

Dynamic Rupture of Frictionally Held Incoherent Interfaces under Dynamic Shear Loading

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ABSTRACT

An experimental investigation was conducted to study the nature of dynamic rupture caused by shear loading, through impact, of interfaces which are held together by friction under external pressure. The dynamic stress field developed during rupture propagation was recorded in real time by a high-speed camera in conjunction with a classical dynamic photoelasticity set-up. Visual evidences of different dynamic propagating rupture modes were recorded. Unlike classical shear cracks in coherent interfaces of finite strength, rupture in frictional interfaces seems to grow without noticeable acceleration phases and at various discreet speeds. At low impact velocities a crack-like rupture mode occurs which becomes super-shear with the increase of the impact speed and a shear Mach cone emanates from the rupture point. For higher impact speeds super-shear and super-sonic Mach lines are observed formatting an unstable slip pulse which subsequently vanishes whereas evidences for extended stick and slip regions are recorded. Increasing the external applied pressure the observed features are intensified.

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 features 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 al., [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 s^{-1} exhibits dilatational, shear and Rayleigh wave speeds $c_l = 1287\text{m/sec}$, $c_s = 1255\text{m/sec}$ and $c_R = 1155\text{m/sec}$ respectively. Plate specimens 9.525 mm thick, 76.2 mm high and 139.7 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 mm and length 51 mm fired using a gas gun with impact speed ranging from 10 m/s to 60 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 $10 - 20 \mu\text{s}$ and a steady part of $40 \mu\text{s}$. 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 as shown in Fig. 2 to produce isochromatic fringes. The photoelastic optical setup was arranged for light field. Isochromatic fringes are contours of maximum in-plane shear stress τ_{\max} governed by the stress optical law

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

where F_{σ} is the material's stress optical coefficient, h is the specimen thickness, σ_1, σ_2 are the principal stresses and $N = n + 1/2$ (with $n = 0, 1, 2, \dots$) is the isochromatic fringe order.

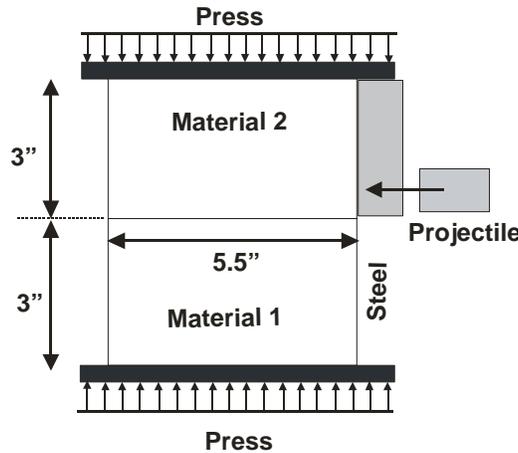


Fig. 1. Bimaterial specimen under uniform external press subjected to impact shear loading.

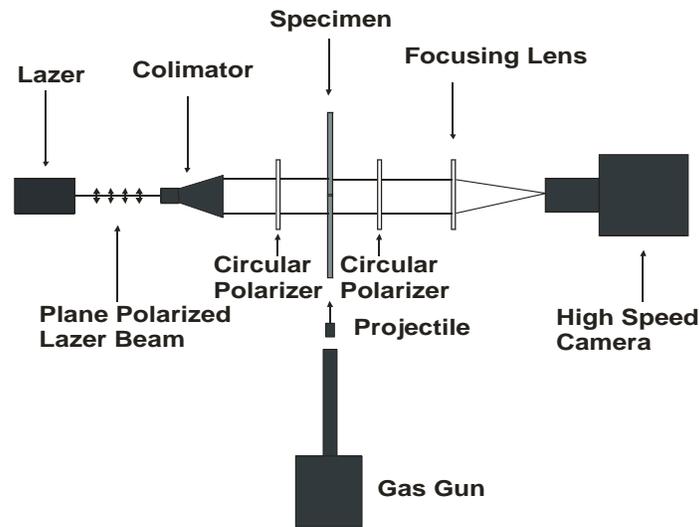


Fig. 2. Dynamic photoelasticity set-up showing a specimen inside a circular polariscope and being subject to impact shear loading by a projectile fired by a gas gun. The resulting isochromatic fringe patterns are recorded by high speed camera.

