Effect of high strain rate on plastic deformation of a low alloy steel subjected to ballistic impact

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Abstract

Some results of an experimental study on high strain rate deformation of a low alloy steel are discussed in this paper. Cylindrical specimens of the steel in quench-hardened and tempered condition were subjected to high strain rate deformation by direct impact using a modified Split Hopkinson Pressure Bar (SHPB). The deformation process is dominated by stress collapse due to thermal softening effect of adiabatic heating in some narrow bands within the material under deformation. The time for the onset of the stress collapse leading to strain localization was found to increase with strain rate. The critical strain at which adiabatic shearing occurs depends on the strain rate and microstructure. Steel samples that were tempered at 425°C exhibit greater tendency to adiabatic shearing than those tempered at 315°C. The time and critical strain for the onset of stress collapse and adiabatic shearing are lower. Whereas single white adiabatic shear bands were observed to initiate and propagate during the high strain rate deformation in samples tempered at 315°C, multiple shear bands were found to initiate and dynamically propagate in the samples tempered at 425°C. Of these multiple shear bands, the one closest to the centre of the cylindrical test pieces were white etching bands while the rest appeared as deformed bands. The higher tendency of the samples tempered at 425°C to formation of adiabatic shear bands has been attributed to increased perturbation in the steel samples as a result of the heat treatment procedure. The type of shear bands formed in the steel at high strain-rates can be explained as due to the accompanying fragmentation of martensite laths and dissolution of carbides during adiabatic heating and shearing, which eventually determines the size of the micro-constituents of the adiabatic shear band and the resolvability by optical microscopy.

Keywords: High strain rate deformation; Adiabatic shear band (ASB); Microstructures; Dynamic failure

1. Introduction

Unlike deformation at low strain rates or under quasi-static loading, which is governed by slip and twinning mechanisms and is relatively homogeneous, deformation at high strain rates is a much complex phenomenon which is characterized by extreme strain localization along narrow bands called adiabatic shear bands (ASBs). The concept of adiabatic shearing during high strain deformation was first raised by Zemmer and Holloman [1] when they attributed the strain localization to adiabatic heating leading to a local rise in temperature along narrow bands. Although shear bands can be observed in a metal that is subjected to lower strain rates, the term adiabatic shear band is used when the strain rate is greater than $10^3 \text{s}^{-1}$ [2]. The susceptibility of a material to adiabatic shear-

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mentation. The analyses of Xue et al. [12], Grady and Kipp [13] and Wright and Ockendon [14] on multiple shear banding indicated periodic and characteristic shear band spacing, a concept which Xue et al. termed self organization of shear bands.

Two types of adiabatic shear bands have been identified in the literature: the white etching bands (also called transformed band) and deformed bands. The deformed bands appear as highly deformed material and consist of highly elongated grains. The white shear band exhibits a characteristic white color when observed under an optical microscope. White etching bands are sometimes referred to as transformed bands because of perceived microstructural transformation into untempered martensite during adiabatic shearing. Given the condition under which adiabatic shearing occurs, the possibility of such phase transformations is very doubtful. The white color of this shear band has widely been attributed to resolution limit of optical microscope in resolving the micro-constituents of the white etching bands which consist of extremely fine (nanosized) subgrains. The large amount of strain in the shear bands during deformation of martensitic steels leads to fragmentation of martensite laths. A study by Derep [15] shows that the microstructure of adiabatic shear bands formed in martensitic armored steels consists of very fine martensite, iron carbides and ferrites having dimension below 300 nm. As a result of their extremely fine microstructure, white etching bands are generally much harder and more brittle than the bulk material. The hardness of the white etching bands in steel is reported to increase with increasing carbon content [2].

The type of bands that will form in steel during high strain-rate deformation depends on its chemical composition, heat treatment condition and strain rates. While Rogers and Shasty [16] recorded white etching bands in quenched and tempered AISI 1018 steel, investigations by Meyers and Wittman [2] showed that deformed bands are formed in the same steel in normalized condition (pearlitic structure). Optical micrograph of a quench hardened and tempered (at 638°C for 1 h) HY-100 steel after deformation at about 10^3 s^-1 showed formation of deformed bands during adiabatic shearing and TEM investigations on this steel revealed highly elongated martensite laths that extended in shear directions and fine equiaxed cells with high dislocation densities [16]. It was suggested by the investigators that the equiaxed cells formed by partitioning of elongated subgrains into rectangular cells followed by a subsequent breakdown of the elongated subgrains consisting mainly of carbides.

