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Study of twinning behavior of powder metallurgy Ti-Si alloy by interrupted in-situ tensile tests

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ABSTRACT

Twinning mechanism of powder metallurgy Ti-Si alloy was investigated by interrupted in-situ tensile tests. Extension twins {10–12} < 10-1-1 > in the fine-grained Ti-Si alloy were found in the uniform deformation period, but no twinning in the coarse pure Ti. Three deformation twinning nucleation mechanisms were proposed: i) local stress concentration by neighboured slip incompatibility, ii) slip/twin oriented relationship in the parent grain and iii) slip/twin transfer by high Luster-Morris oriented relationship. The interior back-stress state, grains rotation and dislocations pile-up drove the occurrence of detwinning phenomenon. Silicon-facilitation twinning verified the hypothesis that the substitutional Si solutes affected the core structures and thus the mobility of screw dislocations. Enhanced driving force and decreased energy barrier of nucleation in the micro/atomic scale were further proposed in the twinning activation. It was expected to deepen the understanding of twinning/detwinning behaviors and supply direct evidences building immature twinning mechanism. In-depth understanding about the relationship among the processing, mechanical properties and microstructure of Ti alloy was facilitated in the present work.

1. Introduction

Ti-Si alloy is one of the most important members of titanium alloys [1–3] and has attracted many scientists in the field of material science owing to its excellent comprehensive mechanical/biomedical properties and high specific strength [4–6]. However, most of the studies related to hypereutectic [4,7] (occurred in 1330 °C) and peritectoid [4,6,8] Ti-Si alloys (occurred in 1170 °C) by casting method were negatively reported by low ductility with moderate strength. The limited solutes, formation of large-sized silicide, coarse grains and casting defects/inclusions led to poor mechanical properties in the as-casting billet.

It was attempted to process ductile Ti-Si alloy with high strength via powder metallurgy in the literature. The relationship between the microstructure and the mechanical properties of processed alloy has been demonstrated in our previous work [9]. The further strengthening-toughening mechanism study has also been conducted by interrupted in-situ tensile tests [10]. Though slipping, especially prismatic slipping, was dominant deformation mode in the uniform deformation period in the as-extrusion Ti-xSi alloy, extension twinning/detwinning phenomena was found in the tensile process of Ti-Si alloy. Mechanical twinning could bring in two effects on the evolution of plastic deformation. On the one side, twinning subdivided the parent grains which increased the slipping barrier and work-hardening rate. On the other hand, twinning shear contributed to the plastic deformation by decreasing work hardening rate [11]. Therefore, suitable application of twins could bring in strong and ductile metals like twinning-induced plasticity steel and nano-twined copper. In all, twinning was a very important deformation mode to influence mechanical properties. The processing temperature [12], strain rate [13], texture [14] and chemical composition [15] significantly affected the twinning. Their mechanisms were not the same in different deformation process and metallic alloys. But it's generally understood that grain size decided the activity of deformation twinning according to the well-known Hall-Petch relationship [16]. The Hall-Petch relationship was usually applied in the yield and flow stress of metals and alloys with respect to their grain size. This relationship was also feasible for deformation twinning. The Hall-Petch slope of twinning is usually higher than that of slipping especially in Ti. Twinning stress (nucleation) is more sensitive to the grain size than that of slipping onset. The required stress value of dense twins is very high exceeding the macroscopic yielding when it came to the fine-grained metals. Thus, slipping mode was more frequently observed in the strained Ti. In the present work, twins were occurred in the fine-grained Ti-Si alloy. Thus the cause of

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twinning is Si solutes in the titanium alloy. But when it came to the alloyed solutes, direct understanding about the effect of solutes on the twinning behavior was much hard. Though many investigations about the effects of substitutional or interstitial solutes on the twinning behavior of single-phase alloy have been conducted, the results are complex and direct conclusion was hard to be drawn [17–19]. For example, the effect of interstitial solutes in metals and alloys is assured to decrease the tendency of twinning deformation. The crystallography of twinning was thought as the cause of this decreasing tendency. About two third of shearing atoms could not take the equivalent octahedral sites in the twinning planes, which may account for the inhibition of twins due to unstable state caused by positioning of interstitial solutes. However, substitutional solutes, like silicon solutes, usually increased the tendency of metals to initiate the twinning deformation [20]. When the concentration of solutes exceeded a critical value the twinning stress could be slightly decreased (similar in the iron-beryllium alloy, niobium-vanadium alloy or molybedenum-rhenium alloy etc. [21]) with greatly enhanced twinning deformation. These observations just verified the hypothesis that the substitutional solute (Si solutes) affected the core structures and the mobility of screw dislocations. But it is regretful that seldom direct observation could supply the evidence for the current hypothesis. In addition, the preliminary hypothesis of solutes-facilitation twinning could not get it clear for our in-depth understanding about the twinning nucleation and growth.

