambda/3$. The second region was an intermediate one where a transition occurred from nearly all specular to nearly all diffuse reflection and included a roughness height range from $\lambda/3$ to 3λ microinches. The third region consisted of values for the roughness height greater than 3λ and corresponded to almost total diffuse reflection. These facts: (1) that the intensity approached a constant for large values of roughness heights (2) a sharp transition occurred in the slope in the region where the average wavelength was equal to the roughness height, and (3) the manner in which the curve approached the intensity axis suggested a theoretical curve as shown in Figure 9 as contrasted by the experimental curve represented by the dotted line. It is noticed that the theoretical curve consisted of only two regions by purpose, a specular region and a diffuse region. The point of abrupt change would occur where roughness height is much less than the wavelength of light. Some reasons why the experimental curves did not conform to the theoretical curve were that not any samples had a roughness height value low enough to be entirely specular in nature and also that the proficorder can not

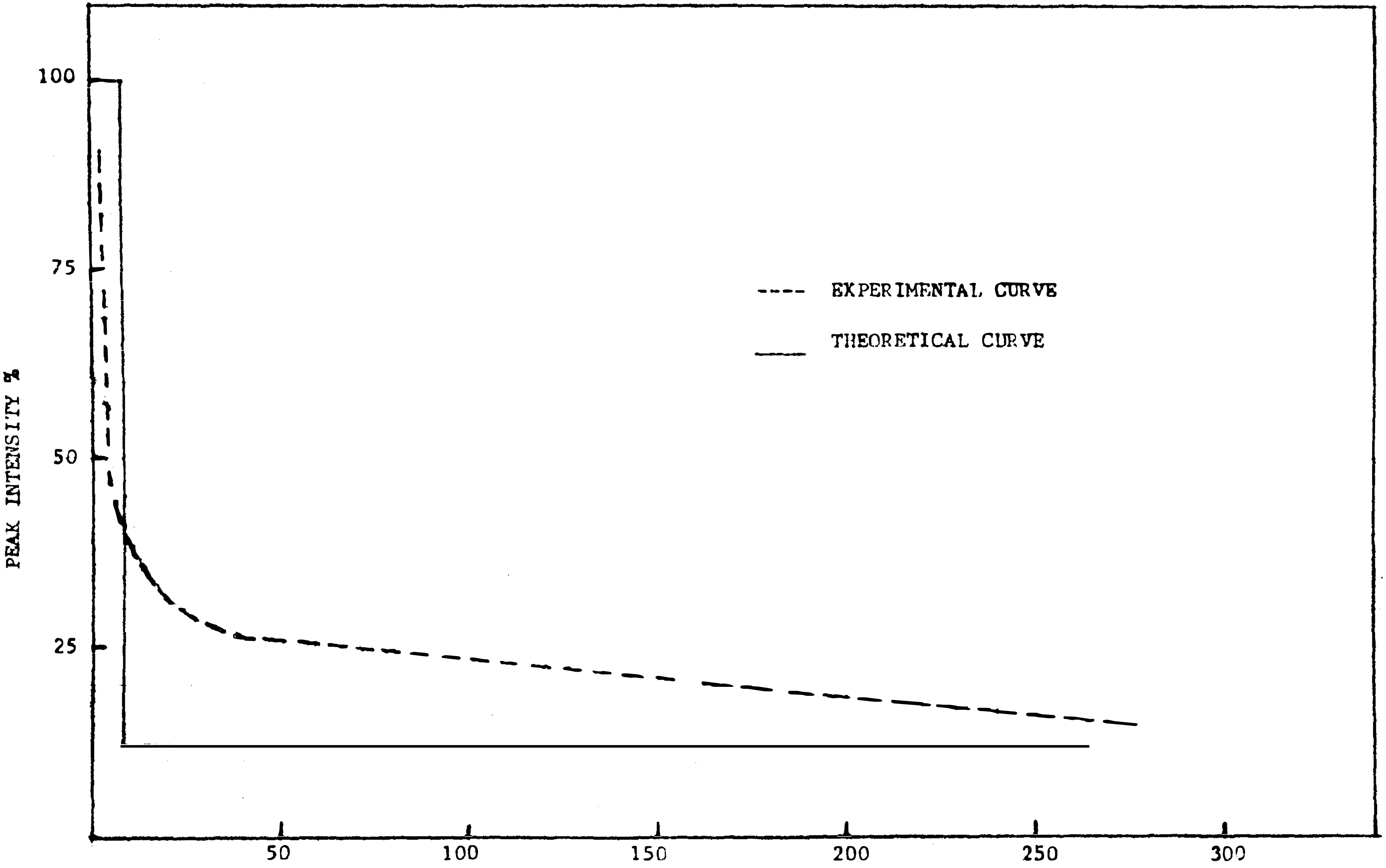


FIG. 9 ROUGHNESS HEIGHT MICROINCHES

accurately determine roughness heights of such low values.

Some similar investigations could be performed with aluminum alloys as well as pure aluminum metal using monochromatic light on surfaces of known roughness height values. The wave lengths used should range from the shorter wave length region of the spectrum to longer wave-length region. Also, the amount of absorption of light by such a surface should be studied to see if it varies much with changes in the roughness height. If an instrument could be devised so that the specular and diffuse components could be measured separately, the reflecting power of a surface could be analyzed much easier.

