Journal of
Mechanical
Science and
Technology

Journal of Mechanical Science and Technology 21 (2007) 1445~1451

Microstructure analysis of aluminum extrusion: grain size distribution in AA6060, AA6082 and AA7075 alloys

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(Manuscript Received May 31, 2007; Revised August 30, 2007; Accepted September 30, 2007)

Abstract

Microstructure and material flow of aluminum alloys have a significant influence on the mechanical properties and surface quality. In extrusion of aluminum billets at high temperatures the microstructure is dependent on the alloy and the forming and temperature history. A prediction of grain size and precipitation is of increasing importance in order to design the process by adjustment of parameters such as punch speed, temperatures, and quenching. To give references for microstructure prediction based on material flow, and with it strain and strain rate history, this paper deals with the microstructure during the extrusion process of AA6060, AA6082, and AA7075 alloys. Billets have been partly extruded to axisymmetric round profiles and the microstructure of the press rests consisting of the billet rests in container and die has been considered. Furthermore, these rests have been analyzed to show the material flow, dynamic and static recrystallization based on macro etchings and visible microstructure under different conditions, e.g. as in the area of high strain rate near the container wall, or in dead zones [1]. To allow an accurate simulation of the extrusion process, punch force and temperature conditions during the tests have been measured and are presented in this paper, too.

Keywords: Extrusion; Microstructure; Simulation

1. Introduction

The analysis and prediction of microstructure in extrusion processes of aluminum alloys has become of increasing importance in recent years. Models for grain size development and recrystallization prediction have been used in combination with finite element codes over the last years by many researchers such as [2, 3]. This effort is not only motivated by the determination of the microstructure itself, but by predicting the mechanical product properties after heating, extrusion, and quenching without performing time and cost expensive experimental extrusions and characterizations. To model and simulate the microstructure evolution, reference experiments and characterizations have to be done under controlled process conditions that can be used for parameter identification and for verification, e.g. based on finite element simulations.

Komarek et al. have presented that a dynamic recrystallization occurs in extrusion, and the recrystallized grain size is a function of extrusion parameters and post extrusion heat treatment [4]. Analyses of microstructure based on etched billet rests have been presented in the early 1980th by Sheppard and Paterson [5]. There, a comparison of the occurring microstructure was presented which was based on the material flow of indirect and direct extrusion. By analysis of macrosections of directly

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and indirectly extruded billets extruded into the quasi-static state, it was possible to show that the extrudate is more homogeneous in the direct extrusion process, resulting in a more uniform grain structure. In addition to the experimental work theoretical analyses based on the upper-bound method have been done.

In [6], a broad range of occurring microstructures in the metal flow in billets of thin-walled extrusions has been presented. The focus of the work was on the macro-, meso-, and microscale evaluation of the structure for 6xxx aluminum. Using a flat die to extrude a profile with thin and heavy sections, both sections are analyzed regarding the structure development in the dead metal zone (DMZ), the shear intensive zone (SIZ), and the main deformation zone (MDZ). It was possible to proof the usage of the metallurgical analysis method using light optical microscopy, scanning electron microscopy, and electron backscatter diffraction to characterize the metal flow and to theorize that the extrusion exit speed is a more dominant factor in controlling the metal flow rather than the profile geometry. But due to the fact that two variables have been altered simultaneously the results cannot be directly compared with other samples.

In many further works the simulation of the deformation path, recorded process parameter, or microstructure analysis has been presented. A combination of all factors is only rarely done. This paper (part I +II) shall give all process analyses in order to provide some reference data for analysis methods, process simulation, and verification based on a simple geometry.

2. Experimental investigations

The experimental investigations have been carried out using a simple axisymmetric die shape in order to guarantee a symmetric microstructure distribution. Based on the geometry shown in Fig. 1, extrusion of three different standard aluminum alloys (EN AW-6060, EN AW-6082, and EN AW-7075) has been done by keeping the process and tool boundary conditions, such as punch speed or container temperatures, as constant as possible. In order to control this procedure and to make it useful for verification in finite element simulation regarding the verification of the process parameter material flow and microstructure, a continuous measurement of punch force and temperatures along the punch travel has been done.

