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Formation of Micro Shear Bands During Severe Plastic Deformation of BCC Alloys

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Abstract

In this work, tendencies of pure Niobium, Fe-20Cr stainless steel, and Ti-36Nb-2Ta-3Zr to formation of micro shear bands inside their microstructures during severe plastic deformation are compared with their mechanical properties. For this purpose, strain hardening behavior and strain rate sensitivity of flow stress of these alloys were measured using tension tests and nano-indentation tests, respectively. Microstructures of the alloys were studied using electron backscattering diffraction method before and after imposition of severe plastic deformation. Results show that increase of the strain hardening exponent and/or strain rate sensitivity of flow stress causes decrease of tendency to formation of micro shear bands during deformation. Moreover, formation of micro shear bands can be approximately predicted using a parameter previously proposed for prediction of formation of macro shear bands.

Nomenclature

ε_p	Equivalent plastic strain	σ	Flow stress
n	Strain hardening exponent	$\dot{\varepsilon_p}$	Equivalent plastic strain rate
m	Strain rate sensitivity exponent	γ	Normalized strain hardening rate
α	Tendency to shear band formation parameter		

1. Introduction

Shear bands are known as microstructural characteristics of metals and alloys often appeared during forming processes due to localization of strain. Considering their size scales, shear bands are generally categorized into two main groups: macro-scale shear bands and micro-scale shear bands. It is belived that macro-scale shear bands could appear during deformation of coarse-grained materials as a result of macroscopic strain localization. The macroscopic strain localization usually ocurs because of an unbalanced heat transfer, a poor lubrication and/or a rapid straining. This type of shear bands penetrates grain boundaries and its width is in range of several hundreds of micrometers. Typically, formation of macro-scale shear bands is undesirable since they cause nucleation of cracks and acceleration of fracture during a forming process [1]. In contrast of macro-scale shear bands, a Micro-scale Shear Band (MSB) spreads inside only one grain and its width is in range of a few hundreds of nanometers to a few micrometers. In comparison to macro-scale shearbands, formation of MSBs causes less acceleration of fracture during forming process while it has been reported that

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they can perform as preferred sites for nucleation of recrystallization during post-deformation annealing [2]. Therefore, this type of shear bands can play an important role in evolution of texture of alloys subjected to deformation and subsequent annealing. Considering these points, a group of previous studies have proposed induction of MSBs for stimulation of recrystallization [3]. One of the proposed methods for induction of MSBs inside microstructure of metals and alloys is imposition of Severe Plastic Deformation (SPD). Among different processes developed during past decades for imposition of SPD, Equal Channel Angular Pressing (ECAP), often known as "simple shear", is acknowledged as the most applicable SPD process due to its little need to complicated machining devices as well as its ability to impose a relatively homogenous plastic strain. Therefore, a couple of studies have focoused on the formation of MSBs inside microstructure of metals and alloys through ECAP processing. For example, previous studies have reported formation of MSBs through ECAP processing of FCC metals like copper and aluminum alloys. It has been reported that both pure and highly-alloyed FCC metals show a considerable tendency to formation of MSBs during ECAP processing [4-6]. Formation of MSBs inside HCP alloys during ECAP processing has been also reported [7]. Despite these works on formation of MSBs during ECAP processing of FCC and HCP metals, formation of MSBs inside microstructure of BCC metals during ECAP processing has remained less considered. In addition, the effects of mechanical properties of a metal on formation of MSBs inside its microstructure have not been clearly investigated yet. For example, although different studies have shown that increase of the strain hardenning and the strain rate sensitivity of flow stress of a metal decreases its tendency to formation of macro-scale shear bands during deformation [7-11], little studies have investigated effects of these properties on formation of MSBs. In addition, previous works are mainly based on simulation or analytical aproaches and a combination of experiments with analytical aproaches has remained less considered.

The aim of this work is to investigate effects of the strain hardenning behavior of different BCC metals and their strain rate sensitivity of flow stress on formation of MSBs inside their microstructures during SPD processing thorugh an experimental approach. For this purpose, formation of MSBs inside microstructures of three different BCC metals subjected to ECAP was studied using Electron Back-Scaterring Diffraction (EBSD) method. Simultaneously, the amounts of MSBs formation inside microstructures of different metals were compared with their abovementioned properties to understand effects of these properties on tendency of the metals to MSBs formation.

