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MEMORANDUM

FINISHING AND INSPECTION OF MODEL SURFACES FOR

BOUNDARY-LAYER-TRANSITION TESTS

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FINISHING AND INSPECTION OF MODEL SURFACES FOR BOUNDARY-LAYER-TRANSITION TESTS

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SUMMARY

Techniques which have been used for finishing and quantitatively specifying surface roughness on boundary-layer-transition models are reviewed. The appearance of a surface as far as roughness is concerned can be misleading when viewed either by the eye or with the aid of a microscope. The multiple-beam interferometer and the wire shadow method provide the best simple means of obtaining quantitative measurements.

INTRODUCTION

It has been well known for many years that surface roughness is a variable of considerable importance in controlling transition from laminar to turbulent flow. In this report techniques which have been used in the Ames Supersonic Free-Flight Wind Tunnel Branch for producing uniform surfaces of known roughness, and quantitatively specifying the roughness will be reviewed in the hope that these techniques may be of use to other people engaged in similar work.

DISCUSSION

General Considerations

Surface roughness can appear in various forms - two-dimensional or three-dimensional, as protrusions or depressions, uniformly or non-uniformly distributed, or combinations thereof. One form can be more critical than another in causing boundary-layer transition. Thus surface roughness instead of being a single variable is composed of several variables which may include such factors as size, shape, spacing, and location of roughness elements.

The most common method of indicating surface roughness is to measure and consider a height dimension only. This procedure apparently stems from the measuring of machined surfaces. For the purposes of the machinist, this simplification is acceptable as indicated by the following statement from reference 1: "The numerous irregularities which form a machined surface and determine its quality, consist of minute ridges and valleys, and the degree of roughness is determined by the magnitude, form and spacing of these irregularities; hence, it is evident that no single figure or dimensional value will represent precisely the condition or roughness quality of a surface but an average or a maximum figure may approximate this quality and be useful in specifying, checking and duplicating within pracitical limits, machined surfaces having finishes which have been found to meet practical requirements." The average or maximum value referred to above is usually either the average deviation from the mean surface (either root-mean-square or arithmetical average), the maximum peak-to-valley height, or the average peak-to-valley height.

A height dimension can be very deceptive for aerodynamic purposes. A single roughness protrusion may trip a boundary layer while a recess of equal value may have no effect. An element of roughness in one location may have a more or less disturbing effect on the boundary layer than the same element in a different location. Furthermore, two surfaces with completely different roughness form or shape may have the same peak-to-valley height but considerable different disturbance effects on the laminar boundary layer. Therefore, until more is known about the effects of surface roughness, surface designation should ideally include the height, shape, spacing, and location of the roughness elements. In addition, or when some of this information is lacking, it would be helpful in many cases to include a description of the procedure used to prepare the surface since presumably a careful duplication of the procedure will duplicate the type of surface.

The instrument used for measuring roughness should preferably not touch, mark, or destroy the surface; it should be capable of measuring large as well as small roughness heights; and, for most general application, it should measure large as well as small objects, flat as well as curved pieces. No single technique will satisfy all of these requirements, but by a combination of techniques to be described in later sections of this report, many of these objectives can be met.

Polishing Procedures

One of the first considerations in polishing is the material to be polished since all materials do not polish equally well. It is commonly agreed that a hard material can be polished to a better finish than a soft material. However, for aerodynamic test models the model material may be dictated by other considerations than surface finish. The models used in the Ames supersonic free flight wind tunnel are usually made of aluminum alloy. Thus most of the procedures and photographs which are part of this report have been developed and obtained with aluminum alloy materials and it is of some interest to note that relatively good surfaces can be obtained even with this material, subject to certain limitations which will be brought out in a later section.

For the models first used, surface roughness was measured with a stylus-type measuring instrument. This device traces across the surface with a sharply pointed stylus and the up and down movements of the stylus are recorded greatly magnified on a graph. Data from these models indicated that random differences in mean transition location existed for supposedly nearly identical models showing that the influences of roughness had not been well controlled. Examination of some of these models with a metallurgical microscope showed that the polishing had been superficial. Machine marks were in many areas still evident; the polishing had altered the basic roughness by very little but had made the surface shiny to the eye. Further examination showed that the groove made by the stylus of the measuring instrument wiped out the scratches made by the polishing abrasive (see fig. 4 of ref. 2), indicating that the instrument was not measuring any except the largest elements of the roughness.

