Identifying Dynamic Rupture Modes in Frictional Interfaces

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ABSTRACT

An experimental investigation was conducted to study frictional sliding at high rates along an interface between two plates subjected to asymmetric impact loading. The two plates are held together by external pressure. We study both the case of identical plates as well as the case of high contrast bimaterials. The dynamic stress field developed during the event was recorded in real time by high-speed photography used in conjunction with classical dynamic photoelasticity. 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 toughness and strength, sliding areas in frictional interfaces seems to grow without noticeable acceleration phases and at various discreet speeds. In addition to high-speed photography a technique based on laser interferometry was used to record in-plane and out of plane particle velocities and slip rate history during sliding. Evidences of pulse-like and crack-like sliding modes were discovered and recorded. The discrete measurements are compared with the full-field high-speed photography images in an attempt to quantify the various observed rupture modes.

Introduction

Rupture of frictionally held, incoherent, interfaces subjected to shear loading is a basic problem in engineering and often occurs dynamically, for example, during materials processing, deformation and failure of fiber reinforced composites. In Geophysics, dynamic rupture of adjoining slabs causes the generation of earthquakes. 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 behind which sliding stops and the surfaces are locked). The question of whether ruptures assume a 'crack-like' or a 'pulse-like' mode and under what circumstances they do so is currently at the center of research activity.

When two surfaces are in contact, their relative motion is resisted by frictional force. The ratio of the tangential force to the normal force is called the coefficient of friction. However, the mechanics of contact and friction is actually quite complex. The interaction of elastic waves with friction has been the subject of many recent investigations. The possible interface waves in unbonded frictionless contact between two different bodies in which separation does not occur have been investigated by Achenbach and Epstein [2]. These "smooth contact Stonely waves" (also known as slip waves or generalized Rayleigh waves) are qualitatively similar to those of bonded contact and occur for a wider range of material combinations. Slip waves with interface separation were found by Comninou and Dundurs [3]. They also investigated the possibility of separation waves and /or stick slip waves in the sliding of two identical half–planes with friction, (Comninou and Dundurs [4]). Their analysis showed that such waves could exist only with singularities at the tips of the slip zones. Comninou and Dundurs [5] also investigated the possible sliding motion of two identical bodies without interface slipping (carpet analogous). Weertman [6] has shown that a coupling between slip and normal stress exists in a frictional interface between dissimilar materials. He concluded that a self healing pulse can propagate along the frictional interface between dissimilar elastic solids, when the remote shear stress is less than the frictional stress of the interface. Adams [7-9] showed that the steady sliding, under Coulomb friction law, of two elastic half-planes which are not very dissimilar is dynamically unstable for arbitrary small values of friction. The instability mechanism is due to destabilization of interfacial slip waves and gives rise to a dynamic instability in the form of self excited motion. These self excited oscillations are generally confined to a region near the sliding interface. He also investigated the sliding, under Coulomb friction law, of two dissimilar bodies due to periodic regions of slip and stick propagating along the interface. He was able to show that stick-and-slip waves can propagate along the interface. The numerical results of Adams [7] suggest a connection between the existence of the generalized Rayleigh waves and the ill-posedness. Ranjith and Rice [10] have shown that when the material pair is such that the generalized Rayleigh wave speed is defined (modest mismatch in material properties), the problem is ill-posed for any value of the friction coefficient, whereas when it is not defined (large mismatch in material properties) the problem remains ill-posed for values of the friction coefficient larger than a critical value.
Numerical studies of the nucleation and propagation of slip pulses using Coulomb friction law at the interface, by Andrews and Ben Zion [11], Ben Zion and Andrews [12] encountered numerical problems. Cochard and Rice [13] found that the Adams instability was responsible for those numerical problems since the cases studied by Andrews and Ben Zion fall in the range in which the generalized Rayleigh wave speed is defined and are thus ill-posed. They showed that the same method gives

results which converge with parameter choices in the well-posed range. In order to regularize the problem, Cochard and Rice [13] replaced the Coulomb friction law by an experimentally based friction law due to Prakash and Clifton (Prakash and Clifton [14], Prakash [15]). This friction law, incorporating memory dependence, transforms the instantaneous variation of shear strength that would follow from an instantaneous variation of normal stress if the Coulomb law was used to a smooth function. The Prakash and Clifton law conserves the main futures of the problem originally studied using the Coulomb law at least qualitatively, e.g. the rupture still occurs as self healing pulses. Ranjith and Rice [10] have shown that this law provides also regularization for the linear stability analysis. However, Ben-Zion and Huang [16] showed that the self sharpening and divergent behavior found earlier by Cochard and Rice [13] with Coulomb friction law exists also with regularized friction for large enough propagation distance or equivalently for long times. Coker et al. [16] 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.

