Experimental Investigation of Multi-Scale Flash Weakening

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Introduction

Weakening of faults by flash heating is regarded as one of the more important processes governing fault friction behavior, particularly during the onset of high-velocity slip and the early phases of earthquake rupture development (Rice, 2006; Beeler et al., 2008; Goldsby & Tullis, 2011). Although experimental studies have documented weakening at high slip-rates, and that the observed weakening behavior is well-characterized by the steady-state, velocity-weakening relation based on flash heating at micrometer-scale asperity contacts (e.g., Rice 2006), the evolution of contact geometries is not well-defined making it difficult to develop a velocity-dependent constitutive relation that describes transient friction during the accelerating and decelerating phases of earthquake slip (Beeler et al., 2008; Proctor et al., 2015). For example, rotary-shear experiments on serpentinite by Proctor et al. (2015) show strong hysteresis in friction, and the behavior during the deceleration phase of a high-velocity sliding event cannot be described completely, even when one accounts for the average increase in temperature of the sliding surface during the high-velocity sliding phase.

The steady-state, flash-weakening friction-relations generally assume contact dimensions of micrometers (e.g., Rice 2006), in accord with the size of particles in fault gouge (e.g., Chester et al., 2005), and the size of contacts observed directly in quasi-static experiments that apply normal loads to ground surfaces of rock (Dieterich & Kilgore, 1994, 1996). There is no reason to assume, however, that frictional contacts that form during seismic slip on natural faults will have the same geometry and normal stress distributions as those of flat, ground surfaces in quasi-static contact. Natural faults surfaces display anisotropic roughness over a range of length scales (e.g., Scholz & Aviles, 1986; Power & Tullis, 1991; Sagy et al., 2007), and Brodsky et al. (2016) propose that these roughness characteristics reflect a scale dependence of the yield strength of contacts, and that different yielding processes operate at different scales.

The purpose of this project was to document the relationship between the characteristics of flash-heated contacts and frictional weakening behavior in order to improve the constitutive descriptions of transient and steady-state flash weakening. The methods employed and experiments conducted in this study were developed from work by Saber et al. (2015, 2016) and Saber (2017), which showed that flash heating at the sample scale is highly variable during frictional sliding at seismic slip rates, and is characterized by mm-size spots and streaks of locally high temperature and normal stress. Model analysis of the experiments informed by the spatial characteristics of flash heating is able to explain better the observations of transient frictional behavior at seismic slip rates including hysteresis, although there is some ambiguity in the model associated with uncertainty of the average lifetime of heating for the mm-size contacts (Saber, 2017). The work reported here removes this uncertainty so as to allow development of robust constitutive models for flash-weakening on fault surfaces with multi-scale roughness.

Methods

We take advantage of our high-speed biaxial rock deformation apparatus equipped with a high-speed thermal imaging (Infrared, IR) camera to document the nature of flash heating of rock surfaces during controlled seismic slip. Our apparatus achieves velocity steps from quasi-static sliding-rates to seismic sliding-rates (~1 m.s\(^{-1}\)) within ~2 mm of slip followed by sliding at constant velocity for up to ~3.5 cm (Saber et al., 2015, 2016). We conduct double-direct shear (DDS) experiments on bare ground surfaces of Westerly granite that are run-in to produce a thin layer of wear product (gouge), and then test the flash-weakening behavior (Barbery et al., 2016a, b). The DDS configuration has two sliding interfaces, each 2 x 3 in (50 x 75 mm) in size. This
sample size allows study of roughness variation over a larger length scale, in both the slip-parallel and -perpendicular directions, compared to many other high-speed friction machines. We grind all surfaces flat to achieve a 6 in² (37.5 cm²) macroscopic contact area on each block, and for a subset of samples grind shallow (50 µm depth) grooves to produce contact areas of 1.5 in² (9.4 cm²) or 0.67 in² (4.2 cm²) over 80 or 36 individual contacts, respectively (Barbery et al., 2017). Each macroscopic contact is diamond-shaped with a contact area of 28 mm² (Figure 1). As a result of the grooved surface pattern, once points come in contact after sliding is initiated they remain in contact for 8.3 mm of slip, the points then break contact for a specific slip distance before they are renewed and the cycle is repeated. All of the sample geometries employ the same contact size and thus produce the same contact period (8.3 mm/velocity=LifeTime, LT), but the sample surface geometries produce a different period of contact separation (RestTime, RT) that is either 0.5, 1, or 2 times the LT. The normal load on the side blocks is set to a value such that every diamond-shaped contact supports an average normal stress of 32 MPa. Using a high-speed IR camera, the sliding surface on one side of the center block is imaged as it emerges from the base of the stationary side block. An area 13.5 mm x 17 mm in size is imaged with a resolution of 36 µm/pixel at a frame rate of 300 Hz, i.e., about every 3.3 mm slip at a sliding velocity of 1 m.s⁻¹.

