Microstructure evolution and flow localization characteristics of 5A06 alloy in high strain rate forming process

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Abstract

In-depth investigation of microstructure evolution rules and flow localization characteristics in high strain rate deformation is helpful to improve the forming limit and forming accuracy of electromagnetic forming process. In present study, split Hopkinson pressure bar tests were carried out to obtain high velocity deformation with initial strain rate ranging from 1000s\(^{-1}\) to 5000s\(^{-1}\). Then, post-deformation samples of 5A06 alloy were analyzed with the aid of metallographic, SEM and TEM instruments. With the increase of strain rate, equiaxed α grains are elongated with an orientation perpendicular to the loading axis and the aggregated β grains become dispersively distributed along the grain boundaries. Adiabatic shear bands occur with elongated voids and band-like structures inside when the strain rate further increase to 4200s\(^{-1}\). Multi-slips operate at the same time and the dislocation structure patterns change from dislocation clusters to dislocation bands and stack faults and then to grain-like structures of approximately 500nm in size with the increase of strain rate. The absolute temperature of adiabatic shear band zone is calculated to be 442K utilizing mathematical model developed in this work, indicating that the grain-like structures could be in-situ sub-grains rather than recrystallization grains.

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1. Introduction

Electromagnetic forming has attracted more and more attentions in manufacturing of lightweight components in automobile, aviation and space applications in respect of its high flexibility, agreeable efficiency and the potential to enhance ductility of metals in the past few decades. In electromagnetic forming, Lorentz force brought by the interaction between induction eddy current and magnetic field is considered as the driving force that deforms work-piece. As a result of it, material undergoes dynamic deformation with a considerable deformation velocity as high as several hundred meters per second (Oliveira et al., 2005). Hence, in electromagnetic forming process, both mechanical and microstructural responses of metals should present obvious differences compared with that in conventional forming regimes, as indicated in our previous work (Yan et al., 2014).

5A06 aluminum alloy is one of Al-Mg-Si rust-proof alloys which shares the advantages in strength, corrosion resistance and formability and thus becomes an appropriate candidate for electromagnetic forming of large thin-wall cylindrical or conical components (Light Metals Processing Manual Writing Group, 1979). According to Yan’s work (2014), 5A06 alloy exhibits the delay of diffuse necking and the dispersive damage in high strain rate deformation may be the causation of the enhanced ductility of 5A06 alloy. In order to reveal this phenomenon of high strain rate hyper-plasticity and further improve the forming limit and forming accuracy of electromagnetic forming process, it is indispensable to exert in-depth study on the microstructural response of 5A06 alloy during high strain rate deformation.

Many investigators have made efforts to illustrate the material characteristics and related deformation mechanisms in high strain rate forming process. According to Ulacia et al. (2011), dominant deformation mechanisms under different strain rate vary from dynamic recrystallization to deformation twinning and this fact further leads to the different deformation behavior and microstructure characteristics in different strain rate regimes. Gotoh et al. (2001) investigated high-rate shearing process of commercially pure aluminum sheet aiming at illustrating the phenomenon of flow localization in high strain rate deformation. Adiabatic shear bands were observed even with a recrystallized structure. According to their mathematical model calculation of this process, not only the adiabatic shear band but also melting might surely take place. Pérez-Bergquist et al. (2011) demonstrated that in three preventative types of aluminum alloys, shear localization is more remarkable in the dynamically deformed samples than quasi-static ones and that slip bands that occur early in the shearing process may cause mechanical recrystallization within the core of adiabatic shear bands. In relatively smaller scales, Li et al. (2011) analyzed different formation mechanisms of dislocation arrangements. Liu et al. (2012) also utilized TEM technique to investigate the microstructure response of 5052 aluminum alloy at microstructure level in dynamic deformation process. It was found that the large amount of dislocation nucleation induces much higher density dislocations of dynamic deformation than the quasi-static ones. The characterizing microstructures comprise closely placed partial dislocations and a few dislocation cells which decrease in size with the increase of dislocation density.

