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EVALUATION OF THE FINISH OF A METAL SURFACE BY A REPLICA METHOD

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ABSTRACT

A method for evaluating surface finish through the medium of a nearly transparent plastic replica of a surface is described. The method consists essentially in passing a narrow beam of light transversely through the moving replica onto a photoelectric cell. Variations in the geometric characteristics of the film, which are associated with the serrations of the surface reproduced, control the intensity of the light passing through the film and reaching the photocell at any instant. The fluctuations of intensity of the transmitted light cause a pulsating voltage in the cell circuit, which is recorded by an electronic voltmeter. This voltage increases with increased surface roughness. The evaluations obtained by this means are very promising. Results for different surface finishes are correlated with profile measurements of the surface determined with the microscope.

CONTENTS

I. INTRODUCTION

During the past decade, great advance has been made in the art of mechanically finishing surfaces, especially of metal objects. In a large measure, this can be attributed to studies in which hitherto unknown correlations of mechanical and physical properties of metals with the character of their surfaces were revealed. Despite this progress and the development of means for closely controlling the type and degree of finish, the modes of specifying and designating them with particularity have not been developed sufficiently to be universally acceptable to industry. The importance of such specifications may be gleaned from the extensive study and discussion of this subject since 1930 by the ASA Sectional Committee (B–46) for the standardization of classification and designation of surface quality [1],[1] sponsored by the American Society of Mechanical Engineers and the Society of Automotive Engineers, under authorization of the American Standards Association. This subject also constituted a major phase

[1] Figures in brackets indicate the literature reference at the end of this paper.

of a broad investigation of surface finish reported by the Institution of Production Engineers (England) [2].

Two essentials for the specification of a surface finish are [1] the qualitative factors, such as distribution and orientation of surface irregularities and defects and [2] the quantitative aspects, which are concerned with the exact depths and spacings of surface irregularities, as well as with the trueness of the surface. Way [3] has described the principal qualitative and quantitative methods for studying surface finish. In addition, he has summarized their salient features, limitations, and disadvantages.

Any device for evaluating surface finish to be acceptable to industry must perform accurately and rapidly, be reasonable in cost, and yield reproducible results. Because of the widespread interest and importance of this subject, the National Bureau of Standards has investigated the application of nearly transparent surface replicas for evaluating surface finish. This study has resulted in the development of a method for evaluating the finish of a surface through the medium of a properly prepared replica of the surface. It is believed that this method offers considerable promise in connection with specifications and standards for surface finish.

II. APPARATUS AND PROCEDURE

This method of surface analysis is based on a rapid and accurate method for preparing a nearly transparent facsimile of the surface to be evaluated. The fidelity of reproduction of minute surface characteristics in replicas consisting of a thin film of a suitable plastic is attested by the fact that such replicas are used in the study of metal microstructures at high magnifications with the electron microscope [4, 5].

The plastic replica of a surface may be produced by different means. In this study it was prepared by applying a suitable solvent to the metal surface, after which a strip of clear plastic film was pressed on. The solvent softened the side of the film adjacent to the surface being examined and permitted it to flow and conform under pressure to the minute surface irregularities. The film dried in about 1 minute and then was stripped readily from the surface. This general procedure for producing replicas of surfaces was brought to the attention of the writer by McDill [6]. In the present study, the solvent used was composed of 80 percent toluene and 20 percent acetone. The plastic was a preformed film of ethyl cellulose, 0.005 inch thick by 1.5 inch wide. In some experiments, an oil-soluble dye was added to the solvent to develop greater detail of the surface serrations [7]. The dyes used were National "Nigrosene B" (black) and National "Oil Red O." The film was pressed on with a special roller of pliable rubber. Characteristic details of replicas produced in this manner are illustrated in figure 1.