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 9.4MPa and impact speeds 24.3m/s and 32.7m/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 2219m/s and 2160m/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 1813m/s and 1868m/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.

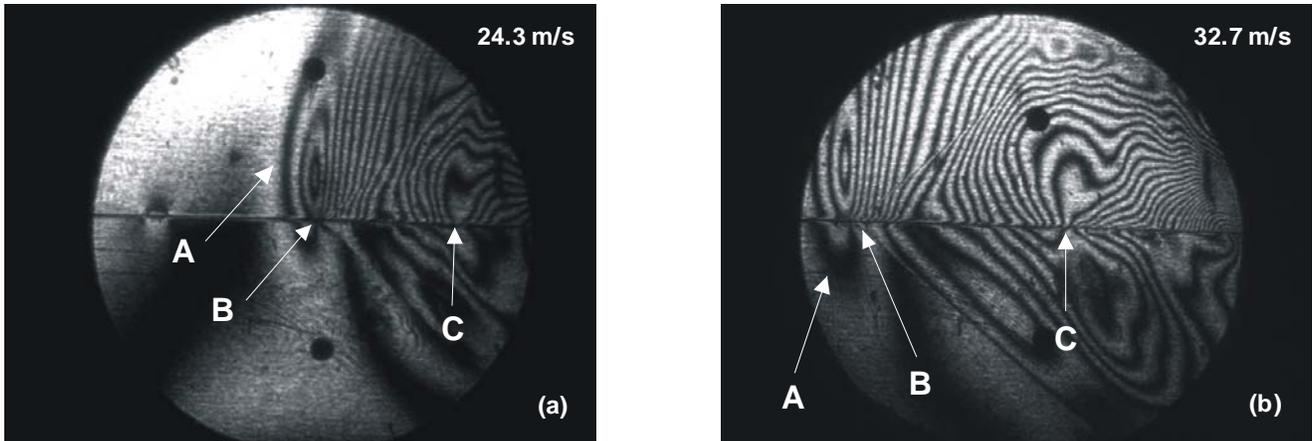


Fig. 3. Isochromatic fringe pattern in Homalite specimens subjected to external uniform press 9.4MPa and impact velocity of (a) 24.3m/s and (b) 32m/s.

Isochromatic fringe patterns are shown for compressive load of 9.4MPa and at the higher impact speed of 42m/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 2514m/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 1.3MPa and the impact speed 48m/s whereas in fig.5(b) the initial pressure was 18.7MPa and the impact speed 45.5m/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 1.3MPa external pressure there is an extended slipping area behind the rupture point which shows that the rupture mode is crack-like, whereas at 18.7MPa 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 P-wave front, the first and second rupture points from where the Mach lines emanate and the Rayleigh like (R-like) fringe concentration point at the interface for the case of 9.4MPa external pressure and 42.2m/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 μ s the two points coalesce. We also measured the positions of the second fringe (Int. P-wave front) behind the head wave and we found that its propagation speed is smaller than the speed of the head wave which shows that the p-wave exhibits dispersion.