However, investigation on microstructure evolution, especially for dislocation structure evolution, of 5A06 alloy under high strain rate forming process is still lacking. Moreover, the mechanism of flow localization and characteristics and evolution rules of dislocation structures inside the adiabatic shear bands need further illumination.

Therefore, aiming at illustrating the physical processes and the internal mechanisms in aluminum alloys under high strain rate forming process, dynamic mechanical experiments of 5A06 alloys were employed with the aids of split Hopkinson pressure bar technique. Microstructure characteristics were examined using OM, SEM and TEM and further characterized and quantitatively analyzed. Special attentions were paid to the change of dislocation structure patterns with strain rate and dislocation microstructure characteristics in flow localization zones.
2. Materials and procedures

2.1. Materials

The material used in this study is from hot rolled sheets of 5A06 aluminum alloy in H112 heat treatment state with a chemical composition (wt%) listed in Table 1.

| Material | Mg   | Mn   | Fe   | Si   | Ti   | Cu   | Zn   | Cr/Ni | Ti   |
|----------|------|------|------|------|------|------|------|-------|------|
| 5A06     | 6.24 | 0.62 | 0.16 | 0.08 | 0.06 | 0.03 | 0.01 | -     | balanced |

The as-received 5A06 microstructure contains equiaxed 30-40μm Al (Mg) α grains with Mg2Al3 β grains decorated along the prior α grain boundaries and MnAl6 and TiAl3 dispersively distributed in the α matrix (Light Metals Processing Manual Writing Group, 1979).

2.2. Split Hopkinson pressure bar experiments

In this study, experiments of split Hopkinson pressure bar tests with strain rate ranging from 1000s⁻¹ to 5000s⁻¹ were employed to cylindrical specimens of 5A06 aluminum alloy measured 5 mm × 5 mm to obtain the dynamic mechanical responses and to provide the high-strain-rate deformed specimens for microstructure analyses. The end surfaces of compressive specimens were mechanical ground and lubricated with grease, moreover, depth of parallelism of the end surfaces was no more than 0.01mm. After split Hopkinson pressure bar tests, the mid diameter and height of deformed specimens are manually measured.

2.3. Microstructure characterizations

The microstructures of the split Hopkinson pressure bar samples of 5A06 aluminum alloys were characterized utilizing field emission scanning electron microscope (FSEM, VEGA TESCAN) with the magnification factor ranging from 200X to 2000X. The dislocation structures observations were revealed by transmission electron microscope (TEM, Tecnai F30G²). The TEM samples preparation mainly comprised slicing samples perpendicular to the tension axis, grounding the samples to a thickness of 60μm, further fine grounding to 30μm, inlaying Φ3 mm copper rings and ion thinning using ion beam thinner. In observation of microstructure of high strain rate deformed 5A06 alloy, special attentions were paid to dislocation structure patterns and the interaction between dislocations and precipitations. The TEM sample corresponding to 5000 s⁻¹ was taken from inside the adiabatic shear bands to illustrate the dislocation structure characteristics when flow localization occurs.

3. Results and discussions

3.1. General description

Microstructure characteristics of 5A06 alloy under different strain rate regimes are presented in Fig. 1. It is obvious that the initial microstructure of 5A06 alloy comprises equiaxed α grains and inhomogeneous distributed β grains. According to literature (Light Metals Processing Manual Writing Group, 1979), this grain boundary precipitated phase is hard and brittle, and existence of this phase tends to worsen the mechanical performance of alloy. β grains in the initial microstructure, as illustrated in Fig. 1(a), aggregate into clusters. With the increase of initial strain rate, the previous equiaxed α grains are elongated with an aspect ratio ranging from 2 to 5 and an orientation perpendicular to the loading axis. Moreover, the previous aggregated β grains split off and become dispersively distributed along the grain boundaries. The splitting mechanism should be mechanical breaking up caused by the transient loading.
When the strain rate further increases, phenomenon of flow localization occurs in a manner of adiabatic shear bands. In metallographic picture shown in Fig. 1(c), a dark-colored band transverses the whole compression specimen. The grains are elongated to a band-like structure in which grain boundaries are barely visible. The SEM image with a magnification of 1000X on the left top of Fig. 1(c) is helpful to scrutinize inside local region of the adiabatic shear bands. It is not difficult to find large amount of elongated voids with a few tiny $\beta$ particles decorated alongside the adiabatic shear bands zone. It is appropriate to hypothesize that the in high strain rate deformation, intense local flow breaks the connection between $\beta$ particles and the matrix $\alpha$ phase, and $\beta$ particles peel off during the preparation of samples.

