Materials Science & Engineering A 605 (2014) 270–285

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

A systematic study of grain refinement during impact of 4340 steel

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ARTICLE INFO

Article history:
Received 19 January 2014
Received in revised form
13 March 2014
Accepted 19 March 2014
Available online 27 March 2014

Keywords:
High strain rate
Adiabatic shear bands
Dislocations
Transmission electron microscopy
Focused ion beam

ABSTRACT

Inhomogeneous plastic deformation at high strain rates and large strains results in the concentration of deformation and strain localization in adiabatic shear bands (ASBs). In the current study, AISI 4340 steel specimens were impacted at increasing strain rates/strains (impact momentums) to capture the formation of adiabatic shear bands. Advanced specimen preparation techniques using Focused Ion Beam (FIB) and extensive electron microscopy were used to identify the sequence of evolution of the shear bands. It was observed that the structure of the shear bands that evolve after strain localization starts out with elongation of the grains due to grain reorientation in the shear direction with the initiation of random and transverse dislocation boundaries along the elongated grains. For higher strain rates/strains during impact, the elongated grains break along the initiated dislocation boundaries resulting in the creation of smaller elongated broken grains and nanograins. Boundary refinement of the broken grains occurring through grain rotation and adiabatic heating results in the evolution of refined grains, subgrains and nanograins. The presence of elongated grains, broken grains, refined grains, subgrains and nanograins within the shear band structures demonstrates that the local deformation is inhomogeneous and that these mechanisms occur concurrently. It is concluded that the evolution of the shear band structure can be considered as a simultaneous layering of microstructures initially driven by dislocations which produce the final structures observed in the shear bands.

1. Introduction

When a solid material is deformed, the strain may become large in narrow zones of the material forming shear bands. Strain localization has been identified as a major failure mechanism in materials under high strain rates and large strains such as in ballistic impact, explosive fragmentation, contact loadings, high-speed shaping and forming, dynamic compaction and welding [1–13]. It is an important mode of damage since it may lead to catastrophic failure instantaneously [6,8]. On the other hand, the potential of severe plastic deformation (SPD) processes such as equal channel angular extrusion (ECAE) and high pressure torsion (HPT) is being used for production of bulk nanostructured materials with special physical and mechanical properties [12,14]. The nanostructured materials produced by SPD processes have similar properties and appearance to those reported for adiabatic shear bands and therefore it is important to understand in detail the entire process of formation of adiabatic shear bands from localization to failure [12,14].

Although there have been numerous experimental and theoretical investigations on adiabatic shear bands, the mechanisms of their nucleation and propagation remain less understood [5,7,10,12,15–17]. This is due in part to the complexity of the problem of formation of these bands, their very narrow nature in the microstructure (~1–350 μm), and the fact that they occur so rapidly that it is almost impossible to observe the actual changes in properties in real time due to the short duration between deformation and failure. These factors have limited the information that can be obtained in order to improve our understanding of the mechanism of formation of adiabatic shear bands and have resulted in scientific questions that have not been satisfactorily answered [6,12,17,18]. To better understand the mechanism of evolution of adiabatic shear bands, post-deformation microstructure characterization and the systematic measurement and observations of the microstructures need to be undertaken [6,17].

The aim of the current study is to systematically impact 4340 steel specimens at successive strain rates/strains (impact momentum) to capture the formation of adiabatic shear bands followed by specimen preparation techniques through the use of a Focused Ion Beam (FIB) and electron microscopy to identify the sequence of events that leads to the evolution of the shear bands.

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http://dx.doi.org/10.1016/j.msea.2014.03.066
0921-5093/

2. Material and experimental procedure

In the current study, cylindrical specimens were cut from a rolled AISI 4340 steel bar (chemical composition in wt%: 0.37–0.44 C, 0.10–0.35 Si, 0.55–0.90 Mn, 1.55–2 Ni, 0.65–0.95 Cr, 0.20–0.35 Mo, 0–0.04 P, 0–0.4 S, Fe—balance), and machined to a diameter of 9.5 mm and a height of 10.5 mm as shown in the schematic in Fig. 1(a). All the machined specimens were austenitized at 850 °C for 1 h and rapidly quenched in oil. The quenched specimens were then tempered at 620 °C for 2 h followed by air cooling. The heat treatment was carried out at the same conditions for all the specimens to have approximately a uniform starting structure prior to impact. Earlier work determined the optimum conditions for producing adiabatic shear bands in 4340 steel using the direct impact Hopkinson Pressure Bar [16,19–21]. The same approach was used to induce adiabatic shear bands in the steel specimens. The tempered specimens were impacted between 140 kPa and 260 kPa corresponding to impact momentums between 39 kg m/s and 50 kg m/s using the Direct Impact Hopkinson Pressure Bar (DIHPB). During the impact, an AISI 4340 steel projectile (18.67 N, 38 mm diameter by 127 mm length) with a hardness of 47HRC is fired by a gas gun, and strikes the specimen attached to a transmitter bar at a high impact velocity. The generated elastic wave is transmitted through the specimen to the transmitter bar. A strain gauge attached to the transmitter bar together with a differential amplifier and a digital oscilloscope is used to monitor the strain history during the impact test. The strain wave data stored in the form of voltage and time is used to study the impact resistance of the specimens [16,19–21]. The impacted specimens were cut, mounted, ground, polished, and etched using a 2% Nital solution as shown in Fig. 1(b). A ZIESS Axiovert 25 inverted-reflected light microscope, equipped with CLEMEX Vision 3.0 Image Analyzer was used to document the occurrence of adiabatic shear bands in the impacted specimens as shown in Fig. 1(c). Microhardness measurements were performed with a Buehler micro-hardness machine by applying a 300g-force (2.942 N) for 15 s on regions within the shear bands and in regions away from the shear bands. A total of 20 hardness values (VHN) were recorded for each region and their average values calculated.