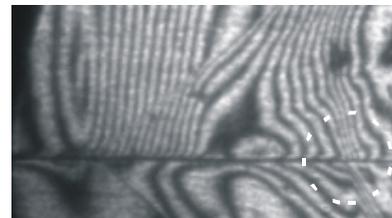
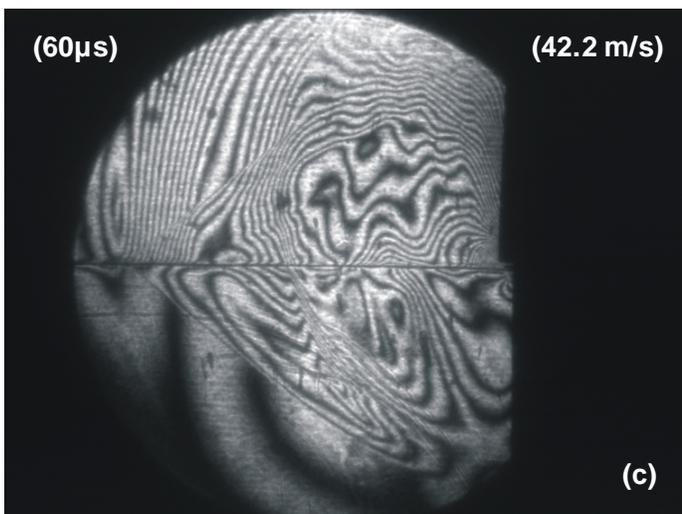
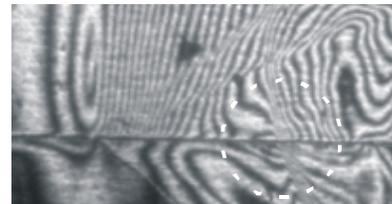
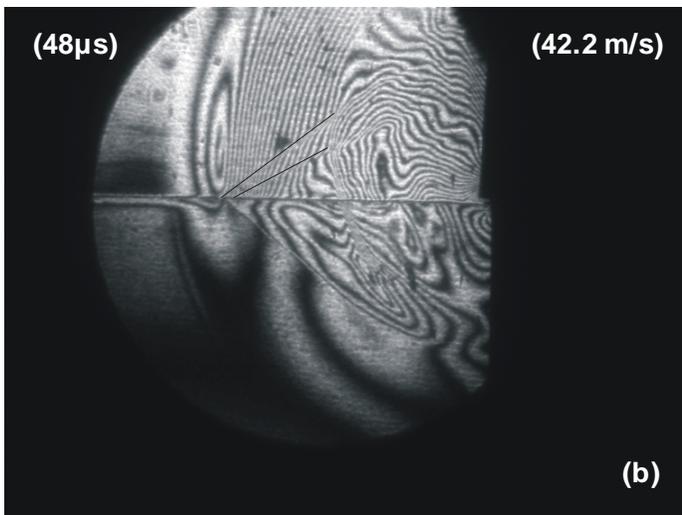
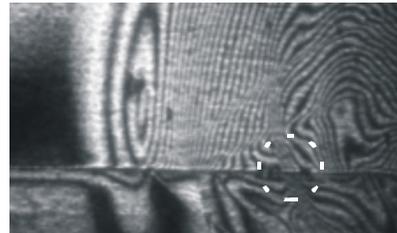
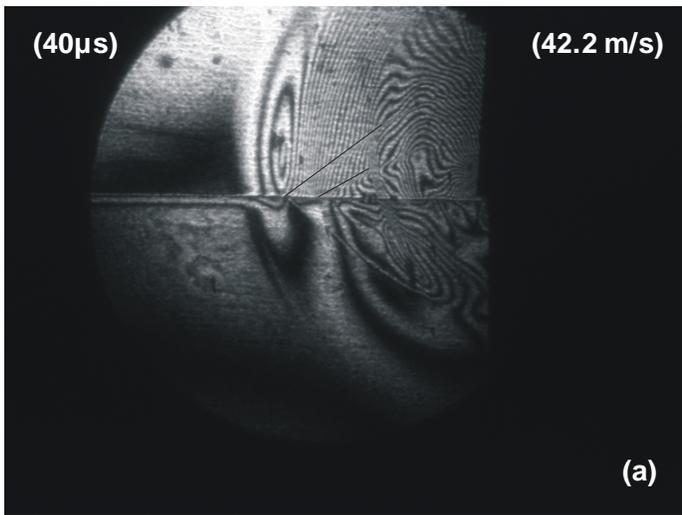


Fig. 4 Isochromatic fringe pattern in Homalite specimens subjected to external uniform press 9.4 MPa and impact velocity of 42.2m/s at time (a) 40 μ s , (b) 48 μ s and (c) 60 μ s .

