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# Grain Shape Evolution and Prediction for AA6082

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Present paper investigates grain texture evolution during the first stages of material response to deformation in direct extrusion of the aluminum alloy 6082. Different process parameters (ram speed, temperature, and extrusion ratio) were tested in order to analyze the dependence of the grain size on strain, strain rate and temperature. Experiments were carried out on a small extrusion press, which allows quenching the products immediately, while the process was also simulated in order to find out the strain distribution in the specimens. Simulation and experimental results were coupled and a correlation between grain thickness and plastic equivalent strain could be found.

***Keywords:*** *Extrusion, Recrystallization, Finite Element Analysis, Microstructure*

## 1. Introduction

Extrusion is a process for manufacturing lightweight profiles of metals like aluminum or magnesium. During extrusion, the workpiece is subjected to high temperatures and high deformations. This causes a change in the microstructure of the workpiece, e.g. in grain structure and precipitations. Hence the process parameters of the extrusion process and the following heat treatment can be used to adjust the microstructure. Therefore, it is crucial to control the evolution of the microstructure during the process on the basis of understanding how recrystallization occurs or rather how the grain size and grain shape change during the extrusion process and how the precipitations are distributed.

Sweet et al. [1] described the influence of the process parameters on the recrystallization of the grains, and according to this, the process parameters are responsible for both the microstructure and the mechanical properties of the profile. Van Geertruyden [2] examined the correlation between the state variables and the microstructure in more detail. Also Doherty et al. [3] wrote about the strong dependence between forms of recrystallization and the deformed state.

Recrystallization occurs during thermo-mechanical processes (e.g. extrusion, rolling) and afterwards. The mechanism during the process is called dynamic or first, after the process static or second recrystallization.

During deformation, a competition occurs between hardening and softening [2]. Hardening is influenced by the increasing dislocation density due to the forming process and the material flow. Softening occurs due to the high temperature. The dislocations can move more freely inside the material and annihilate each other. Hence the flow stress exhibits a constant value at high strains [4]. In aluminum, as an high stacking fault energy (HSFE) material, dislocations are mobile and can glide, cross, and slip easily [5]. In that way, a critical dislocation density is never reached, which means classical dynamic recrystallization, like in β Fe, never occurs, except for pure aluminums [6].

For aluminum, different descriptions for recrystallization are available in literature. The Dynamic Recovery (DRV) theory is described by McQueen [7, 8]. During forming both the subgrain size as well as the wall and internal dislocation densities are constant. Although the grains are elongated, the subgrains are still equiaxed. Hence, the length of high angle boundaries increases and the subgrains are continually rearranged. In addition to that, the Continuous Dynamic Recrystallization (cDRX), described by Gourdet and Montheillet [9], is discussed in literature. The development of new grains

occurs because misorientation of the subgrain boundaries increases during deformation. These occur inside already existing grains.

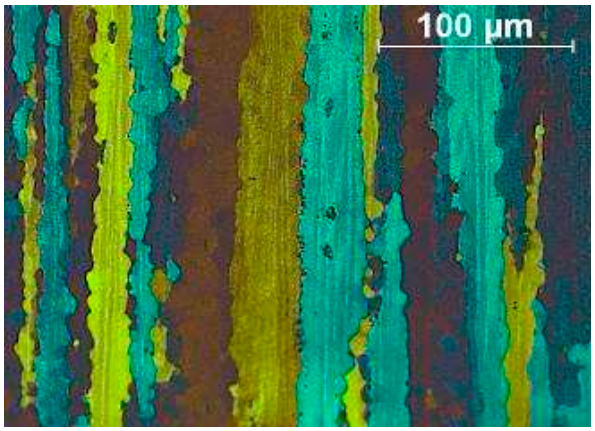


**Fig. 1** Micrograph of En AW-6082, in the middle of an extruded strand.

The Geometric Dynamic Recrystallization (gDRX) is a subset description for the development of new grains during deformation. Several authors have found gDRX [2, 3, 10] in both the rolling and the extrusion process. It is a geometrical approach claiming that elongated grains become serrated and spin off, with the result that new grains have been formed (Fig. 1).

In [4] a relationship for a rolling process between the grain thickness $GS_{th}$, the related strain $\varepsilon$ and the initial grain size $d_0$ is formulated with:

$$GS_{th} = d_0 e^{-\varepsilon} \quad . \tag{1}$$

The gDRX occurs when the subgrain size becomes equal to the grain thickness [4]. De Pari [11] said gDRX starts, if the grain thickness is reduced to 1-2 subgrain diameters.

