Transactions on Engineering Sciences vol 24, © 1999 WIT Press, www.witpress.com, ISSN 1743-3533

Analysis of contact stiffness between metal ground surfaces using thin PET film

Isami Nitta, Takashi Hasegawa
Graduate School of Science and Technology, Niigata University, Ikarashi 2-nocho 8050, Niigata, 950-2181, Japan
Email: nitta@eng.niigata-u.ac.jp. hasegawa@tmtribo1.eng.niigata-u.ac.jp

Abstract

In a previous paper, we developed a thin polymer film method which was able to measure the real contact area. In this paper, this polymer film method was used to analyze the contact stiffness. In unloading and reloading processes, the real contact area and its distribution were measured by this method at each load. As a result, it turned out the non-uniform contact over the apparent contact area at the low normal load corresponded to rapid change in the contact stiffness. As the normal load was increased, the contact condition gradually approached the uniform contact, leading the contact stiffness to almost constant value. These measurements by the thin polymer film method indicated that the waviness had strongly influenced the contact stiffness more than the surface roughness did. In addition, we carried out the numerical simulation of the contact stiffness on the consideration of only the waviness. The simulated results were in good agreement with the experimental results.

1 Introduction

A purpose of this research is to clarify whether a cause of a decrease in static contact stiffness in the vertical direction is surface roughness or waviness. In order to access the contact stiffness, a load-displacement curve of a contact interface under examination, shown in Fig.1, has to be obtained. Usually the contact stiffness is based on the unloading-reloading curves in Fig.1, not based on the first loading

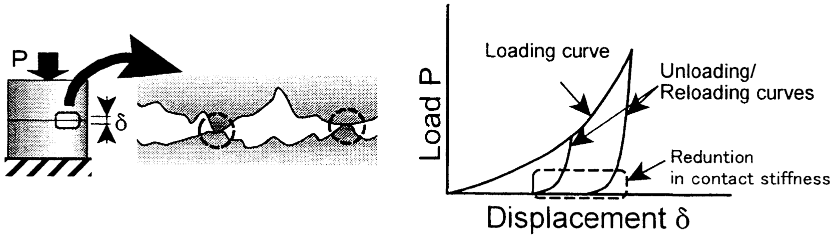

Figure 1: A typical load - displacement curves of solid surfaces in contact

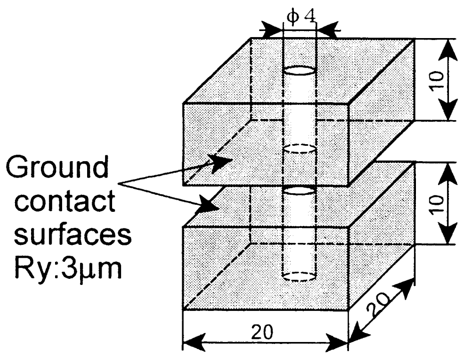

Figure 2: Shapes and sizes of the specimens used

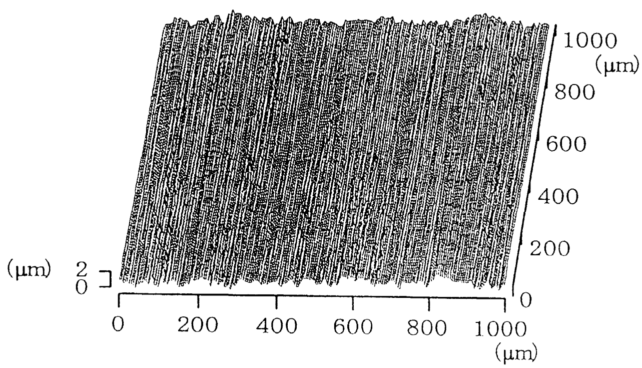

Figure 3: Three dimensional surface profile of the S45C ground surface, Ry 3μm

curve.

