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Real contact area and friction property of rubber with two-dimensional regular wavy surface

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ABSTRACT

The elastic contact of two-dimensional regular wavy surface with a flat surface and its frictional behaviour are studied by using three types of blocks of silicone rubber as specimen. The friction force as well as the real contact area is markedly affected by the shape of the valley of the wavy surface. In the case of the specimens with U-shaped trough, each contact spot touches the neighbours before complete contact, resulting in the extinction of the percolation channels allowing the fluid flow. If the tests were conducted in wet environment, the rate of increase in the real contact area with the load shows sharp drops when each contact spot touches the neighbours, which inhibits the increase in the friction force.

1. Introduction

In general, contact between solids is discontinuous and the real area of contact is a small fraction of the nominal contact area [1]. Greenwood and Williamson [2] have proved theoretically that the real area of contact A_r is almost linearly proportional to the load W by assuming all the contact asperities had spherical surfaces of the same radius and the heights of the asperities were statistically distributed. A linear relation was also obtained when the distribution of radii of spherical asperities were taken into the consideration [3]. These results indicate that information related to the asperity summits becomes important factors to evaluate the growth of the real contact area.

On the other hand, for soft solids, such as rubber, nearly full contact may occur at the interface. Archard [4] had shown from his friction test using crossed cylinders of polymethylmethacrylate (PMMA) that at low loads, the coefficient of friction was constant and independent of the normal load, however when the load was increased, the coefficient of friction fell with increasing load. This result suggested that it is very necessary to make clear the interaction effects between the laterally spaced asperities when the real/apparent contact ratio exceeds characteristic one. Hyuu et al. [5] have studied the elastic contact between a randomly rough surface with a flat surface in a range to the lager real/apparent contact ratio by using finite-element method. Yang and Person [6] have developed multiscale molecular dynamics approach to study the real contact area and interfacial separation from small contact to full contact. Both results have shown that the slope of real/apparent contact ratio versus mean contact pressure curve tends to decrease with increasing the contact pressure. Furthermore, Manners [7] had pointed out that a random surface could not achieve the complete contact under a finite pressure.

Different approaches to elucidate the relation between the real contact area and the load up to the complete contact are to consider the contact of regular wavy surfaces. Westergaard [8] had solved theoretically the contact problem of one-dimensional regular wavy surface with sinusoidal profile. This profile is the only one to have been solved in a closed form up to the complete contact. The authors [9,10] have examined in previous study the elastic contact of various types of one-dimensional regular wavy surfaces including sinusoidal and triangle profiles as shown in Fig. 1 by using finite element method. They have shown that the dependence of the size of the contact area on the load was markedly affected by the shape of the valley of the wavy surface. That was, in the case of the surface with U-shaped trough as shown in Fig. 1(a) and (c), the slope of real/apparent contact ratio versus mean pressure curve tended to infinite when the real contact area approached the complete contact as shown by Westergaard [8] for the sinusoidal profile. On the other hand, in the case of the surface with V-shaped trough as shown in Fig. 1(b) and (d), the slope tends to 0, i.e. the contact pressure to obtain the complete contact raised to an infinite value as pointed out by Manners [7] for a random surface. Even though the statistical approach of randomly rough surface describes the real case more closely, a simpler model is expected to provide a valuable physical picture of the dependence of contact area on normal load. Furthermore, engineering surfaces machined by a face milling or by a lathe

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are characterized by an array of tool marks. It would be worth considering the contact of regular wavy surfaces.

Johnson et al. [11] examined the contact of two-dimensional sinusoidal surface by numerical and experimental studies and represented that with increasing the load, each contact spot changes the shape and size, and then touches the neighbours before complete contact. Although in their experiment, small holes were drilled in the contact body to release trapped air, the results give us very useful information to understand the behaviour of the contact area growth near the complete contact, since the coalescence of the discrete contact spots under the contact of two-dimensional rough surfaces plays an important role in the leakage phenomenon of fluid from the mated surfaces. The authors [12] had shown by comparing the real contact area growth of three types of two-dimensional regular wavy surfaces under atmosphere and decompression environments that the formation of the percolation channels allowing the leakage of fluid from the mated surfaces were also markedly affected by the shape of the valley of the wavy surface. Such the shape of the valley will surely become a crucial factor for the frictional behaviour as well as for the real contact area.

