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A new device for measuring the real area of contact of polymeric material by the perturbation of total internal reflection

S. M. BENABDALLAH, J. LAPIERRE*
*Department of Mechanical Engineering and *Department of Physics Engineering, Ecole Polytechnique de Montréal, P.O. Box 6079, Station "A", Montreal, Quebec H3C 3A7, Canada*

An optical device has been developed to measure precisely and directly the real area of contact (RAC) between a glass prism and a machined polymeric surface. It is based on the perturbation of total internal reflection of a light beam in the region of contact between the two solid surfaces. The optical and electronic components of equipment intended for the measurement of the RAC, given in terms of percentage of the apparent surface of contact, were selected to provide improvements in the way of using this method and have permitted to reach a precision of about 1.5%, and a resolution of 0.05%, for finishes rougher than 1.0 μm centre line average roughness value (CLA). These components also ensure measurements with a calibration factor independent of the material considered and its colouration. The design concepts are outlined, and typical experimental results for a thermoplastic material are presented, which show a good performance of repeatability. The variation of RAC with normal load was investigated with a large range of surface roughness of polymeric specimens. The results are included, and show that the real area of contact varies as 0.88 power of the normal load, with a proportionality constant dependent on the roughness of the contacting polymer surface.

1. Introduction

It has been known for many years that when rough surfaces are brought into contact, the real area of contact under normal engineering load is only a small fraction of the nominal (apparent) area of contact [1]. In recent years, engineers have come to realize that the determination of the contact of rough surfaces is important in the solution of many tribological problems. The theoretical study of the contact of rough surfaces is well advanced and highly successful theories [2, 3] have been developed. On the other hand, experimental work on this topic has not received the attention that was due.

Experimental techniques have been very well reviewed by Woo and Thomas [4]. In the case of polymers, the method most widely employed is the total internal reflection method based on the photometric registration of the disturbance of the internal reflection at the points of contact between a polished glass prism and the rough surface of the specimen. Its popularity for the investigation of the RAC of polymeric bodies is also associated with the fact that the relative RAC of polymers is much greater than that of metals. Accordingly, the relative error of the method is smaller for polymers.

The major disadvantages of this method, and possibilities of improving it, have been considered by Kragelsky and co-workers [5]. But the calibration problem connected with difficulties due to the peculiarity of the method and materials considered has not really been investigated. On the other hand, it is generally recognized that it is necessary to use two photocells to avoid the use of an extremely high stability voltage supply to power the light source. But the relative error on the measurement of a current difference, assumed to be proportional to the RAC, is given essentially by the intensity of fluctuations of the light source. Instead of a subtraction, which is the usual approach that has been used so far, we perform a division operation.

Finally, as far as we know, the distribution of intensity across the light beam has never been paid much attention. We believe that the uniformity of intensity distribution is a major factor to ensure reliable results.

In this paper, we consider in some detail the problems associated with the calibration, compensation of the fluctuations of the light source, and the uniformity of intensity distribution across the light beam.

2. Description of the device

The device shown schematically in Fig. 1 was designed to provide application of a large range of normal loads to the specimen and to measure the RAC [6]. Specific normal load is applied to the specimen by a dead weight hooked to the arm pivot (1). A modified slide projector acting as a light source is shown in position (2). The modified system consists of a condenser and a precision pinhole of diameter 2 mm for spatial filtering, together with an achromatic doublet objective

