Thermally self-controlled friction: Correlation between slip behaviors and surface structures changing during a stick-slip event

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Since the true contact area is much smaller than the apparent contact area, stresses on the true contacts are much larger than the applied stress, and hence the true contacts can be melted after slips during only the order of 0.01 sec even under the conditions for natural seismic slips. The temperature at the true contacts changes depending on the slip history, and the heat generation rate is controlled by the mechanical properties of slip surfaces. Therefore, friction should be understood to be thermally self-controlled (TSC-friction).

The pin-on-disc experiments for various metals conducted by Montgomery (1976) indicated that the steady state friction coefficient fc is determined by the product of normal stress P and slip velocity V that controls the heat generation rate. His conclusions are as follows, for an example of cupper pin on gun steel disc.

1. Flash melting regime (PV:-1000: unit is MPam/s): fc ranges from 0.2 to 0.4, and it decreases as PV increases. Wear rate is very small.
2. Partial melting regime (PV:1000-5000): Once PV exceeds about 1000, fc increases dramatically up to 1.4, and wear rate also increase dramatically.
3. Full melting regime (PV:5000-): fc decreases exponentially as PV increases, and it is as small as 0.3 when PV is larger than 10,000. Wear rate also decreases dramatically, but it increases slowly as PV increases.

According to the flash melting theory by Ettles (1986), fc decreases in proportion to P^-1/4, V^-1/2 and Ph^-1 (Ph is penetration hardness). Tsutsumi & Shimamoto (1997), Otsuki et al. (2003), Hirose & Shimamoto (2004) and Koizumi et al. (2004) demonstrated that fc at the initial melting is abnormally large. This phenomenon can be correlated with the flash melting regime. Within the flash melting regime the temperature of apparent contacts scarcely increases if PV is small, but it becomes higher as PV increases toward the partial melting regime. Since Ph shows the temperature dependence of Arrhenius' equation, Ph decreases dramatically as apparent contacts become hotter. As a result, they can be deeply scraped by asperities, causing the abnormally large wear rate. Mixing of the large amount of wear debris can cool the small amount of melt materials effectively, causing the abnormally large fc in the partial melting regime.

The three regimes mentioned above were defined for the steady state friction where PV was kept constant and the pin was sliding on the flesh surface of the disc. In the non-steady friction, both Ph and the size and spatial distributions of true contacts are state function of slip history. The traditional rate-and-state friction laws may be applicable to seismic nucleation and the TSC-friction governs the main phase of seismic slips.

One way how to verify the TSC-friction in un-steady processes is to compare the change in fc with the change in surface structures formed during the three regimes of one stick-slip event. We concentrated our SEM observations on the both tips of slip surfaces which were free from the overwriting of surface structures formed during the late phases of slips on those during the early slip phases. We found the discrete changes in surface structures for granite, gabbro and glass samples; from carrot-shaped grooves with slight melting (flash melting regime), through the mixture of a large amount of solid grains with a small amount of melt (partial melting regime), to an elongated melt layer (full melting regime). Moreover, the measured data of the slip dynamics indicated that slips in some cases stopped finally or momentarily at the partial melting regime, while slips in other cases could overcome this mechanical barrier. These results suggest that the variety in seismic slip behaviors can be produced spontaneously by the three regimes of friction, and that the additional mechanisms are needed for the termination of seismic slips.