Extrudability in the hot extrusion of medium strength A7xxx alloy

Hyung-Ho JO, Hoon CHO, Kyung-Whoan LEE, Young-Seog KIM and Myung-Keun HAN
Korea Institute of Industrial Technology, 472 Kajwa-4Dong, Seo-Ku, Incheon 404-254, R. O. Korea
TEL: 82-32-5707-051, 134, 140, 165, 100 FAX: 82-32-5707-102 e-mail : johh@kitech.re.kr, hoony67@kitech.re.kr, whoan@kitech.re.kr, kimtree@kitech.re.kr, hanmk@kitech.re.kr
Young-Jig KIM
School of Metall. and Mat. Eng., Sungkyunkwan University, 300 Chunchun-Dong, Jangan-Gu, Suwon, Gyounggi-Do 440-746 R. O. Korea
TEL: 82-31-290-7380 FAX: 82-31-290-7371 e-mail : yjk1122@yurim.skku.ac.kr
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To examine the effect of Mg content on extrudability in 7xxx aluminum alloys, hot extrusion experiments and then microstructure examination by XRD, SEM and EPMA have been performed. The finite element analysis has been also carried out for comparison of extrusion pressure in direct and indirect extrusion process. The total energy consumption from cradle to gate in Al extrusion process has been estimated after calculating the standard data of unit process in LCA inventory analysis. The extrudability and the tensile strength are equal to, or above that of conventional A 7003 alloy even the content of Mg varied from 1.1wt.% to 0.5wt.% alloy. This means that minimizing the content of Mg in A7003 alloy can enhance recovery efficiency during Al scrap recycling. It has been found that energy consumption of unit process can be reduced when the indirect process is used. However, there are little differences in total energy consumption related with increasing Mg content or changing extrusion process at the range from cradle to gate. Thus, for LCA inventory in the extrusion process, a range within the process except mining and extraction has to be introduced.

Keywords: Medium strength A7xxx alloy, Mg content, Extrudability, Direct/Indirect extrusion, LCA inventory

I. INTRODUCTION

The medium strength alloys such as 7003 and 7005 aluminum alloys have been used for a wide range of applications, because of characteristics of excellent weldability, high corrosion resistance and superior plastic working.1-4 The behavior of alloy elements in these alloys is very important in the extrusion process. In addition, not only alloy composition but also die structure, extrusion temperature, extrusion pressure and extrusion rate have considerable influence on extrudability. Therefore, it is necessary to select the amounts of alloy elements for mechanical property and extrudability in medium strength A7xxx alloy. It has been well known that an increment in Zn and Si content does not affect extrudability. However, an increment in Mg content has a significant effect on the extrudability.5 However, in the aluminum industry it has been generally practiced to reduce the Mg content in the extrusion aluminum alloys for enhanced extrudability and recovery efficiency during Al scrap recycling.

The objective of this study is to examine the relationship between Mg content and extrudability in A7003 alloy. The finite element analysis has been also carried out for comparison of extrusion pressure
in direct and indirect extrusion process. The total energy consumption from cradle to gate in Al extrusion process has been estimated after calculating the standard data of unit process in LCA inventory analysis.

II. EXPERIMENTAL PROCEDURE

Three types of 7003 alloy billets (72 mm diameter & 200 mm length) have been manufactured by melting in a high-frequency induction furnace. The chemical compositions of the alloys are shown in Table 1. The homogenization heat treatment was conducted at 550°C for 12 hrs. Cylindrical bars with the extrusion ratio of 13 have been extruded by using a 350-ton horizontal extrusion press. The extrusion die with an angle of $2\alpha=180^\circ$ has been used. The billets were pre-heated in a high-frequency heater at 350, 400 and 450°C for 1 hr. before the extrusion. The extrusion rate and ram speed were 6.5 m/min and 8.12 mm/sec, respectively. Microstructure was examined by SEM (Hitachi S-2700). DEFORM-2D, a commercial code for the evaluation of strong deformation, has been used for finite element analysis since the strain is relatively large during the hot extrusion process.

Table 1. The chemical compositions of the alloy used (wt.%).

<table>
<thead>
<tr>
<th></th>
<th>Mg</th>
<th>Si</th>
<th>Fe</th>
<th>Mn</th>
<th>Zn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>7003A</td>
<td>0.52</td>
<td>0.31</td>
<td>0.39</td>
<td>0.32</td>
<td>5.43</td>
<td>Bal.</td>
</tr>
<tr>
<td>7003B</td>
<td>0.84</td>
<td>0.31</td>
<td>0.37</td>
<td>0.21</td>
<td>5.47</td>
<td>Bal.</td>
</tr>
<tr>
<td>7003C</td>
<td>1.08</td>
<td>0.31</td>
<td>0.36</td>
<td>0.20</td>
<td>5.48</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

In order to calculate “cradle to gate” energy consumption for Al extruded bar, a description rule that can easily connect to a matrix of a process flow is proposed. The unit requirement of fuels and raw materials for Al extrusion process were referred to Japan economical statistical yearbook for the year 1999. The total energy consumption for a production of Al extruded bar was estimated for different contents of Mg in 7003 alloy and for different extrusion process.

III. RESULTS and DISCUSSION

III-A. Effect of Mg content on extrudability

The relations of flow stress to deformation temperature for 7003 alloy are shown in Fig. 1. The flow stress decreases with increasing deformation temperature and with decreasing Mg content. This means that the deformation of these alloys is affected both by the temperature and the Mg content though it is more sensitive to the temperature than the Mg content.