2. Experimental Procedure

99.9% purity Nb, high purity Fe-20Cr ferritic stainless steel (C+N=120ppm), and BCC stabilized Ti-36Nb-2Ta-3Zr (TNTZ) alloy were received in wrought form and they were subjected to different annealing procedures shown in Table 1. Afterwards, their strain hardening behavior was evaluated through tension tests using a strain rate of $5.6\times10^{-4}s^{-1}$ and the strain hardenning exponent was estimated between true strain of 0.05 to 0.15. The strain rate sensitivity of flow stress of these alloys were measured using nano-indentation test. This tests were conducted using the indentation load of 0.5N imposed by different loading rates of 5, 10, 25, and 50mN/s. More details about measurment of the strain rate sensitivity of flow stress by nano-indentation tests are presented elsewhere [12]. In addition, the alloys were subjected to one pass of ECAP through a 90° angled die by the strain rate of $0.001s^{-1}$. The cross-section of the specimens subjected to ECAP processing was 8×8mm squares and their length was 120mm. Fig. 1 illustrates the die set used for ECAP processing. Considering geometry of the used die, an equivalent plastic strain (ε_p) of 1.15 was imposed through each pass of ECAP. The microstructures of alloys were investigated using EBSD method before and after ECAP processing. For this purpose, the transversal plane of specimens were prepared by mechanical polishing and they were studied using JSM-7001F EBSD equipped scanning electron microscope while INCA 4.09 software was used for interpretation of EBSD results.

Table 1
Annealing conditions for different alloys.

Alloy	Nb	Fe-20Cr	TNTZ
Annealing temperature	1473K	1073K	1063K
Soaking time	30min	1h	1h

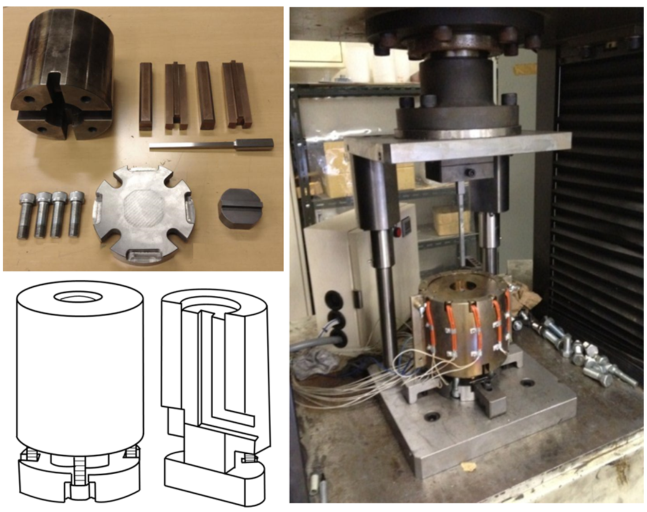

Fig. 1. Illustration of die set used for ECAP processing.

3. Results and Discussion

Fig. 2 (a) compares strain hardenning behavior of the alloys after annealing treatment. Considering hollomon hardenning model presented below [5]:

$$\sigma = K\varepsilon_p^n \tag{1}$$

where σ is the flow stress, n is the strain hardening exponent, and K is the strain hardening coefficient, the amounts of n parameter for Nb, Fe-20Cr, and TNTZ are evaluated equal to 0.268, 0.326, and 0.596, respectively. It is clear that the n parameter of TNTZ is remarkably greater than that of the other alloys. This can be due to occurrence of twinning and/or martensitic phase transformation during deformation of TNTZ similar to what was previously reported for other BCC stabilized titanium alloys [13]. Figs. 2b to 2d compare results of nano-indentation test of these alloys. Considering the strain rate sensitivity of flow stress as below [5]:

$$\sigma = C\dot{\varepsilon}_p^m \tag{2}$$

where $\dot{\varepsilon}_p$ and m are the imposed strain rate and the exponent of strain rate sensitivity of flow stress, amounts of the m parameter of TNTZ, Fe-20Cr, and Nb are evaluated equal to 0.19, 0.157, and 0.115, respectively.

Fig. 3 compares microstructure of the alloys before and after ECAP processing. As can be seen in Figs. 3a to 3c, there are fully recrystallized grains characterized by equilibrium sharp boundaries inside microstructures of the alloys subjected to annealing treatment. It is noteworthy that the average grain size of Nb, Fe-20Cr, and TNTZ before ECAP processing was evaluated as 43μm, 90μm, and 59μm, respectively. As shown in Figs. 3d to 3f, elongated grains appear inside microstructures of the alloys after imposition of ECAP. In addition, many MSBs are induced within these elongated grains. However, fractions of microstructure of the alloys occupied by MSBs are remarkably different. For instance, the microstructural studies shows that the fraction of MSBs after ECAP processing of TNTZ, Fe-20Cr, and Nb is equal to 11%, 37%, and 52%, respectively. This remarkable difference in the fraction of microstructure occupied by MSBs can be interpreted as different tendencies of these alloys to formation of MSBs during ECAP. Comparing these results with the abovementioned amounts of n and m parameters of the alloys, one can infer that the tendency to formation of MSBs during ECAP decreases with increase of n and m. To compare effects of n and m parameters of an alloy on its tendency to formation of macro-scale shear bands during deformation, a combinative parameter was proposed as below [14]:

