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DETERMINATION OF SURFACE FINISH QUALITY OF METALS BY MEANS OF OPTICAL METHODS*)

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R I N G K A S A N

Pengukuran kekasaran permukaan-permukaan logam biasanya dilakukan dengan menentukan harga rms. dari seluruh distribusi jarak dari lembah kepuncak beserta orientasi dari setiap faset yang membentuk kekasaran permukaannya. Pengukuran kebesaran-kebesaran ini secara mekanis dilakukan dengan mempergunakan profilometer. Akan tetapi, metoda ini terbatas untuk permukaan - permukaan yang ukuran kekasarannya lebih besar dari pada ukuran ujung jarum profilometer yang dipakai; lagipula metoda ini termasuk dalam jenis yang disebut "destructive testing". Tulisan ini menguraikan suatu alternatip dengan memakai metoda secara optis dan mempergunakan teori-teori Davies dan Beckmann. Instrumentasi yang dipergunakan ialah suatu Perkin-Elmer 621 Spectrophotometer dengan sistim sinar rangkap dan yang telah dimodifikasikan. Hasil-hasil yang diperoleh dengan mempergunakan berbagai jenis logam yang permukaannya

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telah dikasarkan secara sebarang memberikan kecocokan yang cukup baik bila dibandingkan dengan teori dan hasil - hasil eksperimentil yang ada hingga saat ini.

A B S T R A C T

Determination of surface - finish quality is done by measurements of its rms. values of surface roughness and slopes. Mechanical measurements of these properties are done by using a profilometer. This method, however, is limited to surface having asperities larger than the size of the profilometer's tip and is of destructive type of testing. Alternate techniques using optical method based on the theories of Davies and Beckmann are presented. The instrumentation used was a double - beam, modified Perkin-Elmer 621 Spectrophotometer. Results using several randomly roughened metallic surface show good agreement with the existing theory and experimental results.

INTRODUCTION

Surface finish inspection of many products has been mainly done by random sampling inspections. The results are expected to represent the quality of the entire production output of certain kind. Quantitative measurements of the surface finish is given by means of knowing the rms. values of surface roughness σ and surface slopes m. For randomly roughened surface, σ is defined as the standard deviation of the surface heights' distribution. The values of the surface slopes m's are defined similarly, but for the tangents of the local slopes.

Mechanical measurements of surface - finish are commonly done by using a profilometer. This instrument uses a fine diamond stylus moved across the surface and thus follows the contour of the surface undulations, and its up and down movements are electronically amplified and integrated. The readouts are either rms. (root mean square) or arithmatic value of the surface roughness distribution. The rms. surface slopes m's are in this case obtained through a relationship between σ's and the so called auto-correlation distance defined as the standard deviation of the statistical distance between the peaks of the surface asperities (7). Mechanical surface

roughness measurements, however, are limited to surfaces with undulations larger than the dimension of the profilometer's stylus. Moreover, this method is a destructive test in nature and is prohibitive in many applications.

Many precision type products, however, may require strict individual non-destructive type quality control inspection and more accurate techniques are therefore needed. Some examples of these products are, for instance, microminiature parts used in various gyroscopic components, various components used in the weapon systems, etc. The optical methods based on the theories of Davies (2) and Beckmann (3), can be developed into a more accurate method of surface finish inspection technique. Both theories can accurately calculate the rms. surface roughness, however, the application of Beckmann's theory to calculate the rms. surface slopes is still under continuing investigation with inconclusive results (4,5).

This paper presents two different optical methods to determine the quality of metal surface finish using a double-beam spectrophotometer. These methods have been successfully employed by Abdulkadir (4) and Abdulkadir and Birkebak (12).

THEORY

The theoretical models used to determine the surface roughness parameters are based on the assumption that the normalized bidirectional reflectance in the specular direction consist of a component contributed by the specular (coherent) reflectance and another component contributed by a diffuse (incoherent) term. Mathematically, Davies' theory is expressed as the spectral specular reflectance of any surface normalized by the spectral specular reflectance of polished surface of the same material, both taken at the same observation angle Ψ,

$$\frac{\rho_{s,\lambda}}{\rho_{sp,\lambda}} \simeq e^{-\left(\frac{4\pi \cos\Psi\ \sigma_o}{\lambda}\right)^2} + \frac{2^5 \pi^3}{m_o^2} \left(\frac{\sigma_o}{\lambda}\right)^4 \cos^3\Psi\ \Delta\omega \qquad (1)$$

where σ_o is the optical rms. roughness, λ is the wavelength used and $\Delta\omega$ is the solid angle of observation. Beckmann's theory for the same condition gives, as presented by Houchens and Hering (6),

$$\frac{\rho_{s,\lambda}}{\rho_{dh,\lambda}} \simeq e^{-\left(\frac{4\pi \cos\Psi\ \sigma_o}{\lambda}\right)^2} + f_{ic}\,\frac{\cos\Psi}{\pi}\,\Delta\omega \qquad (2)$$

where

$$f_{ic} = \pi^2\left(\frac{1}{\lambda}\right)^2 \exp\left[-\left(\frac{4\pi\ \sigma_o\ \cos\Psi}{\lambda}\right)^2\right] \sum_{n=1}^{\infty} \frac{\left(4\pi\ \frac{\sigma_o}{\lambda}\ \cos\Psi\right)^{2n}}{n(n!)} \qquad (3)$$

The specular reflectance has been normalized by directional reflectance $\rho_{dh}(\Psi)$ of the roughened material. The first term on the right side of equation (1) and (2) is the specular (coherent) term and the second is the diffuse (non - coherent) term. The relationship between 1, the autocorrelation distance between the roughness' peaks and m, the rms. value of the surface slopes, has been shown by Bennett and Porteus (7) to be

$$1 = \frac{\sigma_o}{m_o}\sqrt{2} \qquad (4)$$

The dimensionless parameter σ_o/λ is called the optical roughness, and is a measure of the relative value of the surface roughness with respect to the wavelength involved. As σ_o/λ becomes smaller, there is a wavelength region beyond which one is not able to distinguish the surface asperities and the surface looks smooth. In this situation one expects the specular term to be a dominant factor in both Davies' and Beckmann's equations. Inspection of both equations (1) and (2) verifies this observation, i.e. that their second terms can be neglected wrt. the first ones.

