Adhesive contact mechanics of viscoelastic materials

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Abstract

Several experimental investigations performed over the last decades clearly indicate that the contact behavior of rubbery-like materials is highly affected by a complex interplay between adhesion and viscoelasticity. Viscoelasticity is a major source of friction: the hysteretic losses occurring during the cyclic deformations induced by sliding or rolling motion are eventually responsible for a lateral force opposing the relative velocity. In 1963, Grosch's experimental study (1) demonstrated that the overall dependence of the viscoelastic friction on the sliding velocity is highly affected by the presence of interfacial adhesion: the measured friction coefficient is found substantially increased compared to corresponding adhesiveless conditions. This evidence might depend on different mechanisms. First, in the presence of adhesion, the contact area is enlarged, therefore a larger amount of volume undergoes cyclic deformation leading, in turn, to higher dissipation. Additionally, adhesive interactions induce significant amount of energy dissipation close to the contact edges, responsible for adhesion hysteresis. This phenomenon is usually referred to as "small-scale viscoelasticity". Importantly, it is often identified as a primary source of adhesive strength enhancement. Indeed, experiments demonstrate that the maximum tensile load (i.e., the pull-off force) might be significantly increased compared to theoretical predictions of models assuming a purely elastic rheology. Notably, this evidence is observed both in rolling contacts (2) and dynamic normal indentation (e.g., approach-retraction cycles) (3,4). Many of the existing studies in the field rely on scale separation: the material response is assumed to be purely elastic within the bulk, with viscoelastic losses localized close to the contact area's boundary. Viscoelasticity is therefore completely accounted by introducing an effective velocity-dependent energy of adhesion. However, neglecting the bulk viscoelasticity while modelling adhesive contacts might prevent tackling many of the observed phenomena. Moreover, a comprehensive theory of viscoelastic adhesion is currently lacking and the overall effect of the interplay between adhesion and viscoelasticity on the contact behavior is not fully understood yet. Aiming at filling this gap in the literature, we present a novel energy approach for viscoelastic adhesive contact mechanics. The energy formulation relies on the virtual work principle: the variation of adhesive energy due to virtual variations of the contact area must be balanced by the work of internal stresses. The theoretical framework has been developed either for steady state sliding or rolling contacts (5,6) and general unsteady conditions (7). The proposed theory provides results in solid agreement with many of the experimentally observed phenomena. In steady state sliding contacts (5,6), the adhesion-induced increase of viscoelastic friction is predicted, and the overall trend of the friction coefficient vs. the sliding velocity is a similar fashion to Grosch's experimental results (1). In agreement with experimental observations provided by Charmet and Barquins (2) the pull-off force is velocity-dependent and significantly increased compared to static conditions. Adhesion enhancement is correctly predicted

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in general unsteady conditions (7), in the so-called JKR dynamic contacts. In this case, the effect of viscoelasticity on the effective adhesion is found highly dependent on the specific enforced loading time-history. At relatively low velocity, the adhesive strength enhancement depends on small-scale viscoelastic losses. However, a different fundamental mechanism is also identified, in agreement with experimental observation (3,4): when the retraction of the indenter starts from a fully relaxed state, the pull-off force is highly increased even at very high retraction speed. This result depends on the glassy elastic response of the material, that prevents the contact area from decreasing, eventually resulting in a flat-punch like behavior. Importantly, under these conditions, the contact behavior cannot be predicted by exploiting the JKR elastic adhesive model with increased effective adhesion energy.

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