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Formation mechanisms of nanostructures in stainless steel during high-strain-rate severe plastic deformation

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Abstract

We have investigated the formation mechanisms of nanostructures within adiabatic shear bands formed in stainless steel samples deformed by high-strain-rate forced shear. Twinning is shown to play a critical role in the initiation of nanostructures. Secondary twins directly led to the formation of elongated subgrains. Microtwins inside shear bands promoted division and break-down of the subgrains, which further refined the microstructures.

Keywords: Nanostructure; Grain refinement; Adiabatic shear localization; Stainless steel

1. Introduction

Adiabatic shear localization can be considered as a unique consequence of severe plastic deformation (SPD) at high-strain-rates. The process is controlled by a thermally assisted mechanism. Once thermal and strain softening leads to rapid deformation localization, a band-like region (shear band) forms via a nearly adiabatic process. The total shear strain within shear bands may reach 5–20, which qualifies it as severe plastic deformation. Experiments show that significant grain refinement can occur within shear bands. Although the formation and microstructural characteristics of shear bands have been extensively reported in the literature [1–9], little systematic work has been conducted on the formation mechanisms of nanostructures within shear bands. These nanostructures are formed under very high-strain-rate, a condition very different from those in conventional severe plastic deformations [10].

Various fine substructures within shear bands with sizes ranging from a few nanometers to submicrons have been reported [11–14]. Several mechanisms have been proposed to explain the formation of these substructures. They include phase transformation [2], recrystallization [12], dynamic recovery [13] and mixed modes. There is no consensus concerning which mechanism is the controlling one. Large plastic deformation, high-strain-rate and high local temperature are expected to affect the structural evolution within a shear band. Yamaguchi et al. [10] reported that higher strain rate did not display a significant effect on the microstructure formed during equal channel angular pressing (ECAP). However, the strain rate in their work is much lower than that experienced inside a shear band. Murr et al. [15] discussed the grain refinement in shear bands as the result of the SPD process but did not clarify the formation mechanism of the substructures. To our knowledge, no systematic experimental study has been reported on the formation mechanisms of nanostructures in materials subjected to high-strain-rate severe plastic deformation.

This paper reports a detailed study on the nanostructures formed within shear bands in cold-rolled AISI 316L stainless steel deformed by a Hopkinson bar test at a shear strain rate of $10^5\ s^{-1}$. The formation mechanisms are discussed based on our experimental observations.

2. Experimental procedures

A cold-rolled AISI 316L stainless steel (SS 316L) plate was used in the current study to investigate nanoscale deformation within shear bands. The cold-rolled SS 316L plate was obtained from an annealed plate subjected to multiple passes of cold rolling to an accumulated strain of 32%. The composition of SS 316L is 0.019 C, 16.82 Cr, 1.72 Mn, 2.07 Mo, 10.04 Ni, 0.028 P, 0.01 S, 0.4 Si and 68.1 Fe, all in weight percentages. Forced shear

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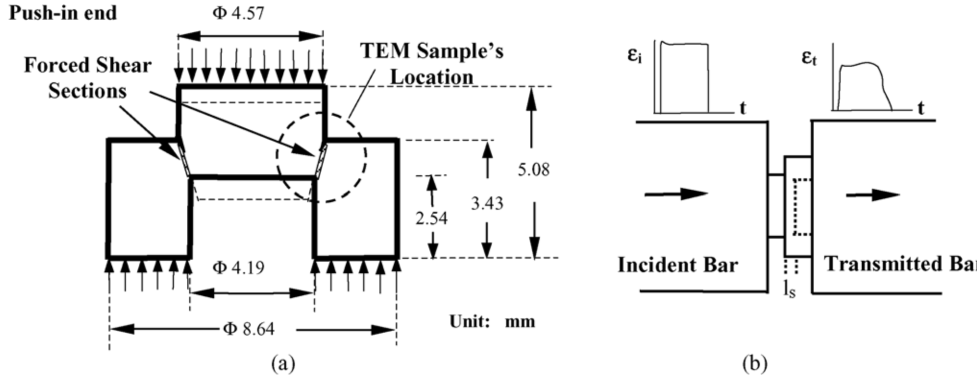

Fig. 1. (a) Configuration of the forced shear test with the hat shaped specimen and (b) the schematic loading condition by which the hat shaped specimen was sandwiched between the incident and transmission bars in a compressive Hopkinson bar system.

