ADIABATIC SHEARING AND ASSOCIATED CRACKS IN BALLISTIC STEEL TARGETS

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ABSTRACT

The present study describes the adiabatic shearing and the associated cracks that occur in a steel target due to the penetration of a high velocity projectile. The observed cracks are classified as those formed in the shear bands, the flow lines and in the regions just ahead of the projectile tip in the bulged back surface of the target plate. The initiation, propagation and termination of the cracks in the shear bands and in the flow lines are studied. Cracks just ahead of the projectile tip are observed to follow some preferred paths. The understanding of the adiabatic shearing and the formation of these cracks is of relevance in the selection of armour materials.

KEYWORDS

Adiabatic shear; ballistic properties; steel; shear band cracks; white etching layers.

INTRODUCTION

Adiabatic shearing in projectile impact studies has been reported frequently. However, only a few of these discuss the phenomenon of the associated cracking (Manganello and Abbott, 1972; Gleen and Leslie, 1971; Wingrove, 1973; Stock and Thompson, 1970; Woodward, 1979; MeBar and Shechtman, 1983). When a projectile penetrates the plate the metal at first undergoes large, homogenous deformation to form a cavity identical to the projectile shape. As the projectile penetrates further into the target plate localised deformation takes place in a small region adjacent to the projectile-target interface. At this interface nearly adiabatic conditions exist and a white etching layer is formed due to intense heating which causes phase transformation in steels (Craig and Stock, 1970). Such a white etching layer is shown in Figure 1. Most of the impact energy is absorbed by the general deformation of the metal caused by projectile penetration. Some amount of energy is also absorbed by the friction between the projectile and the target plate. The remaining energy is absorbed to some extent by shear band formation along the planes of maximum shear stress. In steel these shear bands are classified as (A) transformed bands appearing

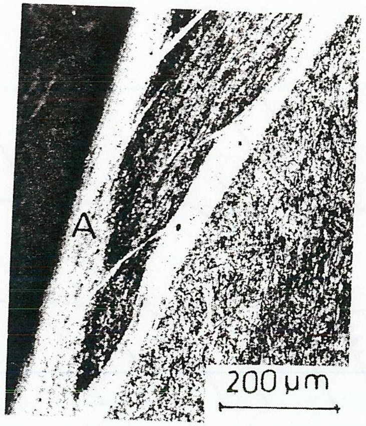

Fig. 1 Photomicrograph of a white etching layer (A) at the Projectile-target interface.

white upon etching, with well defined width and (B) deformed band of intense shear with no phase transformation associated with it. Cracking occurs in the target plate to absorb the still remaining energy.

Many times cracks are seen within the shear bands. Bedford, Wingrove and Thompson (1974) suggest that in the transformed bands cracks can nucleate during the formation of adiabatic shear band and propagate along with the band. A crack may also nucleate and propagate after transformed band is completely formed. Cracks can also form along the interface between the matrix and the band which is the heat affected zone (Tirupataiah and Raju, 1982). Backman and Finnegan (1973) separate the two events of band formation and crack formation. They suggest that adiabatic shear band occurs during compressive conditions and the cracks must form after the compressive conditions have disappeared. They feel that the cracks form after phase transformation in the case of transformed bands and is a direct result of large deformations in the case of deformed bands.

The phenomenon of crack initiation, propagation and termination in the material that is subjected to impact loading is not very clear. The present study examines the cracking phenomenon in the projectile penetrated steel targets. Cracks are classified as those formed along the shear bands (both transformed and deformed bands) and those along the flow lines. An attempt is made to explain the initiation and propagation of these cracks.

EXPERIMENTAL

Quenched and tempered high strength alloy steel plates were impacted with projectiles at a velocity in the range of 600-700 m/sec. The penetrated portions of the target material were sectioned, polished and etched with 2% Nital. They were examined metallographically using an optical microscope.

