Recrystallization behaviour of AA6063 extrusions

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Abstract. Cylindrical profiles of an AA6063 aluminium alloy were produced in a lab-scale direct extrusion set-up. The extrusion was performed at 300 °C, 450 °C and 550 °C, respectively, with the same ram speed. Immediate water quenching was applied to the profiles and the end of billet (butt-end) after extrusion. Microstructure and texture of the material in different states were measured by electron back-scattered diffraction. Only the profile extruded at 300 °C, was found in the deformed state after extrusion, featuring a fibrous grain structure and a strong <111> and weak <100> double fibre texture. Post-extrusion annealing of this profile at 450 °C resulted in an almost fully recrystallized structure (recrystallized fraction of 87%) and with a texture similar to that of the as-deformed state. The profile extruded at 450 °C was almost fully recrystallized (recrystallization fraction 91%) already after quenching, and with a texture characterized by a weak <111> and strong <100> double fibre. The profile extruded at 550 °C showed a partially recrystallized grain structure with recrystallization fraction of 71%, and with a texture dominated by a <100> fibre. The influence of the deformation conditions on the recrystallization behaviour, in terms of recrystallization kinetics and mechanisms, are discussed in view of these results.

1. Introduction

Due to aluminium’s extremely good formability, aluminium profiles with very complex shapes can be extruded. However, productivity and for some high demand application areas consistent properties may be a challenge. One main issue is grain structure control and the ability to produce extrusions with a homogenous grain size and texture through the thickness of the profile. The microstructure of the extrusions is strongly dependent on the extrusion parameters [1-3] and on the microstructure of the billet material itself [4, 5]. This work aims to investigate the influence of extrusion temperature on the microstructure evolution and the recrystallization (RX) behaviour of an AA6063 aluminium alloy after axisymmetric extrusion. The motivation is to establish a better understanding of the recrystallization behaviour as basis for further development of numerical models for the recrystallized grain size and texture in this and similar alloys after extrusion.
2. Material and experiments

2.1. Material
The material investigated was an AA6063 alloy (chemical composition in wt% Si 0.4; Mg 0.5; Fe 0.096; Mn 0.017; Ti 0.01; Ga 0.012; Al remaining). After direct chill (DC) casting, the material was homogenized at 580 °C for 135 min, with a heating rate of 250 °C/h and a cooling rate of 400 °C/h. The grain structure and texture of the billet material were measured by electron back-scattered diffraction (EBSD) in a field emission scanning electron microscope (FESEM) equipped with the TSL OIM software, while the back scatter electron mode (BSE) was used to characterize the particles.

It was found that the initial grains were of equiaxed shape with an average diameter of 90 μm. The texture of the as-cast material was a random texture. The average diameter of the constituent particles was 1.4 μm, whereas the volume fraction was about 0.4%. There were no fine second-phase particles which could retard the RX process.

2.2. Lab-scale extrusion
Billets of 20 mm diameter and 22 mm length were machined from the homogenized material. Cylindrical profiles of 3 mm diameter were produced by direct extrusion in a laboratory scale direct extrusion set-up. Hence, the average accumulated strain at the end of extrusion was about 3.8. The container, billet, die and ram were heated together to the testing temperature before the start of extrusion. A thermocouple of type K with a diameter of 0.5 mm was inserted in the die in such a way that it ended at the circumference of the bearing in the middle of the 3 mm long bearing channel. The thermocouple did have contact with the flowing metal and recorded the temperature during extrusion.

The results reported in this paper refer to extrusions performed at 300 °C, 450 °C and 550 °C, respectively, with the same ram speed of 4.5 mm/s. The ram stroke was 9 mm, which accounted for an extrusion time of 2 s. At the end of extrusion, the extruded material and the die were immediately pushed into cold water while the press ring was retracted. The end of the billet and the profile were quenched below 300 °C within 2 s after the end of deformation, reading from the recorded temperature history by the installed thermocouple in the bearing.

2.3. Post-extrusion annealing treatment
The profile extruded at 300 °C was cut into small pieces along the extrusion direction (ED). A sample close to the end of the billet was annealed at 450 °C for 10 s in a salt-bath, followed by quick water quenching.

