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Shear strain localisation and fracture in high strength structural materials

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ABSTRACT

Purpose: The purpose of this paper is to investigate the factors variables influencing the plastic deformation and failure in some high strength metallic materials under high velocity impact.

Design/methodology/approach: The materials were tested in compression at strain rates ranging between 10^3 and 10^4 s^{-1} using direct impact Hopkinson Pressure Bar. Microstructural evaluation before and after mechanical loading at high strain rates was carried out to determine the mechanisms of plastic deformation and failure of the materials under study at high strain rates.

Findings: Plastic deformation in the materials is dominated by shear strain localization along adiabatic shear bands (ASBs). Cracks are initiated and propagated along these bands leading to failure. Occurrence of adiabatic shear bands and cracking tendency of these bands are significantly influenced by strength and microstructure. Whereas homogeneous materials show the least tendency for shear strain localization and adiabatic shear failure, the presence of hard precipitates or secondary phase particles promotes the occurrence of adiabatic shear bands. Other variables such as strain and strain rate also show considerable influence on shear strain localization and susceptibility of a material to adiabatic shear failure.

Research limitations/implications: The results of these investigation provides an understanding of how various microstructural variables can influence adiabatic shear failure in metallic materials and are significant in enhancing a more efficient material design for use in high strain-rate related applications.

Practical implications: This research is particularly significant in military applications where these materials are used as armour plates and can be subjected to extremely rapid loading condition as in ballistic impact or explosion fragmentation.

Originality/value: Results of these investigations offers a qualitative model for predicting the conditions which promote occurrence of ASBs in metallic materials.

Keywords: Metallic alloys; Plastic deformation; Strain localisation and fracture

MATERIALS

1. Introduction

Strain localization along narrow bands dominates deformation and fracture of materials subjected to extreme loading conditions such as ballistic impact or explosion fragmentation. These narrow bands are called adiabatic shear bands (ASBs), the occurrence of which precedes materials fragmentation at high strain rates. Most materials failures at high strain rates are traced to shear strain localization and occurrence of adiabatic shear bands [1].

Several constitutive models and theories have been developed to explain the occurrence of adiabatic shear bands in metals and alloys [2-4] and diverse opinions are expressed as to the mechanism of formation of adiabatic shear bands. These include phase transformation [5], dynamic recrystallization [6], grain elongation and fragmentation [7], dislocation re-distribution and patterning [8] among others. The fact that formation of adiabatic shear bands is the precursor to failure is not in dispute among researchers on high strain rate behaviour of engineering materials. However, a lot more work need to be carried out in identifying how microstructural variables and testing conditions influence the occurrence of adiabatic shear bands in various engineering materials that are commonly exposed to high strain-rate deformation in service. The authors of the present study have carried out several investigations on the occurrence and failure of adiabatic shear bands in several alloy steels, aluminium and tungsten alloys, composite and ceramic materials. Based on the results of these investigations, a qualitative model for the prediction of occurrence, microstructure and properties of adiabatic shear bands is presented and discussed in this paper. The intent is to provide a platform for predicting the conditions which promote the adiabatic shear failure in metallic materials. A microstructural model for the crack initiation and propagation along adiabatic shear bands is also discussed.

2. Experimental method

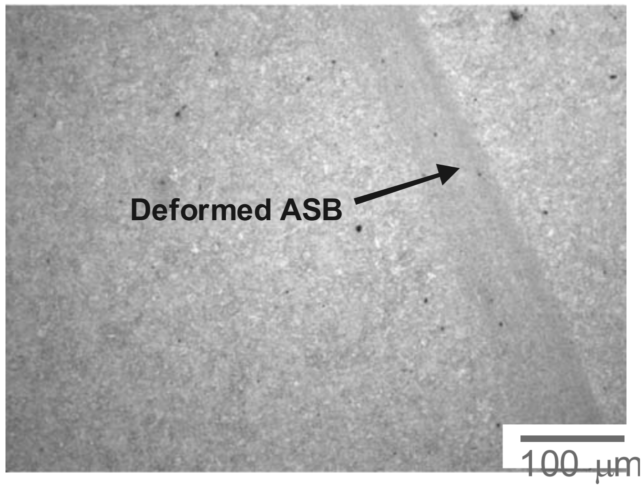
High strain rate tests on the materials of interest were carried out using fully instrumented direct impact Hopkinson Bar. The materials investigated include high strength low alloy steels, dual phase steel, aluminium 6061-T6 and 5083 H131 alloys, and alumina particles reinforced aluminium alloy composite. The strain rate ranged between 10^3 and 10^4 s^{-1}. The experimental procedure is discussed in details elsewhere [9]. The influence of variables such as microstructure, sample geometry, strain, strain rate, strain-rate sensitivity on the dynamic stress-strain rate curves and occurrence of thermo mechanical instabilities leading to adiabatic shear banding were investigated. Dynamic stress-strain curves obtained from these investigations are discussed in earlier publications [9-11]. Optical and scanning electron microscopic evaluation of the investigated materials were carried out after high velocity impact to investigate conditions favouring occurrence of ASB and identify the failure mode along the shear bands.

