Tensile Properties and Blow Forming of 5083 Aluminum Alloy Recycled by Solid-State Recycling

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The tensile properties and blow forming characteristics of 5083 Al alloy recycled by solid-state recycling were investigated from the viewpoint of oxide contamination. Three types of machined chip with different volumes were recycled by hot extrusion and hot rolling in air. Oxide layers, which were contaminants from the machined chip surface, were distributed in the extrusion direction for the recycled specimens. Oxygen concentration in the recycled specimens increased with the total surface area of the machined chips per unit volume. From the result of the tensile tests performed at 773 K, the elongation to failure of the specimen made of larger machined chips was lower, than that of the specimens made of larger machined chips, in spite of their same strain rate sensitivity of 0.5. Similarly, in the blow-forming tests at 773 K, the specimen made of smaller machined chips exhibited a lower formability. The low elongation to failure and formability of the recycled specimens made of larger machined chips are likely to be attributed to a greater contamination of oxide. Thus, oxide contamination has a detrimental effect on the superplastic properties of recycled Al alloy.

Keywords: aluminum alloy, solid-state recycling, tensile test, superplasticity, blow forming

1. Introduction

For the reduction in CO₂ emission produced by vehicles, the application of Al alloy to the structural components of vehicles is increasingly becoming important due to the high specific strength of this alloy. Currently, Al alloy ranks the second metal in term of consumption around the world, and hence its recycling is an important technology for materials circulation. The energy for recycling by remelting aluminum scraps is about 10^3 J/t, which is only 5% of the smelting energy from bauxite. Hence, aluminum scraps should be recycled to reduce environmental loads. Actually, the recycling of aluminum scraps is being carried out by some recycling processes based on remelting.

Effective recycling entails the production of high-performance materials from scraps with low energy consumption. Solid-state recycling without remelting is a low-energy process. In this recycling, metal scraps are directly recycled by hot extrusion and other thermo-mechanical treatments. In our previous study, it was revealed that the solid-state recycled 5083 Al alloy from machined chips showed a high strength due to grain refinement. Thus, solid-state recycling is a promising process for metal scraps.

Recently, superplastic blow forming has become one of the major near-net-shape forming processes for 5083 Al sheets. Because the solid-state recycled 5083 Al alloy possesses a fine-grained microstructure, superplastic blow forming may be realized for solid recycled Al alloy. However, our previous study showed that the elongation to failure of a solid-state recycled Al alloy is lower than that of an extruded specimen processed from an as-cast ingot, particularly, at elevated temperatures. Oxide contamination is responsible for the poor formability of the solid recycled Al alloy. In the present study, three types of 5083 Al alloy machined chip with different volumes are recycled by hot extrusion and hot rolling, and the tensile properties and blow forming characteristics of the solid recycled Al alloy are investigated from the viewpoint of oxide contamination.

2. Experimental Procedure

Chips were prepared as scraps by machining an as-received 5083 aluminum alloy block in a lathe without lubricants. Three types of machined chip with different volumes were prepared as shown in Fig. 1. The average volume, thickness and width of the machined chips are summarized in Table 1. The scraps cleaned by acetone were filled into a rectangular container with cross-sectional dimensions of 50 mm × 30 mm and then extruded at 723 K at an extrusion ratio of 6:1 in air. The cross-sectional dimensions of the extruded bar was 50 mm × 5 mm. For comparison, an as-received 5083 Al alloy block was also extruded under the same conditions as those of the extrusions of the scraps. After the extruded bars were annealed at 803 K for 3.6 × 10⁴ s, they were rolled at room temperature up to a rolling ratio of 80%. Finally, the rolled specimens were annealed at 593 K for 7.2 × 10³ s. The rolling direction was perpendicular to the extrusion direction (see Fig. 2). In the present study, the specimens recycled from the three types of machined chip and specimens from a virgin ingot are called the "specimen from small machined chips", "specimen from medium-sized machined chips", "specimen from large machined chips" and "virgin specimen", respectively.

The microstructure of the specimens was observed by OM (optical microscopy). The image of oxygen in the specimens was detected by EPMA (electron probe microanalyzer). Oxygen concentration in the specimens was measured by the
infrared absorption method. Tensile specimens of 10 mm gage length, 5 mm gage breadth and 1 mm gage thickness were machined. Tensile tests were carried out from room temperature to 773 K at initial strain rates of $10^{-4} – 10^{-2} \text{s}^{-1}$, where the angle between the tensile direction and the rolling direction was 0 degrees. In addition, step strain rate tests were carried out at 773 K at strain rates of $10^{-5} – 10^{-1} \text{s}^{-1}$ to analyze strain rate sensitivity.

Discs of 70 mm diameter were machined in the blow forming tests. The specimens were clamped between two hollow dies and subjected to N$_2$ gas pressure at 773 K to induce bulging. Cups of 20 mm height were formed in a die cavity, which was 40 mm in diameter.

