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Dynamic Recrystallization of 7055 Aluminum Alloy During Hot Deformation

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Abstract: Compression tests were performed at temperatures from 350 to 450 °C with different strain rates of 1.0×10^{-2} and 1.0×10^{-1} s^{-1}. The microstructures of deformed samples were investigated by electron backscatter diffraction (EBSD). Microstructure observations indicated that under present deformation conditions, fraction of new grains increases with the Z value. It was found that different nucleation mechanisms for DRX were operated in hot deformed 7055 alloy, which was closely related to deformation condition. DRX nucleation and development were discussed in consideration of bulging of original grain boundaries and occasional subgrain rotation near the grain boundaries. Discontinuous dynamic recrystallization (DDRX) which occurred in a local area was also proved to be a nucleation mechanism at higher Z value for 7055 alloy.

Introduction

7055 aluminum alloy has been widely used for aeronautical applications due to their desirable specific mechanical properties [1,2,3], which are greatly influenced by the microstructure characteristics. Thermomechanical processing plays important part in microstructure characteristic, so it is necessary to study the thermomechanical processing of 7055 aluminum alloys. The control of microstructures during the manufacturing process is critical for quality and properties of the finished product [4]. Dynamic recrystallization and dynamic recovery are important processes for the microstructure evolution during high temperature deformation, and are part of the scientifically and industrially important subject of thermomechanical processing [5]. The dynamic recrystallization during high temperature deformation of aluminum alloys with high stacking fault energy is generally continuous dynamic recrystallization which occurs by converting subgrain structures to high angle grains [6]. So the research of microstructure characteristic, especially boundary characteristic, is very important to understand and control properties. However, the microstructure characterization during dynamic recrystallization of aluminum alloys has not been studied in detail because of the obstacles of traditional analysis techniques. Recently, the electron backscatter diffraction (EBSD) technique has been widely used to study the microstructure characteristic of alloys during dynamic recrystallization and dynamic recovery [6,7]. The main aim of the present work is to acquire the microstructure characteristic of 7055 aluminum alloy during dynamic recrystallization by EBSD in detail. Particular attention was paid to the role of subgrain rotation with regard to the nucleation of DRX.

Experimental procedure

The material used in present work was commercial 7055 aluminum alloy ingot with a main composition of Al-7.87Zn-2.16Mg-2.05Cu-0.05Mn-0.12Zr. Axisymmetric compression (AC) specimens of Φ10 mm×15 mm were machined from homogenized material with grains of major intercept length (80±10) μm. The flat ends of the specimen were recessed to a depth of 0.2 mm groove [8].

Hot compression tests were conducted using Gleeble-1500 thermal mechanical simulator at temperatures from 350 °C to 450 °C with different strain rates of 1.0×10^{-2} and 1.0×10^{-1} s^{-1}. The maximum of true strain is 0.7. In order to minimize the frictions between the specimens and die during hot deformation, the grooves were filled with the lubricant of graphite mixed with machine oil. The deformed samples were quenched to room temperature in order to preserve the as hot-deformed microstructures. Specimens deformed under different conditions were sectioned longitudinally for microstructure analysis. The samples for EBSD investigation were machined and then electrolytically polished using a solution mixture of 30% nitric acid in methanol as the electrolyte.

Results and Discussion

Flow characteristic. Typical stress-strain curves obtained by compression tests are shown in Fig. 1, which shows that the curves start with a same slope and then disperse (Fig. 1 a and b). The flow stress curves exhibit similar feature which is quite typical for FCC materials implying the occurrence of dynamic recovery during hot deformation at 1.0×10^{-1} s^{-1} of strain rate [9]. The true stress–strain curve at 1.0×10^{-2} $s^{-1}$of strain rate shows a stress drop with true strain increasing, followed by a steady state region, which indicates that dynamic recrystallization may happen during the hot deformation. Peak stresses increase with temperatures decreasing (55.7 MPa at 350°C and 0.01/s, 39.7 MPa at 400°C and 0.01/s, 26.2 MPa at 450°C and 0.01/s, 59.8 MPa at 400°C and 0.1/s, 34.5 MPa at 450°C and 0.1/s), as illustrate in Fig. 1a and b. The results indicate that 7055 aluminum alloy is sensitive to negative temperature.