3. Results and discussions

3.1. Shear strain localization

Optical micrographs showing strain localisation along ASBs in martensitic AISI 4340 steel Figs. 1and 2. The morphology of the shear bands depend on the microstructure of the parent material. Both deformed and transformed (also called white etching) ASBs are observed in steels specimens. Whereas occurrence of white etching bands are more pronounced in martensitic steels, deformed bands are more commonly formed in steels with pearlitic structures and in dual phase steels. Deformed bands contain essentially highly distorted grains as a result of large strain in the shear band region. Transformed bands appear white when viewed under optical microscope. Mechanisms of initiation and propagation of both types of shear bands are well covered in the literature [12-14].

The tempering condition of martensitic steels also shows considerable influence on the type of shear bands formed. The higher the tempering temperature, the higher the tendency for the occurrence of deformed ASB rather than transformed ASB. Also the amount of strain that is generated at the shear band propagation front can influence the type of shear band that is formed. This explains why some shear bands change from transformed bands to deformed bands in steels before the propagation eventually stop as shown in Fig 2a. A further investigation on deformation behaviour of a rolled homogeneous alloy steel also confirms the influence of strain rate on the type of adiabatic shear formed in steel. At strain rate of up 3000 s^{-1}, no ASB was observed in the impacted samples, as the strain rate was increased to about 3100 s^{-1}, deformed ASB was formed. Transformed ASBs were observed in the steel samples, when the strain rate exceeded 3700 s^{-1}. This study shows that the shear bands are harder than the bulk material and the hardness of transformed bands is greater harder than that of deformed band. For example the average hardness value observed in the bulk material, deformed ASBs and transformed ASBs in a roll homogeneous alloy steel after high velocity impact are shown in Fig. 4.



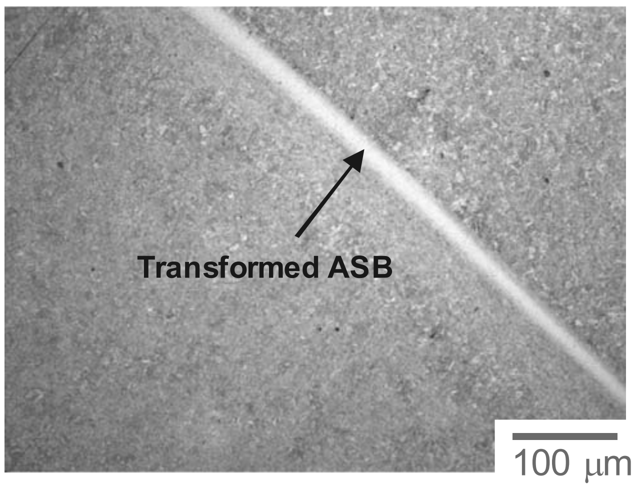


Fig. 1. Deformed and transformed ASB in martensitic AISI 4340 steel subjected to high velocity impact

