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The effect of shear load on frictional healing in simulated fault gouge

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Abstract. We report on frictional strengthening (healing) in granular quartz gouge as a function of time of true stationary contact. To distinguish between the slip-dependent [Ruina, 1983] and time-dependent [Dieterich, 1979] friction constitutive laws, we designed tests similar to conventional slide-hold-slide (SHS) tests except that shear load was completely removed prior to holds. We find large healing values (0.033-0.054 for holds of 10^1-10^2 s) compared with quasi-static SHS experiments, and our data indicate time-dependent weakening in contrast with strengthening observed from SHS tests. Gouge layer compaction increases with increasing hold time, comparable to observations from conventional SHS tests. Our data indicate that purely time dependent processes have a minor influence on healing under the conditions studied and/or that such effects are efficiently erased by particle rearrangement during removal/reapplication of shear load. The data are not adequately described by either the time (Dieterich) or slip (Ruina) dependent state evolution laws.

Introduction

Studies of rock friction and their application to fault mechanics have given rise to several constitutive laws describing second-order friction variations in terms of slip, sliding velocity, and state of the frictional shear zone [*Dieterich*, 1979; *Ruina*, 1983; *Rice*, 1983; *Chester and Higgs*, 1992; *Reinen et al.*, 1994; *Perrin et al.*, 1995; *Ohnaka et al.*, 1997]. Of these, the slip-rate and state-variable friction laws have been the most extensively studied and most widely used in theoretical models of earthquake rupture [see recent reviews by *Marone*, 1998a; *Scholz*, 1998]. However, in the context of these laws, there are two fundamentally different views of how frictional strengthening occurs. In one law, which we refer to as the Dieterich law, friction evolution proceeds with the time of stationary contact, whereas in the other, which we refer to as the Ruina law, slip is the fundamental requirement for friction evolution. Although the laws share certain features, they predict qualitatively different scaling relations and dynamic behavior in theoretical models of earthquake rupture [*Rice*, 1993; *Perrin et al.*, 1995; *Rice and Ben Zion*, 1996]. Thus, a key issue for laboratory friction studies and their application to faulting is that of validating the constitutive laws for friction evolution and restrengthening under a range of conditions.

The existing database on frictional healing and state evolution is dominated by studies involving the combined effects of quasi-stationary contact time and slip. In a few studies, Dieterich-type time dependent healing has been suggested to be dominant [*Beeler et al.*, 1994; *Nakatani and Mochizuki*, 1996]. However, the existing studies are limited to rock surfaces (initially without gouge) held in quasi-stationary contact. Under these conditions, shear load is non-zero during intervals of frictional restrengthening and both slip- and time-dependent mechanisms may operate.

To further distinguish between the evolution laws, and to extend detailed studies of friction evolution to granular fault gouge, we have performed experiments involving true stationary contact. In these tests shear load is totally removed prior to hold periods, and we directly compare the results with data from conventional slide-hold-slide (SHS) experiments. Our friction data for short times of true stationary contact (10^1-10^2 s) show significantly higher static friction levels than conventional SHS tests. In addition, we find negative healing rates, and thus decreasing static friction as a function of hold time in contrast to conventional SHS experiments. Comparison of our data with similar data for sliding between rock surfaces indicates significant differences, which may relate to processes inherent to shear within granular material.

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Experiment Procedure and Results

Conventional SHS tests [e.g. *Dieterich*, 1972, 1978; *Chester and Higgs*, 1992; *Beeler et al.*, 1994; *Marone*, 1998b] involve shear at a given load point velocity followed by "holds" initiated by setting the load point velocity to zero. We show data from such experiments performed on granular quartz gouge with initial grain size 50-150 μm and layer thickness of 2.1 mm (Figure 1; *Marone*, 1998b). The layers were sheared between granite forcing blocks at room temperature and humidity, and with a constant normal stress of 25 MPa. During a hold, friction decays owing to creep and elastic interaction with the testing apparatus (Figure 1a). After a hold, when loading is restarted, shear stress increases to a maximum corresponding to the traditional definition of "static" friction. The difference between static friction and pre-hold sliding friction is taken as a measure of healing ($\Delta\mu$). For rock and simulated fault gouge $\Delta\mu$ is typically in the range 0.002-0.02 for hold times (t_h) of 10^1-10^2 s, depending on loading rate [*Marone*, 1998a]. Healing rates, defined as $\beta = \Delta\mu/\Delta\log_{10}t_h$, are generally 0.005-0.02 per decade t_h (Figure 1b). During a hold, measurements of gouge layer thickness show compaction with increasing t_h (Figure 1c). In these tests healing is accompanied by both slip- and time-dependent processes, making it difficult to separate their effects [*Beeler et al.*, 1994; *Marone*, 1998a].

