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The contact area of elastomers as a function of the sliding velocity

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ABSTRACT – The friction in tribo-systems that contain viscoelastic materials, such as elastomers, is relevant for a large number of applications. Examples include tyres, hoses and conveyor belts. To quantify the friction in these applications, one must first understand the contact behaviour of such viscoelastic materials, both in static and in dynamic situations. This work discusses an experimental study into the change of the contact area with the sliding velocity. The results show that there is a threshold velocity, above which the size of the contact area significantly reduces.

1. INTRODUCTION

It is well known that for purely elastic materials, the contact area and shape during sliding remain constant and are independent of the sliding speed [1]. This is, however, not the case for materials when plasticity is involved. For example, the shape of the contact area between a rigid sphere and a plastic deforming material is circular in the static case, while it is semi-circular when sliding occurs. However, the size of the contact area remains constant, allowing to describe the contact behaviour during sliding from the static contact behaviour.

In the case of elastomers, both the shape and the size of the contact area during sliding differ from the static case [2-4]. A recent study by Arvanitaki et al. [2] showed a reduction of the contact area and a change in the shape of the contact area with increasing velocity. At low sliding velocities the contact is semi-static, meaning that the contact area is equal to the static contact area and, with increasing velocity, remains constant until a certain velocity is reached. At the threshold velocity the size of the contact area starts to decrease, as described by Ludema and Tabor [3]. Fukahori et al. [4] studied waves of detachment appearing in the contact area while a rigid indenter slides over an elastomer. Next to their observations that the waves of detachment appear only under certain conditions, they showed that the contact area between the elastomer and the rigid indenter changed, both in shape and in size with a varying sliding velocity in all the studied cases.

Despite that the changes in the shape and size of the contact area between an elastomer and a sliding rigid indenter are known, currently there is no general function that allows predicting or calculating the contact area as a function of the sliding velocity.

2. METHODOLOGY

A tribological system composed of an elastomeric spherical pin sliding against a smooth glass plate is considered. The elastomeric indenter has a radius $R = 3$ mm. Sliding experiments were performed employing a pin-on-disc set-up at an applied normal load of $F_N = 2$ N and velocities between 3.6 and 638 mm s^{-1}. A camera was fitted normal to the plane of contact and pictures of the contact area were taken at different sliding velocities. A schematic illustration of the set-up is shown in Figure 1.

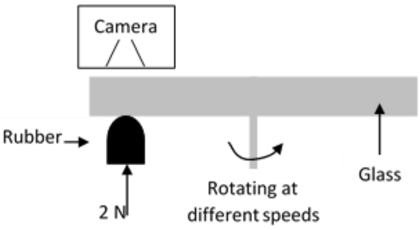

Figure 1 Schematic of the experimental set-up.

3. RESULTS AND DISCUSSION

The set-up allows recording the contact area between the glass plate and the rubber pin in the static case and at several sliding velocities. Figure 2 a) shows the contact area in the static case. It can be seen that the contact area has a circular shape. Figure 2 b) shows the contact area at a sliding speed of 118 mm/s, the shape of the contact area changes when sliding takes place; the contact area becomes elliptical, with the major axis normal to the sliding direction.

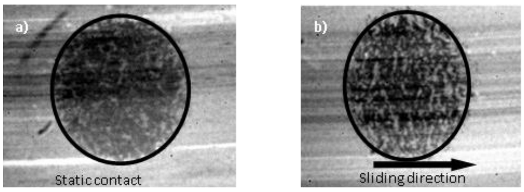

Figure 2 Photographs of the contact area, a) in static contact, b) in sliding contact at 118 mm/s.

The contact area was measured in the static case (i.e. at 0 mm/s) and for seven sliding velocities: 3.6 mm/s, 15.2 mm/s, 24.8 mm/s, 70.5 mm/s, 118.2 mm/s, 249.8 mm/s and 638 mm/s. The dimensionless contact area from the average of 10 measurements was taken at each sliding velocity; the results are shown in Figure 3, as the plot has a logarithmic scale, the static contact is plotted at a sliding speed of 10^{-5} m/s. Qualitatively, the results show similar behaviour as those reported by Arvanitaki et al. [2] and Fukahori et al. [4]. It can be seen that the contact area is fairly constant with sliding velocity until 200 mm/s, after which it sharply drops with increasing sliding velocity.

