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THE REAL AREA OF CONTACT MEASURED ON ELASTOMERS

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In this paper optical profilometry is used to measure the roughness deformation of a rough elastomer in contact with a smooth glass plate. Two conditions are considered: a wet and a dry contact.

In the wet contact, the deformed roughness texture is hardly influenced by the contact load. This is probably caused by a high stiffness of the liquid film, compared with the asperity and bulk stiffness.

In the dry contact, increased asperity flattening is observed with increasing load. Besides, different deformations occur at different length scales: Small scale asperities still persist on extensively flattened larger scale asperities. This is probably by asperity interaction, which will be more significant at the smaller length scales, where the distance between the asperities is smaller compared to the asperity height.

1. INTRODUCTION

The tribology of rough surfaces has received much attention during the last decades. One of the items studied is the roughness deformation under static load, which is e.g. important in the case of boundary and mixed lubrication. Up till now several models have been developed to predict the real area of contact, but experimental verification appears to be difficult.

Recently a new method for measurement of the deformed roughness texture of elastomers under static load has been developed and presented by Visscher and Struik (1992a) and by Visscher (1992). It uses an optical profilometer, which is able to scan the surface roughness through a (possibly loaded) glass plate on it.

This paper provides a brief literature review on the real area of contact, followed by description of the experimental method used by the authors. Next preliminary measurements, both with and without a liquid in the contact area, will be presented and discussed. Finally a brief discussion will be given on the determination of the real area of contact and on the used method for the measurement.

2. LITERATURE REVIEW

The literature will be briefly reviewed here. More elaborate reviews can be found in Thomas and King (1977), Woo and Thomas (1980), Bhushan (1985a), McCool (1986), Visscher and Struik (1992a), Hendriks (1992b, 1993) and Visscher (1992 pp. 69ff.).

2.1. Theoretical work

In general, theoretical work concerns the real area of contact in dry contacts. Different modeling of the roughness texture is applied. Greenwood and Williamson (1966) described the asperity summits with spheres of equal radius but of different height and Onions and Archard (1973) considered the different length scales in the roughness texture, modeling the roughness by small spheres superimposed on larger spheres. Majumdar and Bhushan (1991) also accounted for the different length scales, but used fractals to describe the roughness texture. Numerical calculations of the roughness deformation under static load are presented by Lai and Cheng (1985), Lubrecht and Ioannides (1991), Xian and Zheng (1991) and Lee and Cheng (1992). Different predictions are obtained for the real area of contact, due to the different modeling of the roughness texture.

In most papers, asperity interaction is not considered. Interaction is caused by deformation of the bulk material and can have a significant influence. According to Vergne et al. (1985), roughness valleys can possibly persist due to this interaction, even at high loads. Podbevsek (1992 section 5.3) showed that a non-contacting asperity can be lowered by the load on a neighbouring higher, contacting asperity. Therefore, negligence of interaction probably yields overestimation of the real area of contact.

2.2. Experimental work

A large number of experimental methods have been applied to study the real area of contact. Bhushan (1985a), investigating magnetic tapes, discussed different methods possibly suitable for polymeric materials. The most important methods are the electrical and the optical, but most are not suitable for polymers. Bhushan (1985b) chose interferometry and found that the real area of contact can be seriously overestimated (e.g. by 30 percent) due to the small slopes in the roughness texture of magnetic tapes, which make the boundary between the contact area and the surrounding non-contacting area unclear. Bhushan stated, that the accuracy would increase with increasing roughness slopes. However, the interference pattern is disturbed by light scatter at higher slopes, which makes interpretation of the picture difficult or even impossible (Visscher, 1992 pp. 126-127). Furthermore, present methods often provide an idea of the real area of contact only, but do not yield an indication of the total deformation of the roughness texture. This latter point, however, appears to be important, as will be discussed in section 7 below.