Examination of these replicas showed, as was expected, that the degree of transparency decreased with increased roughness of the original surface. However, of greater significance was the fact that the rougher the metal surface, the more pronounced became the variation in the geometry of the reproduced pattern. This fact led to the development of an apparatus for evaluating surface roughness, based on the

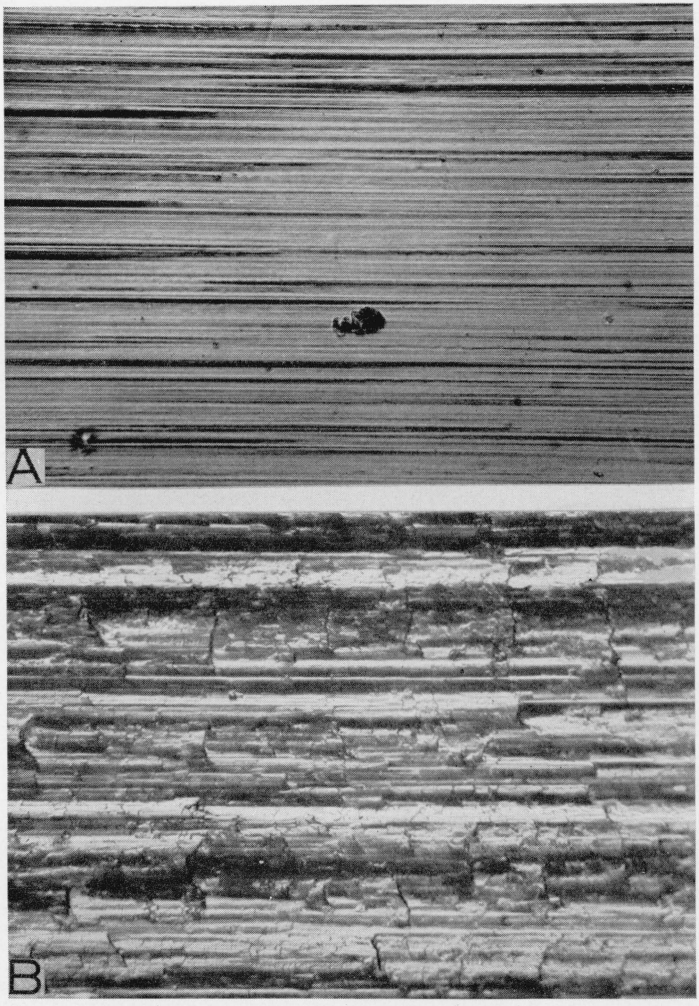

FIGURE 1.—*Micrographs obtained from plastic replicas.*

A. Finely ground surface; *B*, coarse-shapered surface. Photographed with transmitted light. Magnification ×100.

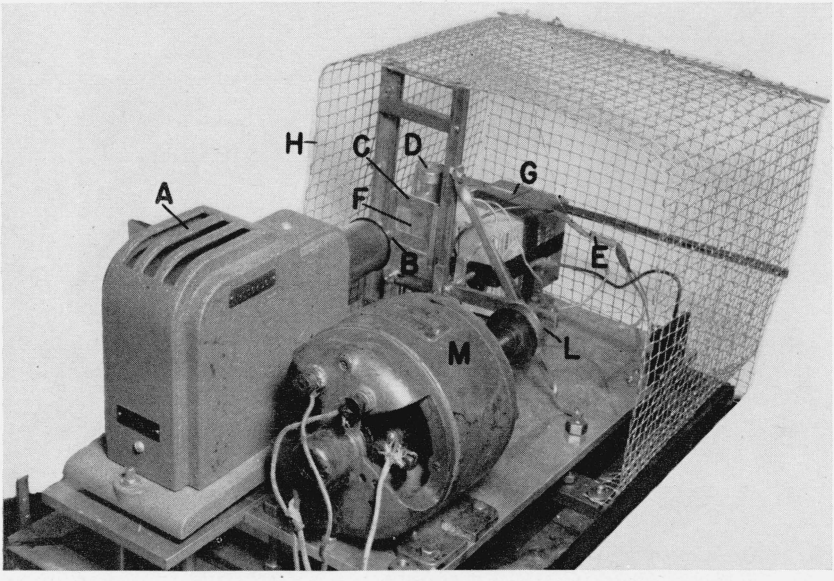

FIGURE 2.—*"Replica" surface analyzer developed at the National Bureau of Standards.*

A, Light source; *B*, condensing lens; *C*, frame for holding replica of surface finish; *D*, photoelectric (cesium) cell; *E*, 5-megohm resistance; *F*, replica; *G*, 90-volt B, battery; *H*, screen for shielding out stray currents *L*, cam and lever for actuating frame *C*; *M*, motor for driving cam and lever *L*.

degree of variation of the geometric characteristics in a nearly transparent replica.

