RUPTURE OF FRICTIONALLY HELD INCOHERENT INTERFACES UNDER DYNAMIC SHEAR LOADING

G. Lykotrafitis and A.J. Rosakis
Graduate Aeronautical Laboratories, Mail Stop 105-50,
California Institute of Technology, Pasadena, CA 91125, USA

ABSTRACT

An experimental investigation was conducted to study frictional sliding at high rates along an interface between two identical plates under impact shear loading. The plates were held together by external pressure and one plate was subject to edge impact near the interface. The dynamic stress field developed during the event was recorded in real time by high-speed photography used in conjunction with classical dynamic photoelasticity. Visual evidences of pulse-like and crack-like sliding modes were discovered and recorded. Depending on the choice of experimental parameters (impact speed and superimposed quasi-static pressure), we observe sub-Rayleigh, intersonic and even supersonically propagating pulses. Unlike classical shear cracks in coherent interfaces of finite strength, sliding areas in frictional interfaces seems to grow without noticeable acceleration phases and at various discreet speeds. A relatively broad head wave that emanates from the interface and is caused from the interaction of the impact wave with the preexisting static stress field was observed. There was a cusp in the stress contours at the interface, indicating that the propagation speed was slightly faster along the interface than in the bulk. The propagation speed of the rupture tip was greater than $\sqrt{2}$ times the shear wave speed. Supersonic trailing pulses were also observed. Mach lines with different inclination and emanating from the rupture zone tips were discovered. In addition, behind the rupture point there were different structures which traveled at the Rayleigh wave speed. In one of them the fringes passed continuously from the upper plate to the lower plate which indicates that a relatively wide contact region was formed.

1 INTRODUCTION

Rupture of frictionally held, incoherent, interfaces is a basic problem in engineering that arises in many cases including, for example, materials processing, deformation and failure of fiber reinforced composites as well as earthquake dynamics. There are two widely accepted approaches describing dynamic shear rupture (Rice [1]). The most classical approach uses elastodynamic shear crack models (behind the leading edge of sliding, the surfaces continuously slide and interact through contact and friction). More recently, models that describe ruptures as 'self-healing' slip pulses have been introduced (behind the leading edge of sliding, there is sliding for a finite length followed by surface locking).

Classical dynamic fracture theories (Freund [2]) of growing shear cracks have many similarities to the frictional rupture process. These theories treat the rupture front as a distinct point (sharp tip crack). The crack-like rupture of coherent interfaces, separated by similar and dissimilar solids subjected to dynamic shear loading, has been the subject of extensive experimental, numerical and analytical investigations in the past years and has been summarized by Rosakis [3] in a recent review. Of relevance to the present study is the persistent occurrence of intersonic shear rupture in coherent interfaces separating identical monolithic solids. A special rupture speed of $\sqrt{2}\,c_S$ as the speed separating regions of unstable and stable intersonic shear crack growth has been identified. The traditional view of seismology has also been based on crack-like models of rupture (Das [4]). According to this view, slip increases smoothly with distance behind the rupture front continuously in time until arrest waves propagate back from the final event boundaries and cease motion at all points. Inversions of seismic data for slip histories indicate, however, that earthquake slip often occurs as narrow propagating pulses with rise time one order of magnitude smaller than the event duration.

The possibility of generating interface waves in unbonded frictionless contact between two dissimilar solids, when separation does not occur, was first investigated by Achenbach and Epstein [5]. Adams [6] showed that sliding along a bimaterial interface governed by Amontons-Coulomb friction is unstable to periodic perturbations, with an instability growth rate proportional to the wave number, for a wide range of friction coefficients and material properties. Rajnith and Rice [7] found that for moderate material contrast for which the generalized Rayleigh wave exists, there are unstable modes for all values of the Coulomb friction coefficient. On the other hand, when the material contrast is large enough so that the Generalized Rayleigh wave does not exist, such unstable modes appear only for a friction coefficient larger than a critical value. For lower values of friction coefficient periodic disturbances are stable (diminishing with time giving rise to stable sliding). Instability of periodic perturbations makes the response of a material interface with Coulomb friction ill-posed (no solution exists) to generic (non-periodic) perturbations or pulses. Numerically, the instability creates grid-size dependence of calculations. Ranjith and Rice [7] demonstrated that an experimentally based rate and state dependent friction law (Prakash [8]), in which the shear strength in response to an abrupt change in normal stress evolves continuously with time, provides well-posedness (regularization) to the problem of generic perturbations propagation (solutions for non-splitting single pulses can be found). Coker et al. [9] analyzed numerically the frictional sliding along a planar interface between identical elastic solids under impact shear loading. The interface is characterized by a rate and state dependent frictional law. They report crack-like, pulse-like and mix rupture modes, depending on the loading conditions and the surface properties.