We have performed similar experiments on simulated fault gouge in a double-direct shear testing apparatus [see *Marone*, 1998b, for details]. Thick layers of granular quartz powder (3 mm thickness, initial grain size 50-150 μm) were sheared between grooved steel forcing blocks with contact dimensions of 10x10 cm^2. Rough surfaces ensured that shear occurred only within the layer and post-experiment observation of the layers show that this was the case. To minimize gouge loss along the unconfined edges of the layers, lubricated plates were attached to the stationary side blocks of the sample assembly. All experiments were conducted using closed-loop hydraulic servo-control. Sample shear was maintained using load point displacement feedback, and normal load across the sample was held constant throughout (25 MPa). Our experiments differ from conventional SHS tests in that holds were preceded by a rapid decrease of shear load to zero, completed in 2.5-3s for the unload velocity of our tests (-300 μm/s). Shear load was zero until the end of the hold when reloading occurred at the initial rate. Hold times were varied from 10^1 - 10^4 s and, for the tests discussed here, load point velocity was 300 μm/s before and after holds. A few tests were performed with loading velocities of 10-100 μm/s and these show similar results. While the experiments reported here involved steel forcing blocks, we have also performed identical tests using Westerly granite [as per *Marone*, 1998b] which show quantitatively similar results. Extensive testing in trial experiments indicated that healing varied significantly with displacement and slip history. Thus, the data reported here are from experiments with identical slip histories (including velocity steps and the load cycle at 5mm shear displacement) throughout each test (Figure 2). Holds were implemented as consecutive pairs with the same hold times used for the first and last sets (Figure 2a). We investigate the effect of t_h by varying it for the middle pair of holds.

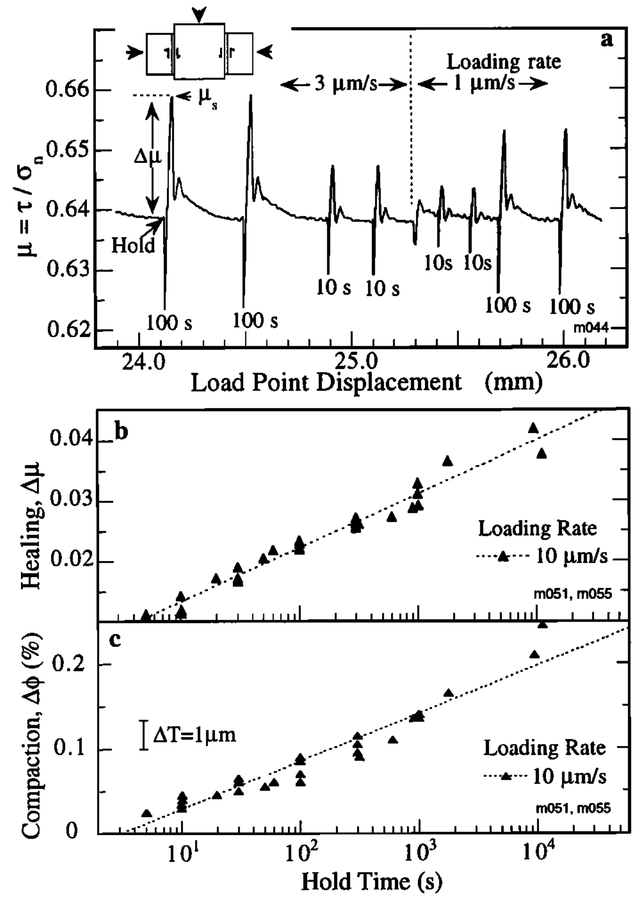

Figure 1: Data from SHS tests [*Marone*, 1998b]. **a.** Friction data are plotted against load point displacement. During a hold, load point position is held constant. **b.** Healing data, for loading velocity of 10 μm/s, indicate that Δμ is a function of hold time. **c.** Compaction during holds, for one gouge layer, is plotted versus hold time for the same experiments shown in (b). Data show that porosity decreases with hold time.