3. THE METHOD

The real area of contact is measured using the optical profilometer shown in fig. 1. It is derived from a compact disc transducer, described by Bouwhuis

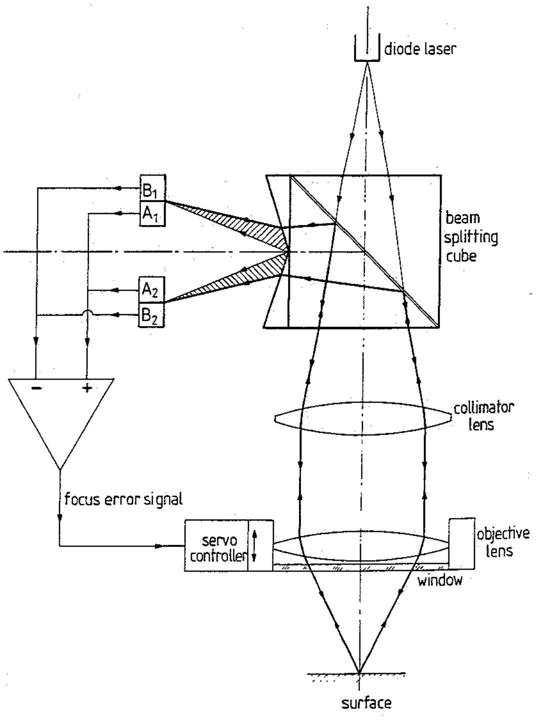

Figure 1 Optical profilometer.

and Braat (1978) and by Bouwhuis et al. (1987), and used for contactless shape and roughness measurements (Struik and Chang, 1987). The principle of the method is, that four photodiodes (A_1, A_2, B_1 and B_2) receive the same amount of light when the surface is in focus and the so-called **focus error signal** is zero. If the surface is out of focus, the outer diodes (B_1 and B_2) receive a different amount of light than the inner diodes (A_1 and A_2) and the focus error signal is positive or negative, depending on the surface position (above or below the focal plane of the objective lens). When out of focus occurs, the objective lens is moved by the servo controller to a position where the focus error signal is zero again, focusing the lens onto the surface. Measurement of the lens position during scanning then yields the shape and the roughness profile of the surface.

The accuracy in the height measurement is about 0.01 µm and the resolving power, determined by the focus spot diameter, is about 1 µm.

The same method can be applied to measure the deformed roughness profile when a glass plate is pressed onto the scanned surface (fig. 2). This additional glass plate influences the measurement, due to additional reflecting surfaces and due to refraction, which causes spherical aberration. These factors are investigated and measures are taken to reduce or eliminate their influence (see Visscher, 1992 section 5.3; Visscher and Struik, 1992a and 1992b). The most important factor is the reflection on the contacting glass surface, which can disturb the measured profile significantly. This influence is not well understood at the moment and this reflectance should therefore be eliminated, when the deformed roughness profile is to be measured quantitatively.

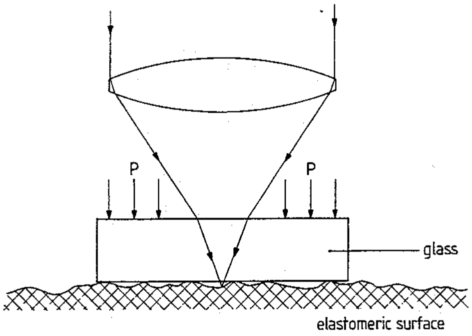

Figure 2 Scanning through a glass plate loaded onto the surface.

4. MEASUREMENTS WITH LIQUID IN THE CONTACT AREA

The liquid used in the contact is an oil mixture of 75 percent Shell Ondina 15 and 25 percent of Shell ondina 68. This mixture has an equal index of refraction as the glass plate and reflection on the contacting glass surface is therefore avoided.

The measurements are performed on a flat piece of polyurethane. The undeformed roughness texture and the derived height distribution are shown in fig. 3.