Thornley et al showed that a presence of the contacting surfaces decreased the stiffness[1]. Afterwards, the analysis of this phenomenon became active. In 1965 Greenwood and Wilamson succeeded in calculating the load-displacement relationship of the contacting interface on the assumptions that all surface asperities were spherical shape having the same radius and their peaks were distributed according to the Gauss distribution[2]. The GW model seemed to be reasonable. Afterwards, many researchers came to think that the load-displacement curve was theoretically obtained if the deformation characteristic of the asperity and the probability density function of the asperity tips were determined[3,4]. Thus, the waviness has been omitted in almost all case of accessing the contact stiffness, although the distinction between roughness and waviness is arbitrary. In a previous paper[5], the authors examined the contact stiffness between a superconducting wire and a spacer of glass fiber reinforced plastics, GFRP. It was found out that the waviness of the GFRP spacer markedly affected the contact stiffness in the unloading and reloading processes. From this analogy, it can be predicted that the waviness also will largely affect the contact stiffness even for a metal-metal combination.

In this paper, metallic ground surfaces having almost same roughness and different waviness were prepared to measure the load-displacement curves in the unloading and reloading processes. The computer simulation of the load-displacement curves on consideration of only the waviness were carried out and the experimental and calculated curves were compared with each other. In addition, contact patterns, namely, distributions of the real contact area, were measured by the polymer film method that we developed in previous work. As a result, It was found that the waviness affected the contact stiffness more than the roughness did.

2 Experimental details

2.1 Specimens

Figure 2 shows shapes and sizes of the specimens used in this paper. Materials of the specimens were mild carbon steel S45C and stainless steel SUS304. Contact surfaces of the upper and lower specimens were ground to the roughness, Ry, of 3 μm. In the experiments the two specimens were set so that the ground directions of the upper and lower specimens were at right angles with each other. The holes were made at the centers of the specimens to measure the displacements.

Figure 3 shows a picture of the typical surface roughness of the S45C specimen obtained by repeated stylus profilometry. The three-dimensional profile maps of the other specimens were similar to this. Figure 4 shows waviness of each specimen obtained by repeated stylus profilometry and a moving average method. Specimen pairs of No.1 and upper specimens of No.2 for both S45C and SUS304

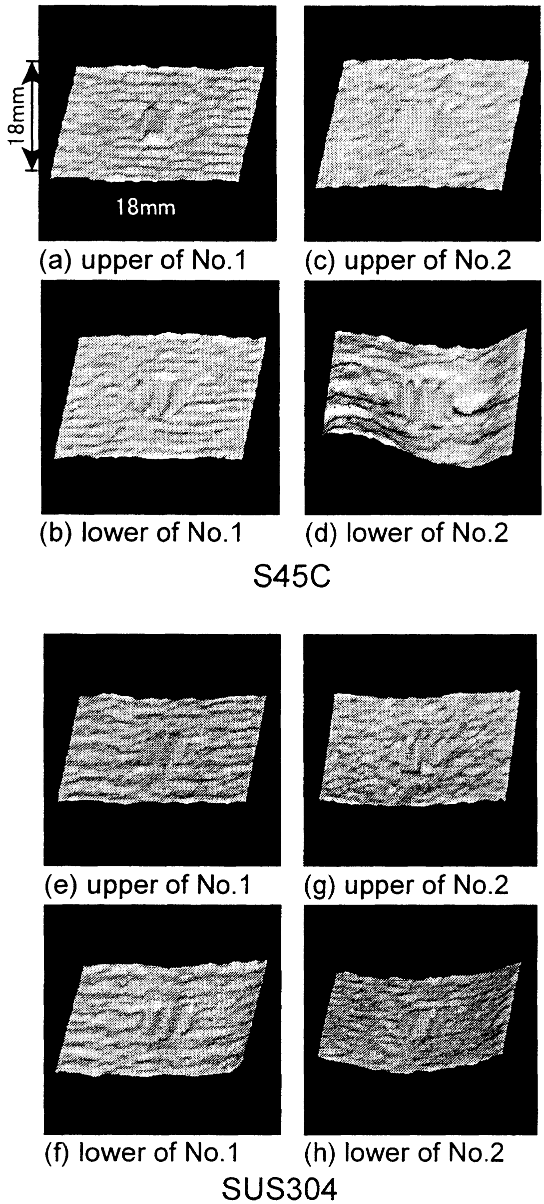

Figure 4: Waviness of each specimen surface for S45C and SUS304, produced by some smoothing of the profile curves