A high strain-rate deformation study on a pearlitic 4340 steel at 1.8 x 10^3 s^-1 using a dynamic punch test by Zurek [7] showed formation of white etching band consisting of fine ferrite grains and elongated as well as spheroidized cementite. It was suggested that spheroidization of cementite occurred due to both the fragmentation of cementite plates and to short circuiting carbon and iron and carbon diffusion paths associated with the creation of the very fine ferrite grains. Fragmentation and spheroidization of cementite during adiabatic shear bands has also been reported by Chen et al. [18] during adiabatic shearing in pearlitic SS400 steels. The present study is focused on how certain microstructural variables and strain rates influence the type and morphology of adiabatic shear bands formed in AISI 4340 steels during ballistic impact.

2. Experimental procedure

Cylindrical steel rods, 9.55 mm diameter and 10.55 mm long, machined from AISI 4340 steel were austenitized at 843°C for 30 min and oil-quenched. The as-quenched steel samples were tempered at 315 or 425°C for one hour. High strain-rate deformation tests on these samples were conducted using a modified Split Hopkinson Pressure Bar (SHPB), which has been discussed elsewhere [4]. The samples were impacted by high velocity projectile constructed from AISI 4340 steel having a hardness value of 47 HRC. The projectile has a diameter of 38 mm and is 127 mm long.

The firing pressure was varied so that the projectile could strike the samples at impact speed which varies between 20 and 30 m/s. On striking the specimen, elastic waves are generated, which travel through the specimen to an output bar, from which it is collected by a strain gauge. A strain pulse amplifier connected to the strain gauge amplifies the strain signal. An oscilloscope connected to the strain signal captures the amplified strain signal in form of voltage–time data which are converted to strain–stress data. The impacted samples were cut, grinded, polished, etched and subjected to microscopic evaluation of adiabatic shear bands formation for various heat treatment conditions and strain rates.

3. Results and discussion

3.1. Analysis of stress–strain curves

A typical stress–strain curve for the samples during impact loading is presented in Fig. 1. Both the strain (ε) and strain rate (ε) increase with deformation time. The strain rate increases almost linearly as strain increases from the inception to the end of deformation. The curves show a clear yield
Strain rate as a function of impact velocity for samples tempered at 315°C.

Point, which signals the onset of plastic deformation. Strain hardening effect of the plastic deformation dominates the deformation process until a maximum flow stress ($\sigma_{\text{max}}$) is reached. The true strain corresponding to the maximum flow stress varies depending on the strain rates. Beyond the maximum flow stress, thermal softening begins to play a major role in the deformation process. Consequently, the flow stress decreases progressively with further increase in strain. As strain increases, a critical strain ($\varepsilon_{\text{crit.}}$) is reached where a sharp drop in stress is noticeable, indicating stress collapse resulting in mechanical instability and strain localization.

The strain rate depends on the velocity at which the projectile strikes the test specimen. The firing pressure was adjusted to produce different projectile velocities. The higher the impact velocity, the greater is the amount of deformation at any given time ($\varepsilon_t$) and the greater is also the rate of deformation (Fig. 2). The effects of impact velocity on the flow stress of samples tempered at 315°C as a function of time, strain and strain rate are presented in Figs. 3 and 4, respectively. The average strain rate of the samples that were deformed by projectile striking at impact velocities of 20.5, 22.49, 30.15 and 30.29 m/s were calculated to be 998, 1092, 1380 and 1420 s$^{-1}$, respectively. Depending on the impact velocity, the average strain rates varied between 800 and 1100 s$^{-1}$ at the inception of deformation and between 1240 and 1850 s$^{-1}$ just before the completion of the deformation process. The higher the impact velocity (strain rate), the greater is the yield or maximum attainable flow stress.

