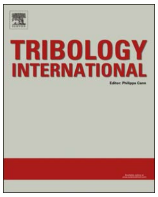
Tribology International xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint



Alteration of friction force of a harmonically excited elastomeric pillar

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ARTICLE INFO

Keywords:
Friction force
Harmonic excitation
Frictional adhesion
Elastomeric pillar

ABSTRACT

The friction force of a single elastomeric pillar on a smooth substrate is investigated under harmonic base excitation. Friction force variation is acquired for various excitation frequencies with a constant base acceleration where the pillar stays in stick regime. The peeling behavior of the pillar for different harmonic base displacements is discussed. The apparent work of adhesion is demonstrated via energy equilibrium at the contact interface. It was observed that a harmonic force may alter the interface adhesive nature, and the adhesion and friction coupling can be tuned via the excitation frequency.

1. Introduction

Managing the friction, adhesion and wear is one of the oldest desire of the engineers to implement reliable and energy efficient mechanical devices. Functional surfaces have been progressively leading enhanced surfaces in terms of their tribological properties [1,2]. One of the techniques to functionalize the surfaces is the method of texturing via adding, removing, moving or self-forming of the materials on the surface [3]. Surface texturing has become an important mechanism to tune the adhesion, friction and wear of the interacting surfaces for wet and dry contacts. For the hard solid–solid contact, it is primarily utilized for the efficient operation of the lubricants to decrease the friction, adhesion and wear by acting as a reservoir and forming regions of trapping to the wear debris [4–6]. Similarly, the surface texturing is used to control the adhesion and friction of the soft solid–solid contacts that is mainly inspired by nature [7–9].

Friction of adhesive elastomers in the soft solid–solid contact is an important parameter of the adhesive nature of the soft contact interface [10,11]. Furthermore, the friction of textured surfaces by using different patterns of elastomeric pillars are of great of interest due to the enchantment on interfacial properties of the contact interface [7,12,13]. It is widely accepted that in a frictional loading of elastomeric pillars with various loading conditions, i.e. dragging with a constant velocity, there are three phases in response of the pillars: (1) stick, (2) partial (micro) slip and (3) full (gross) sliding motion [14]. In stick phase, it is obvious that the pillar is in full contact with the counterpart. As the loading increases, friction force at the contact interface subsequently increases and there is a partial (micro) slip in the contact zone. Moreover, at some critical displacement, the contact is partly lost due to the bending displacement of the pillar resulting a tilting behavior for a flat-punch tip [7,15,16] and rolling motion for a hemispherical tip geometry [17]. During this state, the loading first overcomes the adhesive junction stresses in the contact zone and thereby loosing surface energy and converting into frictional dissipative energy. In the meantime, the edge of the pillar is exposed to the frictional stresses due to the bending deflection of the pillar. Hence, it is important to emphasize that the different loading conditions result into different tilting behavior where the friction–adhesion coupling needs to be identified in the possible stick and micro-slip regime. As the loading further increases, full sliding motion occurs when the friction force overcomes the limiting friction force [18].

In the soft–soft solid contact, adhesion and friction tuning can be performed via one of the two different methods with no resulting effects on the chemistry between the synthetic pillars and the surface. The methods are as follows: (1) optimization of the constructional and structural parameters of the synthetic pillar, i.e., material, pillar dimensions, pillar tip geometry, number of pillars, and backing layer thickness [19–23] and (2) adjustment of external parameters on the fly, which constitutes varying pillar loading parameters such as velocity and normal load [17,24,25]. The first method suggests that the coupled adhesion and friction forces may mainly be tuned to yield specific interfacial properties and play a passive role in controlling the adhesion and friction. However, in the second method, only the external loading conditions affect the structural response in terms of friction without altering any constructional parameters. Therefore, investigating the friction force of a single pillar is essential to obtain favorable friction force that does not affect the constructional parameters of the pillar under various loading conditions. Previous studies have only investi-

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http://dx.doi.org/10.1016/j.triboint.2017.03.007
Received 15 October 2016; Received in revised form 3 March 2017; Accepted 6 March 2017

Please cite this article as: Sümer, B., Tribology International (2017), http://dx.doi.org/10.1016/j.triboint.2017.03.007

gated the friction force of the pillars under constant tangential velocity [17,24,25]. Alternatively, we suggest that friction–adhesion coupling may also be tuned on the interface by applying a tangential force with a frequency component. It is possible to integrate an active film such as a piezoelectric ceramic or polymer into the backing layer of the pillars, thereby enabling the application of a base motion [32,33]. This results in local tuning of the frictional–adhesion mechanism at the interface, which subsequently allows active control of the adhesion and friction coupling.

In this paper, we investigate the friction force of a single pillar under harmonic loading conditions with the intention of contributing a new path of study on the integration of dry adhesives to the devices. As a continuation of our previous work [17], a single pillar constructed using polydimethylsiloxane (PDMS) on a meso-scale is investigated to examine the frictional adhesion of a single pillar under harmonic loading conditions. The millimeter scale of the pillar allows us to measure the dynamic behavior of the pillar tip using a single-point laser vibrometer. The friction force of the pillar on a smooth surface is obtained via application of a base harmonic excitation; the pillar is excited in a way that it remains in stick phase with the substrate throughout all excitations. Section 2 details the pillar fabrication and experimental set-up; Section 3 presents the results and discussion; lastly, Section 4 provides the conclusion.