Transactions on Engineering Sciences vol 24, © 1999 WIT Press, www.witpress.com, ISSN 1743-3533

had less waviness. Only the lower specimens of the No.2 pairs had larger waviness, about 5μm in peak to valley value over whole apparent contact area. For example, the S45C specimen pair of No.2 corresponded to Fig.4(c) and Fig.4(d) with less and larger waviness.

2.2 Experimental apparatus

Figure 5 shows a schematic diagram of an experimental apparatus. Details of the

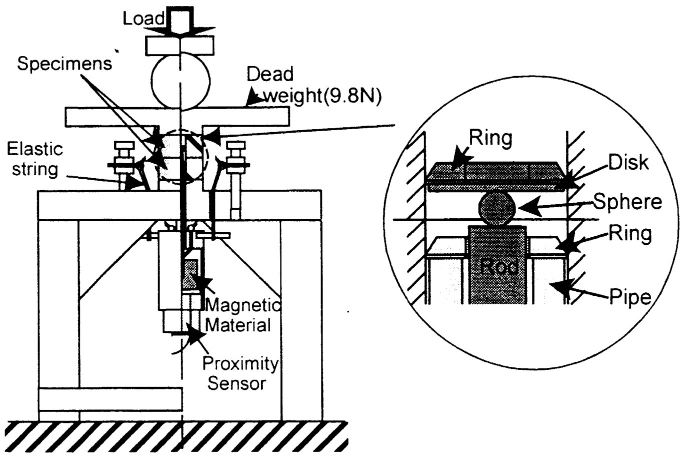

Figure 5: An experimental apparatus

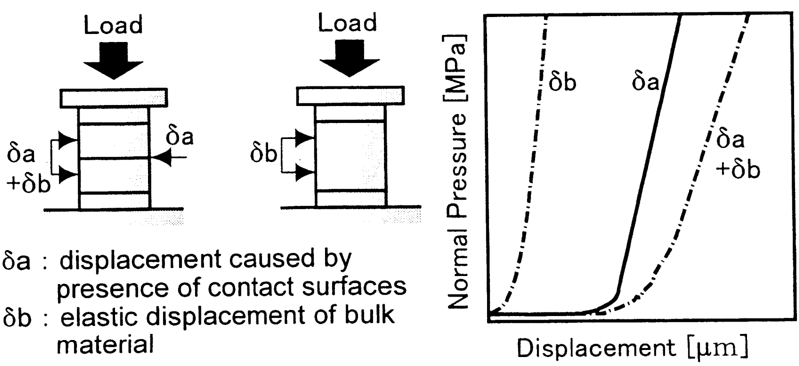

Figure 6: Explanation of the displacement used in this paper

upper and lower specimens are also shown. Two rings were attached in the holes of the specimens near the contact interface. A distance between the two rings, when the two specimens were brought into contact, was 3.6 mm. The displacement of the upper ring was transmitted to the magnetic material under the lower specimen through the sphere and the rod, while the displacement of the lower ring to the proximity sensor through the pipe. Thus, the relative displacement between the proximity sensor and the magnetic material could be regarded as the relative displacement between the upper and lower rings. The rod and the pipe were always pulled upward by the force of elastic strings. A dead weight of 9.8 N was put on the upper specimen to prevent the two specimens from being moved by the elastic strings. The proximity sensor was calibrated with an electric micrometer before the experiments. The apparatus in Fig.5 was placed on the hydraulic loading unit. Signals of the proximity sensor and the loading unit were linked to a microcomputer.

2.3 Experimental procedures

The relative displacement measured consist of displacements δa and δb, as shown in Fig.6. The displacement δa is caused by the presence of the contact interface. The displacement δb is due to the elastic displacement of the bulk between the two rings. Thus the displacement δb could be measured, if a specimen without the contacting surfaces was used. Hereinafter we use the term 'displacement' to indicate the displacement δa.

