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Effect of Material Flow during Extrusion on Recrystallization Behaviour of AA6082

Tanja Pettersen[1] , Shariar Abtahi[2], Jan Anders Sæter[1], Trond Furu[1], Hans-Erik Ekström[3]

[1] Hydro Aluminium R&D Materials Technology; N-6600 Sunndalsøra, Norway
[2] NTNU, Department of Materials Technology, N-7034 Trondheim, Norway
[3] Sapa Technology, SE-61281 Finspång, Sweden

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Abstract

During extrusion of round profiles of a AA6082-alloy, circular recrystallized regions were found for certain extrusion conditions [1-4]. In addition to a ring of recrystallized material at the surface, a second ring was occasionally found deeper in the profile. The present work was carried out to investigate the origin of this recrystallization pattern. Special attention has been paid to the deformation history of the metal passing through the die. FEM simulations and extrusion with markers (contrast material) was conducted in order to study the metal flow during extrusion, and the material from these extrusion trials were used to test different hypotheses for the origin of the recrystallized rings.

1. Introduction

During extrusion, the material undergoes a complex deformation-, with combinations of deformation modes, variation in temperature, strain rate and strain as a function of the position in the profile. The as-deformed microstructure and texture constitutes the basis of the concurrent or subsequent recrystallization process, and together with the recrystallization process hence becomes important in controlling the properties of the final product. In extrusion, one of the aluminium alloys where the recrystallization process is particularly important is the alloy AA6082. Extruded products of this alloy are frequently found to contain mixed grain structures, with a fibrous fine subgrain structure mixed with coarse recrystallized grains in other parts of the profile. These recrystallized regions impair the properties of the profile, and are undesirable.

To investigate the evolution of microstructure and texture during extrusion, a series of extrusion experiments producing round bars of 6082-alloys have previously been performed and reported [1-4]. In these experiments four different extrusion speeds, three different die geometries and four different homogenization treatments were combined, giving a matrix of 33 trials. The chemical composition of the material used was 0.18-0.19 wt% Fe, 0.94 wt% Si, 0.63-0.64 wt% Mg and 0.50-0.52 wt% Mn. The different homogenization treatments were given to produce material with different size distributions of coarse and small particles, and included (1) 585°C for 3 hours, (2) 590°C for 16 hours, (3) 550°C for 8 hours and (4) 590°C for 8 hours followed by 550°C for 4 hours.

The three different die designs used in the experiments all gave round profiles of 45 mm diameter, and were manufactured with (N) 5 mm feeder and 23 mm bearing, (S) 5 mm feeder and 5 mm bearing and (D) 23 mm feeder and 5 mm bearing.

When investigating the microstructure of the extruded round profiles [4], recrystallized grains were seen to form one or two separate rings. The first ring appeared at the surface while the second one was 2-5 mm from the surface. The surface-ring was found in most of the samples, while the second ring was found primarily in the samples extruded with long feeder and short bearing length (D). In some of the samples, single coarse grains appeared instead of the rings or parts of the rings. For some samples no coarse recrystallized grains could be distinguished, but different contrast at the same distance from the surface gave evidence that the microstructure was modified in this layer. Recrystallization was more pronounced after high extrusion speeds and high homogenization temperatures. The 2-step homogenization procedure gave a recrystallized layer that was thicker than that after the homogenization at 585°C, but thinner than that after homogenization at 590°C. The combination of high homog temperature and high speed was found to result in joining of the surface- and the ring in the middle of the profile. While in the samples homogenized for 3 hours at 585°C no inner ring was observed.

Based on the results from these previous investigations of recrystallization [1-4] in round profiles, the present work looks more closely into the origin of the inner recrystallized ring. One die-geometry and a set of extrusion parameters have been chosen and extrusion experiments have been performed to further illuminate the deformation conditions in the profiles. A brief modeling treatment has been made of the extrusion process.