Appendix I

Measurements of Intensity by the Goniophotometer

TABLE I Sample #1 Average roughness height = 2.15u"

Angle of View	Intensity %	Angle of View	Intensity %	Angle of View	Intensity %
	$Z_i = 30^\circ$		$Z_i = 45^\circ$		$Z_i = 60^\circ$
25°	0	40°	0	55°	0
26	25.1	41	37.5	56	39.1
27	51.2	42	64.5	57	68.6
28	61.0	43	65.7	58	69.7
29	61.8	44	66.5	59	69.8
30	62.2	45	66.8	60	70.5
31	61.2	46	66.6	61	68.7
32	60.5	47	65.4	62	68.2
33	58.4	48	63.8	63	67.7
34	24.2	49	48.7	64	53.6
35	0	50	0	65	0

TABLE 2 Sample #2 Average roughness height = 1.07u"

Angle of View	Intensity %	Angle of View	Intensity %	Angle of View	Intensity %
	$\angle i = 30^\circ$		$\angle i = 45^\circ$		$\angle i = 60^\circ$
25°	0	40°	0	55°	0
26	42.2	41	50.9	56	78.8
27	66.1	42	71.5	57	81.5
28	70.5	43	76.4	58	85.6
29	74.4	44	76.8	59	86.2
30	75.5	45	77.1	60	87.6
31	73.5	46	74.4	61	85.1
32	70.5	47	73.6	62	83.2
33	66.9	48	70.1	63	79.5
34	43.5	49	44.2	64	45.6
35	14.1	50	12.1	65	17.5
36	0	51	0	66	0

TABLE 3 Sample #3 Average roughness height = 0.93µ"

Angle of View	Intensity %	Angle of View	Intensity %	Angle of View	Intensity %
	$\angle i = 30^\circ$		$\angle i = 45^\circ$		$\angle i = 60^\circ$
25°	0	40°	0	55°	0
26	15.5	41	48.2	56	44.1
27	71.1	42	75.4	57	85.1
28	86.5	43	90.1	58	88.6
29	87.1	44	90.5	59	93.5
30	88.4	45	90.9	60	94.2
31	86.2	46	90.8	61	92.2
32	85.1	47	88.5	62	90.5
33	82.2	48	82.8	63	84.1
34	73.2	49	76.5	64	77.5
35	9.5	50	9.8	65	8.3
36	0	51	0	66	0

TABLE 4 Sample #4 Average roughness height = 1.53u"

Angle of View	Intensity %	Angle of View	Intensity %	Angle of View	Intensity %
	$\angle i = 30^{\circ}$		$\angle i = 45^{\circ}$		$\angle i = 60^{\circ}$
24°	0	39°	0	54°	0
25	11.2	40	12.0	55	14.2
26	37.6	41	34.1	56	34.1
27	53.4	42	59.1	57	66.6
28	57.8	43	67.4	58	74.5
29	59.1	44	67.6	59	75.5
30	59.3	45	66.5	60	74.6
31	58.9	46	64.2	61	73.1
32	58.1	47	62.1	62	71.4
33	56.2	48	59.5	63	69.2
34	44.4	49	49.9	64	49.5
35	19.1	50	19.5	65	21.0
36	0	51	0	66	0

TABLE 5 Sample #5 Average roughness height = 1.58u"

Angle of View	Intensity %	Angle of View	Intensity %	Angle of View	Intensity %
	∠i = 30°		∠i = 45°		∠i = 60°
24°	0	39°	0	54°	0
25	14.1	40	13.4	55	14.5
26	29.9	41	31.6	56	39.5
27	48.6	42	58.4	57	64.5
28	59.6	43	68.9	58	76.4
29	64.1	44	72.4	59	79.5
30	65.2	45	73.5	60	80.9
31	64.2	46	72.8	61	79.9
32	62.4	47	71.8	62	78.8
33	58.6	48	67.6	63	73.1
34	50.4	49	57.1	64	61.4
35	28.1	50	32.1	65	29.1
36	9.0	51	12.4	66	15.2
37	0	52	0	67	0

TABLE 6 Sample #6 Average roughness height = 176u"

Angle of View	Intensity %	Angle of View	Intensity %	Angle of View	Intensity %
	Zi = 30°		Zi = 45°		Zi = 60°
20°	2.6	20°	0.9	35°	0
25	5.9	30	3.9	40	4.1
26	6.2	40	9.1	45	7.2
27	6.4	41	9.3	50	9.0
28	6.4	42	9.6	55	9.8
29	6.5	43	9.6	56	10.1
30	6.6	44	9.6	57	10.1
31	6.4	45	9.8	58	10.2
32	6.4	46	9.6	59	10.4
33	6.4	47	9.6	60	10.5
				61	10.1
34	6.2	48	9.6	62	9.8
35	6.1	49	9.1	63	9.5
50	1.5	50	8.6	64	9.5
				65	8.8
60	0.7	60	4.3	70	8.2
70	0	70	1.2	75	6.5

TABLE 7 Sample #7 Average roughness height = 288u"