After a study of polishing or finishing procedures along with some experience, the following procedure was adopted to finish the models: Each model is finished either by hand or with the aid of mechanical devices to give relative motion between the polishing abrasive and the test surface. The grade of the abrasive is changed progressively from coarse to fine. After each grade of abrasive, the direction of polishing motion is changed. This speeds up the cutting action of the abrasive but, more important, makes it easier to determine when scratches from the prior abrasive used have been removed. It must be emphasized that scratches from a previous step must be removed before starting on the next step. Abrasive papers and cloths are changed frequently and never reused. As a matter of good practice, models are handled only with lens paper even during the rough or preliminary polishing. After each polishing step, models are washed with an absorbent cotton swab saturated with either alcohol or distilled water. (No evidence has been found that wet cotton will scratch aluminum.)

Although a dust-free atmosphere would be desirable, it has not been found to be essential. Proof that dust particles mix with the abrasive or that the dust particles are larger than the abrasive particles has not been evident although it has been suspected a few times. The polishing described herein was done in a rather standard engineering office with asphalt tile floor, a wall of windows, and conventional forced air heat and ventilation system.

The final finishing step determines the character of the surface. Polishing in one direction gives two-dimensional roughness which is sometimes desired in fundamental boundary-layer investigations, although care must be used in applying the polishing pressure uniformly to minimize the amount of surface waviness. In the small models involved (under 3 inches in diameter and 12 inches in length) it has not been difficult to keep the surface waviness small.

On some of the small-scale models tested, it has been found of great importance to have symmetrical nose tips and leading edges without abrupt changes in slope (ref. 2). To achieve this condition the model is inspected very carefully in these regions. If it is necessary to reshape the nose tip, for example, it is done with the polishing abrasive while viewing the model through the microscope. Since the surface area at the tip is relatively small, very little actual effort but considerable care is required to remove the objectionable asymmetry. The desired shape of these areas may also dictate the type of polishing abrasive to use, either paper or cloth. The finest abrasives are applied with a cloth which can provide a smoother finish than paper. However, the use of cloth will usually result in rounding off tips or edges, which if objectionable, might dictate the use of paper at a sacrifice to the surface smoothness. After a surface has been prepared, considerable care is required to insure that the surface roughness is not changed prior to the ultimate testing of the surface. Surfaces may change as a result of careless handling or corrosion effects, or erosion during testing.

Inspection of Surface Roughness

Although quantitative measurements of the roughness elements are the ultimate goal of any investigation of surface roughness, the procedure for inspecting the surface during and after surface preparation will be considered first since this procedure determines to a large extent the reliability of the quantitative measurements. Every individual element of roughness present on a surface obviously cannot be measured, hence areas must be selected for measurement which represent closely the vastly greater unmeasured areas. Careful inspection during the preparation of the surface insures obtaining a uniform surface from which a few spot check measurements will adequately describe the surface. If the surface is not uniform, of course, the spot check procedure will not be adequate.

Microscopic inspections were found to be necessary for both qualitative and quantitative control. Models are usually inspected with a low power microscope (100X or less) or an optical comparator (an optical device differing from a microscope for this purpose only in having a greater working distance and larger field of view than a microscope) during the preliminary polishing and often during the final polishing. This relatively low power is usually adequate to determine whether or not scratches from a coarser grade of abrasive have been removed by the succeeding finer grade. After the final polishing, examination is made by means of a metallurgical microscope ranging in magnification from 100X to 2000X. The metallurgical microscope differs from other microscopes mainly in having an internal illuminator which permits the light to be directed normal to the surface being examined. Most of the examination is done at magnifications below 500X. For conventional dry objectives the maximum practical magnification for direct inspection is on the order of 500X. Higher magnification provides no more information since the resolution is dependent on the numerical aperture (N.A.) and the wave length of the light used for illumination. Since examination of an entire model surface is not practical at high magnification, most of it or representative areas are inspected with a low power microscope and areas are selected for higher magnification inspection and measurements. In addition to the visual inspection with the microscope, photomicrographs are taken of the surfaces and nose profiles. This provides a record that can be used to compare surface characteristics and nose shapes of different models. Figure 1 shows a group of photomicrographs showing different degrees of surface finish.

Measurement of Surface Roughness

Among the various methods for measuring surfaces which are described in the literature (Thielsch in ref. 3 gives the major optical methods), several are of particular interest: microscopic examination, the interferometric method, optical sectioning, replica techniques, mechanical sectioning, and the stylus-type measurement. None of these methods will prove advantageous for every case; that is, the method selected will depend on the particular job for which it is to be used.

