TRANSITION ON THE FAILURE BEHAVIOUR OF DYNAMICALLY SHEAR LOADED CRACKS

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An experimental technique is presented for subjecting cracks to high rates of shear (mode-II) loading. By means of the shadow optical method of caustics, the dynamic crack tip loading conditions are investigated for both the phase of loading and the subsequent phase of failure. A failure mode transition is observed when the loading rate exceeds a certain limit. At low rates, failure is controlled by fracture processes. At high rates, failure is controlled by the formation of adiabatic shear bands, a process not considered by fracture mechanics so far.

INTRODUCTION

Cracks that are subjected to tensile (mode-I) loading usually extend in their original direction, i.e. they propagate along the ligament of the specimen. When subjected to in-plane-shear (mode-II) loading, however, the cracks deviate from their original direction and propagate at an angle of about 70° with respect to the ligament. This behaviour is predicted by various crack propagation criteria, e.g. the maximum tensile stress criterion, and it is verified by many experimental results (1).

This investigation considers the failure behaviour of cracks or notches subjected to dynamic in-plane-shear loading. A technique for generating high rates of shear laoding is described and data on the obtained shear stress intensification rates are presented. Experimental results on the failure behaviour of steel specimens are reported. A failure mode transition is observed when the local stress intensification rate exceeds a certain limit. The different failure mechanisms that control these processes are discussed. A summarizing overview of work previously reported by the author (2), (3), (4) is given in this paper.

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EXPERIMENTAL TECHNIQUES

A specimen with two parallel edge cracks or edge notches is impacted by a projectile having a diameter d equal to the distance h of the two cracks, as is schematically shown in Fig. 1. The impinging projectile initiates a compressive wave in the middle part of the specimen that generates a mode-II loading at the crack tips. The sign of loading is different for the two notches. The mode-II loading condition should apply for the early time range of the impact event, i.e. until waves that are reflected at the finite boundaries of the specimen will interfere with the crack tip. The specimen is completely free; it is not hold in a special loading fixture. But a correct alignment of the specimen perpendicular to the impact direction is necessary.

A cylindrical steel projectile of 50 mm diameter is used to impact the specimen. The projectile is accelerated by an air gun to velocities v_o ranging from 10 m/s to about 100 m/s. Typical specimen dimensions are about 100 mm x 200 mm. The usual crack lengths are about half the specimen width. Specimens made from transparent model materials are utilized in pre-experiments aimed to study the feasibility of the presented loading technique to generate high rates of shear loading; steel specimens are used in the main experiments for investigating the failure behaviour.

The resulting shear stress intensifications are monitored by means of the shadow optical method of caustics. The specimen (transparent or made from steel) is illuminated by a parallel light beam. Due to changes in the refractive index of the material and/or deformations of the specimen surface near the crack tip the light rays are deflected from their original direction, thus forming characteristic light intensity patterns in real or virtual image planes, located behind of or before the specimen (see Fig. 1). A detailed description of the shadow optical method of caustics is given in a review article (5).

Shadow optical light intensity patterns are shown in Fig. 2 for conditions of tensile (mode-I) and in-plane-shear (mode-II) loading. Differently shaped shadow areas (dark regions) are obtained for the two conditions of loading. These shadow regions are surrounded by areas of light concentration (high density of bright lines). The dark areas are separated from the bright areas by sharply bounded curves, called caustic curves. The size of the shadow patterns is quantitatively correlated with the stress intensity factors K_I or K_{II}. For the dynamic events under consideration caustics are photographed by a Cranz-Schardin high speed camera.

EXPERIMENTAL RESULTS

Loading Phase

Pre-experiments have been performed to check whether indeed an undisturbed mode-II loading is obtained with the described loading technique and to get an estimate on the stress intensification rates $\dot{K}_{II}$ that can be realized.

