Paper

Static and Dynamic Fracture Characteristics of the MIM Ti-6Al-4V Alloy Compacts Using Fine Powder

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ABSTRACT
Titanium alloys show not only the excellent mechanical properties but also good biocompatibility. However, they show normally poor machinability, which become the disadvantage of high processing cost. Metal injection molding (MIM) process is one of the techniques to improve that drawback. Because MIM process can produce the three dimensional complex shaped parts at low cost. Ti-6Al-4V is a typical titanium alloy and the MIM compacts show high static strength as same as wrought materials. However, their fatigue strength is a little low level as compared to wrought materials. To improve the mechanical properties of Ti-6Al-4V alloy compacts, it is important to refine the grain size and increase the relative density. In this study, the effects of the particle size of the powders on the mechanical properties were investigated. The use of a fine powder improved the mechanical properties because of their high density. Moreover, the crystal grain growth was restrained as compared to the case of the same relative density using larger powder.

KEY WORDS
metal injection molding, Ti-6Al-4V, mechanical properties, density, grain size

1 Introduction
Titanium alloy which has high specific strength, stable mechanical properties from low to high temperatures, excellent corrosion resistance and biocompatibility is used primarily in the aerospace industry, and is also used in various fields at present. However, they show normally poor machinability due to low thermal conductivity, low Young’s modulus and high strength, which become the disadvantage of high processing cost. Metal injection molding (MIM) process is one of the techniques to improve the drawback, because MIM process can produce the three dimensional complex shaped parts at low cost. Although Ti-6Al-4V is a typical titanium alloy and the MIM compact show high strength comparable to wrought materials with respect to the static fracture1,2), their fatigue strength is a little low level as compared to wrought materials3). A fine powder has a high specific surface and thus has a high surface energy. Therefore, their sintering promotes and the relative density increases, so that improvement of mechanical properties is expected4). On the other hand, use of a fine powder in MIM might increase the amount of binder and the impurity such as oxide. In this study, the effects of the particle size of the powders on the static and dynamic mechanical properties are investigated by using fine Ti-6Al-4V powder.

2 Experimental procedure
A fine Ti-6Al-4V powder (AP & C, Advance Powders and Coatings Inc.) was produced by the plasma atomization. The SEM images are shown in Fig. 1 and the chemical composition of the powder is shown in Table 1 including normal powder. The average particle size is 15.0 μm of fine powder and 22.6 μm of normal powder2). In this paper, these powders are named as Fine and Normal powders. Both powders are sphere shape. The binder used was composed of paraffin wax (69 %), carnauba wax (10 %), atactic polypropylene (10 %), ethylene vinyl acetate (10 %), and di-n-butyl phthalate (1 %). Volume ratio of powder and binder was 65:35.

Tensile and fatigue specimens shown in Fig. 2 were produced by injection molding. The paraffin wax was removed by performing solvent debinding in heptane atmosphere. After that, the remained binder was removed by holding 1 hour at 600 °C in argon atmosphere. Sintering was carried out under vacuum at the temperature from 1100 °C to 1300 °C for 2 hours. In the case of normal powder, sintering was carried out at 1350 °C for 4 hours. Some of the compacts sintered at 1100 °C and 1300 °C were subjected to hot isostatic pressing (HIP). HIP was carried out in argon atmosphere under the pressure of 103 MPa at 900 °C for 2 hours. After that, compacts were annealed at 843 °C for 2 hours followed by gas fan cooling to room temperature.

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For each compact, relative density and oxygen content were measured and microstructure was observed. Then, tensile test and rotary bending fatigue test were carried out.

3 Result and discussion

The relationship between the sintering temperature and the relative density is shown in Fig. 3. Compared to normal powder compact, it was possible for fine powder to obtain the high densified compact even at lower temperature and for shorter time. Because the sintering was promoted by using a fine powder. The relative density increased with increasing the sintering temperature, then reached at around 98 %. The relative density became almost 100 % after HIP treatment.