Microscopic examination.- In addition to its use for qualitative control of the surface during preparation, the microscope can be used for quantitative measurements of width, length, spacing, and location of the roughness elements, and it gives an indication of the height and the shape of the elements. The latter two parameters are obtained by focusing on the peaks and depressions in turn and noting the direction and vertical distance traveled by the microscope tube. The precision of height measurement is dependent on a short depth of focus relative to the roughness height. In cases where the roughness can be seen in profile, either the microscope or the optical comparator can be used to obtain the height and shape of the roughness elements. For example, the screwthread models of reference 2 were measured with the comparator. The range of roughness height in this case was from 0.0002 to 0.0010 inch. Wade in reference 4 subsequently used the comparator to measure V-shaped roughness from 0.003 to 0.010 inch in height. It must be kept in mind, however, that the microscope alone as a measuring device will not always reveal irregularities on the surface. This will be shown later in the case of a relatively deep scratch which was not readily detectable on an otherwise smooth surface.

Interferometric method.- The multiple-beam interferometer will measure a relatively smooth and reflective surface in a roughness height range of 0 to 20 microinches. The interferometer (see, e.g., ref. 5) consists of a metallurgical microscope, a monochromatic light source (e.g., a mercury vapor lamp and green filter), and a partially coated mirror (of about 70-percent reflectivity). To use this equipment as an interferometer, the mirror is placed on or very close to the surface to be examined. The monochromatic light is directed into the internal illuminator of the metallurgical microscope, and through the objective lens to the mirror and surface. Part of the light is reflected from the mirror toward the eye; the rest, neglecting absorption, is transmitted to the surface and from it reflected back to the mirror, where again part is reflected and part transmitted to the eye. The difference in the length of the optical path of the two beams - one reflected from the mirror surface and the other from the model surface - causes interference. When the path difference is any multiple of the wave length, reinforcement of the light takes place, and for multiples of one-half the wave length, annulment takes place and no light is visible. This results in the production of interference fringes (see figs. 2 and 3). The multiple reflections control the relative width of the light and dark fringes. Large numbers of reflections give fine line fringes which can be read more precisely than fringes of equal width. The reflectivity of the interference mirror should closely match that of the surface for maximum fringe contrast and definition. As the reflectivity of the model and the interference mirror increase, definition and contrast improve. Since the field of view of the microscope is small, the area of the mirror actually in use is small, so that curvature of the mirror is not objectionable.

When green light of a wave length of 5461 Å is used, each fringe denotes a change in elevation of the surface relative to the mirror of 10.75 microinches. The fringe pattern obtained represents a contour map of the surface with respect to both curvature and roughness or irregularity, and the roughness can be measured insofar as the resolution allows. Roughness greater than 20 microinches usually cannot be measured because in areas where the slope of the roughness is large, the fringes will appear to run together and will be indistinguishable from one another. If a greater magnification were used, the spacing between the fringes would be greater and the range of roughness which could be measured might be increased somewhat. The magnification used is limited by the thickness of the interference mirror which sets the minimum working distance of the objective lens used.

Interferograms of the smoother surfaces shown in figure 1, namely (a), (b), and (c), are shown in figure 2. This figure shows fringe patterns from three cylindrical aluminum surfaces. In the interpretation of these patterns the fringe shift or deviation of a fringe from its mean line is indicative of the roughness. For example in (a), the fringes, in general, shift no more than a fourth of the width between fringes. This then indicates roughness of a fourth of the half wave length of green light (5061 Å) or approximately 3 microinches. For the cylinders used for these pictures it is simple to distinguish between holes and protrusions on the surface. The change in the actual spacing of the fringes denotes the curvature of the cylinder so the widest separated fringes are closest to the mirror. A fringe shift in this direction then denotes a depression, and a shift away indicates a raised portion. The presence of pits is indicated in figure 2(a) and the largest one seen is in the order of 10 microinches in depth. In the photomicrograph of this particular surface (see fig. 1(a)), these pits appear as well as inclusions in the aluminum alloy. It is believed these pits were caused by excessive pressure used in polishing, the inclusions being pulled from the metal by the abrasive. Quite frequently inclusions appear as protrusions on the surface. In figure 2(c) the difficulty mentioned in following fringes is demonstrated. In some areas the fringe shift can be followed only through two fringes thereby indicating the roughness somewhere close to but in excess of 20 microinches.

