



Influence of lubricant properties and contacting velocity on real contact formation between rubber and glass in a contact process

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ABSTRACT

The ability of rubber to grip on a wet surface is important for applications to footwear outer-soles and vehicle tires. Generally, friction behavior of rubber depends on real contact, which is generated in the process of contact with a floor. Real contact formation under lubricated conditions is influenced by the contacting velocity and dewetting behavior, which is related to the spreading coefficient and lubricant viscosity. This study investigated the influences of contacting velocity, spreading coefficient, and viscosity on real contact formation in a rubber–glass contact process. Real contact area decreased with an increase in these three parameters, and correlated positively with the ratio of characteristic dewetting velocity to contacting velocity.

1. Introduction

Rubber is a soft material that permits a large real contact area A_r between two substrates. It has been reported that the friction force increases with A_r [1]; thus, it is reasonable that rubber has been applied to shoe soles and vehicle tires for improving their grip properties. However, this property deteriorates due to lubricant intervention, which can relate to an increased risk for slipping accidents under wet conditions in the case of shoe soles.

Considering the macroscopic aspect, for the case of an interface between an outer-sole and a floor, real contact is repeatedly created during walking, running, and jumping; real contact is also continuously created between a vehicle tire and a road during driving. Therefore, it is considered that real contact formation in the contact process is important in controlling the grip properties of footwear and vehicle tires, regardless of lubricant conditions.

Considering the microscopic aspect, as represented by the Greenwood–Williamson model, A_r between nominally flat surfaces is statistically estimated based on the Hertz contact theory [2]. Under a lubricated condition, A_r also depends on lubricant viscosity η and sliding velocity, as explained by the theory of Stribeck curves [3]. In addition, the friction coefficient of rubber under lubricated conditions is sensitive to wettability, which depends on the surface free energies of the substrates and lubricant [4,5]. In this case, it is considered that lubricant between the substrates is squeezed out, as explained by dewetting behavior, which is especially dominant for cases of soft materials [6–11]. The dewetting behavior at a single real contact depends on wettability and η [6–11]. In practical terms, there are many real

contacts between two substrates; however, under such a situation, the relationship between the dewetting behavior and the real contact formation is not yet clarified.

The purpose of this study was to investigate the relationship between real contact formation and dewetting behavior in the process of contact between rubber and glass, where there are many real contacts. To observe real contact formation, the distribution of real contacts and the film thickness between a rubber hemisphere and a glass prism were experimentally measured in a contact process. To discuss the dewetting behavior, the influences of contacting velocity v_c , wettability, and η on A_r were investigated.

2. Material and methods

2.1. Sample preparation

To investigate the influences of wettability and η on A_r , five solutions with different surface free energies and viscosities were prepared. Surface free energies and viscosities were controlled by changing the ratios of mixtures of water deionized with a demineralizer (REP343RB, Toyo Seisakusyo, Ltd., Japan), ethanol (Wako 1st grade, Wako Pure Chemical Industries, Ltd., Japan), and glycerol (Wako 1st grade, Wako Pure Chemical Industries, Ltd., Japan), as shown in Table 1. The surface free energies of the lubricants were measured based on the pendant drop method [12] and the Kaelble–Uy theory [13], as explained in a previous study [5]. The refractive indices and viscosities of the lubricants were measured with a refractometer (NAR-1T SOLID, ATAGO Co., Ltd., Japan) and Ostwald viscometer (2370-03-10, Climbing Co.,

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Table 1
Lubricant compositions and physical properties and selected experimental conditions.

Lubricant	(i)	(ii)	(iii)	(iv)	(v)
Composition, vol%					
Water	100	90	80	60	30
Ethanol	0	10	20	10	10
Glycerol	0	0	0	30	60
Surface free energy, mJ/m ²					
Dispersion	21.8	21.6	17.5	16.2	17.3
Polar	51.0	28.7	22.3	27.5	27.5
Total	72.8	50.3	39.8	43.7	44.8
Spreading coefficient, mJ/m ²	-53.3	-21.8	-13.7	-20.4	-20.3
Viscosity, mPas	0.89	1.06	1.38	3.17	16.1
Refractive index	1.333	1.337	1.344	1.382	1.426
Critical angle, deg.	61.68	62.01	62.61	65.86	70.35
Incident angle, deg.	65.0	65.0	66.0	69.0	73.0

Table 2
Surface free energies of rubber and glass.

