Adhesion of Rubber on smooth and rough Surfaces

1. Introduction
Rubber contacts have many practical applications. The adhesion in the contact influences the function of many machines. Some practical examples are the tire-road contact and the contact of seals with shafts or rods. Further, rubber contacts have relevance for manufacturing processes. Examples are the rubber part to mould contact, which can result in problems while demoulding, or the contact between rubber parts in automatic assembling machines, where the contact makes the separation of rubber parts out of accumulations difficult.

In rubber contacts the adhesion mainly bases on intermolecular forces, e.g. due to van der Waals linkages. Very interesting is a rough estimation of the theoretical possible van der Waals linkages on the nominal contact area combined with the force one linkage could carry. This shows that typical only an extremely small percentage of theoretical possible linkages are active loaded, e.g. 1 of 10⁹, when the maximum adhesion force is observed.

The friction and adhesion behaviour of rubber contacts are important. Adhesion causes also one part of the friction in rubber contacts, cp. [1]. In this paper the adhesion in normal contacts is investigated.

1.1. State of the art
First model based investigations of rubber adhesion were done by Johnson, Kendall und Roberts [2] (JKR model) as well as by Derjaguin, Muller und Toporov [3]. These models base on the Hertzian contact theory [4] and describe the adhesive contact properties for static conditions. The adhesion contact properties considering quick relative movements were analysed by Roberts [5] and Barquins [6]. They observed much larger adhesive forces than in static conditions. Barquins [6] gave a very useful and efficient model to consider the dynamic in the adhesive contact. Many scientists analysed the influencing parameters of the adhesion force:

- First of all, the material properties of the rubber and the contact partner as well as their combination have to be pronounced.

- Further the surface roughness has a large influence. For a long time it was assumed that adhesion can be observed only on smooth surfaces. This is true for static conditions. With high separation velocities adhesion can also be significant on rough surfaces, cp. [7,8]. Results of these adhesion measurements with rough and smooth cylinders are reprinted in Fig. 1. It can be seen that the adhesion force $F_{\min}$ on a rough surface using abrasive paper (c) is smaller than on a smooth surfaces (b) but still significant. With a wet cylinder surface (a) the adhesion effect is small. This analysis has been done with an adhesion pendulum, like that which is described below. Also other scientists observed this effect, like Andersson [9] who separates rapidly tired tread blocks from road surfaces.

- Also very important are the process parameters which describe the dynamic contact: separation velocity, preload and contact duration.

- The separation velocity was investigated e.g. by Roberts [5] using a very interesting test rig where a steel ball rolls inside a rotating cylinder on a rubber surface. Also other scientists, like [6,10,11,12], observed this influence.

- In most investigations the adhesion depends strongly on the preload and contact duration, e.g. [6,8,9,13]. Surprisingly this was not the case in the experimental results of Voll [10,11]. He investigated the rapid separation of a flat, circular, very smooth counterpart from an elastomer plate. Variations of the preload between 5 N and 20 N as well as of the contact time between 1 s and about 1000 s show no significant change in the adhesion force. This discrepancy was the motivation to investigate the adhesion in dynamic contacts here again.

1.2. Analysis of existing results
In static contacts the adhesion forces are often of secondary interest because the dominant forces are gravity forces or Hertzian forces. Only for micromechanical applications, where surface forces dominate against volume forces, the adhesion force is of great interest. Due to the ex-
treme increase of the adhesion force with the separation velocity, e.g. by a factor of 1000, adhesion forces have large importance also for macroscopic dynamic contacts like the tire-road contact.

Focus in this paper is the analysis of preload and contact duration dependencies of the adhesion force. There are different reasons which explain these dependencies:

- Due to the viscoelastic behaviour of rubber the nominal contact area of many contact applications grows with time in contact. The rubber shows creep and relaxation processes. A typical example is a steel ball in contact to a flat rubber sample. In the beginning of the contact the contact area is small due to a large complex elasticity module. If the applied load is feedback controlled and is held constant the contact area grows with time in contact. The maximum contact area is reached when the relaxation process of the rubber is finished after a long time. With increasing contact area the adhesion forces grow, too.

- The viscoelastic material property of rubber influences not only the nominal contact area. If one part has a significant roughness, which is usually the case in engineering applications, the number of microscopic contact areas and there size depend on time. Due to creep and relaxation the real, microscopic contact area grows with time in contact. This causes an increase of the adhesion force, too.

- The steady state contact area given by the JKR model [2] results from a minimum of elastically stored and surface energy. If an increase or decrease of the contact area is reducing the sum of these energies the contact area changes in the direction of this minimum. Never the less in a large range around the minimum value of the contact area the velocity of the change of contact area is very small for rubber materials, cp. [6]. Therefore, usually the contact size is not in the steady state and rubber contacts depend on the actual contact force and the contact force history (preload and contact duration).

- Additionally also processes on the molecular scale can influence the macroscopic contact behaviour, cp. [14,15]. These molecular processes also depend on time. Due to the movement of the chains of the rubber molecular structure van der Waals linkages to the contact partner are permanently built and destroyed. These processes are time and temperature dependent which is typical for rubber. Further, on the molecular scale also diffusion processes are of interest, which can bring some rubber ingredients like oil or resin on the rubber surface and into the contact or bring rubber chains into the counterpart for a rubber-rubber contact.