As previously mentioned, a microscope when used alone may fail to indicate presence of roughness. Figure 3 shows an interferogram and a photomicrograph of an 80-microinch deep groove. The groove, readily indicated in the interferogram, runs vertically through the pictures and has an apparent width of about 1.35 inches at 260X, indicating a true width of about 0.005 inch. The photomicrograph, however, does not readily reveal the presence of the groove. It was visible to the eye but difficult to find with the microscope, except when the interferometric method was used.

Optical sectioning.- The oblique shadow method was described by Tolansky in reference 6. The internal illuminator of the metallurgical microscope is modified to project a line shadow. A line shadow cast obliquely on an irregular surface will create an irregular shadow whose irregularity amplitudes will depend on the roughness height and the obliquity of the angle of projection. Calibration of the lens system is required to determine the angle of projection. The lens system was calibrated by measuring the deflection of the wire shadow across a rod of small diameter. Since the magnification of the system and the diameter of the rod were known, the amount of curvature of the rod in the field of view could be calculated. The calculated curvature in comparison with the observed curvature then calibrates the angle of the shadow. A correction had to be made for apparent curvatures of the wire shadow when cast on a flat surface. This is believed due to the curvature of the objective lens. Consequently, the curvature of the wire shadow in the pictures shown herein should not be interpreted as actual curvature of the surface. It should be mentioned that another wire shadow method described in reference 7 and using the same principle is perhaps more versatile than the one employed here. This method uses a separate projection assembly to project an oblique shadow of a straight edge or slit. The method has advantages in calibration but suffers from mechanical interferences and focusing problems at high magnification.

Wire shadow photomicrographs are shown in figure 4. The measurement of the height of surface irregularities is obtained by measuring the deflection of the wire shadow on the photomicrograph, dividing this by the magnification to obtain the actual deflection, then multiplying this by the calibration factor. At the magnification of 1060X, the factor for the system is 0.8. Whether a deflection indicates a depression or a raised portion cannot be determined from the pictures unless the direction of the light incident in the surface is specified. The light direction projected onto the plane of the surface has been indicated on the prints in figures 4 and 6. A deflection of the shadow in the same direction as the light indicates a depression.

Replica technique and mechanical sectioning.- The replica technique consists of obtaining an impression of the model surface with a casting material. This replica is then examined with an electron microscope and a shadow-casting technique. As pointed out in reference 3, the electron microscope has great advantages over optical instruments in magnification, resolving power and depth of focus. This method may be able to cover the full range of surface roughness. The disadvantages to this method are principally that special skills and expensive equipment are required.

In mechanical sectioning, described more fully in reference 8, the surface to be examined is coated for protection and then cut to provide a cross section which, after being ground and polished, is inspected by microscope. Slicing obliquely through the specimen allows the surface irregularity to be mechanically magnified. This method provides a record of the surface contour of a representative sample. The disadvantages are that considerable care is required in preparing the specimen and the surface examined is destroyed.

Stylus-type measuring instrument.- A stylus-type measuring instrument traces across a surface with a stylus which is displaced as it passes over the roughness elements. (This type of instrument has been investigated in reference 4 where instruments of four different manufacturers were used and compared.) The movements of the stylus are amplified and recorded on a meter or graphically on a chart. Stylus instruments are unsatisfactory for very smooth surfaces. The stylus tip marks the surface and in fact frequently produces a scratch larger than those to be measured. This instrument would be useful, however, for measuring larger roughness, or for measuring surface waviness where the stylus scratch would not be objectionable. Some calculations and physical measurements were made in the hope that the particular instrument used to reach these conclusions had been faulty in some respect. The findings, instead, indicated that the weakness of the instrument is a fundamental one and is a combined geometry and stress problem. Figure 5 shows the theoretical width and depth dimension of a groove that would be made on smooth surfaces of high strength alloys of steel and aluminum for various stylus diameters with a constant stylus force of 1 gram. The depth of the groove is expressed by the equation

$$h = \frac{F}{\pi d \sigma}$$

where F is the stylus force, d is the stylus diameter, and σ is the yield point stress of the material involved. The width of the groove is

$$w = 2\sqrt{dh-h^2}$$

but since h is small compared to d, the h^2 term can be neglected. Combining equations gives

$$w = 2\sqrt{\frac{F}{\pi\sigma}}$$

These equations show that although the depth of the groove can be made negligible by changing the force or the diameter, the width is not affected by a change in the diameter. It is affected only by the square root of the change in the force. Comparison of the aluminum and the steel curves (yield points of 60,000 and 180,000 psi, respectively, chosen for convenience) gives indication of how the stylus might respond on a material which is nonhomogeneous and contains inclusions (typified by the steel) considerably harder than the parent material (aluminum alloy). The stylus would be expected to rise and fall in response to variations in hardness as well as roughness.