2. Experimental Procedures

Full-scale industrial extrusion trials were carried out at Sapa, Finspång. The material used in the experiment was an AA6082 alloy DC-cast and homogenized according to standard industrial practice at Hydro Aluminium. The billet diameter and length was 203 mm and 3.5 m, respectively. The chemical composition of the material was 0.19 wt% Fe, 1.03 wt% Si, 0.66 wt% Mg and 0.53 wt% Mn as determined using spectrographic analysis. Prior to deformation, fine half-circle shaped slits of thickness 2.5 mm were machined from the billets, and the voids were carefully filled with marker-material (Al-2.2% Cu). This is illustrated in Figure 1. For further details on use of marker material, confer [5]. The inner diameter of the container used in the extrusion trials was 210 mm. The die-design was identical to D in [2], *i.e.* the feeder depth and width was 23 mm and 10 mm respectively, and the bearing length was 5 mm. In order to have well defined boundary conditions for FEM simulations, a bearing geometry with closing angles or so-called “choked” geometry was used. The profiles produced in the extrusion trial were round rods with diameter of 45 mm, giving an extrusion ratio of 21.8. The cooling of the profile was carried out using 2350 mm with air-cooling, followed by 3000 mm with water-cooling and finally air-cooling.

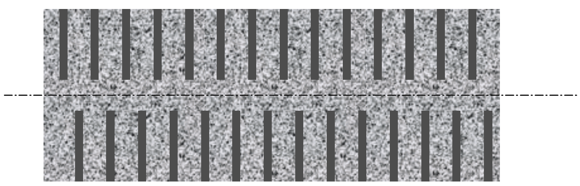

Figure 1: Schematic drawing showing the billet with contrast material before extrusion.

After extrusion the rods were cut in pieces of 100 mm length, and then longitudinally cut to reveal the cross section of the profile. The samples were ground using SiC paper with grit size of 80-120, and etched to reveal the contrast material using Tuckers etch for 1-2 minutes. Finally the samples were sprayed with varnish to preserve the etching pattern.

Samples for optical microscopy were prepared by grinding to a grit size of 1200 followed by electrolytical polish and finally anodising to reveal the grain structure. In the modeling treatment the temperature compensated strain rate (Zener-Hollomon parameter) has been used; $Z = \dot{\varepsilon}\exp(U/RT)$, where $\dot{\varepsilon}$ is the strain rate, U is an activation energy, R is the gas constant, T the temperature. An activation energy of 152 kJ/mol has been used.

3. Results

3.1 Extrusion with Markers

To let the die reach some equilibrium temperature before starting extrusion of the billets with contrast-material, billets without contrast-material were extruded before and in-between the extrusion trials reported here. Hence, extrusion 1,2 and 4 were dummy-extrusions. The material studied from extrusion number 3 and 5 are referred to as C and E respectively. The trials were carried out with a container temperature of 425°C and a billet temperature that started at approximately 470°C, increasing to a value slightly below 550°C during extrusion. The extrusion speed of the C-profile was 11 m/min corresponding to a ram speed of 8.3 mm/s, and the speed of the E-extrusion was 13 m/min corresponding to a ram speed of 10.1 mm/s.

After extrusion the material was studied in the light optical microscope. The result can be seen in Figure 2. As shown in the micrograph, recrystallization only occurred in the contrast material. This was the case for the entire profile length of both profile C and E. The homogenization treatment before extrusion of profile C and E was similar to homogenization treatment (1) in [1-4]. In [4] no recrystallized rings were found in this material. The present result is hence in accordance with previous investigations.

Figure 2: Light optical micrograph showing the cross section of the C-profile in the middle of the profile.

The contrast material was visible as dark gray lines in the profile after etching. The changes in the position of the contrast material were carefully monitored to visualize the flow pattern during extrusion. For each plate of contrast material the distance from the line to the surface was measured at different positions along the profile. The results from these measurements are shown in Figure 3. In this Figure special attention should be given to the region ~2 mm to 5 mm from the surface, as this is the region where the recrystallized inner rings previously were found [4]. As can be seen from the figure the material in the inner part of the profile is less deformed than the material closer to the surface. This is as expected due to the friction conditions in the die.