As we see there is a debate about the different high rate phenomena that occur at the interface of two incoherent half-planes which are subject to dynamic shear loading and until now there are no experimental evidences which would help to analyze the problem. There is a huge literature about experimental work on frictional sliding. However, there is practically nothing on real time observations of sliding in the μsec regime. 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 and conditions, for example the properties of bulk and surface layer materials, the roughness of the surface in contact, the normal stress level, the rate of application of stress, the interfacial slip speed, the history of loading, the temperature and so on. Unfortunately, most dynamic friction laws obtained using various experimental configurations and apparatus, lack the reproducibility of friction data (surveys by Martins et all., [17], Ibrahim [18, 19]). The results of these experiments are multi-branched friction versus slip velocity curves, which even for the same material and the same experimental apparatus depend not only on the properties of the frictional interface but also on the dynamic properties of the apparatus, such as mass, stiffness and damping. This suggests that the friction data obtained in the course of stick-slip motions are not an intrinsic property of the surfaces in contact but they are greatly affected by several of the dynamic variables involved in each particular experiment set up. Prakash [15] employs a plate-impact pressure-shear friction experiment. The use of this experimental configuration allows the investigation of intrinsic dynamic frictional response of a sliding interface on a microsecond time-scale and without the problems associated with the dynamic parameters of the various frictional apparatus. Moreover, the experimental configuration allows critical frictional parameters such as the applied normal pressure, the transmitted shear stress and the interfacial slip velocity to be interpreted using the framework of one-dimensional wave analysis. The experimental results, deduced from the response to step changes imposed on the normal pressure at the frictional interface, reinforce the importance of including frictional memory in the development of the rate-dependent state variable friction models. However, this set-up is not able to bring information about the stress field developed in the specimen and to shed light on the phenomena occurring on the interface.

The purpose of the present work is to study experimentally the high rate events which occur during rupture of incoherent interfaces by applying an asymmetric impact loading experiment and to obtain some information about the nature of rupture. Using dynamic photoelasticity we investigated dynamic rupture in a micro-second time-scale without the problems associated with the dynamic parameters of the apparatus 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.

Experimental setup

Experiments were performed to investigate the nature of dynamic rupture along the incoherent interface of two pieces 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 $10^3\ \mathrm{s}^{-1}$ exhibits dilatational, shear and Rayleigh wave speeds $\mathrm{c_l = 1287 m/sec}$, $\mathrm{c_s = 1255 m/sec}$ and $\mathrm{c_R = 1155 m/sec}$ respectively. Plate specimens $9.525\,\mathrm{mm}$ thick, $76.2\,\mathrm{mm}$ high and $139.7\,\mathrm{mm}$ long and with surface friction coefficient $\mu = 0.7$ were held together by a uniform compressive stress and subjected to asymmetric loading with a cylindrical steel projectile of diameter $25\,\mathrm{mm}$ and length $51\,\mathrm{mm}$ fired using a gas gun with impact speed ranging from $10\,\mathrm{m/s}$ to $60\,\mathrm{m/s}$ (Fig.1). A steel buffer is bonded to the specimen at the impact site to prevent shattering and to induce a 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 $10 - 20\,\mu\mathrm{s}$ and a steady part of $40\,\mu\mathrm{s}$. 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. Dynamic photoelasticity was combined was combined with a laser interferometry - based technique which provides a local particle velocity measurement. A pair of fiber-optic velocimeters was used for the simultaneous measurements of the particle velocities at two adjacent points in the upper and lower plate. The distance of each point from the interface was less than $250\,\mu m$, before compression. Both points had the same horizontal distance from the impact side of the plates. Subtracting the two velocities we were able to obtain the relative velocity history. The velocimeter is constituted by a modified Mach-Zehnder interferometer (Polytec, OFV-511) and a velocity decoder (Polytec, OFV-5000). The decoder was set to a full range scale of $\pm 10\,m/s$ with a maximum frequency of $1.5\,MHz$ and a maximum acceleration of $10^7\ g$. The beam spot size was around $70\,\mu m$ whereas the error of the velocity measurement was 1%. Using the setup we show in Fig. 2, we were able to measure in plane particle velocities accurately and to identify different sliding modes

