Physics of friction -constitutive law and strength law

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As evidenced by direct measurements [e.g., Dieterich and Kilkgore, 1994], shear stress on frictional interface is supported only by the real contacts of limited area. Bowden and Tabor [1964] has developed an adhesion theory of friction, where the macroscopic frictional strength is the product of the real contact area and the shear strength of adhesive junction formed at real contacts. Focus there was to predict the frictional strength. For the relation between the applied shear stress and the resultant deformation (= constitutive law), a simple threshold rule, where junction fails when the junction shear stress tau_c (== applied shear load / real contact area) exceeds the shear strength of the junction.

However, as suggested by the direct effect [Dieterich, 1979], which is a strong exponential dependence of the slip velocity on applied shear stress observed with the real contact area fixed, junction shearing seems to follow a high-stress type flow law, typical of thermally activated rheology. This presentation focuses on a model where such constitutive relation is adopted instead of the simple threshold rule in the classical friction theory. Although such idea has been there and has explained limited aspects of rate and state friction [e.g., Heslot, 1994], we discuss the model of [Nakatani, 2001], where the variability of real contact area is incorporated and thus can predict the full range of rate and state-type constitutive behaviour.

The model assumes that slip velocity is a unique function of junction shear stress tau_c. This model predicts, in addition to the conventional direct effect mentioned above, a complimentary effect of real contact area on slip velocity at a fixed applied stress recently noticed and confirmed in experiments by Nakatani [2001]. The model predicts this latter effect as coming from the change of tau_c caused by the change of real contact area, supporting the validity of the model assumption of sliding driven by junction shear stress.

Further, the magnitude and temperature systematics of these effects examined over 25-800C was found to be consistent with that expected from a thermally activated creep with activation volume of about lattice size, often seen for such processes.

In the above, we have constructed a macroscopic `constitutive law` that gives a slip velocity as a function of the applied stress, with a real contact area as an internal state variable. The usual representation of the `rate and state friction law` can be drawn from this.

Such an understanding of the rate and state friction, however, has not been developed for a long time because a logical positioning of the rate and state friction law was not properly understood. The law (mu = mu* + alnV + THETA) had been mistakenly regarded as an extension of the traditional friction laws, which is a `strength law` to give the frictional strength. The most serious mistake was regarding the direct effect term alnV as another correction term to the frictional strength, in parallel with the real strength changes such as time-dependent healing and slip-weakening, which involves a physical change of the interface state [e.g., Dieterich and Kilkgore, 1994]. However, the mu in the law is actually the applied shear stress, and the rate and state friction law must be regarded a constitutive law, being an elaboration of the verbal constitutive rule in traditional friction, that is, `to slip if applied stress exceeds the frictional strength.` On the other hand, evolution law for the state, which often describes the time-dependent healing and slip-weakening, is a strength law, being an elaboration of the traditional friction law to give frictional strength, for which the symbol mu had been assigned.