CRACK-LIKE AND PULSE-LIKE MODES OF FRICTIONAL SLIDING ALONG AN INTERFACE UNDER DYNAMIC SHEAR LOADING

Demirkan Coker*, Alan Needleman* and Ares J. Rosakis**
*Brown University, Division of Engineering, Providence, RI, 02912, USA
**California Institute of Technology, Division of Engineering and Applied Sciences, Pasadena, CA, 91125, USA

Summary Frictional sliding along an interface between elastic solids under impact shear loading conditions is analyzed numerically. The configuration analyzed consists of two plates of the same material connected along a planar interface. The plates are characterized as isotropic elastic materials and the interface is characterized by a rate- and state-dependent frictional law that also accounts for dependence on normal stress variations. Calculations are carried out for various characterizations of the frictional response and for various impact velocities. Two modes of sliding are observed: a pulse-like mode where the slipping at a point on the interface is of short duration and a crack-like mode where the duration of slipping is much longer. The dependence of these sliding modes on the initial compressive stress, the impact velocity and the friction parameters is explored. The convergence of the numerical results is also considered.

INTRODUCTION

Frictional sliding along an interface between two deformable solids is a basic problem of mechanics that arise in a variety of contexts including, for example, material processing, deformation and failure of fiber reinforced composites and earthquake dynamics. The classical Coulomb type of frictional relation relates the shear stress to the normal stress by a proportionaliy constant μ which can have a dependence on the relative sliding velocity. However, Adams [1] showed that the problem of frictional sliding along an interface between two elastic solids, with sliding governed by Coulomb friction, is unstable to perturbations and hence ill-posed for a significant range of values of μ. Rate- and state-dependent models of friction have been introduced [2-4] that phenomenologically characterize the surface evolution and provide a representation of the transition from static to dynamic friction at constant normal load. For varying normal stress, Prakash and Clifton [5] added an additional state variable to account for their observation of a delay in the change in shear traction following a sudden change in the normal traction. The use of these friction laws regularize the sliding friction problem of elastic bodies with changing normal stress and make it a well-posed problem. In this paper we report on the implementation of a modified form of the rate-state friction model in a finite-element code within a cohesive zone framework to simulate the frictional sliding behavior of two elastic surfaces under dynamic loading.

NUMERICAL BACKGROUND

Friction constitutive law used is a modified version of the Prakash-Clifton rate- and state-dependent law [6] characterized by the relation,

$$T_s = \mu(\theta_1, V_{slip})(\theta_2, \theta_3) \tag{1}$$

where V_{slip} is the relative sliding velocity of the interface, T_s is the shear traction at the interface, θ_i are the state variables characterizing the history of the interface. The evolution equations for the state variables also include a characteristic length and the parameters are chosen so that the shear traction decreases with sliding velocity (velocity-weakening).

A finite-strain finite element code with a cohesive surface formulation is used. The constitutive laws for the cohesive surface relates the traction rates to the displacement jumps and is given by the rate- and state-dependent friction laws. Computations are carried out for the specimen geometry shown in Fig. 1. Two Homalite plates of $L = 150$ mm height and $w = 100$ mm are subject to a uniform compressive stress of magnitude Σ_0. A Cartesian coordinate system $y^1 - y^2$ is used with the origin taken as shown in Fig. 1. At $t = 0$, the plate is subject to a prescribed normal velocity, $V_i(t)$, along a portion of the edge $y^1 = 0$. The duration of the impact velocity is taken to be 25 μs.

NUMERICAL RESULTS AND DISCUSSION

In the first simulation, the plates are subjected to a compressive stress $\Sigma_0 = 0.80$ MPa and the left side of the lower plate is subjected to an impact velocity of $V_{imp} = 40$ m/s. Figure 2a shows the variation of the slip rate at $t = 15$ and $25\mu s$. Initially there is a sharp increase in the slip velocity reaching a peak of 60 m/s followed by a slip velocity of $30 - 40$ m/s behind the propagating front. This represents the crack-like growth mode of the sliding surface where the interface continues to slide behind the initial rupture front. The amplitude of the initial peak does not vary significantly with distance. The rupture front propagates at the longitudinal wave speed of the material. Fig. 2(b) shows the total slip on the interface at different times. Total slip is monotonically increasing with time as expected for an expanding crack-like rupture front.