The apparatus is illustrated in figure 2. Basically, its operation consists in passing a restricted beam of light from light source *A* through an oscillating test replica, *F;* thence onto a photoelectric cell, *D*, thus causing a pulsating current from the 90-volt battery, *G*, to pass through a resistance, *E*, connected in series with cell *D*. The voltage drop across resistance *E* is measured with an alternating-current electric voltmeter (fig. 3). The light striking the cell causes

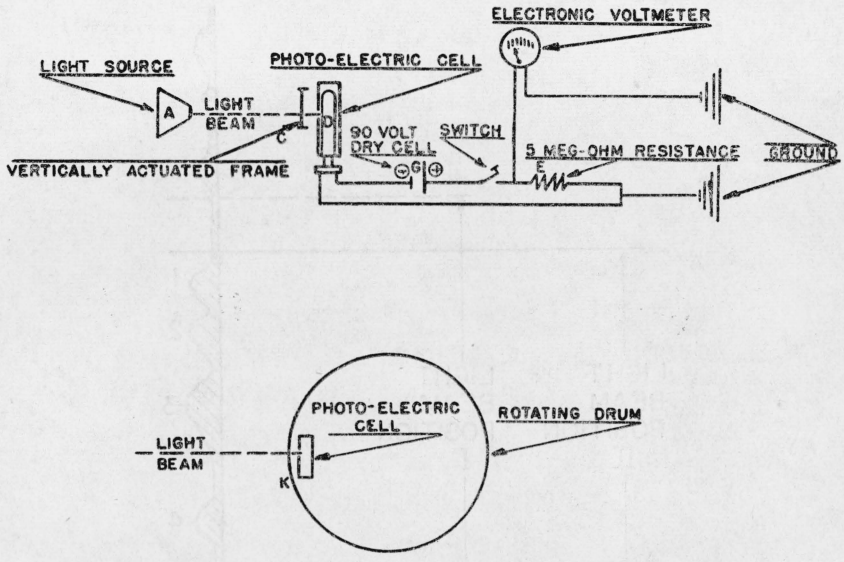

FIGURE 3.—*Electric circuit of the "replica" surface analyzer developed at the National Bureau of Standards.*

The rotating drum, *K*, may be substituted for the vertically actuated frame, *C*, to accommodate extra-long replicas.

a photoemission of electrons from the cell cathode to the plate, thereby closing the circuit and permitting the current to flow through the system, which is diagrammatically illustrated in figure 3. If the intensity of the light striking the cell does not vary, a constant direct current will flow in the circuit, which will not register on the alternating-current voltmeter. However, the light transmitted through the oscillating replica is of variable intensity because of differences in the geometric characteristics of the replica from area to area scanned by the beam, as illustrated in figure 4. These fluctuations of intensity of the transmitted light cause a corresponding variation of electron transmission, which produces a pulsating voltage. Since resistance *E* is constant, the voltage drop is a measure of the current passing through resistance *E*. This current, which is related to the degree of variation of the intensity of light passing through the moving replica, increases as the variations of the geometric characteristics of the different areas of the replica become more pronounced, or in other words, as the degree of roughness of the reproduced surface increases.

It is by reason of this correlation that the roughness of a surface may be evaluated by the "replica" method described. The voltage readings may be calibrated in terms of profile "peak to valley" values of the surfaces, determined with the microscope on the original specimens (fig. 7).

A diagrammatic sketch of the device, illustrating details of the electric circuit, is shown in figure 3. Since the magnitude of the current passing through the circuit is very small and the electronic