### 3. Results and Discussion

#### 3.1 Microstructure and oxide contamination

The microstructures of the specimen from small machined chips and the virgin specimen are shown in Fig. 3, where the RD-TD and TD-ND planes are observed, respectively. The grain sizes were 11.5 μm for the specimen from small machined chips, 13.6 μm for the specimen from medium-sized machined chips, 14.7 μm for the specimen from large machined chips and 13.4 μm for the virgin specimen, where grain size was measured on the RD-TD plane. It is known that dynamic recrystallization occurs during hot extrusion for Al-Mg aluminum alloys.\(^{17-19}\) In the as-received specimen before machining, the grain size was 390 μm. It is therefore suggested that the fine-grained microstructures of recycled specimens are attributed to dynamic recrystallization during hot working. There was no difference in grain size between the specimens from machined chips and the virgin specimen. This indicates that an oxide contamination had no effect on recrystallization.

It is notable that black (dotted) lines in the specimen from small machined chips were observed parallel to the TD-ND plane, that is, the extrusion direction. The black (dotted) lines denote the oxide films of machined chips, as will be shown later. The interval of the black (dotted) lines was approximately 5 to 7 μm for the specimen from small machined chips.

Table 1 Configurations of 5083 Al machined chips used for solid-state recycling.

<table>
<thead>
<tr>
<th>Raw materials</th>
<th>Average width (mm)</th>
<th>Average thickness (mm)</th>
<th>Average weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small machined chips</td>
<td>1.4</td>
<td>0.2</td>
<td>$4.9 \times 10^{-1}$</td>
</tr>
<tr>
<td>Medium-sized chips</td>
<td>3.0</td>
<td>1.2</td>
<td>$1.3 \times 10^{-1}$</td>
</tr>
<tr>
<td>Large machined chips</td>
<td>4.5</td>
<td>1.8</td>
<td>$3.4 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Fig. 1 Photographs of small (a), medium-sized (b) and large (c) machined chips.

Fig. 2 Schematic view of relationship between extrusion and rolling directions on the solid-state recycling.
<table>
<thead>
<tr>
<th>Specimen from small machined chips</th>
<th>RD-TD plane</th>
<th>TD-ND plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin specimen</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Fig. 3  Microstructures of 5083 Al alloy specimens.

<table>
<thead>
<tr>
<th>Extrusion direction</th>
<th>Rolling direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE image</td>
<td>Oxygen image</td>
</tr>
<tr>
<td>Specimen from small machined chips (TD-ND plane)</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Virgin specimen (TD-ND plane)</td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Fig. 4  BSE images and oxygen images obtained by EPMA for the virgin specimen and specimen from small machined chips.
images obtained by EPMA for the specimen from small machined chips and the virgin specimen, where the TD-ND plane is observed. In the specimen from small machined chips, the distinct peaks of oxygen were aligned to the extrusion direction. The interval of the distinct oxygen peaks was approximately 5 μm to 10 μm, which is in agreement with the interval of the black (dotted) lines shown in Fig. 3. Therefore, it is likely that the black (dotted) lines shown in Fig. 3 correspond to the oxide films contaminated during hot extrusion.

The oxide contaminants in the recycled specimens are considered to be introduced from the machined-chip surface. The total surface area of the machined chips introduced in the recycled specimen was estimated from the geometry of the machined chips listed in Table 1, assuming that the machined chips are rectangular. Figure 5 shows the relationship between the oxygen concentration of the recycled specimens and the total surface area of the machined chips in the recycled specimen per unit volume. The oxygen concentration increased with the total surface area of the machined chips in the recycled specimen, indicating that the size of the machined chips is one of the important factors in the control of the contamination level of oxides in solid-state recycling.

3.2 Tensile properties

Table 2 shows the tensile properties of the recycled specimens at room temperature. The recycled specimens showed a good combination of high ultimate tensile strength, high 0.2% proof stress and high elongation to failure. These properties of the recycled specimens are almost the same as those of the virgin specimen. In general, the relationship between yield stress and grain size can be given by the Hall-Petch relation

$$\sigma_y = \sigma_0 + Kd^{-1/2},$$

where $\sigma_y$ is the yield stress for a polycrystalline, $\sigma_0$ is the yield stress for a single crystal, $d$ is the grain size and $K$ is a constant depending on the type of material. The Hall-Petch relation between the 0.2% proof stress and grain size can be shown in Fig. 6, where $\sigma_0$ and $K$ are 150 MPa [20] and 63 MPa μm−1/2 [21], respectively. For reference, the data in our previous research [13] are included in Fig. 6. It can be seen that the data fit a line, suggesting that the dispersed oxides have little effect on the strength of the recycled specimens.