Findings

Numerous experiments were run on the grooved surfaces at the same conditions of normal stress and sliding velocity in order to capture a sufficient number of IR images of the heated surfaces and to check mechanical reproducibility. We find that the frictional strength and critical distance for weakening for each surface geometry are reproducible to within 5% of the average. The average mechanical response for each surface geometry is shown in Figure 2. Capturing IR thermographs from multiple experiments on each surface geometry is valuable because the imaged area covers only a portion of the sliding surface and the distribution of flash heating is variable; moreover, the range in surface temperatures observed is more than 400°C, which is best resolved by conducting repeat experiments using several different temperature-range settings of the IR camera. Representative temperature distributions imaged for each surface geometry is shown in Figure 3.

The main finding obtained from the grooved surface geometry is that the coefficient of friction for high-speed sliding decreases with a reduction in contact rest-time (RT), holding all other parameters (i.e., contact size and LT, normal stress, and sliding velocity) constant (Fig. 2). Thermographs of the slipped surfaces verify that the flash-temperature of contacts generally increase with a decrease in RT (Fig. 3), as would be expected based on thermal modeling of flash heating. Another significant result is that the grooved surface geometry ensures that the average LT of the mm-scale contact population is reset within 8.3 mm of slip after the velocity step to high speed-sliding, which is consistent with observations of steady sliding-strength within several mm of slip after the velocity step (Fig. 2). There is, however, a gradual increase in the average surface temperature with slip because the local elevation of temperature from flash heating during the contact LT only partially decreases during the RT. This phenomenon produces an increase in the average contact temperature with each full LT-RT cycle. Interestingly, even for the geometry with the shortest RT, and thus the greatest number of LT-RT cycles by the end of high-speed sliding, there is little evidence for a significant reduction of frictional strength with slip after the initial transient weakening.

Another important finding is that the samples with grooved surfaces and the smallest total contact area (0.67 in²) display greater dynamic weakening relative to the samples with grooved
surfaces and the larger contact area of 1.5 in². This result is surprising because the diamond-shaped contact size, LT-RT cycles for contacts, and average normal stress on contacts are the same for the samples with the smallest and largest total contact areas. The reason for the significant difference in weakening behavior is uncertain; however, thermographs of the surfaces do suggest that the samples with 0.67 in² area tend to form fewer, but locally higher temperature flash heated spots, as well as narrow heated streaks rather than equidimensional heated spots (e.g., compare images for the LT=RT experiments, i.e., Figs. 3a and 3c). It is important to investigate this finding further because many experimental programs investigating high-speed friction employ samples with relatively small total surface area, which may amplify the magnitude of dynamic weakening.

We compare the results of the present experiments using grooved surfaces in which we control the contact LT and RT to previous rock-on-rock experiments that used flat surfaces (Saber, 2017). Previous work at lower sliding velocities of 100 and 300 mm.s⁻¹ and a lower normal stress of 2 MPa, which produce lower heating rates, display transient weakening over a much greater slip-distance when compared to the highest sliding-rate experiments. As shown by Saber (2017), a thermomechanical model that couples flash-heating and temperature-weakening can determine...
spot temperature and normal stress distributions on the sliding surfaces that satisfy observations, and that simultaneously constrain the material parameters in conventional, flash-weakening constitutive relations. Without knowing the LT and RT for the contact population, however, the model solutions for constitutive parameters are non-unique.

The size of contacts and flash temperature distributions developed on the flat surfaces of Saber’s (2017) experiments are similar to those produced herein. It is noteworthy that we find that the mechanical behavior of the experiments with LT=RT matches the mechanical behavior of analogous tests by Saber (2017) quite well, whereas the tests with a LT>RT are significantly weaker. This finding suggests that the contact spots that develop in samples with flat surfaces (Saber, 2017) also may be characterized as having LT=RT.

The approach we employ to quantify material properties and test friction constitutive relations is to use knowledge of the exact LT and RT of contact populations to constrain flash heating. We
show a simple example for determining the local normal stress of contact spots during sliding given the temperature distributions documented through IR imaging and by knowing the contact LT and RT history for the spot during the high-speed slip (Fig. 5). Current work is extending Saber’s (2017) coupled, thermomechanical model of flash weakening to determine constitutive parameters and uniquely determine normal stress and friction at the mm-contact scale.

Conclusions

- Using high-speed friction experiments employing samples with larger surface areas and geometrically machined, rough surfaces is a viable approach to understanding friction on natural fault surfaces that have been shown to be rough at multiple scales.
- Additional experiments to investigate normal stress, LT-RT variations, and velocity dependence of flash-weakening, and using thermomechanical models that treat coupling of flash heating and temperature weakening, are necessary to constrain constitutive models and material parameters for flash weakening behaviors.
References