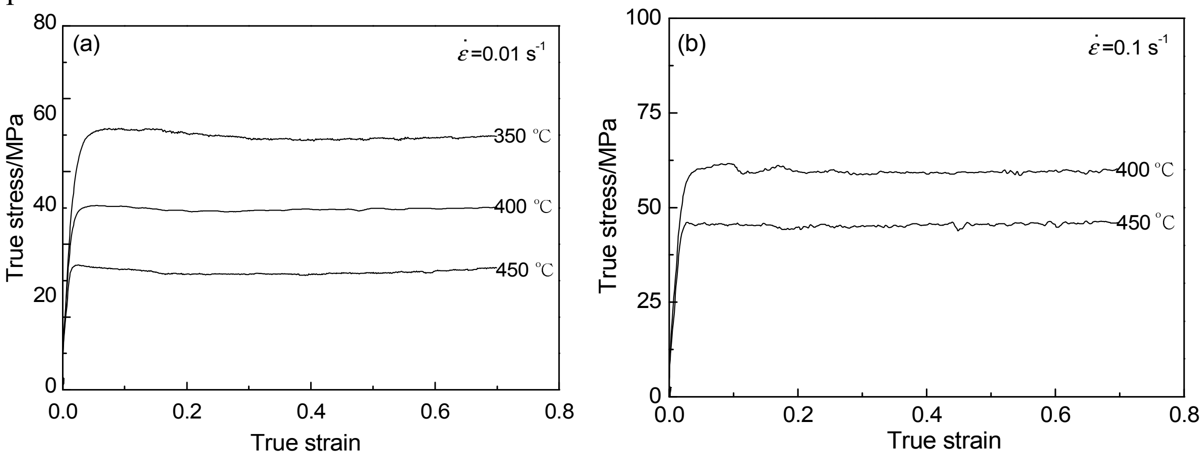

Fig. 1 True stress-true strain curves. (a) $\dot{\varepsilon} = 0.01s^{-1}$, (b) $\dot{\varepsilon} = 0.1s^{-1}$

Microstructure. In order to investigate the subgrain rotation with respect to the nucleation of DRX, samples deformed to different strains were analysed by EBSD. In orientation imaging microscopy (OIM) maps, high angle boundary (>15°) was represented by bold black line, low angle boundaries , including 10°, 5°,3 °and2°, are represented by thin black line, blue line, red line and purple line, respectively. A typical OIM map of 7055 alloy deformed at temperature of 400 °C with a strain rate of 10^{-2} s^{-1} is shown in Fig. 2. It may be noted that at low strains (Fig. 2a), the grains slightly elongated along the direction vertical press direction. There exist a few subgrain with low angle boundaries (3° and 5°) inside grains. With the strain increasing (Fig. 2b), subgrain boundaries (3° and 5°) inside grains increase, meanwhile, subgrain boundaries (10°) appear, which has indicated that dynamic recovery happened. The grain boundaries extensively become serrated and bulging, along which a few small dynamically recrystallized grains have already been developed, which is less than 5μm in size. At a nominal strain of 0.7 (Fig. 2c), the amount of new recrystallized grains has furtherly increased, and the size of new recrystallized grains has also increased.