As we see, there is a debate about the different high rate phenomena that occur at the interface of two incoherent half-planes during frictional sliding and there are no enough experimental evidences so far which would help to analyze the problem. The majority of the existing experimental studies use a large time scale and they are concerned with developing qualitative and/or quantitative relationships between time averaged friction data and various governing parameters. Prakash [8] employs a plate-impact pressure-shear friction experiment and investigates dynamic frictional response of a sliding interface on a microsecond time-scale. However, this set-up is not able to bring information about the stress field developed in the specimen and to shed light on the interfacial process during dynamic rupture.

The purpose of the present work is to study experimentally the high rate events which occur at the interface of two identical elastic plates during sliding cause by an asymmetric impact shear loading. Using photoelasticity in conjunction with high speed photography, we investigated the nature of dynamic rupture in a micro-second time-scale and we were able to capture in real time significant effects like loading pulses, rupture propagation, slip pulses and stick and slip regions at the interface.

2 EXPERIMENTAL SETUP

Experiments were performed to investigate the nature of frictional sliding along the incoherent interface of two plates made of identical material. The material used was Homalite-100, a brittle polyester resin that exhibits stress induced birefringence. It should be noted that Homalite-100 is mildly rate sensitive and at strain rate of $10^3 s^{-1}$ exhibits dilatational, shear and Rayleigh wave speeds $c_l = 1287 m/\sec$, $c_s = 1255 m/\sec$ and $c_R = 1155 m/\sec$ respectively. Plate specimens

$9.525\,mm$ thick, $76.2\,mm$ high and $139.7\,mm$ long, were held together by a uniform compressive stress and subjected to asymmetric loading with a cylindrical steel projectile of diameter $25\,mm$ and length $51\,mm$ fired from a gas gun with impact speed ranging from $10\,m/s$ to $60\,m/s$ (Figure 1). A steel buffer is bonded to the specimen at the impact site to prevent shattering and to induce a more or less planar loading wave. The uniform external load was applied by a press which was calibrated using a load cell. The loading wave as measured from a strain gage glued to the specimen has a trapezoidal form with a rise $10-20\,\mu s$ and a steady part of $40\,\mu s$. Dynamic photoelasticity was used to extract stress field information around the interface. The photoelastic fringe patterns were recorded in real time using a high-speed Cordin CCD camera capable of capturing 16 images at a rate 100 million frames per second. A collimated laser beam of $130\,mm$ diameter illuminated the specimen. Two pairs of circular polarizer plates were placed on either side of the specimen to produce isochromatic fringes. The photoelastic optical setup was arranged for light field. Isochromatic fringes are contours of maximum in-plane shear stress $\tau_{\max}$ governed by the stress optical law

$$2\,\tau_{\max} = \sigma_1 - \sigma_2 = N\;F_\sigma / h\,,$$

where F_σ is the stress optical coefficient of Homalite-100, h is the specimen thickness, σ_1, σ_2 are the in-plane principal stresses and $N = n + 1/2$ (with $n = 0,1,2,..$) is the isochromatic fringe order.