For the development of a microstructure (recrystallization, grain grow) the temperature is one of the most important influencing parameters. In the analyzed case the temperatures have been monitored by thermocouples during the whole heat treatment process starting from initial heating to process handling, extrusion, and cool down. The temperature history is shown in Fig. 2.

It has to be distinguished between temperature of the profile and temperature of the billet. Due to the time that is needed to evacuate the billet from the container after extrusion the billet did not cool down after extrusion for approximately 15 minutes while the temperature of the exiting profile starts to decrease directly after exiting the die. Both have been cooled on ambient air till they reached room

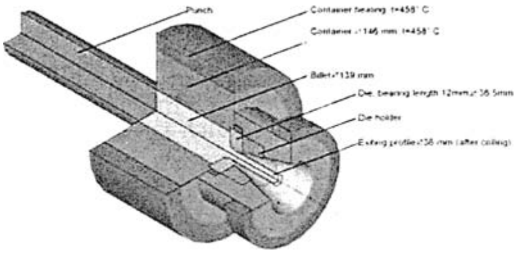
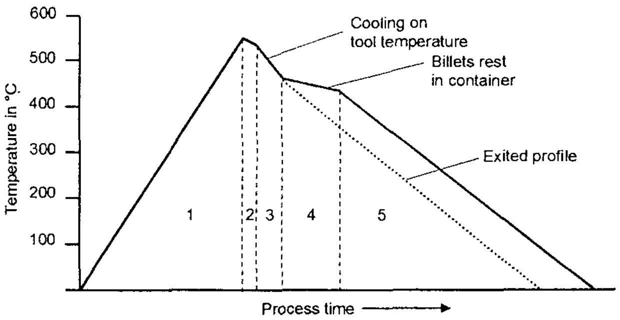


Fig. 2. Geometry for axisymmetric extrusion.



Process:	Time (min)	Temperature
1 Preheating	480	υ_{oven}=550 °C
2 Handling	2	cooling $\Delta\upsilon$=10° C
3 Extrusion	4-6	cooling to tool temperature (υ_{tool}=400-450°C)
4 Remaining time in container	15	
5 Cool down on air	till cool down	υ_{air}= 20°C

Fig. 1. Billet and profile temperature over process time, schematic.

temperature (Fig. 2).

Because an immediately quenching of the press rests after extrusion was not possible the analysis contains dynamic recrystallization during the forming step as well as static recrystallization and grain growth when the material remains at high temperature in the container and during the cool down phase.

To analyse the result quality of the microstructure simulation, it is of significant importance to check as many monitored process conditions as possible to make sure that an accurate forming state is considered. In this case ram load as well as die and profile temperatures have been analyzed in addition to the microstructure. The process monitoring is shown in Fig. 3.

As it can be seen in the curves, after an initial upsetting the occurring punch forces differ for the three alloys due the differed materials strengths. While the EN AW-6060 has a yield point of 36 MPa for a strain rate of 1 and a temperature of 450 °C, the EN AW-6082 has 55 MPa and the EN AW 7075 77 MPa. In dependence of the billet length, and with it the friction length on the container wall, the forces reduce with increasing punch travel to 75 to 80 percent for the two 6xxx alloys. In order not to excess the maximum extrusion press force for the EN AW-7075 alloy, the billet length was reduced to 140 mm instead of 295 mm for EN AW-6082 and 298 mm for EN AW-6060. Due to the different billet length the punch forces reach maximum peak values of 3 to 4 MN at a constant punch speed of 0.3 mm/s.

For an analysis of the material flow and the grain structure in the press rests the extrusion was stopped after a punch travel of approximately 40-50 percent of