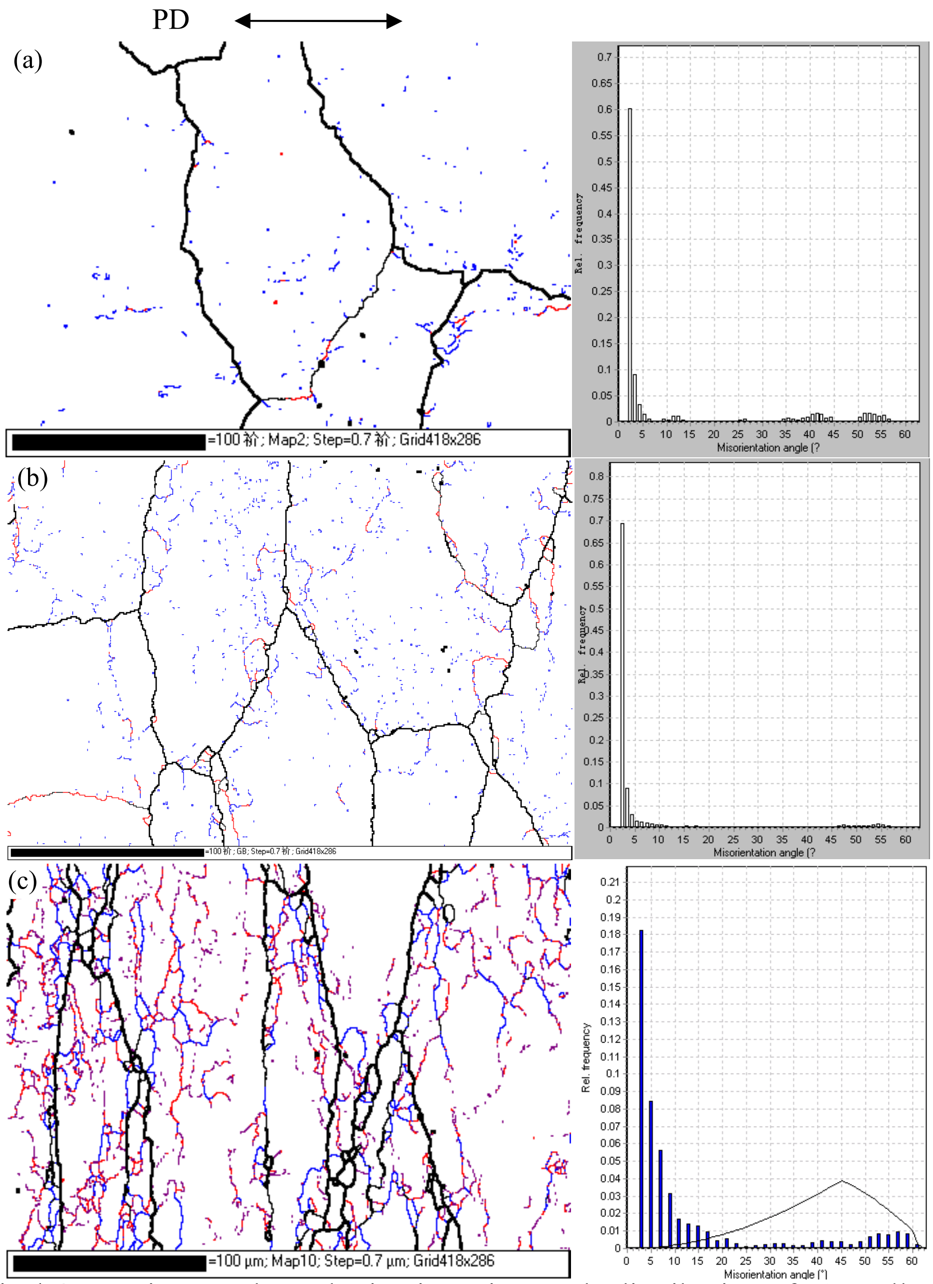

Fig.2 Typical OIM micrographs and misorientation angle distribution of 7055 alloy deformed at 400°C and 0.01 s^{-1}. PD is the pressing direction. (a) ε=0.1 (b) ε=0.3 (c) ε=0.7 (ln$Z$=22.3)
Purple→2°red→3°blue→5° black→10°bold black→15°

Let us examine in more detail the deformed microstructures developed during hot deformation. Typical OIM micrographs of the microstructures formed at a higher deformation temperature (T = 450 °C) are shown in Fig.3. Bulging is hardly observed under OIM micrographs at a strain of 0.3, as shown in Fig.3b. The original grains are elongated evidently and subgrain boundaries increase with increasing strain. At a strain of 0.7 (Fig.3c), bulging can be observed under OIM micrographs, however, dynamic recrystallization grain do not appear.