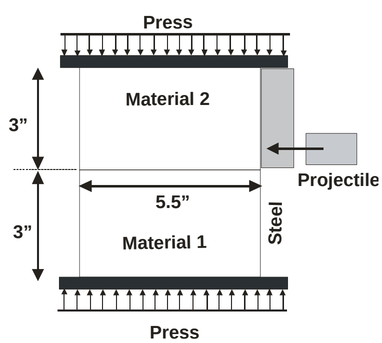

Figure 1: Bimaterial specimen under uniform external press subjected to impact shear loading.

3 RESULTS

Results at different compressive stresses and at different impact speeds are presented. The images in Figures 2(a) and 2(b) show the fringe patterns at selected times for a constant compressive load of $9.4\,MPa$ and impact speeds $24.3\,m/s$ and $32.7\,m/s$ respectively. The impact wave arrives from the left. The position of the longitudinal wave front (arrow A) in each one of the 16 available frames for each case have been measured and wave speeds of $2219\,m/s$ and $2160\,m/s$ have been obtained. Behind the longitudinal wave front a shear Mach cone, formed by a sharp change in fringe density, emanates from the rupture point B. The speed of the rupture point has been measured by two different ways and it is found constant. First we follow the positions of point B in the different frames and using the corresponding frame time we obtained speeds of $1813\,m/s$ and $1868\,m/s$ for the cases (a) and (b) respectively. In the second method we use the Mach angle relationship $v = c_s/\sin\theta$, to obtain the speed v of the rupture point. θ is the Mach angle. The two methods are found to be in agreement to within 3%. Some distance behind the rupture point (B) there is a higher concentration of isochromatic fringes propagating at the Rayleigh wave speed. Other features characteristic of the experiment are: (i) a relatively broad head wave that emanates from the interface. Since this structure is missing in similar experiments, without external pressure, we can safely conjecture that it is caused by the interference of the impact wave with the preexisting static pressure; (ii) there is a cusp in the stress contours at the interfaces, indicating that the propagation speed is faster along the interface than in the bulk; (iii) The fringe density is higher in the plate where the impact loading was applied, showing that energy is not transferred easily through the interface and (iv) the fringe discontinuity at the interface shows that there is a relative sliding between the two faces behind the rupture point reflecting the fact that rupture happened in a crack like mode.

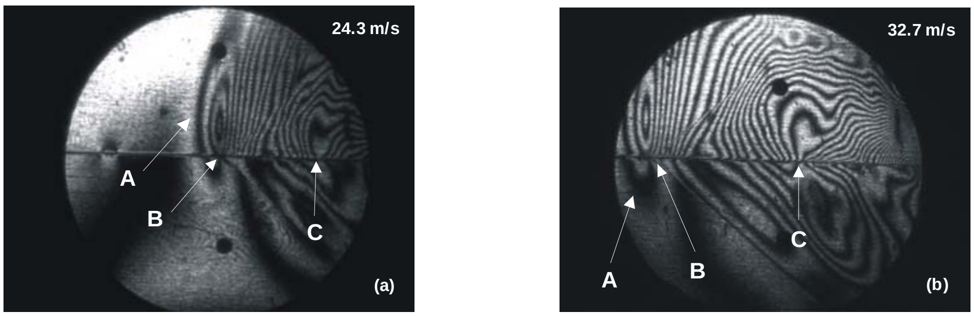

Figure 2: Isochromatic fringe pattern in Homalite specimens subjected to external uniform press $9.4\,MPa$ and impact velocity of (a) $24.3\,m/s$ and (b) $32.7\ m/s$.

Isochromatic fringe patterns are shown for the same compressive load of $9.4\,MPa$ and at the higher impact speed of $42\,m/s$ at three different times $40\,\mu s, 48\,\mu s$ and $60\,\mu s$ in Figure 3. Although the general characteristics we encountered in the slower impact speeds are still preserved new features enrich the picture. Behind the impact wave a shear Mach cone emanating from the rupture point and a singularity (just above point C) which moves with Rayleigh wave speed are formed. In addition, a second Mach line non-parallel with the first one is observed in figure 3(a). This Mach line is at a shallower slope corresponding to the supersonic propagation speed of $2514\,m/s$. Non-parallel shock lines imply a highly transient and unstable contact process and indeed in the figure 3(b) the tip of the second Mach line approaches the tip of the first Mach line. Finally, these two points merge as the second point catches up with the first point (figure 3(c)) and one Mach line continues to be observed in the next recorded frames. In addition, behind the second Mach line there is a fringes concentration that travels at the Rayleigh wave speed. The fringes pass continuously from the upper plate to the lower plate which indicates that a contact region is formed. The above analysis of the pictures taken during this event show that multiple slip and multiple contact zones are formed and some pulses propagate on the interface with distinct constant velocities. These observations are consistent with results produced by D. Coker et al. [9] who investigate numerically the same configuration.

