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Sliding friction across the scales: Thermomechanical interactions and dissipation partitioning

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ABSTRACT

A homogenization framework is developed for determining the complete macroscopic thermomechanical sliding contact response of soft interfaces with microscopic roughness. To this end, a micro–macro mechanical dissipation equality is first established which enables defining a macroscopic frictional traction. The derivation allows both contacting bodies to be deformable, thereby extending the commonly adopted setting where one of the bodies is rigid. Moreover, it forms a basis for the second step, where a novel micro–macro thermal dissipation equality is established which enables defining partitioning coefficients that are associated with the frictional dissipation as it is perceived on the macroscale. Finally, a comparison of the temperature fields from the original heterogeneous thermomechanical contact problem and an idealized homogeneous one reveals an identification of the macroscopic temperature jump. The computational implementation of the framework is carried out within an incrementally two-phase micromechanical test which delivers a well-defined macroscopic response that is not influenced by purely algorithmic choices such as the duration of sliding. Two-dimensional numerical investigations on periodic and random samples from thermo-viscoelastic boundary layers with unilateral and bilateral roughness demonstrate the temperature–velocity–pressure dependence of the macroscopic contact response.

1. Introduction

The multiscale nature of friction has long been recognized (Bowden and Tabor, 2008; Persson, 2000). Friction appears in one form or another at the nano–micro–macro scales and in all cases it represents irreversible energy transfer away from the contact zone, in other words *dissipation*. The goal of this work is to develop a theoretical and computational framework for characterizing how microscopic dissipation accumulates across multiple length scales and manifests itself as sliding friction on an upper scale for soft materials. The differentiating aspect of the work with respect to earlier contributions is twofold: first, both bodies in contact are admitted to be finitely deformable, and second, the aim is to take multiscale thermomechanical interactions fully into account. Overall, the emphasis of the framework will be not only on mechanical contact quantities of interest, such as a friction coefficient, but also on thermal ones, such as how dissipation — as it is perceived on the macroscale — is partitioned onto the contacting surfaces.

Presently, the focus is on the continuum-level modeling of soft interfaces, which are typically associated with biological or synthetic materials. Recently, there has been significant interest in the modeling of tactile perception which requires the

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frictional characterization between skin and textured surfaces or textile materials (Fagiani et al., 2012; van Kuilenburg et al., 2012; Adams et al., 2013; Koç and Aksu, 2013; Ramalho et al., 2013). There has also been interest in the frictional response of compliant engineered surfaces and how these surfaces interact with relatively hard rough or textured surfaces (Shen et al., 2008; Murarash et al., 2011; Brörmann et al., 2013; Bai et al., 2014), rubber being a particular example of technological interest (Le Gal and Klüppel, 2008; Carbone et al., 2009). For such soft materials, a major source of dissipation is the viscoelastic response of the material. The boundary layer in the vicinity of contact zone is continuously and cyclically being loaded by the asperities of the rough surface during sliding, which causes dissipation. Indeed, starting with the early works by Schallamach (1953), Grosch (1963) and others, early models of rubber friction already recognized viscous dissipation as one of the two major contributions, the other being adhesion. While significant advances have been achieved towards a quantitative modeling of rubber friction (Persson et al., 2005), thereby constituting a basis for similar studies for soft materials in general, emphasis has predominantly been on the mechanical aspects that can be concatenated towards a friction coefficient value which depends on a number of contact variables including the pressure and the slip velocity. Studies towards this purpose have been carried out in both infinitesimal (Klüppel and Heinrich, 2000; Persson, 2001; Carbone and Putignano, 2013) and finite deformation regimes (Wriggers and Reinelt, 2009; Temizer and Wriggers, 2010a; De Lorenzis and Wriggers, 2013), all being based on a setting where one surface is smooth and deformable while the other is rough and rigid. On the other hand, from everyday experience one is familiar with how rapidly soft materials can warm up due to friction and how both surfaces can significantly deform, for instance when hands are rubbed against each other. Since viscous response is highly temperature sensitive, the thermal aspects of the problem are just as important as the mechanical ones (Persson, 2014). The macroscopic investigation of these thermal aspects requires more than the temperature dependence characterization of friction. For instance, the microscopically rough interface topography induces a temperature jump across the macroscopic contact interface which influences the temperature distribution in the vicinity of the contact interface (Madhusudana, 1996). More importantly, temperature changes are also governed by how the frictional dissipation is partitioned onto the contacting surfaces as heat flux on the macroscale. On a phenomenological level, a fraction of the mechanical power dissipated is absorbed by one of the surfaces and the remaining by the other (Agelet de Saracibar, 1999). Hence, unless the nature of this partitioning is described accurately, the macroscopic temperature rise and hence its overall impact on friction cannot be appropriately assessed. A major objective in this work will be to provide a non-phenomenological basis for macroscopic frictional dissipation partitioning onto deformable surfaces in sliding contact. Efforts towards this purpose have so far been limited to one-dimensional models that concentrate only on the thermal aspects of the problem (Chantrenne and Raynaud, 1997, 2001; Nosko, 2013).

The microscopic dissipation mechanisms include bulk and interface dissipation. Here, the bulk dissipation will be specialized to soft materials. As representative recoverable and irrecoverable deformation mechanisms, viscoelasticity and damage are considered. While plasticity can also be observed for the materials of interest, in particular for rubber-like materials (Lion, 1997; Miehe and Keck, 2000), the vanishing dissipation contribution due to such irrecoverable mechanisms can be demonstrated through damage alone. Interface dissipation will be limited to microscopic friction while adhesion, which can have a significant contribution to macroscopic friction (Persson et al., 2005; Momozono et al., 2012), is omitted. Nevertheless, adhesive effects can be incorporated through an identical treatment. Despite their significance towards a quantitative understanding of friction, a number of additional simplifications will be admitted in view of the fact that these do not affect the qualitative conclusions to be drawn in this work. These include the omission of inertial effects (Momozono et al., 2012; Bai et al., 2014), the assumption of a single scale of roughness versus a fractal structure (Persson et al., 2005; Pei et al., 2005) and the common choice of a single relaxation time instead of employing a sufficiently large number to capture the relaxation spectrum (Wriggers and Reinelt, 2009; Suwannachit et al., 2012; Carbone and Putignano, 2013).

The work is outlined as follows. In Section 2, the continuum mechanics background for the thermomechanical contact problem is summarized. The presentation here is brief in order to allow a rapid transition to the major discussion yet provides a sufficiently general basis for it. The micro–macro thermal dissipation equality that is central to this work is established in Section 3, based on the statement of its mechanical counterpart in a form that is suitable for two deformable micromechanical samples in contact. Specifically, the partitioning coefficients that are associated with the frictional dissipation as it is perceived on the macroscale will be identified in this section. Subsequently, an incrementally two-phase micromechanical test will be described in Section 4 where the determination of the temperature jump across the macroscopic contact interface will additionally be discussed. Here, the explicit enforcement of the macroscopic contact surface temperatures will be the key to ensuring the algorithmic consistency of the overall homogenization framework, in addition to its thermodynamic consistency that is guaranteed by the micro–macro dissipation equalities. The thermo-viscoelastic material model employed will be outlined in Section 5, which will also enable the verification of various assumptions that were invoked earlier. In Section 6, two-dimensional numerical investigations on periodic/random samples from thermo-viscoelastic boundary layers with unilateral/bilateral roughness will demonstrate the temperature–velocity–pressure dependence of the macroscopic contact response. Finally, concluding remarks address a number of simplifications that have been assumed throughout the work. Specific choices regarding constitutive modeling and the simulation parameters are provided in the appendices.