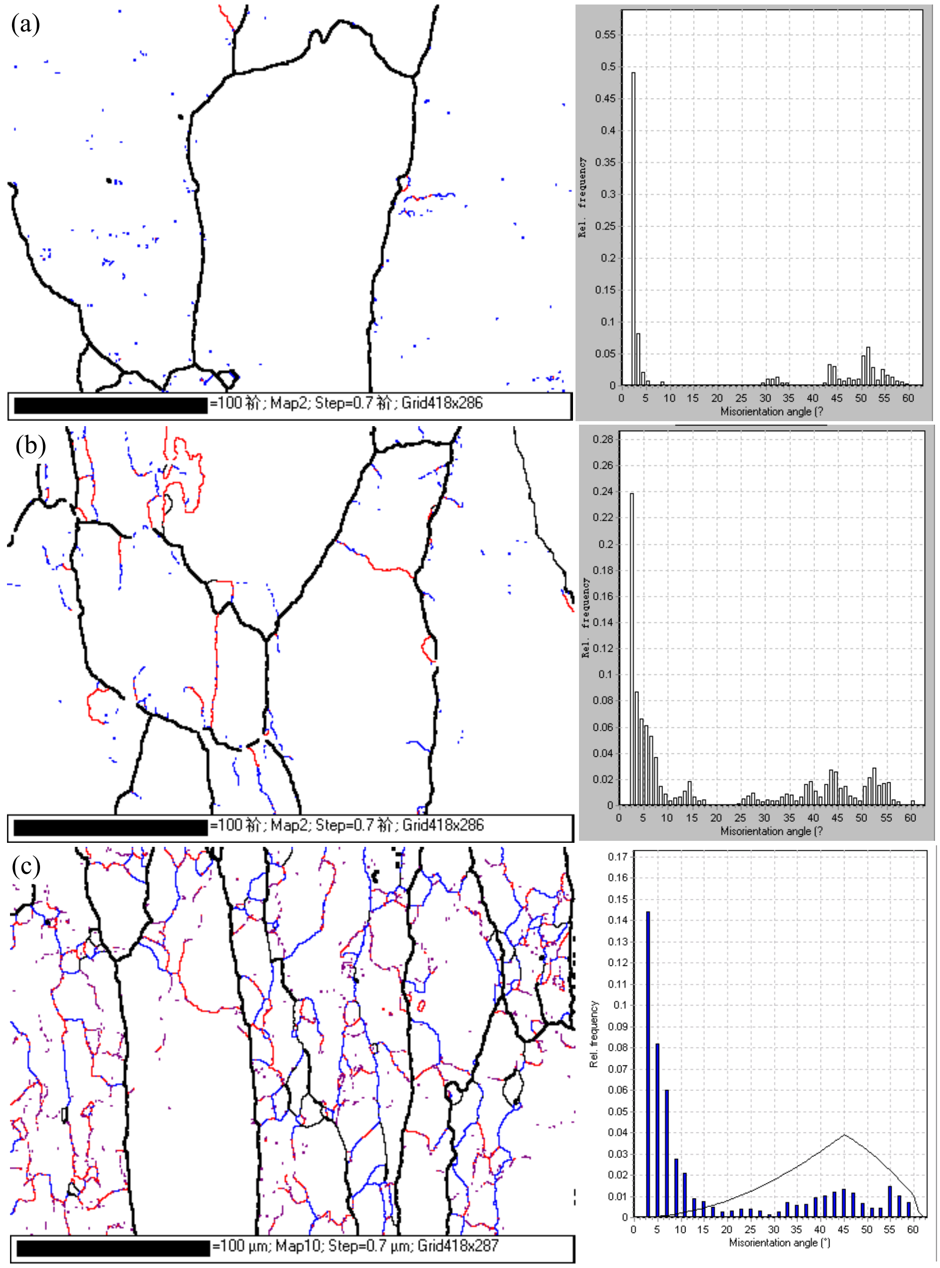

Fig.3 Typical OIM micrographs and misorientation angle distribution of 7055 alloy deformed at 450°C and 0.01 s^{-1}. (a) ε=0.1 (b) ε=0.3 (c) ε=0.7 (ln$Z$=19.6)