This paper examines the relation between strain and grain size in an extrusion product. Therefore experimental as well as numerical investigations have been performed.

## 2. Experimental Procedure

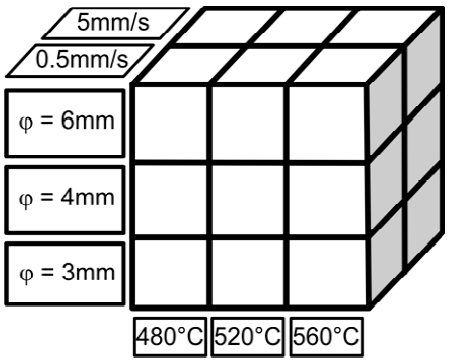


**Fig. 2** Experimental plan.

Experiments were performed by deforming an AA6082 round billet of φ=19mm diameter and 25mm length into a round profile with three different diameters (3, 4 and 6 mm) thus realizing dissimilar extrusion ratios. And the container diameter was 20 mm. The billets were extracted from an AA6082 (φ=140mm) billet by cutting discs with a thickness of 25mm, which provided several blocks for the final turning to the required shape and dimensions.

A ram stroke of 10mm was chosen to leave a butt of 15mm in order to observe all deformation zones in the butt as well as in the extrudate. Experiments were performed at two different ram speeds of 5 and 0.5 mm/s and three different temperatures (480°, 520°, and 560°C). For each combination of parameters, a minimum of three repetitions was planned. In case of any failure, the number was increased to make sure to have statistically firm results. Fig. 2 illustrates the experimental plan.

Before the microstructure analysis, a simplified experimental plan was carried out for tribological investigations, prior to the exposed one [12]. The principal aim was to obtain a correct setting of friction parameters in the FEM code used for strain calculation. This plan was performed by means of visioplastic analyses by insertion of an horizontal grid of rods [12].

### 2.1 Experimental activities

Experiments were performed at laboratory scale on a tensile-compression test press ZWICK250 with a maximum load of 250kN. Fig. 3 shows the container and die designed for these experiments; for all diameters, the dies have the same

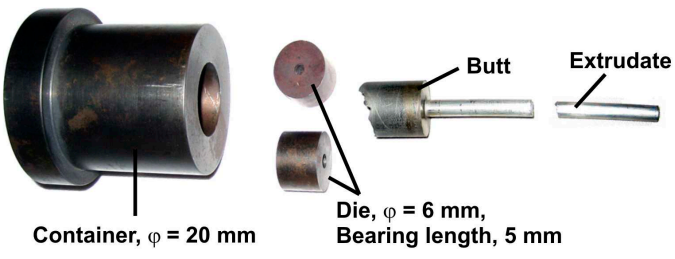


**Fig. 3** Tools: container, butt, die, strand.

bearing length. In contrast to industrial practice, containers were designed to be handled together with the die and the billet, that were cold assembled (billet had been lubricated with boron-nitrate) and then placed in an oven at 600°C. After one hour, the assembly was removed from the oven and placed on the press within a few seconds, in order to avoid a temperature gradient.

Furthermore, a φ=0.8mm hole was produced in the wall of the container to monitor the temperature near the billet-container interface by means of a φ=0.5mm k-type thermocouple. A heating system was also installed around the ram to keep the temperature at 400°C monitored by a thermocouple. Once the container reached the planned temperature, the ram movement was started. At the end of the extrusion process, the extruded profile was cut off and quenched immediately. Also, the assembly was quenched in water within 5-7 seconds after stopping the extrusion process.

**Table 1** Polishing and etching parameters.

| Action | Reagent | Time | Voltage |
|---|---|---|---|
| Polishing | A2 of Struers | 60 s | 20V |
| Etching | Barker reagent | 70s | 20V |

