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Formation mechanisms of recrystallization textures in aluminum sheets based on theories of oriented nucleation and oriented growth

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Abstract: The recrystallization textures in 95% rolled aluminum sheets with different purities and initial textures were investigated. The effects of recovery levels and the dragging effects induced by impurities on the effective driving force and corresponding behaviors of oriented nucleation and oriented growth during annealing were analyzed. The oriented nucleation is a common behavior in the initial stage of primary recrystallization if the effective driving force in deformed matrix is not too high to reduce the necessity of nucleation period. Oriented growth might appear if the temperature is not too high and the grains, of which the misorientation to matrix is about 40°⟨111⟩, have enough time and space to expand growth advantages, while certain reduction of effective driving force is also necessary. The recrystallization textures could be changed by controlling initial textures and effective driving forces which can be regulated by recovery levels and dragging effects.

Key words: aluminum; recrystallization; texture; recovery; stored energy; boundary migration

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1 Introduction

It is known that grain boundary mobility in aluminum is misorientation dependent, and the velocity of boundary migration could reach the maximal value if the misorientation between two neighboring grains is characterized by a rotation around ⟨111⟩ axis about 40°, i.e. 40°⟨111⟩ rotation. The phenomena were confirmed by IBE et al [1] who observed statistically the grain growth behaviors of several hundreds deformed aluminum single crystals during annealing. The systematical investigation offered an important basis of oriented growth (OG), as a mechanism for formation of recrystallization textures. The rapid moving characteristics of 40°⟨111⟩ rotation were reconfirmed by different aluminum bicrystal [2] and polycrystal [3,4] investigations. The detailed atomistic mechanism of the rapid boundary migration could be interpreted to be close to the $\Sigma 7$ CSL (coincidence site lattice with reciprocal density 7) relationship [5] and the corresponding substructure of the boundaries [6,7]. The OG mechanism predicts that different mobilities of boundaries could lead to formation of special recrystallization textures, of which the orientation relation to deformation textures is about 40°⟨111⟩ rotation.

It is known as well, that some recrystallized grains have stronger nucleation advantage and nucleate more frequently during annealing. These nuclei should form somewhere in transition bands [8] by means of strong recovery and polygonization processes of certain substructure in deformed matrix. The substructure with cube orientation indicates strong recovery ability and forms high-angle boundaries easily when it reaches a critical size for growth [9]. The cube substructure has been observed most frequently to turn to cube nuclei, which ensures the formation of strong cube recrystallization texture. The nucleation behavior of cube grains was firstly observed by RIDHA and HUTCHINSON [10] in copper, and is also very common in aluminum alloys [11]. It is obvious that the formation of recrystallization texture is determined here by nucleation process, which is called oriented nucleation (ON), as another mechanism for formation of recrystallization textures.

There has been a long dispute between OG and ON. It is, sometimes, rather confused and hard to identify which one of the two mechanisms is more effective on the formation of recrystallization texture in aluminum. However, the ambiguity might be clarified a little bit

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more if the evolution of driving force for recrystallization and its influence on formation of recrystallization texture are considered.

2 Experimental

Three kinds of aluminum samples (H, C and F) with different initial textures before cold rolling were taken from industry hot bands or ingots, in order to observe the influence of initial grain orientations on the behaviors of oriented nucleation during annealing after cold rolling. Sample H1 with 7.6 mm in thickness had high purity hot band containing initial cube texture. Sample H2 including H2-1 and H2-2 was the same hot band. However, its cold rolling sample was cut in such a way that the rolling direction (RD) was 45° away from the RD of hot band, namely, the RD was 45° rotated around the normal direction (ND), so that the initial texture became rotated cube texture {100}⟨011⟩. Commercially pure sample C1 with 6.0 mm in thickness was cut from a forged ingot containing initial {112}⟨111⟩ texture [12]. An aluminum ingot containing Ti and B as elements for grain refinement was forged in two mutually perpendicular directions, so that an initial Goss texture for cold rolling of sample F1 with 6.9 mm in thickness was obtained. The Goss texture became initial inverse Goss texture {110}⟨110⟩ of sample F2 as the RD and TD (transverse direction) of following cold rolling were exchanged. All the aluminum samples were 95% cold rolled, and their compositions, initial textures as well as the parameters for following recrystallization annealing in salt bath are indicated in Tables 1 and 2. The rolled sample F1 was also annealed directly at 300 °C for 2 s and 10 s without 240 °C pretreatment, in order to observe rapid grain growth process. The microstructures during annealing were observed under optical microscope. {111}, {200}, {220} and {113} incomplete pole figures were determined based on the X-ray diffraction and the necessary orientation distribution functions (ODFs) were calculated.