RESULTS AND DISCUSSION

The optical micrographic study revealed a number of shear bands as well as shear cracks. All these cracks are categorized as those present within (a) the shear bands, (b) along the flow lines (c) the bulged back surface of the target plate, just ahead of the projectile tip.

(a) Cracks Present in the Shear Bands

Often cracks are formed at the projectile-target interface and propagate to some distance along the shear band and finally terminate at one edge of the band, as shown in Fig.2a. Sometime small cracks along the length of the band are also seen to be present as shown in Figs. 2b, 2c and 2d. If these small cracks are very near to each other, they join up by a small 'hair line' crack as shown in Fig.2e. Long continuously running crack along the length of the shear band has also been observed as shown in Fig.2f.

Fig. 2a Crack that initiated at the projectile-target interface and terminated at one edge of the shear band.

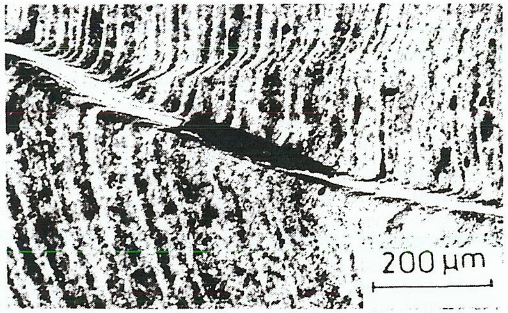

Fig. 2b Photomicrograph showing the initiation, propagation and termination of a crack in a shear band.

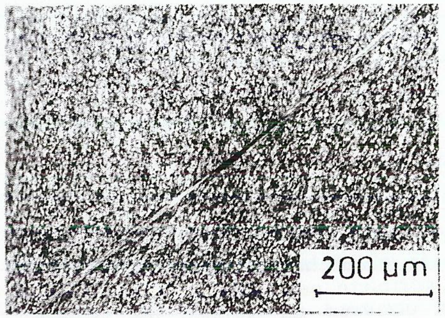

Fig. 2c Photomicrograph showing a small brittle crack in a transformed adiabatic shear band.

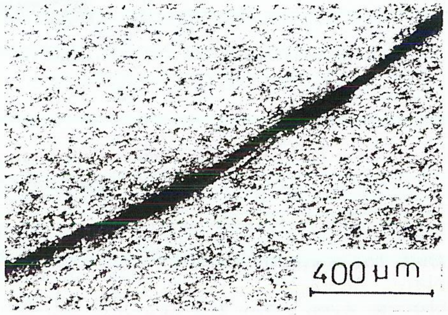

Fig. 2d Multiple, small cracks in a shear band.

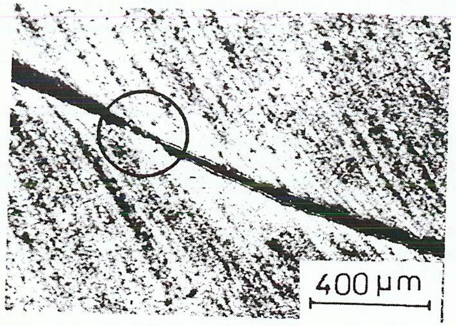

Fig. 2e Two small cracks in a shear band joined up by a 'hair line crack'.

Fig. 2f A long continuous crack along a shear band.

When a projectile penetrates the target plate most of the kinetic energy is absorbed by the large, general deformation that takes place in the target metal. Due to high speed friction between the plate and the projectile a thin white layer is formed to absorb some more energy. In this process of penetration the grains of the target material along the interface will get deformed and elongatged as schematically shown in Fig.3 thereby inducing severe compatability stresses on the grain boundaries. Shear bands nucleate at such interfaces when conditions favour localisation of deformation and then propagate into the target metal along the planes of maximum shear. At the site where the thin white layer forms, the temperature is very high. Consequently the grain boundaries are weakened, providing a possible location for the nucleation of a crack. This crack can form and propagate along the shear band as shown in Fig. 2a.