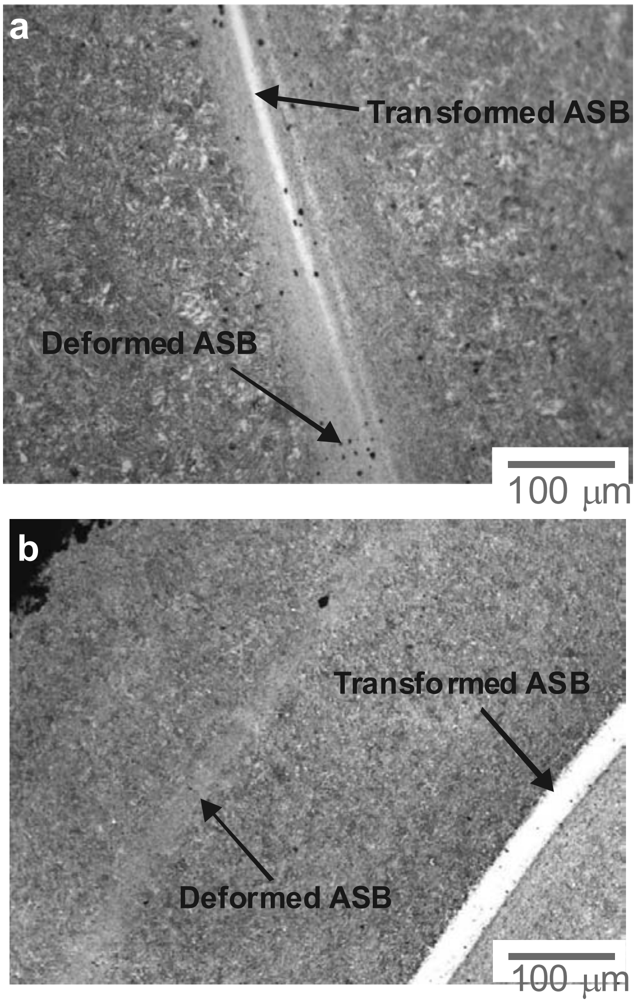


Fig. 2. ASB in martensitic AISI 4340 steels (a) transition between transformed and deformed band (b) two simultaneously propagated ASBs

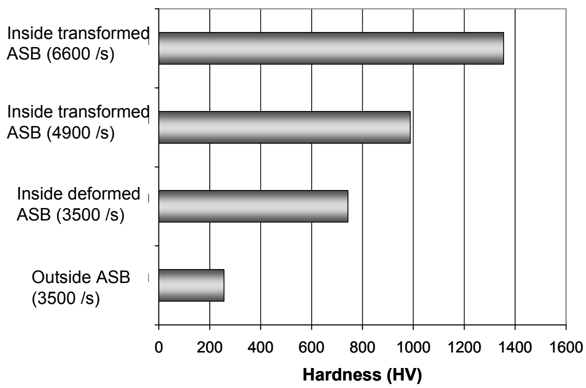


Fig. 3. Hardness inside and outside ASBs in a rolled homogenoeous alloy steel after high velocity impact

Where two ASBs are observed on transverse section of an impacted cylindrical steel specimen, one was observed to be deformed and the other transformed ASB. The deformed bands are in all cases formed near peripheral regions of the transverse section while transformed bands are much closer to the centre of the test specimen (Fig. 2b). Adiabatic heating near the surface will be less intense than inside the specimens as a result of large temperature gradient between the peripheral region and the surface of the specimens. Therefore, it appears that temperature attained in the shear band region can also play a role in the morphology and type of ASB that is formed in the steel. Results of these investigations has shown that deformed bands show greater tendency to fracture than transformed bands while the cracking tendency of transformed band in martensitic steel decreases with increasing tempering temperature. The higher hardness of the white etching band could account for their greater susceptibility to cracking.