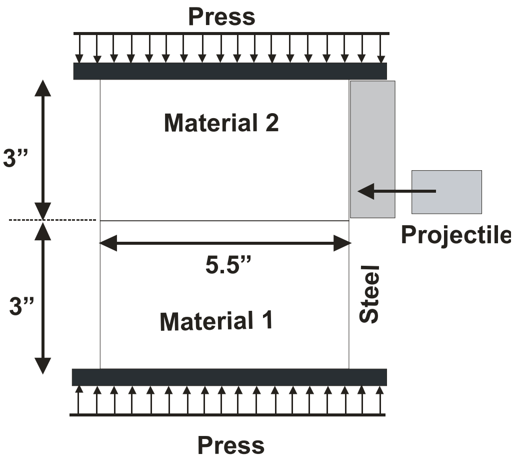

Fig. 1. Bimaterial specimen under uniform external press subjected to impact shear loading.

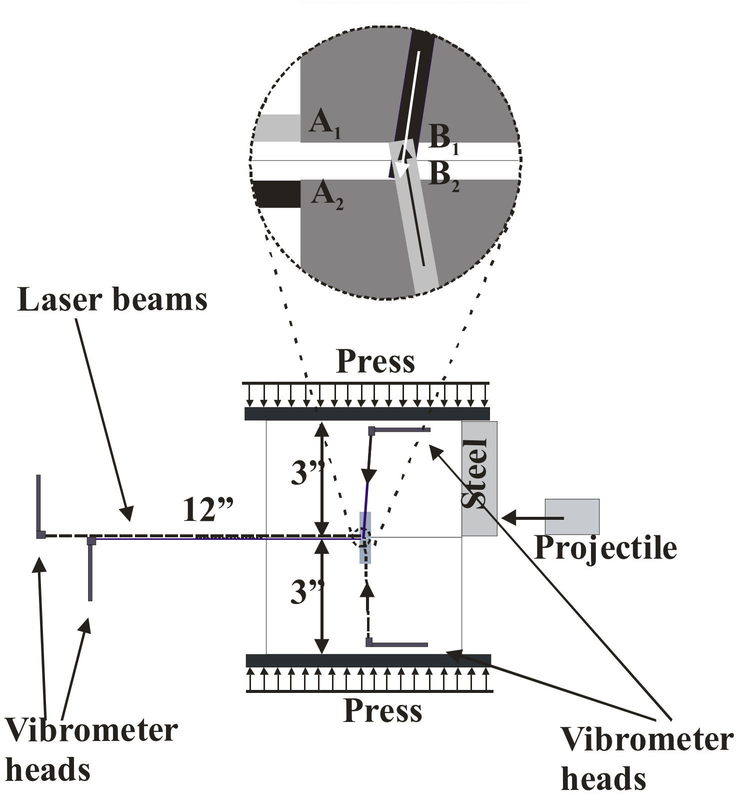

Fig. 2. Velocimeter set-up

Results

Results at different compressive loads and different impact speeds are presented. The images in Fig. 3(a) and (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 leading fringe structure 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 leading fringe structure, a shear Mach cone is formed by a sharp change in fringe density and it 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. Using the relation $v = c_s / \sin\theta$, where v is the speed of the rupture point and θ is the Mach angle, we obtained constant values close to the previous ones. 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 imposed loading are: (i) a relatively broad head wave that emanates from the interface and 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 imposed external 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.