Considering the different reasons for the preload and contact duration dependencies it could be expected that these effects are small for:

- Parallel flat-to-flat contacts because the nominal contact area could not increase,
- Smooth surfaces because the microscopic contact area could not increase,
- Rubber materials with small viscous effects because creep and relaxation is not dominant and influence not very much the contact area.

2. Experimental investigations

2.1. Test rigs

At the Institute for Machine Elements, Design and Manufacturing different test rigs for adhesion measurements has been built and are permanently developed further. One is an adhesion pendulum; see Fig. 2, which has the advantage that the contact duration is very small (about 2 ms, see Fig. 1). This is the range of the typical contact time between a tire tread block and the road during rolling. The pendulum has a very small weight, like 10g, to avoid that hysteretic properties due to the deformation dominate the adhesion effects on the surface. Detailed descriptions of the test rig can be found in [7,8].
Another test rig is the adhesion tester. In this test rig the movement of one contact partner is actuated by an electrodynamic shaker, see Fig. 3. The actuation gives the possibility to vary the preload, the contact duration and the separation velocity independent of each other. This is not possible in the adhesion pendulum, where only the impact velocity resp. drop height and the pendulum mass can be varied. A detailed description of the adhesion tester is given in [12,13].

In the following section some measured results with the adhesion tester are discussed because the preload and the contact duration dependencies are the main focus which can be very good investigated with this test rig.

### 2.2. Experimental results

Fig. 4 reprints some typical measurement results of a contact between a ball and a flat rubber sample using the adhesion tester. The ball has a small surface roughness. The rubber is a special developed, very adhesive compound. Fig. 4 shows the increase of the adhesion force with preload (left) and with contact duration (right), cp. [13]. The left diagram is scaled logarithmical. The measured results build a straight line in the diagram. Therefore, the dependency can be described very well by a power law. The increase of the adhesion force can be explained by an increase of the contact area especially on the macroscopic scale due to viscoelastic properties and the ball to flat contact.

The interpretation in section 1.2, which is based on the increase of macroscopic or microscopic contact area, has been proven by tests between two flat surfaces: A flat rubber plate and a flat glass sample. Immediately the whole nominal area is in contact which is checked optically via the glass plate. Both surfaces have a very small roughness. Especially in the production of the rubber sample the mould finish has to be optimized and additionally a thin layer is added during vulcanization to reduce the roughness of the rubber surface. The results are shown in Fig. 5, cp. [12]. All eight tested rubber materials show no significant preload dependency of the adhesion force (contact duration 5 s, separation velocity about 0.12 mm/s). Also the contact duration dependency of the adhesion force is quiet small (preload approx. 23 N, separation velocity about 0.25 mm/s). Never the less a small increase of the adhesion force can be observed for contact durations larger than 2 s. For some rubber materials this increase is very small, for some other it is a little bit larger.

To compare the effect of the roughness two rubber samples with different surface roughness are produced. One is again very smooth. The other one has a significant roughness due to sand blasting of the mould before vulcanisation. For these tests a new, slightly different compound is used in respect to the results from Fig. 5. The Figure 6 compares the results of the smooth and rough surfaces. For the smooth rubber surface the preload and preload duration dependency is vanished again. But a significant increase of the adhesion force with preload and preload duration can be observed for the rough rubber surface (preload duration 5 s resp. preload approx. 23 N, separation velocity between 1 mm/s and 5 mm/s). A variation of the separation velocity is given in Fig. 7. With the separation velocity the adhesion force is increasing significantly for the rough as well as for the smooth rubber surface. The relative increase is stronger for the rough then for the smooth surface (preload duration 5 s, preload approx. 23 N).

### 3. Conclusion

In the focus of this work is the influence of preload and contact duration on the adhesion force. In contrast to most results in the literature and own investigations, Voll [10,11] showed results where the adhesion force not increase with preload and contact duration. This paper explains the reasons for this dif-
different behaviour. Therefore, physical reasons for the dependencies have been analysed. Main reasons are the viscoelastic behaviour of rubber which results for non-flat-contacts or rough surfaces in an increase of the nominal, macroscopic or real, microscopic contact area. The increase of contact area is the reason for the increase of the adhesion force. This assumption has been proven by adhesion tests between a very smooth, flat rubber samples and a glass plate. Eight typical rubber compounds have been investigated. All of them have usual viscoelastic behaviour. The results show that the constant nominal contact area of the flat samples and the small roughness prevent the preload depend. A comparison of the results proves that the preload and contact duration dependency is significant on rough rubber surfaces and is vanished on smooth rubber surfaces. Also the contact duration dependency is quiet small for this contact configuration. Therefore, the experiments improve the physical explanations of the effects in contact. The rough as well as the smooth rubber tests show a strong influence on the separation velocity. This investigation increases strongly the knowledge of the adhesion effects in contacts.

Literature