Lubricant	Rubber	Glass
Surface free energy, mJ/m ²		
Dispersion	11.0	30.2
Polar	1.7	5.7
Total	12.7	35.9

Ltd., Japan), respectively. A hemisphere of silicon rubber (Sylgard 184, Dow Corning Toray Co., Ltd., Japan) containing 10 vol% titanium oxide (A150, Sakai Chemical Industry Co., Ltd., Japan) was prepared as the rubber specimen. Titanium oxide was added to prevent light transition through the rubber specimen. A concave lens (S-SLB-10-15 N, SIGMA-KOKI Co., Ltd., Japan) was used to mold the rubber. The initial elastic modulus of the rubber was 2.30 MPa, which was measured using a dynamic viscoelastic measurement device (Reogel E4000, UBM Co., Ltd., Japan.). The arithmetical mean height and the radius of curvature were 0.18 μm and 7.62 mm, respectively, which were measured using a One-Shot 3D Measuring Macroscope (VR3000, Keyence Corporation, Japan). A BK7 prism (084.4L100-45DEG-6P-4SH3.5, SIGMAKOKI Co., Ltd., Japan) was used as the glass surface. Table 2 shows the surface free energies of the rubber and glass, which were calculated from the contact angles of deionized water and diiodomethane (Wako 1st grade, Wako Pure Chemical Industries, Ltd., Japan) based on the Kaelble–Uy theory [13].

2.2. Wettability evaluation

As explained in a previous study, wettability between the rubber and glass was estimated using the spreading coefficient S [5]. S was obtained from the following equations:

$$S = \gamma_{\text{RG}} - (\gamma_{\text{RL}} + \gamma_{\text{GL}}), \quad (1)$$

$$\gamma_{ij} = \left(\sqrt{\gamma_i^{\text{d}}} - \sqrt{\gamma_j^{\text{d}}} \right)^2 + \left(\sqrt{\gamma_i^{\text{p}}} - \sqrt{\gamma_j^{\text{p}}} \right)^2, \quad (2)$$

where γ_{ij} is the interfacial free energy between material i and material j [13]; subscripts R, G, and L denote rubber, glass, and a lubricant, respectively; γ_i^{d} and γ_i^{p} are the dispersion and polar components of the surface free energy of material i , respectively [13]. The calculated S values between the rubber, glass, and lubricants are listed in Table 1.

2.3. Experimental apparatus

To determine the relationship between real contact formation and dewetting behavior in the process of contact between rubber and glass, the distributions of real contact and film thickness were quantified based on a total reflection method and light interferometry [14]. Fig. 1(a) shows an overview of the experimental system used for measuring the contact states. The rubber hemisphere was set on the glass prism in the lubricated conditions. In the total reflection method, light from a light-emitting diode (LED) light source (HLV2-22RD-3W, CCS Inc., Japan) penetrated the glass through a light guide (LE-OPT-24, OPTEC FA Co., Ltd., Japan) and internally reflected on the surface of the glass. The light scattered on the interface between the rubber and the glass was observed by a charge-coupled device (CCD) camera (AT-030MCL, JAI Ltd., Japan). In the light interferometry method, the light from another LED light source (HLV2-22BL-3W, CCS Inc., Japan) penetrated the interface between the rubber and the glass through a telecentric lens (TV-2F-110, OPTART Co., Ltd., Japan). Light that reflected from the surfaces of the rubber and the glass was observed by the same camera. The pixel format, pixel size, and frame rate were 12 bit, $3.6 \mu\text{m} \times 3.6 \mu\text{m}$, and 100 fps, respectively. The peaks of the wavelengths in the total reflection and light interferometry methods occurred at 645 nm and 465 nm, respectively. As shown in Table 1, the

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