In the experiments a maximum contact pressure was 80MPa. The load-displacement curves during three loading-unloading cycles were measured for each specimen pair.

The rod and the pipe were removed from the specimens after measuring the displacements. A polyethleneteraphthalate, PET, film was inserted between the two specimens and pressed to measure the distribution of the real contact area at a given contact pressure. The PET film of 0.9 μm thickness was plastically indented by the surface asperities at the real contact points. Thus after unloading we can indirectly obtain the distribution of the real contact area if the indented area on the PET film is measured by image processing.

3 Experimental results

Figure 7 shows the load-displacement curves for the S45C specimen pairs of No.1 and No.2. A slight hysteresis between the first loading and the unloading curves is recognized. In the specimen pair of No.1, the displacement rate, defined as a ratio of displacement increment to a unit contact pressure, gradually decreased with the contact pressure up to the contact pressure of about 5MPa and it became constant over 20MPa. The reason why the displacements at the maximum pressure, 80MPa, are different from each loading process is due to movement of the origin of the

Transactions on Engineering Sciences vol 24, © 1999 WIT Press, www.witpress.com, ISSN 1743-3533

displacement when fully unloaded. The displacements of the specimen pair of No.2 was larger than that of the specimen pair of No.1 since the waviness of the specimen pair of No.2 was larger than that of the specimen pair of No.1. The

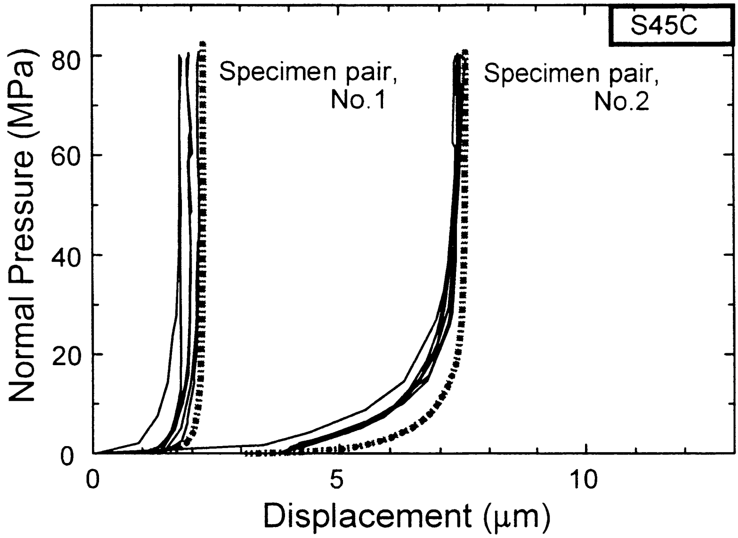

Figure 7: Load - displacement curves for the S45C specimens

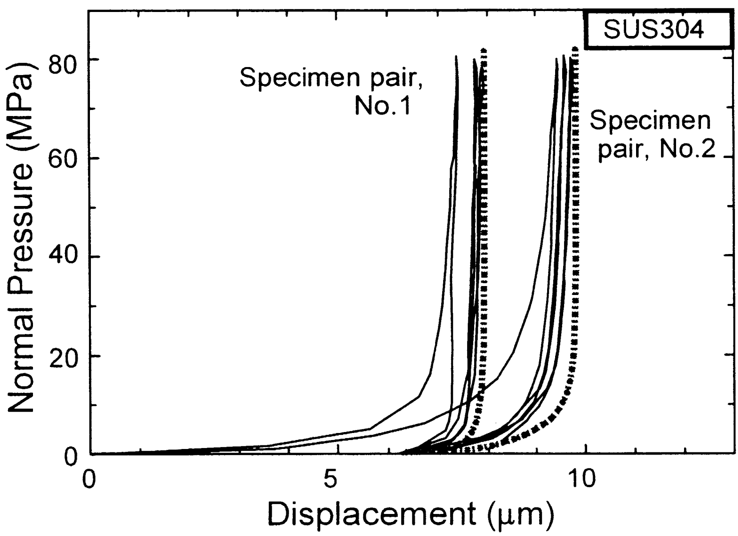

Figure 8: Load - displacement curves for the SUS304 specimens

displacement rate of the specimen pair of No.2 gradually decreased up to the contact pressure of 30MPa. It was almost constant over 40MPa.