The effect of strain rates on the adiabatic shearing in specimens tempered at 315°C shows that the higher the strain rate, the shorter is the time for the commencement of stress collapse and strain localization. Depending on the impact velocity, the critical strain for adiabatic shearing lies between 0.38 and 0.45. The stress–strain and stress–time curves for samples tempered at 425°C are presented in Figs. 5 and 6. For about the same impact momentum of the projectile, the total strains for these samples are generally lower than those for the samples that were tempered at 315°C. The average
critical strain and time for strain localization was found to be about 0.16 and 242 µs, respectively, which are also lower than for samples tempered at 315 °C. These results suggest that the time and critical strain for commencement of strain localization do not only depend on the strain rates, they are also influenced by the microstructure of the steel.

The results of experimental investigation of the formation process of adiabatic shear bands in a structural steel by Marchand and Duffy [19] suggested that shear bands are most likely initiated at a point in the test section and then propagate rapidly as deformation progresses. The propagation speed of about 510 m/s was recorded in the material tested. Schoenfeld and Wright [9] deduced that stress collapse and strain localization occur at the most prominent defect or non-uniformity in a material during rapid deformation. The results of mathematically modeling of adiabatic shearing by Wright and Walter [20] suggested that the time of stress collapse depended on the size of an initial perturbation. Numerical modeling by Li et al. [21] identified uneven stress condition in a specimen under impact as one of the perturbations that can influence shear localization in tungsten alloys. Feng and Bassim [22] reported that adiabatic shear bands cannot be initiated without material or geometrical defects. Nesterenko et al. [23] outlined grain-size inhomogeneity, geometrical softening, Peirce–Asaro–Needleman textural localization and dislocation pile-up release as possible shear band initiation mechanisms in single-phase homogeneous materials. Results of experimental studies by Duffy and Chi [24] indicated that critical strain, at which stress collapse occurs, depends on the size of initial geometrical defects.

Results of our investigation show that stress collapse time and the critical strain required for stress collapse leading to mechanical instability, loss of load carrying capacity and ultimately to strain localization are significantly influenced by strain rates and microstructure. Schoenfeld and Wright [9] gave inhomogeneous distribution of temperature as one of the perturbations that influence stress collapse time. The observed decrease in critical strain for shear localization in the present study as strain rate increases agrees with Ramesh’s [25] observation that shear localization in tungsten heavy alloys is highly dependent on strain rate. The higher strain rate probably increased the perturbation, in the test specimen, which subsequently enhanced the chance of a speedy onset of stress collapse as soon as the adiabatic heating began. Culver [26] showed that the critical strain (ε_{crit}) for the onset of strain localization is influenced by a number of variables as shown in the following model:

$$\epsilon_{\text{crit}} = \frac{n \rho C}{\beta \left(\frac{\partial \sigma}{\partial T}\right)_{\text{ad}}}$$

where $n$ is the strain hardening exponent, $\rho$ the density of the material, $C$ the specific heat capacity, $\beta$ the fraction of deformation energy that is converted to heat, $\partial \sigma / \partial T$ the slope of temperature dependence of flow stress taken at constant strain and strain rate. This model implies that the (ε_{crit}) will be dependent on strain rate ($\dot{\varepsilon}$) for a material in which $n$, $\rho$, $C$ are constant.

The lower stress collapse time and minimum strain needed for adiabatic shearing recorded for steels tempered at 425 °C in comparison to those tempered at 315 °C can be traced back to the microstructural transformation that takes place during tempering of alloy steel at the tempering temperature of 425 °C. Cho et al. [17] suggested that the thermodynamic stability of microstructure may have an influence on the readiness of a material to experience stress collapse and strain localization. Consequently raising the tempering temperature ought to translate to shear localization at higher strains. However, at tempering temperature of 425 °C, tempered embrittlement resulting in segregation of impurities along grain boundaries will occur. The presence of these segregations in the microstructure will increase the microstructural defects and perturbations which promote initiation and propagation of adiabatic shear bands. Increased perturbations in the samples tempered at 425 °C can thus account for the low stress collapse time and critical strain value for shear localization.