4.1. Results

Measurements were performed at five loads and the results of all five measurements are presented by Hendriks (1992a and 1993) and by Visscher (1992). Two results, one at the lowest and one at the highest applied load, are given here in fig. 4 and 5.

Fig. 4a shows a number of higher, flattened asperities at the lower load. The larger areas are indicated by A, B and C and are also shown in fig. 4b, while fig. 4c shows the height distribution curve of the deformed rough-

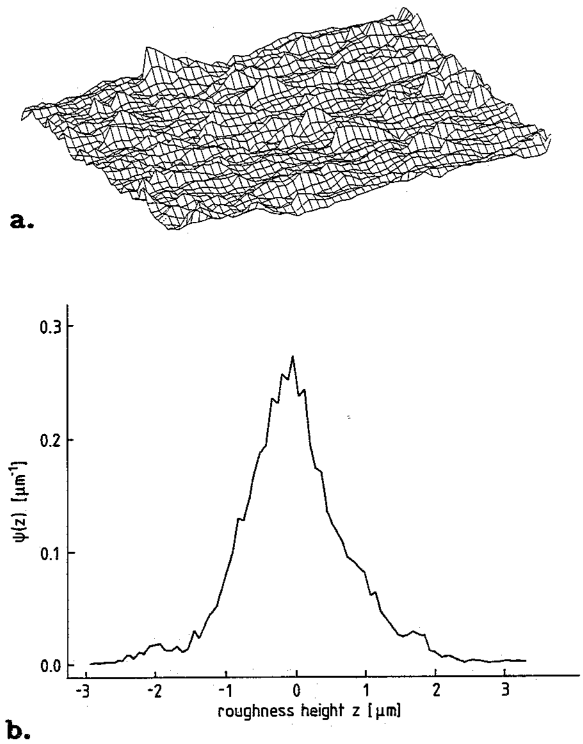

Figure 3 Surface plot (a) and height distribution (b) of the undeformed roughness texture of the polyurethane plate. ($\psi(z)$ = probability density function of the roughness height z)
Measured area = 200 μm × 200 μm;
Sample distance = 2 μm
(in both directions);

ness texture.

Fig. 5 shows the flattened areas and the height distribution curve at the higher load. This measurement is not performed on exactly the same part of the surface, but equal areas (A and B) can be recognized. Besides, ripples are present in the height contour lines, due to some kind of clearance in the test rig. These problems are caused by the fact that the present test rig was initially not designed for three-dimensional measurements.