Figure 2 shows that a comparison of the experimental results of maximum extrusion pressure for 7003 A, B and C alloys with simulation results. It has been found that the maximum extrusion pressure tends to increase with increasing Mg content.
content. Although the experimentally obtained values are a little higher than those of the simulation results, the trend is very similar. The simulation results converge on the actual extrusion pressures as Mg content increased.

Figure 3 shows XRD peaks of intermetallic compounds corresponding to Mg₂Si, MgZn₂, and Al(Fe,Mn)SiZn, respectively. Meanwhile the MgZn₂ phase was not clearly revealed in the SEM micrographs. It was founded that the volume fraction of Mg₂Si phase decreases with decreasing Mg content.

The concentration of Mg in matrix for 7003A alloy by EPMA analysis is 0.4wt.% and that for 7003C alloy is 1.2wt.%.

The extrudability indexes for 7003 A, B and C alloys are shown in Table 2. The extrudability index is normalized by setting the extrusion time for A6063 to be 100. The obtained extrudability index is agreed well with previously reported data, and it seems that the obtained data is reliable. The extrudability index for 7003 alloy is reduced slightly, 83 to 73, as Mg content is increased. These values are larger than the previously reported data (Z=70). Consequently, the extrudability and the tensile strength are equal to, or above that of conventional A 7003 alloy even the content of Mg varied from 1.1wt.% to 0.5wt.% alloy. This means that minimizing the content of Mg in A7003 alloy can enhance recovery efficiency during Al scrap recycling.

### Table 2. Comparison of extrudability index.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Tensile strength (MPa)</th>
<th>Extrusion pressure (MPa)</th>
<th>Data acquire in reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A6063</td>
<td>246(T6)</td>
<td>422</td>
<td>100</td>
</tr>
<tr>
<td>7003A</td>
<td>321</td>
<td>599</td>
<td>83</td>
</tr>
<tr>
<td>7003B</td>
<td>350</td>
<td>619</td>
<td>77</td>
</tr>
<tr>
<td>7003C</td>
<td>358</td>
<td>629</td>
<td>73</td>
</tr>
</tbody>
</table>

III-B. Comparison of extrusion pressure in direct/indirect extrusion process

Figure 4 shows the result of finite element analysis of extrusion pressure for different extrusion processes (direct and indirect) when ram speed is 5mm/sec. The load initially increases very rapidly as the billet upsets to fill the container in both direct and indirect extrusion process. After the maximum load has been reached, the extrusion pressure falls as the billet length decreases until a minimum is reached. In indirect extrusion process, there is no frictional stress at the billet/container interface; therefore, the extrusion pressure is lower than that of direct extrusion in stroke.

![Fig.4. Comparison of extrusion pressure in direct and indirect process by computer simulation.](image_url)

By a multiplication of pressure and stoke, energy consumption during extrusion process was calculated and the results are shown in Table 3.

The energy consumption in direct process is calculated to 2.21*10⁷ N·m but that in indirect
process is $1.98 \times 10^7$ N·m. As above result, reduced energy consumption is 11.6%.

Table 3. Comparison of energy consumption in unit process.

<table>
<thead>
<tr>
<th>Processes</th>
<th>Extrusion Pressure (MPa)</th>
<th>Energy (N·m)</th>
<th>Reduced energy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>550.8</td>
<td>$2.21 \times 10^7$</td>
<td>11.6</td>
</tr>
<tr>
<td>Indirect</td>
<td>532.8</td>
<td>$1.98 \times 10^7$</td>
<td></td>
</tr>
</tbody>
</table>

III-C. LCA inventory estimation in Al extrusion process.

Table 4 shows calculation results of a total energy consumption for Al extruded bar. As the content of Mg in 7003 alloys is increased, total energy consumption is increased 603,357 MJ/ton to 603,900 MJ/ton. Furthermore, use of indirect extrusion process can reduce energy consumption 603,900 MJ/ton to 603,895 MJ/ton.

There are little differences in total energy consumption related with increasing Mg content or changing extrusion process at the range from cradle to gate because the most of energy (>80%) is consumed in not extrusion process but mining and extraction process.

Table 4. Comparison of total energy consumption.

<table>
<thead>
<tr>
<th>Process</th>
<th>0.5%Mg</th>
<th>0.8% Mg</th>
<th>1.1% Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>603,357</td>
<td>603,683</td>
<td>603,900</td>
</tr>
<tr>
<td>Indirect</td>
<td>603,351</td>
<td>603,678</td>
<td>603,895</td>
</tr>
</tbody>
</table>

Thus, for LCA inventory in the extrusion process, a range within the process except mining and extraction has to be introduced.

IV. CONCLUSION

1. As Mg content is increased, the flow stress and the extrusion pressure for 7xxx alloys are increased. It has been thought that an increment in extrusion pressure with increasing Mg content is caused by the solid solution hardening of Mg atoms in the matrix and an increment in volume fraction of intermetallic compound, Mg2Si cause an increment in the extrusion pressure.

2. The extrudability and the tensile strength are equal to, or above that of conventional A 7003 alloy even the content of Mg varied from 1.1 wt.% to 0.5 wt.% alloy. This means that minimizing the content of Mg in A7003 alloy can enhance recovery efficiency during Al scrap recycling.

3. It has been found that Energy consumption of unit process is lower in indirect extrusion process and it is reduced 11.6%.

4. There are little differences in total energy consumption related with increasing Mg content or changing extrusion process at the range from cradle to gate. Thus, for LCA inventory in the extrusion process, a range within the process except mining and extraction has to be introduced.

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