**FACTA UNIVERSITATIS**
Series: **Mechanical Engineering** Vol. 13, N° 1, 2015, pp. 33 - 38

**Original scientific paper**

# EXPERIMENTAL INVESTIGATION OF THE ADHESIVE CONTACT WITH ELASTOMERS: EFFECT OF SURFACE ROUGHNESS

*UDC 539*

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**Abstract.** *Adhesion between an elastomer and a steel indenter was studied experimentally and described with an analytical model. Cylindrical indenters having different roughness were brought into contact with an elastomer with various normal forces. After a "holding time", the indenter was pulled with a constant velocity, which was the same in all experiments. We have studied the regime of relatively small initial normal loadings, large holding times and relatively large pulling velocities, so that the adhesive force did not depend on the holding time but did depend on the initially applied normal force and was approximately proportional to the pulling velocity. Under these conditions, we found that the adhesive force is inversely proportional to the roughness and proportional to the normal force. For the theoretical analysis, we used a previously published MDR-based model.*

**Key Words:** *Adhesion, Elastomer, Surface Roughness, Fracture Criterion for Elastomers*

## 1. INTRODUCTION

In a variety of applications of elastomers adhesive forces play a significant role, which may be desirable or undesirable. The classical adhesion theory was developed by Johnson, Kendall and Roberts for an elastic ball on the rigid flat surface [1]. However, this theory is based on the balance of energy which is released due to propagation of an adhesive crack and the work of adhesion needed to create free surfaces; it is therefore only applicable to purely elastic bodies. Johnson compares the JKR theory with experiments made with gelatin balls [2]. However, this comparison is only valid for very small pulling velocities. For finite velocities, the JKR theory is not valid any more. For viscoelastic adhesive contacts, there is a large number of different approaches (see e.g. the review [3]). In the present paper adhesion between an elastomer and cylindrical indenters of steel is studied experimentally to

Received January 09, 2015 / Accepted March 2, 2015
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determine the influence of varying surface roughness. The theoretical background for our study is given by the concepts described in [4, 5]. It is clear that for very small roughness the surfaces will effectively be ideally flat. This case was investigated in detail in our previous study [6]. It could be shown experimentally that under the conditions studied, the regularities of adhesion with elastomers are completely different from predictions of the JKR theory. In particular, the influence of the geometry (e.g. the radius in the case of cylindrical indenters) differs qualitatively from the results of the JKR theory. We have shown that, for sufficiently fast detachment, the rheology of the elastomer plays the most important role. At the same time, the adhesion force shows strong dependency on the velocity and temperature.

One of the most interesting findings of the previous study was that the adhesion force with a cylinder was approximately proportional to radius $a$ of the cylinder (and not to $a^{3/2}$ according to the JKR theory). For multi-contact problems this would mean that the adhesion force should be proportional to the sum of the radii of all contacts, the so-called *contact length* [7]. Otherwise, the contact length is approximately proportional to the normal load, the coefficient of proportionality being dependent on the roughness [7]. In the present study, we try to prove this hypothesis and to see if under the above conditions the adhesion force is proportional to the applied normal force.

In studying the force dependence of adhesion, we have to distinguish two cases: The critical load case occurs when the normal force is so large that during the initial indentation the adhesive force achieves a plateau and does not change any more with further increasing normal force. This means that the sum of the diameters of the micro-contacts and the macroscopic diameter of the indenter are of the same order of magnitude. In this case, no dependence of the adhesion force on the normal force and on the holding time was found. Our main interest was the sub-critical case. The adhesive force in this case depends on the real contact length. To describe the separation of the indenter from the elastomer, different failure criteria should therefore be used. For the description of the experimental study, a deformation criterion was used [5, 8]. In the subcritical case of loading the real contact length between the elastomer and the rough indenter is time-dependent [9, 10]. Also, elastomeric friction is determined by the viscosity and the adhesion [11]. Understanding the adhesion processes is therefore important for understanding elastomer friction. Finally, both viscosity and adhesion are strongly temperature-dependent [12]. These dependencies make a complete experimental characterization difficult, and in this paper only the normal force and roughness of the indenter were varied. The temperature, pull-off velocity and holding time were constant. In the following, the experimental set-up and the measurement results will be presented.

## 2. Experimental Apparatus for Measuring the Adhesive Force

### 2.1. Set-up

Roughness $R_a$ was measured using a white light interferometer**.** For the measurement of the adhesive force an apparatus was developed, which enables measurements in a temperature range of approx. -80 °C to 80 °C. **Fig. 1** shows the main components and their functions.