The curves are also relatively smooth, indicating no pronounced change in material flow. However, all the curves are seen to have a small region where the distance of the contrast material from the surface is constant. *I.e.* for Plate 1 the region is ~2 mm from the surface (in a position ~250-520 mm from the start of the profile), in Plate 2 the region is ~2mm from the surface (position ~620-860mm), in Plate 3 the region is ~4 mm from the surface (position ~720-960 mm), *etc.*.

3.2 FEM Modeling of the Extrusion Experiment

The computer program Alma was used to simulate the temperature, strain rate and equivalent stress fields during extrusion. A model was built including the container, the die and the aluminium. The dimensions of the different parts were identical to those in the experiment, *i.e.* the diameter of the ram was 210 mm, the feeder depth was 23 mm and the bearing length was 5 mm. A modified Sellars-Tegart material model was used, the friction coefficient was set to 0.4, the inlet radius was 0 mm and the die angle was 2°. The temperature of the ram, container, die and billet was 480°C, 450°C, 385°C and 480-530°C, respectively. The results from the simulations with a ram speed of 12 m/s are shown in Figure 4. As can be seen from the figures, the temperature is slightly higher at the surface (~590°C) than in the center (~540°C-550°C) and Z is seen to be close to constant over the cross section.

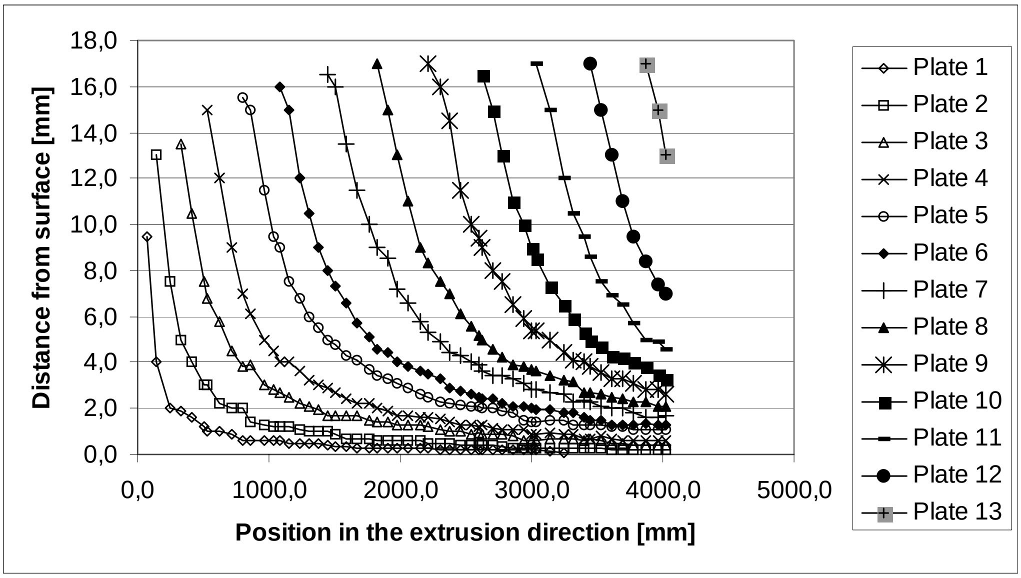

Figure 3: Measurements of the position of the contrast material as a function of distance from the start of the profile. The 0-position, *i.e.* the start of the profile is defined to be in the sample closest to the charge-weld.