3.2. Microscopic analysis

Examination of polished surface of transverse section of the steel specimens after impact shows that the circular cross section of the cylindrical test pieces assumes elliptical shape during impact as a result of adiabatic shearing during deformation. Fig. 7a shows typical macrostructure, as seen under a stereo-microscope, of the transverse section of the impacted samples. On the transverse section, the ASB formed a circular path. A smooth circular path of the ASB was observed in samples tempered at 315 °C while the circular paths of the ASB in the transverse section of samples tempered at 425 °C were characterized with bends and contours as will be shown in subsequent discussions of experimental results. On examining the longitudinal section (cut in direction parallel to the direction of impact loading), it is evident that two symmetrical cones extending outward from the centre of the specimen were formed by the ASBs as shown in Fig. 7b.

Fig. 8 shows typical optical microstructures of the samples tempered at 315 °C after high strain rate deformation. The microstructures reveal clearly formed white etching bands after etching with 2% nital solution. The width of the shear band varies along the path of propagation between 50 and
Fig. 8. Optical micrograph showing single white etching bands formed in the transverse section of the steel samples tempered at 315 °C.

Fig. 9. (a) Rapidly propagating crack inside the ASB. (b) Photograph of a sample which broke into two identical fragments during impact.

100 μm. Adjacent to the white etching bands are highly deformed regions in which the martensite plates are aligned in shear directions. No microstructural details of the white etching band could be observed under the optical microscope. The deformed band becomes less pronounced with distance from the shear band into the bulk material. In all the specimens examined, single shear bands were observed to initiate and propagate across the transverse section of these test specimens.

Adiabatic shearing is a damaging mechanism which impairs the load carrying capability of a material. Rapidly propagating microcracks were found to transform into full blown cracks propagating along the shear bands as shown in Fig. 9a. Some of such cracks penetrated into the bulk material at some points, where the shear band rapidly change direction, leading to fragmentation of some of the samples as shown in Fig. 9b. Examination of the fracture surface shows that samples failed by shear along ASBs and the two cones formed by the shear bands in the test specimen are clearly noticeable on the fracture surface of the fragmented samples. A schematic representation of crack propagation path leading to fragmentation of samples into two parts is shown in Fig. 10.

Fig. 10. Schematic representation of fracture path in failed samples during impact.

Results of optical microscopic investigation of the samples which were tempered at 425 °C and subjected to high strain rate deformation are presented in Fig. 11. The shear bands formed are predominantly white ASBs. As observed in those samples that were tempered at 315 °C, they propagate along circular path across the transverse section of the specimen. While ASBs form smooth circular paths in transverse sections of samples tempered at 315 °C, ASBs bend continuously as they propagate in samples that were tempered at 425 °C. Thus ASBs across transverse sections do not form smooth circular path. Some of the shear bands were found to crack significantly during adiabatic shearing while some samples also failed in a manner similar to that described for samples tempered at 315 °C. Whereas single shear bands were found propagating in a transverse sections of steel tempered at 315 °C, double or triple shear bands were observed in those steel samples that were tempered at 425 °C.

Where multiple shear bands were formed, the one that is farthest away from the edge of the cylindrical test specimen are white etching ASBs while the other bands close to the edge of the specimen are more of deformed bands having grey color like the bulk material. Three dynamically propagating adiabatic shear bands can be observed in sample shown in Fig. 11c. One of the secondary deformed bands propagating simultaneously along with the white etching band is shown in Fig. 11d. The martensite laths that are characteristic of the bulk materials cannot easily been seen in the deformed band under optical microscopy. The martensite plates in the bulk material have become dissolved into smaller and aligned platelets during deformation that they could not easily be resolved by optical microscopy.

