Surface grain structure development during indirect extrusion of 6xxx aluminum alloys

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During extrusion of aluminum alloys, surface imperfections may develop and lead to an undesirable product. One such surface imperfection is a Peripheral Coarse Grain (PCG) structure of recrystallized grains on the extrudate's surface that may penetrate deep into the cross section of the extruded product and influence both mechanical properties and aesthetics. This structure is manifested as a result of a combination of processing parameters such as strain, strain rate and temperature as well as alloy chemistry [1]. Current numerical models are not capable of fully predicting the extent of this structure. In order to develop a comprehensive, predictive numerical model, a set of physical data for specific alloy systems and processing parameters must be created. Attempts have been made to predict the recrystallized depth after extrusion [2–4]. It is proposed that the basis of a unified model for recrystallization depth should be based on a stored energy approach [5]. The results of this paper are a first attempt to quantify the effect of processing parameters on the development of a recrystallized structure. The focus of the work presented here is the Al—Mg—Si (6061) aluminum alloy.

Direct Chill (DC) cast 6061 aluminum alloy billets were provided by Alcoa Technical Center in Alcoa Center, PA, with a chemical composition within the Aluminum Association standards for this alloy. The two alloys studied here represent the 6061 aluminum alloy with a ratio of Cr:Mn of 1:1 (low Cr) and 2:1 (high Cr). Chromium and manganese are typically added to aluminum alloys to increase resistance to recrystallization [6]. The as-cast material was homogenized in a gas fired furnace for 3 hr at 555 °C (1030 °F) and cooled to room temperature at a cooling rate of 16.8 °C/hr (30 °F/hr).

The homogenized material was machined from the mid-radius of the DC cast billet into small-scale extrusion billets which were 1.5 in. (3.81 cm) high and 1.2 in. (3.05 cm) in diameter. The billets were then extruded to cylindrical rods in a servo-hydraulic press capable of rapidly heating the billet and tooling. The billets were indirectly extruded under the conditions shown in Table I. Indirect extrusion on the laboratory scale was used in order to eliminate friction. All extrudates were cooled using forced air and the extrusion die used was a flat-face design. The starting temperature was taken to be the temperature of the billet just before extrusion began as measured from a thermocouple in the die. The billet discard of each extrusion billet was water quenched approximately 1 min after the ram stopped.

TABLE I Experimental conditions used in small-scale indirect extrusion experiments

Material	Ram speed, v	Billet temperature, T_{start}	Extrusion ratio (R)
6061 (Low Cr)	1.3 or 2.6 mm/s (0.05 or 0.102 in./s)	400 or 482 °C (752 or 900 °F)	20 or 40
6061 (High Cr)	1.3 or 2.6 mm/s (0.05 or 0.102 in./s)	400 or 482 °C (752 or 900 °F)	20 or 40

The material was characterized using Light Optical Microscopy (LOM). Samples for LOM characterization were electroetched using a 2.5% Barkers solution at 20 V for 5 min. Electron Backscatter Diffraction (EBSD) was also used to characterize the microtexture at the die exit and extrudate surface. EBSD was performed using a TSL Digiscan camera interfaced with a Philips XL-30 SEM.

Samples of extrudates were cross-sectioned and viewed in the longitudinal plane in order to characterize the recrystallized structure. An example of the microstructure response to an individual processing condition for one alloy of two different Cr levels is presented in Figs 1a and b. In general, it was observed that with more severe processing conditions (i.e., higher extrusion ratio, temperature, and ram speed) the depth of the recrystallized region increased as can be seen in Figs 2a and b. In the case of the extrusion ratio of 40 (Fig. 2b), there were two instances where the PCG depth differed from the general trend. These two cases both involved a lower temperature of the billet and a higher ram speed. At this higher extrusion ratio, the extrusion exit speed is much higher and therefore the quenching effectiveness may not have been as high as for other, slower extrudates.

Additionally, the deformation performed at lower temperature resulted in higher dislocation density and therefore higher energy is stored upon quenching. The annealing response may be therefore accelerated because of the higher stored energy. The small-scale extrusion billets were extruded to approximately 75% of their original length, leaving an extrusion billet discard. Samples of the extrusion billet discard were sectioned

