한국윤활학회지(1996), 제12권 제3호
Journal of KSTLE(1996) Vol. 12, No. 3, pp.26~32

The Effects of Elastomer Layer on Minimum Friction Coefficient

Kyu-Sik Cho

Department of Mechanical Engineering, Korea Air Force Academy

최소마찰계수에 대한 Elastomer층의 영향

조 규 식

공군사관학교 기계공학과

요　약—오랜 역사에 걸쳐 연구자들은, 마찰력은 주로 접착에 의한 것으로 믿어 왔으며 이러한 주장은 실험적으로 증명되지 못했다. 한편, 미끄럼 두 표면 사이의 건식 마찰력은 두 표면 사이의 기계적인 상호작용에 의한 것으로 알려져 있다. 이 연구에서는 두 표면 사이의 기계적 상호작용을 제거함으로써 마찰계수를 감소시키는 방법을 제시하였다. 매끄러운 경한 표면에 얇은 elastomer층을 입힌 비윤활 최소 마찰계수에 대한 본 실험결과는 앞으로 정밀기계부품의 충격을 받는 부위에 응용할 수 있을 것으로 기대된다.

Key words—Dry Sliding Surfaces, Mechanical Interections, Mechanical Effects, Hard Smooth Surface.

1. Introduction

In precision machines and instruments, such as those used in the semiconductor industry, small motions are needed in a dust-free environment. In such applications low friction is needed to prevent stick-slip motions. Also, in medical applications, lubricants cannot be used in certain pumps for obvious reasons. In other applications high friction is desirable, such as in automobile brakes and the like. Throughout the history of humankind, people have cleverly controlled friction to move heavy materials around, the pyramids of Egypt being a good example. However, we are yet to fully understand what causes friction and how to control frictional force without lubrication.

For many decades especially since the work of Bowden and Tabor [1], the notion that friction is caused by adhesion between sliding surfaces has guided the thoughts of tribologists and others. This unfortunate belief has channeled tribology research in wrong directions and has delayed the possibility of lowering friction through surface.

1-1. Engineering by many decades.

Such and his co-workers [2-5] have shown that friction, in a typical engineering situation, is controlled by three factors: plowing of the sliding surface due to the wear particles generated during sliding as well as by other particles, deformation of asperities, and adhesion. The first two are of mechanical origin, whereas adhesion is due to the interatomic interactions, including the formation of solution of the materials in contact. plowing of the sliding interface occurs when wear particles generated at the interface penetrate into both materials and form plowing grooves to accommodate the sliding action. Consequently, the frictional force is initially low, but increases as the number of wear particles entrapped at the interface increases. the plowing action makes the wear particle agglomerate and grow [6]. The situation gets worse in a kinematically constrained system such as a shaft in a bearing where the interface cannot move in the direction of the load to accommodate the particles [7,8].

In order to separate the contributions of mechanical factors to friction from that of adhesion, a number of simple experiments were performed by Suh and his students [2-5]. The simplest experiment was to eliminate the wear particles form the interface by brushing them away from the sliding surface or by blowing them with a jet of air. It was shown that as soon as the wear particles are removed, the friction at the dry sliding interface abruptly decreased [9]. In other extensive experiments, "undulated" surfaces were created to trap wear particles at the sliding interface by creating, through a lithographic technique, an array of pockets of approximately 50 μm deep and 100 μm by 100 μm square in a checkered arrangement [2]. Undulated surfaces were also created by machining micro-grooves on the surface [10]. The use of these undulated surface on identical metal surfaces lowered the coefficient of friction to the same level as the boundary lubricated surfaces, i.e., 0.1.

Careful examination of worn undulated surfaces has indicated that even at such a low friction force, there were micro-plowing grooves, indicating that the friction was caused by plowing of the flat pad surface of the undulated surface. Also carefully polished surfaces which were slid against each other in a boundary lubricant also shows micro-plowing grooves. Furthermore, the frictional force is nearly identical, being approximately 0.1 to 0.2.