experiments were carried out on a compressive split Hopkinson pressure bar (SHPB) using hat-shaped specimens [16,17]. A well-controlled loading condition was used to interrupt the test at a predefined deformation stage, based on an accurate calculation of the deformation speed (relating to strain rate) and loading duration. Fig. 1 illustrates the hat shaped specimen, its dimensions and its loading configuration sandwiched between the incident and transmission bars on a Hopkinson bar system. Both shear and compressive stresses are simultaneously exerted on the shear section. The post-deformation microstructure was examined using optical and transmission electron microscopy (TEM). The TEM samples were thinned and polished to thin foils and were cut to 3-mm disks. The foil disks were dimpled on a Gatan dimpler to locate the perforation position on shear bands and then ion-milled using a Gatan Precision Ion Polishing system (PIPs). A Philip CM30 TEM and a JEOL 3000 F high-resolution TEM, both working at 300 kV, were used to examine the microstructures.

3. Results and discussions

The microstructure of the cold-rolled SS 316L prior to forced shear is shown in Fig. 2. The grains were seen to be elongated slightly along the rolling direction and have an average grain size of 36 μm. A high-density of deformation twins was observed in all grains. Extensively intersected twin boundaries constructed a network pattern in some of the heavily deformed grains. We call these twins the primary twins.

An adiabatic shear band (ASB) was observed in the sample sheared at high-strain-rate. Optical micrographs (not shown) revealed a well-developed adiabatic shear band with a typical width of 11 μm. The shear band exhibits sharp edges distinguishing it from the heavily deformed grains. The local shear strain and local strain rate inside the shear band was estimated to be 17.6 and $1.2 \times 10^6\,s^{-1}$, respectively, from the measurement of the locally deformed traces across the shear band and the signals recorded on SHPB.

The microstructure within a shear band is much finer than that outside the band. It is composed of elongated and/or equiaxed subgrains. Fig. 3 exhibits a region at the shear band boundary. The dashed line separates the shear band from the rest of the heavily deformed area. Inside the shear band, elongated subgrains are predominant while equiaxed subgrains dominate the region near the center of the shear band. The typical grain size varies from 20 to 100 nm. The equiaxed subgrains were generated by sub-dividing the elongated lath substructure.

The driving force for the subdivision of elongated subgrains was the conjugated shear stress in the transverse direction. The unique character for adiabatic shear localization can be attributed to the high-strain-rate ($10^6\,s^{-1}$) and the thermally assisted properties. The former has been reported to cause strain rate hardening for most materials and the latter may lead to a very high local temperature, which significantly softens the material locally. The substructure within shear bands depends on the peak temperature, the cooling rate and material phase relations (for example, time–temperature transformation diagrams). Some potential processes, such as phase transformation, recrystallization and recovery, may happen during or after the deformation. The local temperature increase in the present shear band was estimated to be more than 1000 K if a completely adiabatic assumption was used. However, it was found that the local temperature did not reach such a high level because TEM images did not indicate widespread recrystallization in the shear band.

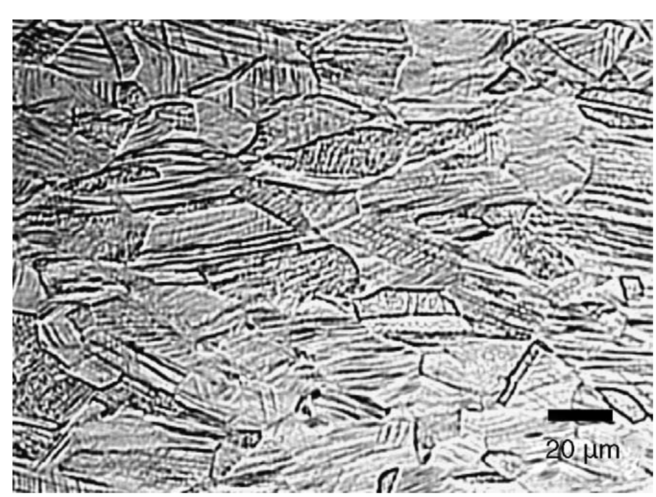

Fig. 2. Microstructure of the cold-rolled 316L stainless steel. Note that high-density of deformation twins exists in all grains and the rolling direction is horizontal.