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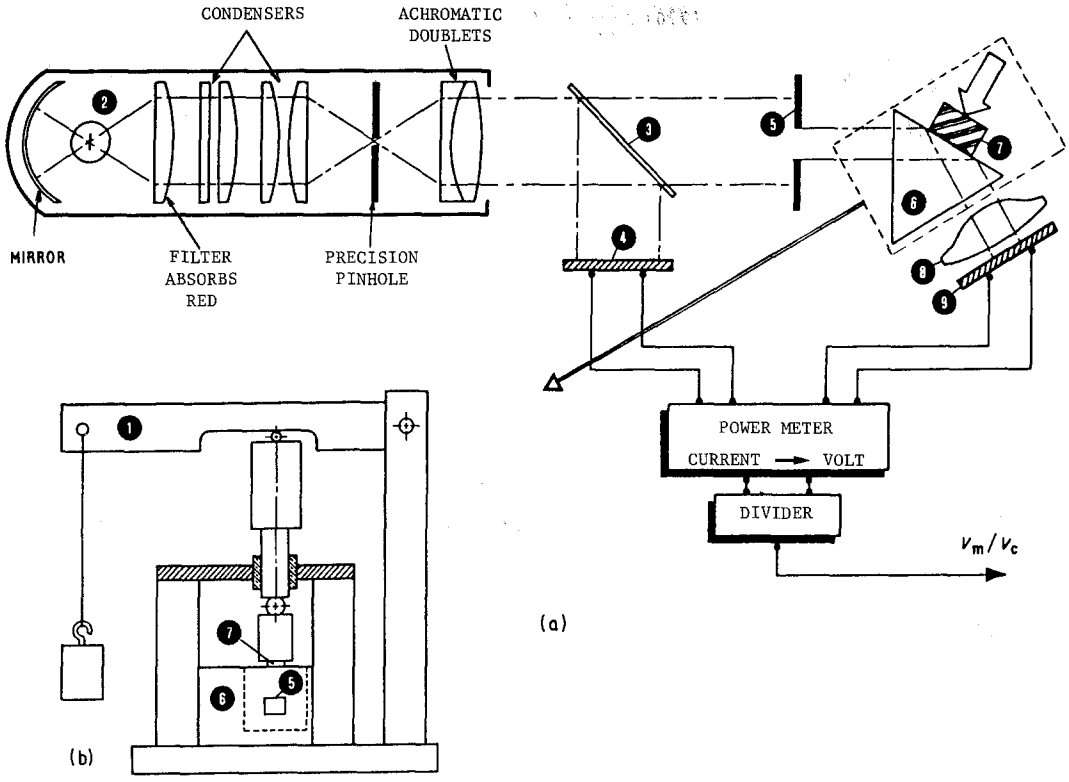

Figure 1 (a) Assembly drawing of the set-up for the measurement of RAC; (b) loading mechanism.

having a focal length of 180 mm and a diameter of 45 mm. In order to provide a parallel and uniform beam of light, those elements have been selected by means of a series of tests involving several combinations of filters and lenses. The uniformity of the illumination across the beam was checked by using a photocell with an aperture of 1 mm diameter, travelling alongside the x and y axes. The results presented in Fig. 2 show that the selected optical arrangement provides a uniform light beam.

The incident beam from the light source passes through a beamsplitter (3). The reflected beam from the splitter falls onto a comparative photocell (4). The transmitted beam is directed through an aperture stop (5) to the triangular prism face (6), making contact with the sample. The aperture stop defines a window which permits illumination of only the nominal area of contact of the sample (7). The light reflected at the sample–prism interface passes through a condensing lens (8) and is focused onto the main photocell (9), thus preventing most of the scattered light due to the roughness of the sample to be measured. A general view of the operating device is shown in Fig. 3.

Each photocell is connected to a power meter with a non-linearity of less than 0.5% of the maximum reading. The two voltages are sent to a high accuracy analogue divider, thus eliminating the effect of the fluctuations of the incident beam as mentioned above. The signal is then filtered with an R-C networks (RC) low-pass filter with a limiting frequency of 3 Hz. We have investigated the possibility of using polarized light to minimize the error associated with penetration of the electromagnetic vibrations into the air gaps formed between contact surfaces [5]. Our preliminary experiments have shown no improvement in that respect. The instrument was calibrated by using a special specimen which consisted of a film of polymeric material fixed on a glass plate. To provide full optical

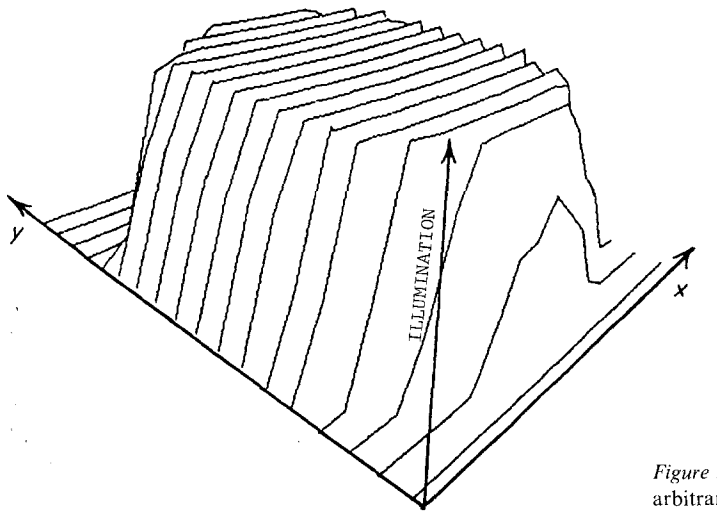

Figure 2 Distribution of intensity across the beam of light in 3D arbitrary scales.

