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Microstructure evolution and nanograin formation during shear localization in cold-rolled titanium

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Abstract

The microstructure evolution within the shear localization areas formed in commercial titanium subjected to cold rolling is systematically investigated. Sheared micro-regions are first initiated followed by the formation of distinct microscopic shear bands, which gradually grow and coalesce to form a macroscopic shear band. The latter contains thin lath structures in the boundary regions, fine elongated subgrains in the outer areas and roughly equiaxed (sub)grains with a mean size of 70 nm in the centre region. The early stage of shear localization involves the formation of twin/matrix lamellae aligned along the shear direction. The lamellae subsequently undergo longitudinal splitting into thin laths, which are in turn subjected to transverse breakdown, giving rise to fine elongated subgrains. The continuing thermally assisted lath breakdown, in conjunction with lateral sliding and lattice rotations, ultimately leads to the formation of roughly equiaxed, nanosized (sub)grains in the macroscopic shear band centre at large strains.

Keywords: Shear band; Nanograin; Titanium; Cold rolling; Grain refinement

1. Introduction

Highly localized deformation in the form of shear bands is a deformation mode which develops in a majority of metallic materials subjected to both dynamic and quasi-static loading. The shear bands formed under the dynamic loading modes have been studied extensively, especially in the past two decades, as their formation generally leads to catastrophic failure under these conditions [1,2]. The residual microstructures within such shear bands have been the subject of a number of detailed investigations using transmission electron microscopy (TEM), facilitated by the band convenient location in a restricted area of the hat-shaped specimens used in dynamic impact experiments [3–16]. The above shear bands usually experience very high levels of strain and strain rate, and the shear localization is frequently considered to be adiabatic with large temperature rises inside the bands [17]. Therefore, these bands are frequently termed "adiabatic" shear bands. As a result of adiabatic heating, the deformation-induced microstructures within these bands often undergo subsequent modifications through the recovery, recrystallization and phase transformation processes [1,10]. The above processes generally contribute to significant microstructure refinement within the adiabatic shear bands through the formation of (sub)grains/fragments, frequently reaching the size of several tens of nanometres. Nevertheless, deformation mechanisms themselves have frequently been able to achieve significant refinement of the adiabatic shear band microstructure, in particular when these mechanisms involved mechanical twinning.

Numerous reports are available in the literature of the occurrence of shear banding in metals deformed by rolling and other quasi-static deformation modes [18–27]. These shear bands generally display microstructure characteristics which differ markedly from those observed within their

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adiabatic counterparts. For example, TEM observations of the shear bands in consolidated ultrafine-grained iron deformed in quasi-static compression by Wei et al. [27] revealed strong texturing as well as elongated and heavily dislocated grains within these bands, which is strikingly different from the microstructure features commonly found in the centre regions of adiabatic shear bands. Several detailed investigations, largely describing the evolution of relatively coarse and/or well-recovered microstructures within shear bands formed during rolling or plane strain compression have been performed using a combination of electron backscattering diffraction with scanning electron microscopy (SEM) and TEM techniques [18,28,29]. In contrast, such investigations on shear band microstructures produced by heavy rolling deformation at room temperature are relatively scarce at present and significantly less detailed. This is partly the reason why these microstructures are extremely fine and contain high dislocation densities, and their investigation is thus relatively difficult and requires the time-consuming TEM technique. Furthermore, systematic investigation of the microstructure evolution within shear bands is hampered by a relatively random distribution of these bands within the matrix, which also causes difficulty in preparation of targeted TEM specimens. The scale and character of the microstructures observed inside shear bands bear some similarity to those generally found in metals processed by severe plastic deformation (SPD) [1,30]. Thus, elucidating the microstructure refining mechanisms operating within the shear bands produced by heavy rolling deformation will, in turn, contribute to a better understanding of the grain refinement mechanisms which occur in other SPD processes.

It is well known that, apart from dislocation slip processes, mechanical twinning plays an important role in plastic deformation of metals with a hexagonal close packed (hcp) structure which has a limited number of slip systems. The predominant twinning systems activated during deformation of hcp titanium at ambient temperature are $\{10\bar{1}2\}\langle 10\bar{1}\bar{1}\rangle$ tensile twins and $\{11\bar{2}2\}\langle 11\bar{2}\bar{3}\rangle$ compression twins, accommodating extension and contraction, respectively, along the *c*-axis [31,32]. The tensile twins appear to be more prominent, as their formation seems to be less sensitive to grain orientation [31]. The activation of deformation twinning results in progressive grain refinement owing to the intersection of twins and the formation of secondary and tertiary twins. This in turn causes a gradual decrease in twin activity, and ultimately leads to saturation in twinning achieved at relatively modest strains, which causes dislocation slip to dominate the deformation process at high strains [32–35]. There is some recent experimental evidence indicating that extremely fine, roughly equiaxed grains with a mean size of 80–100 nm can be obtained in commercial-purity titanium subjected to accumulated roll bonding [36]. It has been suggested that these grains might possibly originate from macro-shear and micro-shear bands, but details of their formation mechanism still remain to be elucidated.

The aim of the present work was to perform a detailed TEM investigation of the microstructure evolution within the areas of localized shear in commercial-purity titanium subjected to heavy cold rolling and to elucidate the microstructure refining mechanisms within the shear bands.

2. Experimental procedures

A commercial titanium plate with a fully recrystallized microstructure and a mean grain size of ~60 μm was used. It was cold rolled at a strain rate of 3 s^{-1} from 12 to 2 mm in thickness with a reduction of 16.7% per pass. The von Mises equivalent strains corresponding to different rolling reductions were calculated as $\varepsilon_{VM} = \frac{2}{\sqrt{3}} \ln(\frac{t}{t_0})$, where t_0 and t are the plate thickness before and after rolling, respectively. The shear strain levels accumulated within the shear bands were estimated using the method described by Xue and Gray III [9]. The microstructure of the deformed samples, both outside and within the shear localization areas, was investigated by SEM and TEM. The SEM study was carried out using a Zeiss Supra 55VP field-emission gun microscope operated at 10 kV. TEM investigation was performed using a Jeol JEM 2100 LaB_6 microscope operated at 200 kV. The observation sections were perpendicular to the transverse direction (TD) of the rolled plate. It is worth noting that only when the surface of the rolled sample was polished and etched could the shear localization areas be observed by optical microscopy or SEM. The etching of the samples was carried out using a solution composed of 50 ml H_2O, 40 ml HNO_3 and 10 ml HF.

In order to perform a systematic TEM investigation of the shear localization areas, which were relatively randomly distributed in the matrix, a special technique for the targeted preparation of thin foils was implemented in the present work. This technique is based on the methods previously described in the literature [3,13]. A slice of the rolled specimen was first cut perpendicular to TD. One side of the slice was metallographically polished and etched so that the shear band location was revealed. This location was marked by a light scratch, and the rolling direction (RD) was marked by a thin marker-pen line. The sample slice was then thinned by grinding from the opposite side to a sheet ~100 μm thick. A disc 3 mm in diameter was subsequently punched out from the sheet, ensuring that the intersection of the two marker lines was located close to the centre of the disc, and the RD was marked through a pair of fine notches placed on the disc rim. The disc was then carefully ground to ~50 μm in thickness and finally subjected to low-energy ion milling in a Gatan PIPS system to perforation.

3. Results

3.1. SEM investigation of the shear localization

Fig. 1 shows the microstructures, observed using SEM, which developed in the areas containing shear localization.