Due to limitations of the experimental setup, sliding velocities above 640 mm/s are not possible, so no data points could be obtained beyond this value. However, it is unlikely that the contact area would become zero for very high speeds and rather it would approach a minimum limit; therefore a constraint to the contact area at very high sliding velocities should be added. As described by Johnson [5], for a contact between a rigid and an incompressible material, the contact area depends on the shear modulus of the material and can be expressed as $A \sim E^{-2/3}$.

The material properties of the elastomer used in this study, Ethylene Propylene Diene Rubber (EPDM) were measured in a Dynamic Mechanical Analysis (DMA). From the measurements was obtained the creep compliance function, $\emptyset(t)$, which is related to the contact area as $A \approx \emptyset(t)^{2/3}$. Table 1 shows the results of the experiments. The ratio between the coefficient of creep compliance with the smallest retardation time, $\emptyset_1$, and the creep compliance in the relaxed state, $\emptyset_r$, allows obtaining the minimum limiting value for the contact area at very high sliding velocity. The ratio is given by:

$$\frac{A_{v\to\infty}}{A_{v=0}} = \left(\frac{\phi_1}{\phi_r}\right)^{\frac{2}{3}} = \left(\frac{4.692\cdot10^{-8}}{3.493\cdot10^{-7}}\right)^{\frac{2}{3}} \approx 0.26 \qquad (1)$$

This means that the contact area at very high sliding velocities is $A_{v>>1m/s} = 0.26\,A_{static}$. Adding this new constraint to the (averaged) measured data points at each velocity gives the fit represented by the dashed black line in Figure 3. This fit is described by:

$$\frac{A_{sliding}}{A_{static}} = \frac{1-\left(\frac{\phi_1}{\phi_r}\right)^{\frac{2}{3}}}{2}.\frac{2}{\pi}.\arctan\left(\frac{v_o}{v}-\frac{v}{v_o}\right)+\frac{1+\left(\frac{\phi_1}{\phi_r}\right)^{\frac{2}{3}}}{2} \qquad (2)$$

Where v_o is determined by the rubber under investigation. The shape of this function for the velocity dependent contact area is similar to the variation of the contact area that Ludema and Tabor proposed in 1966, and also agrees with the more recent findings of Arvanitaki et al. [2]. The function obtained in the present study offers an approximation to the contact area with varying sliding velocity, valid for similar tribo-systems, which can be used to describe any velocity dependent contact phenomena.

4. CONCLUSION

The relation between the size of the contact area and the sliding velocity in the contact between an elastomer and a rigid material can be described by an arctan function. Such a pragmatic function allows the calculation of the size of the contact area over a wide interval of sliding velocities. The parameters of the function can be obtained from a combination of pin-on-disk and DMA measurements. The function can be used in models that describe a range of velocity dependent contact phenomena.

5. ACKNOWLEDGEMENT

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Table 1 Compliance coefficients and retardation times for EPDM.

i	$\emptyset_i$(Pa-1)	λ_i (s)
$\emptyset_r$	$3.493.10^{-7}$	
1	$4.692.10^{-8}$	0.0064
2	$4.903.10^{-8}$	0.0713
3	$8.232.10^{-8}$	0.7284

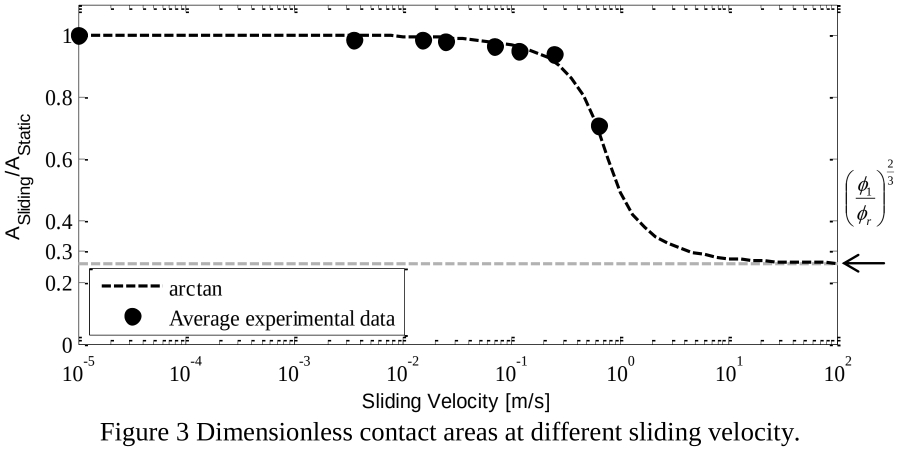

Figure 3 Dimensionless contact areas at different sliding velocity.