Calculations of the stylus penetration were supported by measurements obtained by optical methods. Figure 6 shows pictures of four stylus grooves made on an aluminum surface. The photomicrograph and the interferogram, (a) and (b), show the stylus grooves running horizontally across a diagonal scratch which is of varying depth but is in the order of 30 microinches deep at the place where the stylus traced over it. The interferogram shows that the stylus did measure the depth of the diagonal scratch. This is not surprising since the width of this particular scratch is large compared to the depth and will accommodate the stylus dimension. The wire shadow photograph of this pattern, figure 6(c), is rotated 90° so that the stylus traces run vertically. The top stylus scratch in (a) and (b) is the one at the extreme right in (c). The wire shadow displays ridges on either side of the stylus grooves. By a careful measurement, the grooves are found to be approximately 24 microinches in depth, which is the depth of groove indicated by the calculation for a stylus tip diameter of 0.0005 inch with a contact force of 1 gram.

CONCLUDING REMARKS

For aerodynamic experiments in which surface roughness is a significant variable, particularly boundary-layer-transition experiments, there is a need for very great care in preparing the surface and quantitatively determining its character after preparation. Methods have been described and discussed for accomplishing the preparation and measurement of surfaces. The relative usefulness of these measurement techniques depends on the particular application.

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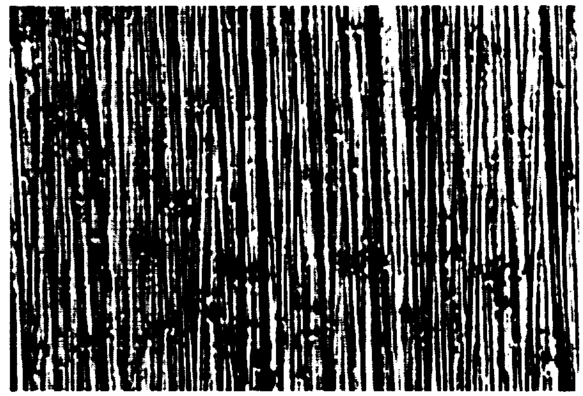
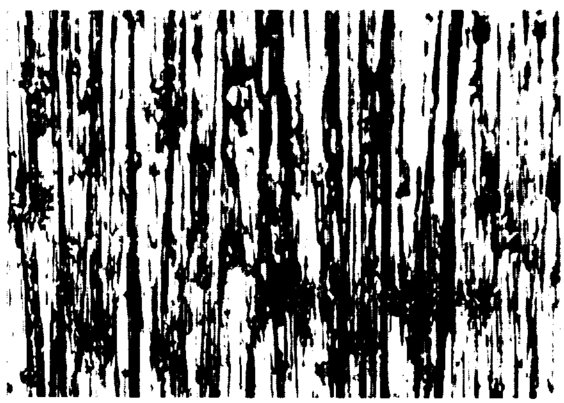
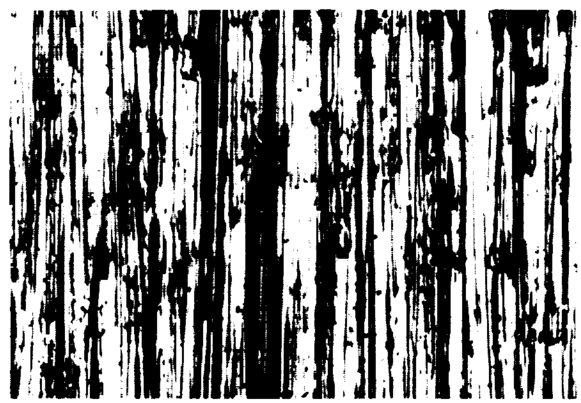
(a) Diamond polishing compound, 1-micron size; 200X.



(b) 4/0 emery polishing paper; 260X.