Figure 8 shows the load-displacement curves for SUS304 specimen pairs of No.1 and No.2. The hysteresis between the first loading and the unloading curves was

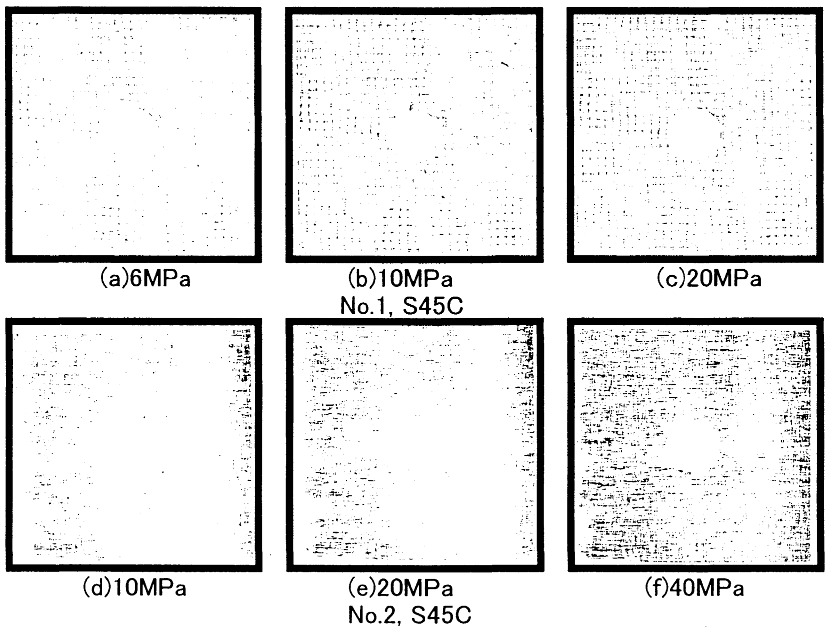

Figure 9: Distributions of real contact area for the S45C specimens at each contact pressure, measured by the thin polymer film method

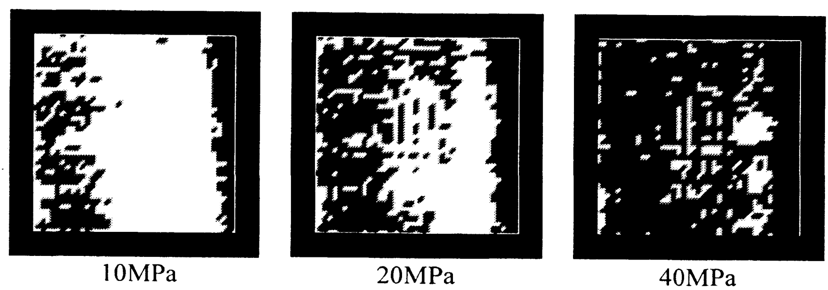

Figure 10: Distributions of real contact area for the S45C specimen pair of No.2, calculated by FEM on consideration of only waviness

Transactions on Engineering Sciences vol 24, © 1999 WIT Press, www.witpress.com, ISSN 1743-3533

larger than that of S45C. The specimen pair of No.2 having larger waviness deformed more than specimen pair of No.1 as in the same way as S45C.

Fig.9 demonstrates the measured distribution of the real contact area of S45C. Black parts in this figure correspond to the real contact area. The distribution of the specimen pair No.1 was not uniform at the apparent contact pressure of 6MPa. It became, however, almost uniform at 10MPa. In the case of the specimen pair of No.2 it was not uniform even at 20MPa but uniform at 40MPa. It can be found from Fig.7 and Fig.9 that the displacement rate is affected by the distribution of the real contact area, that is, the waviness.