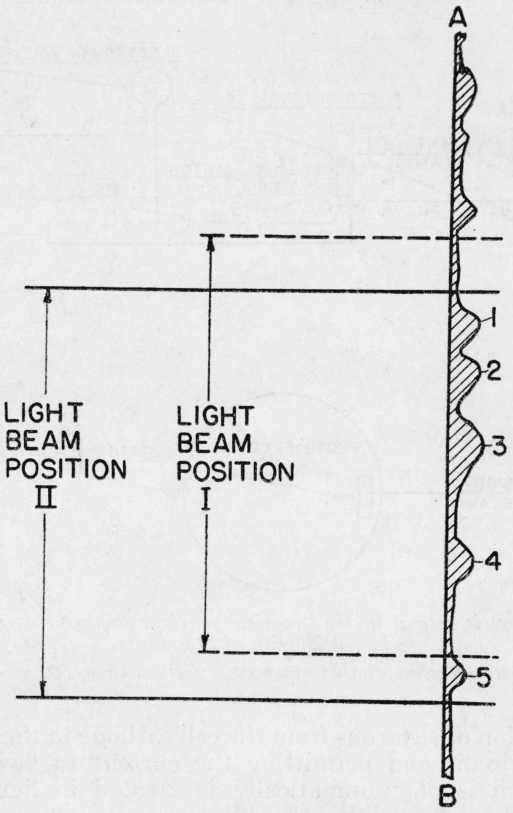

FIGURE 4.—*Example of the manner in which changes occur in the intensity of light transmitted through a moving replica.*

AB represents a section of a replica of a surface finish showing the profile contour. The number and nature of the irregularities included within the limits of the beam in positions I (sections 1, 2, 3, and 4) and II (sections 1, 2, 3, 4, and 5), respectively, differ, and therefore the transmitted light reaching a fixed area, such as the slit of a photoelectric cell, will differ in the two cases.

voltmeter is extremely sensitive, precautions were taken to shield out extraneous currents. This was accomplished by enclosing the apparatus within the properly grounded wire screen, *H*, illustrated in figure 2.

The area of the replica covered by the scanning beam for a single setting is controlled by two factors: (1) The condensing lens, *B* (fig. 2), and (2) the total length of travel of the replica, *F* (fig. 2). The lens limits the width of the beam at the area of contact with the replica. The length of the area covered by this image during a test is

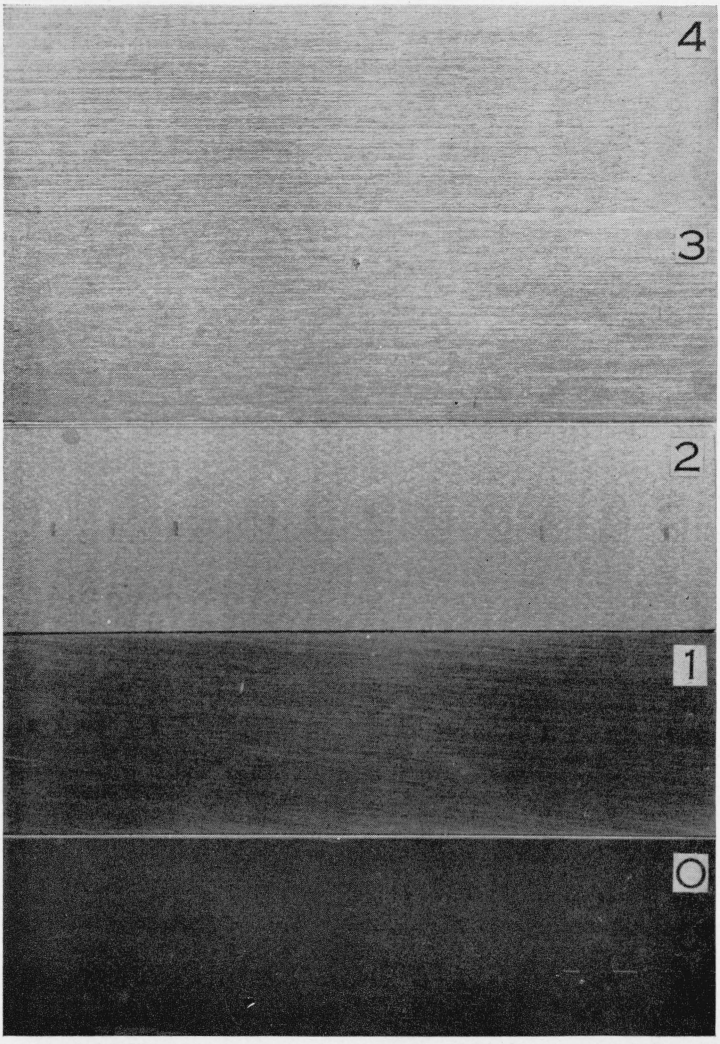

FIGURE 5.—*Characteristic appearances of surfaces of test specimens, photographed by reflected light directly from the specimens; magnification* ×1.