In order to investigate the influence of the static pressure, we compare two cases with very different external applied pressure and similar impact speeds. In figure 4(a) the initial pressure is $1.3\,MPa$ and the impact speed is $48\,m/s$ whereas in figure 4(b) the initial pressure is $18.7\,MPa$ and the impact speed is $45.5\,m/s$.

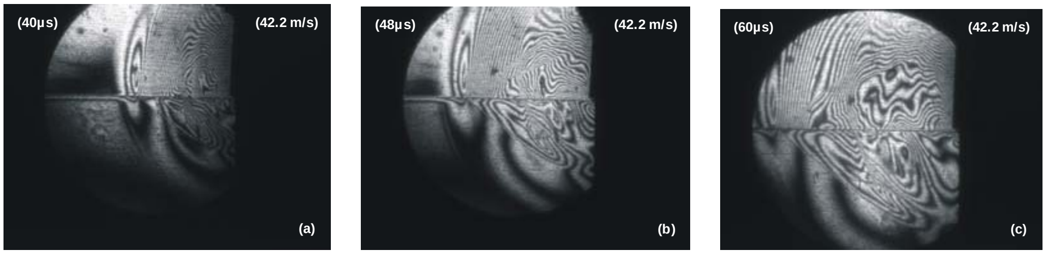

Figure 3: Isochromatic fringe pattern in Homalite specimens subjected to external uniform press $9.4\,MPa$ and impact velocity of $42.2\,m/s$ at time (a) $40\,\mu s$, (b) $48\,\mu s$ and (c) $60\,\mu s$.

We observe that, in the case of the low external pressure, the structure of the head wave is missing whereas the Mach lines are not so prominent and the second Mach line does not appear. From the discontinuity of the fringe pattern on the interface we can conclude that at the case of $1.3\,MPa$ external pressure there is an extended slipping area behind the rupture point which shows that the rupture mode is crack-like. In the second case of $18.7\,MPa$ external pressure, we have a mix rupture mode with continuously slipping wide areas followed by locked regions and propagating pulses.

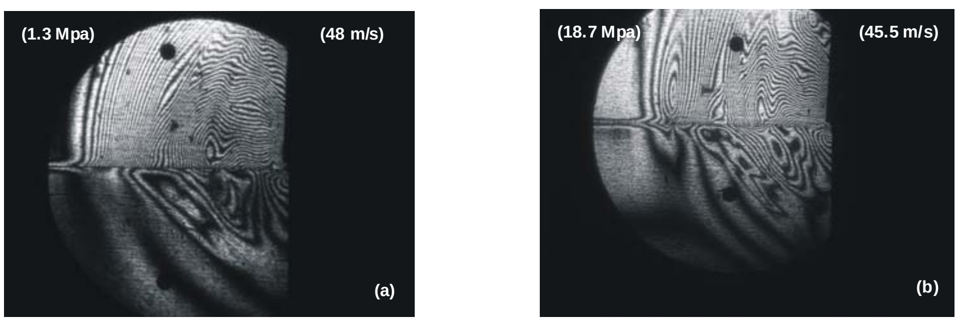

Figure 4: Isochromatic fringe pattern in Homalite specimens subjected to (a) external uniform press $1.3\,MPa$ and impact velocity of (a) $48\,m/s$ and (b) external uniform press $18.7\,MPa$ and impact velocity of $45.5\,m/s$.

