The Influence of Die Bearing Geometry on Surface Recrystallisation of 6xxx Extrusions

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ABSTRACT – The control of the grain structure of 6xxx extrusions has become a requirement for many applications, particularly in the automotive sector. Mechanical properties, corrosion resistance, and formability can all be impacted by this aspect of the microstructure. Often it is a requirement that the product be unrecrystallized in the as extruded condition with a maximum surface recrystallized depth. For some applications, the same degree of control is required after secondary forming and heat treatment operations. The main challenge is to prevent coarse grain at the surface where the material experiences a more severe thermo-mechanical history. Alloy composition and ingot microstructure are known to have an effect on the formation of a surface recrystallized layer. Extrusion conditions also contribute to its creation or otherwise, but often the only option to the extruder is to reduce extrusion speed to unacceptable levels. The use of conic dies has been previously shown to have an impact on this problem. Using data generated on the RTA experimental extrusion press, the current study describes how changes in die bearing length and angle of choke on conventional die bearings can play a major role in controlling grain structure.

INTRODUCTION

Control of extruded aluminum-magnesium-silicon (Al-Mg-Si) alloy grain structures is now being driven by many applications, particularly those within the automotive industry. Other workers have observed\(^1\) that a coarse surface grain size can give rise to a number of problems after forging AA2xxx and AA7xxx alloys, including reduced fatigue resistance, poor machinability, and surface finish. The requirements for alloys such as AA6005A, AA6061, AA6082, and AA6351 can be for a certain maximum fraction recrystallized, a maximum recrystallized depth, or overall recrystallized grain size. Often, it is desirable to retain a non-recrystallized or fibrous structure to take advantage of the strength increase associated with the press effect. In some applications, for example forging stock, these requirements are specified after a separate solution treatment.

In the case of thin wall profiles in the alloys more prone to recrystallize such as AA6063, AA6005A, and some versions of AA6061, control of grain size can be important to ensure freedom from orange peel during cold forming, or to give acceptable anodized appearance for decorative applications. The recrystallization behavior of an extrusion can be controlled to a certain extent by the alloy composition and ingot homogenization and their effects on the dispersoid particle distribution, and there is information in the literature on this aspect of the process.\(^2\) However, until recently there has been little attention paid to the extrusion process itself; that is extrusion conditions and die geometry. Earlier work by the current authors\(^3\) focused on the interrelation between grain structure and billet temperature, ram speed, and extrusion ratio for both press-quenched and solution-treated extrusions.

Figure 1 shows the variation in macrostructure for the medium-strength alloy AA6005A extruded into a 25mm bar (extrusion ratio of 17.5:1), using a wide range of billet temperatures and ram speeds. Three types of grain structure were evident:

- Fibrous/unrecrystallized core with a coarse grain outer band
- Mixed fibrous/recrystallized core and a finer grain outer band
- Fully recrystallized core with fine surface grain.
Figure 1. Macrostructures of press-quenched 25mm bar in AA6005A, as a function of ram speed (from 2mm/s to 30mm/s) and billet temperature (from 350°C to 540°C).

In general, low ram speeds and high billet temperatures gave less recrystallization and promoted a fibrous core. Conversely, low billet temperatures and high ram speeds promoted a fully recrystallized cross section. This trend can be explained in terms of the driving force for recrystallization, or work of extrusion, which is the level of stored work in the material. Although extrusion is a hot deformation process, stored work is present in the product in the form of a recovered substructure. For a given billet temperature, this is controlled by the ram speed and extrusion ratio, which impose a strain rate and total strain on the material. The higher the strain rate, the higher is the flow stress, and the higher is the level of stored work in terms of dislocations arranged in sub-grain structures. Similarly, lower billet temperatures raise the flow stress and increase the work of extrusion. The stored energy is not distributed uniformly in an extrusion, and it is the gradient across the thickness which gives rise to preferential recrystallization at the surface.

