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A comparative study of the transformation kinetics of recrystallization texture of CC and DC 3003 aluminum alloys

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ABSTRACT

The evolution of recrystallization texture in cold-rolled CC and DC AA 3003 aluminum alloys was investigated by X-ray diffraction. The results show that a significant difference in recrystallization texture exists between the CC and DC AA 3003 alloys due to the effect of concurrent precipitation. For the CC AA 3003 alloy, low-temperature annealing of cold-rolled sheets results in very strong M and P recrystallization textures. The strength of the M and P recrystallization textures decrease significantly with increasing annealing temperature. For the DC AA 3003 alloy, the recrystallization texture consists of a major cube component and two minor R and Goss components after annealing at low temperatures. The cube, R and Goss recrystallization textures weaken with increasing annealing temperature. The transformation kinetics of recrystallization texture during isothermal annealing can be well described by the JMAK equation. For the CC AA 3003 alloy the *n* value decreases from about 2.9 to about 0.8 as the annealing temperature increases from 371 °C to 427 °C, while the *n* value is around 1.5 for the DC AA 3003 alloy. The apparent activation energy for recrystallization of the cold-rolled CC AA 3003 alloy is significantly higher than that of the cold-rolled DC AA 3003 alloy.

1. Introduction

Twin-belt continuous cast (CC) processing of aluminum alloy sheets has been used in commercial operations because of its advantage of short procedure, low energy consumption, low production cost and high productivity. In the CC processing, the molten metal is poured between two rotating steel belts to produce a cast slab, which is immediately fed into three consecutive hot rolling mills, forming hot-band products. Due to different processing routes, there are distinct differences in microstructure and texture between CC and direct-chill (DC) cast hot bands, which significantly affect the evolution of microstructure and texture during subsequent processing and hence the formability of aluminum alloy sheets [1–6].

An important aspect of the CC processing is that the CC hot band retains a large amount of elements in solid solution due to the rapid cooling rate of the CC slab. Concurrent precipitation occurs during annealing of cold-rolled sheets. Concurrent precipitation has a profound influence on the recrystallization kinetics, final grain size and recrystallization texture. Concurrent precipitation significantly retards recrystallization [7–9], results in a coarse elongated grain structure [8–12], and increases the activation energy for recrystallization of aluminum alloys [7]. The effect of precipitation on the recrystallization texture of aluminum alloys has been extensively studied [7–9,11–22]. It was found that low-temperature annealing resulted in relatively strong P {011}⟨455⟩ and normal direction (ND)-rotated cube {001}⟨310⟩ textures in commercial Al-Mn-Mg [13] and AA 3103 [14] alloys. A very strong P texture was obtained by low-temperature annealing of cold-rolled CC AA 3015 [7,15], CC AA 3105 [16], CC AA 3004 [11] and DC AA 3103 [8] alloys, and the strength of the P texture decreased with increasing annealing temperature [7,8,16]. In addition to the P texture, a new M {113}⟨110⟩ recrystallization texture was found in CC AA 5083 [17], CC 3003 [18] and DC Al-Mn-Fe-Si [12] alloys. The effect of different relative amounts of hot and cold deformation on the P recrystallization texture in CC 3105 alloy has been reported [16]. It was found that hot deformation strongly promoted the formation of the P texture during recrystallization annealing. The strength of the P texture in aluminum alloys increased with increasing rolling reduction [8,19,20]. The low heating rate was conducive to the formation of the P texture in CC AA 3105 [21], DC Al-Mn-Fe-Si [20] and DC Al-Mn [22] alloys. Although many investigations on the recrystallization texture of supersaturated aluminum alloys have been carried out, there is a surprisingly lack of quantitative information on the formation of the P and M textures as compared to the cube and R textures. In the present study, the hot bands of CC and DC AA 3003 alloys were cold rolled to 90% reduction. The evolution of recrystallization texture in the cold-rolled CC and DC AA 3003 alloys was investigated by X-ray diffraction.

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Table 1
Chemical compositions of CC and DC AA 3003 aluminum alloys (wt%).

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
CC	0.206	0.575	0.155	0.988	0.035	0.022	0.065	0.015	Bal.
DC	0.188	0.515	0.104	1.057	0.039	0.007	0.014	0.022	Bal.

Furthermore, the texture volume fractions were calculated by an improved integration method. The transformation kinetics of recrystallization texture during isothermal annealing was quantified by the Johnson-Mehl-Avrami-Kolmogorov (JMAK) equation.

2. Experimental

The materials used in the present investigation were CC and DC AA 3003 aluminum alloys. The chemical compositions of these two alloys are given in Table 1. The as-received materials were commercially produced CC and DC hot bands. The thickness of the CC and DC hot bands was 2.55 and 3.15 mm, respectively. In order to compare the evolution of recrystallization texture between the CC and DC AA 3003 alloys, the CC and DC hot bands were cold rolled to 90% reduction, and then annealed at different temperatures for various lengths of time in a salt bath, followed by water quenching.

Texture measurements were performed at the quarter thickness of the cold-rolled and annealed sheets. The (111), (200), and (220) pole figures were measured up to a maximum tilt angle of 75° by the Schulz back-reflection method using CuK_α radiation. The orientation distribution functions (ODFs) were calculated from the three incomplete pole figures using the series expansion method ($l_{max} = 16$) [23]. The ODFs were presented as plots of constant φ_2 sections with isointensity contours in Euler space defined by the Euler angles φ_1, Φ, and φ_2. The volume fractions of the cube, Goss, r-cube, r-Goss, β/R fiber and remainder components were calculated by an improved integration method [2,24,25]. The volume fractions of the P and M components were calculated by integration over the angular units of 15.5° from the {011}⟨455⟩ to {113}⟨110⟩ orientations, respectively.