Therefore, for $\sigma_o/\lambda \ll 1$. Davies' equation simplifies to

$$\frac{\rho_{s,\lambda}}{\rho_{sp,\lambda}} \simeq \exp\left[-\left(\frac{4\pi\cos\Psi\ \sigma_o}{\lambda}\right)^2\right] \qquad (5)$$

and Beckmann's equation follows the same form. The normalized reflectance, $\rho_{s,\lambda}/\rho_{sp,\lambda}$ or $\rho_{s,\lambda}/\rho_{dh,\lambda}$, are obtained experimentally and will be discussed later.

Plotting $-\ln(\rho_{s,\lambda}/\rho_{sp,\lambda})$ and $-\ln(\rho_{s,\lambda}/\rho_{dh,\lambda})$ vs. $1/\lambda^2$, one has a set of straight lines from the origin with the slopes equal to $16\pi^2\cos^2\psi\sigma_o^2$. With each element known except σ_o, it can thus be easily calculated. σ_o is then used to calculate m_o. It can be seen, that for $\lambda << \sigma_o$, the specular term can be neglected with respect to the diffusion term in equations (1) and (2). The normalized reflectance of both Davies and Beckmann forms can thus be expressed only in their diffusion terms, and m_o can be easily derived.

INSTRUMENTATION

The experiment was conducted using a Perkin-Elmer Model 621 spectrophotometer. The instrument is of a double beam type and is capable of spectral measurements from 2.5 to 50 μm. The standard PE-621 spectrophotometer is usually employed to study the spectral transmittance or absorptance of any transparent material and also to do chemical composition analysis.

The optical diagram of PE-621 spectrophotometer is shown in Figure 1. A Nernst glower source output is divided into a sample and a reference beam. The sample beam passes through the sample compartment and the reference beam through an optical attenuator. Both beams are interrupted by a chopper, M7, which rotates at 13 cps. The chopper alternately transmits the energy from the reference beam and the sample beam toward a dual - grating monochromator (G1 and G2) through an entrance slit S1. The beams are dispersed into component frequencies and then focused on an exit slit. They then pass through a filter, as essentially monochromatic light, to a thermocouple detector. Any difference in the radiances of the sample and the reference beams result in an AC signal of 13 cps. in the form of radiant energy at the detector. This signal is used in the attenuation servo system to drive the optical attenuator in the direction that eliminates the difference of the beam radiances. The attenuator position is coupled to the pen drive system to move the pen proportional to the distance the attenuator is moved. More detailed information can be obtained from (4).

Modifications to the original alignment of source optics of the spectrometer were made for the measurements of the

specular reflectance and the hemispherical directional reflectance. The original source optics for the reference and sample beam are aligned such that the Nernst glower source is always at their common point of focuses. Therefore, if the Nernst glower is removed and the output from an external source is focused at the point of the original location of the glower, the beam then can be directed towards mirror M1 or M2, Figure 1 and the resulting optical path will follow the original internal optical path. In order to use external source, it was therefore necessary to cut a rectangular opening of about 10x15 cm. in the rear side of the metal cover of the source optics to enable any externally originated source to enter the source's optical compartment.

SPECULAR REFLECTANCE MEASUREMENTS

Figure 2 shows the measurement for the specular reflectance measurements. The test sample was attached to a special holder which in turn was mounted on a vertical shaft. The Nernst glower source, originally installed inside the source compartment, was moved outside and was used to illuminate the sample. The source was installed about 165 cm toward the left side and slightly behind the sample holder (Figure 2). A spherical mirror (no 1) of 75 mm diameter and focal length of f = 200 mm was installed about 43 cm from the glower and about 38 cm in front of the sample. Radiant energy from the Nernst glower was focused by this mirror onto the sample's surface. The solid angle of the incident beam $\Delta\omega$ was selected by partially masking the surface of mirror no 1. By rotating the sample holder about its vertical axis, and adjusting mirror no 2, the angle of illumination wrt. the normal of the test surface could be set at any desired value. Mirror no 2 is a first surface aluminized type and was positioned at the specular reflectance angle. Its focal length and solid angle of collection was the same as mirror no 1. This mirror was located about 22 cm from the test sample and was oriented such that it would focus the reflected beam exactly at the original location of the Nernst glower inside the compartment. The optics are adjusted so that the beam follows the original path for the sample beam.

The reference beam was obtained by collecting the illumination from the same Nernst glower by means of a 100 mm diameter, f = 200 mm spherical mirror no 3, located about 46 cm from the source. An apperture was placed on no 3's surface to control the solid angle such that reasonable instrument readings were obtained. The position and orientation of mirror no 3 were selected such that the radiation was focused at the original location or the Nernst glower and oriented along the

reference beam optical paths. The Nernst glower was operated at the recommended source current of 0.8 amperes.

