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Effect of initial temperature on dynamic recrystallization of tungsten and matrix within adiabatic shear band of tungsten heavy alloy

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ABSTRACT

Uniaxial dynamic compression tests were performed on tungsten heavy alloys (WHAs) at different temperatures. The microstructure evolution of tungsten grains and matrix within adiabatic shear band (ASB) was investigated. With the initial temperature decreased, the width of elongated subgrain observed in both tungsten grains and matrix shows a decreasing tendency, and the dynamic recrystallization (DRX) process within ASB is evidently suppressed and delayed at cryogenic temperatures. Compared with tungsten grain, the DRX of matrix is earlier and more sufficient, and the observed subgrain of matrix is much finer. No twins were observed during DRX of tungsten grains at various temperatures. However, secondary slip micro bands were observed within the elongated subgrain of matrix at −80 °C, with the angle between the micro bands and original subgrain ranging from 38° to 45°, and twins were observed in matrix at a lower temperature of −140 °C.

1. Introduction

ASB is the result of intensive localization of shear deformation and the failure mechanism of a large number of metal materials subjected to high strain rate, especially at explosion, hypervelocity impact and penetration [1–5]. The formation of ASB is related to the strain, strain rate, the initial temperature and the characteristics of the original material. The initiation of ASB at different nominal strain rates were analyzed, which is simulated by numerical methodology, and the interactions between neighboring bands after localization was also investigated [6]. The microstructure evolution within ASB and the DRX process have been extensively investigated in various materials such as Cu, Ti, NiTi alloys [7–9]. In previous studies, the initiation and propagation of ASB were considered to be an unstable phenomenon of materials at a high strain rate when thermal softening is overcoming strain hardening and strain-rate hardening, and adiabatic temperature rise caused by high strain rate was thought to be a critical factor in the formation of ASB [10].

Recent studies on impact and penetration show the existence of DRX in the microstructure evolution within ASB and take DRX as the principal mechanism in accelerating adiabatic shear deformation [11–13]. Two DRX models for microstructure evolution in the theory of ASB are generally accepted. One is rotational dynamic recrystallization model (RDR), which is well known in geological materials; the other is the progressive subgrain misorientation recrystallization model (PriSM), which accounts for the microstructure evolution in a mass of metals [14,15]. The two models are appropriate to explain most of the observed DRX processes within ASB.

In previous studies, Rittel proposed that the microstructure evolution of ASB formation was mainly based on the dynamic deformation process, and the initial temperature prior to localization has a minor influence on the microstructure evolution within ASB [16]. They suggested that in the process of deformation, only a little amount of plastic deformation work converts to temperature rise, while most plastic deformation work exists in the form of dynamic stored energy, which is considered to play a dominant role in the formation of ASB and microstructure evolution. Adiabatic shear failure follows the process of DRX, which leads to softening of materials and plays a key role for inducing ASB failure. According to this theory, the temperature of original materials prior to localization has little effect on the dynamic recrystallization. However, Beladi [17] proposed that different deformation temperatures will diversify patterns of dislocation motion, therefore influencing the process of dynamic recrystallization, but there is limited report available focused on the initial temperature effect on the dynamic recrystallization, especially at cryogenic temperatures. In this study, the WHA specimens processed by hot-hydrostatic extrusion were compressed under uniaxial dynamic condition at various initial temperatures. The purpose of this paper is to investigate the effect of initial temperature on microstructure evolution in both

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tungsten grains and matrix, further to analyze the temperature effect on the process of dynamic recrystallization within a range of temperatures.

2. Experimental

The original material investigated in the present study was as-sintered 93W–4.9Ni–2.1Fe (93W). The as-sintered 93W was processed by hot-hydrostatic extrusion at 1050 °C with a severe plastic deformation ratio of 73% so as to effectively improve the susceptibility to ASB [18]. The equivalent strain of deformed WHA rod is about 2.8. Cylindrical specimens (5 mm diameter × 5 mm) for uniaxial dynamic compression were sliced off from the deformed WHA rod by wire electrical discharge machining (EDM). The angle between the cylinder axial direction and the extrusion direction is 90°. In previous study, we proved that the 90° specimen of the extruded WHA exhibits the best susceptibility to ASB under dynamic compression [19]. In the present work, the initial temperature of specimens were 26 °C, −20 °C, −50 °C, −80 °C, −110 °C, −140 °C, respectively. The 26 °C was the room temperature, the −20 °C and −50 °C were obtained by a mixed solution of liquid nitrogen and ethanol, the −80 °C, −110 °C and −140 °C were obtained by liquid nitrogen vapors. For experiments at temperatures other than the ambient temperature, the specimens were first embedded in a piece of corrugated cardboard, and then specimens with corrugated cardboard were immersed in different media for a time longer than 5 min to obtain the required temperatures. The impregnated corrugated cardboard plays as a thermal insulating course during dynamic tests, and the influence of corrugated cardboard on results is insignificant due to its very low strength. The time of direct contact between the specimen and the bars' ends prior to the arrival of the incident stress wave was controlled as short as possible so as to mitigate the heat transfer before the stress wave arrives at the specimen [20]. Uniaxial dynamic compression tests were conducted using Split Hopkinson Pressure Bar (SHPB) at room temperature with the strain rate ranging from 2500 s^{-1} to 3500 s^{-1}. A striker bar with a length of 200 mm, which was accelerated by an adjustable air brake cylinder, was used to generate pulse duration of 80 μs. All the tested specimens were subjected to the same impact velocity of the striker bar so as to obtain the same loading condition, except the initial temperature. In the dynamic compressions, the velocity of striker bar was controlled at a certain level to obtain integrated specimens, with ASB formed in them. The specimens after dynamic compression were sectioned along the compressing axis, and the sectioned surfaces were polished to a mirror finish in order to observe the localized flow. Scanning electron microscopy (SEM) was employed to observe the morphology of adiabatic shear deformation within ASB. TEM samples with a dimension of 2 mm × 3 mm × 0.1 mm were cut off from the shear region of the polished specimens by EDM. These samples were first hand ground to 20–30 μm, and followed by ion-milling for electron transparency. TEM was employed to reveal the microstructure evolution within ASB.