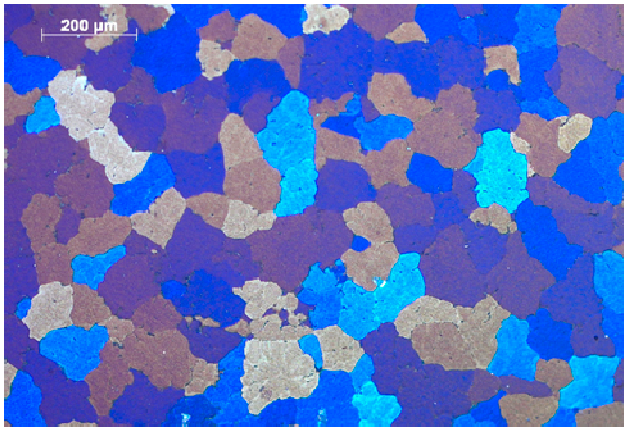


**Fig. 4** Micrograph of etched surface under polarized light.

The specimens were sectioned along the diameter plane by means of a STRUERS-Labotom3 cutting wheel and then polished till a 1000grid. Further polishing was performed electrochemically on a STRUERS LectroPol-5, which was also used for the final etching. Polishing and etching cycle details are shown in Table 1.

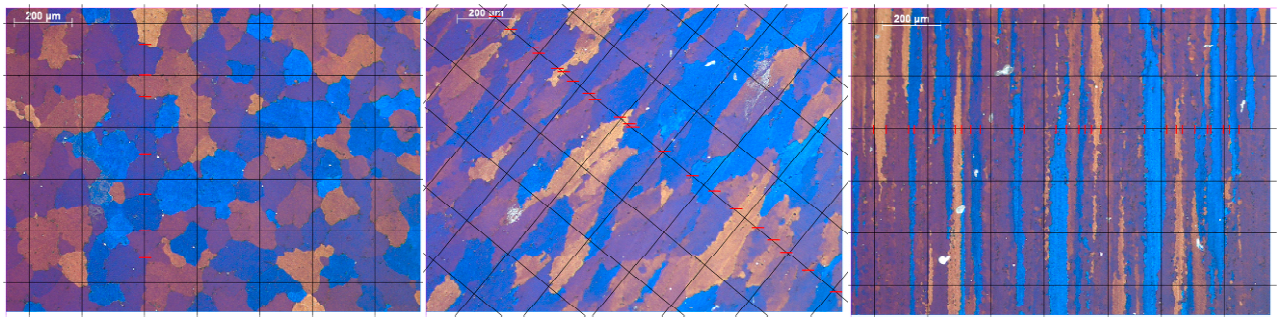


**Fig. 5** Grain counting for three different types of grain shapes.

The etching method was chosen in order to allow a clear visualization of grain shape and boundaries as, under polarized light, grains appear in different bright colors, depending on their crystal orientation, and are therefore easy to identify (Fig. 4).

The grain size evaluation was performed by means of the average linear interception of grains. For this method, an orthogonal grid is laid over the micrograph of a selected spot where measuring is intended. The ratio between the number of times each line intercepts grain boundaries and line lengths provides the average dimensions of the grains in that direction, which is called grain size. Such a methodology requires a good selection of measuring spots, i.e. within the area to be examined the grains should have a homogenous size and shape, and the grid should have a correct orientation (Fig.5). Where grains show a deformation, the grid should be oriented with one axis in that direction to make sure that the true thickness and length are measured and not a mean value of the two. All measurements were performed on micrographs with the same magnification level and grid spacing and on 5-7 grid lines to ensure a good mean value.

Micrographical analyses were performed with a ZEISS Axio Imager. A detailed micrograph of the entire section was taken for each of the analyzed specimens (Fig. 6). This was done with the multiple