Three separate wavelength scans were made to obtain the data necessary to determine the ratio of the specular reflectance of a roughened surface to that of a polished surface of the same material. The spectrophotometer outputs when a roughened surface, posilhed surface or zero reading is made are respectively, $\Delta(r)$, $\Delta(p)$ and $\Delta(z)$. The zero reading is made when the source is blocked off. The experimental results are evaluated by the following equation

$$\frac{\rho_{s,\lambda(\Psi)}}{\rho_{sp,\lambda(\Psi)}} = \frac{\Delta(r) - \Delta(z)}{\Delta(p) \quad \Delta(z)} \tag{6}$$

DIRECTIONAL REFLECTANCE MEASUREMENTS

The evaluation of the experimental data using Beckmann's equation requires the normalization of the specular reflectance by the directional - hemispherical reflectance value for the surface. In order to benefit from the data given previously as $\rho_{s,\lambda}/\rho_{sp,\lambda}(\Psi)$, the present experiment was designed to obtain the result given by

$$[\frac{\rho_{s,\lambda}(\Psi)}{\rho_{sp,\lambda}(\Psi)}]/[\frac{\rho_{s,\lambda}(\Psi)}{\rho_{dh,\lambda}(\Psi)}] = \frac{\rho_{dh,\lambda}(\Psi)}{\rho_{sp,\lambda}(\Psi)} \tag{7}$$

In the case in which the incident radiation is diffusely distributed, it can be shown (8) that the directional - hemispherical reflectance can be replaced by its hemispherical -directional reflectance, provided the angle of illumination Ψ is equal to the angle of viewing θ. The right hand side of equation (7) can therefore be written as $\rho_{hd,\lambda}(\Psi)/\rho_{sp,\lambda}(\Psi)$.

The integrating sphere reflectometer used was a hollow sphere coated in its innerside with a highly-diffusively reflecting material. The one used in this study was 100 mm diameter and made of copper. It had three openings on its wall: one for attaching the test sample, the second opening, 180° from the first one, is for the observation of the test sample.

The third opening, 90° from the other two, is for the illumination beam to enter the sphere, as shown in Figure 3. The innerside of the sphere was coated with Sauereisen potting cement which in turn was covered by glass beads of about 400 micrometers in diameter. The glass beads layer was finally vacuum-coated with a film of evaporated gold. The random pattern of the inner wall roughness diffusely reflects any radiation falling on it.
The gold layer highly - diffusely reflects the infrared radiation which thus gives high infrared radiance inside the sphere.

The sample was carefully clamped in position on the sample opening. The observation hole was cut such that the observation angle was 12° as measured from the surface normal. A second Nernst glower, powered separately, was positioned very close to the integrating sphere. A blockage lip was placed between the Nernst source and the sample such that no direct radiation from the source could fall onto the test sample, a condition required by the analysis of the energy exchange inside the integrating sphere (4).

The radiation reflected from the sample was collected by a 100 mm diameter spherical mirror of f = 150 mm positioned such that it directed the radiation from the sample toward mirror M_1 inside the optical source compartment and along the spectrophotometer optical path. A maximum solid angle of collection of $\Delta\omega \simeq \frac{\pi}{240}$ was used. The entire arrangement is shown in Figure 4. The reference beam was provided by the original Nernst glower source of the spectrophotometer. A partition was installed between the Nernst source and the sample optics (mirrors M_1 and M_3) and thus prevented the radiation from the internal Nernst source from entering the sample slit.

The theory of the energy exchange between surface elements inside the integrating sphere is well understood and will not be repeated in this report. If rough and polished samples are alternately placed on the sample holder, the respective outputs of the detector will be directionally proportional to their directional reflectance values. Since smooth or polished samples show the same values for both the specular and the hemispherical - directional reflectance (9), it can be shown (4) that

$$\frac{\rho_{hd,\lambda}(\Psi)}{\rho_{sp,\lambda}(\Psi)} = \frac{V_a}{V_s} \text{ for } \theta = \Psi \qquad (8)$$

where V_a and V_s are the detector outputs from reading the rough and the smooth samples, respectively, measured with respect to zero reference reading. The zero reference was obtained by placing a blockbody in the place of test sample.

TEST SAMPLES

The test samples were made from the type 304 stainless steel rod of 25.4 mm diameter and 3.2 mm thick. Each specimen was machined to have both surfaces smooth. One side of the surfaces of each set of four samples were further processed to have their roughness ranging from very smooth (polished) to a very rough characteristic. Three sets of these samples were then vacuum deposited with, respectively, aluminum, gold and chrome. Another set was left uncoated and was intended to be stainless steel 304 samples. The rms. values of the surface roughness heights were measured using a profilometer with a G-type tracer point of 25 μm diameter. The respective values of the mechanically measured surface roughness are presented in Table 1.

RESULTS

The specular and hemispherical-reflectance measurements were obtained in the wavelength range from 2.5 to 16 μm. Beyond 16 μm the signal level was too small to be effectively usable. The spectrum range from 2.5 μm to 16 μm is, however, sufficient to obtain the objectives of this study. Figures 5 to 7 are presented to show that the system functioned properly and the results are compatible to the theoretical prediction. Only stainless steel 304 results will be presented in Figures 5 to 7, since the other metals used in this study show similar behavior (4).

Presented in Figure 5 are plots of the normalized specular reflectance $\rho_{s,\lambda}(\Psi)/\rho_{sp,\lambda}(\Psi)$ vs λ for stainless steel 304. The results are similar to those previously reported, such as in (10). The relationships between $\rho_{s,\lambda}(\Psi)/\rho_{sp,\lambda}(\Psi)$ and σ_o/λ are presented in Figure 6 where σ_o has been obtained from eq. (5). For small values of σ_o/λ, the data for all samples fall very close to the theoretical line given by eq. (5). At large values of σ_o/λ, the influence of the diffuse component becomes important and the data no longer follows exactly the theoretical results.