In the case of press-quenched extrusions, this theory is not followed under all conditions. For example at low ram speeds, typical of commercial operation, the amount of recrystallization increases with higher billet temperatures. In fact, for press-quenched extrusions the recrystallized depth increases almost linearly with profile exit temperature. While the work of extrusion provides the driving force for the process, it requires a finite time at temperature to occur. In the case of press-quenched extrusions, the “exposure” time is short and the profile temperature varies with press conditions, such that quenching usually interrupts the process and exit temperature has a dominant effect. When the extrusion is given an additional furnace solution treatment, such as might be done for extruded forging stock or cold-worked profiles, ample time is provided for the recrystallization process to occur. As a result, more recrystallization is encountered in solution-treated products, and the level of recrystallization closely follows the work of extrusion, as shown in Figure 2. Here the amount of recrystallization increases consistently with lower billet temperatures and higher ram speeds. The focus of the current paper is on the role of die bearing geometry on the recrystallization process. A link between die bearing geometry and recrystallization has been known in the industry for some time. However, much of the previous work was conducted without consideration of the interaction with extrusion conditions and the work of extrusion. The research described in this paper was conducted to assess the role of die bearing geometry over a range of press conditions for both press quenched and formally solution-treated extrusions, with the ultimate goal of assisting the extruder to control this aspect of the product.
Figure 2. Macrostructures of solution-treated 25mm bar in AA6005A (soaked five minutes at 510°C and water quenched), as a function of ram speed (2mm/s to 30mm/sec) and billet temperature (350°C to 540°C).

LOW EXTRUSION RATIO 25mm ROUND BAR

Experimental

An AA6082 commercial alloy composition typical of the North American market was DC cast as thin shell 101mm diameter ingots. The nominal composition of this was, in weight %:

AA6082 - Mg - 0.7, Si - 1.0, Fe - 0.17, and Mn - 0.5.

These ingots were cut to 400mm billet lengths, and homogenized with a standard commercial practice. A series of extrusion tests were conducted using the RTA850 US-ton press located in Jonquiere, Quebec. The billets were preheated to the extrusion temperature in less than 60 seconds, using an induction heater. Unless otherwise stated, all extrusions were press quenched using a standing-wave water quench unit located 1.7m from the die face. A 10 percent butt discard was taken to avoid back-end defect. The alloys were extruded over a wide range of press conditions using billet temperatures from 350°C to 540°C, and ram speeds from 2mm/s to 40mm/s. A 25mm round bar (corresponding to an extrusion ratio of 17.5:1) was used for the initial series of tests. All material was water quenched. Grain structure comparisons were made, both in the as-extruded condition, and after solution heat treatment, of samples taken at the middle of each extruded length after etching using Poulton’s reagent. The solution treatment practice was 30 minutes at 540°C, using a salt bath.

A series of dies was manufactured for the 25mm bar profile, as shown in Table 1. In all cases, the dies were of simple flat construction of 38mm thickness, and 100mm diameter, and were run in conjunction with a 100mm diameter ring feeder plate of 25mm depth. The bearings were either flat or flat with the entrance portion of their length choked at different angles, as shown in Figure 1. The identification of the dies gives the overall length of the bearing and the angle of choke (+) or relief (-) of the bearing. Two “extreme” designs were included. In one case, the bearings were short and relieved at an angle of 1.5° (as in a zero bearing design). In another case, a fully choked bearing was employed, one which gradually reduced the metal in the container from a diameter of 106mm...
to the profile size of 25mm. This was achieved with a gradual uniform reduction in cross section throughout the length of the 62mm bearing. In all dies, thermocouples were positioned at the bearing surface, at various positions along their length. These were used to monitor the exit temperature of the extruding aluminum surface. Photographs of some of the bar dies are shown in Figure 4. In the case of the choked dies, the choked portion extended over the entrance half of the land length.

Table 1. Details of 25mm bar dies.