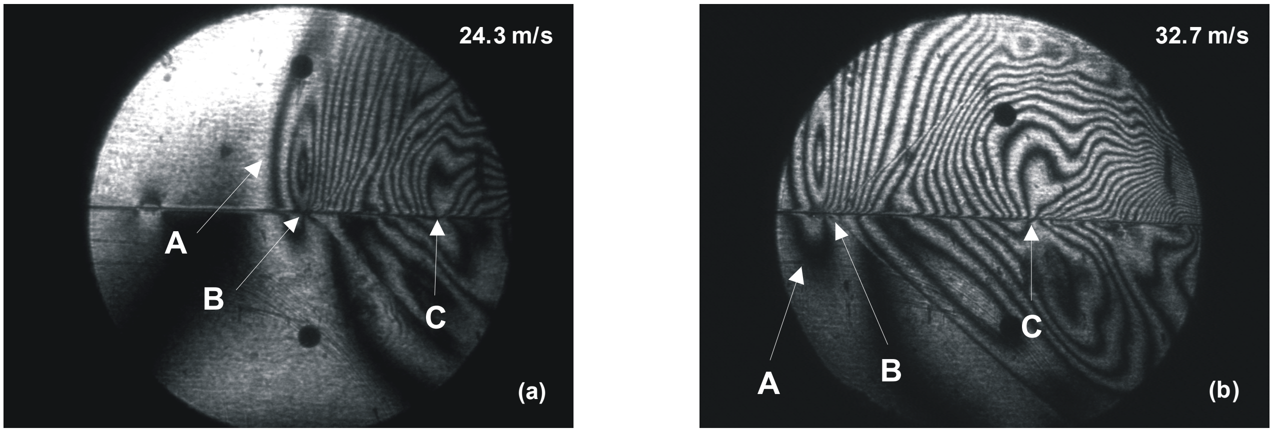

Fig. 3. Isochromatic fringe pattern in Homalite specimens subjected to external uniform press 9.4 MPa and impact velocity of (a) 24.3 m/s and (b) 32 m/s.

Isochromatic fringe patterns are shown for compressive load of 9.4 MPa and at the higher impact speed of 42 m/s at three different times in Fig. 4. Although the general characteristics we encountered in the slower impact speeds are preserved new features enrich the picture. Behind the impact wave the shear Mach cone and the singularity which moves with Rayleigh wave speed are formed. In addition, a second Mach wave line non-parallel with the first one is observed in fig. 4(a) behind the rupture point. The Mach line is at a shallower slope corresponding to the supersonic propagation speed of the point at 2514 m/s. Non-parallel shock lines imply a highly transient and unstable contact process and indeed in the fig. 4(b) the tip of the second Mach line approaches the end of the first Mach line and finally in the last frame (c) these two points merge as the second point catches up with the first point and one Mach line is observed in the next recorded frames. Behind the second Mach line we can see a fringes concentration which is emphasized with a white circle in the magnified view of the area around the interface and it moves with the Rayleigh wave speed. The fringes pass continuously from the upper plate to the lower plate and we can infer that a contact region is formed. The previous 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 observation are consistent with results produced by D. Coker et al. [16] who investigate numerically the same configuration.

In Fig. 5, in order to investigate the influence of the pressure in the event, we compared two cases with very different external applied pressure and similar impact speeds. In fig. 5(a) the initial pressure was 1.3 MPa and the impact speed 48 m/s whereas in fig.5(b) the initial pressure was 18.7 MPa and the impact speed 45.5 m/s which is close to the impact speed of the case with the lower pressure. We observe that the structure of the head wave is missing in the case of the low external pressure and the Mach lines are not so prominent whereas the second Mach line does not appear. From the discontinuity of the fringe pattern on the interface we can conclude that at 1.3 MPa external pressure there is an extended slipping area behind the rupture point which shows that the rupture mode is crack-like, whereas at 18.7 MPa we have a mix rupture mode with continuously slipping wide areas followed by locked regions and propagating pulses.

Fig. 6 show the position histories of the leading fringe structure front, the first and second rupture points from where the Mach lines emanate and the interface wave for the case of 9.4 MPa external pressure and 42.2 m/s impact speed. As we see the variation is very well approximated as linear within the 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 at around 50 μs the two points coalesce.

