Probing the micromechanics of a multi-contact interface at the onset of frictional sliding

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Résumé :

Nous discuterons le rôle de la rugosité interfaciale sur la transition entre contact statique et frottement cinématique, sur l'exemple d'une surface élastomère plane et rugueuse et d'une surface de verre sphérique et lisse. Nous utilisons une méthode de corrélation d'images pour mesurer les champs de déformation et de contrainte dans le plan de la surface élastomère au cours de la mise en charge tangentielle. Nous observons une région annulaire de micro-glissement qui envahit progressivement le contact, coexistant avec une région centrale collée. Les caractéristiques principales de ces mesures locales sont correctement décrites par le modèle classique de Cattaneo et Mindlin (CM). Cependant, une comparaison quantitative détaillée révèle des différences significatives qui reflètent les hypothèses simplificatrices sous-jacentes au scénario CM. En particulier, nous montrerons que, au lieu du comportement rigide-plastique considéré dans le modèle CM, l'interface obéit à une loi de frottement du type élasto-plastique mettant en jeu une longueur caractéristique associée à la rugosité. Nous discuterons cette loi constitutive locale à la lumière d'un modèle récent dérivé pour les interfaces multi-contact macroscopiques chargées de façon homogène.

Abstract :

We will discuss the role of surface roughness on the transition between static and kinetic friction, on the example of a flat rough elastomer in contact with a spherical smooth glass surface. Digital Image Correlation is used to monitor the in-plane elastomer deformation as the shear load is increased. An annular slip region is found to progressively invade the contact, in coexistence with a central stick region. The main features of these local measurements are correctly captured by Cattaneo and Mindlin (CM)'s model. However, close comparison reveals significant discrepancies that reflect the oversimplifying hypothesis underlying CM's scenario. In particular we will show that, instead of the rigid-plastic behavior assumed in CM's model, the interface obeys an elasto-plastic-like friction law involving a roughness-related length scale. We will discuss this local constitutive law in the light of a recent model derived for homogeneously loaded macroscopic multi-contact interfaces.

Keywords : Sliding transition, Multicontact interface, Cattaneo and Mindlin's scenario, Digital Image Correlation, Local friction law, Displacement field.

1 Introduction

The transition from static to sliding friction is a crucial process in various fields, ranging from contact mechanics, earthquakes dynamics to human/humanoid object grasping. In the classical Amontons-Coulomb's framework, when two solids are brought into contact under normal load P and subjected to a shear force Q, no relative motion occurs until Q exceeds some threshold value $Q_s = \mu_s P$, where μ_s is called the static-friction coefficient. However, in most real situations, the transition from static to dynamic friction does not follow this ideal simple scenario. As soon as $Q > 0$, partial slippage generally sets in owing to the large stress heterogeneity within the contact zone, which depends on the geometry of the objects in contact as well as on the loading conditions. Understanding this incipient sliding regime thus requires to gain access to the interfacial micromechanics within the contact zone.

In the past ten years, several experimental groups developed new optical methods to obtain spatially resolved mechanical measurements [1,2], which triggered intense subsequent theoretical and numerical investigations [3-7]. By patterning a smooth elastomer's surface with a regular grid of micro-markers, Chateauminois and coworkers were able to monitor, using Particle Image Velocimetry techniques, the entire 2D displacement field at the interface. They applied this procedure to a smooth sphere loaded against a smooth flat elastomer block in a torsional configuration [8]. In their experiment, macroscopic adhesion was important due to the smoothness of the surfaces in contact. In most practical situations however, interfaces are rough at microscopic length scales, giving rise to a multi-contact frictional interface at which macroscopic adhesive effects are strongly reduced. Here, we expand on this two-dimensional approach. We report on micromechanical measurements at the onset of sliding between a smooth sphere and a flat elastomer block whose surface is microscopically rough. These results have been recently published in [9].