2.4. Microstructure characterization
The microstructure of the three as-extruded profiles and the post-extrusion annealed sample was measured by EBSD. The scan was made in the TD - ED plane of the cylindrical profiles (TD: transverse (radial) direction). The scanned areas were positioned very close to the butt-end, where the quenching was fastest and the material flow was close to steady state. The scanned area for the profile extruded at 300 °C was 0.5 mm along ED and 1.5 mm along TD, covering the region from the centre to the surface. The scanned areas for the other three samples covered the whole diameter region, i.e. 3 mm along TD. The step size in EBSD for the profile extruded at 300 °C and its post-extrusion annealed counterpart was 1 μm, whereas the step size was 3 μm for the other two profiles.

Recrystallized grains were identified as those being partly or fully surrounded by high-angle boundaries (defined as misorientation angles larger than 15°), with grain size larger than 6 times the scanning step size and a grain orientation spread (GOS) below 2°. The GOS was calculated by first averaging the orientation for each grain. The spread was then obtained by averaging the deviation between the orientation of each point in the grain and the average orientation for the grain. The GOS parameter has been found to be a successful approach with respect to EBSD data to discriminate between recrystallized and deformed grains [6]. Once the recrystallized grains were identified, the RX fraction could be evaluated. The recrystallized grain size is given in terms of the equivalent circle diameter.
The crystallographic texture was analyzed by using all scanning points. ED inverse pole figures (IPF) were employed to illustrate the texture.

3. Results and discussion

3.1. Results

The microstructures of the profiles extruded at three different temperatures are shown in Figure 1. Figure 2 illustrates the microstructure of the profile extruded at 300 °C and then annealed at 450 °C for 10 s. The colours in Figure 1 and 2 were coded according to ED IPF, where grains of the <111> and the <100> fibre texture are in blue and red colours, respectively. The corresponding textures of the three profiles and the post-extrusion annealed sample are shown in Figure 3 by means of ED IPFs. The RX fraction, average recrystallized grain size and the maximum intensities of the <100> fibre and of the <111> fibre are compiled in Table 1.

The profile extruded at 300 °C features an elongated, fibrous grain structure, as shown in Figure 1(a). Grains of the <111> fibre and of the <100> fibre appear alternating in the micrograph along TD. The area fraction of grains of the <111> fibre texture is larger than that of the <100> fibre. The difference in area fraction of the two texture fibres is also reflected by the texture strength, where a strong <111> and weak <100> double fibre is shown, see Figure 3(a). The <111> fibre is nearly 4 times stronger than the <100> texture fibre. Such a strong <111> and weak <100> double fibre has previously been reported as the deformation texture for axisymmetric extrusion of face-centred-cubic (FCC) metals [1, 7, 8]. The RX fraction is 15% by the criteria of GOS < 2°. However, no large equiaxed grains can be found in Figure 1(a). The recrystallized grains may be attributed to experimental error (low EBSD pattern quality for this profile) and to RX ‘nuclei’ which were too small to be well resolved in the current scan. The profile extruded at 300 °C was regarded to be in the deformed state.

The profile extruded at 450 °C features an equiaxed grain structure, as shown in Figure 1(b). The RX fraction is 91%. Hence, the profile is near fully recrystallized. The average grain size was 27.8 μm. The texture is a very weak <111> and strong <100> double fibre, where the <100> fibre is about four times stronger than the <111> fibre.

The profile extruded at 550 °C has a RX fraction of 71%, and can thus be considered as partially recrystallized. It is observed in Figure 1(c) that the recrystallized grains are of equiaxed shape. The average size of those recrystallized grains was 40 μm. There is a gradient of grain size along TD (radial direction), i.e. the size of recrystallized grains increases from the surface towards the centre, until the un-recrystallized region in the very centre of the profile. The texture is a single strong <100> fibre, as shown in Figure 3(c) and Table 1.

As described above, the as-extruded profile produced at 300 °C was in the deformed state. The microstructure after post-extrusion annealing at 450 °C for 10 s is shown in Figure 2. The RX fraction after post-extrusion annealing is 87%, similar to the RX fraction for the 450 °C extrusion, while the average grain size was 12.3 μm. The texture of the post-extrusion annealed sample is shown in Figure 3(c). The texture is a <111> and <100> double fibre, and both fibres are of similar intensities.