4 Calculation of the displacement based on the waviness

The load-displacement curves in the unloading and reloading processes were obtained by the finite element method taking only waviness into consideration. Table 1 demonstrates mechanical properties of S45C and SUS304. For the FEM analysis the contacting surface was equally divided into 20 sections in both horizontal and vertical directions. In the depth direction the specimen was unequally divided into 10 sections: finer meshes toward the surface.

Table 1 Mechanical properties of S45C and SUS304

	Young's modulus	Poisson's ratio
S45C	206 GPa	0.3
SUS304	190 GPa	0.3

Dotted lines in Fig.7 show the calculated curves by the FEM. It is found that the calculated curves are qualitatively equal to the measured ones in both specimen pairs of No.1 and No.2, although the origins of the calculated curves were moved to the right direction. The reason why the calculated displacements are smaller than the measured ones is to omit the surface roughness in the calculation. In the specimen pair of No.1 the displacement rate gradually decreased up to about 4MPa. The same phenomenon was observed in the measured result. In the specimen pair of No.2 the displacement rate became smaller up to about 30MPa. Over 30MPa the displacement rate remained almost constant. As mentioned above, the contact surfaces were assumed to have no surface asperities. Thus, the displacement rates in the calculation are slightly smaller than those in the experiment over 30MPa. It is because of the elastic deformation induced by the surface asperities. The same things as in the case of S45C are recognized in SUS304.

Figure 10 shows the distributions of the real contact area predicted from the calculation. They are found to be in good agreement with the experimental ones.

5 Discussion

Form the above experiments, it was found that the primary factor that decreased the contact stiffness was the waviness. The surface roughness, that is, the surface asperities, causes the contact interface to largely deform in the first loading process, because the surface asperities will be plastically deformed at their tips. However, the asperity tips will elastically deform in the next unloading process. The elastic deformation based on the surface asperity is smaller than that based on the waviness. The elastic deformation based on the waviness is found to have large scale since the waviness induced the bulk deformation as shown in Fig.11.

Therefore, the waviness needs to be made smaller for the better contact stiffness. So far many researchers concerning the contact stiffness have given their attention to the surface roughness and ignored the waviness. One reason for that is no realistic way to measure the waviness over a wide range of the apparent contact area. In this work, the 3-dimensional stylus profilometry was used to measure the surface profile and computed the waviness. It took about three hours to measure one apparent contact area. Thus, the development of quick measurement technique of the whole apparent contact area is a key technology to promote this kind of work.

6 Conclusions

In order to examine which affects most the contact stiffness, roughness or waviness, the load-displacement curves were measured using the ground surfaces of S45C and SUS304. The load-displacement curves were also calculated by the finite element method taking only waviness into consideration. As a result, it was found that the elastic deformation caused by the waviness was larger than that by the surface roughness in the unloading and the reloading processes. Thus the waviness affects the contact stiffness more than the roughness does. Therefore, the waviness needs to be made smaller for the better contact stiffness in the solid contact.

References

1. Thornley, R.H., Connolly, R. , Barash, M.M. & Koenigsberger, F., The effect of surfaces topography upon the static stiffness of machine tool joints, Int. J. Mach. Tool Des. Res., **5**, pp. 57-74, 1965.

2. Greenwood, J.A. & J.B.P. Williamson, Contact of nominally flat surfaces, Proc. R. Soc. London Ser.A, **295**, pp. 300-319, 1966.

3. So, H. & Liu, D.C., An elastic-plastic model for the contact of anisotropic rough surfaces, Wear, **146**, pp.201-218, 1991.

4. Myshkin, N.K., Petrokovets, M.I. & Chizhik, S.A., Simulation of real contact in tribology, New directions in tribology - Plenary and invited papers from the first world tribology congress, pp. 329-337, 1997.

5. Isami, N., Shiobara, H. & Iwabuchi, A., Contact stiffness of glass fiber-reinforced plastics(in Japanese), Cryogenic engineering, **33**, pp. 290-299, 1998.