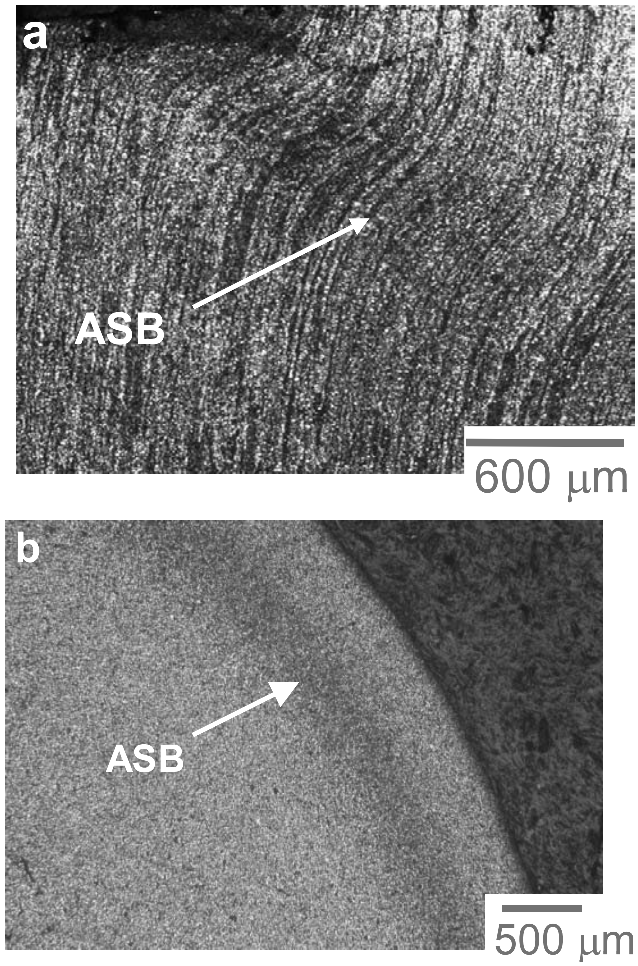


Fig. 4. deformed bands in dual phase after high velocity impact a: longitudinal section (b) transverse section

Figure 4 shows deformed bands observed in dual phase steel after high velocity impact. Shear flow in the shear bands is easily noticeable on the longitudinal section. No transformed band was observed in this steel. Results of our investigations have shown that when viewed on transverse section, ASB contains finer grains and higher martensite content than the bulk materials [10]. Deformed band similar to the one in the longitudinal section of dual phase steel is observed on the transverse section of Aluminium 5083 H131 alloy after high velocity impact (Fig 5). However in Aluminium 6061-T6 alloys, fragmented grains were observed inside the deformed bands (Fig. 6). The shear band formation in the Aluminium 6060-T6 alloy consists of three steps: elongation of grains, orientation of grains in shear flow direction and finally fragmentation of the grains leading to shear bands having finer grains than the bulk material.