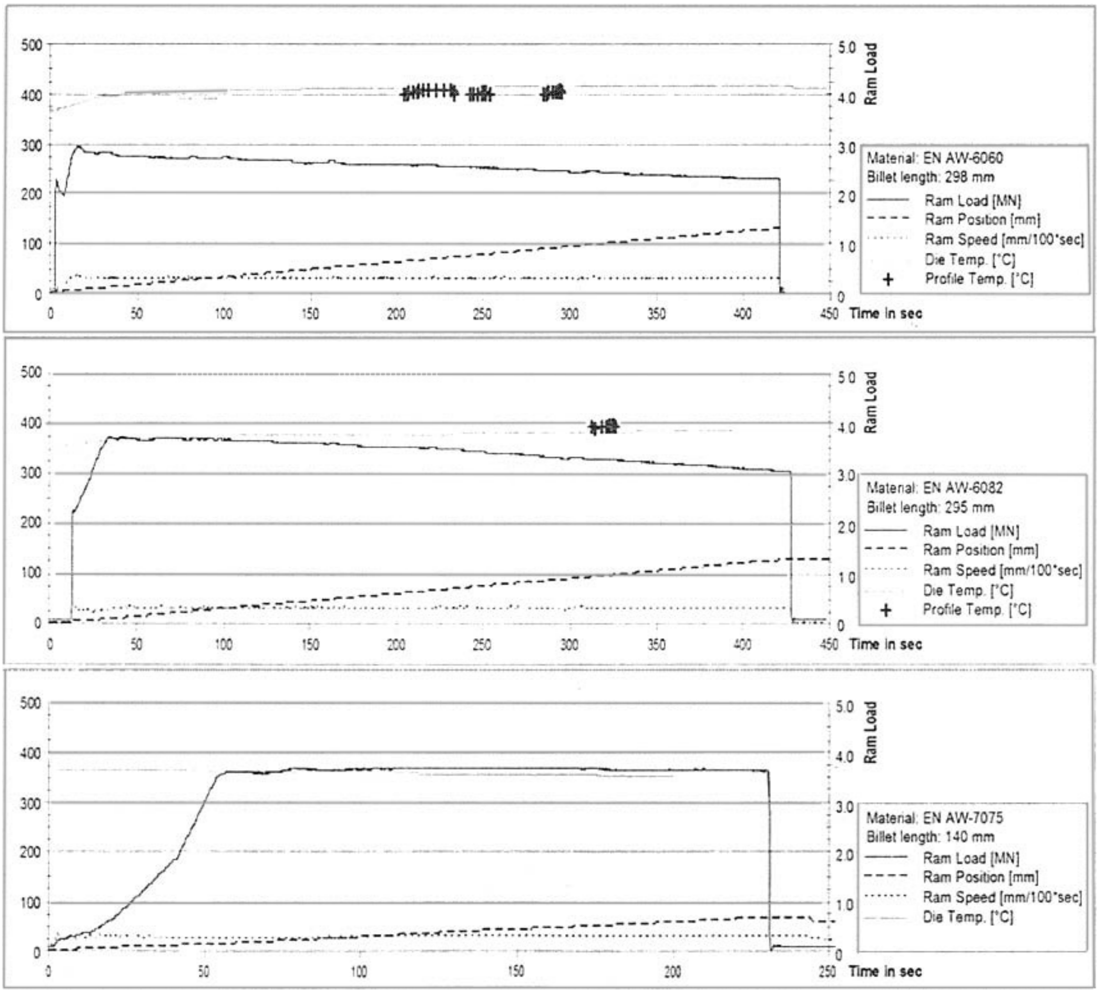


Fig. 3. Monitored process conditions during the extrusion of different aluminum alloy billets.

the billet's length (punch travel EN AW-6060 s_{Ram} = 128 mm, EN AW-6082 s_{Ram} = 126 mm, EN AW-7075 s_{Ram} = 67 mm) in order to have a large area for an analysis of the material flow with different strain conditions.

As it can be seen in the profile temperature measurement the initial temperature of 550 °C of the preheated billet in the oven decreases to an exiting temperature of the profile of approximately 400 °C. Due to the container temperature of 450 °C and the die temperature of 360 °C to 380 °C the material flowing through the die cools down. Parallel, the die temperature increases. Except for the measurement of the profile's exiting temperature the profile was not considered any further.

After the maximum punch travel has been reached the extrusion was stopped and the billets have been evacuated from the container after a remaining time of 15 minutes to open the container and to press out the rests. This was done by cutting the exiting profile, driving the punch and container with the press rest backward, and finally pressing the rest with the punch out of the container. Due to the friction and the contact of the billet to the container wall the previously nearly plane die side of the billet was cambered even more the softer the material was.

After removing the billets, these cooled down slowly on ambient air to room temperature.