The surface rms slopes m is calculated from the diffusion term in eq. (1), where, for wavelength below a given value,

the influence of the specular term is relatively negligible. The value of λ used in the calculation of m was selected when the magnitude of the specular term is around 1% of the total reflectance. Figure 7 shows the plot $\rho_{hd,\lambda}(\Psi)/\rho_{sp,\lambda}(\Psi)$ vs σ_o/λ for stainless steel test samples. In the region where the wavelengths are large compared to the surface roughness σ_o, the hemispherical - directional reflectance approaches the specular reflectance value and therefore, as σ_o/λ approaches zero, the curves of $\rho_{hd,\lambda}(\Psi)/\rho_{sp,\lambda}(\Psi)$ approaches unity. The results compare favorably with those presented in Reference (11).

The complete results of the rms. and arithmatic values of the mechanically measured surface roughness, the optical values of surface roughness and slopes, are presented in Table 1 for the entire samples. The correlation between the mechanical and optical surface roughness is presented in Figure 8 and the data points are in general in the vicinity of the predicted line proposed by Birkebak (1).

CONCLUSIONS AND RECOMMENDATIONS

An experimental technique has been presented which uses a double - beam spectrophotometer to measure the rms. surface roughness and slopes. Both Davies' (2) Beckmann's (3) theories have been used to calculate the optical values of the rms. surface roughness, with the first theory also applied to calculate the rms. values of surface slopes. The results compare favorably with those previously obtained using different techniques.

Some automation, as suggested by Bennett and Porteus (7) and was later patented by Bennett (13) shows the practical application of Davies' theory. Other possibilities still remain open, including the application (and further study) of Beckmann's theory.

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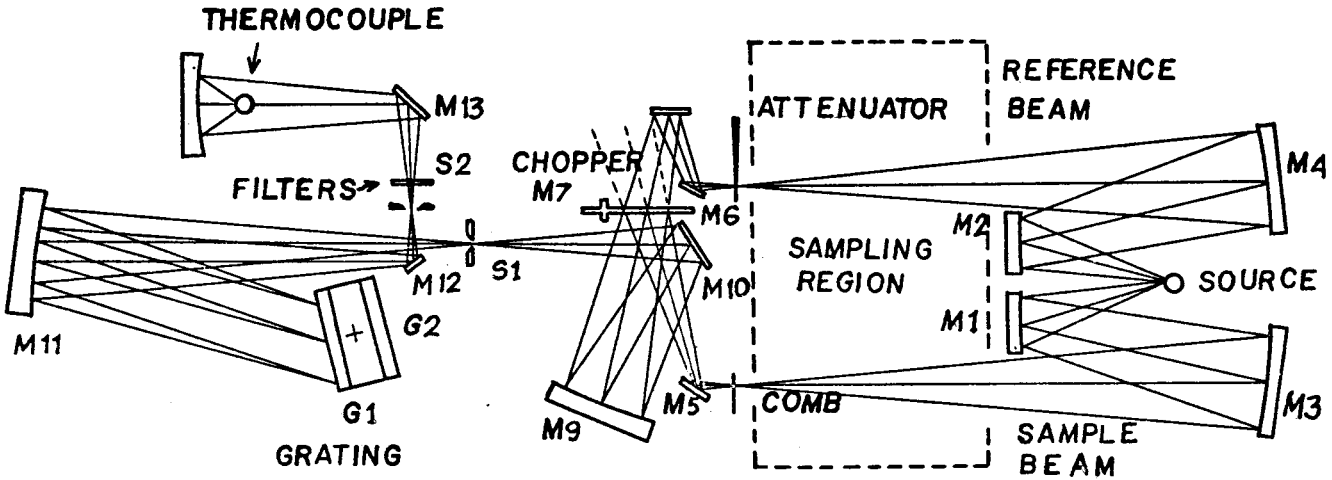
Table 1
Surface properties of the test samples

Test Samples		Mechanically Measured Surface Roughness		Optically Measured		
				Surface Roughness σ		Surface Slopes m (From Davies)
		RMS. Value σ_m	ARITH. Value σ_A	From Davies	From Beckmann	
Aluminum	# 2 [1]	0.343 µm	0.309 µm	0.657 µm	0.676 µm	0.688
	# 3	0.686 "	0.628 "	1.012 "	1.091 "	1.002
	# 4	1.431 "	1.287 "	1.586 "	1.88 "	1.220
Gold	# 2	0.285 "	0.252 "	0.567 "	0.537 "	0.472
	# 3	0.652 "	0.601 "	0.961 "	0.963 "	0.847
	# 4	1.236 "	1.191 "	1.547 "	1.598 "	1.094
Chrome	# 2	0.301 "	0.267 "	0.640 "	0.565 "	0.557
	# 3	0.770 "	0.660 "	1.504 "	1.056 "	0.510
	# 4	1.274 "	1.109 "	1.788 "	1.665 "	1.392
Stainless Steel	# 2	0.339 "	0.305 "	0.804 "	0.590 "	1.020
	# 3	0.660 "	0.720 "	0.875 "	1.076 "	0.635
	# 4	1.194 "	1.084 "	1.422 "	1.563 "	2.126

1) All samples numbered "one" are smooth polished.



S1, S2 : Slits
Source : Nernst Glower

Figure 1: Optical diagram PE-621 Spectrophotometer.