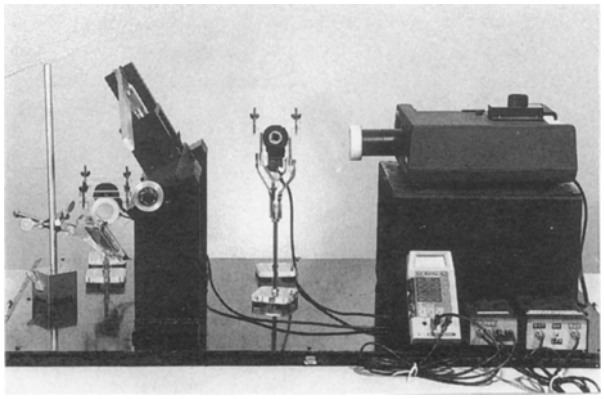

Figure 3 General view of the operating device.

contact, the space between the prism and the film was filled with an immersion medium. The full scale of measurements covers the range from zero to full contact (RAC = 1) according to the equation

$$\mathrm{RAC} = (1 - V_m/V_c)K$$

In this formula, V_m and V_c are the voltages obtained from the main and comparative photocurrents. Zero contact is obtained when no sample is present and then V_m is set equal to V_c as a zero setting. The calibration factor K is given by

$$K = V_c/(V_c - V_m)$$

at full contact. Our approach, which is distinguished by the use of a dividing circuit instead of a subtracting circuit, leads to a calibration factor K which to the best of our knowledge following several experiments appears to be independent of the material tested. Besides this inherent innovating property, this instrument can be used without special attention to environment, the set-up is easy to build and does not need high technology components.

3. Experimental results

All the results presented here were obtained for a polymeric sample (ultra-high molecular weight polyethylene, Hercules 1900, supplied by Solidur) with a nominal contact area $A_n = 200\,\mathrm{mm}^2$ and a surface hardness (Kenton Micro-hardness Tester) $H = 73.2\,\mathrm{MPa}$.

Measurements of the RAC were carried out within the range of nominal contact pressures 7×10^{-3} to 0.8 MPa, on samples having roughness of the contacting surface varying from 0.5 to 3.2 μm CLA, at room temperature. These experimental results are plotted in Figs 4 and 5, where the ordinate is the bearing area ratio of the real contact area RAC to the nominal contact area A_n, and the abscissa is the dimensionless load $W^* = W/(A_n \times H)$, where W is the actual load and H the surface hardness. During those tests, the measurement of the RAC was made 20 sec after each loading in order to ensure stable conditions.

Fig. 4 shows the results of six consecutive tests obtained with six different samples of the same roughness, 0.85 μm CLA. These points appear to follow a power law which was established through a least-square fit. A good level of repeatability is shown.

In Fig. 5, data presented on a double logarithmic scale appear to be consistent with the experimental results of a number of workers [4]. The lines were constrained to take the form

$$\mathrm{RAC}/A_n = \alpha(W/A_n \times H)^m$$

In this case $m = 0.88$ and the proportionality constant α has a value which depends on the roughness of the contacting polymer surface. The results show a divergence from the fitted lines at $W^* > 4 \times 10^{-3}$ when the initial value of roughness of the specimen decreases (CLA < 0.85 μm). This slower increase in the bearing area ratio (RAC/A_n) with load is due to the changes in properties of the surface caused by the decrease of surface parameters of the softer material, roughness and mean slope, whilst the mean peak radius of curvature increases with loading [7]. Those changes cause the plasticity index to decrease and might influence the deformation of the contact which occurs plastically rather than elastically for $W^* > 4 \times 10^{-3}$.

