Application of Metal Injection Molding to Al Powder

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ABSTRACT

Metal injection molding (MIM) was applied to Al powders. Sintered Al compacts were prepared by MIM in this study. At first, sintered pure-Al compacts were prepared under various process conditions. The relative densities of the compacts debound in Ar gas and sintered at 650 °C for 2 hr in vacuum of $10^{-3}$ Pa order were 86 %, 90 % and 96 % when the average particle size were 20 μm, 10 μm and 3 μm, respectively. The 3 μm powder compact had the excellent tensile strength of 120 MPa and elongation at fracture of 19 % at room temperature. Next, the addition of Si powder to Al powder was examined to improve sinterability of Al powder. Regardless of Al powder size, the addition of Si powder widely enhanced densification of sintered Al compacts. Using Al powder of 35 μm, the relative density of the sintered pure-Al compact was only 66 %, while that of the sintered Al-1 mass%Si compacts went up to 89 %. When Al powder of 11 μm was used, the sintered Al-1Si compacts had the relative density of 97 % and the tensile properties close to annealed wrought pure-Al.

KEY WORDS

MIM, Al, density, tensile property, Si

1 Introduction

Parts of Al-based materials have been mainly manufactured by ingot metallurgy (I/M) previously. On the other hand, powder metallurgy (P/M) is also attractive process for Al-based materials because this process has the possibility that the parts having fine and homogeneous microstructure can be manufactured in near-net-shape. However, Al powder has sintering resistance because of its strong surface oxide. From the above-mentioned reasons, there have not been so much researches about MIM process for Al based-materials[1-3], previously. In this study, MIM process was applied to Al powder. At first, the influence of process conditions on the properties of sintered pure-Al compacts were investigated. Subsequently, the addition of Si powder to Al powder was investigated to improve sinterability of Al powder.

2 Influence of process condition for MIM on the properties of pure-Al compacts

Average particle size of using pure Al powders are three kind of 20 μm, 10 μm and 3 μm. These powders were mixed with organic binder based on paraffin wax and polymethyl methacrylate. The green compacts which size is 50 mm (l) × 50 mm (w) × 2 mm (t) are prepared from these compound. Table 1 shows influences of the process condition for MIM process on the oxygen and carbon contents, and relative density of the sintered compacts. The debinding temperatures were 325 °C in air and 380 °C in Ar gas so that apparent debinding rate was almost 90 %. All compacts were sintered at 650 °C for 2 hr. This sintering temperature is nearly upper limit because the melting point of pure-Al is 660 °C. Relative densities were calculate on the theoretical density for aluminum of 2.70 g/cm$^3$. The density of sintered compacts increase with decreasing particle size of powder if other process conditions are same. The sintered compacts debound in air contain more oxygen than those of debound in Ar gas. Sintering vacuum level also affects the content of oxygen of sintered compacts. It decreases with increasing the degree of vacuum at sintering. From these results, it is known that Al powder is easily oxidized during debinding and sintering. The relative density tends to be high when oxygen content is low from Table 1. The high oxygen content considered to be obstructive factor to consolidation.

The sintered compacts debound in air contain more carbon than that debound in Ar gas. From thermal analysis of organic binder, heating loss at 500 °C in air was 96.5 %, while that in Ar gas was 99.5 %. It is considered that the difference of heating loss reflects carbon content of the sintered compacts. Fig. 1 shows tensile properties at room temperature of the sintered compacts debound in Ar gas and sintered in $10^{-3}$ Pa order vacuum.

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The tensile properties enhanced with decreasing Al powder size. The sintered compact using 3 μm powder had good tensile properties of UTS = 120 MPa and ε = 19 %. Fig. 2 shows SEM images of fracture surfaces after tensile test of the sintered compacts shown at Fig. 1. Ductile fracture surfaces of which facets sizes correspond to the original powders sizes are observed for all compacts. The reason obtained high tensile properties at the sintered compact using 3 μm powder are considered not only high density but also fine and close connection between the original powders shown in Fig. 2.

Fig. 3 shows relationship between sintering temperature from 635 °C to 650 °C and relative density of sintered compacts debound in Ar gas and sintered in $10^{-3}$ Pa order vacuum. Hold time at each...

### Table 1  Influences of the process condition for MIM on the oxygen and carbon contents, and relative density of the sintered compacts.