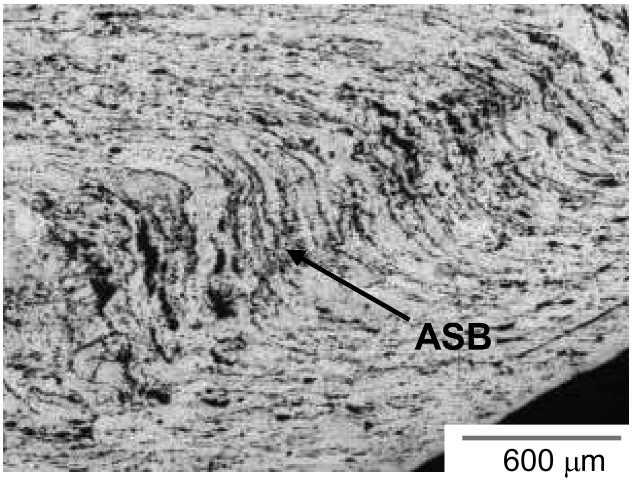


Fig. 5. ASB in Aluminium 5083 subjected to high velocity impact

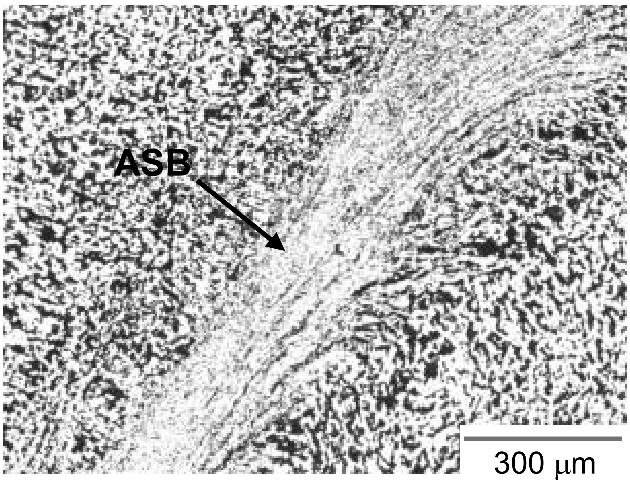


Fig. 6. ASB in Aluminium 6061-T6 subjected to high velocity impact

Microstructural evaluation of alumina particle-reinforced aluminium 6061-T6 matrix composites shows that although reinforcement of the aluminium alloy with hard ceramic particles increases strength and stiffness, it increases the susceptibly of the alloy to strain localization and occurrence of ASB under high velocity impact. Thermal softening and intensive shear strain in ASB force a more densely parking of the alumina particle reinforcement in Aluminium 6061-T6 alloy as shown in Fig. 7. The higher the ceramic particle content, the greater is the susceptibility to occurrence of ASB and the higher the tendency for cracking. The failure of this material along adiabatic shear bands is described in details in an earlier publication [11].

Finite element calculations on the occurrence of adiabatic shear bands in a high strength low alloy steel shows that ASBs are initiated at sites of imperfections and defects in the microstructure. Evolution of ASB with impact time of the steel specimen is shown in Fig. 8. The figure shows three stages of deformation that culminate in strain localisation and occurrence of adiabatic shear bands: In the first stage there is no plastic deformation, then thermal softening and strain hardening compete leading to a relatively homogeneous plastic deformation. In the final stage, thermal softening predominates leading to visco-plastic instabilities and occurrence of ASBs. Results of these investigations suggests that distance between precipitates limits the width of formed ASBs in alloy steels and increase localised strain within these bands to strain sufficient to initiate cracks.

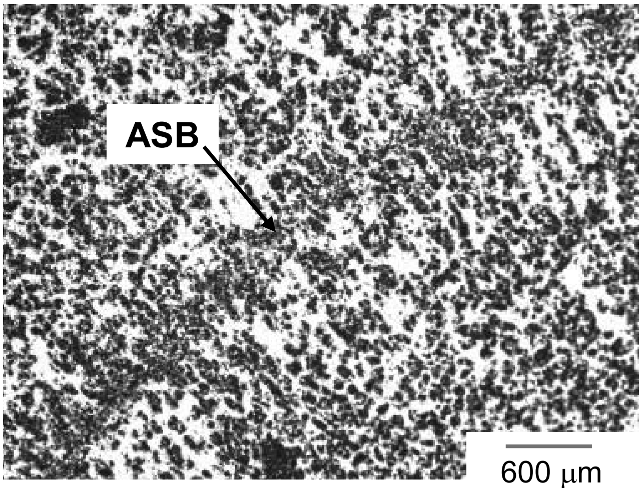


Fig. 7. ASB in particulate MMC subjected to high velocity impact

Occurrence of adiabatic shear bands is traced to retention of heat converted from impact energy in certain region leading to excessive thermal softening and strain localisation along the narrow bands.

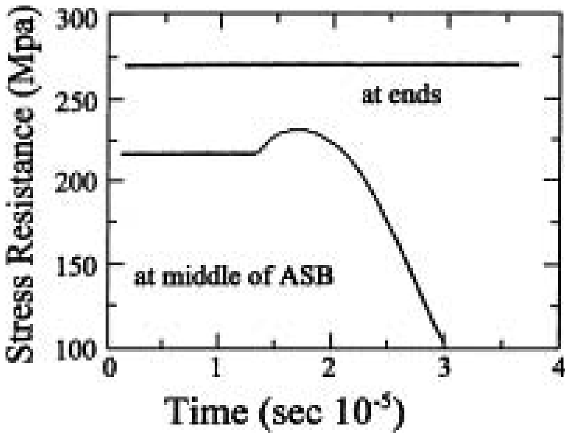


Fig. 8. The influence of deformation time on stress resistance change in martensitic alloyed steel

Our observations that occurrence of adiabatic shear bands is related to the presence of defects and imperfections is corroborated by Armstrong et al [14] who have also traced initiation and propagation of adiabatic shear bands to dislocation pile up that is enhanced by inclusion and precipitates. Armstrong and Zerilli [15] suggested that a local rise in temperature and softening can be produced when a dislocation pile-up pierces through a grain boundary creating a site for shear band initiation. Analyses by Meyers et al [16] suggested that microstructural evolution at high strain rates begin with a homogeneous distribution of dislocations that rearrange themselves into dislocation cells which eventually become elongated sub-grains that subsequently break down into equi-axed microcrystalline structure as strain increases. Elongation and fragmentation of grains along shear bands are evident in the microscopic evaluation of Aluminium 6061-T6 alloy in the present investigation.