Specimen	Type of finish	Average "peak to valley" profile depth (microscopic section) [a]	Average profile evaluations (RMS)	Replica surface analyzer evaluation diaphragm *B* [b]
		in.×10^{-6}	*in.*×10^{-6}	*mv*×10^{-1}
0	Polished	11	1.5	8
1	Lapped	28	4	16
2	Fine-ground	46	7 to 11	25
3	Fine-shapered	320	65 to 70	54
4	Coarse-shapered	720	150 to 170	92

[a] Eac value is the average of 50 to 60 determinations made on 3 sections of each specimen.
[b] Diaphragm *B* consisted of an alinement of 10 holes, each about 0.05 in. in *diameter*, with centers spaced approximately 0.12 in. apart.

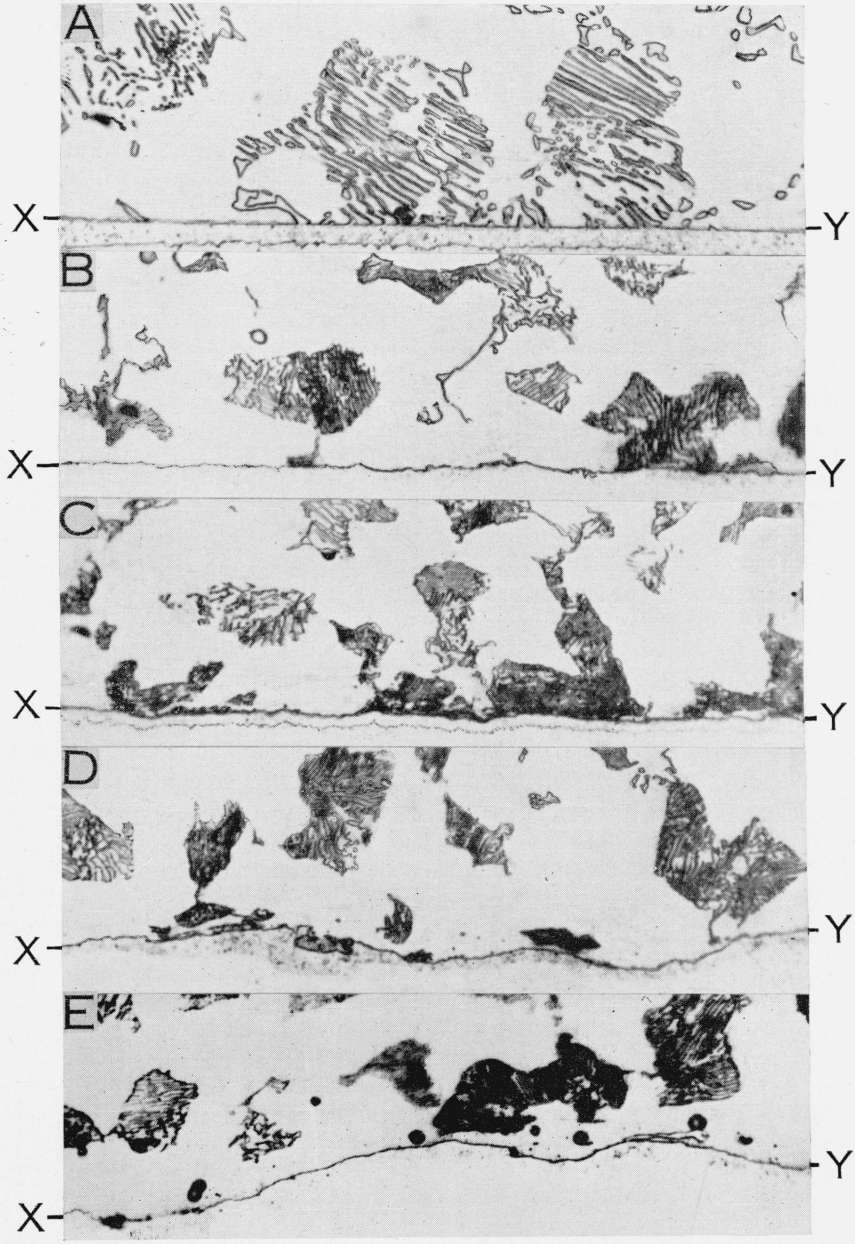

FIGURE 6.—*Micrographs of sections of the test specimen showing the contour of the profile (indicated by trace XY) of the surface of each.*