There has been some controversy in the generally acceptable explanation for the white color of the adiabatic shear bands that form in steels during high strain deformation. It has been suggested that the white shear band is a product of austenite to untempered martensite during adiabatic shearing [27,28]. In this case, the heat generated during adiabatic heating is considered to be high enough to convert the structure

Fig. 11. Optical microstructure of transverse sections, after high strain rate deformation, of steel samples tempered at 425 °C. (a) White etching ASB in the steel. (b) Crack initiation and propagation in the ASB. (c) Three dynamically propagating ASBs. (d) Secondary deformed band.
of the steel to martensite which is subsequently quenched by the surrounding matrix. The suggestion of reverse martensitic transformation has also been made to be the actual transformation taking place during adiabatic shearing leading to formation of white ASBs in steels [29]. Considering the very short time involved in adiabatic shearing, it is most unlikely that both austenite formation and subsequent transformation to untempered martensite could have occurred. It is generally believed that carbides and martensites plates are broken down and dissolved during adiabatic shearing resulting in very fine carbides and martensites which are too fine to be resolved using optical microscopy.

Several TEM studies on white ASB in steel has shown the shear bands to consist of very fine cells less than 100 nm in size [29,30]. Witrman et al. [31] reported that the white etching ASBs in an explosively deformed AISI 4340 steel consist of very fine Fe5 C2 carbides and very fine martensite laths and suggested that white etching forms because the dissolution of carbides changes the etching characteristics of the structure. The carbides were 5–150 nm in thickness and formed as films on the internal twin boundaries. In the transition region between the white ASBs and the matrix, cementite carbides with diameter varying between 5 and 200 nm were observed. The very fine microstructure observed in between the matrix and the white etching bands in the present study may therefore consist of these very fine cementites and fine highly deformed martensites lath that are aligned in the shear flow directions. Investigations by Meyers show that shear bands in stainless steels consist of two regions: one region comprises of extremely fine grains 0.1–0.2 μm, well defined grain boundaries as well as a low density dislocations and another region having a glassy region that was formed by a solid-state amorphitization process.

The multiple ASBs observed in steel samples that were tempered at 425 °C can be explained by perturbation theory which has been used earlier to explain the low critical strain required for adiabatic shearing and the short stress collapse time. The presence of segregations, which form in the microstructure at the tempering temperature offer many initiation sites for adiabatic shear bands and enhance multiple adiabatic shear banding in these steel samples. The variation in the nature of the shear bands from the characteristic white shear bands to grey color similar to that of the matrix can be traced back to the intensity of the fragmentation and dissolution of carbides and martensite laths during adiabatic shearing. It is suggested that the adiabatic heating and strain rate in the band displaying white color is so intense as to completely dissolve the carbides into extremely fine cells that are optically not resolvable. On the other hand, the strain rate in the shear band displaying the characteristic grey color of the bulk material is sufficient to highly deformed martensite laths and aligns them in shear direction. The deformed martensites plates have sufficiently reduced in size and aligned so well that they can easily been distinguished form the characteristic martensite laths in the bulk material as can be seen in Fig. 11d.

4. Conclusion

The response of AISI 4340 steel to rapid deformation at high strain rates has been investigated. Deformation is governed by two simultaneously occurring processes of strain hardening and thermal softening due to conversion of the large fraction of deformation energy into heat. At the onset of plastic deformation, strain hardening dominates the deformation process, during which deformation will be homogeneous. The flow stress depends on the impact velocity which determines the strain rates. As deformation proceeds, adiabatic heating occurs along narrow bands and thermal softening begins to dominate the deformation process. Flow stress subsequently decreases with increasing strain. A critical strain is eventually reached, whereby mechanical instability occasioned by stress collapse occurs resulting in strain localization along narrow bands. The time as well as the critical strain for the onset of stress collapse decrease with increasing strain rate. The time and critical strain for the commencement of adiabatic shearing is lower in steel samples tempered at 425 °C than for those tempered at 315 °C, an effect which can be attributed to increased perturbation caused by segregation in the microstructure of the steel samples that were tempered at 425 °C. Multiple shear bands were found to simultaneously initiate and propagate in the samples tempered at 425 °C. One of such multiple bands appears as distinct white etching ASB while the rest are essentially deformed bands which have features similar to the bulk material but with fine carbides and highly deformed and aligned martensite laths. It can be concluded that the type of shear bands formed during adiabatic shearing is a direct consequence the intensity of accompanying fragmentation and dissolution, which eventually determine the size of the micro-constituents of adiabatic shear band and resolvability using optical microscopy.

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