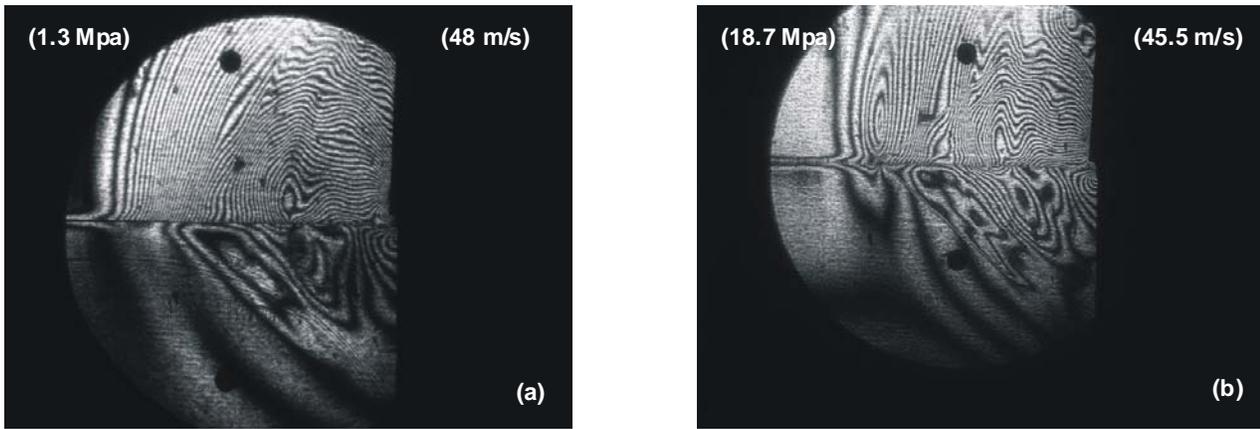


Fig. 5. Isochromatic fringe pattern in Homalite specimens subjected to (a) external uniform press 1.3MPa and impact velocity of (a) 48m/s and (b) external uniform press 18.7MPa and impact velocity of 45.5m/s .

The speeds of the P-wave front, the first rupture point and the Rayleigh like (R-like) structure at the same external pressure 9.4MPa and at different impact speeds are depicted in Fig. 7. The speed of the R-like structure is ranged, within an experimental error, between 1064m/s and 1288 m/s, the P-wave speed is ranged between 2219m/s and 2383m/s. The speed of the first rupture point varied from 1813m/s to 2001m/s with a clear tendency to increase with the increased impact speed. We also note that the speed of the rapture point is within the range $(\sqrt{2}c_s - c_l)$ of stable crack propagation speeds (Rosakis [20]).