The edges were preserved by electroplating with about 0.0002 in. of copper and about 0.002 in. of nickel. Etched with 4-percent picric acid solution (in alcohol); magnification ×1500.
A, Polished surface; *B*, lapped surface; *C*, fine-ground surface; *D*, fine-shapered surface; *E*, coarse-shapered surface.

regulated by the setting of the eccentric and lever L (fig. 2). The shorter the focal length of lens B, the narrower the image. A 16-millimeter lens, which was found most suitable for the tests reported in this paper, produced a rectangular image about 0.2 inch wide by 0.01 inch high in one case and 0.2 inch wide by 0.004 inch high in the second case (fig. 7). The eccentric and lever were adjusted to permit a ¾-inch length of travel of the replica. Thus the dimensions of the area covered for a single test setting were about 3/16 inch by ¾ inch. In cases that require the analysis of exceptionally long surfaces, the rotating frame, K, (fig. 3) could be used for supporting the replica.

Two factors that influence the sensitivity of the test are the dimensions of the slit in the shield over the photoelectric cell D (fig. 3) and those of the diaphragm (not illustrated) inserted between light source A and lens B (fig. 2) to restrict the vertical dimension (height) of the beam of light projected through lens B. The optimum height of the light beam and of the slit in the cell shield is influenced by several factors, such as intensity of light source, type of diaphragm used, etc. In the present study the slit in the shield of the photocell was approximately 0.25 inch inch long by 0.03 inch wide. The diaphragms used are illustrated in figure 7. The height of the beam as revealed by the image formed on the test replica was about 0.01 inch.

Although the rate of oscillating the test replica influenced the current flow and therefore the reading on the meter, the rate was not critical.

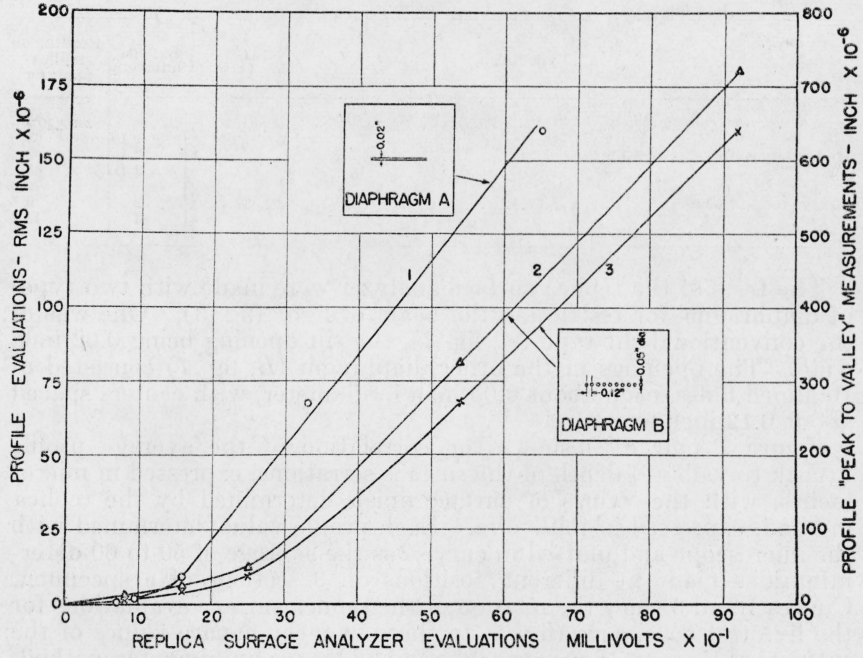

FIGURE 7.—*Curves showing relationship of "replica" surface analyzer evaluations to (1) profile "peak-to-valley" measurements determined with the microscope, and (2) profile evaluations expressed as root-mean-square values.*

Curve 1, replica versus profile evaluations (RMS)—approximately 0.02-in. wide slit diaphragm used on "replica" surface analyzer; curve 2, replica versus profile "peak-to-valley" measurements determined with the microscope; curve 3, same as curve 1, except diaphragm had alinement of 10 holes, each about 0.05-in. in diameter with centers spaced approximately 0.12 in. apart.