Angle of View	Intensity %	Angle of View	Intensity %	Angle of View	Intensity %
	$\angle i = 30^\circ$		$\angle i = 45^\circ$		$\angle i = 60^\circ$
10°	2.5	5°	0	10°	0
25	4.5	10	2.5	20	2.5
26	4.8	15	3.5	30	4.1
27	4.8	20	4.1	40	6.4
28	4.8	30	6.5	55	8.1
29	4.8	40	6.5	56	8.5
30	4.9	41	6.5	57	8.5
31	4.8	42	6.7	58	8.5
32	4.8	43	6.8	59	8.6
33	4.5	44	6.9	60	8.6
34	4.5	45	6.9	61	8.5
35	4.4	46	6.5	62	8.5
50	2.7	47	6.5	63	8.5
60	0.9	48	6.5	64	8.3
70	0	49	6.3	65	8.1
		50	6.1	70	7.5
		70	4.2	80	6.5
		80	0		

TABLE 8 Sample #8 Average roughness height = 142u"

Angle Of View	Intensity %	Angle of View	Intensity %	Angle of View	Intensity %
	∠i = 30°		∠i = 45°		∠i = 60°
10°	7.5	5°	0	10°	0
25	8.5	10	2.5	20	2.5
26	8.7	20	4.1	30	4.1
27	9.0	30	6.5	40	6.4
28	9.1	40	10.1	55	14.2
29	9.3	41	10.4	56	14.5
30	9.5	42	10.7	57	14.7
31	9.3	43	11.0	58	14.7
32	9.2	44	11.1	59	14.7
33	9.1	45	11.1	60	14.5
34	8.9	46	11.2	61	14.3
35	8.6	47	10.9	62	13.9
50	2.7	48	10.7	63	13.6
60	0.9	49	10.5	64	13.3
70	0	50	10.4	65	12.8
		70	4.2	70	7.5
		80	0	80	6.5

TABLE 9 Sample #9 Average roughness height = 21u"

Angle of View	Intensity %	Angle of View	Intensity %	Angle of View	Intensity %
	∠i = 30°		∠i = 45°		∠i = 60°
10°	5.1	20°	2.6	20°	0
20	15.5	30	10.0	30	1.5
25	20.9	40	22.0	40	4.5
26	21.6	41	23.8	55	25.5
27	23.3	42	24.7	56	26.8
28	23.6	43	25.7	57	27.5
29	24.1	44	26.3	58	27.9
30	24.2	45	26.6	59	28.3
31	24.4	46	26.6	60	28.4
32	24.1	47	25.8	61	27.6
33	23.4	48	24.6	62	26.7
34	22.2	49	23.2	63	25.5
35	21.2	50	21.1	64	24.2
40	13.5	60	7.5	65	22.5
50	4.1	70	1.6	70	13.1
60	0.6	75	0	80	3.2

TABLE 10 Sample #10 Average roughness height = 11.2u"

Angle of View	Intensity %	Angle of View	Intensity %	Angle of View	Intensity %
	∠i = 30°		∠i = 45°		∠i = 60°
10°	0	20°	1.4	35°	0
20	7.1	30	4.1	40	2.5
25	17.8	40	22.1	50	10.9
26	28.1	41	26.2	55	22.2
27	35.2	42	35.2	56	25.1
28	38.5	43	38.4	57	34.1
29	41.7	44	41.6	58	37.8
30	42.0	45	42.0	59	40.1
31	41.1	46	41.3	60	40.7
32	40.2	47	41.1	61	40.3
33	37.5	48	38.2	62	38.5
34	33.1	59	34.2	63	37.6
35	21.6	50	24.2	64	31.8
40	8.1	60	3.5	65	21.7
50	1.1	65	0	70	9.5
55	0			80	1.5

TABLE 11 Sample #11 average roughness height = 98u"

Angle of View	Intensity %	Angle of View	Intensity %	Angle of View	Intensity %
	∠i = 30°		∠i = 45°		∠i = 60°
10°	4.2	10°	1.6	20°	1.4
20	5.1	20	3.2	30	3.1
25	6.5	30	6.1	40	5.6
26	7.1	40	10.1	50	9.4
27	7.6	41	11.2	55	10.6
28	8.2	42	12.3	56	11.5
29	8.8	43	13.5	57	12.8
30	9.4	44	13.9	58	13.7
31	10.0	45	14.5	59	14.2
32	12.2	46	14.6	60	14.8
33	14.5	47	14.5	61	14.6
34	12.5	48	14.0	62	14.4
35	10.8	49	13.3	63	14.1
50	3.8	50	12.1	64	13.5
60	1.6	60	5.6	65	11.7
70	0	70	2.9	70	7.6
		80	0.6	80	2.2

TABLE 12 Sample #12 Average roughness height = 0.95u"