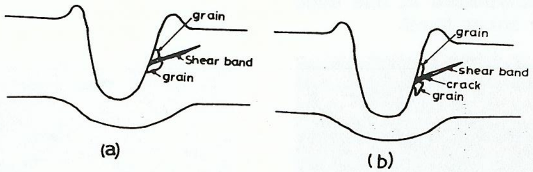

Fig. 3 Schematic explanation of the crack formation at the projectile-target interface.

A possible mechanism by which cracks are nucleated along the shear bands away from the projectile-target interface is given below. Due to the fact that the impact process does not result in complete perforation of the target plate, homogenous deformation would have occurred all through the impact process even after the shear bands are formed. As a result dislocations moving along the slip planes in the bulk of the material will be obstructed by the shear band having an entirely different texture from that of the matrix. This will result in pile up of dislocations at the shear band-matrix interface causing the crack to be nucleated. Such a situation is schematically shown in Fig.4. It must be noted that the slip lines indicated in the Fig.4 will generally tend to follow the macroscopic flow lines.

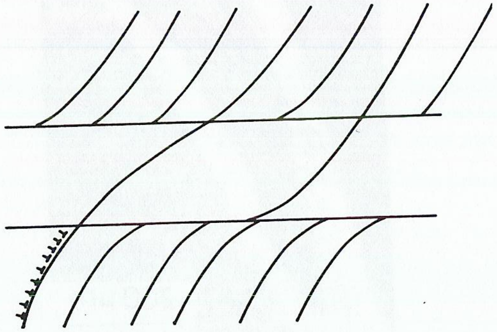

Fig. 4 Schematic explanation of the crack initiation, propagation and termination in a shear band.

When the temperature in the shear band exceeds the transformation range, austenite will form and this relatively soft layer will help to open up or widen the crack that is propagating in the shear band. This will result in a long continuous crack as shwon in Fig. 2f. On cooling the transformed bands will be hard and provide a potential site for the nucleation of brittle type of crack whose propagation may be aided by the tensile stress waves. Such cracks will be small in length, formed only just to relieve the stress field in the transformed band which is of martensitic structure. Such a typical crack formation, either single or multiple in character, is shown in Fig.2c and 2d. Sometimes when these cracks are very near to each other, they may join together by a 'hair line' crack as shown in Fig.2e.

(b) Cracks Present along the Flow Lines

Cracks are seen to form many times along the flow lines as shown in Fig.5a and b. Fig.5a shows cracks along the flow lines at the tip of a shear band. Fig.5b shows clearly how a number of small cracks formed along the flow lines and joined up together appearing as long cracks on either side of the shear band. Cracks can nucleate along the flow lines as shown in Figs.5a and b in the following way.

Initially the target material rather undergoes homogenous deformation over a volume comparable to the crater volume resulting in the formation of flow lines. But once it is energitically favourable to localise deformation shear bands form propagating along the planes of maximum shear stress. The shear band as it propagates through the material causes the material above to be displaced with respect to the material below. This is clearly indicated by the severe displacement of the flow lines in the shear band region as shown in Fig.5c. The shear band propagates by shearing the material in front of it to a critical shear displacement or equivalently to a critical shear strain. Thus, in front of the shear band tip there is always present, a severely sheared region Such a region is illustrated in Fig.5a. Obviously the flow lines within this severely strained volume is likely regions for the formation of cracks as found in Fig.5a. If these cracks are very near to each other they will join up by propagating under the influence of the reflected tensile waves and appear as long cracks as shown in Fig.5b. Here the band has propagated further after the cracks have formed along the flow lines. Thus we see long cracks along the flow lines on either side of the shear band.

Fig. 5a Photomicrograph showing cracks along the shear band (A) and the flow lines (B) ahead of the shear band tip.