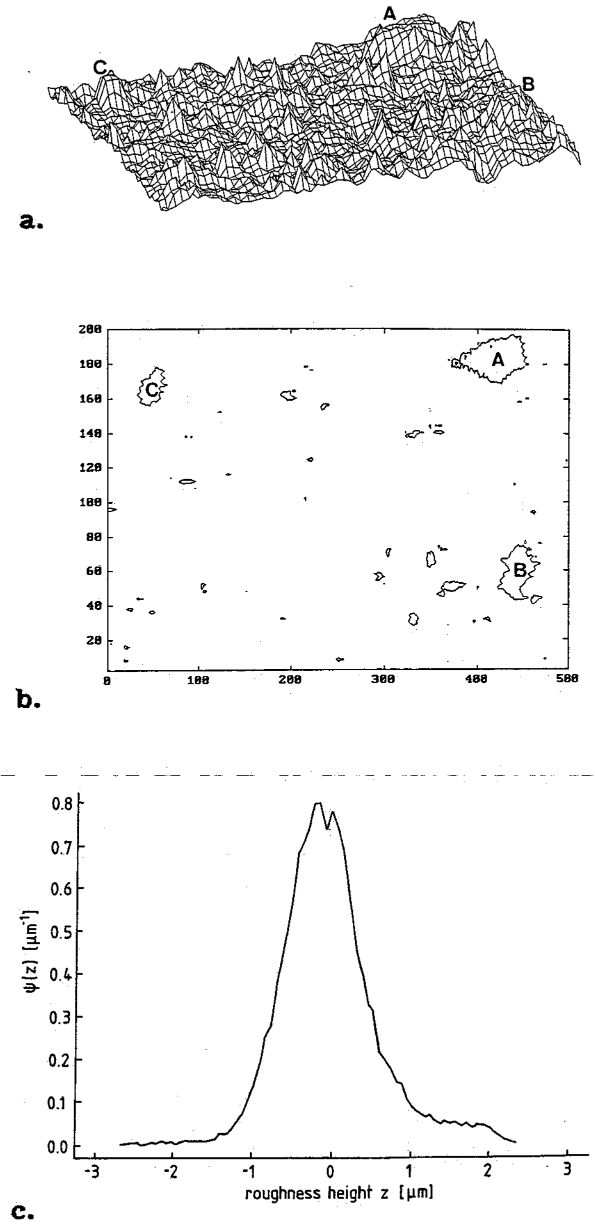

Figure 4 Surface plot (a), highest height contour lines (b) and height distribution (c) of the deformed roughness texture of the polyurethane plate at an average contact pressure of 0.032 MPa and with liquid.
Measured area = 500 μm × 200 μm;
Sample distance = 2 μm
(in both directions);

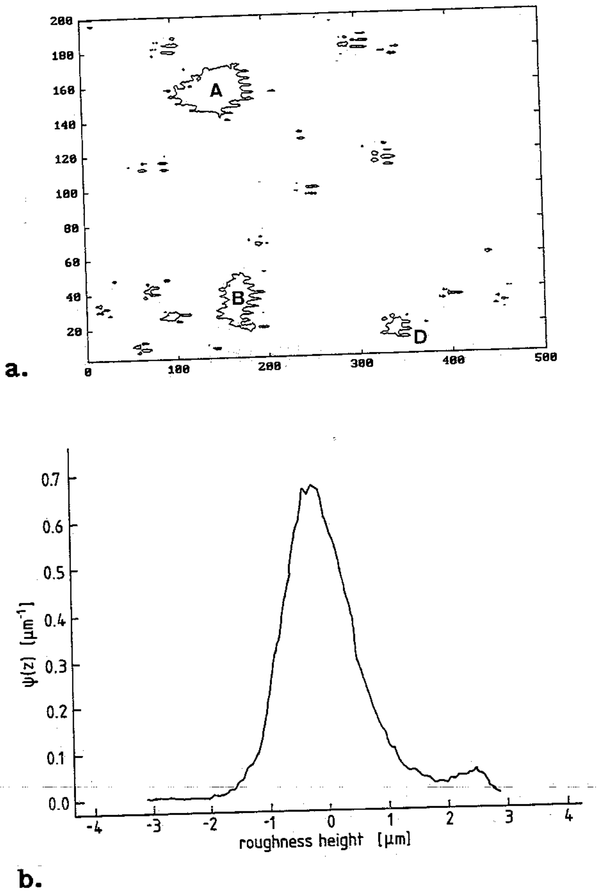

Figure 5 Highest height contour lines (a) and height distribution (b) of the deformed roughness texture of the polyurethane plate at an average contact pressure of 0.15 MPa and with liquid.
Measured area = 500 µm × 200 µm;
Sample distance = 2 µm (in both directions);

4.2. Discussion

Only a few asperities appears to be flattened at both loads. Also, the differences between the measurement at the higher load and the measurement at the lower load are small. This is illustrated in fig. 6, where the standard deviation σ of the roughness height distribution as well as the size of the areas A and B are shown for the different loads. These parameters are clearly not load-dependent. The differences found in σ must be subscribed to the fact that the measurements are not performed on exactly the same part of the surface. The differences in derived dimension of the areas A and B are probably caused by uncertainty in the determination of these dimensions (see section 6 for further discussion).