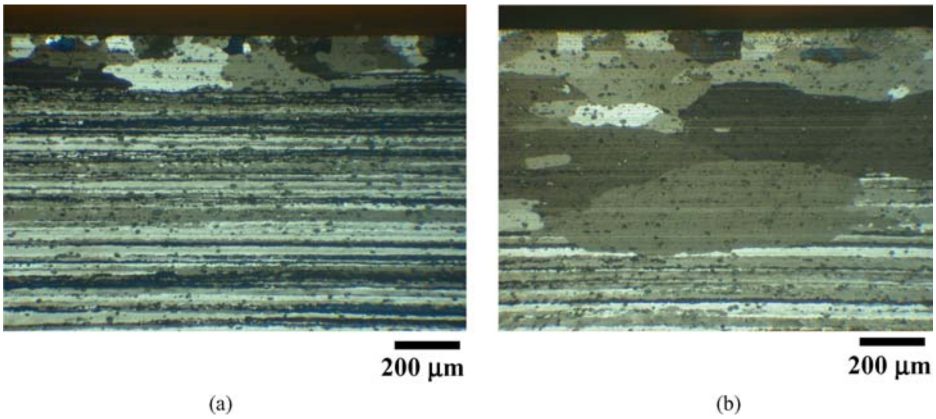

Figure 1 6061 Aluminum alloy extruded at $v = 1.3$ mm/s, $T_{\text{start}} = 400\,^{\circ}\text{C}$, $R = 20$ for two different chemistries: (a) high Cr and (b) low Cr.

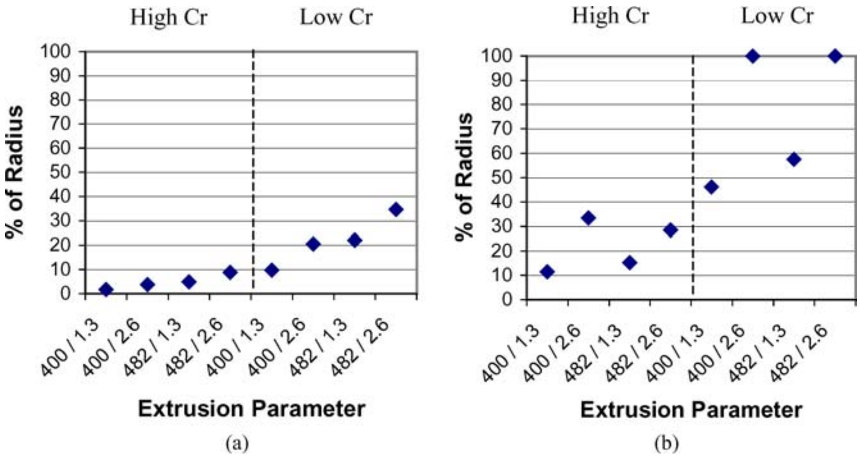

Figure 2 Comparison of Peripheral Coarse Grain depth for an extrusion ratio of (a) $R = 20$ and (b) $R = 40$.

for each processing condition in order to determine the structure just at the die exit. Fig. 3a shows a magnified image of the material as it exits the die. It should be noted that there was a lag of approximately 1 min between the the end of extrusion and water quenching of the extrusion billet discard. Therefore, it should be expected that some postdeformation annealing has occurred. Small, equiaxed grains lie in the dead metal zone adjacent to the die exit. These grains are possibly formed because of geometric dynamic recrystallization (GDRX) [7, 8]. It can be seen in Fig. 3a that the Peripheral Coarse Grain structure has its origins within the deformed billet. Fig. 3b shows an Orientation Imaging Microscopy (OIM) map of the material under different conditions as it exits the die and highlights 15° or higher boundaries.

It is apparent that extrusion process parameters have a strong effect on the recrystallized depth of the extrudate. In general, the depth increased with increased energy, which can be expressed in terms of increasing the ram