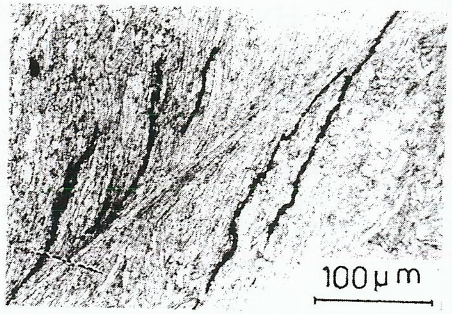

Fig. 5b Small cracks joined up with each other along the flow lines on either side of a shear band.

Fig. 5c Photomicrograph showing the severe shear displacement of the flow lines causing a shear band.

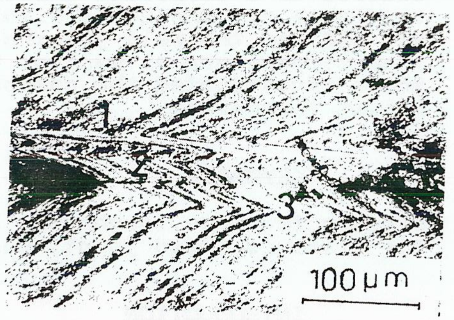

Fig. 6 Photomicrograph showing a transformed shear band (1)along with two deformed bands - one with a crack (2) and one another (3) yet to completely form.

A typical transformed adiabatic shear band along with two deformed shear bands - one with a crack and the other yet to fully form - is shown in Fig.6. The situation shown in this figure is an example of the complexity in the formation of shear bands and the associated shear cracks. Here the transformed adiabatic shear band (1) formed at first and the deformed shear band (2) with a crack along it formed latter. Subsequently another deformed band (3) tried to form because of the shear displacements in the flow lines but it has not yet fully developed.

(c) Cracks Present in the Bulged Back Surface of the Target

Cracking has also been observed in the portion of the target material just ahead of the projectile tip. These cracks fallow some preferred paths. Typical cracking in this region is shown in Fig.7a. When the projectile hits the target plate compressive waves are set up in the material. They travel to the back surface of the plate and are reflected back as tensile waves. When the intensity exceeds the fracture stress of the material, cracking occurs. These cracks have been found consistently to follow the logarithmic spiral slip planes as schematically shown in Fig.7b. These slip line fields closely match with the observed paths of the cracking.

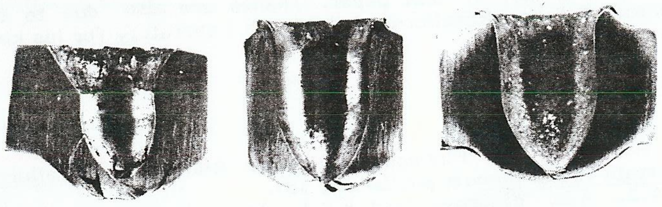

Fig. 7a Observed crack paths in the region just ahead of the projectile tip.

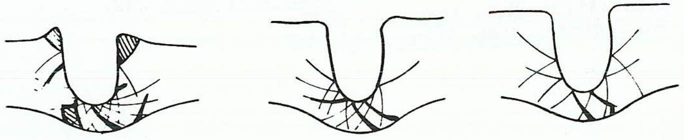

Fig. 7b Schematic diagram showing the qualitative slip line fields in the target material.

CONCLUSIONS

When a projectile penetrates a target plate, cracking takes place at various regions. These cracks are classified as those associated with (a) the shear bands (b) the flow lines and (c) the back bulged region of the target plate. The cracks in the shear bands mostly start from the interface, though some sharp small brittle type of cracks could be identified along the shear band. Cracks associated with flow lines form mainly at the intersection of the slip plane and the shear band. This is postulated as due to the pile up of dislocations at the intersection point causing a stress concentration leading to crack nucleation.

Cracking at the back side of the plate follows a preferred logarithmic spiral path. This cracking is mainly due to the reflected tensile stress waves. These reflected tensile stress waves help the propagation of the cracks not only at the back bulged portion of the target material, but also of those cracks that form in the flow lines or in the shear band.

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