Apparently, increase of contact load does hardly or not affect the roughness deformation. This can be explained, when the contact load is largely supported by the liquid and not by contacting asperities. Then increase in contact load yields impression of the bulk material and not of the asperities. Evidence for this idea is given by a measurement presented by Visscher (1992 fig. 5.4 page 81) and by Hendriks (1993), where flattened but non-contacting asperities are shown. Also, Johnson et al. (1972) found for EHL contacts that the film stiffness is often much larger than the asperity and bulk stiffness. The same can be true for the present contact situation, in which the average thickness of the "squeezing" film is much less then the contact dimension (roughly 1 µm and 20 mm respectively). Therefore the liquid can not squeeze out of the contact and the film stiffness will be very large due to the liquid's low compressibility.

5. MEASUREMENTS WITHOUT LIQUID IN THE CONTACT AREA

Measurements were also performed on the dry contact situation. Then no liquid is present in the contact area and the roughness profile is measured inaccurately due to reflection on the glass (see section 3 above). However, only one reflecting surface (the glass to elastomer interface) is present in the

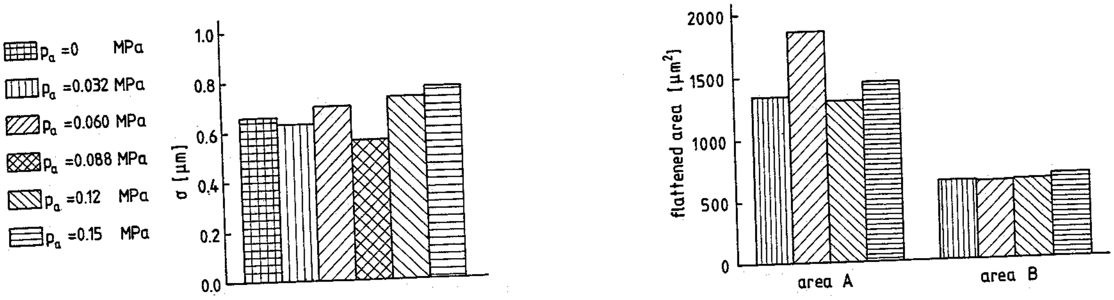

Figure 6 Standard deviation σ of the roughness height distribution and the derived dimensions of the flattened areas A and B, measured with liquid in the contact area at different values of the average contact pressure p_a. (The areas A and B were not present in the measurement at 0.088 MPa, due to horizontal shift between the measurements)

real contacts and the measurements are therefore reliable within these real contacts. These measurements can thus be used to determine the real area of contact, enabling experimental verification of the contact models like reviewed in section 2.1.

5.1. Results

Measurements were performed at six loads on the same piece of polyurethane as in section 4 (see fig. 3 for the undeformed roughness texture). The results of all six measurements are presented by Hendriks (1993) and by Visscher (1992) and two results are shown here in fig. 7. The roughness height distribution is not derived, because of the unreliability in the height measurement outside the real contacts.

5.2. Discussion

Fig. 7 clearly shows the increased flattening at higher loads and one can expect that the real area of contact can easily be derived from these plots. However, this is not as easy, due to an interesting feature found when looking more closely to the results, as will be discussed now.

Fig. 8 shows a cross section of fig. 7b, in which flattened areas are found on a length scale of the order of 10 μm. Within these flattened areas, smaller scale height variations are found. These height variations are

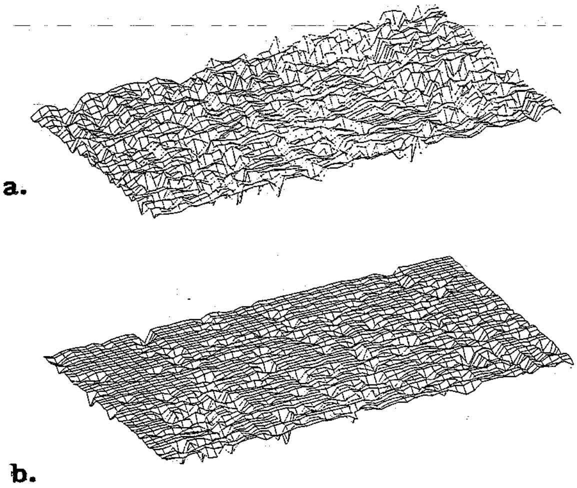

Figure 7 Measured surface plot of the deformed roughness texture of the polyurethane plate in dry contact with the glass plate.
Measured area = 512 μm × 256 μm;
Sample distance = 2 μm (in both directions);
a. Average contact pressure = 0.06 MPa
b. Average contact pressure = 0.12 MPa