3. Results

3.1 Material flow and microstructure analysis of the macro sections

To analyze the microstructure the billets have been prepared for metallurgic investigations. After cooling down the rests were sawn next to the symmetry plane and machined and polished in order to prepare the etching. The three specimens were chemical etched at room temperature for 5-8 minutes with 90 ml H_2O, 15 ml HCl, and 10 ml HF based on Flick procedure.

Fig. 4 shows the macrosections of the billets after the etching procedure in the symmetry plane. As shown in [7], it can be observed on the macro etching that the micro structure differs significantly regarding to the grains position in the material flow. Aiming at a complete analysis of the material deformation path during extrusion, the macro images of the complete billet are shown and micro images along the

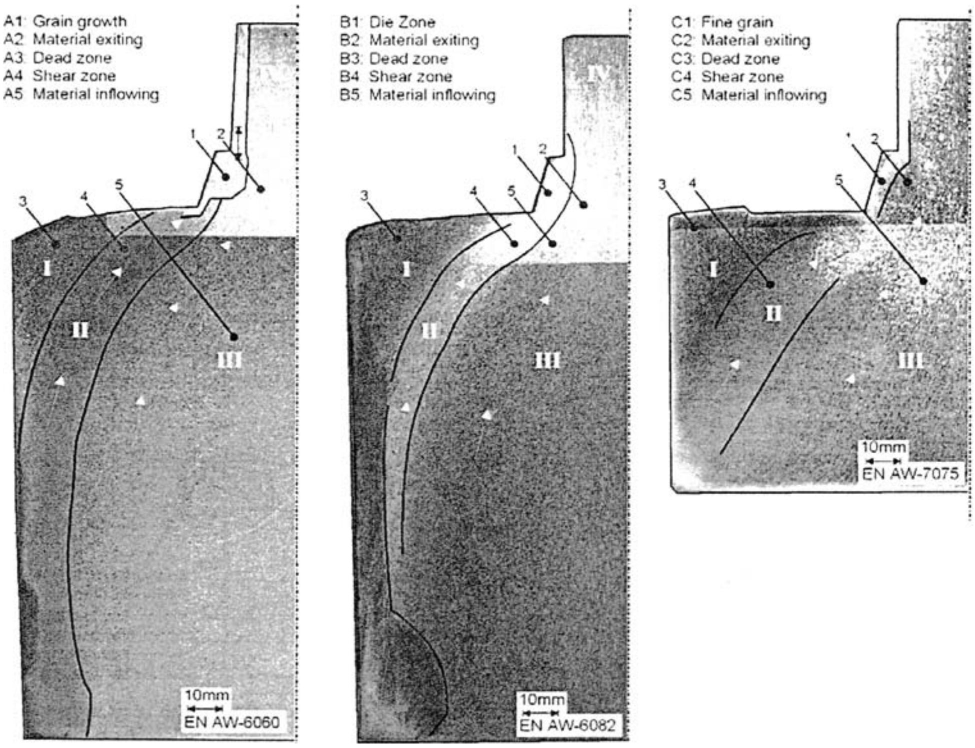


Fig. 4. Macro etching of the EN AW-6060, EN AW-6082, and EN AW-7075 extrudate.

deformation path, too. For all alloys mainly four different zones develop which can be distinguished by their etching response like grain pattern, grayscale level, and reflection can be seen. In order to give a good contrast in the printout, the brightness and contrast of the digital pictures has been adapted. The "tapered" look of the billets is caused by the angle of taking the photographs in order to reduce reflections. Tentative material flow lines have been used in order to separate the major zones of the deformation process.

All three aluminum alloys show the same basic zones of deformation for direct extrusion: Zone I is the dead metal zone (DMZ). The material stays nearly without movement in this region during the extrusion process. It is exposed to high temperatures and high hydrostatic pressure, but only less strain and strain rate. The microstructure in this area is dominated by the initial microstructure. Because of the absence of plastic deformation no dynamic and no static recrystallization will occur. Furthermore no grain growth will appear according to the lack of recrystallization. Zone II is the shear intensive zone (SIZ) of deformation and outlines the DMZ. Caused by the change-over to not or only very limitedly moving material (DMZ and container wall) and the main material flowing into die direction, the grains in this area undergo high shear strain deformation. The original grains after homogenization orientate tangentially to the material flowing and preferentially elongate to long narrow banded grains. The direction changes approximately hemispherical with decreasing distance to the die opening due to the material flow. The material flows in the exiting profile and flows concentrated in the boundary areas of the profile. This effect of extremely stretched and deformed material at the profile's surface can be seen even more clearly in [8]. Here, a visio-plastic analysis with rods of a different aluminum alloy within one billet shows the difference in deformation of the material inflowing in the profile center and the profiles surface areas. Due to the high grade of deformation and even highest occurring strain rates these areas are expected to show most dynamic recrystallization and even grain growth. The material in the SIZ has to undergo highest strains and strain rates in the billet and due to dissipation of plastic work higher temperatures will occur.