Having demonstrated that the coefficient of friction can be reduced from 0.7 to 0.1 by eliminating plowing by wear particles and that even the low friction observed with the undulated surface is due to the micro-flowing action, one must ask what would be the coefficient of friction if all mechanical effects could be eliminated fro, the sliding interface. It should be low, but how low?

The purpose of this paper is to propose a hypothesis for eliminating mechanical effects and obtaining very low friction, and to present experimental results which show that the hypothesis is reasonable.

1-2. Hypothesis

Wear particles are always generated from sliding interface, because all engineering surfaces have asperities at the atomic scale [12]. These atomic-scale asperities locally deform the surface leading to permanent displacement of atoms of the counterface, i. e., plastic deformation. Therefore, we need a material that can undergo a large elastic deformation to accommodate the kinematic requirements at the sliding interface and yet does not consume any energy by deforming only elastically. Also the atoms at the surface should be bound to each other covalently, which is a directional bond, and thus cannot readily adhere to the counter-surface. The material must also be hard so as to withstand the normal load and not undergo large visco-elastic deformation which also consumes energy. Unfortunately such a material does not exist. Very hard materials like diamond fulfill some of these requirements but not all; it cannot accommodate the asperities of the counterface by elastically deforming. Other hard materials are too brittle and they can generate surface cracks, leading to wear and high friction.

To create a model material, a thin elastomeric coating was applied on a smooth hard substrate to meet all the desired requirements. Elastomer was chosen to allow large elastic deformation but limit viscoelastic deformation by controlling the cross-linking density. The hard substrate supports the normal load and prevents a large bulk deformation.

There is a conceptual difference between the present hypothesis and the idea of using soft films as solid lubricants as reported in the literature [13-15]. A solid lubricant is meant to shear easily and deform plastically even by a small tangential force and therefore reduce the resistance of the interface to relative motion. The damage to the surface during sliding is natural and expected by design. The typical friction coefficient of such surfaces in dry sliding is about 0.1 - 0.2. However, the model material sought in this study is designed to reduce the resistance to the relative motion by elastic deformation at the surface and not undergo bulk plastic deformation.

2. Experimental

2-1. Materials and Testing

A hard substrate in the form of a smooth silicon wafer was coated with a thin layer of polyurethane for the purpose of creating an elastomeric surface layer that can deform elastically, is covalent, and yet does not undergo bulk deformation. A thick coating behaves as a bulk material, which can undergo large deformation during loading as well as sliding. Such deformation can lead to large friction forces and tearing. A description of the polyurethane coating, the silicon wafers and the glass balls used as pins are

Table 1. Description of the polyurethane coating

Coating material	Bayhydrol 121
Coating appearance	clear
Tensile strength (MPa)	46.19
Elongation at break (%)	150
Modulus at 100% elongation (MPa)	34.89
Hardness (pencil)	2H

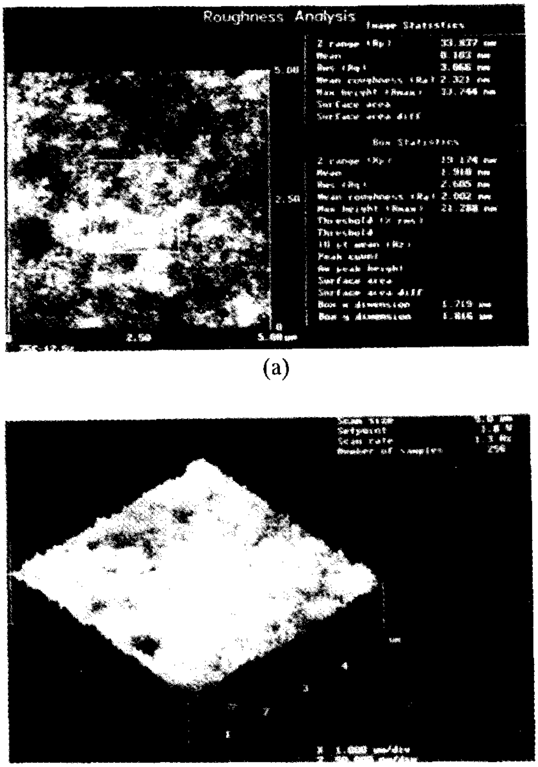
Table 2. Properties of silicon wafers and glass pins

Material	Hardness (MPa)	Modulus (GPa)
Silicon wafer (100) orientation	8,000	110
Glass balls (4 mm diameter)	6,000	70

given in Table 1 and Table 2.