3.2. Adiabatic shear band failure and specimen fragmentation

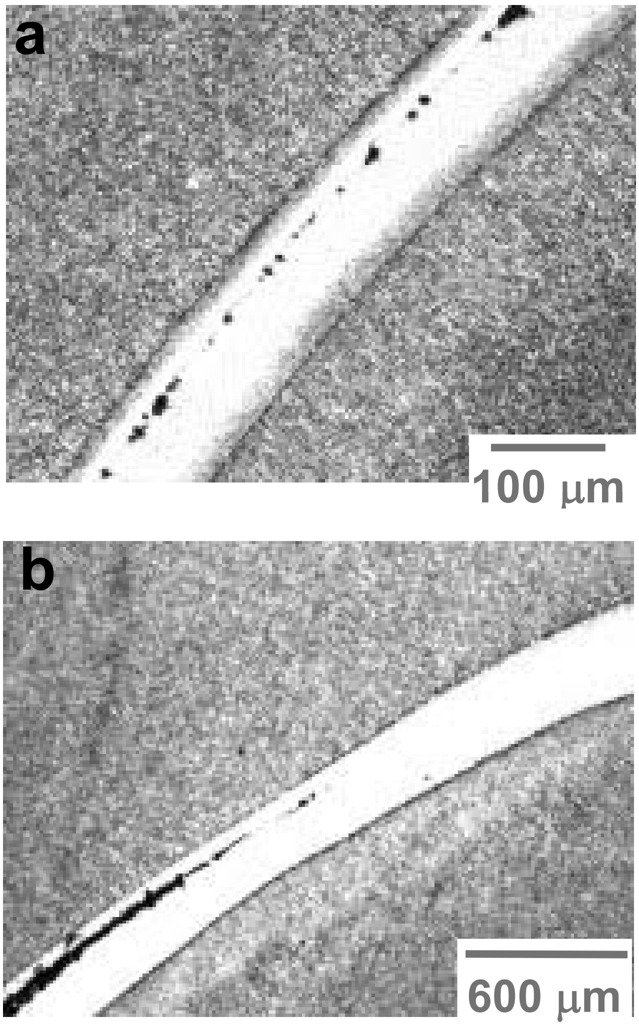


Fig. 9. Crack initiation (a) and propagation (b) along ASB in AISI 4340 steel subjected to high velocity impact

In all the materials investigated, cracks are initiated in ASB leading to specimen fragmentation along the shear bands (Fig 9). The transformed bands formed in steel shows higher tendency to cracking than deformed shear bands. Five stages have been identified for the process of crack initiation and propagation inside ASB's in martensitic high strength low alloy steels: (a) formation of microvoids inside the shear bands, (b) coalescence of these microvoids to form void-clusters which elongate parallel to the shear bands, (c) initiation of micro cracks from the ends of the void-clusters (d) lengthwise growth and interconnection of adjacent microcracks (e) crack growth and propagation to failure. Microstructural model for the crack initiation and propagation inside ASBs are schematically presented in Fig. 10.