Fig.4 shows the OIM micrographs and misorientation angle distributions of 7055 alloy deformed at different Z value. Elongated microstructures consisting of numerous substructures are aligned roughly vertical to pressing direction (PD). It may be noted that at high *Z* value (Fig. 4a), the grain boundaries extensively become serrated and bulging, along which some small dynamically recrystallized grains, roughly 5 µm in size, have already developed. Meanwhile, there exist a few dynamically recrystallized grains in the original grain interior. The microstructure is composed of working hardened grains and dynamically recrystallized grains, which appears as necklace structures near some original boundaries (Fig. 4a). At ln*Z* value of 23.2 (Fig. 4b), the low angle boundaries decrease, diameter of dynamically recrystallized grains increase. It is apparent in the Fig. 4c that dynamic recovery has significantly occurred in the sample of deforming at low *Z* value, and subgrains have coarsened. The amount of dynamically recrystallized grains is less than that at the high *Z* value. But some dynamically recrystallized grains are more than 10µm in diameter. It is found in Fig. 4 that microstructures during hot deformation are sensitively affected by the parameter *Z* value. With *Z* increasing, more defined subgrains are developed inside original grains, and the amount of dynamically recrystallized grains incease. At high temperatures and low strain rate (low *Z* value), dislocation movement and annihilation become easier and faster, which fasten the dynamic recovery. So there has not enough deformed energy for dynamic recrystallization. At low temperatures and high strain rate (high *Z* value), a lot of dislocation locally accumulate because of slow dynamic recovery and multitudes of the second phase, so that local deformation energy is high enough for dynamic recrystallization.