Fig. 3 shows a high speed series of shadow optical photographs obtained with a specimen made from the model material PMMA (Polymethylmethacrylat). The shadow patterns at the tip of only one of the two notches are shown. The picture interval time of this high-speed series of photographs is 2 us. A comparison of the experimentally observed caustics with the theoretically predicted curve (see Fig. 2) indeed indicates an almost undisturbed mode-II loading. More detailed investigations (3) reveal some influence of a superimposed mode-I loading for the very beginning of the impact event which, however, is of minor importance in this context. Disturbances in the caustics of the last few frames provide an indication of the onset of crack instability. Quantitative data on the stress intensification rate $\dot{K}_{II}$ are shown in Fig. 4 for experiments performed with specimens made from the model material Araldite B and the high strength maraging steel X2 NiCoMo 18 9 5. The impact velocities have been 12 m/s or 13 and 33/ms, respectively. The maximum crack tip stress intensification rates $\dot{K}_{II}$ are about 2×10^5 $MNm^{-3/2}s^{-1}$ for Araldite B and 2×10^7 $MNm^{-3/2}s^{-1}$ for steel. These stress intensification rates are extremely high; they are of the same order or even higher than those obtained with Hopkinson bars.

Failure Phase

Main experiments have been performed to study the failure behaviour of the dynamically impacted specimens. For an Araldite B and a high strength steel specimen Fig. 5 shows shadow optical pictures photographed a few microseconds after instability in a low rate experiment. The obtained photographs show an undisturbed tensile mode-I caustic. Furthermore, it is seen that the cracks propagate at an angle of about 70° with respect to the ligament. Thus, the observed crack propagation angle is a further indication that a pure mode-I loading condition applied for the starter notch.

A systematic series of experiments has been performed to study the failure behaviour of steel specimens subjected to different rates of loading. Two steels have been investigated: the high strength maraging steel X2 NiCoMo 18 9 5 and the Chromium Molybdenum steel 42 CrMo 4. In the experiments, the notch tip acuity and the impact velocity were varied: notches with tip radii ranging from ρ = 0.8 mm to precracked notches were utilized and impact velocities ranging from 12 m/s to 72 m/s were applied. The strain at the tip of the notch increases with the acuity of the notch (i.e. with decreasing values of the notch tip radius), futhermore, the rate at which this notch strain builds up increases with the impact velocity. Both parameters thus control the local strain rate at the tip of the notch: the higher the acuity and the higher the impact velocity the higher the notch tip strain rate. The observed damage paths are graphically shown in Fig. 6. The following characteristics of the damage behaviour are recognized:

I) In the case were a notch of low acuity (ρ = 0.85 mm) is impacted at a low velocity (v_0 = 13 m/s) no damage is observed. The notch does not become unstable. The maximum strain resulting for this impact event is not sufficient to cause instability.

II) With increasing notch tip strain, i.e. for combinations of high notch tip acuity but low impact velocities, or for low notch tip acuities but high impact velocities damage is obtained in a direction that forms an angle of about 70° with respect to the ligament. Only the beginning of the damage path is shown in Fig 6. In all experiments complete failure of the specimen is observed, i.e. damage spreads across the entire specimen thus dividing the specimen into two halfs. A photograph of the damage surface is reproduced in Fig. 7. It shows the usual characteristics of a fracture surface: roughness as it is typical for this steel and shear lips at the edges of the surface. Thus failure as expected from fracture mechanics considerations is obtained.

III) When the notch tip strain rate is increased further, i.e. when notches of high acuity are impacted at high velocities a completely different failure behaviour is observed: damage develops in a direction which is almost identical with the original direction of the notch; actually the damage path is inclined by a small angle with respect to the ligament, but to the opposite side where the 70° cracks are observed. Furthermore, damage extends over a limited length only and comes to arrest in almost all cases. But the damage length increases with increasing notch tip strain rate. In one experiment performed at a very high notch tip strain rate (precracked notch, impact velocity v_0 = 53 m/s) complete failure of the specimen was observed. A typical photograph of the resulting damage surfaces is given in Fig. 8. This damage surface looks very different from the fracture surface shown in Fig. 7. It shows large smeared over regions that have a shiny mirror-like appearance. Furthermore, there is no indication of any shear lips: damage extends straight to the very end of the cross section of the specimen.

Metallographic micrographs of a cut through the specimen perpendicular to the damage surface are presented in Fig. 9 for the two steels investigated. Heavily sheared localized bands are visible. The shear band photographed with the steel X2 NiCoMo 18 9 5 shows a continuously increasing concentration of shear deformation towards the central region of the shear zone. With the steel 42 CrMo 4 a white edging band is visible indicating that a phase transformation has taken place with this material in the central region of the shear band. In particular the white edging band is associated with a strong increase of hardness with respect to the base material, as is indicated by Fig. 10. The highly deformed (or also transformed) central zone of the shear band after having been formed obviously failed subsequently by a fracture process; as it is clearly indicated by Fig. 9b. Details of the formation of shear bands due to the adiabatic conditions and softening processes that control this damage process shall not be discussed here (for details see (6,7)).