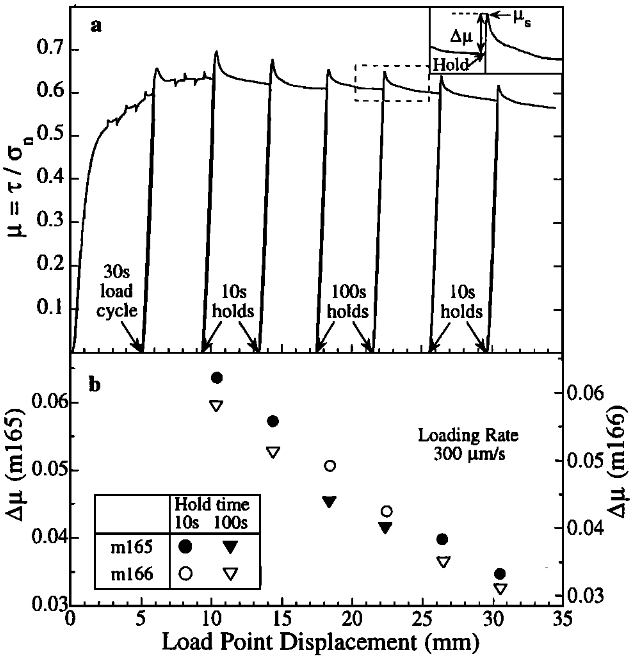

Figure 2: Friction data from zero-load tests. **a.** Friction versus load point displacement for a representative experiment. Hold cycles began at regulated points in the slip history. **b.** Healing data from two experiments shown versus displacement. Y-axes are offset due to differences in base friction between tests, and to allow direct comparison. Experiment m165 consisted of a sequence of hold pairs with duration 10s, 100s, and 10s. For test m166, the times were reversed. The data show a strong displacement dependence and a systematic effect of hold time on healing.

The general features of our data, including frictional healing, absolute values of static friction (μ_s), and the decay toward steady-state after μ_s, are similar to those of previous work [*Marone and Kilgore*, 1993; *Beeler et al.*, 1994; *Marone*, 1998b; compare Figures 2a and 1a]. That is, a single SHS cycle exhibits stable sliding prior to unloading and initiation of the hold. On reload after a hold, friction initially increases to a maximum and subsequently evolves to stable-sliding. To remain consistent with fixed load point SHS data, we quantify healing (Δμ) in the same manner as previous studies (Figure 2a insert). Hold times are measured from the point at which shear stress becomes zero to the point at which reloading begins. The time required for unloading depends on the sliding friction level, and for the experiments reported here varies from 2.5-3 s. For a given experiment, sliding friction and Δμ decrease with increasing shear displacement (Figure 2). This slip-dependent weakening is poorly understood, but is reproducible in our experiments and consistent with previous work on the effects of shear localization [*Beeler et al.*, 1996; *Marone*, 1998a]. By conducting the hold sequence in the manner described, we can identify variations in frictional healing. The data for two representative experiments show that healing for the third and fourth hold times (at displacements of ~18 and 22 mm, respectively) depart systematically from the nearly linear friction-displacement trend of the other holds (Figure 2b). Data from experiment m165 show lower Δμ values for the two 100s holds compared to the trend of the 10s holds. Conversely, for experiment m166 the two 10s holds yield greater healing than the trend defined by the 100s holds. The data indicate that the effect is reversible and not a function of hold sequence order (Figure

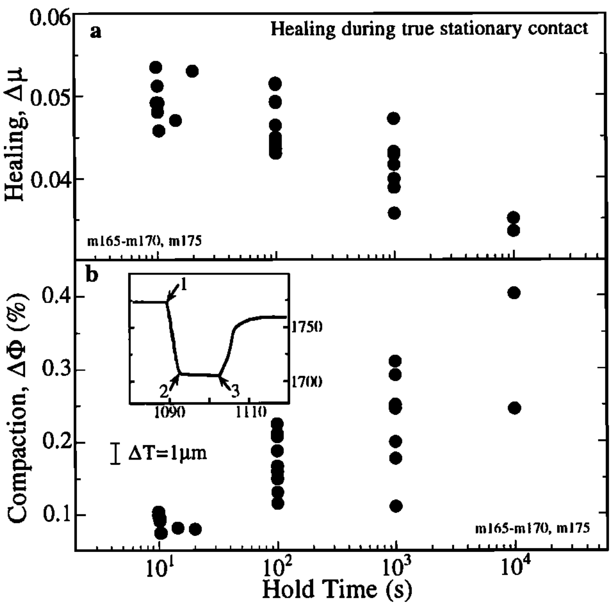

Figure 3: Data from all zero-load SHS tests. **a.** Δμ plotted versus hold time. Data are corrected for displacement effects, and scatter indicates experiment reproducibility. Static friction and Δμ decrease with increasing t_h. **b.** Layer compaction for those tests shown in (a). Inset shows time history of layer thickness (in micron) for one 10s hold. Data have been corrected for geometric layer thinning, and for Poisson distortion of the forcing blocks. Labels 1, 2, and 3 indicate the start of unloading, point when shear load is zero, and start of reloading. Porosity reduction from 2 to 3 is calculated, and data show porosity decreases with t_h.