$$\alpha = \frac{1-\gamma}{m} \tag{3}$$

Here, α is the tendency of alloys to formation of macro-scale shear bands and γ is normalized strain hardening rate obtained as below:

$$\gamma = \frac{1}{\sigma}\frac{d\sigma}{\varepsilon} \tag{4}$$

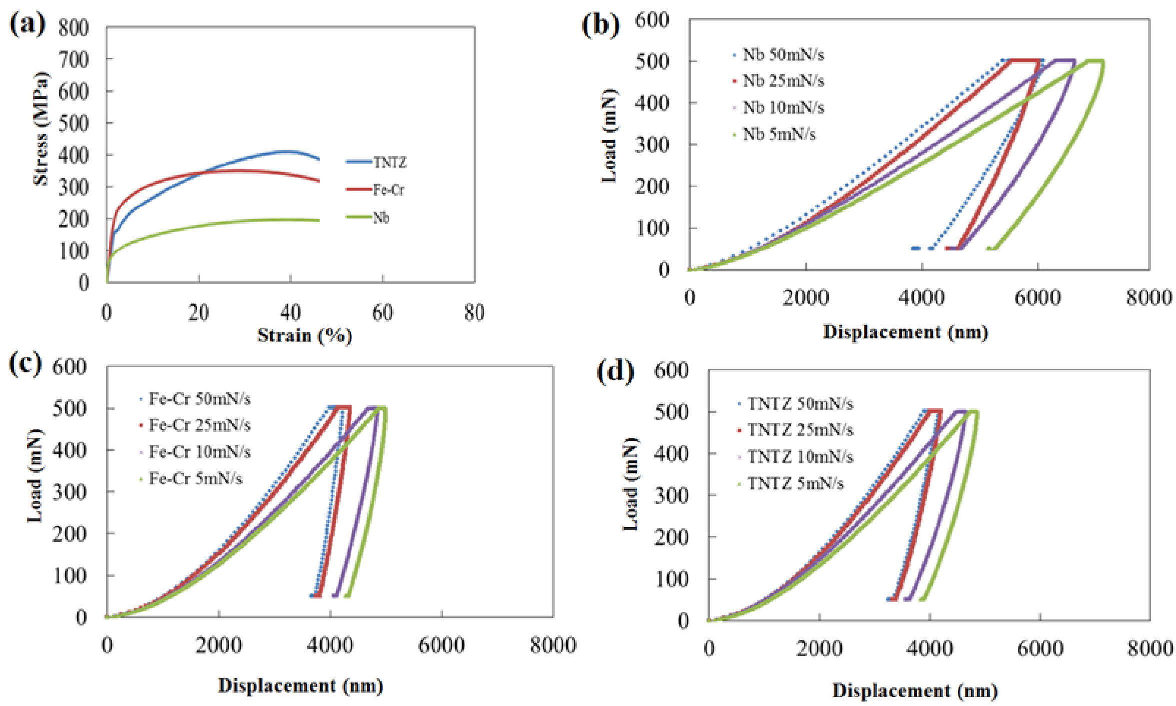

Fig. 2. (a) Strain hardening behavior of different alloys; Results of nano-indentation test for: (b) Nb, (c) Fe-20Cr, (d) TNTZ.