2 Experimentals

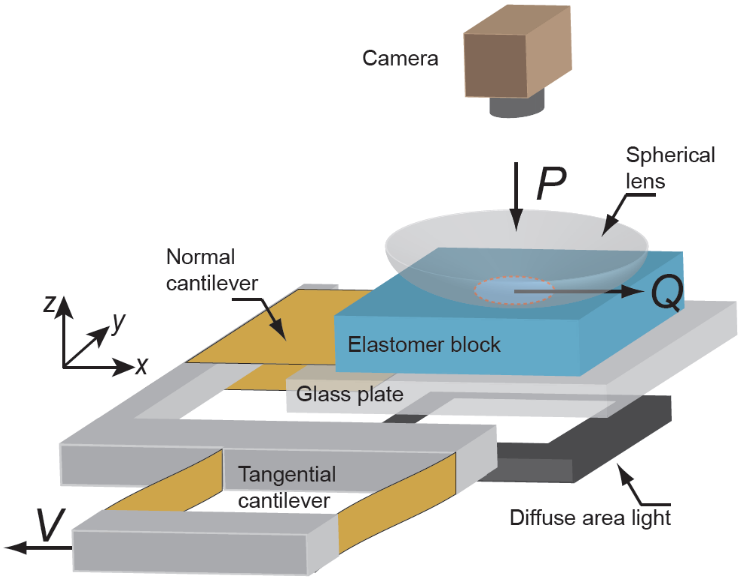

FIG. 1 – Sketch of the experimental setup.

Figure 1 shows a sketch of the experimental setup. It consists of a planoconvex glass lens (radius of curvature R = 128.8mm) glued onto a lens holder and rigidly attached to an optical table. The lens surface is in frictional contact against a thick elastomer block. The latter is loaded *via* a set of two orthogonal cantilevers to a translation stage that can be driven at constant velocity V. Two capacitive position sensors, each facing the mobile part of one cantilever, allow one to measure both P and Q, respectively the normal and tangential (shear) force in the range [0–2 N]. Imaging of the contact is done by illuminating the interface through the transparent elastomer block. Images of the interface are recorded with a CCD camera.

The elastomer block (50 × 50 mm, thickness 15mm) is made of crosslinked PolyDiMethylSiloxane (PDMS). The free surface of the elastomer block is rough with a characteristic thickness h of the rough interface, defined as the standard deviation of the height distribution, is measured to be 0.595 μm. The block's Young's modulus is E = 3.43 MPa. Its Poisson's ratio is 0.5.

Interfacial displacement fields were computed from snapshots acquired at 8 frames/s (Δt = 0.125 s), using a Digital Image Correlation technique (DIC) [25]. This method consists in finding, for a given sub-image centered at position (x, y) in a reference frame, the displacement (u_x, u_y) that provides the maximum intensity correlation with a subsequent (deformed) image. A 2D correlation function was computed using a direct calculation. Sub-pixel resolution was achieved by fitting the correlation function with a 2D Gaussian surface using the pixel of maximum correlation and its 8 nearest neighbors.

We performed a series of 6 experiments in which the elastomer block was driven at a prescribed velocity V = 5 µm/s, under constant normal force P in the range [0.1–1.4 N]. For all runs, P was found to vary by less than 1% over the duration of the experiment and the apparent contact zone remains circular.

3 Results

Figure 2 shows typical results for the displacement fields measured. As soon as Q increases, the displacement in the outer region of the apparent contact increases. In contrast, the measured displacement remains essentially null within a central circular region. As Q increases, the radius of this stick region decreases and eventually vanishes, marking the onset of the macroscopic sliding phase.