2b). We find similar results from all our zero-load SHS tests, with data consistently showing that longer t_h yields smaller Δμ.

To compare data between experiments we remove the displacement effect by using a linear approximation to the healing data for the first and last hold pairs. This approximation is used to interpolate healing values to a common reference displacement of 20 mm (Figure 3). The detrended values (0.033-0.054) are large compared to those observed from conventional SHS experiments, especially for short t_h (e.g. Figure 1b). Furthermore, in contrast to the positive healing rates, β, observed in conventional SHS experiments, our data indicate negative β (-0.005 per decade t_h ; Figure 3a) consistent with observations from individual experiments (Figure 2b). We also measured gouge layer thickness for the tests and calculate compaction from the start to the end of each hold (points '2' to '3' of Figure 3b inset). Compaction increases approximately linearly with $\log_{10} t_h$ with a rate comparable to standard SHS tests (e.g. Figure 1c).

Implications and Summary

Our data are consistent with the results of conventional SHS experiments in that static friction is greater than pre-hold sliding friction, and thus Δμ is positive. However, the large magnitude of Δμ (for $t_h<10^2$ s) and our negative healing rates contrast with previous room temperature studies of conventional SHS tests. The fact that we do not observe a positive healing rate suggests that processes other than time-dependent strengthening are important for friction evolution and healing in gouge. Our results do not rule out time-dependent processes, such as gouge consolidation. However, such effects must be negligible or efficiently destroyed (perhaps by particle rearrangement and internal shearing) during removal or reapplication of shear load. Particle rearrangements within the gouge layer are implied by the observation of compaction during holds (Figure 3b), and consolidation effects may explain the large values of Δμ. For example, if backward slip between neighboring particles (permissible under zero macroscopic shear load) were sufficient to alter shear band geometry, or if time-dependent granular micro-cracking during holds eliminates geometric barriers to shear, Δμ could decrease with hold time. However, detailed microstructural analyses and numerical modeling are needed to identify the underlying micromechanical processes, and these are beyond the scope of this paper.

The distinctions between our healing data and those of standard SHS studies may be analyzed using rate- and state-dependent friction constitutive laws. The laws describe time and velocity dependence of friction, μ, by a relation often written as:

$$\mu = \mu_0 + a\ln\left(\frac{V}{V_0}\right) + b\ln\left(\frac{V_0\theta}{D_c}\right) \qquad (1)$$

where μ_0 represents steady-state friction for slip at a reference velocity V_0, V is sliding velocity, D_c is a critical slip distance, θ is a state variable, and a and b are scaling constants. The laws differ in their description of state evolution. Here, we focus only on two state evolution laws [*Dieterich*, 1979; *Ruina*, 1983]:

Dieterich law:
$$\frac{d\theta}{dt} = 1 - \left(\frac{V\theta}{D_c}\right) \qquad (2)$$

Ruina law:
$$\frac{d\theta}{dt} = -\frac{V\theta}{D_c}\ln\left(\frac{V\theta}{D_c}\right) \qquad (3)$$

It is apparent from (2) and (3) that for true stationary contact (V=0) the Dieterich law predicts state evolution and frictional healing while the Ruina law does not. In Figure 4 we show nu-

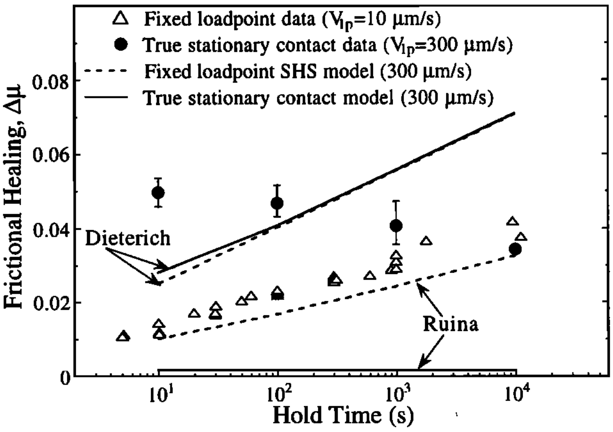

Figure 4: Healing predicted by the Dieterich and Ruina friction laws are compared to laboratory data. Forward modeling used friction parameters determined from velocity steps (a=0.0066, b=0.0066, D_c=45μm). Healing predictions are shown for both conventional and zero-load SHS tests using a loading velocity of 300 μm/s. For comparison, we plot the mean values of our zero-load data for each hold time (bars indicate data range), and replot the data of Figure 1b. The Dieterich law predicts strong positive healing rates, while the Ruina law predicts very different healing rates dependent on shear load. Neither the level of Δμ nor the healing rate of our data are well matched by model predictions.