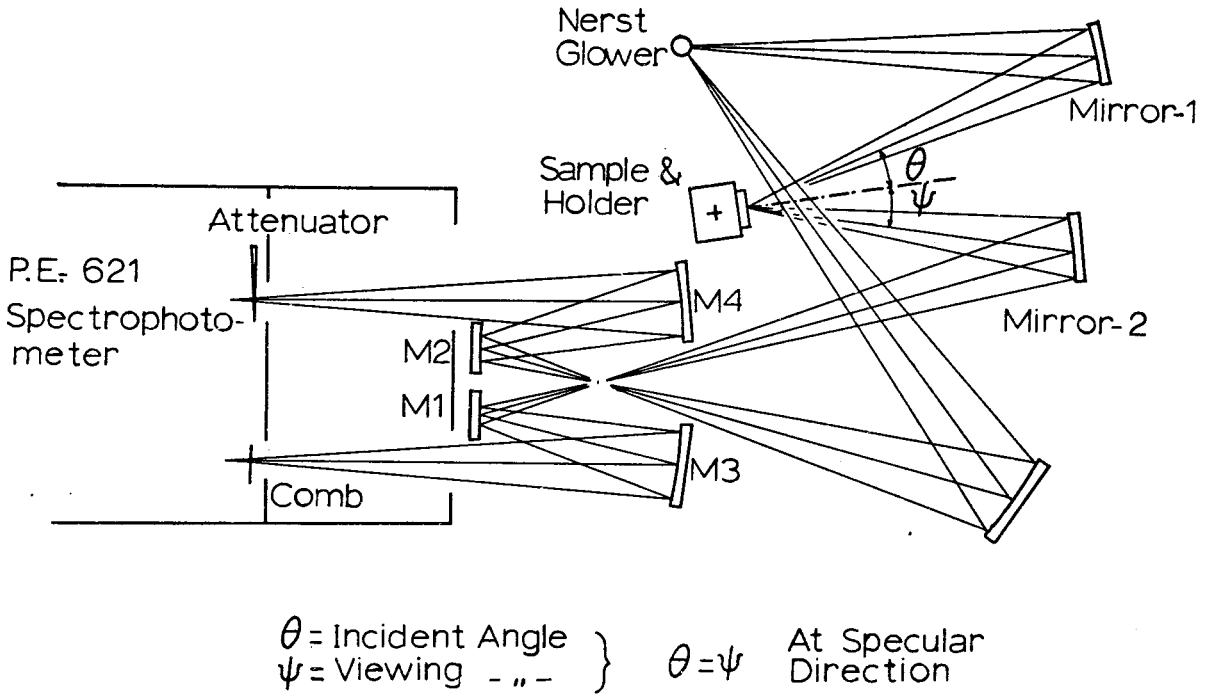


Figure 2: Experimental Set-up used with Davies Theory.

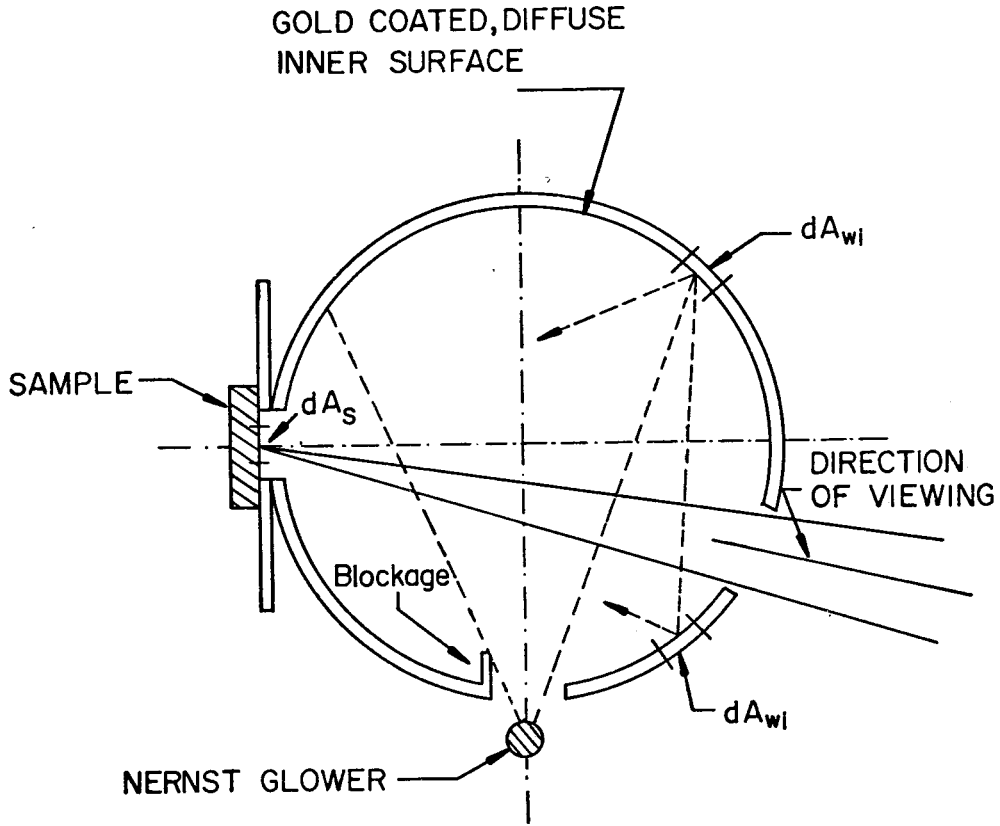


Figure 3: Energy transfer mode of integrating sphere.