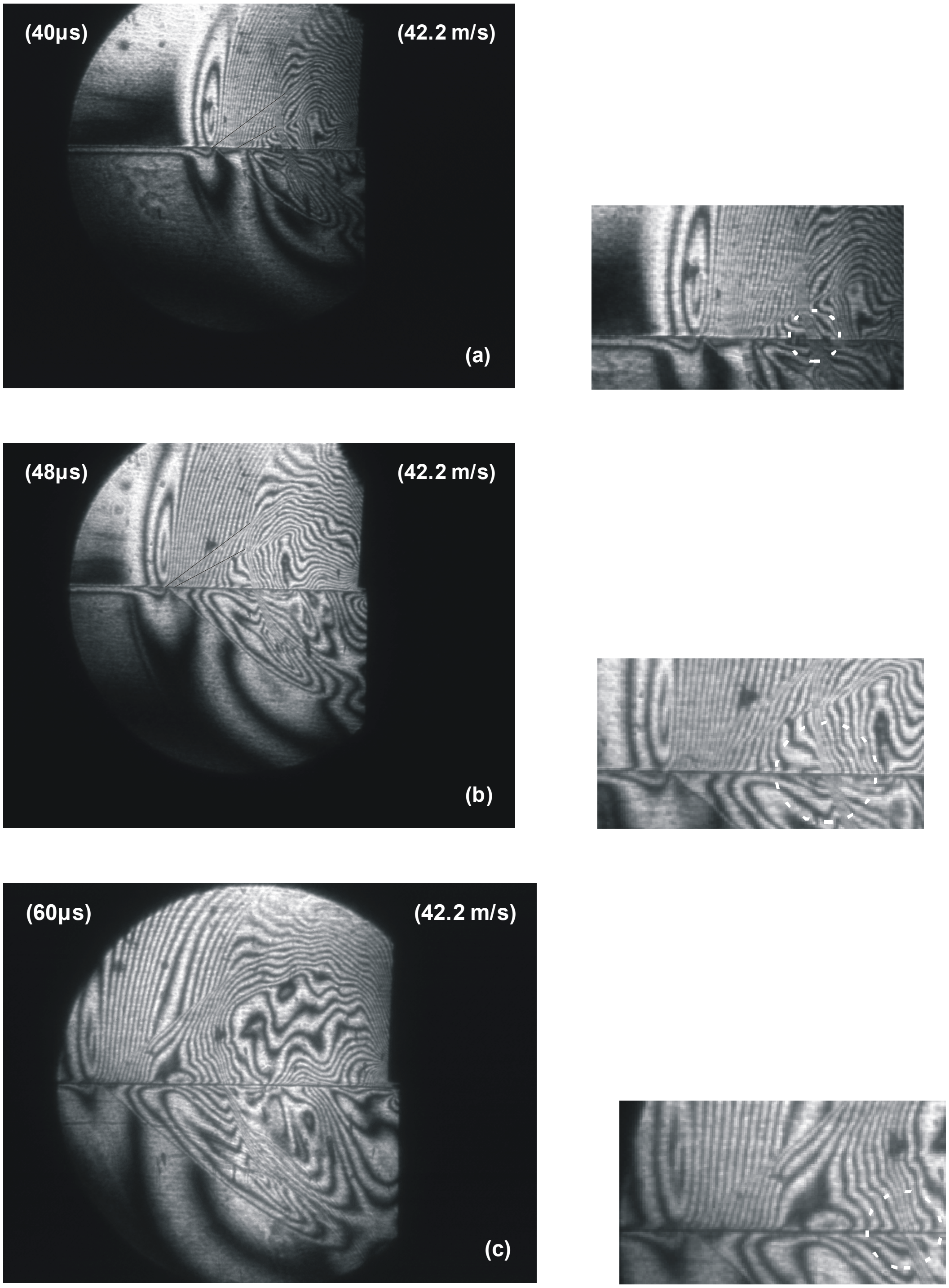

Fig. 4 Isochromatic fringe pattern in Homalite specimens subjected to external uniform press 9.4 MPa and impact velocity of 42.2 m/s at time (a) 40 μs, (b) 48 μs and (c) 60 μs.