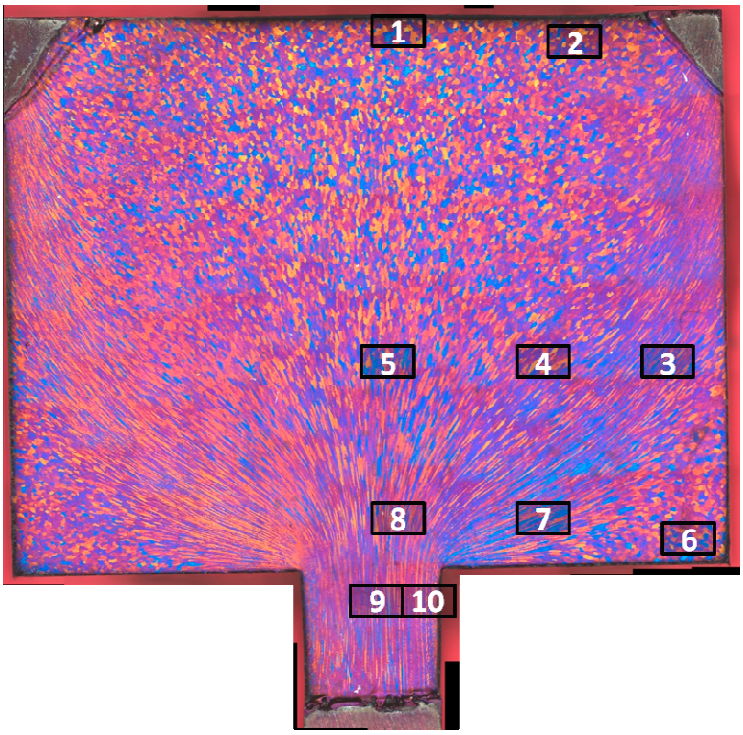


**Fig. 6** Overview of the grain structure of a butt, with measured spots.

purpose of having a good overview of grain deformation distribution, ease of choice of spots where to numerically evaluate grain size and ease of localization of close up pictures. A micrograph "map" was generated through combining several high resolution images of small areas.

One of the three specimens was analyzed for each experimental condition (temperature, velocity and diameter). For each specimen, the grain sizes were measured in ten spots (Fig. 6) that were previously selected with the aim to have a wide range of deformation zones. These zones were consistently analyzed for all specimens.

## 3. Numerical Procedure

Along with experimental activities, a simulation campaign was carried out by means of DEFORM 2D with the main aim of defining strain distribution and the strain values for the investigated spot to be coupled with grain size.

A two dimensional model was used for an easy of axisymmetric discretization. For an easy simulation, container and die were considered as a single object which had been discretized, contrary to this the punch was not. A heat transfer coefficient between billet and container/die was set at a value of 11 N/s/mm/C while friction factor was set as deduced by tribological investigation to 1 with sticking condition on ram, container and die face except bearings [12]. The FEM evaluation was saved every 0.5mm of the ram stroke.

In order to couple the simulated strains to the measured grain size, simulations were calibrated and validated on the basis of experimental extrusion parameters as load and temperature. The effective strain was chosen to be indicative to

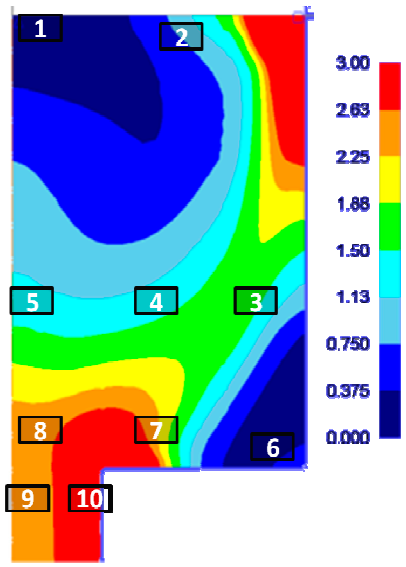


**Fig. 7** Strain distribution on FE model and measurement spots.

be coupled with grain deformation. Spots of grain size measurements on real specimens were localized for each corresponding simulation, and the mean deformation inside the spot area was retrieved.

## 4. Results

The simulated strain was combined with the experimental measurements for both length and thickness of the grains. Initial grain size was also been analyzed. Fig. 8 shows the graph corresponding to such a coupling: effective strain is on the x-axis and grain thickness on y-axis.

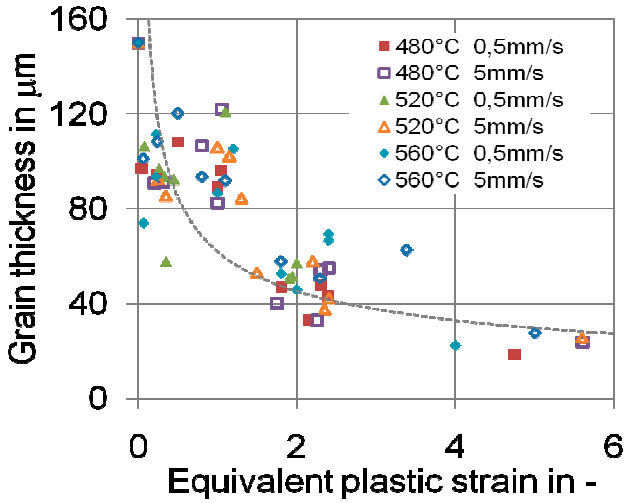


**Fig. 8** Coupling of strain with grain thickness for φ=6mm dies.

A first observation that could be done upon experimental measurements and micrographs and upon grain size-strain coupling is the absence of perceptible differences in the results of the temperature or the ram velocity variation. This is well evident in Fig. 8 where dots of different experimental parameters are homogeneously distributed within each other without showing different trend or values.