Thus, the maximum reading for each of the tests made was obtained within the limites of 200 to 300 oscillations per minute.

III. EXPERIMENTAL OBSERVATIONS AND DISCUSSION

In order to ascertain the practicability of the replica method for surface analysis, the five specimens shown in figure 5, which differed among themselves significantly in their surface roughness, were prepared. The characteristic contour of the profile for each specimen is shown in figure 6. Surface facsimilies made from each of these specimens by the use of both clear and dyed solvents were submitted to test on the "replica" surface analyzer (fig. 2).

Replicas containing dye had the advantage of revealing somewhat better the details of the metal surface than did those without dye. However, the results obtained on the surface analyzer with color-free duplicate replicas of the same surface were distinctly more reproducible. Typical results obtained on duplicate color-free replicas are given in table 1. Because of this reproducibility, the evaluations given in this report are based on results obtained with replicas prepared without dye. Nevertheless, the use of dye for this purpose appears to have merit and warrants further study.

TABLE 1.—*Typical results obtained on duplicate replicas, prepared without the use of dye*

Type finish	Replica number	Reading on replica analyzer
		$mv \times 10^{-1}$
Moderately course shapered finish	1A	63
	2A	62
	3A	65
Finely ground finish	1	9.6
	2	9.8
	3	10.0

The tests of the replica surface analyzer were made with two types of diaphragms for restricting the beam of light (fig. 3). One was of the conventional slit type (*A*, fig. 7), the slit opening being 0.02 inch wide. The openings in the other diaphragm (*B*, fig. 7) consisted of 10 alined holes, each about 0.05 inch in diameter, with centers spaced about 0.12 inch apart.

Figure 7 (curve 2) shows the correlation of the average profile ("peak to valley") depth of the surface serrations, expressed in microinches, with the values of surface finish determined by the replica method, expressed in millivolts. Each profile value determined with the microscope and plotted in curve 2 is the average of 50 to 60 determinations made at different positions on 3 sections of a specimen. Curves 1 and 3 show the relation of the replica surface evaluations for the five test specimens (fig. 5) to the root-mean-square values of the surfaces of these specimens, as determined by the profilometer method. Curves 1 and 3 show that the rate of change of the values secured on the replica surface analyzer for the same differences in surface roughness was greater with diaphragm *B* than with *A*. The curves in figure 7 indicate that the replica method of surface analysis is especially sensitive to small changes in surface roughness for the finer grades of

finish. It is within this range that many of the conventional means for evaluating surface finish are not sufficiently sensitive.

The results reported should be considered as being strictly applicable to surface markings, which are approximately unidirectional. Further work is planned to ascertain the effect of orientation of surface markings on the evaluation of surface finish by the replica method.

Although the apparatus shown in figure 2 is relatively crude, it yielded very promising results. Even more promising results appear probable with the incorporation of certain other known types of slits, light sources, and means for scanning the film with the light beam. None of these was immediately available for the present study. The development of a suitable technique for using dyes in preparing these replicas may aid in further increasing the sensitivity of this method of surface analysis.

Some of the salient features of the replica method of surface analysis are (1) easy maintenance of a permanent record of a surface finish, (2) rapid average evaluation of a considerable length and width of surface at one setting, (3) simplicity of operation, (4) absence of the personal factor, (5) preservation of a surface, even for soft materials such as lead or tin-base bearing metals, and (6) availability of the method, since the replica may be prepared in one locality and transported to the location of the analyzer. This procedure might also prove useful in evaluating surfaces not readily accessible with present means for surface analysis. There are indications that the method described also may be applicable for evaluating the corrosion pitting of metals.

IV. SUMMARY

A new method for evaluating surface roughness is described, which involves the use of rapidly produced plastic replicas of variable transparency. Evaluations of surface finish made by this method on five specimens that differed significantly in degrees of finish were correlated with profile values of these surfaces determined by (1) the profilometer method (as root-mean-square values), and (2) the microscope on cross sections ("peak-to-valley" values). These data show that this replica method is especially sensitive for the evaluation of surfaces having high degrees of finish.

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