significantly larger than the glass plate's roughness (of the order of 0.1 μm and 0.01 μm respectively) and can therefore not be explained by the glass plate's roughness. Instead, smaller scale "real contacts" appear to exist within a larger scale flattened area. A 1 μm scale "contact" is perhaps also not a real area of contact, but may also have smaller scale contacts within its area. This compares to the idea of describing the roughness texture by fractals, but smaller scale contacts (smaller than some micrometer) can not be resolved by the profilometer due to the focus spot diameter, which is about 1 μm.

A possible explanation for the existence of small scale roughness on large scale flattened areas is the larger asperity height to wavelength ratio at smaller length scales (see Hendriks, 1993). Interaction is then more significant at the smaller length scales than at the larger length scales and the smaller scale asperities still persist when the larger scale asperities are largely flattened.

A consequence of this feature is, that the real area of contact can in principle not be determined. Nevertheless, the "real area of contact" can in practice be derived for a particular length scale, ignoring the effects occurring at smaller scales.

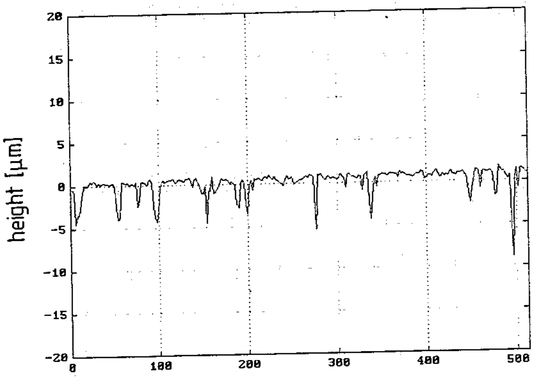

Figure 8 Cross section of fig. 7b.

Fig. 9 shows a first rough estimation of the real area of contact at a length scale of the order of 10 μm (Hendriks 1993). This curve is not a straight line, perhaps due to the fact that the different measurements were not performed on exactly the same part of the surface, but the real area of contact on this length scale is more or less proportional to the contact load.

Verification of contact models has not been performed yet, because more research is required (see section 6 and 7 below). Further investigation is in progress and will also include measurements at higher loads.

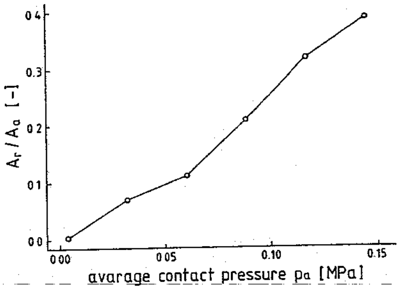

Figure 9 Ratio of the real area of contact A_r and the apparent area of contact A_a versus contact load.

6. DERIVATION OF THE REAL AREA OF CONTACT

Determining the real area of contact from a measurement, the following two points must be considered:

- The different length scales in the roughness texture;
- The reproducibility.

The former item is already discussed in section 5.2 above. The real area of contact can only be determined on a particular length scale. Consequently, one must first consider which length scale(s) is/are important for the problem considered and the measurement parameters (resolving power and measurement length) must be chosen accordingly.

How the real area of contact on a particular length scale can be determined accurately is still subjected to investigation and will be discussed in more detail by Hendriks (1993).

