A THERMOELASTIC INVESTIGATION OF FRICTION PHENOMENA

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ABSTRACT

We have studied dynamic friction phenomena using a variety of experimental measurement approaches. We have combined thermoelastic stress analysis (TSA) and optical microscopy to measure both the stress field and the interface slip displacement in a model frictional contact. We use a plane stress, fiber pullout-type geometry to produce a line contact interface. The interface operated in the partial slip regime with no gross sliding. The stress field and slip displacement information allow us to construct a friction constitutive relationship directly from experimental data. We also use complementary interface modeling to physically interpret the experimental observations. The results suggest that the interface slip zone size is a nominally linear function of pullout force, while the interface slip displacement responds as a second-order function of distance along the interface. When combined, these observations suggest a scaling law for per-cycle energy dissipation of the form \( E \sim F_o^3 \), where \( F_o \) is the forcing amplitude. Experimental and modeling results are presented to support this conclusion.

BACKGROUND

Experimental characterization of frictional interface behavior presents a variety of challenges, perhaps most notably the desire to obtain spatially-distributed response information. Using an array of single-point sensors is difficult due to packaging constraints, as well as durability issues for sensors placed directly on the contact interface. We have recently turned to a full-field, non-contacting approach to interface characterization using thermoelastic stress analysis (TSA) and optical microscopy. TSA allows us to capture thermal signatures around a contact interface during time-dependent load events, velocity reversals, and stick-slip transitions. Optical approaches allow us to visualize the relative displacement field across the interface and estimate slip distances. This extended abstract details our experimental configuration, testing procedures, and some basic results of frictional characterization using thermoelastic methods and complementary models.

TEST SETUP AND MEASUREMENT APPROACH

We have examined a frictional interface with the plane stress, fiber pullout-type geometry shown in Figure 1. The pads and pullout specimen are fabricated from a single piece of PMMA, with the contact surfaces finished by a series of polishing operations to an average surface roughness of 6 \( \mu \)m. The clamp load is applied using a hydraulic actuator, while the specimen is pulled at a controlled rate by a piezoactuator with the pullout force measured by a load cell. The friction coefficient was characterized as \( \mu = 0.14 \). We conducted tests with pullout displacements on the order of 100’s of \( \mu \)m at both quasi-static and low frequency (< 50 Hz) conditions.

The TSA temperature field is captured using a DeltaTherm infrared camera with resolution of 0.003 K, typically over a spatial field of a few cm spanning the contact area. Figure 2 shows a typical TSA profile. Part (a) shows the in-phase TSA image, which clearly illustrates the normal stress in the pullout fiber near the contact edge. A line scan along the interface [Figure 2(b)] reveals the transition from slip at the leading edge to stick at the interior of the contact. The TSA signal is strong and uniform in the slip zone, where all of the thermal energy is generated.

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RESULTS

We have compared the TSA results for slip length with predictions of a shear-lag-type model developed as part of this research effort [1]. We have performed pullout experiments at various displacements (corresponding to different pullout stresses), and interfacial slip length has been determined using line scans as shown in Figure 2(b). The analytical model used for comparison employs components of both shear-lag theory (for large slip zones) and contact mechanics (for small slip zones) to develop a consistent set of predictions which match the experimental results reasonably well (Figure 3). Here, we have normalized the pullout stress by the stress required to completely slip the interface, and the slip length by the total interface length. At small slip length, the behavior is governed by edge-of-contact effects, in which the (rounded) corner geometry promotes slip. This effect is captured by the contact mechanics approach, while the specifics of the corner geometry are neglected in the shear-lag analysis. At larger slip length, the details of the edge of contact are less important, and the shear-lag theory lines up reasonably well with the experimental observations.

We have also implemented an optical microscopy approach in which a FIB ruler is milled onto each side of the interface. By inspecting the interface for relative displacement of the components, we have mapped the slip displacement onto a second-order function of distance from the stick-slip boundary. These results, when combined with the slip length behavior of Figure 3, suggest a power law scaling for energy dissipation of the form $E \sim F_0^3$, where $E$ is the frictional energy dissipation and $F_0$ is the pullout stress amplitude. This result is not entirely unexpected in light of the many dissipation scaling results reported in the literature containing power law exponents between 2.5 and 3.0.

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REFERENCES