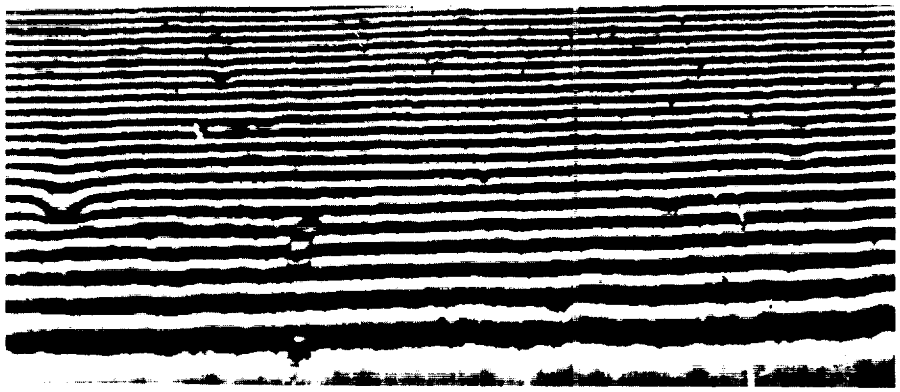
(c) 600 silicon carbide abrasive paper; 260X.



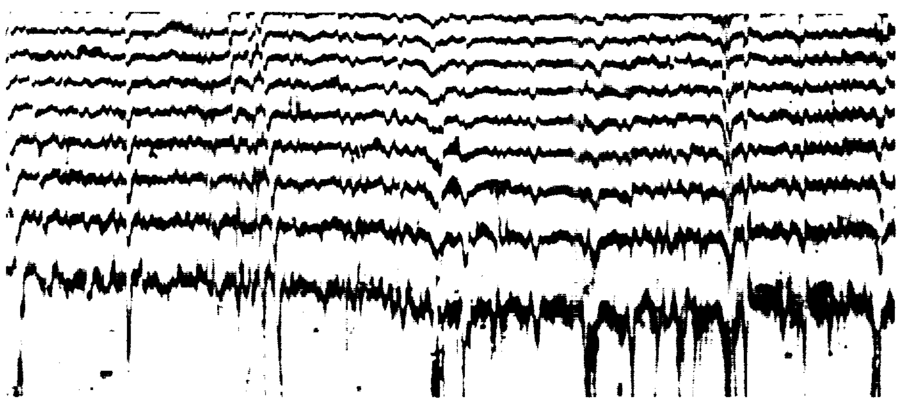
(d) 400 silicon carbide abrasive paper; 260X.

(e) 320 silicon carbide abrasive paper; 260X.

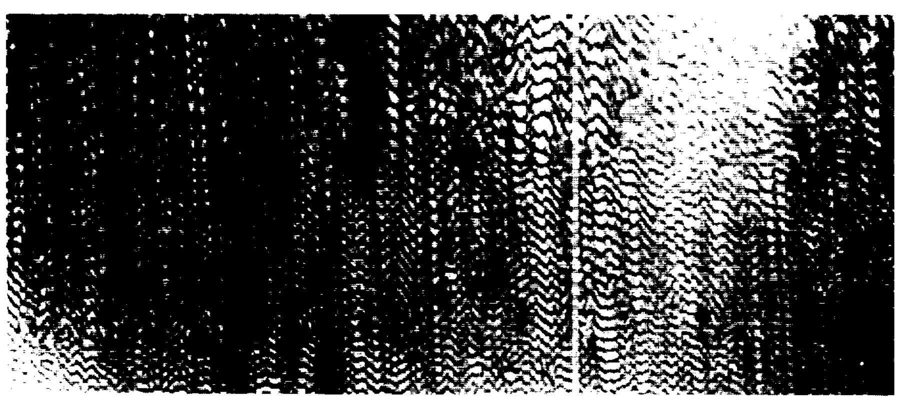
Figure 1.- Photomicrographs of different surface finishes on an aluminum surface.



(a) Diamond polishing compound, 1-micron size; 200X; roughness range 1-3 microinches.