merical computations using each law coupled with a relation to describe quasi-static elastic interactions with the testing apparatus: $d\mu/dt = k\,(V_o - V)$, where V_o is taken as loading velocity prior to a hold and k is apparatus stiffness divided by normal stress ($k=10^{-3}$ μm^{-1} for our apparatus). The calculations are carried out for the boundary conditions of conventional SHS experiments and for those of our experiments involving true stationary contact (Figure 4). The model predictions differ significantly for the Ruina law which is consistent with the assumed effects on healing, whereas the differences are minor for the Dieterich law. The numerical simulations show that neither law provides a reasonable fit to our friction data. The Ruina law predicts less healing for true stationary contact compared to conventional SHS tests, which is inconsistent with our data. The Dieterich law predicts time-dependent strengthening, even for holds where $\tau_{hold}=0$, which is also inconsistent with the data. Conversely, for $t_h<10^2$s the Dieterich law predicts slightly greater healing for true stationary contact compared to conventional SHS tests, in qualitative agreement with our data. The inconsistencies between model predictions and our data are surprising as previous studies have shown that many types of friction data can be modeled by the rate- and state- friction laws [e.g. *Beeler et al.*, 1994; *Marone*, 1998a; *Scholz*, 1998]. Our data indicate a systematic relationship between changes in friction and porosity and, thus, by including a porosity (or consolidation) term the laws may be capable of describing friction evolution under a wider range of conditions.

It is instructive to compare our results with both conventional SHS experiments and other tests on bare rock surfaces designed to investigate the constitutive laws [*Beeler et al.*, 1994; *Nakatani and Mochizuki*, 1996]. Our experiments differ from these studies in two important ways: 1) we considered true stationary contact by varying shear load and thus involving large perturbations from steady state conditions, and 2) we studied shear within a granular layer rather than slip on bare surfaces. *Nakatani and Mochizuki* [1996] studied shear between smooth granite surfaces at a normal stress of 5 MPa in which shear load (τ_{hold}), rather than load point displacement, is maintained constant during holds. They found large values of $\Delta\mu$ (0.02 to 0.10 for 30 s holds and $0.08 < \tau_{hold}$ (MPa) < 4.21) and that $\Delta\mu$ increased with both t_h and τ_{hold}. Their data show that the healing rate β (their parameter B) remains positive for low values of τ_{hold}, in contrast with the negative β from our zero-load SHS tests. They interpreted their non-zero β values as an indication of time-dependent healing, consistent with the Dieterich law. However, their observed positive dependence of healing on τ_{hold} (for constant t_h) is inconsistent with numerical simulations using the Dieterich law (Figure 4). If time-dependent healing were dominant, $\Delta\mu$ and β should scale inversely with τ_{hold} for short t_h, and show little dependence on τ_{hold} for longer t_h, rather than directly as they observe. This is because slip, which disrupts the effects of time-dependent healing, increases with τ_{hold}.

Beeler et al. [1994] also carried out experiments on initially bare surfaces, focused on the origin of friction evolution. They varied the effective apparatus stiffness, which causes differences in the accumulated slip during holds, and found that the rate of healing was unchanged. Thus, their data for initially bare granite surfaces support Dieterich-type time-dependent healing. When the results of *Beeler et al.* [1994] and *Nakatani and Mochizuki* [1996] are combined with our zero-load SHS data, it is apparent that neither the Ruina nor Dieterich laws adequately describe frictional healing as a function of both t_h and τ_{hold}.

The generality of this result as applied to other conditions of pressure, temperature, and chemical environment remains to be tested. However, from our previous work [*Karner et al.*, 1997] we know that time dependent healing during true stationary contact has an important effect at hydrothermal conditions. As applied to earthquake faulting, our data suggest that time dependent processes may be important during the interseismic period, but that such mechanisms may be insufficient to produce healing in the spatio-temporal vicinity of a dynamic rupture where large, rapid variations in stress may destroy time-dependent healing effects. As dynamic, time-dependent healing has been shown to be a requirement for slip-pulse type rupture expansion in some cases [e.g. *Perrin et al.*, 1995] it is important to further investigate these effects in laboratory experiments.

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