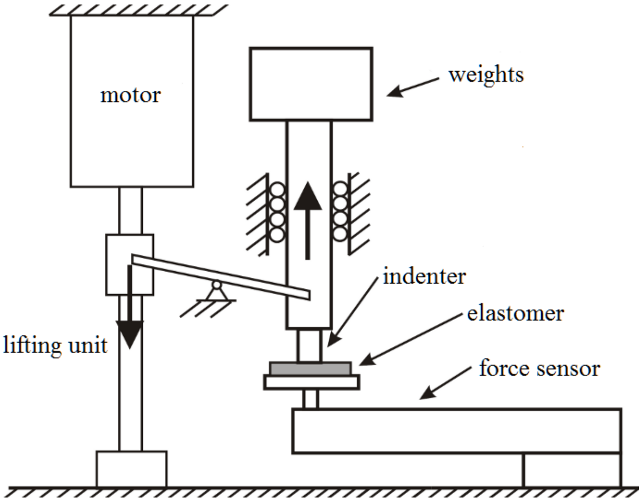


**Fig. 1** Principle sketch of the apparatus for the measurement of the adhesive force (temperature regulation not shown)

The normal force is produced with fixed weights, which are made with an accuracy of 0.1 g. The maximal normal force is limited by the nominal load of the force sensor, at 50 N. The lower limit of 1.5 N is due to the weight of the indenters and the fixture. The indenter is moved with a stepping motor which drives a thread spindle. A special lever system ensures that the indenter and its holder can only be moved vertically. The lever system also makes sure that the only applied force is in the normal direction. The structural implementation of the motor drive takes the resonance frequency of the force sensor into account. The stepping motor can be operated at variable speed and acceleration, and allows controlling the displacement precisely. Cooling is provided by gaseous nitrogen flowing through a conduit system around the sample holder. Preliminary tests have shown that there is no difference between direct and indirect cooling with nitrogen. For attachment of the material sample a gimbal bearing was designed, which makes sure that the sample is held horizontally. The measurement procedure starts with the insertion and alignment of the material sample and sealing of the measuring apparatus. Subsequently the normal force is adjusted by attaching weights. Next, the desired temperature is adjusted. When the material specimen has reached the test temperature, the indenter is set down on the elastomer in a controlled manner. After a pre-defined contact time, the indenter is pulled off by means of the lifting unit. The force necessary to detach the indenter from the elastomer is measured.

### 2.2. Experimental results

In this section, we present the measurement results. The experiments were carried out with different rough cylindrical indenters. These were pressed into the elastomer with different normal forces. The adhesion force and the displacement of the indenter were measured, as shown in Figs. 2 and 3.

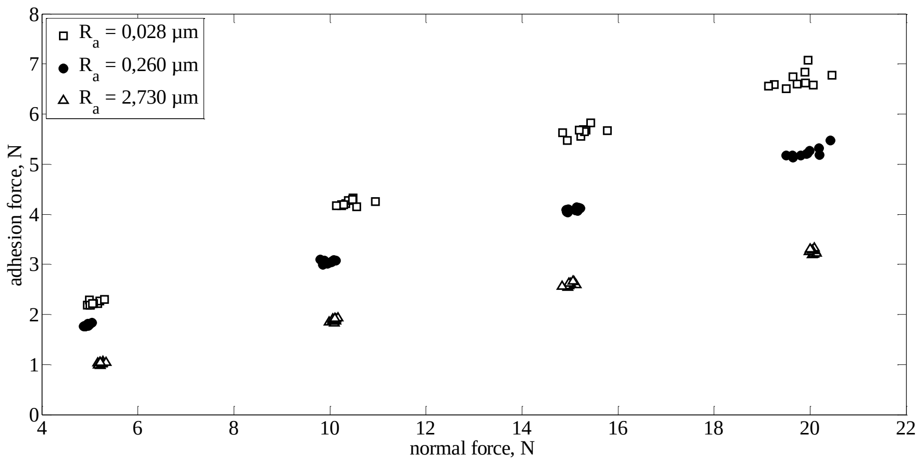


**Fig. 2** Dependence of the adhesion force on the normal force and surface roughness

Fig. 2 shows that the adhesion force is inversely proportional to the roughness and proportional to the normal force. The indenters had a diameter of 14 mm. The pull-off velocity, hold time and temperature were kept constant.