<table>
<thead>
<tr>
<th>Average particle size of powder material (μm)</th>
<th>Debinding atmosphere</th>
<th>Degree of vacuum at sintering (~Pa order)</th>
<th>Oxygen content (mass%)</th>
<th>Carbon content (mass%)</th>
<th>Relative density (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>—</td>
<td>—</td>
<td>0.57</td>
<td>0.01</td>
<td>—</td>
</tr>
<tr>
<td>10</td>
<td>—</td>
<td>—</td>
<td>0.81</td>
<td>0.01</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>—</td>
<td>—</td>
<td>0.99</td>
<td>0.01</td>
<td>—</td>
</tr>
<tr>
<td>20</td>
<td>Air</td>
<td>$10^{-3}$</td>
<td>2.31</td>
<td>1.04</td>
<td>66.5</td>
</tr>
<tr>
<td>20</td>
<td>Ar gas</td>
<td>$10^{-3}$</td>
<td>0.75</td>
<td>0.21</td>
<td>86.5</td>
</tr>
<tr>
<td>10</td>
<td>Air</td>
<td>$10^{-3}$</td>
<td>2.95</td>
<td>1.03</td>
<td>67.2</td>
</tr>
<tr>
<td>10</td>
<td>Ar gas</td>
<td>$10^{-3}$</td>
<td>0.92</td>
<td>0.23</td>
<td>89.8</td>
</tr>
<tr>
<td>3</td>
<td>Air</td>
<td>$10^{-3}$</td>
<td>1.99</td>
<td>0.87</td>
<td>85.9</td>
</tr>
<tr>
<td>3</td>
<td>Ar gas</td>
<td>$10^{-3}$</td>
<td>1.47</td>
<td>0.17</td>
<td>96.3</td>
</tr>
<tr>
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<td>$10^{3}$</td>
<td>2.40</td>
<td>0.32</td>
<td>64.8</td>
</tr>
<tr>
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<td>Ar gas</td>
<td>$10^{3}$</td>
<td>1.14</td>
<td>0.20</td>
<td>83.8</td>
</tr>
<tr>
<td>10</td>
<td>Ar gas</td>
<td>$10^{-3}$</td>
<td>0.92</td>
<td>0.23</td>
<td>89.9</td>
</tr>
</tbody>
</table>
sintering temperature is 2 hr. The densities of the sintered compact using 10 μm or 20 μm powder rapidly decrease with decreasing sintering temperature. Sintered at 635 °C, they are only 62 %. On the other hand, the density of the sintered compact using 3 μm powder shows a little decrease with decreasing sintering temperature. It is considered that consolidation of 3 μm powder starts at lower temperature.

3 Effect of Si Powder Addition

It was known from previous researches that addition of elemental powders to Al powder promoted consolidation of Al powder. It is investigated here whether these results can be applied to MIM process. Si (Silicon) was selected as the additional element. There is the eutectic point on Al-11.7 wt.%Si (Al-11.3 at%Si) at 577 °C in the Al-Si binary phase diagram. Therefore, it can be expected that consolidation of Al powder is promoted by liquid phase formation with this eutectic reaction.

At first, the influence of addition content of Si powder to Al powder on the densities of sintered compacts was investigated in the press molding process without organic binder. Average particle size of Al and Si powders are 20 μm and 2 μm, respectively. The green compacts are cylindrical shape (10 mmL × 10 mmϕ) and they were sintered at 625 °C for 2 hr. The results is shown in Fig. 4. Sintered pure-Al compact has low density of 1.59 g/cm³ (relative density: 59 %), while addition of Si powder widely raises the density of sintered pure-Al compact. It became clear that addition of Si powder was effective to consolidation of Al powder in the press molding. However, more than 1 wt.%Si powder addition did not contribute to raising densities of sintered pure-Al compact. Therefore, the addition content of Si powder for MIM process were fixed to 1 wt.%, hereafter this composition was called Al-1Si.

Average particle size of Al powders using for MIM process are 35 μm, 20 μm and 11 μm. These Al powders were mixed with Si powder of 2 μm before kneading with the organic binder. The content ratio of organic binder to mixed powder were 38 vol%. Tensile test-piece (length: 110 mm, width: 7.5 mm, thickness: 4.0 mm) was prepared by injection molding. The green compacts were debound in Ar gas at 380 °C and then sintered in vacuum(10⁻³ Pa) at prescribed temperature for 2 hr. Fig. 5 shows appearances of green and sintered compacts. Line shrinkages by sintering of pure-Al and Al-1Si are 6.8 % and 14.2 %, respectively.