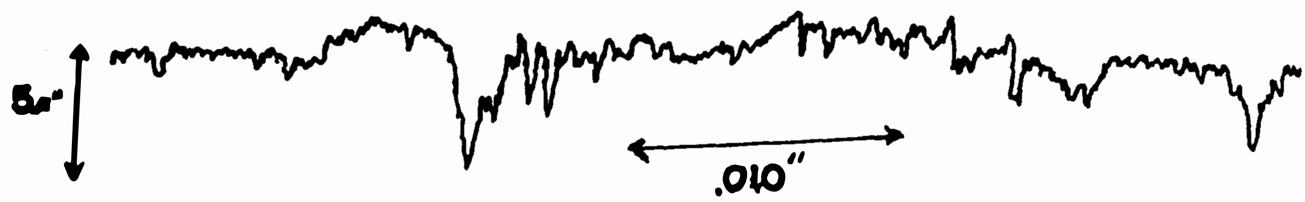
Angle of View	Intensity %	Angle of View	Intensity %	Angle of View	Intensity %
	$\angle i = 30^\circ$		$\angle i = 45^\circ$		$\angle i = 60^\circ$
23°	0	36°	0	52°	0
24	5.4	37	2.1	53	1.8
25	49.4	38	2.4	54	2.8
26	88.6	39	3.9	55	6.5
27	91.2	40	14.6	56	28.5
28	92.1	41	74.4	57	89.8
29	92.3	42	90.8	58	94.2
30	93.1	43	92.5	59	94.5
31	91.4	44	93.6	60	94.9
32	88.6	45	93.5	61	93.8
33	58.6	46	92.9	62	93.4
34	25.4	47	92.1	63	92.3
35	3.1	48	90.1	64	81.2
36	1.1	49	62.5	65	7.0
37	0	50	6.5	66	2.1
		51	1.5	67	0