Bayhydrol 121, a polycarbonate-based aqueous polyurethane (PU) dispersion comprising polyurethane, N-methyl pyrrolidinone, and triethylamine available from Miles Industries, was coated onto the single crystal silicon wafers by dipping the wafers into PU solutions. This elastomer was chosen for ease of coating. The PU solutions were prepared by diluting Bayhydrol 121 with deionized water and by mechanical stirring. Each solution contained 0.5% by volume of a nonionic surfactant, a fluoroaliphatic polymeric ester, to improve wetting of the of the silicon surface by the PU solutions. Silicon wafers (100 orientation) that had been rinsed with deionized water and allowed to air dry were mechanically lowered into PU solutions by attaching one end of a thread to the wafer and the other end of the thread to a motor that controlled the rate of the wafer's descent into and ascent out of the PU solution, limiting it to approximately 0.2 cm/s. Coated wafers were air dried overnight (about 15 hours) and then were baked at 140°C. The baking temperature, which affects the crosslinking density of the film, was varied to study its effect on the friction coefficient. In addition, some coatings baked at 140°C were electron beam irradiated and were friction tested later. The entire process of making solutions, coating silicon wafers, and air drying samples was done in a class 100 controlled environment to minimize the effect of airborne particles.

The thickness of the layer ranged from 0.09 μm (made from 5% PU solution) to 0.25 μm (made from 12.5% PU solution). The film thickness measurement was performed using a surface profilometer steps down from the film onto the surface of the silicon was measured. An image of a coating with 0.25 μm thickness which is taken with an AFM under the tapping mode is shown in Fig. 1a&b. The features in the 3-d image are enhanced about 20 times in the z-direction. The peak-to-valley and RMS roughnesses of the film were 34 nm and 3 nm respectively.



(a)

(b)

Fig. 1. Two (a) and three (b) -dimensional views of the surface of a 0.25 μm thick coating of Bayhydrol 121 on silicon.

Dry sliding friction tests were conducted on coatings of varying thickness and normal loads using a standard reciprocating pin-on-disc tribometer. The normal load was varied from to 1 to 5 grams. The sliding speed during all tests was 0.3 cm/s.

2-2. Results

The friction coefficient as a function of sliding distance is plotted in Figs 2. through 5. The baking

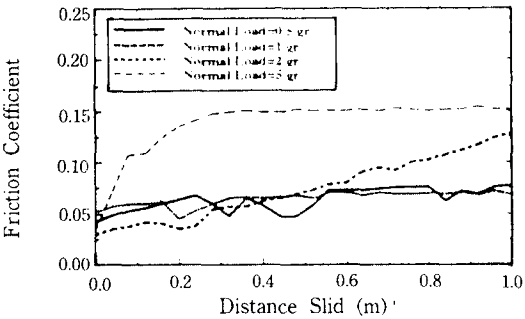


Fig. 2. Plot of friction coefficient vs. distance slid for four different normal loads. Coating Thickness= 0.09μm.

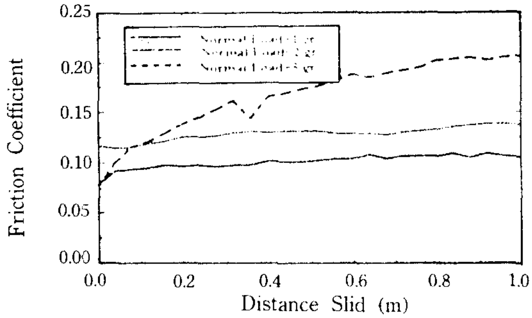


Fig. 3. Plot of friction coefficient vs. distance slid for three different normal loads. Coating Thickness= 0.12μm.