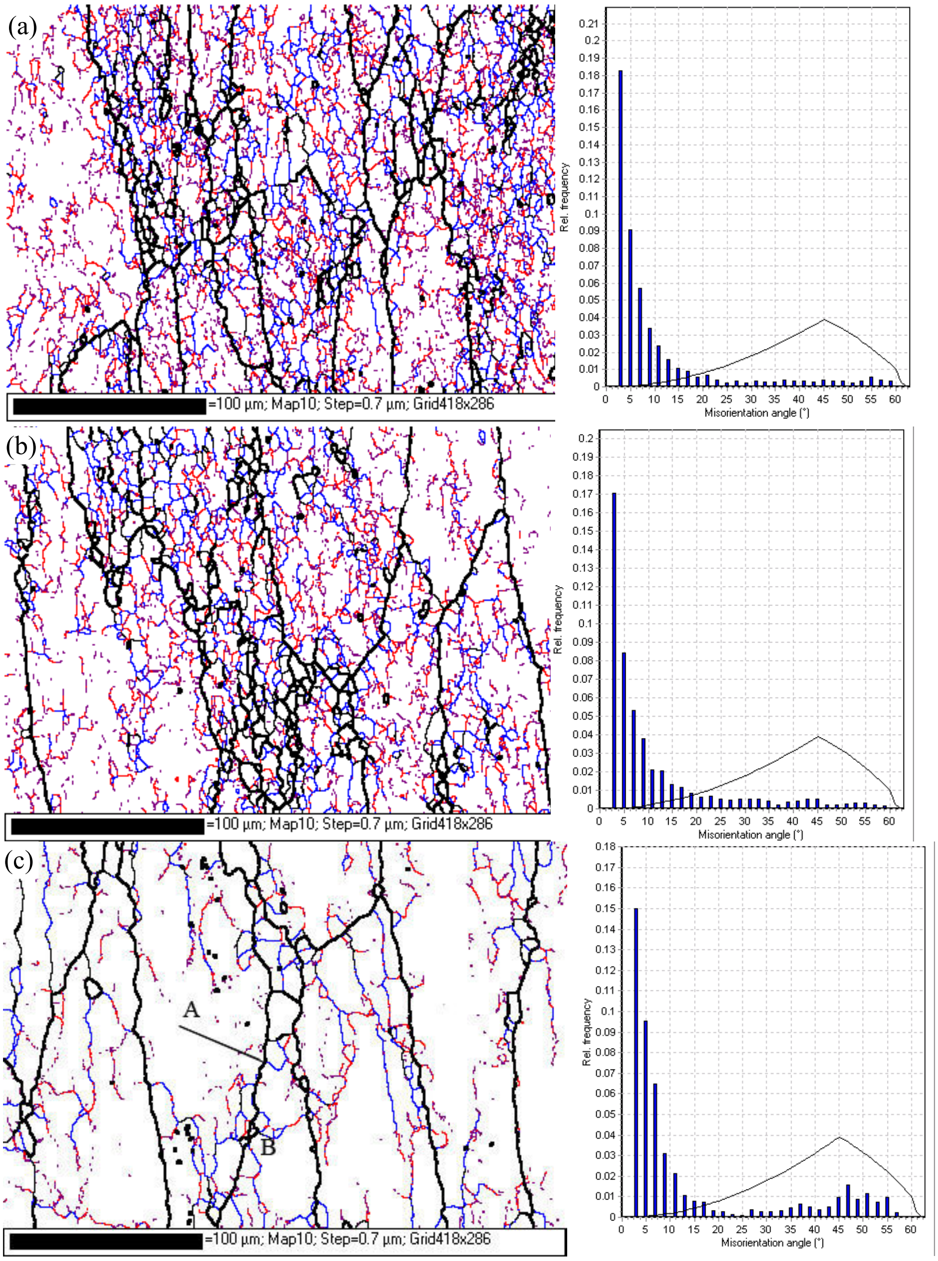

Fig.4 EBSD orientation maps and misorientation angle distribution of 7055 alloy deformed to strain of 0.7 under different compression *Z* values. (a) 350 °C, 0.01 s^{-1}(ln*Z*=23.9) (b) 400 °C, 0.1 s^{-1}(ln*Z*=23.2) (c) 450 °C, 0.1 s^{-1}(ln*Z*=21.9)

Mechanisms of dynamic recrystallization. The nucleation mechanism of DRX has been well studied and understood in previous works [6,10,11,12]. Three types of dynamic recrystallization are likely to produce such a microstructure: (i) discontinuous dynamic recrystallization (DDRX), i.e. the classical recrystallization, which operates by nucleation and grain growth; (ii) continuous dynamic recrystallization (CDRX), which involves the transformation of low angle boundaries into high angle boundaries; and (iii) geometric dynamic recrystallization (GDRX), generated by the fragmentation of the initial grains. Aluminium and its alloys exhibit very high rates of dynamic recovery because of high stacking fault energy, which is generally expected to completely inhibit dynamic recrystallization. However, the formation of new grains during hot deformation of aluminium alloy has been frequently reported [12].Discontinuous dynamic recrystallization, which is commonly observed in low stacking fault energy metals, remains exceptional in aluminium and aluminium alloys. Nevertheless, it seems to occur in two specific cases, in high purity aluminium and in aluminium alloys containing large particles [10].

The initiation of DRX in 7055 aluminium alloy is characterized by serrated grain boundaries, as shown in Fig. 4, which is closely related to the strain-induced grain boundary migration [7]. The emergence of such grain boundary morphology implies that the recrystallization mechanism belongs to the continuous dynamic recrystallization (CDRX). The cumulative misorientations (Fig. 5) along the line (Fig. 4c), from the interior of the grain (A) to the original high-angle boundary, show the large orientation gradients which develop at the boundaries, particularly within the serrations. In Fig. 4c, these have not yet developed into separate identifiable grains, except at B. The mechanism involves an interaction between grain boundary deformation and the grain boundary serrations [13,14] as shown in Fig.6. High angle grain boundaries develop serrations due to interaction with the deformation substructure, as shown in figure Fig.6a. Grain boundary sliding can then only occur on parts of the boundary, e.g. A, whilst other regions (e.g. B) have to accommodate the strain by plastic deformation (Fig.6b), leading to shear and local lattice rotation as shown in Fig.6c. Whether the deformation at the boundaries involves actual grain boundary sliding, or local plasticity close to the boundaries is not yet established. It is interesting to note that it has been suggested that the mechanism of Fig.6 may be responsible for the nucleation of continuous dynamic recrystallization in 7055 alloy.

