Effect of temperature on the friction coefficient at intermediate slip rates

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One of the most remarkable discoveries over the last decade in the fault mechanics is the extreme velocity-weakening frictional behavior observed in laboratory experiments [e.g. Tsutsumi and Shimamoto, 1997]. These observations are explained by several mechanisms such as melt-lubrication [e.g. Nielsen et al., 2008], silica-gel formation [Di Toro et al., 2004], build-up of pore pressure due to decomposition or desorption of water [O'hara et al., 2006], phase transformation and generation of weak material [e.g. Han et al., 2007], flash heating of microscopic asperities [Rice 1999, 2006; Tullis and Goldsby 2003; Beeler et al., 2007; Noda 2008], and so on.

Some of these mechanisms are sensitive to the temperature on the sliding surface, T, while most of the existing experiments are at room temperature initially, and the fault surface is heated by the friction. Because the experimental conditions (the normal stress, slip rate history (V(t)), and the boundary condition in the thermal conduction) are not necessarily same as ones on the natural fault at depth during an event, it is not appropriate to apply the observed rate-dependency directly to a simulation of the earthquake rupture. In order to investigate the physical processes operating on the fault surface an construct a rate-, temperature-, and state-dependent friction law, it is essentially important to conduct friction experiments with controlling T and the V independently. For this purpose we set up a rotary shear apparatus at Chiba University which was first developed for the friction of ceramics, and reported by e.g. Senda et al., [1999]. This apparatus can slide a simulated fault at 1-500 mm/s for an annular sliding surface with ˜25 mm and ˜15 mm outer and inner diameters. An induction coil around the sample assembly heats sample holders on which about 5 mm thick rock samples are fixed. A thermocouple is attached to one of the sample holders about 7 mm from the sliding surface, and the measured temperature can be controlled up to 1000 ^{o}C within 1 ^{o}C in accuracy.

We have conducted a series of friction experiments with calc-alkali gabbro at fixed V (5 and 20 mm/s), at various T from the room temperature to 900 ^{o}C increased by steps by 100 ^{o}C, and at 0.5 MPa normal stress. The starting material consists mainly of cpx (38.3%), opx (7.3%), plagioclase (27.1%), k-feldspar (4.4%), quartz (10.0%), and actinolite (8.7%), with small amount of biotite (2.2%), magnetite (1.3%), ilmenite (0.7%), apatite (SM), saponite (SM), and talk (SM) where SM stands for small amount. The friction coefficient, f, is from 0.7 to 0.8 at room temperature, decreases down to 0.55-0.6 with increasing temperature to 800 ^{o}C, and increases to around 0.8 at 900 ^{o}C. The gouge generated in the experiments is gray-colored below 200 ^{o}C and becomes brown-colored with gradual darkening as the temperature increases. The gouge consists mainly of non-crystalline particles the majority of which show a chemical composition similar to actinolite based on qualitative analyses, indicating that they are produced by crashing and mechanical amorphization of the actinolite. The difference in its color may reflect the difference in the degree of oxidization. After the experiment at 900 ^{o}C, we observed patches of red-brown non-crystalline material stacked on the sliding surface, probably produced by the frictional melting. The melt patches associated with the increase in f is consistent with the previous work. The range of the f is similar to one observed by Tsutsumi and Shimamoto [1997] for Gabbro although the experimental condition is different; they changed the slip rate without controlling the temperature, and we fix the slip rate and control the temperature. Our results illuminate the importance of the temperature change during seismically rapid fault sliding.