The latter item, dealing with the reproducibility of the measurements, also needs more investigation. Considering e.g. fig. 4b and 5a, a particular flattened area can emerge or disappear when a following measurement is performed on a slightly different part of the surface: e.g. area C in fig. 4 and area D in fig. 5. Consequently, the derived real area of contact can be different when measured on a different part of the surface.

Besides, a waviness with a wavelength of e.g. 1000 μm can yield differences in the real area of contact between parts of the surface in the valleys of the waviness and parts on the summits of the waviness: It is possible that contact only occurs on the waviness summits, when its amplitude is large compared with the roughness height variations. Then measurements must in principle be performed on a part of the surface larger than the wavelength of the waviness, but an objection can be, that the sample distance must be increased to keep the number of measurement points restricted to a practical level.

Finally, the reproducibility in determination of the dimension of one single area appears to be somewhat questionable, as it appears in fig. 6 that the dimension of area A is significantly larger at an average contact pressure of 0.060 MPa than at the other pressures, smaller as well as larger.

Further investigation on the determination of the real area of contact is necessary and in progress. More details will be presented by Hendriks (1993).

7. DISCUSSION ON THE EXPERIMENTAL METHOD

Finally some remarks will be made on the characteristics of the experimental method used.

As already mentioned in section 2.2 above, it is preferred to measure the whole deformed roughness texture instead of the real area of contact only. The reason is, that the different deformations at different length scales can then be studied, yielding better physical insight into the contact problem as illustrated in section 5.2. Using a method which only measures the real area of contact, only the larger scale "flattened areas", as e.g. shown in fig. 8, are found or only the smaller scale contacts, present on the larger scale flattened area, are determined, depending on the resolving power of the used device.

For the dry contact situation, the (deformed) roughness texture is not measured quantitatively well with the method used in this paper. However, the differences in deformation at the different length scales are shown qualitatively, which enables the derivation of the "real area of contact" (or: the flattening) at different length scales. Therefore this method is in essence suitable for further, more detailed investigation of the contact problem.

8. CONCLUSIONS

Optical profilometry is helpful to study both the wet and the dry contact of a rough elastomer and a glass plate. The conclusions of the measurements presented above will be listed below.

Measurements with liquid in the contact area

Measurements on a polyurethane surface show that the roughness height distribution is not affected by the load, after initial deformation has occurred at lower loads. Also, the size of flattened areas found in the measurements remains constant at increasing load.

An explanation for these results is probably, that a large part of the contact load is supported by the liquid and not by the contacting asperities.

Measurements on the dry contact

In the dry contact situation, contacting flattened areas are found and their size (of the order of 10 μm) is more or less proportional with the load. However, these "large scale" flattened areas are not smooth and therefore, different "real areas of contact" can apparently be found on different length scales.

The importance of this result is, that the "real area of contact" is only defined for a particular length scale and one must first consider which length scale(s) is (are) important, before the real area of contact is determined.

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REFERENCES

Bhushan, B., 1985a, "The real area of contact in polymeric magnetic media - I: Critical assessment of experimental techniques", *ASLE Trans.*, Vol. 28, No. 1, pp. 75-86

Bhushan, B., 1985b, "The real area of contact in polymeric magnetic media - II: Experimental data and analysis", *ASLE Trans.*, Vol. 28, No. 2, pp. 181-197

Bouwhuis, G., and **Braat, J.J.M.**, 1978, "Video disk player optics", *Applied Optics*, Vol. 17, No. 13, pp. 1993-2000

Bouwhuis, G., **Braat, J.J.M.**, **Huijser, A.**, **Pasman, J.**, **Rosmalen, G. van**, and **Schouhamer Immink, K.**, 1987, "*Principles of optical disc systems*", Adam Hilger Ltd., Bristol and Boston, 3rd ed. (1st ed. 1985), ISBN 0-85274- 785-3

Greenwood, J.A., and **Williamson, J.B.P.**, 1966, "Contact of nominally flat surfaces", *Proc. Royal Soc. London*, Vol. A295, pp. 300-319