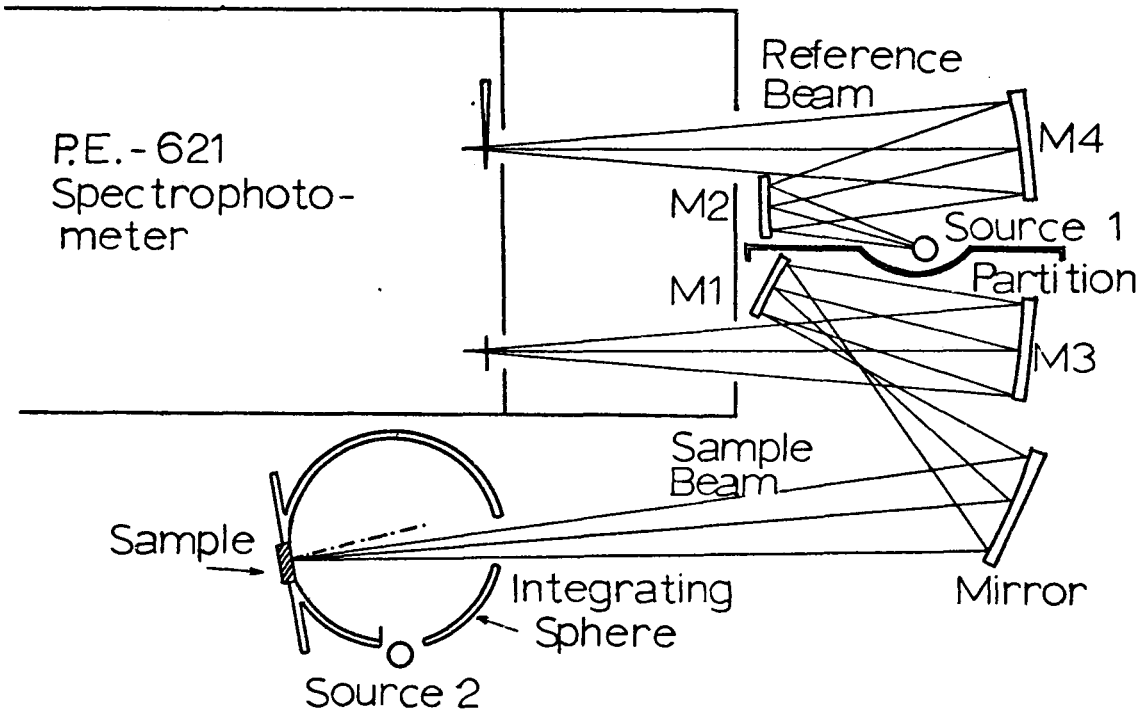


Figure 4: Experimental set-up used with Beckmann's theory.

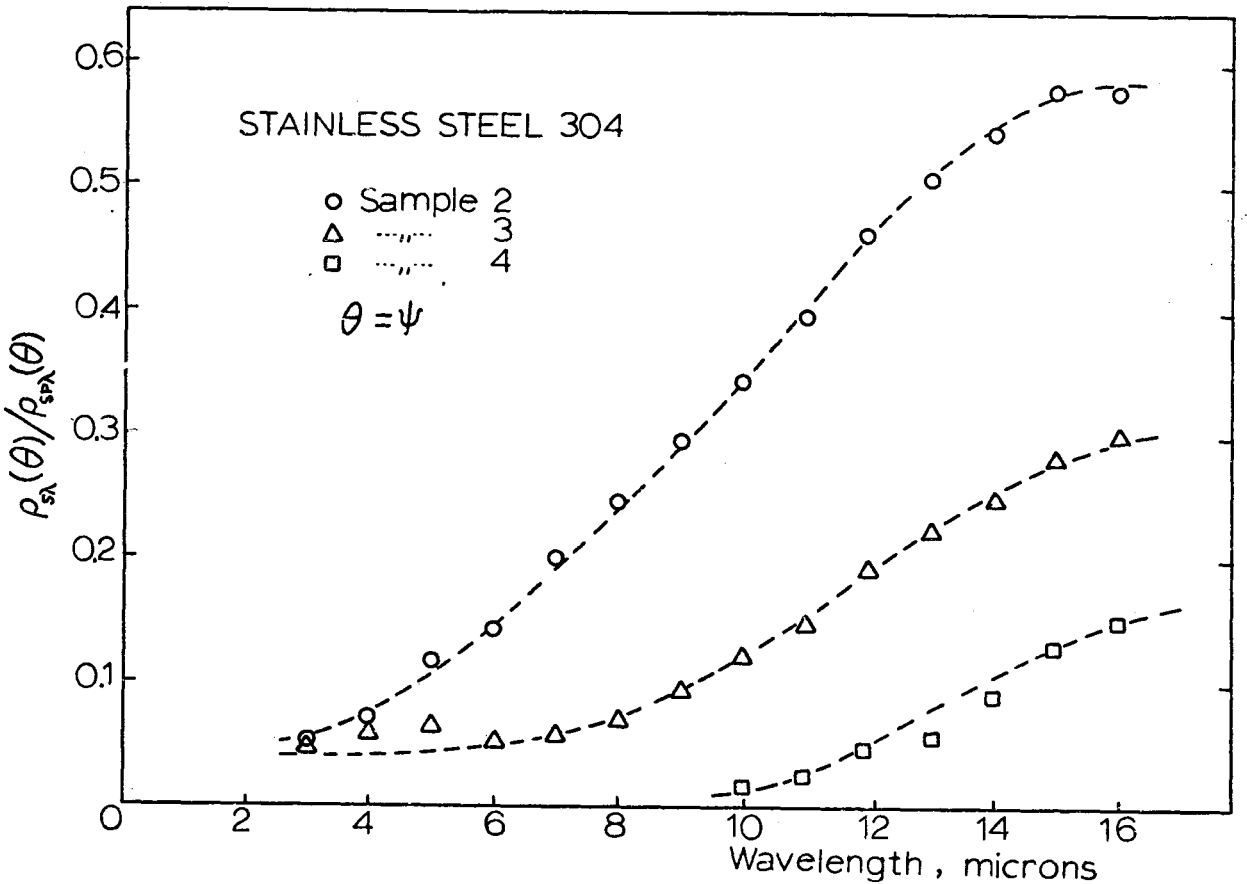

STAINLESS STEEL 304
Sample 2
3
4
θ = ψ
$\rho_{s\lambda}(\theta)/\rho_{s\lambda}(\theta)$
0.6
0.5
0.4
0.3
0.2
0.1
0
2
4
6
8
10
12
14
16
Wavelength , microns