In contrast to this zone, the material in the main deformation zone III (MDZ) flows directly into the die orifice. The grains do not deform initially or deform only rarely within the billet. They have to undergo a translatoric movement that leads to a plastic deformation only next to the die opening. The grain structure again is mainly influenced by the initial grain size after homogenization. It has to undergo high temperatures and high hydrostatic pressure and with decreasing distance to the orifice strain and strain rate increase. Dynamic recrystallization in this zone can appear only in short distance to the die exit.

The fourth zone is the exiting profile zone (EPZ) that shows the result of all the influences the material undergoes before. In this zone the microstructure can differ drastically, depending on the recrystallization history in relation to the position in the profile. Highest strains, strain rates, and also cooling rates occur next to the surface.

3.2 Analysis of microstructure and material flow on meso level

Considering the different loading paths when material particles follow the flow, the microstructure has to be interpreted in order to explain recrystallization and grain growth in the extrusion process. Based on the macro etchings of Fig. 4, an analysis of the meso level has been carried out to study the flow lines and the microstructure seen in the macro etchings (Fig. 5).

Analysis of the EN AW-6060 shows the most apparent differences in microstructure in relation to the different forming zones. The grains in the DMZ (Fig. 5, A3) show an approx. equiaxed size. Due to relative small plastic strain and strain rate it is assumed that these grains show the initial grain size and structure, which can be expected when little forming occurs.

In contrast to this, the grains in the SIZ (Fig. 5, A4) have an oriented, fibrous structure with an angle changing in dependence of the distance to the die. The grains got deformed in a long but narrow banded shape with an aspect ratio equal to extrusion ratio. Considering the area of the single grains, they are equal to the material in DMZ. Compared to this, the grains of DMZ show an approximately diameter of 135 μm and the grains of the shear intensive zone a length of 324 μm and a width of 54 μm. The angle of the grains increases from 0° to extrusion direction near the container wall to approximately 45° when flowing into the die orifice.

Analyzing the course grains next to the surface of

Table 1. Forming states for the positions based on Fig. 4 and Fig. 5. calculated by FEM simulations.

	A1, B1	A2, B2	A3, B3	A4,	B4	A5	B5
Long billet: EN AW-6060, EN AW-6082	φ_{Eqiv}= 5.3, $\dot{\varphi}$ =0.25	φ_{Eqiv}=4.1, $\dot{\varphi}$ =0.05	φ_{Eqiv}=2.0, $\dot{\varphi}$ =0.00	φ_{Eqiv}=3.8, $\dot{\varphi}$ =0.03	φ_{Eqiv}=4.46, $\dot{\varphi}$ =0.05	φ_{Eqiv}=1.9, $\dot{\varphi}$ =0.02	φ_{Eqiv}=3.5, $\dot{\varphi}$ =0.07
	C1	C2	C3	C4		C5	
Short billet: EN AW-7075	φ_{Eqiv}= 5.5, $\dot{\varphi}$ =0.21	φ_{Eqiv}=4,4, $\dot{\varphi}$ =0.16	φ_{Eqiv}=2,0, $\dot{\varphi}$ =0.00	φ_{Eqiv}=1.1, $\dot{\varphi}$ =0.02		φ_{Eqiv}=2.0, $\dot{\varphi}$ =0.05	

the die orifice (Fig. 5, A1), these show a grain size of approximately 1000 μm diameter. Because there are no excessive deformed grains visible although these result from material of highest strain and strain rates (see Table 1) a recrystallization process and, furthermore, an abnormal grain growth must have taken place. This recrystallization process could have been dynamic (during the deformation) or static (after extrusion has ended) or even a combination of these. Especially the slow cooling of the billet rest' gave enough time for a post extrusion recrystallization. For an analysis of recrystallization dynamics an identification of what has happened here is not clearly possible.