Fig. 6 shows the relationship between sintering temperature and relative densities of sintered pure-Al and Al-1Si compacts prepared by MIM. The full density of Al-1Si was estimated to 2.694 g/cm³ from the densities of Al and Si. When the particle sizes of Al powder was 35 μm, 20 μm and 11 μm, the relative densities of pure-Al compacts sintered at 650 °C were 65.9 %, 76.8 % and 83.3 %, respectively. On the other hand, the relative densities of Al-1Si compacts sintered at 635 °C were 87.9 %, 93.2 %, 97.1 %, respectively. From this results, addition of Si powder is very effective to consolidation of Al powder by MIM process regardless of Al powder size. Furthermore, the densities of sintered Al-1Si...
Compacts increase with increasing sintering temperature from 620 °C to 640 °C. These are gradual increases compared with that of the sintered pure-Al compacts using 10 μm or 20 μm powder at Fig. 3.

Fig. 7 show SEM images of the cross-sections for sintered pure-Al and Al-1Si compacts of which powder size of pure-Al are 11 μm. Sintering temperature is 650 °C for pure-Al and 635 °C for Al-1Si. On the microstructure of sintered pure-Al compact, original powder shapes still remained and a lot of open pores are observed because of low density. As to the sintered Al-1Si compact, percentage of pores decreases as compared the sintered pure-Al compact but precipitated phases as pointed with arrow are observed in the microstructure.

Fig. 8 and Fig. 9 show WDS mapping images of sintered pure-Al and Al-1Si compacts by EPMA. It is known from oxygen mapping for sintered pure-Al compact, that oxygen is distributed in the pores i.e. original powder surfaces. About sintered Al-1Si compact, oxygen and silicon contents are high in the precipitated phase. From the quantitative analysis by WDS, Al/Si ratio of this precipitated phase became 90/10 (at%), which is near the composition of the Al-Si eutectic point at 577 °C. From these results, it is considered that this precipitated phase is eutectic structure generated along boundary between the original Al powders.

Table 2 shows the tensile properties of sintered pure-Al and Al-1Si compacts at room temperature. The sintered pure-Al compact using 11 μm powder shows low elongation of 5.2 % because of low density. As to the sintered Al-1Si compact, the tensile properties are higher as the powder size is small, in other words, the density becomes high. Besides, there is a little difference between the tensile properties of the compacts sintered at 625 °C and 635 °C because the difference of their densities are small as shown in Fig. 6. The sintered Al-1Si compacts using 11 μm powder has the tensile strength of more than 100 MPa and the elongation of more than 20 %. This tensile properties is close to annealed wrought pure-Al. From this result, it was known that 1 wt.%Si was not enough amount to change the tensile property of pure-Al.
Conclusions

Sintered aluminum compacts were prepared by metal injection molding (MIM) in this study. At first, sintered pure-Al compacts were prepared under various process conditions. Next, the addition of Si powder to Al powder was examined to improve sinterability of Al powder. The results can be listed as follows.

(1) The relative densities of the pure-Al compacts debound in Ar gas and sintered at 650 °C for 2 hr in vacuum of 10⁻³ Pa order were 86 %, 90 % and 96 % when the average particle size were 20 μm, 10 μm and 3 μm, respectively.

(2) The tensile properties of the sintered pure-Al compacts increased with decreasing Al powder size. The sintered compact using 3 μm powder had the tensile strength of 120 MPa and elongation to fracture of 19 % at room temperature.

(3) Regardless of Al powder size, the addition of Si powder widely enhanced the density of sintered Al compacts. When the particle sizes of Al powder was 35 μm, 20 μm and 11 μm, the relative densities of pure-Al compact sintered at 650 °C were 66 %, 77 % and 83 % respectively, while those of Al-1Si compacts sintered at 635 °C were 88 %, 93 %, 97 % respectively.

(4) The sintered Al-1Si compacts using 11 μm powder had the tensile strength of more than 100 MPa and elongation of more than 20 %. This tensile properties was close to annealed wrought pure-Al.

References