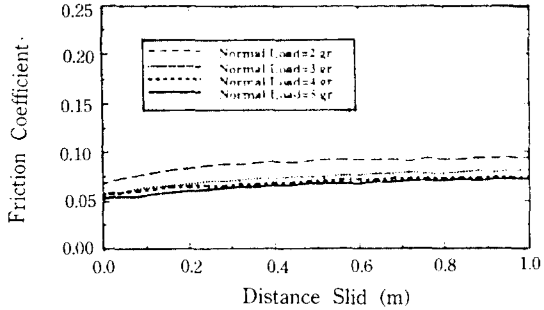


Fig. 4. Plot of friction coefficient vs. distance slid for three different normal loads. Coating Thickness= 0.2μm.

temperature was 140°C but the thickness and the normal load were varied.

Figure 2 is for the case of a 0.09 μm thick coating. when the film was 0.12 μm friction coefficients as shown in Fig. 3 were obtained. Fig. 4 and Fig. 5 correspond to 0.2 μm and 0.25 μm thick coatings.

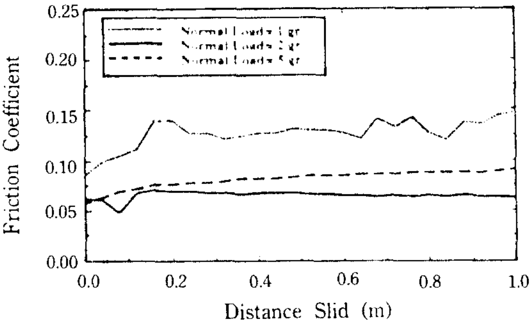


Fig. 5. Plot of friction coefficient vs. distance slid for three different normal loads. Coating Thickness= 0.25μm.

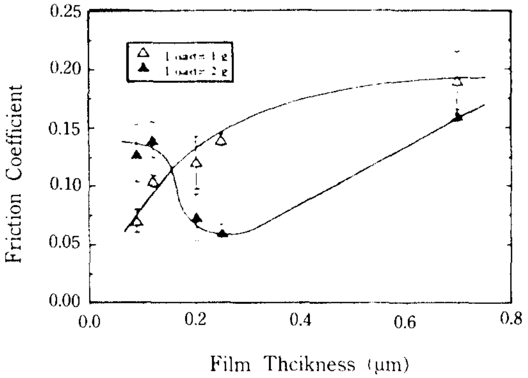


Fig. 6. Dependence of friction coefficient on the film thickness for 1g and 2g normal loads. Distance slid=1m.

The effect of film thickness on friction coefficient is shown in Fig. 6 for a 1 g and 2 g normal load. For the 2 g normal load friction coefficient shows a minimum when the film thickness is less or more than 0.2 μm it increases to a high value. On the other hand, for the 1g normal load, as the thickness decreases, the friction coefficient decreases with a minimum value at a film thickness of 0.09 μm.

Unbaked coatings along with coatings baked at different temperatures were also used to carry out experiments. Also some coatings baked at 140°C were electron beam irradiated to further increase the cross-linking density of the film. No direct measurement of the cross-linking density was performed. The friction coefficient of six different films including unbaked, baked, and baked at 140°C and irradiated is shown in Figs. 7 and 8. The film thickness was 0.25 μm. For a 2 g normal load, the unbaked or the baked at 75°C film gave a friction coefficient reaches a

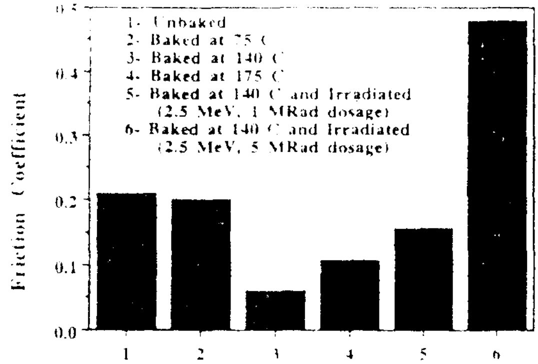


Fig. 7. Friction coefficient of 0.25μm thick films prepared under different baking and irradiation conditions. Normal Load=2g.