APPENDIX II

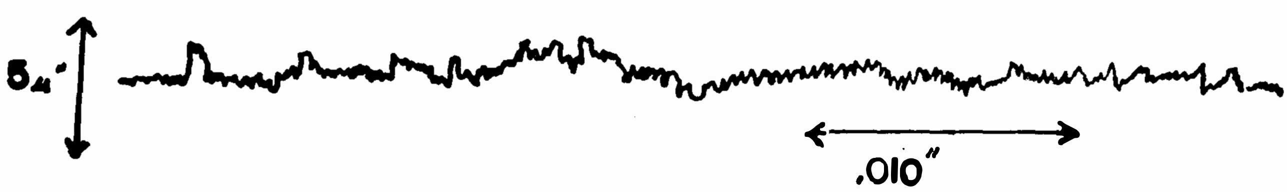
PROFICORDER TRACES FOR THE SURFACES OF THE SAMPLES

SAMPLE 1

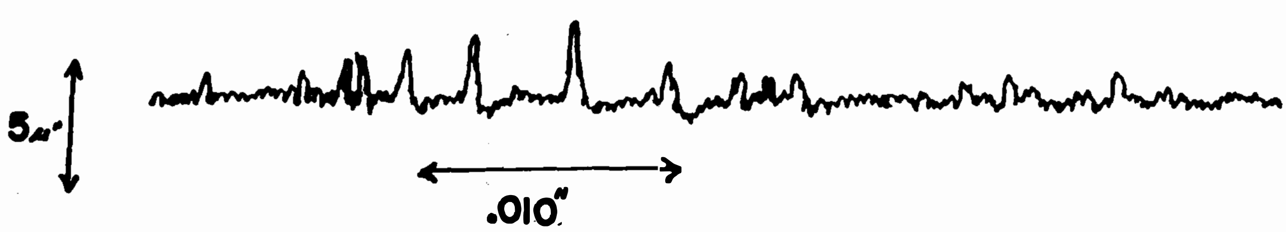
SAMPLE 2



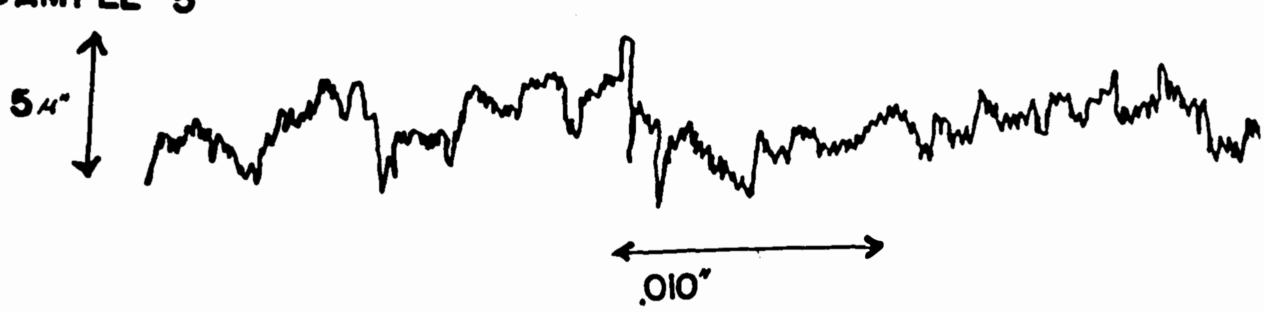
SAMPLE 3



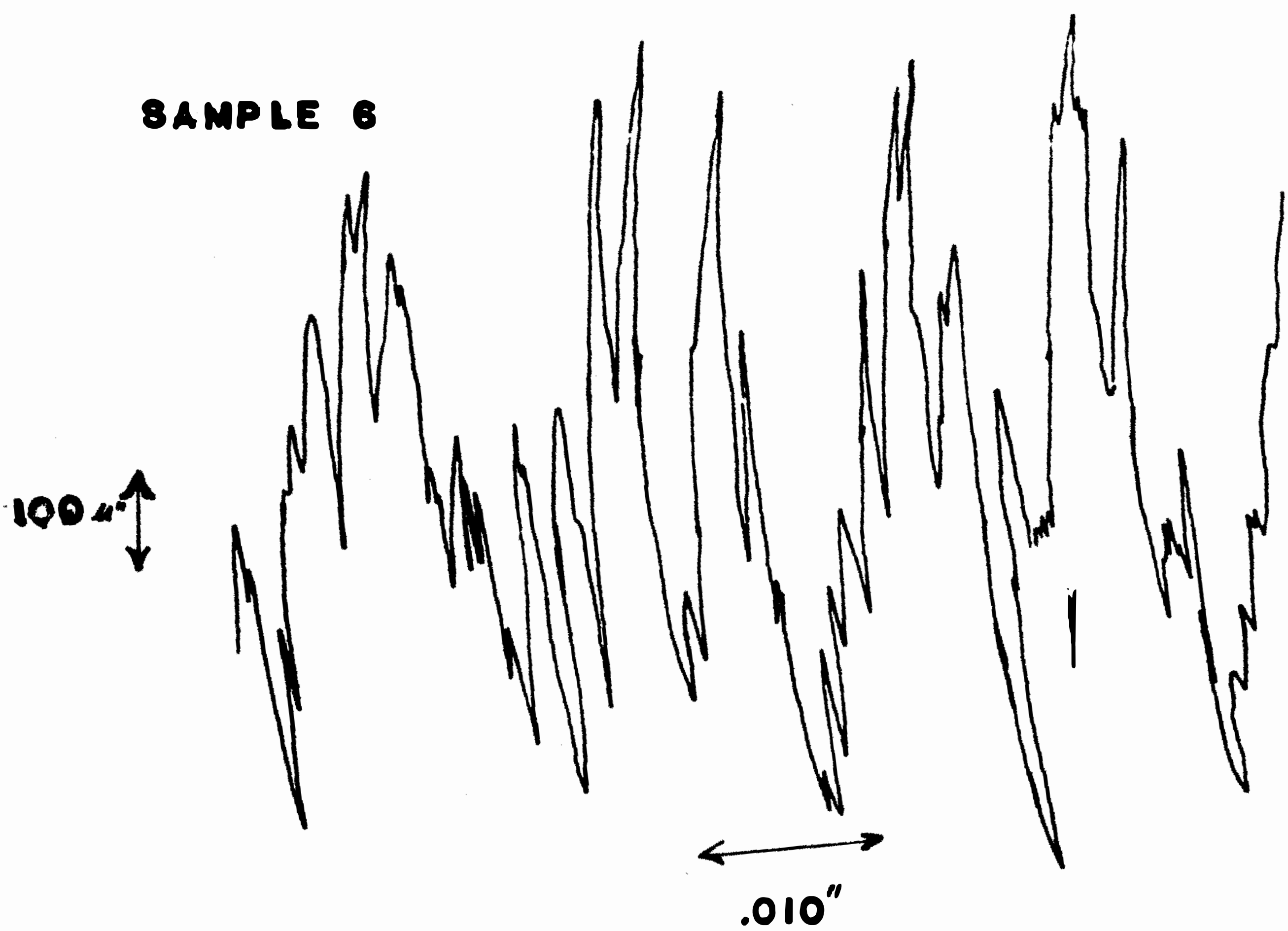
SAMPLE 4



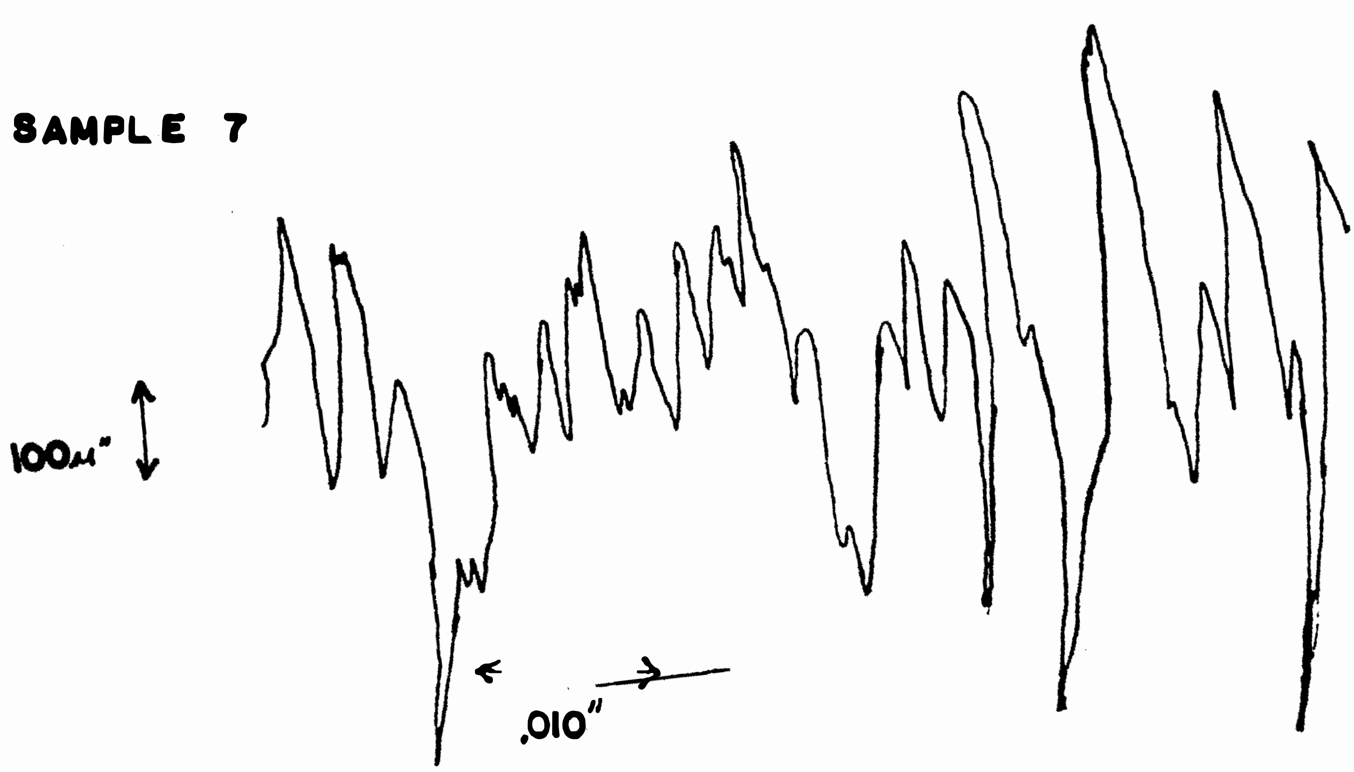
SAMPLE 5



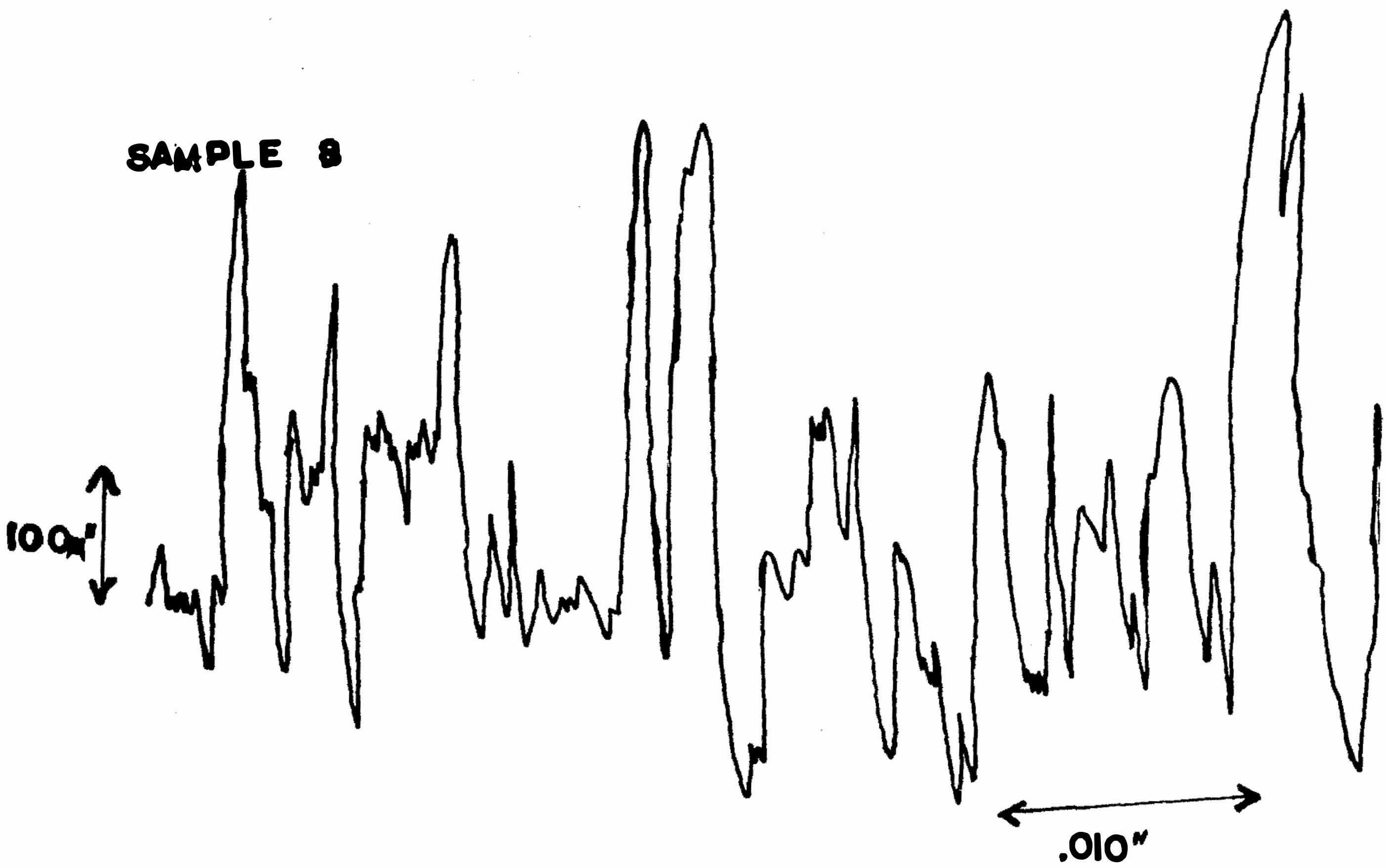
SAMPLE 6



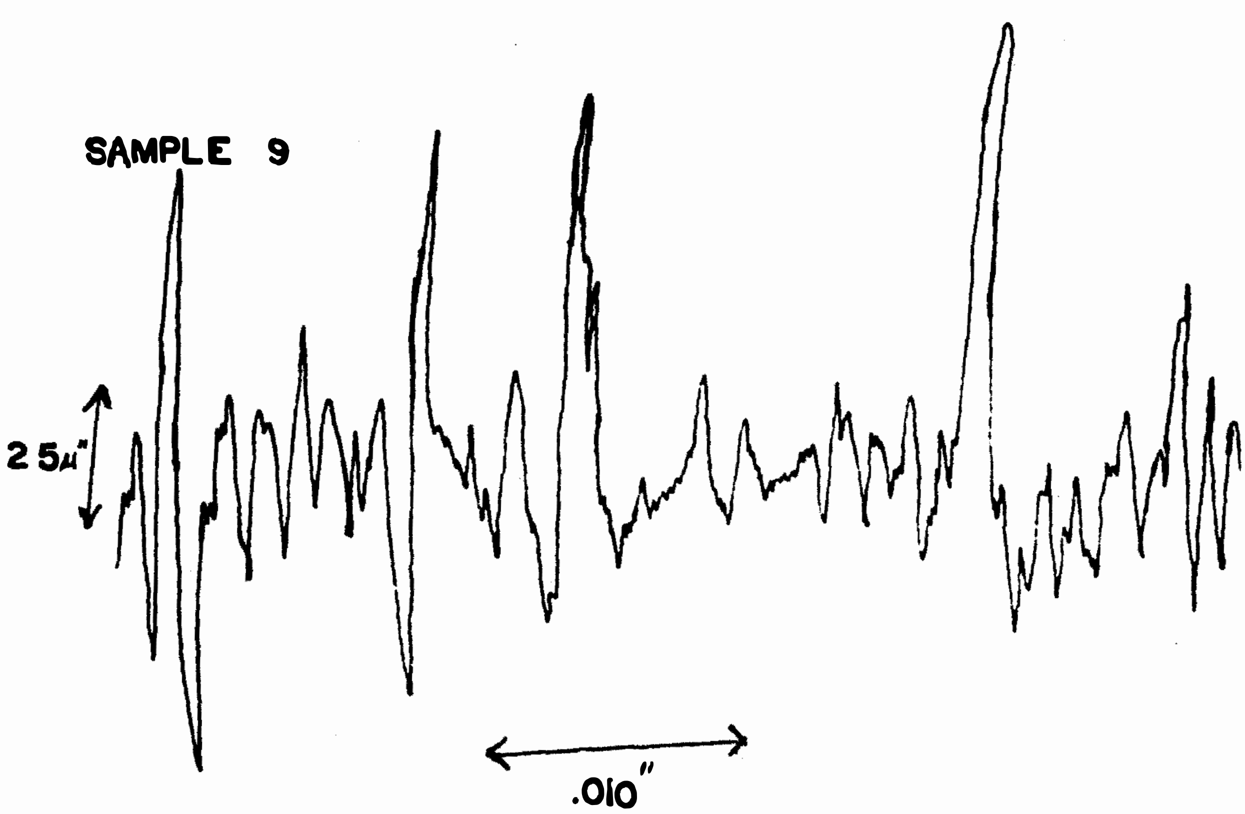
SAMPLE 7



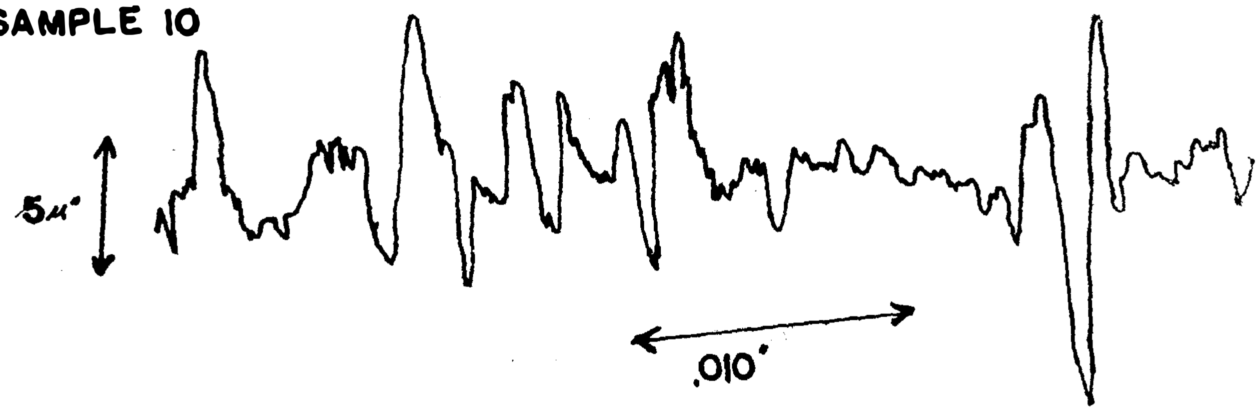
SAMPLE 8



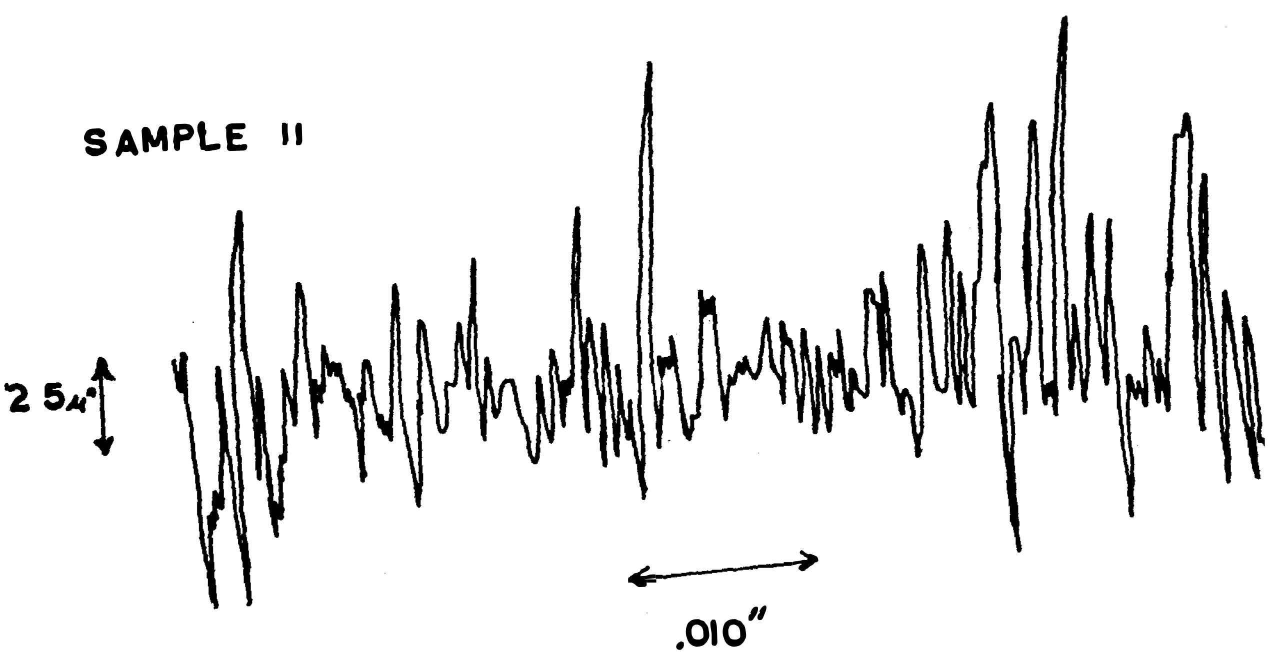
SAMPLE 9



SAMPLE 10



SAMPLE 11



SAMPLE 12

Acknowledgements

The writer wishes to express his appreciation to the members of the Physics Department for their help during his period of study at the University of Richmond. In particular, he thanks Dr. Billy W. Sloope, who directed the research, for his