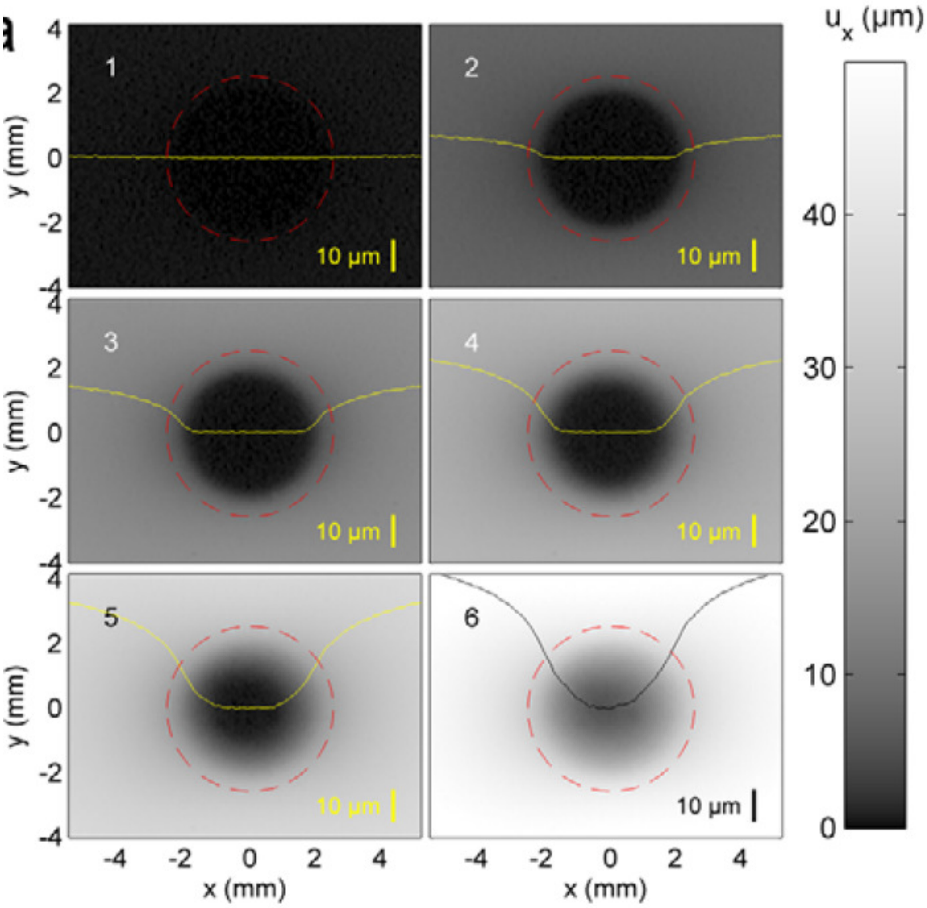

FIG. 2 – Snapshots of the 2D displacement fields u_x at P = 0.5N for 6 instants during the incipient loading of the contact. On all displacement fields, the red dashed circle delimits the initial apparent contact area of radius. The yellow curves (respectively black curve) on snapshots indexed 1 to 5 (respectively 6) are cuts of the u_x 2D displacements fields.

These precise local mechanical measurements are directly amenable to comparison with existing theoretical models of incipient sliding. The first model, for a nonadhesive elastic sphere-on-plane contact, was derived independently by Cattaneo and Mindlin (CM) [10]. CM's calculations assume that (i) both surfaces are smooth, (ii) the pressure distribution σ_{zz} within the contact is unchanged upon shearing and given by Hertz contact theory, and (iii) Amontons-Coulomb's law of friction is valid locally at any position within the contact, i.e. slip occurs wherever the shear stress σ_{xz} reaches $\mu\sigma_{zz}$, μ being the macroscopic friction coefficient.

We performed a detailed comparison between our measurements and the results of CM's model [9]. We found that our measurements agree with CM's model, not only qualitatively with the existence of an inner stick region surrounded by a growing annulus of slip, but also quantitatively since both displacement and stress distributions are found to follow reasonably well the predicted shape and amplitude. However, close comparison reveals discrepancies, the most striking being that the displacement in the vicinity of the center of the contact is not strictly null during the transient phase, but slowly increases with Q.