3. Results and discussion

ASB is observed under all specimens subjected to various initial temperatures. Fig. 1a–f shows the SEM micrographs of ASB within specimens subjected to 26 °C, −20 °C, −50 °C, −80 °C, −110 °C and −140 °C respectively. It can be observed that the as-extruded WHAs exhibit a good susceptibility to ASB even subjected to cryogenic temperatures. Furthermore, with the decrease of initial temperature, the shear strain within ASB shows a decreasing tendency, demonstrating that the initial temperature has some influences on adiabatic shear banding of WHAs.

TEM was employed to investigate the microstructure feature within ASB. Fig. 2 shows the TEM micrographs of severe deformed tungsten grains within ASB at various initial temperatures. Fig. 2a displays the microstructure of the −20 °C specimen, fine recrystallized grains with an average dimension of 350 nm were observed, and the corresponding selected area electron diffraction (SAED) pattern in the top right corner shows an approximate ring feature, indicating a random orientation of the recrystallized grains [21]. Fig. 2b–d exhibit the microstructure of −50 °C, −110 °C and −140 °C specimens respectively, and lamellar structures composed of large numbers of elongated subgrain were clearly observed, with an average width of about 180 nm, 150 nm, 140 nm respectively. The SAED patterns in the top right corner show an accumulated and increased misorientation between adjacent subgrain, which displays a decreased ring feature, indicating that the DRX process within ASB is suppressed and delayed at a lower temperature. No twins were observed in tungsten grains within ASB at various temperatures, illustrating that the DRX process of tungsten grains within ASB is mainly based on the dislocation mechanism [22].

Fig. 3 shows the TEM micrographs of severe deformed matrix within ASB at −50 °C and −140 °C specimens respectively, which exhibits distinctions compared with those of tungsten grains within ASB. Elongated subgrain in matrix within ASB was observed, and the average width of subgrain of −50 °C and −140 °C specimens is about 60 nm and 35 nm respectively. It is obvious that the width of subgrain shows a decreasing tendency with the decreased initial temperature, which is consistent with the result of tungsten grains. By contrasting the corresponding SAED pattern in the top right corner of Fig. 3a with Fig. 3b, it can be observed that the DRX process in −50 °C specimen is more sufficient than that of −140 °C specimen, indicating that the DRX process of matrix within ASB is suppressed by the lower temperature, Moreover, the observed elongated subgrain in matrix is much thinner and finer than that in tungsten grains within ASB, and the corresponding SAED pattern in the top right corner of both Fig. 3a and Fig. 3b shows an approximate ring feature, indicating the formation of equiaxial recrystallization grains. Obviously, the DRX process of matrix is more sufficient than that of tungsten grains within the same ASB. There are two reasons responsible for this phenomenon. First, the matrix phase is mainly composed of nickel and iron, which are much softer than tungsten phase, resulting in a more localized shear strain compared with tungsten grains. Moreover, the melting point of matrix is lower than that of tungsten phase, thus it was supposed that the DRX process of matrix can be completed with relatively lower thermal activation free energy than that of tungsten phase. The two factors make the DRX process of matrix more sufficient and mature than that of tungsten phase.

The DRX process of tungsten phase and matrix phase within ASB is suppressed by cryogenic temperatures. As is well known, RDR is mainly based on dislocation multiplication, dislocation motion and dislocation rearrangement [23], in the process of which temperature provides thermal activation energy for the transformation of dislocation configuration and metastructure. The decreased temperature suppresses the process of that dislocation cells transforming into subgrain-boudaries, thus delays the process of dynamic recrystallization. With the temperature decreased, the process of dislocation multiplication and rearrangement is suppressed, which delays the formation of new subgrain-boundaries. As a result, subgrain within ASB is further elongated under shear stress, with the width of elongated subgrain decreased. The decreased width of elongated subgrain is responsible for the decreasing dimension of final equiaxial recrystallized grains.

In the present study, the microstructure evolution of tungsten phase within ASB at all temperatures is consistent with the RDR mechanism, and no twins were observed in the DRX process of