<table>
<thead>
<tr>
<th>ID</th>
<th>Total Length mm</th>
<th>Choke Length mm</th>
<th>angle deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>R 6 -1.5</td>
<td>6</td>
<td>zero bearing</td>
<td>-1.5</td>
</tr>
<tr>
<td>R 12 +1</td>
<td>12</td>
<td>6</td>
<td>+1</td>
</tr>
<tr>
<td>R 25 0</td>
<td>25</td>
<td>flat</td>
<td>0</td>
</tr>
<tr>
<td>R 35 +3</td>
<td>35</td>
<td>17.5</td>
<td>+3</td>
</tr>
<tr>
<td>62 CSR</td>
<td>62</td>
<td>varying</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Die schematic.

4a) R6mm -1.5°, zero bearing
4b) R12mm +1°
4c) R 35mm +3°
4d) 62 CSR with 100mm opening

Figures 4a) through 4d). Examples of the dies used (note thermocouple holes in bearings).

Extrudability

Pressure data from the tests is given in Figure 5. This shows that breakthrough pressure increased significantly with increases in both bearing length and choke angle. The zero bearing die (R 6 -1.5) gave the
lowest pressure, and the CSR die gave the highest. Compared to the 25mm flat bearing (R 25 0), which can be considered normal for this type of product, the 12mm bearing with one degree of choke gave six percent lower pressure, which is significant. Increasing the bearing length to 35mm and increasing the choke angle to three degrees gave a further increase in pressure of about six percent. All these effects are consistent with higher bearing friction as the effective bearing length is increased. In general, a higher extrusion pressure for a given die geometry would be expected to give a decrease in potential extrusion speed. Extrusion surface exit temperature as measured by the die bearing thermocouples was higher with the longer choked bearings. However, it was possible to extrude significantly faster without speed cracking with this type of bearing. For example, AA6082 at a billet temperature of 500°C, could be extruded through the conventional 25mm long flat bearing die at a maximum speed of 34mm/s ram speed without speed cracks, while both the die with a long bearing and three degrees of choke (R 35 3) and the CSR die could be extruded at over 40mm/s without any signs of cracking.

![Breakthrough pressures at 350°C and 500°C at a ram speed of 20mm/s](image)

**Figure 5.** Breakthrough pressures at 350°C and 500°C at a ram speed of 20mm/s.

**Grain Structure**

Typical macro-sections for the various dies in the as-extruded and solution-treated conditions for billet temperatures of 350°C and 500°C are shown as a function of ram speed in Figures 6a and 6b. The results are quantified in Figure 7, which gives plots of the fraction of the radius recrystallized vs. ram speed. The macrographs are laid out with the best results on the left of the figure. Overall, the AA6082 alloy exhibited good resistance to recrystallization and in the press quenched condition, a fibrous core was always produced. In most cases, a thin peripheral coarse grain (PCG) layer was present and although this not always evident in the macrographs, the finite thickness can be seen in Figure 7. In terms of extrusion conditions, the results are consistent with earlier work, in that the recrystallized depth always increased with ram speed for all dies.
Figure 6a. Press-quenched grain structures of the 25mm bar extruded through the five test dies at speeds of 5mm/s, 20mm/s, 30mm/s, and 40mm/sec. Billet temperature is 500°C.

Figure 6b. Solution-treated grain structures for the 25mm bar extruded through the five test dies at speeds of 5mm/s, 20mm/s, 30mm/s, and 40mm/sec. Billet temperature is 500°C.
Figure 6c. Press-quenched grain structures of the 25mm bar extruded through the five test dies at speeds of 5mm/s, 20mm/s, 30mm/s, and 40mm/sec. Billet temperature is 350°C.

Figure 6d. Solution-treated grain structures for the 25mm bar extruded through the five test dies at speeds of 5mm/s, 20mm/s, 30mm/s, and 40mm/sec. Billet temperature is 350°C.
Figure 7a. Percentage recrystallized for the five test dies as a function of ram speed. Billet temperature is 500°C, press quenched.

Figure 7b. The percentage recrystallized for the five test dies as a function of ram speed. Billet temperature is 500°C, solution treated.
Figure 7c. Grain structures of the 25mm bar extruded through the five test dies at speeds of 5mm/s, 20mm/s, 30mm/s, and 40mm/sec. Billet temperature is 350°C, press quenched.