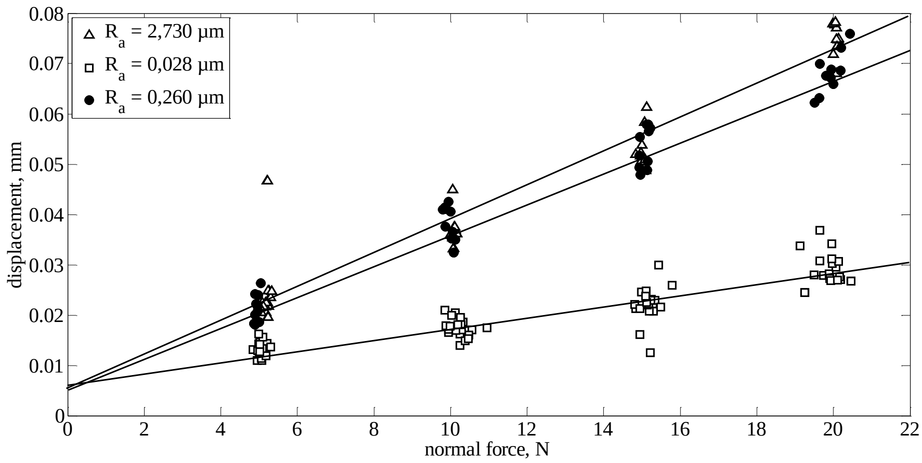


**Fig. 3** Dependence of the displacement on the normal force and surface roughness

In Fig. 3, the other main result of this investigation shows the displacement of the indenter as a function of the normal force. The displacement is also proportional to the normal force, and increases with increasing roughness, until saturation is reached.

## 3. THEORETICAL INTERPRETATION

In [4] and [5] it was shown that adhesion of elastomers is essentially determined by two factors: the rheology of the elastomer and the "failure criterion". In a previous work [6] we have shown that, at least for some elastomers, the so-called deformation criterion [4] is the suitable failure criterion. During a fast pull-off the rheology of the material can be approximated as a Newtonian fluid with viscosity $\eta$. Under these conditions, we have derived and verified a simple relation for the adhesion force

$$F_A = 4Dv_0\eta \;, \tag{1}$$

where $D$ is the diameter of cylindrical indenter and $v_0$ is the pull-off velocity. The influence of temperature on the adhesive force could be accounted for by the dependence of the viscosity on the temperature given by the Arrhenius equation

$$\eta(T) = Ae^{\frac{B}{T}} \,. \tag{2}$$

where $A$ and $B$ are empirical constants, which are determined by experiments. The equation (1) can also be written in the general form

$$F_A = 4L_C v_0\eta \,, \tag{3}$$

where $L_C$ is the “contact length”. It is defined as the sum of the diameters of all micro-contacts. In this form, the equation has also been confirmed for fractal surfaces by direct numerical simulations [9]. For rough surfaces, the contact length for small forces is roughly proportional to the normal force [7]

$$L_C \approx \frac{F_N}{hG} \,. \tag{4}$$

Here, $h$ is the root mean square of the roughness and $G$ is the shear modulus. Substituting this into Eq. (3) we obtain the adhesion force

$$F_A = \frac{4v_0\eta}{hG} F_N \,. \tag{5}$$

The adhesive force is, in this case, inversely proportional to the roughness and the shear modulus and proportional to the normal force. The Eqs. (3) and (4) are valid in the subcritical case of loading [5]. These dependencies were confirmed by our experimental results and are shown in **Fig. 2**. It would be interesting to examine whether, in our case, the deformation criterion for the fracture process is valid. As follows from the above analysis, as well as [4] and [5], the deformation criterion means that a cylindrical stamp always breaks off at a certain distance from the undisturbed surface, independently of the previous history. This means that if elastomer is loaded with some normal force so that it is indented by some indentation depth and then is pulled away, it has first to move this path back and then additionally the critical displacement before it detaches. This would mean that the vertical displacement will be approximately proportional to the normal force. This was also confirmed experimentally, as shown in Fig. 3. The intersection of all lines $F_N \to 0$ corresponds to the critical displacement. In our case, the critical displacement is approximately equal to 0.006 mm. The offset (Fig. 2) of the adhesion force ($F_N \to 0$) is outside of the experimentally measurable parameter space. Small normal forces were not investigated in this study.

## 4. Conclusion and Outlook

We have investigated the dependence of the adhesion between an elastomer and a steel cylindrical indenter on the surface roughness of the punch. Our results are compatible with the "deformation criterion" for the fracture of adhesive contact and with a viscous nature of the adhesive force.

Further experiments are planned that would detect the transition between subcritical and critical load. In order to describe the influence of roughness more precisely, experiments with a larger number of different rough indenters will be carried out. To understand the offset of the adhesion force, measurements at smaller normal forces will be needed. For a complete characterization of the adhesion processes, investigation of the adhesion in the complete parameter space “normal force – geometry – pull off velocity – temperature” is needed. This extended study is planned for the near future.

**Acknowledgements**: *The author is grateful to V.L. Popov, M. Popov and R. Heise for discussions, and Deutsche Forschungsgemeinschaft for financial support.*

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