The influence of Zener drag on recrystallization behaviour of twin-roll cast AA8079 alloy after homogenization

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Intermediate annealing is a crucial step of aluminum foil production. The as-cast material hardens during rolling and an annealing step is required at intermediate gauges to soften the material and restore its ductility. Generally, fine recrystallized structure could assure sufficient ductility for further rolling and processing. Recrystallization of the material during intermediate annealing can be controlled by a microstructure tailored during homogenization. Recrystallization behaviour of a twin-roll cast aluminum alloy AA8079 was studied. The as-cast strip was homogenized at 420 °C and 580 °C and rolled down to two different thicknesses. Evolution of microstructure of rolled materials during a model intermediate annealing was studied, and Zener drag and particle stimulated nucleation were determined as mechanisms controlling recrystallization.

1 Introduction

Several properties make aluminum an optimal material for use as packaging foil stock [1]. The AA8079 alloy is a low alloyed material containing iron and silicon. The equilibrium solubility of both elements in aluminum is low, which leads to a formation of intermetallic particles [2].

Twin-roll casting (TRC) reliably produces strips several millimeters thick [3-6], which is beneficial for the production of foil stock materials, as it reduces the number of required rolling steps during downstream processing when compared to traditional casting methods such as direct chill casting. During TRC the melt is poured on water cooled rolls where it rapidly solidifies [7]. As a result, the as-cast material has a gradient structure along the normal direction of the strip. A homogenization annealing step is required before further processing. This step is traditionally performed at temperatures above 520 °C in order to facilitate phase transformation of present phases of the Al-Fe-Si system into thermodynamically stable Fe-rich phases. This annealing step also changes size and morphology of particles [8]. Distributions of particles and present phases in the as-cast state depend on a specific alloy composition, casting speed and casting gauge [9-12]. Particles of the stable phase grow coarse during homogenization at high temperatures [8], which leads to a promotion of particle stimulated nucleation (PSN). PSN is an effect commonly used to facilitate the formation of a fine grained structure. Deformation zones with high dislocation density form around coarse particles during rolling and serve as nucleation sites for new grains during annealing [13].

However, a lower temperature of homogenization might be of industrial interest due to possible energy savings. Homogenization at lower temperatures does not facilitate noticeable changes in particle size and distribution. Therefore, PSN does not occur and a fine grained structure ought to be reached through an increased influence of Zener drag (ZD) [14]. ZD is a retarding force of grain boundary motion caused by the presence of fine particles. Retarding grain boundary motion allows nucleation of a larger number of grains, which leads to a finer grain structure.
The influence of homogenization temperature on a distribution of intermetallic phases in AA 8079 alloy was studied and mechanisms controlling softening of the material after subsequent rolling and annealing were determined.

2 Experimental methods

The experimental AA8079 alloy had a high Fe/Si ratio >> 1 containing 1.06 wt. % Fe and 0.06 wt. % Si. Thickness of the as-cast TRC strip was 7 mm. Samples cut from the strip were homogenized at two different temperatures (420 and 580 °C). Each sample was heated from room temperature for 8 h, soaked at the selected temperature for 8 h and then furnace cooled back to room temperature for another 8 h. Afterwards, the samples were cold rolled to 600 µm or 60 µm gauges and subjected to a model intermediate isochronal annealing. The isochronal heating was performed with an effective heating rate of 1 K/min. The annealed samples were then water quenched to room temperature.

Light optical microscope (LOM) observations were performed using Zeiss Axio Observer 7 in a bright field and polarized light regimes. Scanning electron microscopy (SEM) observations were done in a FEI Quanta 200F electron microscope. Microhardness was measured with the Qness Q10 device. Samples for all these measurements were prepared using a combination of mechanical polishing with SiC papers and electro-chemical polishing and etching methods. Samples for LOM and SEM particle observations were polished at room temperature in a 0.5 % solution of HF in ethanol. Samples for grain observations were polished at -15 °C in Barker’s reagent. All observations and measurements were performed in a transversal direction of studied strips.

3 Results and discussion

3.1 Recrystallization behavior

Evolutions of microhardness of rolled materials homogenized at different temperatures are shown in figure 1. The thicker material (600 µm) fully recrystallizes around 300 °C regardless of the homogenization temperature, and microhardness remains constant within an experimental error at higher annealing temperatures. The thinner material (60 µm) has higher initial microhardness due to a higher degree of plastic deformation during rolling. However, the thinner material softens over an extended temperature range. This range is smaller for the material with higher homogenization temperature. The influence of homogenization temperature on a grain structure in these materials is strong. The microstructure of specimens annealed isochronally to 350 °C is shown in figure 2. The microstructure differs significantly in both materials at this temperature. The thicker material (600 µm) homogenized at 420 °C coarsens significantly at 350 °C. The recrystallized grains are elongated in the rolling direction. Their size is approximately (50 ± 7) µm in the normal and (250 ± 50) µm in the rolling direction. The thicker material homogenized at 580 °C contains a bimodal grain structure. Coarse elongated grains appear close to the surface of the strip and fine equiaxed grains are located in the center of the strip. The coarser grains are approximately (111 ± 6) µm long in the rolling direction and approximately (52 ± 7) µm long in the normal direction. The finer grains in the strip interior have a diameter of (45 ± 5) µm.
Figure 1. Evolution of microhardness during isochronal annealing after two different temperatures of homogenization and two different reductions.

The behavior of materials rolled to 60 μm is inversed. The material homogenized at 580 °C has coarser grains (slightly elongated, approx. (33 ± 8) μm in the ND and (42 ± 9) μm in the RD) while only partially recovered and partially recrystallized fine-grained structure was observed in the material homogenized at 420 °C.