Since the strain at the notch tip varies proportional to $1/\sqrt{\rho}$, where ρ is the notch tip radius, and furthermore, since the rate at which the strain builds up, increases proportional to v_0, where v_0 is the impact velocity, the term $v_0/\sqrt{\rho}$ is proposed as an appropriate quantitative measure of the notch tip strain rate. The observed experimental findings have been plotted as a function of this parameter in Fig. 11.

For notch tip strain rates less than $(v_0/\sqrt{\rho})_{TF}$ damage does not occur. The initial notches stay stable. For notch tip strain rates between the threshold values $(v_0/\sqrt{\rho})_{TF}$ and $(v_0/\sqrt{\rho})_{SB}$ failure occurs by tensile fracture processes that extend at an angle of about 70° with respect to the ligament, causing complete failure of the specimen. This failure behaviour is in accordance with fracture mechanics considerations. At the notch tip strain rate $(v_0/\sqrt{\rho})_{SB}$ a failure mode transition takes place: For notch tip strain rates higher than this value failure occurs by localized shear bands. This failure is limited in length and it extends in a direction which is almost identical with the direction of the original starter notch. Despite of the very different test parameters utilized in the experiments the observed damage lengths obviously follow the same curve, which thus seems to be able to uniquely describe the experimental data.

SUMMARY AND DISCUSSION

A technique has been presented for subjecting cracks or notches to high rates of in-plane-shear (mode-II) loading. The stress intensification during the phase of loading and the subsequent phase of failure has been investigated by means of the shadow optical method of caustics. The following observations are made: (1) The dynamic shear loading arrangement is a rather simple experimental technique yielding an almost undisturbed mode-II loading. (2) The maximum stress intensification rates $\dot{K}_{II}$ are very high. They are one or even two orders of magnitude higher than those obtained with usual drop-weight experiments. (3) At low loading rates a fracture behaviour similar to that under quasi-static conditions of loading is obtained, which is readily understood by the concept of fracture mechanics (regions I and II in Fig. 11). When the loading rate exceeds a certain limit, a failure mode transition is observed from fracture to localized shear band processes (region III in Fig. 11). The observed shear band mechanism represents a novel failure mode that is not considered by the concept of fracture mechanics so far.

Shear bands are one of the major processes that control damage at high rates of loading. Thus shear band processes are of great practical relevance in high rate applications. Usually high impact velocities are necessary to generate shear bands. In the described experiments failure mode transition from fracture to shear band processes, however, is observed at rather modest impact velocities (of the order of 10 m/s) only. This is due to the fact that notches are used as stress-strain-raisers in the presented experiments. Similar stress-strain-rising effects apply for many other technological processes, e.g. when chippings are formed in metal cutting processes; and indeed shear band damage is observed with fast cutting tools as utilized in modern production technology. Several other examples could be given on the occurance of shear bands in common industrial applications. Thus shear band damage is not only a high rate phenomenon but is also observed at modest velocities when strain concentrations are effective.

Research is currently performed to extend the fracture mechanics concept into the regime of high rates of loading where damage is controlled by shear banding: the general approach of fracture mechanics is adopted but shear bands instead of cracks are concidered as failure process. The described loading technique lends itself as an appropriate tool for generating the necessary experimental data since both failure mechanisms, i.e. fracture and shear bands are generated by the same apparatus through simple variations of the test parameters. The shadow optical method of caustics is utilized to study the local conditions at the tip of a shear band. The results are expected to yield detailed information on the initiation and propagation behaviour of shear bands.