Figure 5

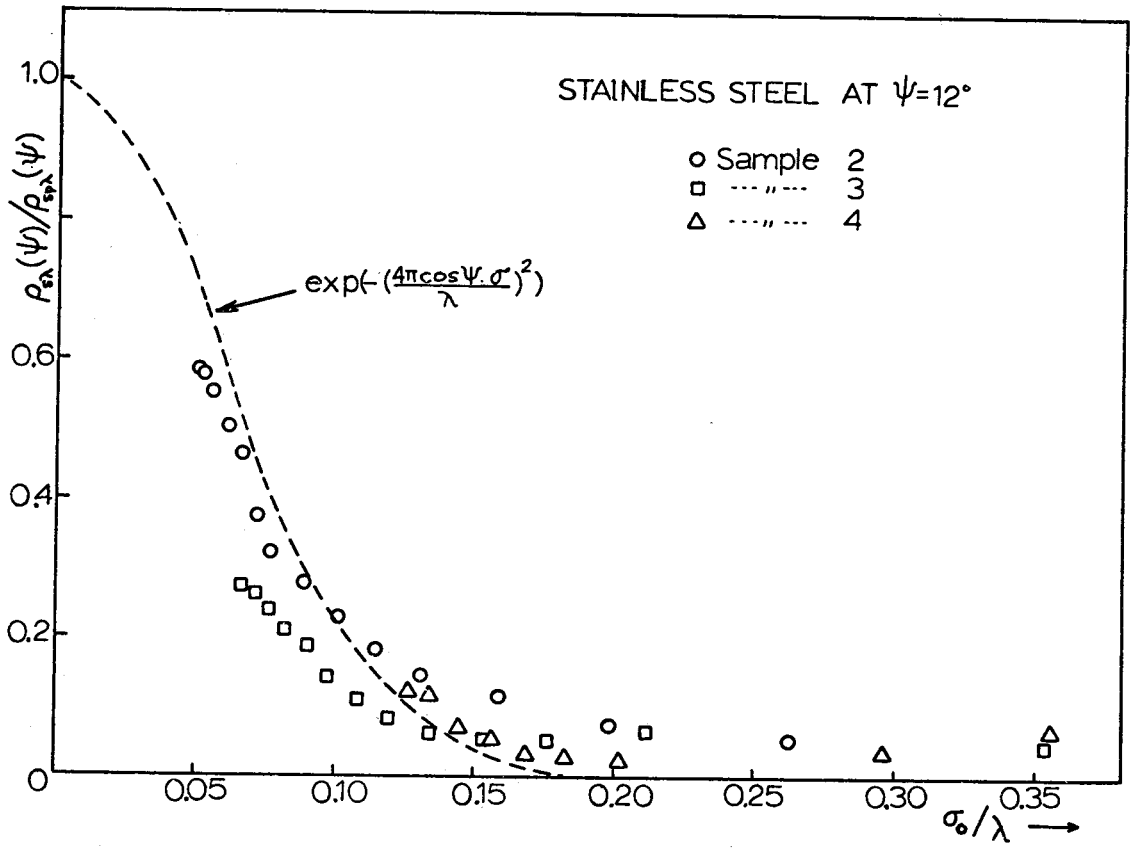

STAINLESS STEEL AT ψ=12°
o Sample 2
□ ---,,--- 3
Δ ---,,--- 4
exp(-(4πcosψ.σ/λ)²)
ρsh(ψ)/ρsp.(ψ)
1.0
0.6
0.4
0.2
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
σ₀/λ