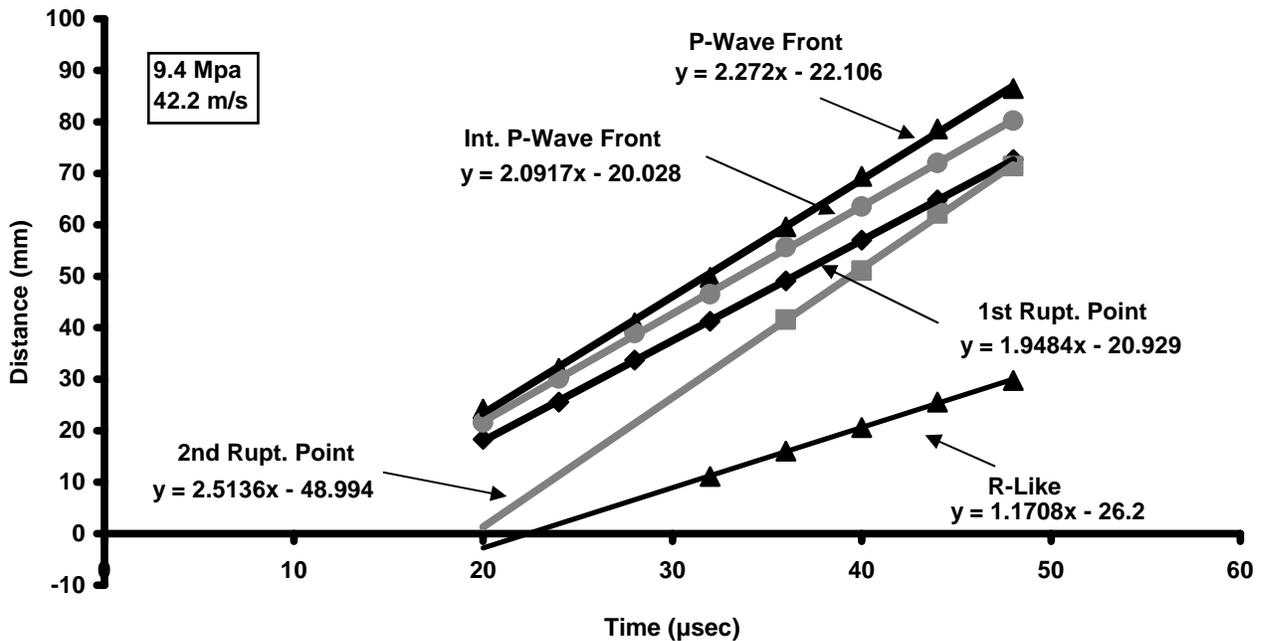


Fig. 6. Time history of the exterior and the interior P-wave front, 1st and 2nd rupture point, and of the interface wave. External pressure 9.4MPa , impact speed 42.2m/s .

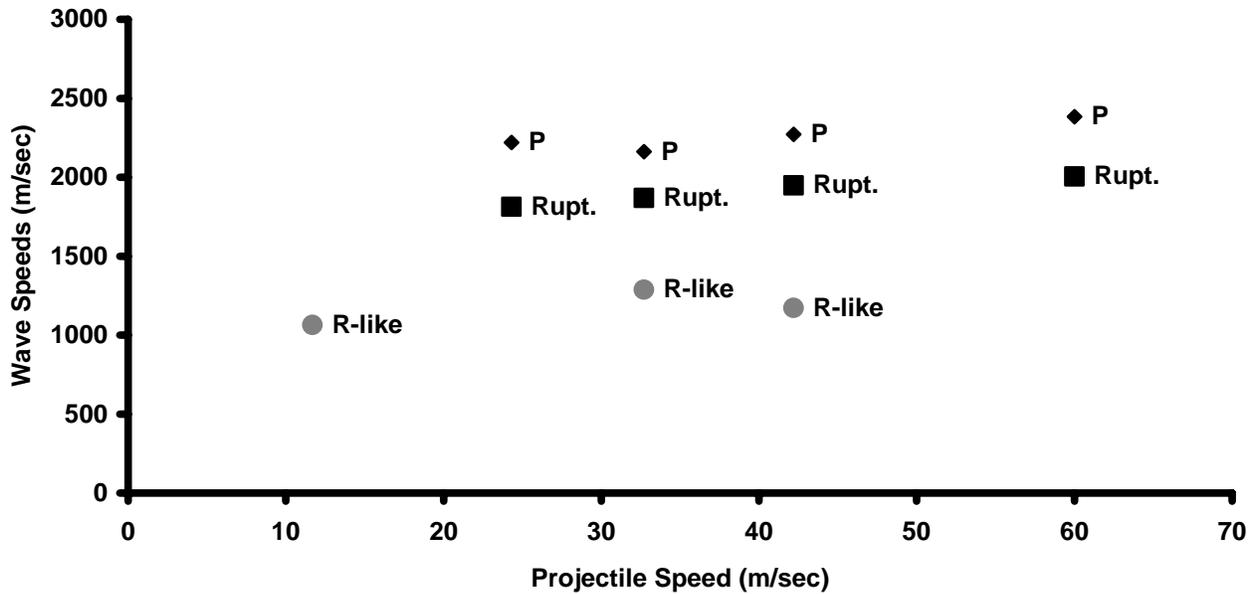


Fig. 7. Wave speeds along the interface for different projectile speeds under external pressure 9.4 MPa .

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 modifying the external pressure and the impact velocity we were able to capture in real time 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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