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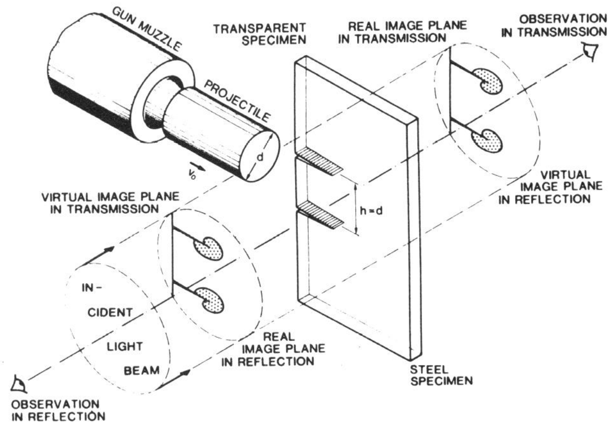


Fig. 1 Experimental set up (schematically)

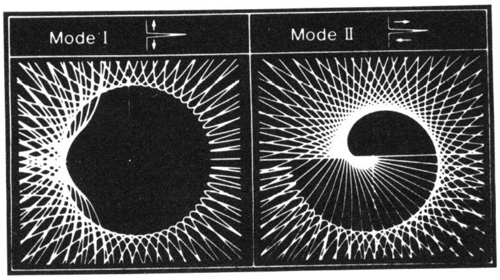


Fig. 2 Shadow optical light intensity distribution and caustics

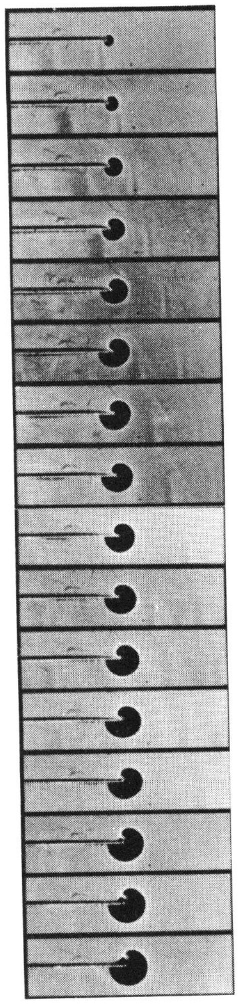


Fig. 3 High speed series of shadow photographs (PMMA, picture interval time 2 μs)

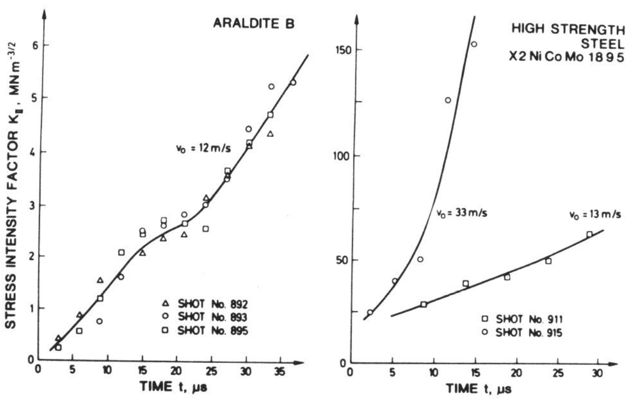
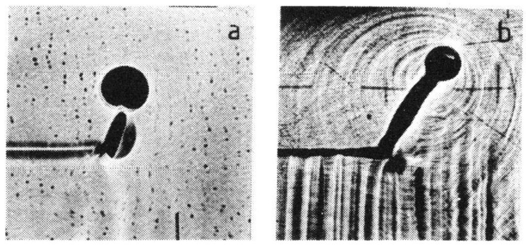


Fig. 4 Dynamic K_{II}-SIF history

Fig. 5 Shadow photographs after instability. (a) Araldite B (b) Steel X2 NiCoMo 18 9 5