3.2. Dislocation structure characteristics

In order to elucidate the detailed physical process and the mechanisms, in-depth investigation of dislocation structures of 5A06 alloy under high strain rate forming process is necessary. The TEM micrographs shown in Fig. 2 are taken from split Hopkinson pressure bar tested specimens to reveal the dislocation structure evolution rules of 5A06 alloy. As depicted in Fig. 2(a), the dislocation density is quite high in matrix $\alpha$ phase, while dislocation lines or other dislocation structures are rarely found in $\beta$ particles (the one in the centre of the micrograph). Additionally, dislocation lines in the matrix tangle with others and finally form dislocation clusters. In consideration of dislocation density, the results found in this study coincide with those demonstrated by Liu et al. (2012). As we know, high strain rate forming process, dislocations proliferate in several hundred microseconds. In virtue of the high strain rate and high strike loading, multi-slip-systems tend to operate at the same time and there is not sufficient time for dislocations to slip a long distance until they meet other dislocations during the loading process. Hence, the dislocation clusters come into being in this way.

In Li’s point of view (2011), for FCC metals, the mode of the dislocation arrangements change from regular patterns e.g. veins, persistent slip bands, labyrinth and cell patterns to dipole array and stacking faults with the increase of alloying elements. For pure aluminium, the plastic deformation mechanism should be wave slip and cross slip, and the microstructure patterns are mainly dislocation cells. However, 5A06 alloy is solution strengthened aluminium alloy and the interaction between solute atoms and dislocations cannot be ignored. Just as indicated in Fig. 2(b), dislocation bands and stack faults are both notable. Additionally, regions with high dislocation density exist not only in $\alpha$ matrix but also in $\beta$ particles and stack faults are observable inside the $\beta$ particles, as illustrated in Fig. 3(a). It is quite reasonable that when the strain rate continuatively increases, the
relatively soft α matrix lose its deformation compatibility and the β particles don’t have enough time to rotate to a preferred direction and undergo severe deformation. Moreover, according to Fig. 3(b), dislocation bands distribute adjacent to the α-β grain boundaries which is an indicator of planar slip.

Fig. 3. Detailed illustration of stack faults and dislocation bands: (a) 3000s⁻¹; (b) 3800s⁻¹.

When it comes to Fig. 2(c), equiaxed grain-like structures with a diameter of approximately 500 nm are found in the adiabatic shear bands zone of the sample corresponding to strain rate of 5000s⁻¹. Some of the grain-like structures have high dislocation density or wave-like dislocation patterns in it and the others are nearly free of dislocation lines but with the boundaries pretty distinct. Not like what was found in Gotoh’s work (2001), the size of the structure in Fig. 2(c) is far below the average size of recrystallized grains and it is not quite clear whether or not the condition of recrystallization can be satisfied in this process. Mathematical calculations will be put forward in next section.

