EXPERIMENTS ON DYNAMIC SLIP

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ABSTRACT

Dynamic friction along interfaces between two materials is examined through experiments. An electromagnetic loading device is used to generate a compressive stress wave that is then made to interact with a frictionally held interface at different orientations. For some range of orientations, the resulting combinations of normal and shear stresses exceed the frictional sliding threshold and therefore introduce dynamic slip. The propagation chararacteristics of this slip are then examined through dynamic photoelasticity.

1 INTRODUCTION

Friction between surfaces has been the subject of intense investigations from time immemorial! In recent years, while there has been a spurt of activities in understanding friction and adhesion at the atomic scale (driven primarily by the development/promise of MEMS and nanoscale devices), there has also been a renewed interest in understanding the dynamics of macroscopic constitutive description of friction, postulated in phenomenological terms, either through the simple model of Amontons-Coulomb or through the more sophisticated models developed by Dietrich [1] and Ruina [2]. There has also been an emphasis on the propagation of crack like sliding and slip pulses at interfaces (Burridge, [3], Weertman, [4], Adams, [5], Ranjith and Rice, [6], and others). Examples of high speed contact sliding where such phenomenological models are quite important include rail-gun applications, where a projectile is accelerated along a track with significant normal pressure and sliding velocities in the range of 1 – 2,000 m/s at launch and earthquakes where slip in the form of pulses may travel at speeds faster than the shear wave speeds in the crust (Archeleta, [7]). Oden and Martins [8] present a significant review of the literature on dynamic friction focusing primarily on metallic materials applicable to technological problems. There is also a vast literature on geophysical applications (see for example, Heaton, [9], Marone, [10]). In the last three decades there have been a string of analytical, numerical and limited experimental investigations on the dynamics of slip at high slip speeds that have provided the impetus for the current investigations. Two types of models have been considered in the literature: growth of a mode II crack with energy dissipation required to generate new surfaces across which frictional sliding occurs and slip pulse propagation along previously created frictionally held surfaces. We review these models briefly in the following paragraphs.

Burridge [3] considered the self-similar extension of a mode II crack in a cohesionless interface between two identical materials with Coulomb friction – the mode II analog of the Broberg problem for mode I cracks – and found that the slip may propagate at the speed of the dilatational wave speed C_d without a singularity if the static friction is low. It should be noted that this analysis unifies the consideration of the problem of mode II crack propagation and frictional slip propagation. Andrews [11] modeled a mode II crack through a slip-weakening model for the crack tip cohesive zone and identified in numerical simulations that the growing shear crack nucleated a daughter crack ahead and accelerated to a speed of $\sqrt{2}C_s$ (the speed regime between the shear wave speed and the dilatational wave speed is referred to as the intersonic regime). Broberg [12,13] and Freund [14] analyzed the nature of the crack tip stress fields and energy flow into the crack tip region in mode II cracks and established that the crack tip possesses a square root singularity at the speed of $\sqrt{2}C_s$ and hence mode II cracks may grow at this speed. More recent models based on a cohesive zone at the crack tip suggest that other intersonic speeds are attainable as well, either in an unstable or stable condition. However, few experimental results are available; Rosakis *et al.,* [15] observed shear cracks in bonded biomaterial interfaces to propagate at $\sqrt{2}C_s$; this was the first direct measurement of intersonic crack growth under shear loading. Ravi-Chandar [16] demonstrated that even in homogeneous materials (without a weak interface), when trapped within a groove shear cracks may grow at speeds in the intersonic range by sequential nucleation of daughter cracks or echelon cracks; isochromatic fringe patterns from one such experiment in a Homalite-100 plate is shown in Figure 1. From the abrupt slope changes in the isochromatic fringes, the location of the shear Mach line can be identified; the $\pm 45^\circ$ inclination of the Mach line indicates that the crack is growing at a speed of $\sqrt{2}C_s$.