This problem has been theoretically analyzed by Bureau and coworkers in the context of a plane-on-plane frictional contact configuration [11]. The surface topography is described using Greenwood-Williamson's model [12]. In addition, the response of each asperity upon tangential loading is described by CM's model. The model predicts the evolution of the ratio Q/P as a function of the relative displacement δ of the centers of mass of both solids in contact, in the form $Q/P=\mu\,(1-e^{-\delta/\mu L})$, where μ is a microscopic friction coefficient and where $L=h\,(2-\nu)/2(1-\nu)$ is an elastic length whose value is controlled by the *rms* roughness of the interface h, and which depends on the material properties only through the Poisson's ratio ν. Figure 3 shows that this model accurately reproduces our local measurements.

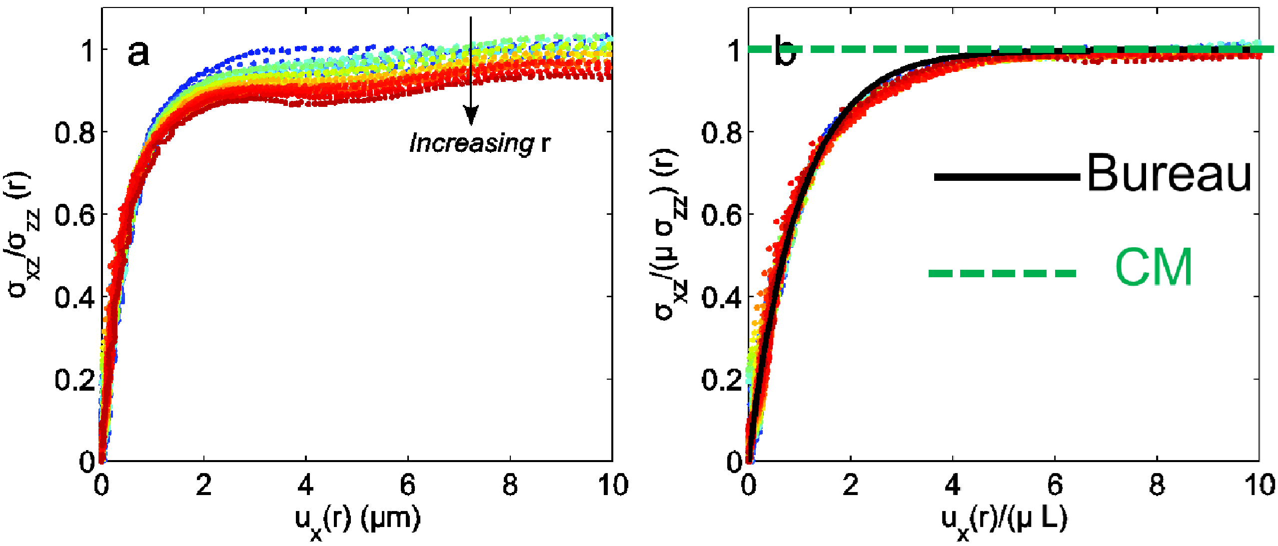

FIG. 3 – (a) $\sigma_{xz}\,/\,\sigma_{zz}$ versus u_x for P = 0.7N, at different r. Small-r valued curves are shown in dark blue, while large-r valued curves are in dark red. (b) $\sigma_{xz}\,/\,\mu\sigma_{zz}$ versus $u_x/(\mu L)$ for the same load at different r. The solid black curve is $1-e^{-\alpha}$ with α a dimensionless increasing number.

4 Conclusions

Overall, the present study suggests the need to replace the rigid-plastic-like Amontons-Coulomb friction law with an elasto-plastic constitutive friction law in CM-like derivations of the displacement/stress fields, and more generally in any micromechanical analysis of contact mechanics problems [13]. The effective modulus of the elastic part of this constitutive law is i) proportional to the local applied pressure and ii) inversely proportional to the thickness of the rough interfacial layer. The type of measurements developed and validated in this work opens the way for more focused studies in any other contact geometry or loading configurations, for which no explicit model might be available. The time resolution of the measurements being entirely controlled by the frame rate of the imaging system, we anticipate that the very same method could also be used in the fast transient regimes involved in frictional instabilities.

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