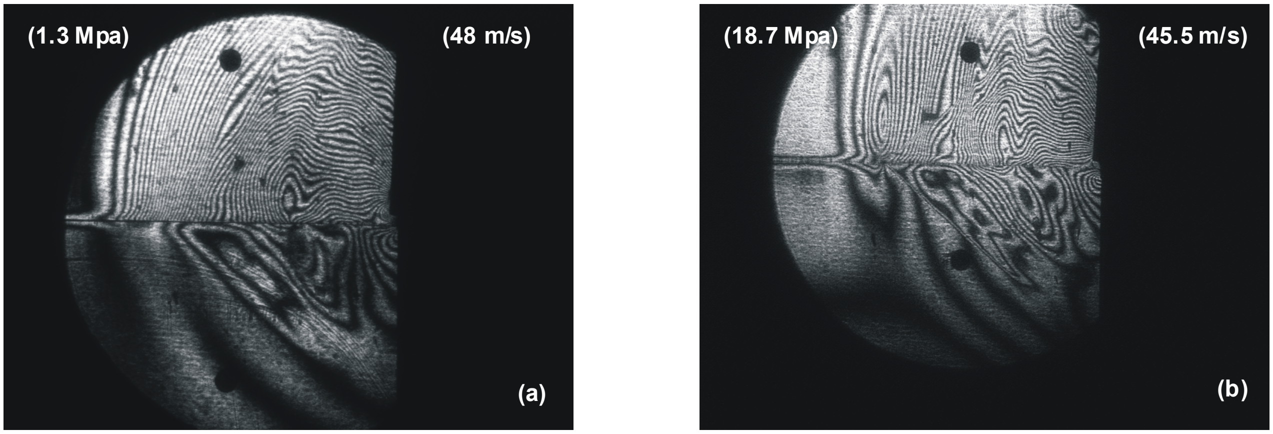

Fig. 5. Isochromatic fringe pattern in Homalite specimens subjected to (a) external uniform press $1.3\mathrm{MPa}$ and impact velocity of (a) $48\mathrm{m/s}$ and (b) external uniform press $18.7\mathrm{MPa}$ and impact velocity of $45.5\mathrm{m/s}$.

The speeds of the leading fringe structure front, the sliding tip and the interface wave structure at the same external pressure $9.4\,MPa$ and at different impact speeds are depicted in Figure 7(a) and Figure 7(b). The speed of the sliding leading edge varied from sub-Rayleigh to super-shear with a clear tendency to increase with the increased impact speed. We notice that the speed interval from c_R to c_S is forbidden for the speed of the sliding tip. We also note that for a wide range of impact speeds the sliding tip speed is within the range $\left(\sqrt{2}\,c_s - c_P\right)$ of stable crack propagation speeds (Rosakis 2002). Finally, we found that the speed of the interface wave is ranged, within an experimental error, between c_R and c_S.

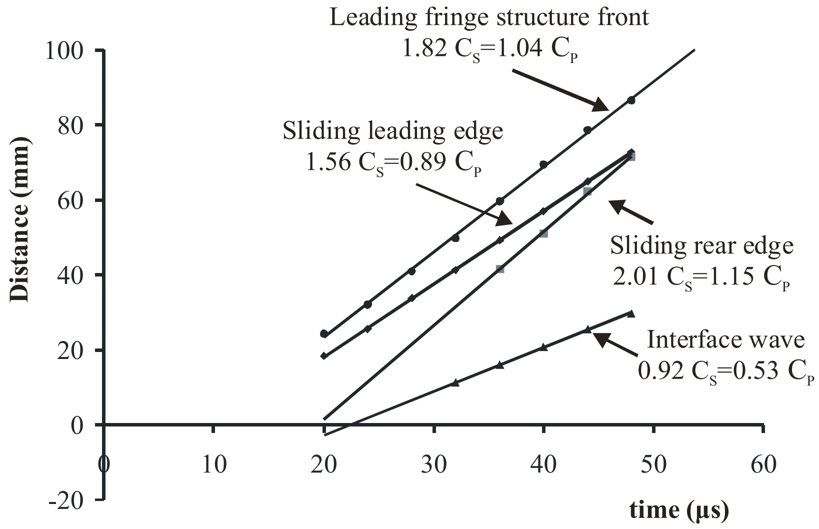

Fig. 6. Time history of the leading fringe concentration front, 1st and 2nd rupture point, and of the interface wave. External pressure $9.4\mathrm{MPa}$, impact speed $42.2\mathrm{m/s}$.

