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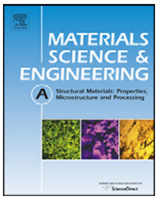

Dynamic deformation response of a high-strength, high-toughness Fe–10Ni–0.1C steel

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ABSTRACT

The results of an investigation of microstructural evolution during quasi-static and dynamic deformation of a Fe–10Ni–0.1C steel containing small amounts of V and Mo are reported. In the as-received condition, the steel has a lath martensite microstructure with a mean lath size of ~150 nm, and MC carbides dispersed in it with a mean size of ~20 nm. During dynamic deformation (strain rates of $1 \times 10^3\ s^{-1}$ to $4 \times 10^3\ s^{-1}$), depending on strain and strain rate, shear localization occurs and is accompanied by an optically visible shear band (~20 μm wide). In the situation where the localization process is in its early stages (lower rates, lower global height strains, or both), the microstructure shows severe local deformation within the band but the initial microstructure is still discernible. With progression in severity of localization, there is clear and reproducible evidence for a central region (~6–8 μm wide) within the shear band composed of ~300 nm size equiaxed grains. Electron microscopy characterization of these grains confirms the presence of both, austenite, with a low dislocation content, and heavily dislocated and/or twinned ferrite. Composition measurements from the individual grains confirm partitionless transformation. When the test conditions are further intensified, a crack "chases" the shear band, with the crack running either partway or all the way through the band and therefore through the sample. Examination of the resulting fracture surfaces provides evidence for the presence of a thin liquid film layer (perhaps 10–20 nm or less) at various locations within the shear band that presumably has no shear resistance. Together, these observations provide a microstructural footprint for how deformation progressed during shear localization, a sense for the accompanying thermal profile within the shear band, and evidence for the intensity of localization in this alloy in the condition it was examined.

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1. Introduction

When metals and alloys are deformed at high strain rates, a phenomenon that is frequently observed is the formation of narrow zones of highly localized deformation known as shear bands. Such localization implies a loss in the load-carrying capacity of the highly deformed material within the shear band [1–3]. Localized temperature increase due to prevailing adiabatic conditions in dynamic deformation leads to thermal softening that counteracts work hardening to the point where the instability sets in. Adiabiatic shear bands (ASB) have been observed in machining, ballistic impact, high-velocity forming, etc. and in a variety of materials including alloys of Cu, Al, Ti and steels. These localized shear bands occur more readily in materials with a low work hardening rate, low strain-rate sensitivity, low thermal conductivity and a high thermal softening rate. Traditionally, shear bands have been classified into two types, deformed bands and transformed bands, the latter suggestive of a transformation having occurred within the band during (or after) its formation [2,3]; Nakkalil [4] however, points out that deformed and transformed bands are only an outcome of the extent of adiabatic strain localization occurring during deformation and are not to be viewed as two separate phenomena.

In relation to microstructure evolution within the shear band, Marchand and Duffy [5] proposed a three-stage process for strain localization during dynamic deformation in a HY-100 steel. The first stage was one of homogeneous plastic strain distribution followed by a second stage where strain distribution was inhomogeneous. In the second stage, as deformation evolved, a continuous increase in the magnitude of localized strain and a decrease in the width of the region over which localization occurred, were noted. A sudden and rapid drop in flow stress signaled the onset of acute localization (the third stage), possibly triggered at a single nucleation event. In HY 100, this third stage appeared to set in at a nominal strain around 38%, with local strains within the shear band being as high as 1900%; the shear band width was documented as 20 μm. Lastly, they noted that the shear band width becomes narrower as the magnitude of the localized strain increased. The shear band velocity

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was calculated to be around 500 m/s and shear strain rate within the band was $4 \times 10^5\,\mathrm{s}^{-1}$, the latter in good agreement with the results of Giovanola [6] for a 4340 steel and of Clos et al. [7] for low carbon steels.

In a range of materials, the observation in post-deformed specimens of fine equiaxed grains has been attributed to continuous dynamic recrystallization and the underlying mechanism has been a topic of discussion for several years. Reviews on the subject and other recent research articles [8–18] extensively discuss the origin and possible underlying mechanisms.

In steels, transformed bands may be as narrow as 5–10 μm and often appear white after etching with Nital (nitric acid–methanol) solution. In many high-strength steels, the possibility of phase transformations (austenite formation in the band followed by its conversion to martensite during subsequent rapid cooling [7,19–21] and in other instances, even formation and retention of δ ferrite [22]) occurring within the shear band as a consequence of adiabatic heating in combination with high strains has been proposed, based on inferences from post-mortem microstructural observations of shear bands. Others [23,24] have claimed that they have not seen evidence for such phase transformations. Furthermore, some investigations report the absence of carbides within the band, apparently fully dissolved [7,25], while others [23,24] have observed them within the shear band. Prior to dissolution, Clos et al. [7] show that the carbides are drawn out into “thin strings” from the roughly globular morphology in the undeformed state.