Their microstructures are shown in Fig. 4 and the relationship between the sintering temperature and the grain size is shown in Fig. 5. Number of pores was decreased with increasing the sintering temperature. Compared to normal powder compacts, size of pores was decreased although their number was increased in fine powder compacts. Microstructure showed the lamellar structure of α + β phase at all sintering conditions. The sintering conditions affected on the grain growth, so the grain size of compact sintered at 1100 °C was about 50 μm but the compact sintered at 1300 °C showed the coarse grains about 150 μm. From these results, the use of a fine powder seemed to improve the mechanical properties because high relative density and small crystal grains size were obtained by lower sintering temperature for shorter time.

Table 1 Chemical composition of powder.

<table>
<thead>
<tr>
<th>Composition (mass%)</th>
<th>C</th>
<th>O</th>
<th>N</th>
<th>H</th>
<th>Fe</th>
<th>Al</th>
<th>V</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine powder</td>
<td>0.01</td>
<td>0.17</td>
<td>0.02</td>
<td>0.013</td>
<td>0.06</td>
<td>6.19</td>
<td>3.83</td>
<td>Bal.</td>
</tr>
<tr>
<td>Normal powder</td>
<td>0.015</td>
<td>0.115</td>
<td>0.004</td>
<td>0.007</td>
<td>0.045</td>
<td>5.96</td>
<td>4.35</td>
<td>Bal.</td>
</tr>
</tbody>
</table>
The result of oxygen content measurement is shown in Fig. 6. The oxygen content were almost constant around 0.3 mass%. Moreover, the amount of oxygen is not changed by HIP treatment. Although the elongation of MIM Ti-6Al-4V alloy compact was affected by oxygen content, in this study, all oxygen contents of sintered compacts were less than 0.35 mass%. It could be considered that elongation was not affected by oxygen content. The use of a fine powder may increase the amount of impurities, however, a significant difference was not measured.

The relationship between the relative density and the tensile strength is shown in Fig. 7, and the elongation is shown in Fig. 8, respectively. With the increase of the relative density, tensile strength and elongation were improved. When the relative density exceeded 98 %, increase of the tensile strength was slight, even HIP treated compact with full density. The sintered fine powder compacts at 1350 °C showed the highest strength, but the decrease of elongation is considered to be due to the coarsening of crystal grains. Maximum tensile strength and elongation were 980 MPa and 14 %. These values satisfy JIS60 defined by Japanese Industrial Standards. The strength was increased about 100 MPa by using a fine powder as compared to normal powder.

S-N curves are shown in Fig. 9. Maximum fatigue strength obtained in this study was about 380 MPa of the compacts sintered at 1100 °C. Fatigue strength of fine powder compacts is improved.
in all conditions as compared to normal powder compacts. This is considered to be due to the increasing of relative density and the suppressed grain growth.

Fatigue fractured surfaces are shown in Fig. 10. The crack seems to propagate in the direction of the arrow from the circle area. Effects of grain size were observed on the fractured surface. In the compact sintered at of 1100 °C, fine fractured surface unit was observed as compared to the compact sintered at 1300 °C with large fractured surface unit.

The relationship between the fatigue strength, grain size and relative density is shown in Fig. 11 (11-19). Fatigue strength was improved by grain refinement following with the Hall-Petch relation. Moreover, fatigue strength was increased with increasing of relative density. In the case of comparable density, fatigue strength tended to have affected by the grain size as in the expression of the Hall-Petch. Therefore, the fatigue strength of compacts sintered at 1100 °C was high in spite of a little low relative density.
4 Conclusion

In this study, the effects of the particle size of the powders on the static and dynamic mechanical properties are investigated. Followings are the summarized results:

(1) In the case of a fine powder, sufficient relative density and small crystal grains can be obtained by sintering at lower temperature for shorter time than normal powder.

(2) Tensile strength and fatigue strength were increased by using a fine powder due to the small crystal grain size and small pore size.

(3) Fatigue strength affected by the grain size as in the expression of the Hall-Petch.

References


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