helpful suggestions, criticisms, and assistance in the analysis of the data and to Dr. Addison D. Campbell for advice and criticism. Thanks are also extended to the Metallurgical Research Laboratories of Reynolds Metals Company for the use of their instruments, and supplying the aluminum metal used. To his many associates who aided and helped him, especially Mr. W. W. Berkey for his help with the proficorder, Mr. J. T. Hayden who helped draw the goniophotometric graph paper, Mr. E. Kersey for the photographs, and the members of the Electrochemical Finishing Section, Messrs. H. J. Coates, M. T. Carter, C. A. Grubbs, and J. W. Cook, he thanks for their advice and counsel. To Mr. Erik F. Barkman who gave much encouragement, assistance, and advice during the investigation, the writer expresses his deepest graditude.

References

1. James F. Hagen and Earl E. Lindberg, "A Discussion of Instrumentation for Determining Surface Roughness of Machined Parts", General Motors Engineering Journal v. 1, July - August (1954) page 18-23

2. American Standards Association, "Surface Roughness, Waviness, and Lay", American Standard B 46.1

3. A. F. Gorton, "Reflection from and Transmission Through Rough Surfaces", Physical Review, Col. 7, Series II (1916)

4. T. K. Chinmayanandam, "Specular Reflection from Rough Surfaces", Physical Review, Vol. 13, Series II (1919)

5. Gardner Laboratory Inc., 5521 Landy Lane, Bethesda 14, Maryland

6. P. Bouguer, Optice de diversis luminis gradibus dimentren des. Book 2, Section 3, Art. 3 (1762)

7. H. J. McNicholas, Equipment for measuring the reflective and transmissive properties of diffusing media. J. Research NBS 13, 211, (1934)

8. L. A. Wetlaufer and W. E. Scott, "The measurement of gloss" Ind. Eng. Chem., Anal. Ed. 12 647 (1940)

9. H. K, Hammond III and I. Nimeroff, Measurement of sixty-degree specular gloss, J. Research NBS, 44, 585 (1950)

10. Parry Moon and J. Laurence, Construction and Test of a Goniophotometer, JOSA 31 130 (1941)

11. Micrometrical Manufacturing Company, Ann Arbor, Michigan

12. Alchemize Corporation, Congress Expressway and 625 South Kolmar Chicago 24, Illinois.

13. James F.Hagen and Earl E. Lindberg "Design Consideration Applying to Specification of Surface Finish for Machined Parts" <u>General Motors Engineering Journal</u> v. 1, July - August (1954) pages 18-23.

14. Military Standard 10A,Surface Roughness, Waviness and Lay. Standardization Division, Office of the Assistant Secretary of of Defense, Washington 25, D. C. (1955)