3.3. Flow localization characteristics

Flow localization is the earlier stage of damage and fracture in high strain rate forming process and characterized by severe local flow of materials and a band-like adiabatic shear zone occurs under compression. In this work, the adiabatic shear bands were formed in an extremely short time interval at room temperature. It is proper to hypothesize that the heat generated from plastic deformation brought by high strain rate compression process concentrates in the adiabatic shear bands zone. According to the appearance of adiabatic shear bands shown in Fig. 1(c), the temperature rise of the adiabatic shear bands zone follows Equation (1), in which \( L \) and \( H \) stand for the central diameter and height of the deformed specimen, \( \theta \) the angle formed by the adiabatic shear band trace and the radial direction of the compression specimen, \( w_{\text{half}} \) the half width of adiabatic shear bands. These parameters provide the conversion rule from temperature rise of sample to temperature rise of adiabatic shear bands zone.

\[
\Delta T_{\text{adbs}} = \Delta T_{\text{samp}} \cdot \frac{L \cdot H}{2 \cdot (L/2 \cos \theta) \cdot 2w_{\text{half}}} = \left( \frac{\eta}{\rho c_p} \int_0^{\sigma_y} \sigma d \varepsilon \right) \frac{L \cdot H}{2 \cdot (L/2 \cos \theta) \cdot 2w_{\text{half}}},
\]

where \( \Delta T_{\text{adbs}} \) describes the temperature rise caused by heat conversion from plastic work, where \( \rho \) is the mass density, \( c_p \) is the heat capacity at constant pressure and \( \eta \) is the Taylor-Quinney coefficient indicating the fraction of plastic work converted to heat which set as 0.9 in this paper in reference to Kapoor et al. (1998). The half width of adiabatic shear band can be calculated using Equation (2) which was developed in previous work (Yan et al., 2014).

\[
w_{\text{half}} = \left( \frac{\chi w_{sp} \left[ \tan \theta - \sqrt{3} (\eta \sigma_{\text{room}} / \beta) \right]^{1/2}}{(\rho c_v \varepsilon_{\text{nom}} H_{\text{spec}} \sin \theta)} \right)^{1/2}
\]

where \( \chi \) is a material constant, \( w_{sp} \) stands for the width of shearing effect region, \( \sigma_{\text{room}} \) the yield stress at room temperature, \( \beta \) and \( n \) are the work hardening coefficient and work hardening exponent, these values were obtained by curve fitting using the quasi-static constitutive curve in our previous work (Yan et al., 2014). In addition, \( c_v \) is the heat capacity at constant volume, \( \varepsilon_{\text{nom}} \) represents nominal strain rate, and \( H_{\text{speci}} \) the initial height of split Hopkinson pressure bar specimen. The setup parameters and results calculated with the aid of above developed
model are listed in Table 2. The temperature rise in adiabatic shear bands is 149 K according to the calculation result which is quite close to the value given in the handbook (Japan Light Metal Association, 1972). Adding the room temperature 293 K (at which the test was performed) to 149 K, we obtain 442 K as the absolute temperature of adiabatic shear bands region. However, in the light of Light Metals Processing Manual (1979), the recrystallization temperature of 5A06 alloy is above 743 K, i.e. the temperature rise in this work is insufficient for recrystallization of 5A06 alloy. Hence, in consideration of the size and morphology of the grain-like structure in Fig. 2(c), it is advisable to take them as in-situ sub-grains. The formation mechanism of this kind of in-situ sub-grains is quite interesting and will be further discussed in our series work.

| Setup parameters | Results |
|------------------|---------|
| Parameters       | Results |
| Values           |         |
| Parameters       |         |
| Values           |         |

4. Conclusion

With the increase of strain rate, the equiaxed α grains are elongated with an aspect ratio ranging from 2 to 5 and an orientation perpendicular to the loading axis, the previous aggregated β grains split off and become dispersively distributed along the grain boundaries in high strain rate forming of 5A06 alloy. When the strain rate increases to 4200 s⁻¹, adiabatic shear bands occur with elongated voids and band-like structures inside. In high strain rate forming, multi-slips operate at the same time and the dislocation structure patterns change from dislocation clusters to dislocation bands and stack faults and then to grain-like structures of approximately 500 nm in size with the increase of strain rate. A mathematical model was proposed to calculate the absolute temperature in adiabatic shear bands zone. The result turns out to be 442 K and in this condition the grain-like structures could be in-situ sub-grains rather than recrystallization grains.

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