3.2. Discussion

The extrusion temperature has a great influence on the extrusion microstructure. Extrusion at 300 °C resulted in a deformed microstructure in the profile, whereas the profiles were fully or partially recrystallized when extrusion took place at 450 °C and 550 °C, respectively. The texture of the deformed profile was a typical strong <111> and weak <100> double fibre. At higher extrusion temperatures, the <100> fibre got stronger at the expense of the <111> fibre. The maximum intensity of the <100> fibre was four times stronger than that of the <111> fibre for extrusion at 450 °C. At 550 °C, the <100> fibre was dominant in the texture, while the <111> fibre was less than random. Due to fast dynamic recovery, discontinuous dynamic recrystallization will be suppressed for the current material [9]. Since the recrystallized texture is different from the deformed one, geometrical dynamic recrystallization or continuous dynamic recrystallization are also excluded [9]. Static recrystallization (sRX) is the
responsible RX mechanism for the RX behaviour of extrusions at high temperature. However, the sRX kinetics at 450 °C is very fast; recrystallization is nearly completed (RX fraction of 91%) within the delay time 2 s from the end of deformation to quenching. It is noted though that the kinetics is slower at the higher extrusion temperature of 550 °C. This can be explained by a slower sRX kinetics with a lower Zener-Hollomon parameter (less driving force for recrystallization) [10]. For the post-extrusion annealed sample at 450 °C, the RX fraction was 87% after 10 s. The post-extrusion annealing texture is a near-equally strong <111> and <100> fibre. This texture is clearly different from that of the high temperature extrusions, where the <100> fibre is dominant.

Figure 1. EBSD micrographs of the microstructure of profiles extruded at (a) 300 °C, (b) 450 °C and (c) 550 °C. Dark lines represent boundaries of misorientation larger than 15°.
Figure 2. EBSD micrographs of the microstructure of the profile extruded at 300 °C and post-extrusion annealed at 450 °C for 10 s. Dark lines represent boundaries of misorientation larger than 15°.

Figure 3. The ED IPFs of the profiles extruded at (a) 300 °C, (b) 450 °C, (c) 550 °C and (d) the profile extruded at 300 °C and post-extrusion annealed at 450 °C for 10 s.

Some preliminary considerations with respect to the different RX textures, based on the ‘oriented nucleation’ theory [11], can be made. It has been reported in the literature [7] that the <100> fibre grains have a lower stored energy than the <111> fibre grains, due to their faster recovery rates. Hence, the <100> fibre grains are potent nuclei for the recrystallization [7]. Both profiles extruded at 450 °C and 550 °C have a very strong <100> fibre. The post-extrusion annealed sample also has a stronger <100> fibre compared to that of the deformed state. All these RX textures give supports for the <100> fibre nucleation assumption for the current material. For the post-extrusion annealed sample significant <111> fibre nucleation has also taken place, given the relatively strong <111> fibre present in the RX texture. However, with increasing deformation temperatures, <100> fibre grain nucleation clearly
becomes the preferred nucleation mechanism, at the expense of the <111> fibre grains which get less favourable. The reason, however, is not clear, and more thorough investigations should be made to explain these different RX behaviours.

| Table 1. Summary of texture, RX fraction and average diameter of recrystallized grains for the three extruded profiles and the post-extrusion annealed sample. |
|-----------------------------|----------------|----------------|----------------|----------------|
| Extrusion temperature      | Post-extrusion annealing | RX fraction | Max. <100> fibre intensity (times random) | Max. <111> fibre intensity (times random) | Average recrystallized grain size (μm) |
| 300 °C                     | -              | 15%           | 4.6            | 17.5          | -              |
| 450 °C                     | -              | 91%           | 7.9            | 1.9           | 27.8           |
| 550 °C                     | -              | 71%           | 21.7           | <1            | 40             |
| 300 °C                     | 450 °C, 10 s   | 87%           | 8.1            | 10.4          | 12.3           |

4. Conclusion
The extrusion temperature is shown to have a great influence on the RX behaviour of the AA6063 material. For high temperature extrusion (above 450 °C for the alloy and processing conditions in the present work) the extruded profiles recrystallize directly after extrusion due to fast sRX, and the <100> fibre is the dominant RX texture component. The kinetics, however, of sRX decreases again at the highest temperature, due to less driving force for recrystallization. For warm temperature extrusion (300 °C in this work) the profile is in the deformed state after extrusion, featuring a strong <111> and weak <100> double fibre texture. After post-extrusion annealing at higher temperature, the texture is an equally-strong <111> and <100> double fibre texture, which is clearly different from the textures after high temperature extrusion. This difference may be explained by orientated nucleation under different extrusion temperatures, i.e. <100> fibre grain nucleation is the preferred nucleation mechanism and outweigh the <111> fibre grains, which become even less favourable for nucleation at higher extrusion temperatures. Further investigations should be made to fully understand the different RX textures and behaviours at high temperature extrusion and the post-extrusion annealing after warm extrusion.

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