Temperature rise within the shear bands have been previously measured using infrared detectors and have been reported to be as high as 1000 °C depending on the material under investigation [1,6,23]. More recently, Guduru et al. [26] used a newly-developed infrared high speed camera to demonstrate the presence of highly non-uniform temperature distribution along the length of the shear bands with “hot-spots” being present and have questioned the validity of theoretical models that had assume laminar flow [27,28]. However, it is worth noting that the spatial resolution of these infrared detectors are not very high compared to the dimensions of the shear band in many high strength steels which is of the order of 10–20 μm (e.g. see data and comments in Ref. [29]) and thus it is likely that these estimates of temperatures do not reflect the highest temperatures experienced within the band, particularly considering the presence of “hot spots” within the shear band as observed by Guduru et al. [26]. Calculations [13,30] using the Zerrilli–Armstrong model or other models like the mechanical threshold stress model have provided maximum temperatures ranging from 650 °C to over 1400 °C, depending on the material and test conditions.

The subject of crack nucleation within the ASB, propagation, and final fracture during dynamic deformation has also received attention. The fact that a crack propagates within the ASB often implies the presence of a tensile stress state perpendicular to the band, a situation that may arise from wave propagation and reflection during dynamic loading as well as due to thermal effects (dilatational gradients) [4]. Lee et al. [31] characterized the microstructure within shear bands in a ballistically impacted HY100 steel and reported the presence of many cracks within the ASBs and suggested that MnS inclusions were possible initiation sites for these cracks. They also claimed melting and infiltration of the molten metal into these cracks. Clos et al. [7] measured the void density within the shear band (formed during dynamic deformation of two different steels) in the localization and post-localization phases and concluded that voids formed at the carbide–matrix interfaces within the shear band during the localization stage but eventually collapsed completely during the post localization phase, much like void closure during hot isostatic pressing. Timothy and Hutchings [32] have studied initiation and growth of cracks within shear bands in titanium alloys and describe the process in terms of void nucleation, coalescence and growth, the surface morphology being dependent on the density of void nucleation sites and the tensile stress state across the shear band. Teng et al. [33] have performed detailed numerical studies of ASB formation and crack nucleation and growth within the ASB. A key finding from their calculations was that the local hot spots developed in the shear band, experimentally documented in [26], act as crack nucleation sites and the macroscopic crack evolved by the linking of these microcracks rather than by the propagation of a single crack.

In earlier work, Bryant et al. [34] observed melting in microligaments prior to final separation in two Ti alloys loaded under dynamic conditions; further, they performed numerical calculations that showed that the melting point in these alloys could be exceeded under adiabatic conditions, primarily based on high yield stress, low thermal conductivity and a high stress concentration factor in the ligaments. Recently, Murr and Pizaña [35] noted that melting is simply an extreme mechanism/outcome of deformation at high strain rates and provide several examples of melting, particularly in association with dynamic recrystallization. They show micrographs of microdendrites formed in situations where tungsten rod penetrators impacted rolled homogeneous armor steel.

Walley [36] has provided a recent exhaustive review on the various aspects of shear localization in metals and alloys. It is evident from the discussion above and also from [37] that while the understanding of the scientific aspects of shear localization has advanced significantly in recent years, there is still confusion, debate and discussion on the subject of shear banding and cracking within shear bands in high strength steels, as well as in the understanding of the underlying mechanisms that explain microstructure evolution within the shear bands.

In this paper, we present our results of detailed characterization of the initial and deformed structures using transmission electron microscopy techniques. Specimens were deformed both quasi-statically and dynamically over a range of strains and strain rates. To overcome the problem of magnetic interference in the electron microscope, specimens were excised from the ASB using focused ion beam techniques while carbides were analyzed using several extraction replicas. A low-carbon, 10Ni steel with excellent static yield strength and high Charpy impact toughness was selected as a candidate for dynamic deformation studies. Despite the excellent static properties that are often utilized as characteristics for alloy selection, the propensity for deformation localization during dynamic deformation was found to be acute in this steel.

2. Experimental procedure

A block of low-carbon steel with nominal composition shown 0.09%C–10.0%Ni–1.2%Mo–0.6%Mn–0.5%Cr–0.1%V (wt.%) was obtained in the fully-heat treated condition. Static properties in this condition include a tensile yield stress of 1.18 GPa, tensile strength of 1.24 GPa, elongation of 23%, maximum reduction in cross sectional area of ∼70% and a Charpy impact toughness of ∼200 J at −70 °C.

In order to study the microstructure evolution during deformation, cuboidal specimens with the dimension of 4.2 mm × 4.2 mm × 6.3 mm were subjected to quasi-static compression tests at room temperature in an Instron testing machine to different compression height strains (15%, 30% and 50%) over a range of quasi-static and intermediate strain rates ($10^{-4}\,\mathrm{s}^{-1}$, $10^{-2}\,\mathrm{s}^{-1}$ and $1\,\mathrm{s}^{-1}$).

Dynamic compression tests using the split-Hopkinson bar setup were performed on specimens 4.2 mm × 4.2 mm × 4.2 mm in dimension using a various combinations of projectile length and gas gun pressure to obtain a range of strain rates ($1 \times 10^3\,\mathrm{s}^{-1}$ to $4.5 \times 10^3\,\mathrm{s}^{-1}$) and height strains. Nano-indentation measurements were made using a Hysitron Tribo Indenter to assess hardness vari-

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