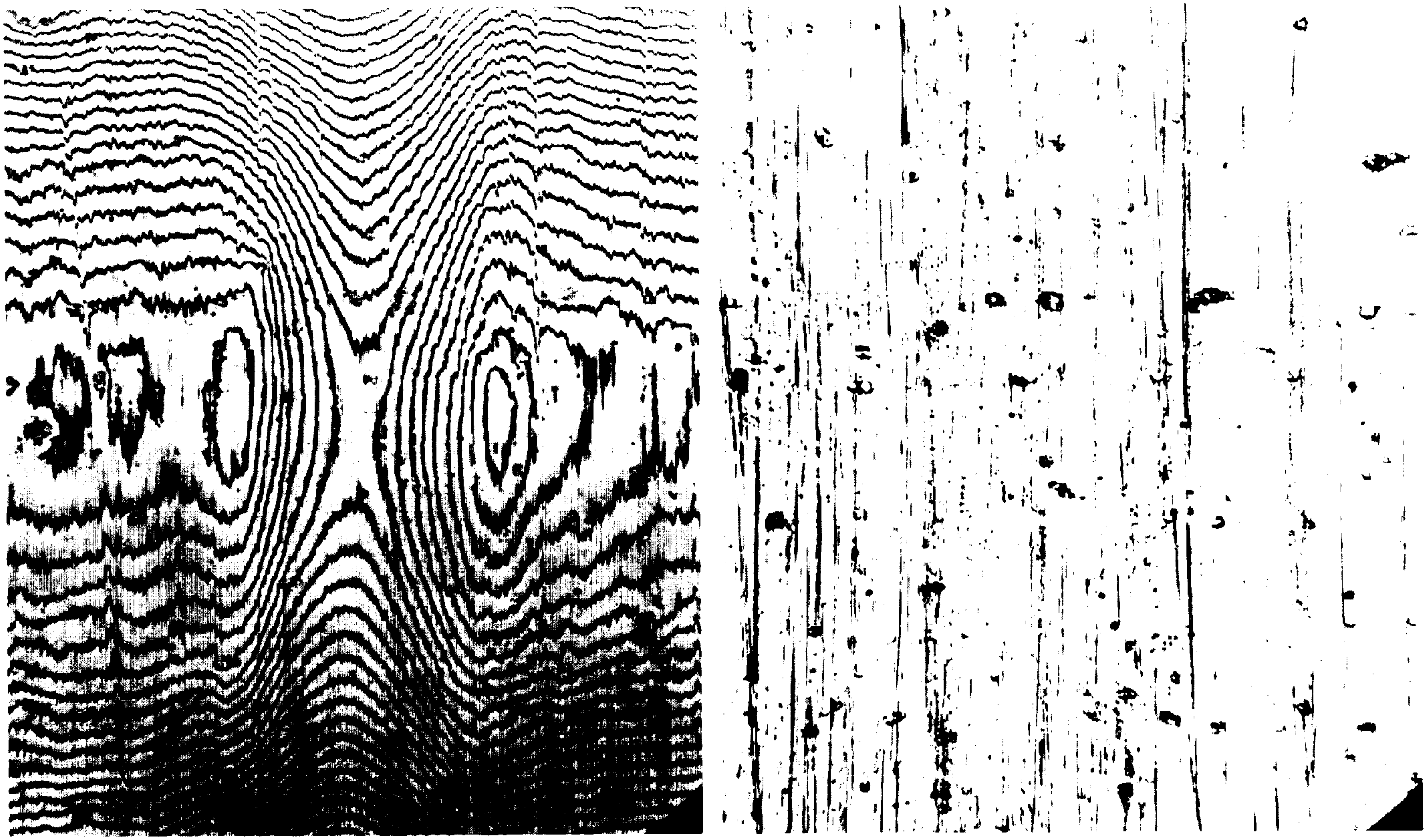


(b) 4/0 emery polishing paper; 260X; roughness 3-6 microinches.



(c) 600 silicon carbide abrasive paper; 260X; roughness undetermined except greater than 20 microinches in some areas.

Figure 2.- Interferograms.



(a) Interferogram. (b) Photomicrograph.

Figure 3.- 80-microinch-deep groove; 260X.