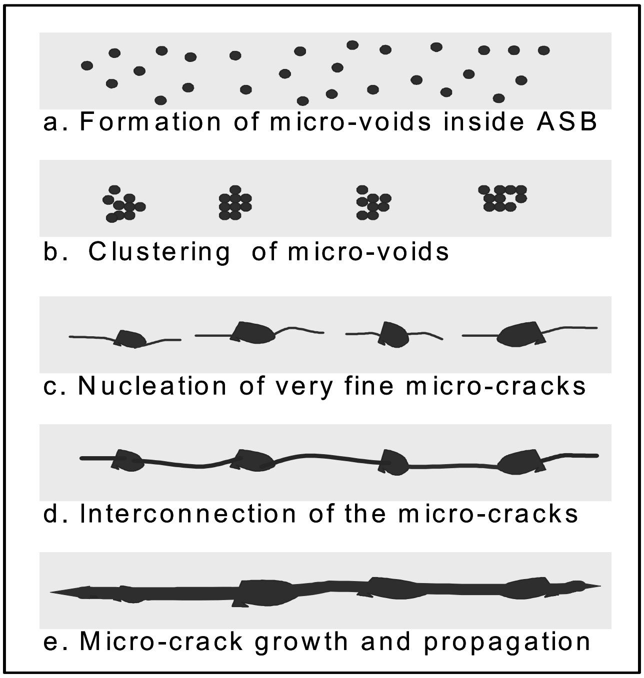


Fig. 10. Microstructural model for crack initiation and propagation inside ASB in martensitic AISI 4340 steel

Scanning electron microscopic examination of the fracture surfaces of failed AISI 4340 steel samples that fragmented under high velocity impact shows two distinct fracture modes along the ASB (Fig. 11); (a) highly elongated dimples suggesting ductile shear failure along the shear bands and (b) knobbly fracture suggesting possibility of melting inside the shear bands during impact. The aspect ratio of the elongated dimples observed inside the shear bands is influenced by the tempering temperature of the martensitic steel. Analysis by Chen *et al* [17] shows that a temperature rise of up to 1527 °C can be generated in localised zone of an impacted target plate, depending of the thickness of the plate. This temperature is sufficiently high enough to cause melting inside the adiabatic shear bands. The fracture mode varies from one point to another. This may not be unconnected to temperature variation inside the shear bands leading to ductile fracture mode in some region and knobbly fracture mode in the other. In most cases a transition layer of less than 5 μm separates the region containing ductile fracture and knobbly fracture modes.

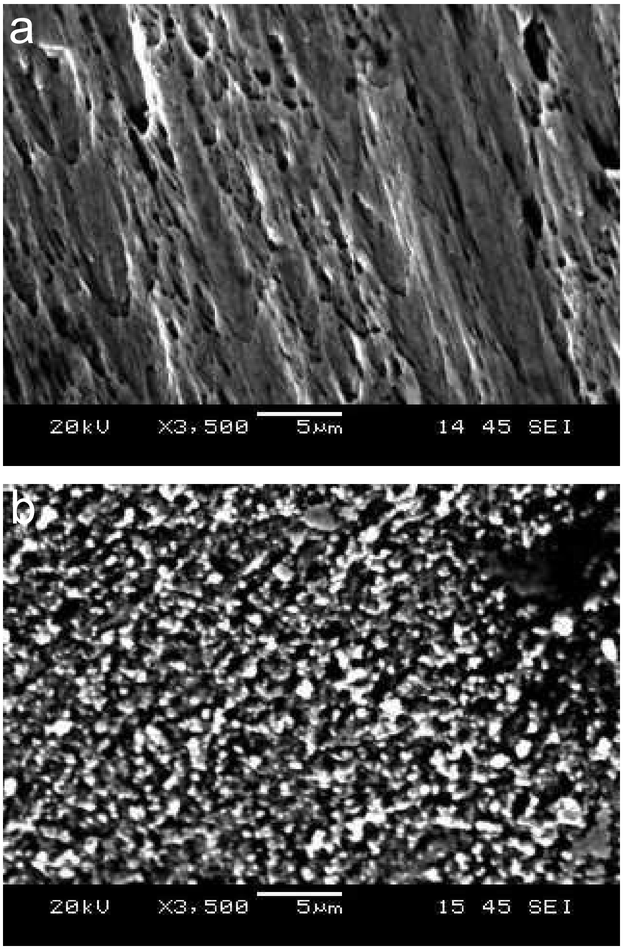


Fig. 11. Fracture surface of showing (a) ductile shear and (b) knobbly fracture modes along ASB in oil quenched and tempered AISI 4340 steel

4. Conclusions

Strain localisation and occurrence of adiabatic shear bands play prominent roll in deformation and failure of investigated high strength materials under high velocity impact. The occurrence, morphology, width and cracking susceptibility of the shear band are dependent on the strength and microstructure of the material. The presence of hard particles or secondary precipitates in the microstructure of an alloy promotes occurrence of ASB. Whether a deformed or transformed ASB is formed in steel also depends on the microstructure, strain rate strain and on the intensity of adiabatic heating during deformation.

Acknowledgements

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