Hendriks, C.P., 1992a, "*Meting van de vervormde ruwheid van elastomeren onder statische kontaktbelasting - deel 1: Dataverwerking en interpretatie*", Eindhoven Univ. Tech., The Netherlands, Report no. T&M D53

Hendriks, C.P., 1992b, "*Modellen van het statisch belaste, droge kontakt - Literatuuroverzicht*", Eindhoven Univ. Tech., The Netherlands, Report no. T&M D54

Hendriks, C.P., 1993, M.Sc. Thesis, Eindhoven Univ. Tech., The Netherlands (to be published)

Johnson, K.L., **Greenwood, J.A.**, and **Poon, S.Y.**, 1972, "A simple theory of asperity contact in elastohydrodynamic lubrication", *Wear*, Vol. 19, pp. 91-108

Lai, W.T., and **Cheng, H.S.**, 1985, "Computer simulation of elastic rough contacts" *ASLE Trans.*, Vol. 28, No. 2, pp. 172-180

Lee, S.C., and **Cheng, H.S.**, 1992, "On the relation of load to average gap in the contact between surfaces with longitudinal roughness" *Trib. Trans.*, Vol. 35, No. 3, pp. 523-529

Lubrecht, A.A., and **Ioannides, E.**, 1991, "A fast solution of the dry contact problem and the associated sub-surface stress field, using multilevel techniques", *J. Trib. (Trans. ASME F)*, Vol. 113, No. 1, pp. 128-133

Majumdar, A., and **Bhushan, B.**, 1991, "Fractal model of elastic-plastic contact between rough surfaces", *J. Trib. (Trans. ASME F)*, Vol. 113, No. 1, pp. 1-11

McCool, J.I., 1986, "Comparison of models for the contact of rough surfaces.", *Wear*, Vol. 107, No. 1, pp. 37-60

Onions, R.A., and **Archard, J.F.**, 1973, "The contact of surfaces having a random structure", *J. Phys. D: Appl. Phys.*, Vol. 6, pp. 289-304

Podbevsek, F.P., 1992, "*On the roughness deformation of elastomers under static load: Asperity interaction*", Report Eindhoven Univ. of Tech.

Struik, K.G., and **Chang, F.M.**, 1987, "Measurement of shape and roughness by a modified compact disc sensor coupled to a personal computer", *Proc. 4th Int. Seminar on Precision Engineering*, Cranfield Inst. of Technology, UK, pp. 81-90

Thomas, T.R., and **King, M.**, 1977, "*Surface topography in engineering: a state of the art review and bibliography*", BHRA Fluid Engng., Cranfield (UK), ISBN 0 900983 66 3

Vergne, Ph., **Villechaise, B.**, and **Berthe, D.**, 1985, "Elastic behavior of multiple contacts: Asperity interaction", *J. Trib. (Trans. ASME F)*, Vol. 107, No. 2, pp. 224-228

Visscher, M., 1992, "*The measurement of the lubricant film thickness and the roughness deformation of lubricated elastomers*", Ph.D. Thesis, Eindhoven Univ. of Tech., the Netherlands

Visscher, M., and **Struik, K.G.**, 1992a, "The measurement of the roughness deformation of elastomers under static load", *Proc. 8th. Int. Coll. "Tribology 2000"* (Organized by the Technische Akademie Esslingen, Germany), paper 9.6

Visscher, M., and **Struik, K.G.**, 1992b, "Optical profilometry of mechanically inaccessible surfaces", paper presented at the ASPE 1992 Annual meeting (to be published in *Prec. Engng.*)

Woo, K.L., and **Thomas, T.R.**, 1980, "Contact of rough surfaces: A review of experimental work", *Wear*, Vol. 58, pp. 331-340

Xian Ling, and **Zheng Linqing**, 1991, "A numerical model for the elastic contact of three-dimensional real rough surfaces", *Wear*, Vol. 148, pp. 91-100