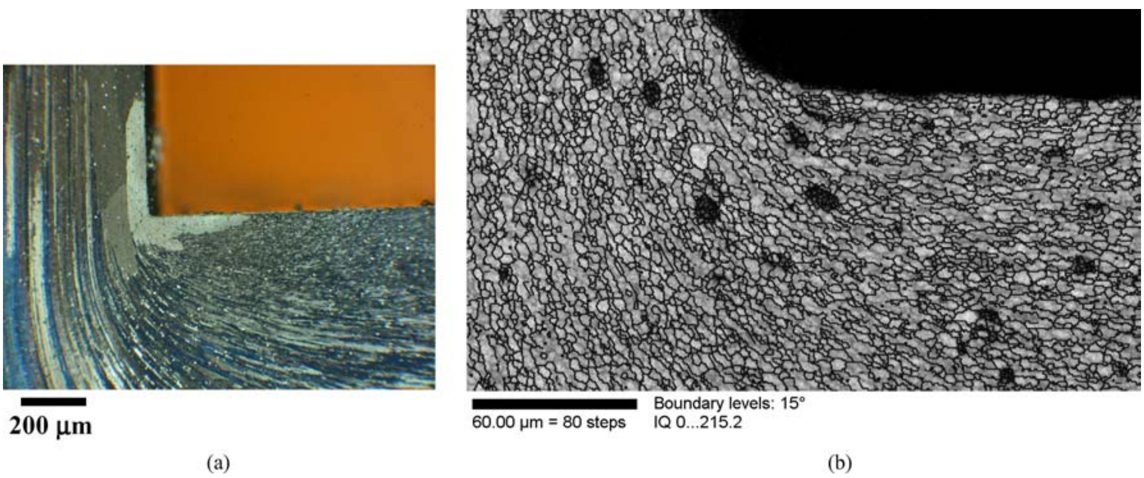

Figure 3 (a) Microstructure at the die exit of a billet indirectly extruded to approximately 75% of the original billet length. (b) OIM map of billet at die orifice showing fine, equiaxed grains flowing into the surface of the extrudate. Black lines representing boundaries of 15° or higher.

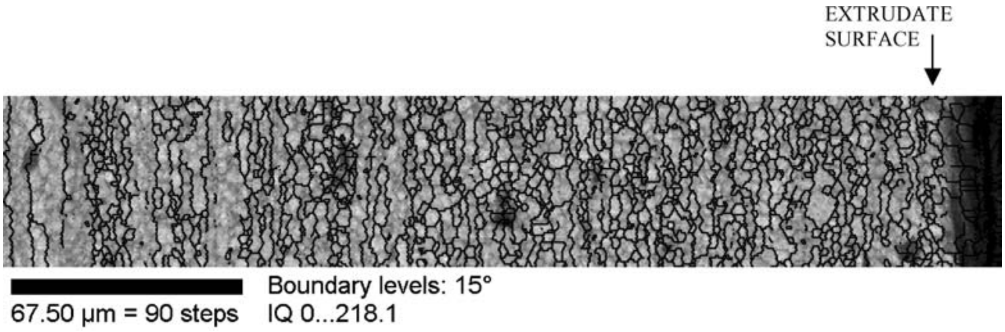

Figure 4 OIM Map of extrudate surface without any large grain formation. Notice the small grain size with black lines representing boundaries of 15° or higher.

speed, extrusion ratio, and starting billet temperature. Confusion still exists in the literature as to what annealing phenomenon is responsible for the development of the large grains at the surface of the extrudate.

In order to predict the depth of coarse recrystallized grains, a correlation must be made between the stored energy in the extrudate and critical strain, strain rate, and deformation temperature for recrystallization to begin. Before this prediction can be made, the nature of metal flow and the development of the microstructure at the surface of the extrudate must be very well understood. Additionally, depending on strain, strain rate and temperature gradients, the depth of the PCG formation can vary. The small, equiaxed grains that are present in the dead metal zone and surface of the extrudate are highly unusual and have not been reported in the literature. It is proposed here that the large grains shown in Fig. 3 are statically recrystallized grains growing into the deformed material within the billet after deformation ends. The small, equiaxed grains in the dead zone may form a preferential site for recrystallization and grain growth. Fig. 4 shows an Orientation Imaging Microscopy (OIM) map of the extrudate surface with boundaries of 15° or higher.

Many attempts to describe the recrystallization kinetics are usually based on constitutive equations, for example using the Zener Holloman parameter, Z. It has been known that Z increases from the center of an extruded material to the surface because of the inhomogeneity of metal flow through the die orifice. A more comprehensive determination of the developing microstructure in terms of stored energy must be made beyond Z in order to predict the depth of the recrystallized layer [9]. It is evident that Z parameter needs to incorporate temperature gradient present in the deformed profile, which is very difficult to measure or simulate. However, the combined result of strain rate and temperature can be evaluated using the OIM technique.

Further experimental analysis, including Orientation Imaging Microscopy (OIM), can be performed in order to determine the change in stored energy from the center to the surface of the extrudate. The map in Fig. 4 shows that the grain size at the surface of the extrudate is very small, on the order of several microns. The stored energy can be measured from these maps in terms of subgrain size and subgrain misorientation, which has been related to stored energy in cold deformed aluminum elsewhere [10].

The effect of processing parameters on Peripheral Coarse Grain structure immediately after deformation in the small-scale indirect extrusion experiments was determined. In general, the depth increased with increasing the ram speed, Cr content, extrusion ratio, and starting billet temperature. The evolution of deformed and recrystallized material was observed and a relation between the extrusion parameters and microstructural evolution was made. It is proposed that the Peripheral Coarse Grain structure is a result of static recrystallization after deformation. OIM measurements showed that a very small grain size exists at the surface of the extrudate with boundary misorientations of 15° or higher. These grains likely have resulted from a dynamic recrystallization process and may contribute to an unstable structure that could promote the static recrystallization that leads to the Peripheral Coarse Grain structure.

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