Figure 7d. Grain structures of the 25mm bar extruded through the five test dies at speeds of 5mm/s, 20mm/s, 30mm/s, and 40mm/sec. Billet temperature is 350°C, solution treated.
In the press quenched condition, the higher billet temperature of 500°C tended to give more recrystallization, but this did not change significantly during solution treatment. The lower billet temperature of 350°C gave less PCG (peripheral coarse grain) at the press; however, significant recrystallization took place during solution treatment for all dies. In terms of the various die geometries, generally the longer, more heavily choked bearings performed the best, giving less recrystallization at the press and after solution treatment compared to the flat bearing control (R 25 0). The zero bearing die (R 6 -1.5) was the worst in this respect, and always gave slightly more recrystallization than the control, and was the only die to give any recrystallization at the press for the 350°C billet temperature. The CSR die (R 62 CSR) and the long bearing choked die (R 35 3) performed similarly and were best overall. With both dies it was possible to extrude at speeds of up to 20mm/s at the higher billet temperature with no recrystallization at the press, or after solution treatment. However, under conditions of high stored energy, such as the 350°C billet temperature, even these dies gave some recrystallization after solution treatment. The short bearing choked die (R 12 +1) gave less recrystallization than the control die, while at the same time giving lower extrusion pressure.

HIGH EXTRUSION RATIO FLAT STRIP

Experimental

As with the round bar, a series of dies was manufactured with a 41mm x 3 mm aperture with different bearing lengths and angles, as shown in Table 2. In this case, two lengths of 3mm and 6mm were used, as well as three bearing angles, flat, one degree choke, and three degrees choke. For the dies with choke, the choke angle was only applied over the entrance half of the bearing length. In these tests, the billet temperature was maintained at 480°C, and the dies were extruded at ram speeds of 2mm/s, 5mm/s, 10mm/s, and up to 15mm/s, until speed cracking was observed.

Table 2. Details of 41mm x 3mm strip dies.

<table>
<thead>
<tr>
<th>ID</th>
<th>Total Length mm</th>
<th>Choke Length mm</th>
<th>Angle deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>F 3 0</td>
<td>3</td>
<td>flat</td>
<td>0</td>
</tr>
<tr>
<td>F 6 +3</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>F 6 +1</td>
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<td>1</td>
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<tr>
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<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>F 6 0</td>
<td>6</td>
<td>flat</td>
<td>0</td>
</tr>
<tr>
<td>F 3 +1</td>
<td>3</td>
<td>1.5</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 8 shows the end of one of the apertures. The spark-eroded hole for the bearing thermocouple is visible, along with the choke angle on the entrance half of the die bearing.

Figure 8. Aperture of one of the flat strip dies showing the bearing thermocouple holes.
Extrudability

As with the round bar profile, increasing the length and choke angle both caused an increase in extrusion pressure, with an equal contribution of lengthening and choking. As one would expect, the exit temperature as measured by thermocouples in the die bearings, was higher with the longer choked bearings, as shown in Figure 9.

![Graph showing extrusion pressure and exit temperature changes with lengthening and choking.]

**Figure 9.** Die bearing temperatures vs. speed extruded at 480°C through the 41mm x 3mm flat strip dies.

One might reasonably expect that the higher extrusion pressure and surface exit temperature of metal leaving the die would cause a reduction in the limiting speed for hot tearing. In fact, the opposite was true. The limiting speed increased with lengthening and choking of the bearing, as shown in Table 3.

<table>
<thead>
<tr>
<th>ID</th>
<th>Total Length mm</th>
<th>Choke Length mm</th>
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<tr>
<td>F 6 0</td>
<td>6</td>
<td>flat</td>
<td>flat</td>
<td>12</td>
</tr>
<tr>
<td>F 3 +1</td>
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<td>F 6 +1</td>
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</tr>
<tr>
<td>F 6 +3</td>
<td>6</td>
<td>3</td>
<td>3</td>
<td>&gt;15</td>
</tr>
</tbody>
</table>

Table 3. Hot tearing/speed cracking speeds for 41mm x 7mm strip dies.