It is clear that those changes have a lesser effect for

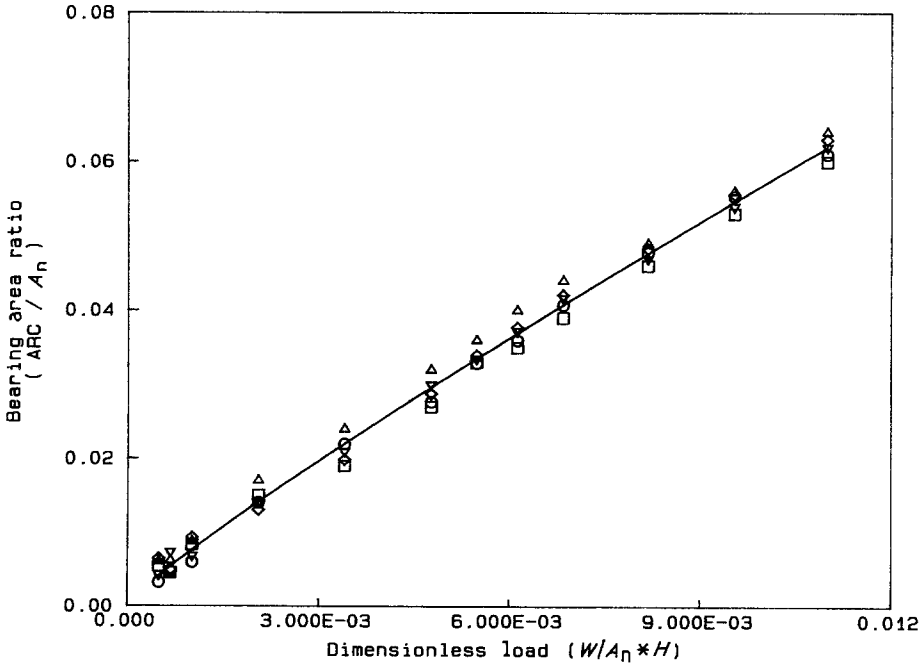

Figure 4 Bearing area ratio against dimensionless load for six different samples of UHMWPE, CLA = 0.85 μm. The solid line is the least-square fit to a power law.

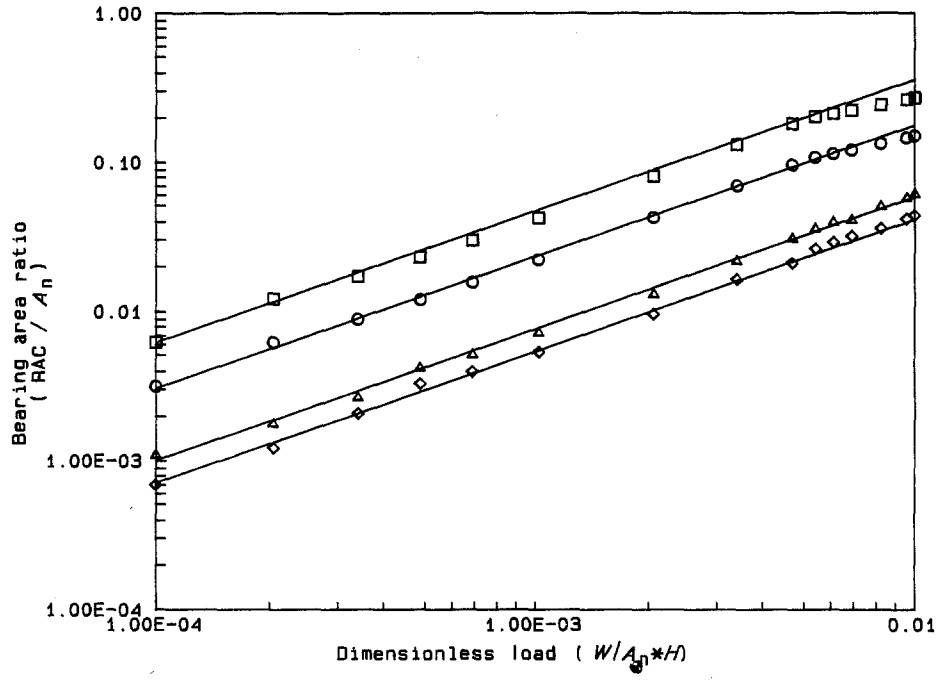

Figure 5 Bearing area ratio against dimensionless load for UHMWPE with different surface roughness. □, CLA = 0.5 μm; ○, 0.7 μm; △, 0.85 μm; ◇, 3.2 μm.

materials with surface of contact which are initially not smooth (CLA > 0.7 μm).

4. Conclusions

A reliable and direct method based on total internal reflection has been used for measurement of the real area of contact of polymeric materials. Polymeric samples of UHMWPE were tested using the device and the measurements of the bearing area ratio as a function of the dimensionless load appear to be consistent with the experimental results of a number of workers.

Our experimental results enabled us to find the correlation $RAC/A_n = \alpha(W/A_n \times H)^m$ with $m = 0.88$ and the proportionality constant α value depending on roughness of the contacting polymer surface. However, a deviation was observed when $(W/A_n \times H) > 4 \times 10^{-3}$ for smooth surfaces with CLA < 0.7 μm. This is due to changes in the properties of the surface causing a decrease of the plasticity index. This correlation shows that bearing area is not proportional to load. This agrees with the results of the multiple asperity model analysis [8].

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