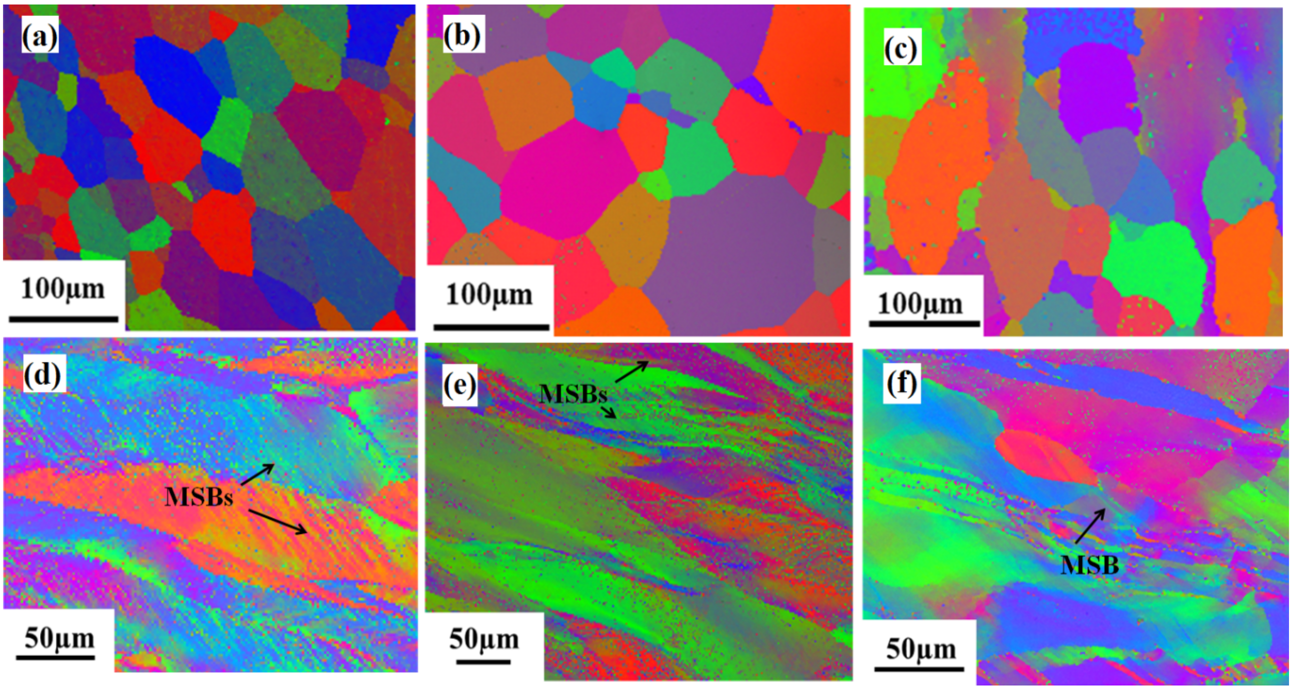

Fig. 3. Microstructure of annealed: (a) Nb, (b) Fe-20Cr, (c) TNTZ; Microstructure of: (d) Nb, (e) Fe-20Cr, (f) TNTZ after processing by one pass of ECAP.

On the other hand, it was previously reported that macro-scale shear bands appear when parameter crosses a critical amount of 4-5 [14-15]. Similarly, one may propose a critical amount for parameter to predict formation of MSBs.

Comparing Eqs. (1), (3), and (4), one can propose that can be rewritten as below:

$$\alpha = \frac{1 - \frac{n}{\varepsilon p}}{m} \quad (5)$$

Considering ε_p imposed by ECAP equal to 1.15 and the evaluated amounts of m and n parameters of different alloys mentioned above, parameter of TNTZ, Fe-20Cr, and Nb in final stage of one ECAP pass are calculated equal to 2.5, 4.4.5, and 6.7, respectively. Comparing these numbers with fraction of MSBs inside microstructure of different alloys after ECAP processing, one can infer that fraction of MSBs remarkably increases when α parameter crosses a critical value. For instance, when α parameter increases from 2.5 to 4.5, the fraction of MSBs increases from 11% to 37%. Despite this, a limited increase of this fraction due to increase of α parameter from 4.5 to 6.7 can be observed. Therefore, it can be inferred that the critical value of parameter for formation of MSBs should be in range of 2.5 to 4.5. However, it may be questioned that why a small presence of MSBs can be seen in TNTZ whereas α parameter is less than the critical amount. To answer this question, it is notable that different grains of a polycrystalline alloy subjected to ECAP have different plastic deformation behaviors since their crystallographic alignments in relation to shear direction of ECAP are different. Therefore, the imposed plastic strain could be concentrated on a group of grains which have more perfect orientations for plastic deformation [16]. Considering this fact and remembering Eq. (5), one may infer that the local imposed plastic strain inside a limited group of grains of TNTZ could be enough for formation of MSBs and therefore, MSBs can be initiated in this group of grains.

4. Conclusions

Considering what mentioned above, it can be concluded that:

1. Increase of the strain rate sensitivity of flow stress and the strain hardening susceptibility of an alloy decreases its tendency to formation of MSBs during ECAP processing.

2. Degree of MSBs formation inside an alloy subjected to ECAP can be approximately evaluated through calculation of parameter which was previously proposed for prediction of formation of macro-scale shear bands.

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