Comparing the structure inside the die orifice (Fig. 5, A2) and in the material inflow zone (Fig. 5, A5) no further abnormal grain growth can be seen. Although the grains in the inner areas of the profile undergo large deformation, too, the grains didn't grow like in the area next to the surface. Comparing image A5, and image A2, the larger strains at the surface gets visible by higher plastic deformation of the grains, especially compared with image A3.

The images of the EN AW-6082 alloy show a comparable material flow behavior. As it can be seen, the etching does not lead to an as good view on the single grain like the etching of the EN AW-6060 alloy. Based on the visible flow lines caused by the different colors of grain and grain boundaries, the inflow of extremely deformed material from the SIZ into the profile's surface can be seen. But although the deformation path is comparable with the one of EN AW-6060, no abnormal grain growth is visible at the profile's wall. Furthermore, the way of etching does not allow analyzing the recrystallization behavior. Considering the EN AW 7075 aluminum alloy, the single grains and even recrystallization becomes visible. The material flow shows that again material from the billets center as well as material from the SIZ flows in the exiting profile. Especially the fine, approximately round shaped grain visible in Fig. 5, C1 showing the microstructure in the pocket near the surface seems to be recrystallized during or after the extrusion process. Compared with grains from the DMZ (Fig. 5, C3) showing a very fine grain, it seems that grain growth has taken place. Analyzing the material before inflowing in the die orifice, a recrystallization visible by small, equiaxed, nearly round shaped grains within the material flow of largely stretched grains becomes visible.

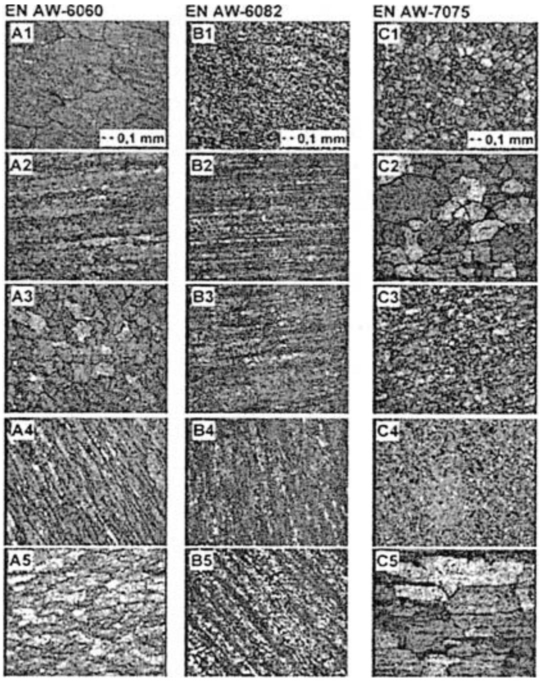


Fig. 5. Meso analysis of macro etched EN AW-6060, EN AW-6082, and EN AW-7075 extrudate.

4. Conclusion

1. The experimental procedure of extruding EN AW-6060, EN AW-6082, and EN AW-7075 has been presented within this work to give a reference punch force and temperature evolution for simulating this processes. In addition to the basic process data, the billets were cut and the microstructure was analyzed based on etchings and light optical microscopy and

finite element simulations for selected positions.

2. It could be shown that the occurring microstructure of the exiting profile strongly depends on alloy and process conditions as well as on the deformation history. In dependence of the particles path to the die orifice, they have to undergo a wide range of different strain states. For an accurate prediction of microstructure evolution the strain, strain rate, and temperature have to be considered. These can be calculated e. g. by means of FEM simulations.

3. The forming area can be divided in several zones in dependence of different strain states. Considering this, the microstructure has to be analyzed considering of the structure along the flow line. The nearer the exiting material is located to the profile's surface the more material from the shear intensive zones is contained. Due to large strain and strain rates dynamic and static recrystallization followed by abnormal grain growth can occur.

Acknowledgements

This work was carried out with the financial support of the MIUR (Italian Ministry for Research and Innovations) and the Transregional Collaborative Research Center/TR30 funded by the German Research Foundation (DFG).

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