Study of the initial morphology and constituents of the tempered steel specimens prior to impact was carried out as a baseline for comparison to the final microstructure after impact. Detailed analysis was conducted on the steel specimens using a JEOL 5900 Scanning Electron Microscope (SEM), a JEOL 2100F TEM/STEM and a JEOL 2010F TEM. The small width of the shear bands renders conventional preparation of thin foil cross sections for Transmission Electron Microscopy (TEM) difficult because the perforation produced using techniques such as double-jet polishing and ion milling generally do not coincide with the shear band area. To better select the shear band regions for preparing thin foils for

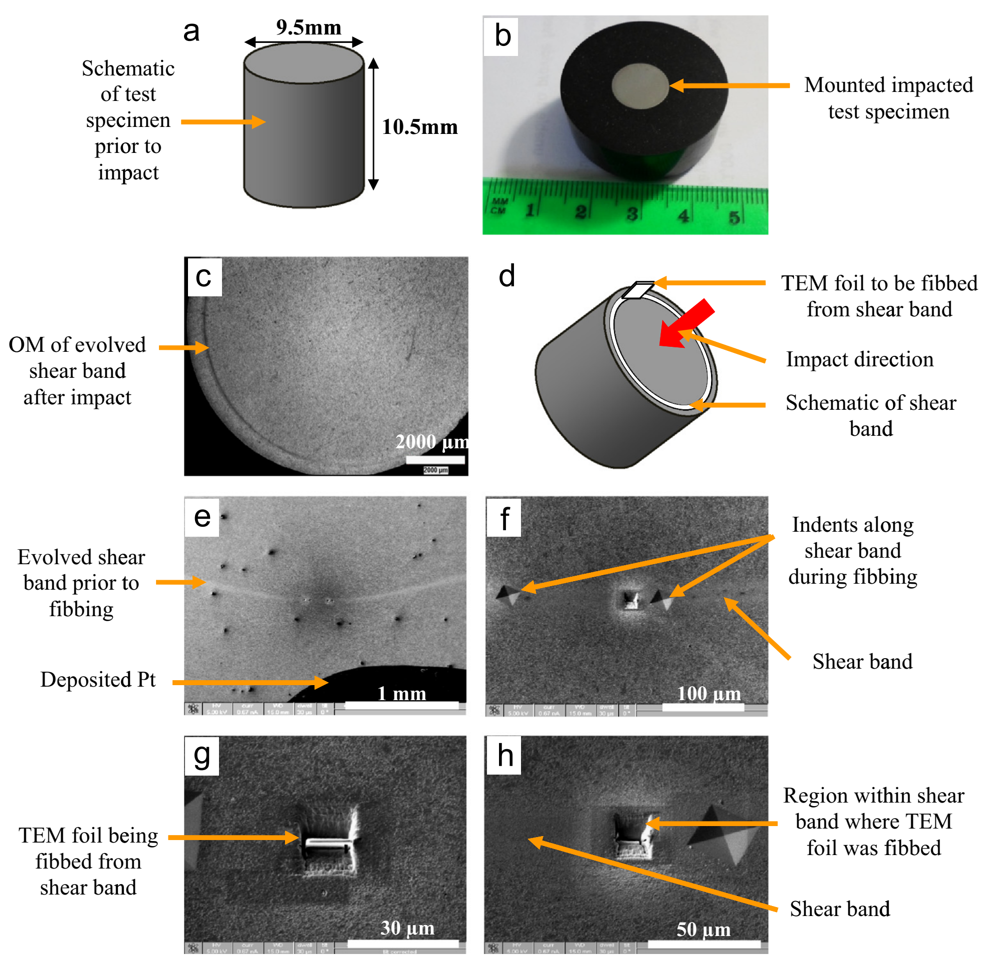

Fig. 1. (a) Schematic of test specimen prior to impact, (b) mounted specimen after impact, (c) optical micrograph of evolved shear band after impact, and (d) schematic of impacted specimen showing the impact direction, evolved shear band and direction of TEM foil to be fibbed. Secondary Electron Images (SE-SEM/FIB) of (e) evolved shear band prior to fibbing, (f) indents along shear band during fibbing, (g) TEM foil during fibbing and (h) region where TEM foil was fibbed.