Figure 6

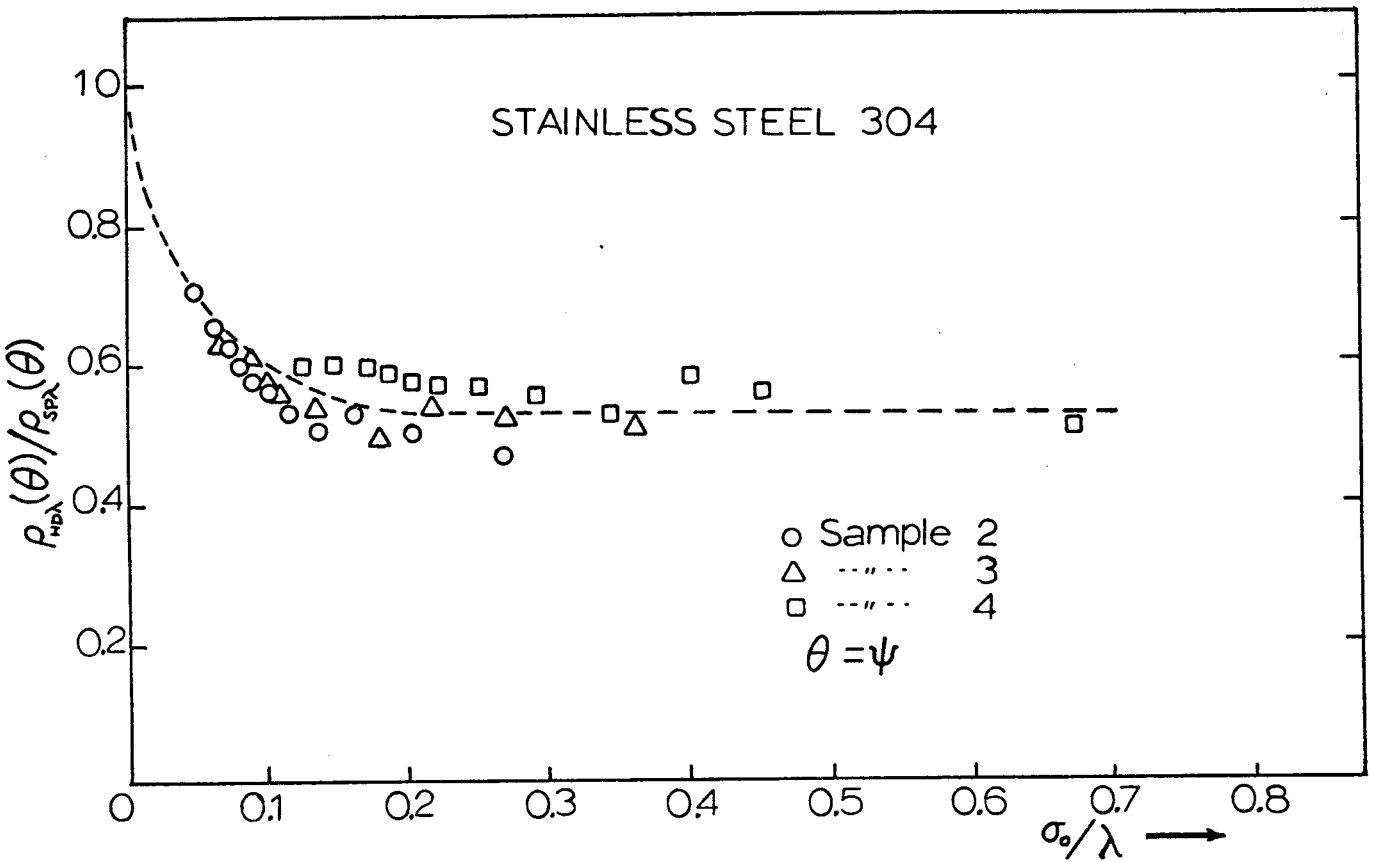

STAINLESS STEEL 304
1.0
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$\rho_{HDA}(\theta)/\rho_{SPA}(\theta)$
σ_o/λ
o Sample 2
Δ ---"--- 3
□ ---"--- 4
$\theta = \psi$

Figure 7

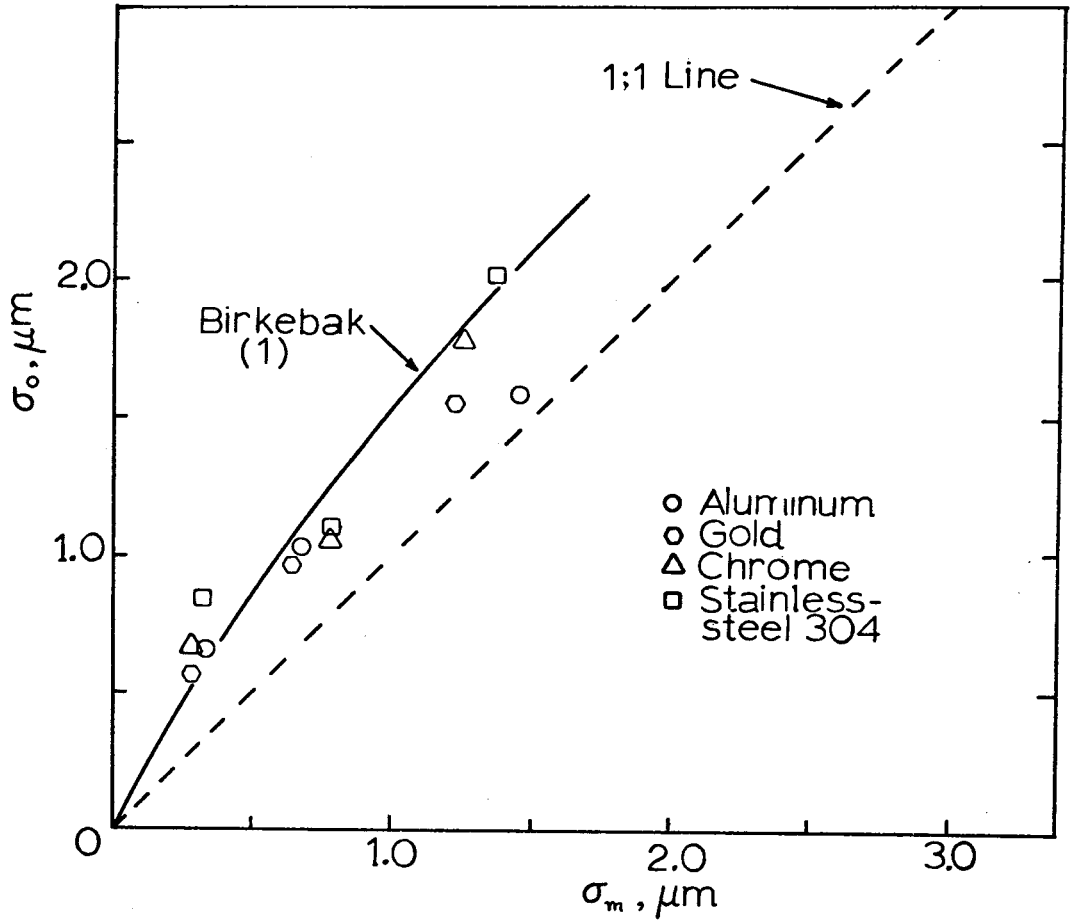

1;1 Line
Birkebak
(1)
2.0
1.0
0
σ_o, μm
1.0
2.0
3.0
σ_m, μm
Aluminum
Gold
Chrome
Stainless-
steel 304

Figure 8

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