3. Results

3.1. Evolution of Recrystallization Texture

Fig. 1 shows the texture evolution of the cold-rolled CC AA 3003 alloy during isothermal annealing at 371 °C, 399 °C and 427 °C. During annealing of the cold-rolled sheets, recovery and recrystallization took place. The β fiber rolling texture was converted into the recrystallization texture. It is noted that there was no significant change of texture during recovery of the cold-rolled sheets. The evolution of recrystallization texture depended strongly on the annealing temperature. At 371 °C, the strength of the β fiber rolling texture started to decrease after about 3 h. The intensities of orientations along the β fiber decreased with increasing annealing time. At the same time, two new P and M components started to form. The intensities of the M and P orientations increased with increasing annealing time. After complete recrystallization at 32 h, the resulting recrystallization texture was characterized by strong M and P components. At 399 °C, the strength of the β fiber rolling texture started to decrease after about 15 min. The intensities of orientations along the β fiber decreased with increasing annealing time, whereas the intensities of the M and P orientations increased. After complete recrystallization at 3 h, the recrystallization texture still consisted of strong M and P components. At 427 °C, the strength of the β fiber rolling texture decreased after about 2 s. After complete recrystallization at 15 min, the recrystallization texture consisted of a major P component and a minor M component. The intensities of the M and P orientations were lower than those at 371 and 399 °C. The recrystallization textures of the cold-rolled CC AA 3003 alloy after annealing at 454 and 482 °C are shown in Fig. 2. At higher temperatures the β fiber rolling texture disappeared after a short incubation time. The resulting recrystallization texture consisted of a weak P component.

Fig. 3 shows the texture evolution of the cold-rolled DC AA 3003 alloy during isothermal annealing at 288 °C, 316 °C, and 343 °C. It is noted that the texture evolution of the cold-rolled DC AA 3003 alloy during annealing was completely different from that of the cold-rolled CC AA 3003 alloy. At 288 °C, the strength of the β fiber rolling texture started to decrease after about 2 min. The intensities of orientations along the β fiber decreased with increasing annealing time, whereas the intensity of the cube orientation increased. After complete recrystallization at 2 h, the recrystallization texture consisted of a major cube component and two minor R and Goss components. As the annealing temperature increased, recrystallization took place and finished at a shorter time, and the cube and R textures weakened. Fig. 4 shows the recrystallization textures of the cold-rolled DC AA 3003 alloy at temperatures above 371 °C. It is seen that the recrystallization texture changed from a weak cube texture to a weak 22.5° ND rotated cube texture as the annealing temperature increased from 371 °C to 482 °C.

Figs. 5 and 6 show respectively the evolution of the β fiber during annealing of the cold-rolled CC and DC AA 3003 alloys, where the intensities of orientations along the centerline of the β/R fiber were plotted as a function of the angle φ_2. For the cold-rolled CC AA 3003 alloy, the maximum intensity of the β fiber was located at an orientation close to the S orientation, and the intensity of the B orientation was higher than that of the C orientation. The intensities of orientations along the β fiber decreased almost uniformly as recrystallization proceeded. This suggests that the B, S and C components have the same trend for recrystallization. This behavior was different from the change of the β fiber found in AA 5000 series aluminum alloys [3,26,27]. In AA 5000 series aluminum alloys the C and S components were the first to recrystallize followed by the B component so that the decreases in the intensities of the C and S orientations were larger than that of the B orientation after the onset of recrystallization. For the cold-rolled DC AA 3003 alloy, the maximum intensity of the β fiber was also located at an orientation close to the S orientation, and the intensity of the B orientation was similar to that of the C orientation. The intensities of orientations along the β fiber decreased after the onset of recrystallization. It is noted that the decrease in the intensity of the B orientation was significantly larger than that of the C and S orientations at the early stage of recrystallization. This suggests that the B component is easier to recrystallize than the C and S components in the cold-rolled DC AA 3003 alloy. This behavior is opposite to the phenomenon observed in AA 5000 series aluminum alloys [3,26,27].

3.2. Transformation Kinetics of Recrystallization Texture

In order to give a more complete survey of the evolution of recrystallization texture during annealing, the texture volume fractions were calculated by an improved integration method [2,24,25]. Figs. 7 and 8 depict the texture volume fractions as a function of annealing time at different temperatures for the cold-rolled CC and DC AA 3003 alloys, respectively. It is seen that significant changes in the texture volume fractions occurred during recrystallization. For the cold-rolled CC AA 3003 alloy, the volume fractions of the β fiber, Goss, and cube components decreased as recrystallization proceeded, whereas the volume fractions of the P, M, r-cube, and remainder components increased. For the DC AA 3003 alloy, the volume fraction of the β fiber component decreased as recrystallization proceeded, whereas the volume fractions of the cube, r-cube and remainder components increased. The volume fraction of the Goss component hardly changed with annealing time.

The effect of annealing temperature on the recrystallization textures of the CC and DC AA 3003 alloys is shown in Fig. 9, where the ratio (M_i/