Weertman [4] showed that a self-healing slip pulse (initiating slip at its leading edge and terminating slip at its trailing edge) can be generated across a frictional interface between dissimilar materials. Weertman suggested that a self-healing slip pulse may propagate in an unstable manner even when the global stress state is subcritical for frictional slip. Adams [5] showed that frictional slip is indeed possible at intersonic speeds and determined the nature of the stress waves radiated from such a slip event under the assumption of Coulomb friction. Archuleta [7] suggested that frictional slip in earthquakes may propagate at speeds in excess of the shear wave speed and Heaton [9] proposed self-healing slip pulses to account for the short duration of slip at a point in comparison to the total duration of the earthquake. Xia et al [17] have recently shown that frictional slip across interfaces with a quasi-static pre-stress can also grow into the intersonic regime. Numerous researchers (Martins et al, [8], Ranjith and Rice, [18] and others) have discussed the fact that the slip pulse propagation problem with Coulomb frictional model is ill-posed. Rice and co-workers have approached regularization through the use of a rate and state dependent constitutive model for friction. On the other hand, Martins and Simoes [8] suggest that introducing a dependence on normal stress based on a length scale might regularize the problem. While this debate continues, the critical need is for some additional experimental insight into the nature of the frictional constitutive law at high slip speeds.

It is evident that both shear cracks and slip pulses may propagate at speeds in excess of the shear wave speed – i.e., the continuum model of shear crack and slip pulse propagation based on elastodynamics is a rather good description of the mechanics. We describe an experimental scheme for the determination of dynamic frictional behavior.

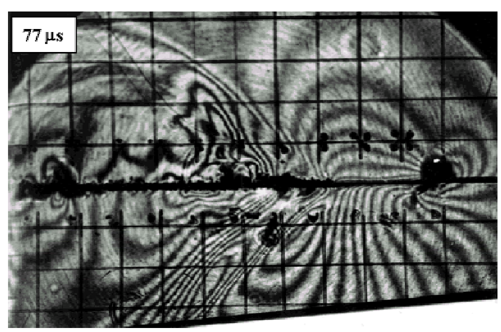

Figure 1. Isochormatics from an intersonic crack in Homalite-100

2 EXPERIMENTAL ARRANGEMENT

Frictional slip occurs at different sliding velocities – in the range from a few μm/s to a few hundred m/s. Our interest is in the high end of the speed range, when slip occurs across the interface at speeds comparable to the elastic wave speeds in the material. With this in mind, a novel apparatus has been constructed for the study of friction under such extremely high rates of loading. Essentially, the stress state across a frictional interface is brought to the critical state behind the dilatational wave. If slip occurs across the interface, it will be forced to run along the interface at this speed. Through variation of the quasi-static or dynamic pre-stress on the frictional interface, and through variation of the stress pulse, the approach to criticality can be altered almost at will. The loading scheme is described below.

The electromagnetic loading scheme is based on the interaction between two current carrying conductors was used by Ravi-Chandar and Knauss [19] to examine the fundamental issues regarding dynamic fracture. We have modified this apparatus to delve into the fundamentals of dynamic friction. Different implementations of the loading method are possible, allowing for variations in the loading applied on the interface. In the implementation used in this study, two specimen plates (0.25 in thick) are machined to have an interface at an angle α as illustrated in Figure 2. The interface is preconditioned to appropriate roughness in order to evaluate its frictional characteristics. The two specimen plates may be made either of the same material or of different materials, generating different frictional characteristics to be evaluated. A static preload below the slip threshold can be applied through a load frame; alternatively, a dynamic stress can be superimposed through a stress wave generated from a second electromagnetic loading system. A flat copper strip is folded back on itself or wrapped into a coil with the space between the layers filled with an insulator such as mylar. This assembly is then introduced at the bottom of the specimen plate as indicated in the schematic diagram in Figure 2. When a current flows through the copper loop, each leg generates a magnetic field surrounding it. The current vector in each leg interacts with the magnetic field of the other leg to produce an electromagnetic repulsion that forces the conductors apart. Since the two legs of the copper coil are confined in the slot between the specimen and a backing plate, the coils do not move apart, but simply press upon the surfaces of the backing plate and the specimen with a uniform pressure. The current in the copper-coil is generated by a discharge from a capacitor bank with a storage capacity of 60 kJ. The time history of the current which dictates the magnitude and duration of the pressure applied on the specimen may be controlled by suitable choice of inductors that form the pulse shaping circuit; we generate a nearly trapezoidal pulse, with a rise to the peak amplitude in about 25 μs, and a total duration of about 150 μs. For typical coils used in our experiments, the crack surface pressures are in the range of 1 MPa to ~1 GPa.