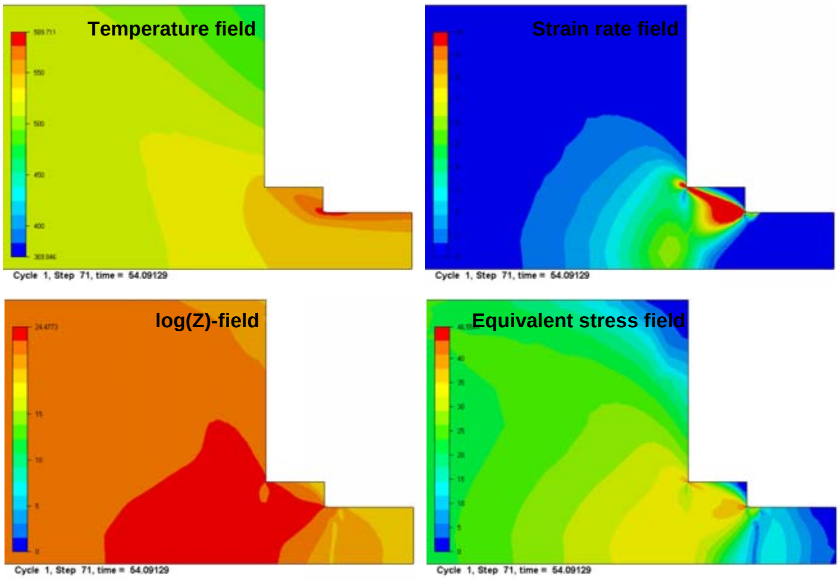

Figure 4: Temperature, strain rate, equivalent stress and log(Z) close to the die exit. The simulation was carried out with ram speed of 12 m/s (exit speed of 260 m/s).

4. Discussion

The following discussion will consider the origin of the recrystallized inner rings in the extruded rods. As shown above, the temperature, strain rate and the effective stress will change over the cross section of the profile. Hence, the resulting changes in as-deformed microstructure have to be considered as the possible origin of the recrystallized ring. The cooling rate after extrusion will change over the cross section, creating differences in temperature that has to be evaluated with respect to the resulting recrystallization pattern. Finally, local deformation conditions in the die, not given by the modeling treatment, such as localized shear deformation, will create differences in stored energy over the cross section of the profile. The presence of such regions is treated in this investigation.

The simulations in Fig 4 shows the changes in temperature, strain rate, Z and stress over the cross section in the profile. The high surface temperature combined with constant Z should indicate a constantly decreasing probability of recrystallization when moving from the surface to the center. Although a thin recrystallized ring is found at the very surface, this does not explain the origin of the 2nd recrystallized ring inside the deformed region.

The final resulting microstructure will be partly determined by the cooling conditions. The cooling will start at the surface, and gradually move into the profile. Before cooling the temperature-profile is as illustrated in Figure 5. Combining this with cooling at the surface, gives a region below the surface with maximum temperature. Provided that the cross section is thick enough compared to the rate of recrystallization, the effect of the cooling will not reach the subsurface part of the profile before recrystallization has occurred. However, the simulations of the cooling showed that for the present geometry this would only be the case for a material with a much lower heat conductivity (~100-1000 lower).

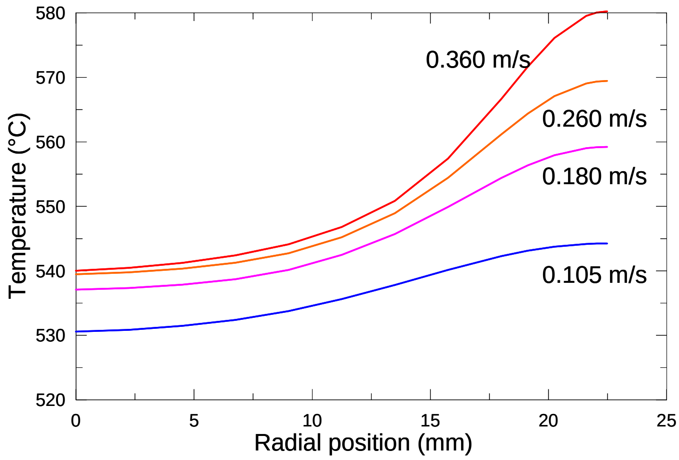

Figure 5: Temperatures at the die exit as obtained by FEM modelling. The position 25 mm corresponds to the surface, and 0 mm corresponds to the centre. The numbers in the figure are exit speeds.