The variation in ultimate tensile strength and elongation to failure at 773 K as a function of strain rate for all the specimens is shown in Fig. 7 as a function of testing temperature. The tensile strength of the recycled specimens from the machined chips was almost the same as that of the virgin specimen. However, the elongation to failure of the specimens from the machined chips was lower than that of the virgin specimen at elevated temperatures of more than 573 K. It should be noted that contamination of oxides had a detrimental effect on elongation at elevated temperatures, not at room temperature.

Figure 8 shows the variation in elongation to failure at 773 K as a function of strain rate. A large elongation more than 200% was attained at 10−4 s−1 for the specimens from medium-sized machined chips and large machined chips. However, the specimen from small machined chips showed a lower elongation of 117% at 10−4 s−1. As shown in Fig. 8, elongation decreases with increasing oxygen concentration. Cavity nucleation is stimulated due to the oxides introduced from the machined-chip surface, resulting in premature fracture in the solid recycled specimen. Therefore, it is suggested that a large amount of oxide contaminants in the specimen from small machined chips causes excessive cavity formation, resulting in a lower elongation. The variation in flow stress at 773 K as a function of strain rate for all the specimens is shown in Fig. 9. A high strain rate sensitivity of 0.5 was obtained in the strain rate range from 10−4 to 10−3 s−1 for all the specimens. Hence, superplastic behavior due to grain boundary sliding is considered to occur for all the specimens, regardless of the oxygen concentration.
in the range investigated.

Another important result in Fig. 9 is that at a low strain rate below $10^{-4}$ s$^{-1}$, stress depended on oxygen concentration and strain rate sensitivity decreased with increasing oxygen concentration. This is likely to be associated with the presence of threshold stress. Threshold stress can be estimated by extrapolation to zero strain rate of a straight line which the data give as $\sigma$ vs $\dot{\varepsilon}^m$ on a double-linear scale,$^{22}$ where $\sigma$ is the stress, $\dot{\varepsilon}$ is the strain rate and $m$ is the strain rate sensitivity. By using the data in Fig. 9, the threshold stress of the specimens were estimated, as shown in Fig. 10. The threshold stress was estimated to be about 5 MPa for the specimen from small machined chips and about 2 MPa for the virgin specimen, respectively. Hence, the strengthening due to the dispersion of oxides is considered to be 3 MPa, which is lower than the flow stress at $10^{-4}$–$10^{-5}$ s$^{-1}$ ($\approx 12$–$7$ MPa) for the specimen from small machined chips. Therefore, it is conclusively demonstrated that oxide contamination contributes little to the strengthening, but results in a low elongation to failure at elevated temperatures.

3.3 Blow forming

Blow forming tests were carried out at 773 K at a pressure of 0.5 MPa. The stress at the dome apex can be given by$^{23}$

$$\sigma_e = \sigma_i = \frac{PB}{4S} \left( H + \frac{1}{H} \right),$$

(2)

where $\sigma_e$ is the stress in the circumferential direction, $\sigma_i$ is the stress in the thickness direction, $P$ is the forming pressure, $B$ is the die radius, $S$ is the thickness and $H$ is the relative dome height. The strain rates at 0.5 MPa are of the order of $10^{-4}$ s$^{-1}$.
from eq. (2) and the results in Fig. 9. The results of the blow forming tests are shown in Fig. 11. The cup-shaped virgin specimen was successfully formed. However, the specimen from small machined chips was fractured before it formed a cup shape. On the other hand, the specimens from medium-sized machined chips and large machined chips exhibited better formability than that of the specimen from small machined chips. This trend of formability is the same as that of elongation at 773 K by as determined tensile tests. This indicates that poor formability for the specimen from small machined chips is attributed to a large amount of oxide contaminants. The results in the present investigation point
out the importance of the control of the contamination level of oxides for the formability of the solid recycled Al alloy. Further research is needed to reduce the detrimental effect of oxide contamination on formability in the recycled Al alloy.

4. Conclusions

The tensile properties and blow forming characteristics of 5083 Al alloy recycled by solid-state recycling were investigated. The results are summarized as follows.

(1) Three types of machined chip with different volumes were recycled by hot extrusion and hot rolling, and oxide contamination was investigated. Oxide layers, which were contaminants from the machined chip surface, were distributed parallel to the extrusion direction in the recycled specimens. Oxygen concentration in the recycled specimens increased with the total surface area of the machined chips per unit volume. Therefore, the size of machined chips is an important factor for the control of the contamination level of oxides in solid-state recycling.

(2) The recycled specimens exhibited almost the same properties in term of strength and elongation to failure as the virgin specimen. However, at 773 K, the recycled specimens showed lower elongation than the virgin specimen, and the elongation decreased with increasing oxygen concentration. The same trend was found in the blow forming tests, that is, formability decreased with increasing oxygen concentration. Thus, oxide contamination has a detrimental effect on the formability of recycled Al alloy.

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