Variation of the angle α can be used to alter both the ratio of the shear stress to normal stress

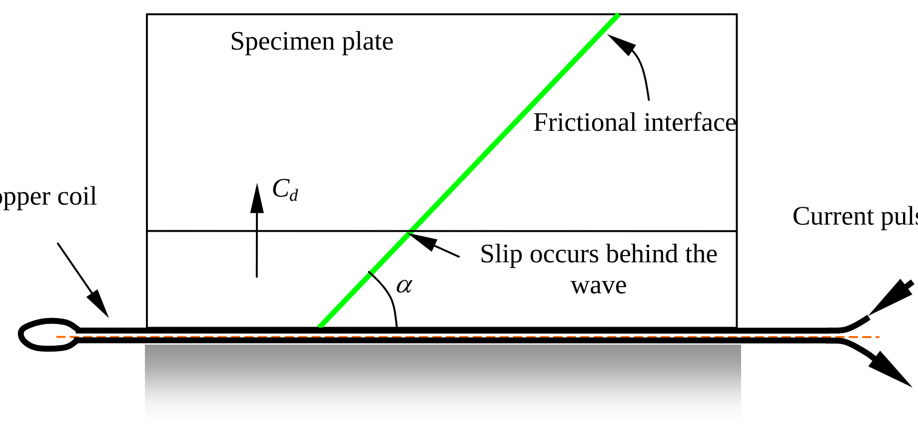

Figure 2. Scheme for dynamic friction characterization.

in the loading pulse as well as to alter the trace velocity of the loading wave along the interface. Essentially, the loading of the interface occurs at the trace velocity = $C_d\ /\sin\alpha$. We note that this loading configuration is equivalent to an infinite plate, with a well characterized stress state behind the dilatational wave for the duration of the current pulse; hence this represents a "clean" experiment where the input conditions are clearly identifiable. The waves from the slip across the frictional interface can be monitored to determine the relationship between the shear stress and the slip rate. Variation of the angle α of the interface with respect to the dilatational wave will introduce various ratios of the shear stress to the normal stress on the interface, generating slip, stick-slip and other behavior of the interfaces to be examined.

3 EXPERIMENTAL OBSERVATIONS

Different diagnostic schemes can be used depending on the nature of the specimen material. In our initial experiments, we used polycarbonate and Homalite-100 plates as the specimen material; these materials are birefringent and hence when viewed between two circular polarizers, they produce fringes that represent contours of constant shear stress, called *isochromatics*. This fringe pattern can be photographed in a high-speed camera to track the growth of the slip pulse; examples of the use of this technique from one experiment is shown in Figure 3. Here, selected images from a high speed sequence are shown; the images are 11 μs apart. The grid lines mark 10 mm squares; the interface is along the horizontal line identified in Figure 3a. The side along which the compressive pulse is applied is shown by the thick white line in Figure 3a. The isochormatic fringes indicate clearly that behind the dilatational wave that corresponds to the applied compressive loading pulse, there is a distinct pulse that propagates along the interface; shear waves emanating from this pulse leave a characteristic pattern of shear Mach lines that can be identified by the concentration of isochromatic fringes inclined at $\pm 45^\circ$ with respect to the interface. These Mach line indicate that (a) the crack is growing at a speed of $\sqrt{2}C_s$ and (b) that after a brief slip event, the material behind the slip pulse does not exhibit relative slip, but is in fact frictionally held once again. Our results also suggest that through variation of the angle α slip propagation at different speeds may be observed. For example, in other experiments, it was found that the slip pulse propagated at or above the dilatational wave speed.

For frictional interfaces with the same material on either side, the isochromatics may be interpreted directly in terms of the shear stress along the interface. Preliminary determinations of the shear stress along the interface are shown in Figure 4. The shear stress is seen to build-up gradually to a maximum (of about 10 MPa) at the leading edge of the slip pulse and to decay rapidly over a 5 mm length. No singularities are observed in keeping with the analysis of Burridge [3]. If these measurements are coupled with additional measurements of the particle velocity on either side of the frictional interface, one can obtain a characterization of the dynamic frictional constitutive law; this work is in progress.

4 CONCLUSION

A new method of applying dynamic loading on frictionally held interfaces has been developed. With this loading, it is possible to bring the stress state at the interface to the slip threshold at speeds greater than the dilatational wave speed in the materials that constitute the system. Propagation of a slip pulse along the interface resulting from this loading was observed; both intersonic and supersonic slip pulses were observed. The isochromatic fringe patterns in terms of the shear stress along the sliding interface. With this scheme we have demonstrated that slip pulses may propagate at arbitrary speeds, set by the applied loading.