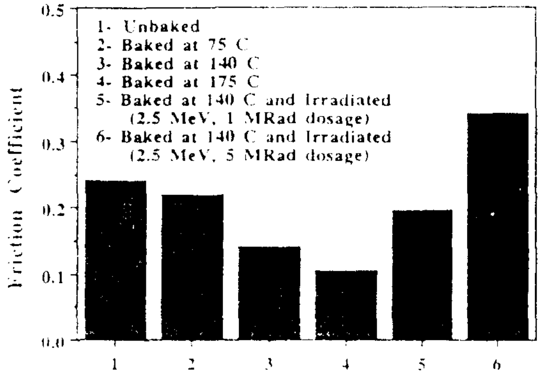


Fig. 8. Friction coefficient of 0.25μm thick films prepared under different baking and irradiation conditions. Normal Load=1g.

minimum of 0.06, and at higher baking temperatures it yields greater friction coefficients. Irradiation of baked samples at 140°C causes the friction coefficient to further increase. When the normal load is 1g, the plot has the same trend except the minimum friction coefficient is 0.1 and it occurs at a baking temperature of 170°C as shown in Fig. 8.

Worn surfaces of polyurethane films with a thickness of 0.25 μm tested under a 2 g normal load were examined in the tapping mode of the AFM. The tapping mode ensures that no further damage is done by the silicon nitride tip of the AFM to the film surface. Figure 9 shows the wear track on a film which is unbaked. The corresponding friction coefficient was 0.21. When the baking temperature was 140°C a friction coefficient of 0.06 was obtained and a plowing groove on the wear track is

Fig. 9. Three-dimensional view of the worn surface of an unbaked film tested under 2g normal load. Film Thickness=0.25μm.

Fig. 10. Three-dimensional view of the worn surface of a film baked at 140C and tested under 2 g normal load. Film Thickness=0.25μm.

shown in Fig 10. Finally, the samples baked at 140°C and irradiated with 1MRad electron beam radiation exhibited a friction coefficient of 0.35 and the wear track is shown in Fig. 11. A comparison of the worm surfaces reveals that a higher friction coefficient is obtained where the mechanical damage to the surface is higher.

Friction experiments were also conducted on polyurethane films using the atomic force microscope in contact mode [16]. The AFM tip was scanned over a distance of 10 μm at a frequency of 2.44 Hz. This corresponds to a scan speed of 48.8 μm/s. The normal and lateral forces on the AFM tip were calculated from the deflections and spring constants of the cantilever and are shown along with the friction coefficients in Table 3. The low friction coefficients obtained in AFM are approximately equal to the low values obtained with a high normal load with

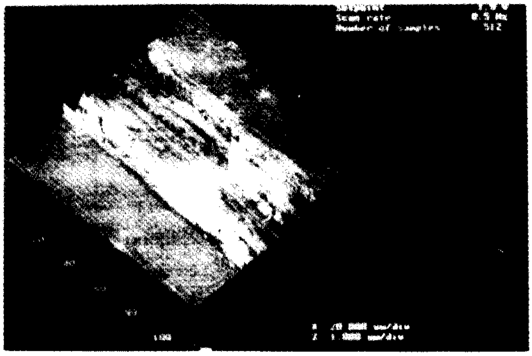


Fig. 11. Three-dimensional view of the worn surface of a film baked at 140C and irradiated with 2.5 Mev energy beam at 1 MRad dosage and tested under 2g normal Load. Film Thickness=0.25μm.

the pin-on-disc tribometer.