Figure 2. Microstructure of the TRC material after homogenization at 420 or 580 °C, rolling with two reductions and isochronal annealing up to 350 °C.

3.2 Influence of particle distribution

The driving force of recrystallization is a result of a high stored deformation energy. Particles and other material defects retard recrystallization. The influence of Zener drag of particles was quantified through microscopic observations. A simplified equation (1) can be used to quantify this retarding force [14]:

\[ F = \frac{2\pi r^2 \rho}{3} E \]
\[ P_Z = \frac{3 f \gamma_{GB}}{4 R}. \] (1)

In this equation \( f \) is the volume fraction of particles, \( R \) is their diameter and \( \gamma_{GB} \) is grain boundary energy. Grain boundary energy depends on a specific type of boundary and material. We assume a value of 0.3 J/m² for certain high angle grain boundaries in aluminum [15]. Size and volume fraction of particles is affected by a selected homogenization temperature. LOM images are used to determine the volume fraction of particles (figure 3) as they offer better statistics from a larger area of the sample. SEM images are more suitable for the determination of the particle size due to a better resolution (figure 4).

LOM images show particles distributed in eutectic colonies in material homogenized at 420 °C. These particles are fine and contribute to the control of recrystallization by ZD (figure 3 a), 4 a)). The material homogenized at 580 °C contains bimodal particle distribution with a combination of finer and coarser particles (figure 3 b), 4 b)). The coarse particles serve predominantly as potential nucleation sites after rolling and contribute to recrystallization controlled by PSN. Summary of measured particle volume fractions, the size of particles and an estimate of Zener drag according to equation (1) is shown in table 1.

![Figure 3. LOM image of a material homogenized at: a) 420 °C and b) 580 °C.](image)

![Figure 4. SEM image of a material homogenized at: a) 420 °C and b) 580 °C.](image)

| Temperature | Particle Volume Fraction f [%] | Diameter R [μm] | Zener Drag Z [kPa] |
|-------------|--------------------------------|-----------------|-------------------|
| 420 °C      | 8 ± 1                          | 0.3 ± 0.1       | 43 ± 11           |
| 580 °C      | 6 ± 1                          | 0.5 ± 0.1       | 24 ± 5            |

Table 1. Characterization of particles and estimation of Zener drag
The cold rolling process does not affect volume fraction or size of particles. However, the simplified equation (1) only applies for materials with homogenous distribution of particles and uniform particle sizes. This is not the case of the studied material. Thresholding of images is not exact either. As a result, the values of Zener drag are rather apparent and they affected by a large experimental scatter (table 1).

Fenomenological description of the effect of inhomogeneous particle distributions on recrystallization is difficult. Nes claims that a grain boundary moving through parallel layers of particles of thickness $d$ and spacing $l$ experiences effective Zener drag $P_{Z'}$ in these layers given by equation [14]:

$$P_{Z'} = \frac{l}{d} P_Z.$$  

This effective Zener drag is higher than Zener drag in a material with random particle distribution, but two major cases have to be considered – a boundary that is normal or parallel to the rolling direction. The normal boundary is retarded by the Zener drag given by equation (1) if it stretches over multiple particle layers or is not retarded at all when constrained within one interdendritic space. The parallel boundary is not affected by Zener drag in between dendrites and is pinned by Zener drag according to equation (2) after it reaches a layer with particles. This means that the retarding forces are weaker in the direction of eutectic dendrites (RD) than retarding forces in the normal direction. As a result, recrystallized grains can grow faster in the rolling direction, which results in elongated grains. Those were observed in the thicker material (600 µm) homogenized at 420 °C. This material coarsened significantly despite the higher apparent Zener drag value. Birol [8] shows, that this is a result of a preferred growth of several selected. The thinner material homogenized at 420 °C shows the smallest grain size after partial recrystallization. This could be a result of changes in particle distribution caused by rolling. SEM observations show that interdendritic spacing of particles decreases with increasing reduction (figure 5 a), b), and the value of ZD is closer to the one given by the equation (1). This implies a higher value of ZD in the rolling direction, which prevents preferential growth in this direction. The above-mentioned facts are confirmed by SEM (figure 5) in materials annealed up to 300 °C – a temperature at which recrystallization starts. The thicker material (figure 5 b)) contains grains already coarsened in the rolling direction (highlighted by the white oval), while no such grains are observed in the thinner material (figure 5 a)).

![Figure 5. Particle distribution in TRC materials homogenized at 420 °C, and annealed up to 300 °C after rolling to: a) 60 µm, b) 600 µm.](image)

The Zener drag of particles is weaker in materials homogenized at 580 °C. However, the increased nucleation through PSN results in a formation of fine recrystallized grains. Grain sizes after recrystallization are similar for both material thicknesses. However, grains in the thinner material (60 µm) are slightly elongated.
4 Summary
The studied material was homogenized at two different temperatures (420 and 580 °C) in order to
tailor processes controlling recrystallization. Both materials homogenized at 580 °C behave similarly
regardless of thickness. Recrystallization of these materials results in a coarser structure with grain
diameters between 30 and 50 μm in the central part of the strip thanks to the influence of PSN.

The Zener drag of particles in the material homogenized at 420 °C is higher. Behavior of the
thicker material is in accordance with previously published results, and softening controlled through
Zener drag yields coarse grains at 350 °C. However, softening process differs significantly after
rolling to 60 μm. The material retains partially recrystallized fine grained structure at 350 °C. This
grain structure is significantly finer than the one controlled by PSN in materials with higher
homogenization temperatures.

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