Grain Structure

Typical press quenched microstructures for the various dies extruded at a billet temperature of 480°C and ram speeds of 2mm/s are shown in Figure 10. The recrystallized depth increased with speed for all dies, and this data is presented in Figure 11. The conclusions from these tests are that without exception, a decrease in PCG depth was obtained with increased bearing length and choke angle.
10a) 3mm, flat bearing  
10b) 6mm, flat bearing  
10c) 3mm, 1° choke

10d) 6mm, 1° choke  
10e) 6mm, 3° choke

Figures 10a) through 10e). Grain structures of the flat strip profile, at 50 percent of the extruded length with a billet temperature of 480°C, ram speed of 2mm/s.

Figure 11. Plot of percentage recrystallized vs. ram speed.
DISCUSSION

In the case of both the round bar and the flat strip, the grain structures after solution heat treatment followed the expected trend with extrusion conditions, that is the recrystallized depth increased with the work of extrusion (higher ram speed – lower billet temperature). With the press-quenched profiles, higher ram speed and billet temperature both increased the thickness of the recrystallized layer.

Regarding the difference in performance of the dies, increasing bearing length and choke angle consistently reduced the generation of peripheral coarse grain at a given speed, both at the press and after solution treatment. This indicates the stored energy in the surface zone was reduced by these configurations. The exact mechanism for this is still not well understood, but it is believed to be associated with the acceleration of the extruded surface as it passes over the corner of the aperture between the die plate face and the bearing entrance. It is useful to consider the extreme case of the zero bearing die, which always resulted in a thicker recrystallized layer in these tests. Here, the slower moving outer material within the billet has to quickly accelerate to the bulk extrusion speed when entering the aperture to form the product surface. This effect will impose a strain rate increase. For the choked dies this acceleration is more gradual, resulting in a lower strain rate. In addition, compared to the long flat bearing control dies, it was also possible to apply choke to a shorter bearing length and still reduce PCG formation.

Relative to the conventional flat die, all the longer bearing choked dies showed speed improvements of the order of 15 to 50 percent for both the rod and flat profiles before speed cracking occurred. Again, the mechanism is not well understood. While one might have thought that speed cracking is primarily a result of surface melting of the metal as it passes over the die bearing, this does not appear to be the case. The die bearing thermocouples clearly show that the long bearings do generate higher temperatures. It is to be noted that although the zero bearing die with the relieved bearing gave the lowest extrusion pressure, it performed poorly both in relation to coarse grain and hot cracking speed. This type of die is normally good for speed improvements with AA6063-type alloys, where it can delay the onset of pick-up. However, it would appear that the mechanism of speed cracking is not only linked to exit temperature, but also the way the metal flows through the die. One possible explanation is that the tensile stress experienced by the surface material as the extrusion leaves the die, controls whether or not the surface cracks. The level of this tensile stress is probably a function of the surface acceleration, which can be influenced by the die bearing profile.

CONCLUSIONS

- Increasing both bearing length and choke angle increases extrusion pressure;
- Exit temperature (including die bearing temperature) is similarly increased;
- Thickness of the PCG layer in the as-quenched profiles can be significantly influenced by both the length and choke angle of the bearing. In particular, with the 3mm thick flat strip, speeds with acceptable PCG thickness can be several times higher with long choked bearings;
- Thickness of the PCG layer can also be significantly reduced by correct selection of bearing length and choke angle, providing the extrusion conditions are controlled to promote minimum recrystallization;
- The maximum speed without speed cracking was significantly increased by lengthening and choking the bearing (within the range of the test parameters). This is an interesting conclusion in that while the temperature of the extruding material is increased by lengthening and choking the bearing, the “speed cracking” speed is raised. The implication is that temperature alone does not control speed cracking, but the state of compression or tension at the extrusion surface is a contributory factor;
- The one negative aspect of this approach is that in some cases, the as-extruded surface quality is poorer with long bearings.
REFERENCES