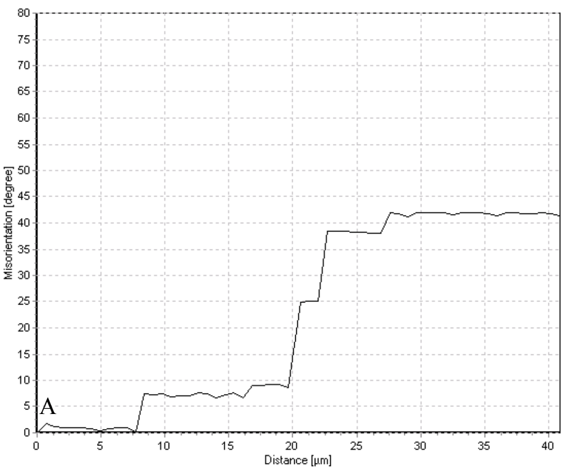

Fig. 5 Cumulative misorientations of line A in Fig. 4c

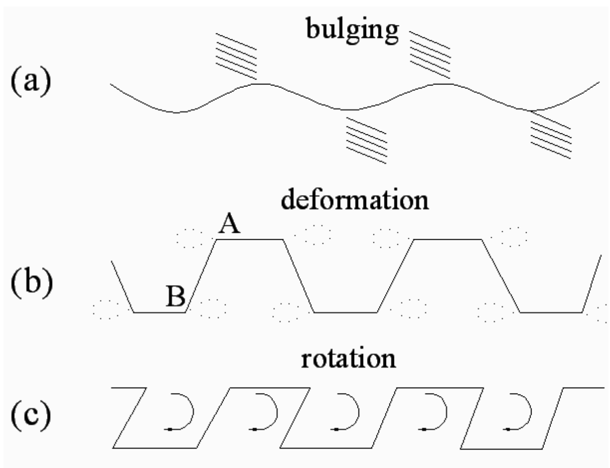

Fig. 6 Mechanism of dynamic recrystallization by lattice rotation.

It can be concluded from the above results that the DRX nucleation of 7055 aluminium alloy can be operated by bulging of the original grain boundaries, which assists by subgrain rotation. The subgrain rotation owing to grain boundary shearing would result in the evolution of local orientation and strain gradients, contributing to the nucleation of DRX grains. From the present analysis, deformation condition (Z value) has a great influence on the nucleation mechanisms of DRX in 7055 aluminium alloy. At the same time, bulging cannot be considered as the only nucleation mechanism. DDRX also plays an important role in the nucleation of DRX in 7055 aluminium alloy, especially at a lower deformation temperature. The deformation temperature (T), strain rate ($\dot{\varepsilon}$) can be very well described by a hyperbolic sine equation [15]. The hot working of the alloy is similar to that of high-temperature creep of pure aluminium, where the process is thermally activated by rate-controlling of dislocation generation and dislocation annihilation. During deformation at lower temperature, dislocation movement becomes difficult. The second phase particles, including the undissolved particles during homogenization and the precipitate on the hot deformation can also prevent the movement of dislocation. During hot deformation at lower temperatures, dynamic recovery cannot balance hard-working. With strain increasing, multitudes of dislocations locally gather near the second particles. When distortion energy formed by dislocations stress field reach the energy of developing dynamic recrystalization, dynamic recrystalization happens.

Summary

The microstructure in a commercial 7055 aluminium alloy during compression to different strains at various temperatures from 350 to 450ºC with different strain rates of $10^{-1}$and 10^{-2} s^{-1} was studied in the present work. The flow stress curves of 7055 aluminum alloy deformed from 350 to 450 ºC are characterized by dynamic recrystallization at 10^{-2} s^{-1} of strain rate. New grains form by bulging of original grain boundaries and occasional subgrain rotation near the grain boundaries. DDRX which occurs in a local area is also proved to be a nucleation mechanism at higher Z value for 7055 alloy.

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