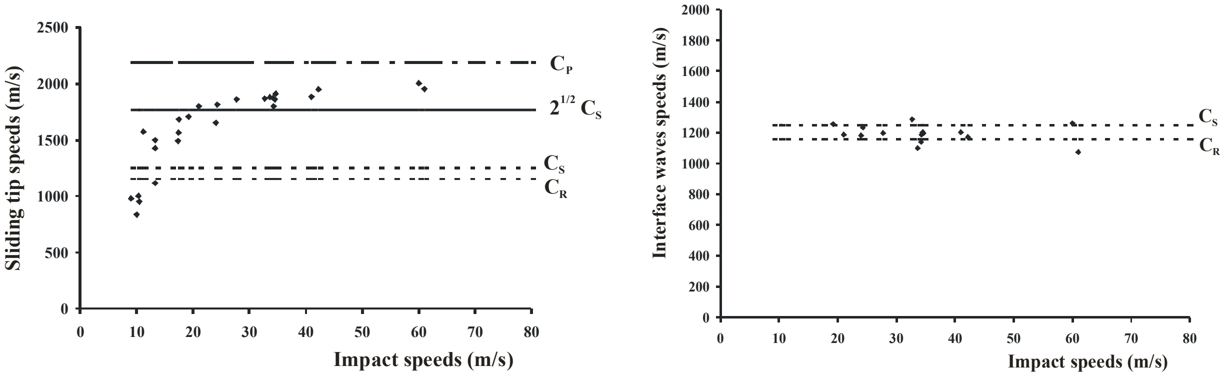

Fig. 7. Sliding tip speeds along the interface for different projectile speeds under external pressure 9.4MPa and Interface wave speeds for different projectile speeds under external pressure 9.4MPa.

In Fig. 8 we combine the Dynamic Photoelasticity with a velocimeter measurement. The confining pressure was 9.4MPa and the projectile speed was $13.2\,m/s$. The fringe concentration points B_1, B_2 and B_3 identified at the fringe pattern in Fig. 8a correspond to abrupt changes in sliding velocity depicted experimentally for first time in Fig. 8b. We recorded the sliding velocity history at a position on the interface which was at 30 cm from the impact side of the plate. Synchronizing the digital camera with the velocimeter we were able to make the correspondence between the fringe concentration points and the points shown at the velocity vs. time diagram in Fig. 8b. B_1 signifies the initiation of sliding, whereas B_2 and B_3 are points of very fast velocity change. After B_3 the sliding mode is clearly crack-like, whereas between B_1 and B_2 we have the formation of pulses. We finally note that the pulses are self sustained since we can clearly see the fringe concentration points propagating along the interface during almost the whole recording time till strong reflective waves from the left side of the specimen change the fringe pattern.

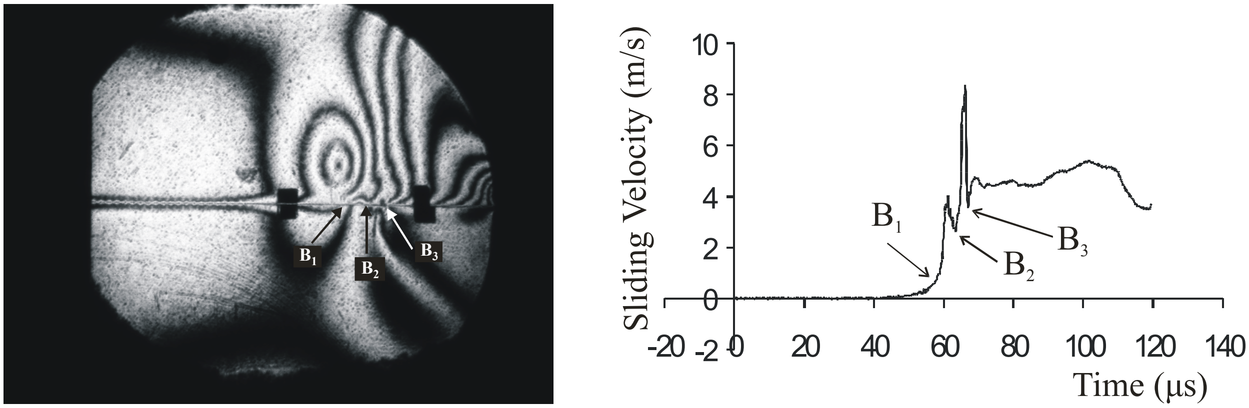

Fig. 8. First time experimentally identified mode of sliding. The external pressure was 9.4MPa and the projectile speed was $13.2\,m/s$

Summary

Dynamic sliding along the interface of two Homalite plates held together by compressive stresses subject to impact shear loading was investigated. The experimental configuration we used allowed us to study dynamic rupture in micro-second time scale without the problems associated with the dynamic parameters of the apparatus. Using dynamic photoelasticity and particle velocity measurement, we were able to capture for first time experimentally 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.

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