Table 1 Chemical composition of experimental Al alloys

Sample	Composition, *w*/%
H1, H2-1, H2-2	Fe: 0.0004, Si: 0.0008, Cu: 0.0003, Al: >99.998
C1	Fe: 0.032, Si: 0.032, Cu: <0.001, Al: >99.9
F1, F2	Fe: 0.0027, Si: 0.0045, Cu: 0.0003, B: 0.0009, Ti: 0.01, Al: 99.98

Table 2 Experimental Al alloys, initial texture and parameters of recrystallization annealing

Sample	Main initial texture before cold rolling	Recrystallization annealing after 95% cold rolling
H1	{100}⟨001⟩	(240 °C, 600 s)+ (300 °C, 10000 s)
H2-1	{100}⟨011⟩	(240 °C, 600 s)+ (300 °C, 10000 s)
H2-2	{100}⟨011⟩	300 °C, 316 s
C1	{112}⟨111⟩	500 °C, 900 s
F1	{110}⟨001⟩, {110}⟨221⟩	(240 °C, 600 s)+ (300 °C, 10000 s)
F2	{110}⟨110⟩, {110}⟨114⟩	(240 °C, 600 s)+ (300 °C, 10000 s)

3 Results and discussion

3.1 Formation of recrystallization texture dominated by ON

Figures 1(a) and (b) give the initial textures of high purity aluminum samples before cold rolling. The initial cube {100}⟨001⟩ and rotated cube {100}⟨011⟩ are clearly to see in samples H1 and H2, respectively. The initial textures resulted in strong S {123}⟨634⟩ and Cu type {112}111⟩ texture respectively after 95% cold rolling (Fig. 1(c)), which indicates the close connection between initial texture and rolling texture in Al [12,13].

The cold-rolled samples H1 and H2-1 were firstly pretreated at 240 °C for 600 s to conduct a strong recovery while the stored energy and driving force for recrystallization were reduced drastically. The samples were then annealed at 300 °C for 10000 s, after which the primary recrystallization was completed. Cube recrystallization texture formed in both samples, while it was much stronger in sample H1. Comparing Figs. 1(a) and (b) with Figs. 2(a) and (b), it looks that the more the cube texture before cold rolling was, the stronger the cube texture after recrystallization became. Cube orientation is generally not a stable one during rolling deformation. However, some cube substructure could survive the rolling deformation [10,14,15]. It is also possible during rolling that some grains shift their orientations in a path, in which certain cell blocks might stagnate as they pass by near cube orientation [8,15]. The survived or stagnated cube substructure indicates stronger nucleation advantage [9], which could nucleate more frequently during annealing [16]. Therefore, the growth of cube grains will determine the formation of cube texture. Its density depends on how much cube substructure has survived the rolling deformation, which is surely initial texture dependent. It is obvious that the formation mechanism of recrystallization texture (Figs. 2(a) and (b)) was dominated by ON.

On the other hand, OG process could also help to form such a strong cube texture in Fig. 2(a), since the misorientation between cube orientation and four variants of rolling S texture in sample H1 (Fig. 1(c)) is just about 40°⟨111⟩, which could lead to rapid growth of