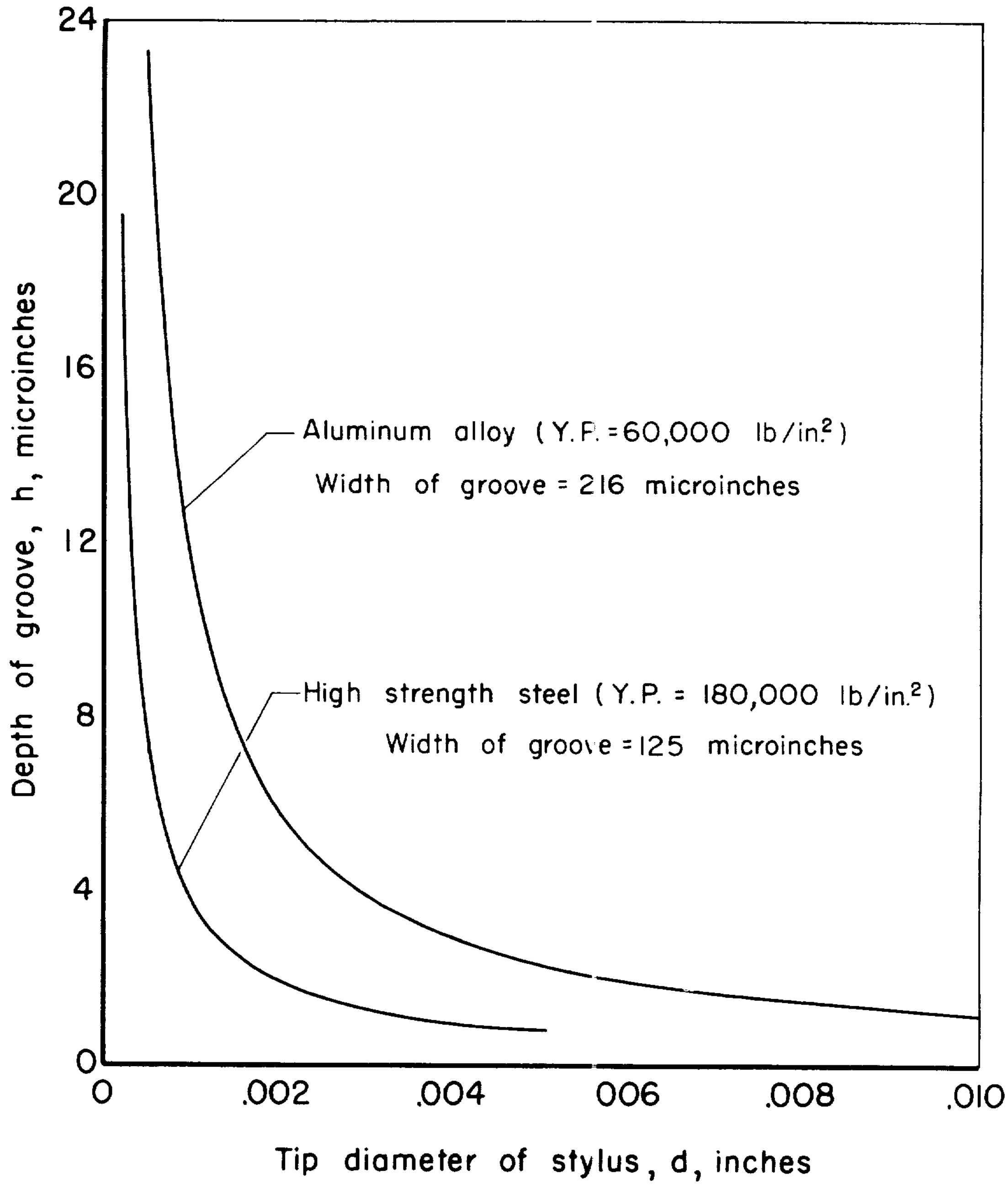
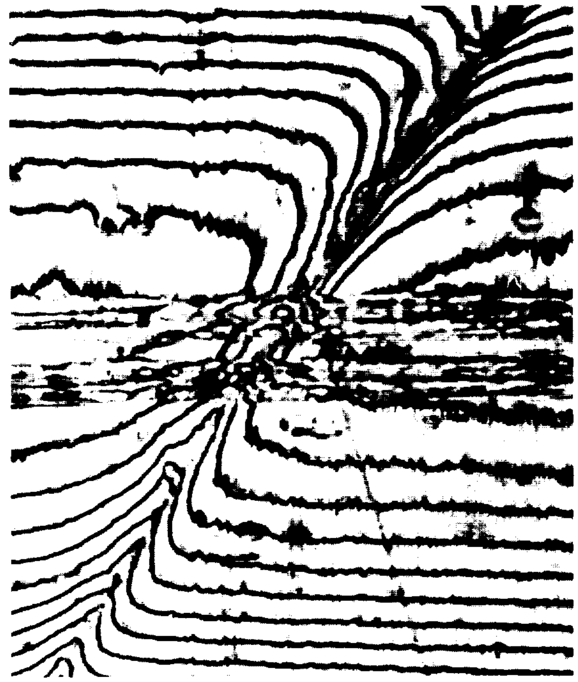


Figure 5.- Depth of groove which would be made by styluses of various diameters with a bearing force of 1 gram on aluminum and steel.

(a) Photomicrograph; 260X.



(b) Interferogram; 260X.

(c) Wire shadow photomicrograph; 1700X. (Arrow indicates direction of light.)

Figure 6.- Stylus grooves across a 30 microinch scratch. Depth of stylus grooves 24 microinches.