As previously found [1-4], the recrystallized ring was most frequent when using dies with a long feeder. If the feeder is long enough, a discontinuity in the aluminium flow could develop. Such discontinuity cause severe deformation and localised heating, which both promote the recrystallization processes. Figure 6 schematically illustrates the situation close to the inlet of the die for two slightly different assumptions. For both cases it is assumed that the velocity in the interior of the die is larger than close to the surface. In Figure 6a) there is a discontinuity in the velocity from surface to centre. This will create a shear band, which in turn will give higher probability for formation of a recrystallized region. In Figure 6b) there is a gradual but steep change in the velocity from the low surface velocity (v_2) to the higher centre velocity (v_1). This will create a region with high deformation and high temperature, leading to a higher probability for recrystallization.

In the present work, contrast material was inserted into the billets before extrusion to reveal discontinuities in the material flow. The effect of a shear band/high deformation region on the appearance of the contrast material in the die and in the profile is shown in Figure 6. As can be seen from the figure, if the velocity difference leads to a region with higher deformation than the surroundings, the contrast material will have a change of direction in the profile. As seen in Figure 3, the curves of contrast material were relatively smooth, indicating no pronounced change in material flow. However it should be noted that for many of the plates, a small region of contrast material was found to be approximately parallel to the extrusion direction indicating a region with localized shear deformation. The parallel sections of the curves were found in the region where the second ring was observed (*i.e.* 2–5 mm from the surface). It should be stressed that this region of parallel contrast material is rather small, and further investigations are needed to establish the above hypothesis.

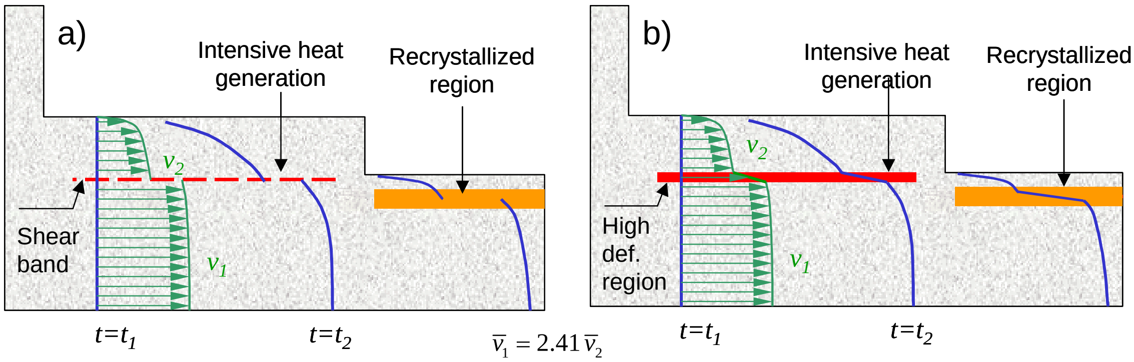

Figure 6: Schematic drawing showing two different hypothesis for formation of a region of high deformation in the subsurface layers of the profile. Blue lines indicate marker material.

5. Conclusions

In the present work contrast material was inserted into the material to investigate the material flow. FEM modeling of the process was also carried out. The Zener-Hollomon parameter was seen to be close to constant over the cross section of the profile, and the temperature was seen to decrease from the surface to the center, this could hence not explain the formation of recrystallized rings. The cooling of the profile changes over the cross section of the profile, however, due to the high thermal conductivity of aluminium, this could not explain the formation of the recrystallized ring. The investigations of the contrast material, showed small regions of contrast material that was parallel to the extrusion direction, however, these regions were too small to confirm the hypothesis of formation of a high deformation region leading to recrystallized rings.

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