The objective of this study is to elucidate how the friction force can be controlled by the texture design of the contact surface. Sliding tests between three types of blocks of silicone rubber with two-dimensional regular wavy surface and flat glass surface were conducted under dry and wet conditions. The effects of the surface profile and existence of fluid between mated surfaces on the friction force were studied by means of grasping these effects on the growth of the real contact area. It have been known that the friction of polymers can be attributed to two sources, that is, a deformation terms and an adhesion term originated from the interface between mated surfaces [13]. Recently topographic dependence of friction with micro- and macro-patterned elastomer has been investigated by close surveys [14–21]. These results give us great help to understand the possible mechanism for the cause of the friction. Furthermore, there have been several studies to approach the mechanism of fluid leakage in seals and of fluid flow at the interface based on the percolation theory [22–25]. Nevertheless, little attention seems to have been paid to the shape of the valley. In this study, we focused on how the surface profile, particularly the shape of the valley, controls the formation of the percolation channel and the contact area, and then we clarified its contribution to the friction property.

2. Experimental procedures

2.1. Specimens

Three types of blocks of silicone rubber with different type of surface profile were used as specimens. The block had a shape of quadrangular prism with a base 9 mm × 9 mm and a height of 5 mm. Fig. 2 shows the surface profiles of the specimens measured using a 3D laser profilometer. The preparation procedure of these specimens was the same as the previous study [12]. In the case of the specimen A, a metal mould (A) was manufactured by using a ball nose cutter controlled by machining centre to form a two-dimensional sinusoidal profile expressed by the following equation:

$$z(x,y) = \frac{R}{2}\cos\left(\frac{2\pi x}{\lambda}\right)\cos\left(\frac{2\pi y}{\lambda}\right) \tag{1}$$

The wavelength λ is 3 mm and the maximum height R is 75 μm. In the case of specimens B and C, at first, a metal mould (B) was manufactured by the rotating ball nose cutter with the tip radius of 15 mm being pressed into its surface periodically in a staggered arrangement with a pitch of 3 mm. Second, a resin mould (C) was prepared to which the surface of the metal mould (B) was transferred. Then liquid silicone was poured on these three moulds simultaneously. And the specimens were peered off from the moulds after the liquid silicone solidified at room temperature. That is, specimens A–C have surfaces to which the surface profiles of the moulds A–C were transferred, respectively. As the result, in the case of specimen B, spherical asperities are arranged periodically on the surface and there exist V-shaped troughs between the asperities. And specimen C has a surface with the reversed profile of specimen B. From a geometrical consideration, the theoretical maximum asperity height of specimens B and C becomes 75.2 μm. It had been confirmed in previous study that surface profiles prepared by using these moulds showed good agreement with the geometrically ideal profile, respectively. However, it becomes clear from Fig. 2 that the specimen B prepared in this study has a slightly concaved surface and the generation of casting flash is observed at the edge of the surface of specimen A. Although these geometrical errors would affect the contact status, it will be shown below that the errors did not affect the core of the subject in this study.

Tensile test of silicon rubber was also conducted using specimens in a shape of narrow strip with a width of 10 mm, a

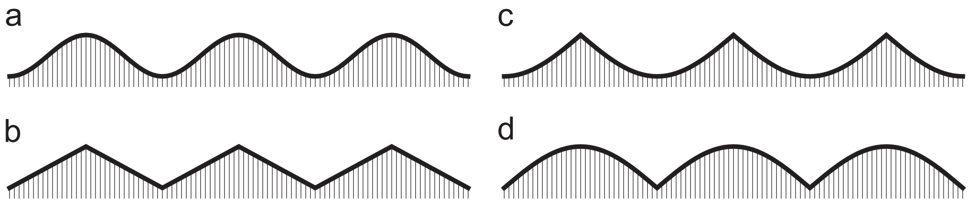

Fig. 1. Typical profiles of one-dimensional regular wavy surfaces: (a) sinusoidal; (b) triangle; (c) sequence of U-shaped valley; (d) sequence of V-shaped valley.

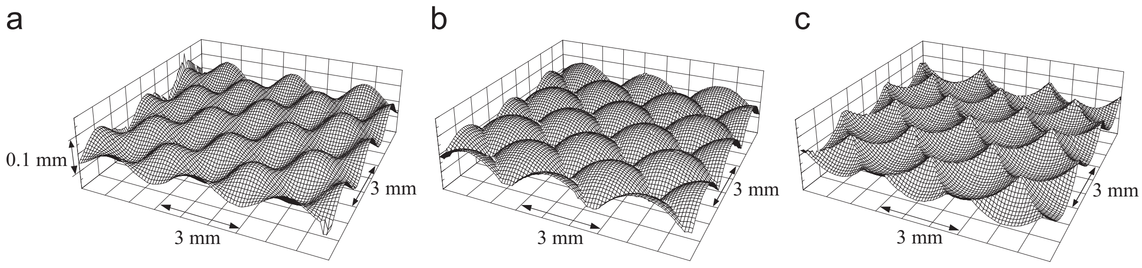

Fig. 2. 3D area maps of specimens before experiment: (a) specimen A; (b) specimen B; (c) specimen C.