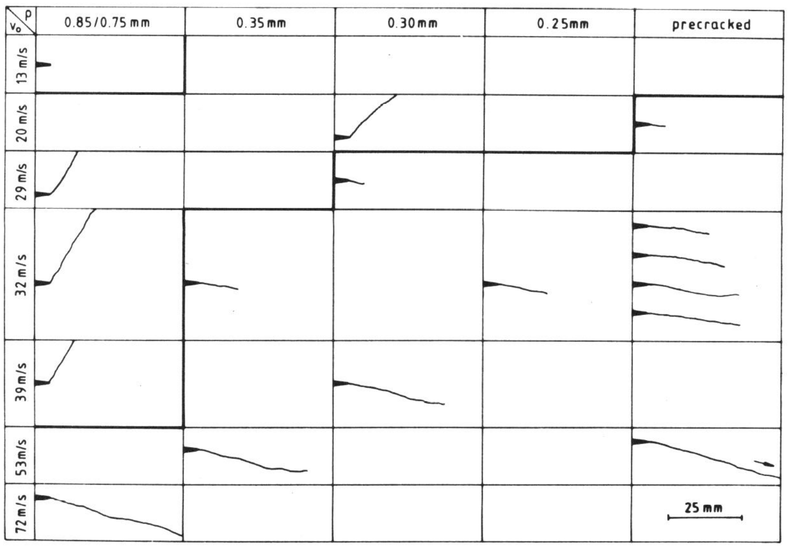


Fig. 6 Damage paths

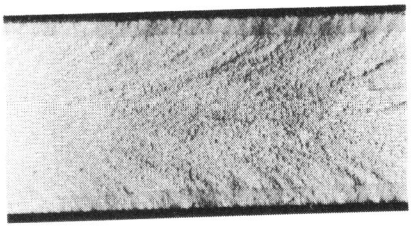


Fig. 7 Fracture surface at low notch tip strain rates, Steel X2 NiCoMo 18 9 5

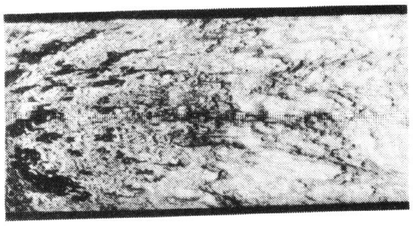


Fig. 8 Damage surface at high notch tip strain rates, Steel X2 NiCoMo 18 9 5

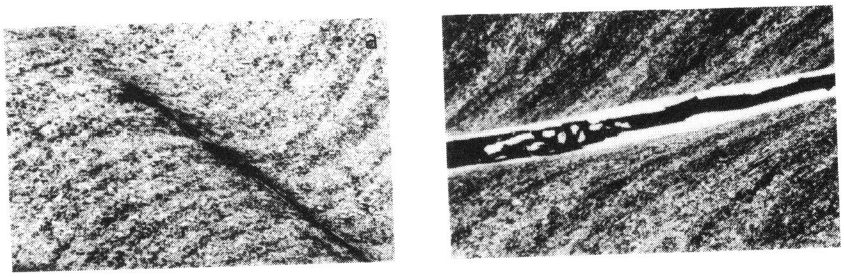


Fig. 9 Micrographs of shear bands, (a) deformed band, Steel X2 NiCoMo 18 9 5, (b) transformed band, Steel 42 CrMo 4

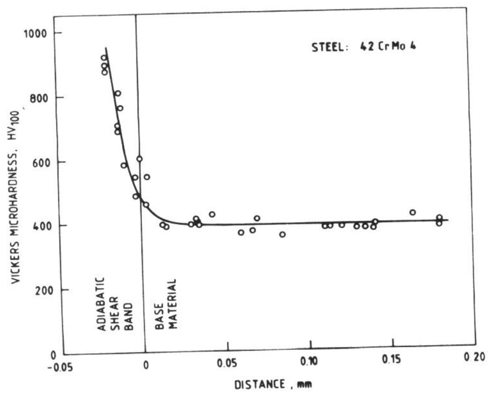


Fig. 10 Hardness profile across shear band

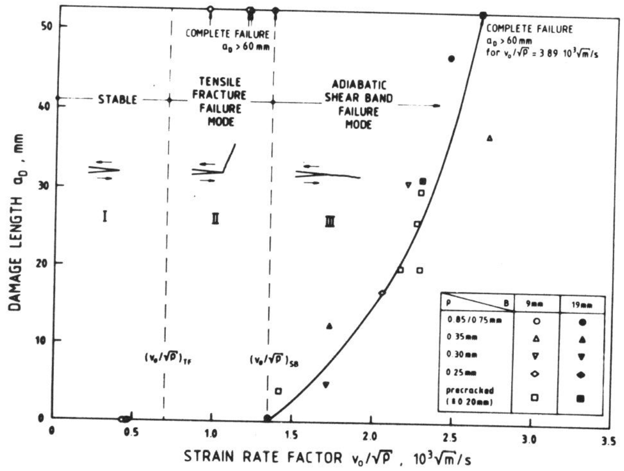


Fig. 11 Dynamic shear failure diagram