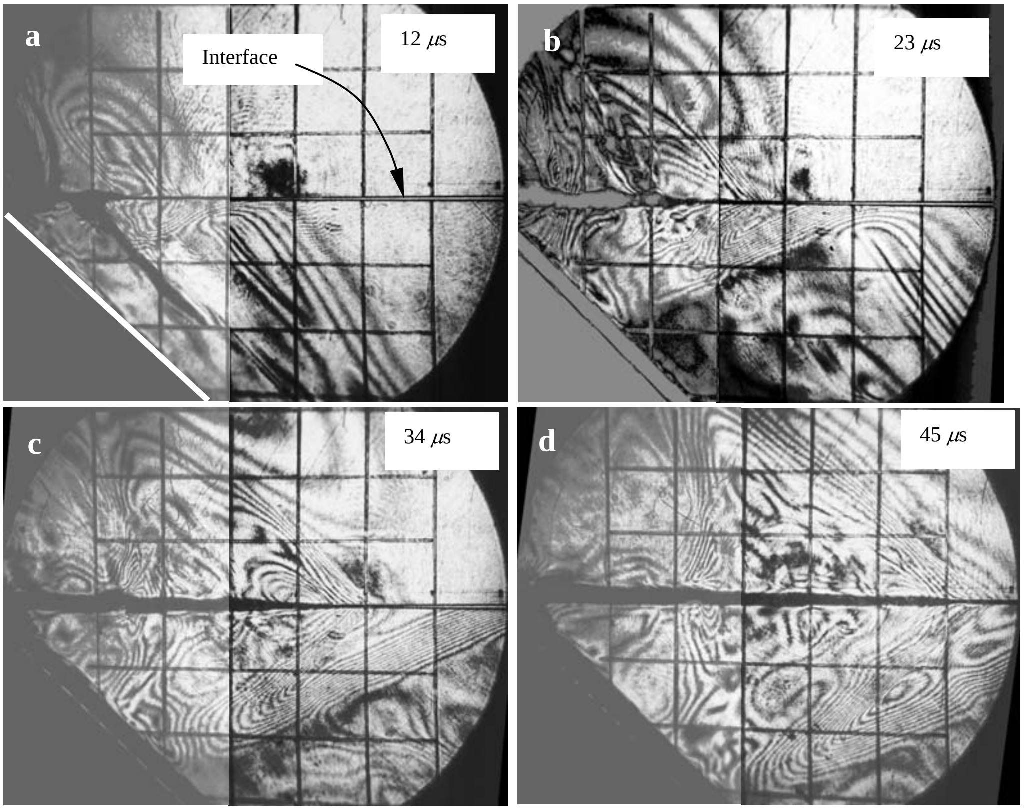

Figure 3. Selected frames from a high speed sequence indicating slip propagation in an interface between two polycarbonate plates.

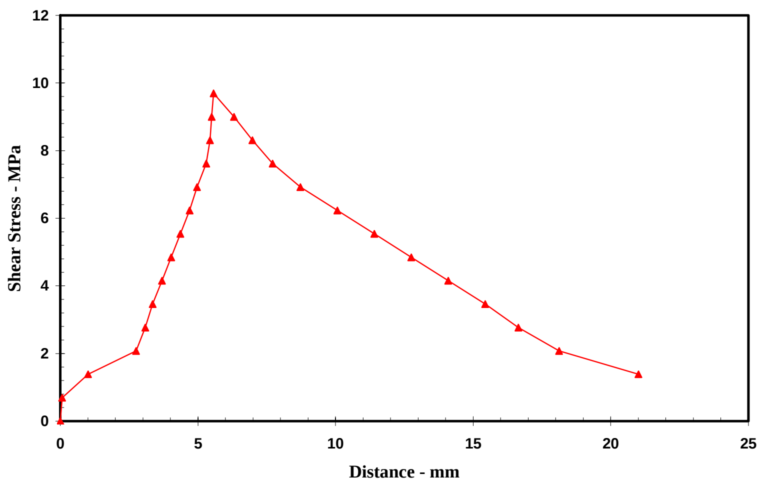

Figure 4. Variation of the shear stress in the slip zone.

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