Therefore, the current work focused on the twinning mechanism of powder metallurgy Ti-Si alloy by interrupted in-situ tensile tests, which was positive in the in-depth understanding about the relationship among the processing, mechanical properties and microstructure of Ti alloy. It is also expected to deepen our understanding of twinning/detwinning behaviors in the uniform deformation and to supply observed evidences building immature twinning mechanism in the Ti alloys.

2. Experimental

2.1. Materials processing

The round-bar material was fabricated by powder metallurgy method (mixing Ti powder and Si powder by simple rock milling) and hot extrusion [9]. The previous work showed the uniform solid solution was finished without beta phase and brittle silicide. In addition, the strengthening-toughening mechanism was already studied by in-situ tensile tests [10]. It's worthy to be noted that the major role in the present work was to study the effects of Si solid solution in the twinning mechanism.

2.2. In-situ tensile tests and interval observation

The in-situ tensile tests of post-extrusion sample were implemented by high-accuracy micro-tensile machine under SEM/EBSD observations. The as-extruded round bar was machined into plate-like samples as the in-situ tensile samples. The samples were mechanically polished prior to the in-situ tensile tests in order to get clear SEM/EBSD observation of surface slipping and twinning band. Afterwards electrolytic polishing solution with perchloric acid and acetic acid was performed in removing residual stress of the sample surface, which was a necessary pre-treatment of EBSD scanning. In order to follow the microstructure and orientation evolution during the tensile deformation without influencing stress state, the ordinary microindentation marker in the tracing grains was not applied prior to tensile deformation. Capturing the environmental grains was feasible to trace the studied zone. EBSD measurements and SEM capturing were conducted in each step of in-situ tensile process. The only uniform deformation (before necking) existed in the tensile process. In this process, twinning/detwinning phenomena was observed. Surface information in the interval tensile process was captured by SEM (JSM-6500F, JEOL). The trace observation/analysis methods of activated twinning (detailed in [22]) were utilized similar to our previous work [10].

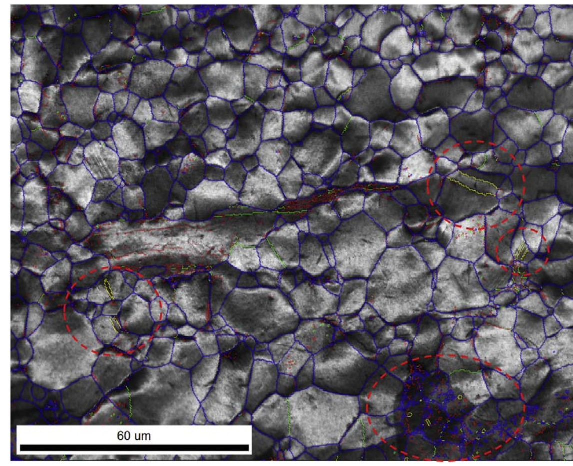

Fig. 1. Grain boundary map showing the occurrence of extension twinning in the 5% strain stage (the red and green colored low-angle grain boundaries; yellow in the extension twinning boundary, rotation angle is set as 86° with 5° deviation). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

3. Results

3.1. Investigation of twins

The {10–12} < 10-1-1 > extension twins were found in the strained Ti-0.70Si as shown by Fig. 1. No twins could be found in the as-extrusion microstructure, which has been reported by our previous work in the microstructure and the mechanical properties of Ti-Si alloy [9]. Moreover, the twins orientation was in accordance with the 86° ± 2° rotation from the parent grains along the < 2–1–1 0 > axis as depicted by Fig. 2 and Table 1. Compression twinning could not be found in the current situation in 600 strained grains. Fig. 3 presented the severe shearing displacement out of sample surface with a prominent twinning area in the slipping grain. But there existed only twins without obvious slipping band in the strained grain, which were highlighted by red arrows in the Fig. 3. Generally, both deformations in the pure Ti and Ti-0.70Si sample had similarity in the plastic deformation characters like elongated trend of the strained grains along the tensile axis, grown stress/strain concentration and granular rotation [10]. While it's different to find a small fraction of extension twins (1.3% in all the statistical deformed grains) only in the strained Ti-0.70Si sample.

3.2. Detwinning phenomenon

Fig. 4 showed detwinning phenomenon with 10% strain in the uniform deformation period. In the continuous strain, the twins may be relieved by the intragranular rotation or dislocations pile-up in the interior grain. Low angle grain boundaries gradually replaced twinning boundaries as Fig. 5. Therefore, in the traditional plastic deformation, twins were hard to be found. The one factor was shown here the twin boundaries were easily transformed to LAGB (low angle grain boundaries) or moved to grain boundaries with the final annihilation. On the other hand, the recrystallization in the extrusion usually nucleated near the high strain energy sites like twin boundaries with the sacrifice of twins. Therefore, prismatic slipping was usually seen as the dominant deformation mode in the fine-grained Ti alloy. Accompanying with detwinning process, slipping trace gradually invaded the original twinning area. On the other hand, the rough surface with microprotru-

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