Dots appear aggregated in clouds which are distributed along a well defined curve shown in Fig. 9a. Spots with a null strain show a grain size equal to the original one, i.e. of undeformed state, thus suggesting the absence of recrystallization phenomena under sole thermal solicitations. When the strain increases, the grain thickness decreases till a size of about 25-30µm; a further increase in strain does not generate a grain refinement. It is observed that this border is around a strain of 3. This observation can also be made in Fig. 9b where the grain length is on the y-axis. The grain length increases to up to six times of the initial one. At a strain level of around 3, the length decreases abruptly. Hence, this observation an existing recrystallization at a strain of 3 is obvious. Apparently, this is the time the grains cannot get thinner, because they reach 1-2 subgrain diameter.

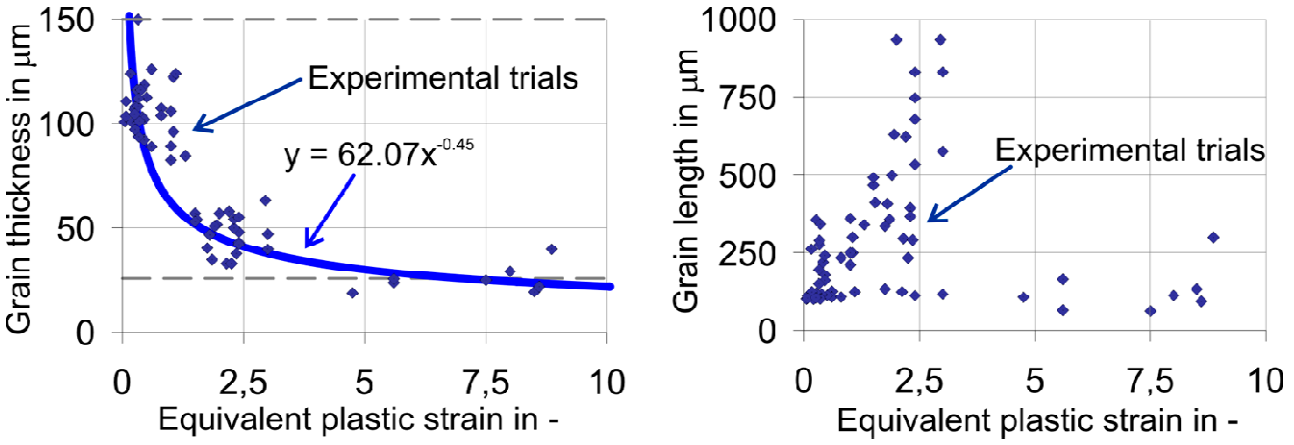


**Fig. 9 a)** Coupling of strain with grain thickness; **b)** Coupling of strain with grain length.

On the basis of the results shown above for the grain size evolution, the grain thickness can be predicted by the following equation:

$$GS_{thickness} = 62.07\varepsilon^{-0.45} \quad (2)$$

It is important to notice that this equation holds its prediction validity within a range of grain thickness which is primarily limited by initial grain size and at the end by the size of 25-30µm. This value was already shown as the minimum size the grains stabilize at. It is therefore more appropriate to predict grain thickness through an algorithm which defines three steps. Eq. 2 is used in the middle step of grain thickness refinement, that is between 150µm and 25-30 µm. The form of the equation is different to that of eq. 1. But the fitting of such an equation was not satisfactory, because the grain thickness was underestimated at a strain around 2.

## 5. Conclusions

An experimental and numerical procedure was shown in order to characterize the microstructure evolution during the hot extrusion process. A correlation between grain thickness and plastic equivalent strain could be found and the beginning of the dynamic recrystallization could be fixed. It is also be shown, that the influence of process temperature and ram speed did not have any effect on the grain size evolution during the process. On this basis a simulation of the development of the grain thickness in the extrusion process can be done in future with the proposed algorithm enhancing a great tool to find the right process parameters to get a well-adjusted microstructure.

## 6. Acknowledgments

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