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Shear banding in commercial pure titanium deformed by dynamic compression

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Abstract

A cylindrical hexagonal-close-packed Ti sample was pre-deformed by dynamic compression to produce coarse-grained and ultrafine-grained structures in different parts of the sample followed by further dynamic compression to failure, making it possible to explore the effect of stored strain and grain boundary energy on shear banding in the material. A long shear band that formed during the final compression process passed through a complete diagonal of the sample. Electron backscattered diffraction was used to systematically investigate the shear-banding-induced structural evolution. Results show that the original stored energy in the matrix plays a significant role in the competition between deformation-induced grain refinement and grain growth, which determines the final average grain size in a shear band. Shear banding leads to grain reorientation such that one close-packed $\langle 11\bar{2}0\rangle$ direction and one $\langle 10\bar{1}0\rangle$ direction in most grains are parallel to the local shear direction and the normal direction to the local shear plane, respectively. The grain orientation in the shear band favours prismatic $\langle a\rangle$ slip, while the texture in the matrix, which is a stable compression texture, benefits the basal $\langle a\rangle$ slip. The results advance our understanding of the shear banding behaviour in heterogeneous deformation conditions and also the overall mechanical behaviour of materials under dynamic compression.

Keywords: Shear banding; Microstructure; Texture; Ti; EBSD

1. Introduction

Shear bands are narrow regions in materials, which have localised severe plastic flow caused by strain-softening-induced plastic instability [1–3]. Shear banding has significant effects on the processing, plastic deformation, catastrophic failure and mechanical properties of materials and therefore has been extensively investigated for decades [1,2,4–11]. Shear banding events occur easily during high-strain-rate plastic deformation in materials with low thermal conductivity such as Ti and its alloys [11–13] due to the slower heat dissipation than heat production in the materials. Both theoretical [14–17] and experimental [1,3,18,19] investigations have been conducted to understand the critical conditions for the plastic flow instability and the grain refinement mechanism within shear bands. Most of the previous studies on shear banding were conducted on coarse-grained samples. In order to produce and easily find a shear band, samples were normally hat-shaped and were deformed at high strain rates using split Hopkinson bars [1,20]. Results show that grains in shear

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bands are finer than the surrounding coarse-grained matrix areas and this is explained as a result of deformation-induced grain refinement, deformation-induced temperature rise and the consequent recrystallization during the severe plastic deformation process in the shear bands [1,14,21].

Recently, ultrafine-grained (UFG, <1 μm) materials have attracted significant research attention due to their excellent properties [22–25]. Shear banding in UFG Ti materials is easier than in coarse-grained materials because of the low strain hardening and low rate sensitivity in UFG Ti materials [26,27]. A large amount of crystalline defects, which store a significant amount of energy, in UFG materials could also affect shear banding behaviour [28]. Little has been done so far to understand shear banding in UFG materials, which prevents us from complete understanding of the overall deformation mechanisms of UFG materials.

Compared to high-strain-rate deformation of hat-shaped samples that makes the investigations of shear banding relatively easy, the conventional compression test of cylindrical samples is more important because it is not only an easy method to deform samples but also a popular way to test the mechanical properties of materials. Compressed cylindrical samples normally fail in a similar way – shear fracture along a diagonal direction of the samples irrespective of strain rates [9,11,12,29–31]. Because of the frictional force between the compression anvils and the compressed sample, the compressive deformation is not uniform throughout the whole sample [32–36], leading to different stored energies in different parts of the sample. As such, shear banding behaviour is more complicated in compressed cylindrical samples than in the simple shear deformation in hat-shaped samples. Although this makes the exploration of shear banding mechanisms difficult, it nevertheless provides an opportunity to study the stored energy effect on shear banding behaviour. Little structural information on the shear banding in the conventional cylindrical sample compression has been reported, which affects our understanding and proper control of compression deformation.

Crystallographic orientation of grains affects significantly the deformation behaviour of materials. Understanding the texture evolution during shear banding is critical for a complete understanding of the shear banding mechanism. However, texture evolution induced by shear banding has been less investigated compared to the grain refinement process in shear bands. Previous investigations using transmission electron microscopy failed to provide detailed information on texture in shear bands [18,20,21].

Crystallographic pole figures have been widely used to describe the orientation of crystals. Electron backscatter diffraction (EBSD) is the most effective technique to determine the crystallographic orientation of individual grains in crystalline materials [32,37]. Data from EBSD include information on the size, morphology and orientation of individual grains, which are critical for understanding the deformation and corresponding mechanical properties of materials. Unfortunately, only a few reports have been available on EBSD investigations of shear bands [38] and some of the reports failed to provide detailed microstructures in shear bands [20,28] probably because of a relatively poor spatial resolution of EBSD or poor sample preparation. The spatial resolution of EBSD can be significantly improved through the use of a field emission gun and low accelerating voltage, and appropriate sample preparation [39], making it possible to successfully explore the texture in shear bands in UFG materials [40].

This research aimed to apply the EBSD technique to investigate the shear banding behaviour in cylindrical Ti samples processed by dynamic compression. The compression deformation introduces heterogeneous strain distribution in the cylindrical samples, leading to the formation of both coarse-grained and UFG structures in a sample prior to shear banding. This makes it possible to investigate the complicated texture evolutions and to compare the grain sizes in a shear band and its surrounding matrix in coarse-grained areas with low stored energy and UFG areas with high stored energy. The study advances our understanding of the shear banding behaviour in heterogeneous deformation conditions and also the overall mechanical behaviour of materials under dynamic compression.

2. Experimental procedures

A commercially pure α Ti plate was used in this study. The material is of a hexagonal-close-packed (hcp) crystal structure and contains minor amounts of impurities including 0.08 wt.% O, 0.01 wt.% H, 0.01 wt.% N, 0.005 wt.% C and 0.035 wt.% Fe. The plate was annealed at 1073 K for 1 h, yielding a homogeneous equiaxed microstructure with an average grain size of 85 μm. Cylindrical samples for dynamic compression processing were cut from the as-annealed plate. The samples have a diameter of 10 mm and a height of 15 mm with the height parallel to the normal direction of the plate.

Dynamic deformation processing was performed using a dynamic compression facility at room temperature. A Ti cylindrical sample was placed on the lower anvil of the compression facility and compressed by the upper impact anvil at a high loading rate. The estimated deformation strain rate was $\sim 10^2$–$10^3\ s^{-1}$. True deformation strain was calculated using the equation $\varepsilon = \ln(h_0/h_f)$, where h_0 and h_f are the initial and final heights of the sample, respectively. The sample failed at the strain of 0.8, which underwent three impacts from the as-annealed state as shown in Fig. 1a. The accumulated strain after each of the three dynamic loadings was 0.24, 0.5 and 0.8, respectively. The compression direction is indicated using a big black arrow and the shear failure plane is marked by a white arrow in Fig. 1a.

Cross-sectional samples for microstructural characterization were prepared from samples with accumulated strain of 0.5 and 0.8 along the loading direction. Fig. 1b