Figure 5 depicts the position histories of different characteristic points at the interface for the case of $9.4\,MPa$ static pressure and $42.2\,m/s$ impact speed. In particular, the position histories of the P-wave front, of the first and second rupture points from which the corresponding Mach lines emanate and of the fringe concentration point of the Rayleigh like (R-like) structure are shown. As we see, the variation is very well approximated as linear, within an experimental error, and thus we can conclude that the different speeds are constants. These speeds were obtained through a linear interpolation on the experimental data. We clearly see that the second rupture point moves with higher speed than the first and in about $50\,\mu s$ the two points coalesce. We also measured the positions of the second fringe behind the head wave and we found that its propagation speed is smaller than the speed of the head wave. This fact shows that the p-wave exhibits dispersion.

The speeds of the P-wave front, the first rupture point and the Rayleigh like (R-like) structure at the same external pressure $9.4\,MPa$ and at different impact speeds were also measured. The speed of the R-like structure is ranged, within an experimental error, between $1064\,m/s$ and $1288\,m/s$, the P-wave speed is ranged between $2219\,m/s$ and $2383\,m/s$. The speed of the first rupture point varied from $1813\,m/s$ to $2001\,m/s$ with a clear tendency to increase with impact speed (or decreasing compressive stress) from just above $\sqrt{2}\,c_s$ to c_l.

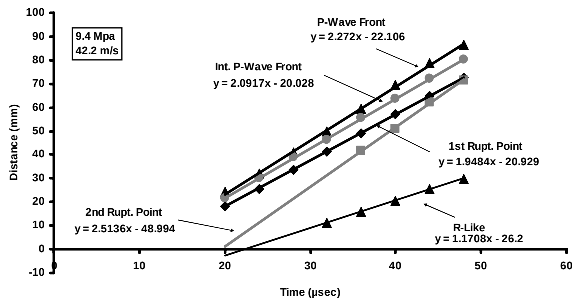

Figure 5: Time history of the exterior and the interior P-wave front, 1st and 2nd rupture point, and of the interface wave. External pressure $9.4\,MPa$, impact speed $42.2\,m/s$.

SUMMARY

Dynamic sliding along the interface of two Homalite plates held together by compressive stresses and subjected to impact shear loading was investigated. Using dynamic photoelasticity and modifying the external pressure and the impact velocity we were able to capture in micro-second time scale significant effects like loading pulses, rupture propagation, slip pulses and to identify crack-like and pulse-like rupture modes and stick and slip interfacial regions as well.

REFERENCES

[1] Rice, J.R, New perspectives on crack and fault dynamics, Mechanics for a New Millennium (Proceedings of the 20th International Congress of Theoretical and Applied Mechanics, 2000, Chicago), eds. H. Aref and J. W. Philips, Kluwer Academic Publishers, 1- 23, 2001.

[2] Freund, L. B., "Dynamic fracture mechanics". Cambridge, UK, 1990.

[3] Rosakis, A.J., Intersonic shear cracks and fault ruptures, Advances in Physics 51, No. 4, 1189-1257, 2002.

[4] Das, S., Application of dynamic shear crack models to the study of the earthquake faulting process. Int. J. Fract., 27, 263-276, 1985.

[5] Achenbach, J.D., Epstein, H.I., Dynamic interaction of a layer and a half-space, J. Eng. Mech. EM5, 27-42, 1967.

[6] Adams, G.G., Self-excited oscillations of two elastic half-spaces sliding with a constant coefficient of friction, ASME J. Appl. Mech., Vol. 62, 867-872, 1995.

[7] Ranjith, K., Rice, J.R., Slip dynamics at an interface between dissimilar materials, J. Mech. Phys. Sol., Vol. 49, 341-361, 2001.

[8] Prakash, V., Frictional response of sliding interfaces subjected to time varying normal pressures, ASME J. Trib., Vol. 120, 97-102, 1998.

[9] Coker, D., Lykotrafitis G., Needleman, A., Rosakis, A.J., Frictional sliding along an interface under dynamic shear loading, (Submitted), 2004.