3. Discussion

The basic idea that the frictional force between sliding surfaces is dominated by mechanical interactions is supported by the experimental results presented in this paper. The low friction coefficients obtained under normal loads of a few micrograms in AFM and a few grams in our tests shows that if adhesion were the only component of friction, it would contribute to a friction coefficient of even less than 0.05. The plowing damage to the surface of the film with a friction coefficient as low as 0.06 indicates that even under this low frictional condition the mechanical interactions are not totally eliminated and have some contributions in the friction coefficient. Perhaps the value of 0.03 obtained in AFM could be considered as a lower limit of friction coefficient for this particular film.

The film thickness plays a critical role in the frictional behavior of polyurethane coatings. When the friction coefficient is plotted against the film thickness for a certain normal load, three regions are apparent. If the film is too thick it would act as a bulk which undergoes a large deformation and dissipates energy through hysteresis or tearing. A very thin film, on the other hand, might be removed easily during the early cycles of a test and causes partial contact of the pin with the hard substrate. There is a region between these two which is an optimum thickness with respect to the friction coefficient.

Table 3. Vertical deflection (d), angular deflection (ψ), normal force (N), lateral force (N), lateral force (L), and friction coefficients (f) of 2.5 μm thick films

d (nm)	ψ (μrad)	N (nN)	L (nN)	f
100	10.0	45.5	6.88	0.15
500	14.8	228	10.2	0.045
550	15.3	250	10.5	0.042
650	16.6	296	11.4	0.039
750	17.0	341	11.7	0.034

The freedom of surface molecules of the film to respond elastically to the deformation field imposed by the moving asperities is an important factor in the low friction coatings. If the molecule chains are not crosslinked, as in the unbaked samples, the film can undergo a large amount of plastic deformation. This is the reason for having a high friction coefficient of 0.2 and a highly deformed wear track after the test. In this case, the polymer film simply acts as a solid lubricant. On the other hand, over crosslinking can cause the film to become brittle and undergo fracture at the surface and delamination at the interface with the hard substrate. It is just the right cross-linking density, which in our work was obtained at a baking temperature of 140°C, which gives a low friction coefficient and the minimum damage to the surface.

Clearly, we have neither optimized the properties of the elastomer used nor the properties of the substrate. The purpose of the preliminary experiments presented here was to check if the hypothesis is valid. The results are encouraging. The friction coefficient of these experiments are nearly an order of magnitude lower than those of undulated surfaces. Although the examination of the wear track shows a minimum of damage, it is likely that there were damages which absorbed energy and thus contributed to friction. The minimum friction without any mechanical damage would have been smaller than the friction values obtained.

What then is the minimum friction coefficient? The answer is that the minimum friction is that which exists when mechanical factors are totally absent from the interface and only the adhesive forces play a role. The minimum coefficient of friction will then be clearly material dependent. It appears that the minimum friction between dry sliding surfaces may be less than 0.01 for a covalent elastomer coated surface on a hard substrate.

The ideal thickness of the surface coating for minimum friction will be dependent on the normal load. The thinner the coating, the lighter should be the normal load. As the load increases the coating can be thicker. The ideal thickness of the coating for a large flat surface in sliding contact with another flat surface (in contrast to the pin-on-disc experiment) may be dependent on the flatness and the surface roughness (i.e., the long and short-range surface perturbations). However, with the same coating material used in the experiments reported here, the ideal thickness is expected to be in the same range. Experiments will be performed to verify if this is true.

The implications of such low friction surfaces are many. Instruments, machine tools, and biomedical instruments can benefit using the ultra low friction materials. A patent has been filed based on the results presented partially in this paper [17].

4. Conclusions

(1) A hypothesis was presented as to how mechanical components of the friction force can be eliminated.

(2) Experimental results obtained with model surfaces which consist of a hard smooth surface coated with an elastomeric surface layer support the hypothesis.

(3) The minimum friction that can be achieved with such a system is the adhesive component between the elastomer layer and the counterface. This can be very low if mechanical components are totally absent. For the model surface coated here, it is about 0.03.

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