In the second simulation, the applied compressive load is increased to $\Sigma_0 = -8.0$ MPa MPa and the loading speed is decreased to $V_{imp} = 20$ m/s. Fig. 2c shows snapshots of the relative slip velocity along the interface at times of 30, 31,

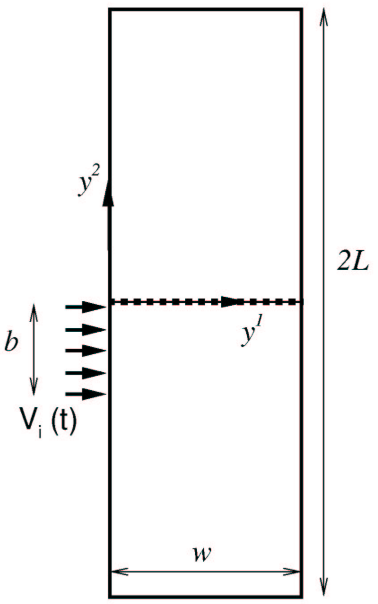

Figure 1.

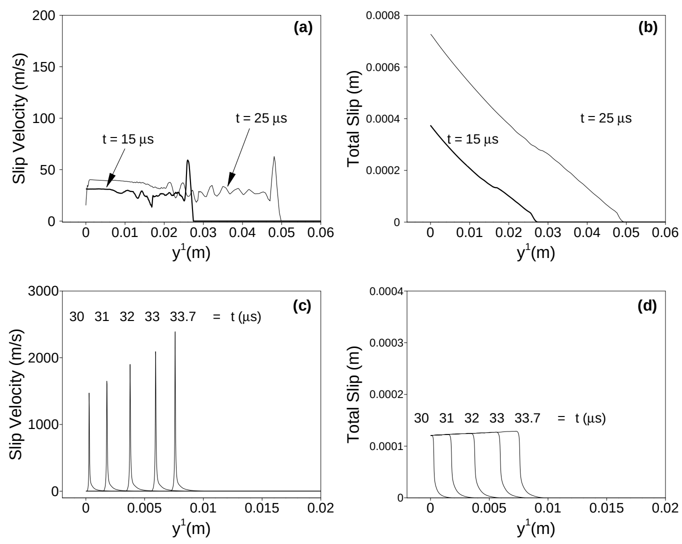

Figure 2.

32, 33, and 33.7 μs. At a fixed time the slip velocity increase drastically from zero to a peak value than drops down to zero again in a very short distance. This behavior represents a self-healing pulse and propagates at the longitudinal wave speed. The peak slip velocity increases with distance and time, and becomes an unstable slip pulse. Fig. 2(d) shows the total slip with time. In contrast to the crack-like mode, the total slip stays at a constant value after the initial jump in the slip distance showing that the sliding surfaces are locked together behind the rupture.

CONCLUSIONS

Computational simulations with a rate- and state-dependent friction constitutive relations for the interface showed the existence of self-healing slip pulses in the interface between two plates under dynamic shear loading conditions. Increasing impact speeds and increasing compressive load resulted in a transition from an enlargening crack-like frictional sliding to self-healing pulse-type frictional sliding. These slip pulses were unstable as the peak slip velocity value increased with distance.

References

[1] Adams, G. G.: Self-Excited Oscillations of Two Elastic Half-Spaces Sliding with a Constant Coefficient of Friction. *J. Appl. Mech.* **62**:867–872, 1995.

[2] Dieterich, J. H.: Modeling of Rock Friction 1. Experimental Results and Constitutive equations. *J. Geophys. Res.* **84**:2161–2168, 1979.

[3] Ruina, A. L.: Slip Instability and State Variable Friction Laws. *J. Geophys. Res.* :–, 1983.

[4] Rice, J. R. and Ruina, A. L.:Stability of Frictional Sliding. *J. Appl. Mech.* **50**:343–349, 1983.

[5] Prakash, V. and Clifton, R. J.: Pressure-Shear Plate Impact Measurement of Dynamic Friction for High-Speed Machining Applications. *Proc. 7th Int. Congress on Exp. Mech., SEM, Bethel, CT*: 556–564, 1993.

[6] Povirk, G. L. and Needleman, A.: Finite Element Simulations of Fiber Pull-Out. *J. Eng. Mat. Tech.* **115**:286–291, 1993.