2. Materials and method

In this section, the fabrication techniques and novel experimental setups are introduced. Following the production of a single pillar, it is excited in the fixed–free boundary condition to obtain a structural response from the pillar, thus revealing its natural frequency. An additional experiment constituted the pillar being harmonically excited under fixed-contact boundary conditions in order to reveal friction–adhesion coupling under harmonic loading.

2.1. Pillar fabrication

The pillar is constructed using PDMS (Sylgard 184, Dow Corning). A replica of the pillar formed using aluminum is manufactured with dimensions identical to those of the pillar. Afterward, silicone rubber is poured onto the aluminum replica to obtain the master template. Then, PDMS solution with a mass ratio of 10:1 to its curing agent is poured into the master template and put into a vacuum chamber to remove bubbles from the solution. The solution is subsequently left to cure for 48 h at laboratory conditions and the pillar is smoothly skinned from the template after the curing period. The pillar is manufactured in meso-scale [8,9] due to the physical limitations on the measuring dynamic response and mechanical gain of the shakers. The dimension of the pillar is 6 mm in diameter and 24 mm in height which results an aspect ratio of 4.

2.2. Structural response of the pillar

The pillar is harmonically excited via base excitation; the structural response, i.e., pillar displacement and velocity, and the magnitude of base acceleration are measured via a customized experimental set-up as is illustrated in Fig. 1. The aim is to determine the first natural frequency of the pillar under the fixed–free boundary conditions. The experimental set-up comprises an electrodynamic shaker (K2007E01, the Modal Shop) to excite the linear stage, which acts as the surface for the pillar, a vibrometer (CLV-2534, Polytec Inc.) to measure the displacement and velocity of the pillar, and an accelerometer (Bruel & Kjaer) to measure the acceleration of the moving base. Because the pillar is composed of a transparent polymer, a reflective thin tape is placed onto the pillar with a position of L_r from the tip. The pillar and the accelerometer are attached to the moving stage via double-sided tape. The base is part of a pressurized air bearing moving stage. Pressurized air flow passes through micro-channels within the base to yield nearly frictionless motion. The base and electrodynamic shaker are connected via a stinger and mechanical coupling component. Here, the stinger is a slender rod that ensures axial force transmission with high shear and bending moment rejection. In addition, the stinger is used to protect the shaker from any misalignment and mechanical coupling. Within the set-up, the base can only move and slide in one direction, thus reducing all constructional effects of the experimental set-up on the structural response of the pillar. All measurements are obtained via a signal analyzer (01dB-Metravib) in real time, and the accompanying analyzer software (dBFA Suite) is used.

The frequency response function (FRF) is obtained as the ratio of the displacement or velocity of pillar tip with respect to the base, respectively. To obtain the FRF, a simple harmonic sinusoidal input signal is sent to the shaker from the signal analyzer at each excitation frequency. The resulting measured parameters of five experiments are recorded in the software. Afterward, the displacement and velocity of the base are calculated from the measured maximum acceleration value A_b via a simple harmonic equality:

$$u_0(\omega) = \frac{A_b}{\omega^2}, \quad \dot{u_0}(\omega) = \frac{A_b}{\omega} \tag{1}$$

where ω is the excitation frequency, $u_0(\omega)$ and $\dot{u_0}(\omega)$ are the maximum displacement and velocity of the base, respectively, which are illustrated in Fig. 2. The frequency response function of the pillar is determined based on the two response ratios in order to validate and compare the displacements $u_2(L_r, t)$ and $u_0(t)$ and velocities $\dot{u}_2(L_r, t)$ and $\dot{u_0}(t)$ of the pillar and base, respectively, as follows:

$$FRF = \frac{u_2(L_r, t)}{u_0(t)}, \quad FRF = \frac{\dot{u}_2(L_r, t)}{\dot{u_0}(t)}. \tag{2}$$

The FRF of the pillar is given in terms of the mean value and standard deviation, as given Fig. 3, and the fundamental frequency of the pillar is observed around 59.5 Hz under the fixed–free boundary conditions.

2.3. Measuring friction force of the pillar under harmonic excitation

Here, the experimental set-up to determine the natural frequency of the pillar is modified with the addition of a vertical motorized linear stage and force sensor, which is illustrated in Fig. 4. A smooth surface (plain glass) is adhered to the measurement area on the force sensor. The force sensor (Kistler 9317c), which is attached to the motorized linear stage (Newport Corp., MFA-CC), can simultaneously measure the normal load and friction force and produce charges according to the magnitudes of the forces. In compliance with the measurement scheme of the force sensor, the accumulated charges of the force sensor are sent to charge amplifiers. Two different type of charge amplifiers (Kistler 5073 and 5015 A) are used to convert the obtained charges to electrical voltage. Kistler 5015 A is used due to obtain higher resolution during friction force measurement. The remaining components, i.e., the electrodynamic shaker (K2007E01, the Modal Shop), vibrometer (CLV-2534, Polytec Inc.), accelerometer (Bruel & Kjaer), pressurized air slide, and same signal analyzer, are as shown in Fig. 1. Additionally, the reflective tape used in FRF measurements is also utilized in this experiment with no change in location on the pillar.

The objective of this study is to investigate the alteration of friction force of an elastomeric pillar to observe the friction–adhesion coupling at the contact interface in stick regime by exciting the pillar harmonically. To do this, the excitation frequency bandwidth is selected such that it involves the first mode of the structure. In the literature, the characterization methods of mechanical structures in a harmonic excitation are performed in two distinct techniques [26]: (1) the excitation force is controlled and remained constant at each excitation frequencies, (2) the excitation force is controlled to get the same response (displacement, velocity or acceleration) of the mechanical