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Warm compaction of Al_2O_3 particulate reinforced powder metallurgy iron-base composite①

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[Abstract] Mechanical properties of the warm compacted alumina particulate reinforced powder metallurgy composite materials was compared with those of the materials obtained by conventional cold compaction. Factors affecting the properties of the warm compacted material such as compaction temperature, lubricant content and alumina content were studied. A 3% (mass fraction) alumina particulate reinforced iron-base composite with a green density of 7.0 g/ cm^3 can be obtained by pressing the powder with a pressure of 700 MPa at 175 ℃. The sintered materials have a density of 6.88 g/ cm^3, a tensile strength of 512 MPa and an elongation of 1.3%. Results show that as alumina content increases, density and mechanical properties of the composite decrease.

[Key words] warm compaction; powder metallurgy; Al_2O_3 particulate reinforced iron-base composite; mechanical property

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1 INTRODUCTION

References focused on warm compaction were first published in 1994[1, 2]. It is a relatively simple and economical process that can produce sintered iron-base parts with relatively high density. Its potential is tremendous. Recently, it played an increasing role in the high performance parts, especially in the automobile industry worldwide[3~7]. It is well known that increasing density is the best way to increase the performance of powder metallurgy (P/M) parts, especially the mechanical property. Conventional P/M processing can produce iron-base P/M parts with a density less than 7.1 g/ cm^3 (a relative density of 90% approximately). The mechanical properties of P/M parts are substantially less than those of the full density counterpart. In those processes that can produce iron-base P/M parts with high density such as powder forging, double press/double sinter (DP/DS) and Cu infiltration, warm compaction is the most economical and effective way[8]. Warm compaction is a relatively simple process that modified from the conventional P/M technique. The tooling and the specially treated powder were heated to 130~ 155 ℃ before compaction[1, 2]. Compared with the conventional technique, both green density and green strength were increased. With a minor modification on the conventional press, the technique can produce parts with a density slightly over 7.4 g/ cm^3. With DP/DS technique parts with a density of 7.65 g/ cm^3 can be obtained[9, 10]. An iron-base powder metallurgy material with a green density of 7.31 g/ cm^3 (a relative density of 92.5%) was obtained by pressing a powder mixture with a pressure of 700 MPa at 175 ℃ using a special lubricant that was developed by our group[11~13]. Except for the lower cost it offer, other advantages of the warm compaction process include higher green and sintered mechanical property, lower ejection force needed, higher effective load on the compact and less spring back effect.

Composite materials can offer smaller coefficient of thermal expansion, lower specific density, better mechanical property at elevated temperature and better tribological behaviors. Particulate reinforced P/M iron-base composite materials were developed in the past few decades. Problems encountered in the fabrication of this type of materials include high porosity and low mechanical property by using traditional P/M methods. Therefore, non-conventional techniques were developed. Bovanick used co-deposition method to produce a 16% Al_2O_3/Fe composite material that have a tensile strength of 225 MPa at 650 ℃ compared to a tensile strength of 190 MPa for the same composite material but produced by extrusion. Warm compaction is effective in producing high performance P/M iron-base parts and it should be suitable in the production of iron-base composite materials with low content of ceramic particulate.

The aim of this paper is to study the effect of warm compaction on the alumina particulate reinforced iron-base composite material and to obtain a composite with a relatively high density. Alumina is chosen due to its stability at high temperature. Factors affecting the property of the warm compacted composite material such as compaction temperature, lubricant content and alumina content are studied and these results are compared with those of the material

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obtained by conventional cold compaction.

2 EXPERIMENTAL

Atomet 1001 atomized iron powder produced by Quebec Metal Powders, Canada, phosphorus iron (P iron) with 16.7% P(mass fraction), Al_2O_3 particulate with size of 12 μm and a special lubricant, which was developed by our group for warm compaction application, were used in this study. The compositions (mass fraction) of the mixed powder are 2% Cu, 3.2% phosphorous iron, 0.8% graphite, 0 ~ 7 % Al_2O_3 particulate and balanced Fe with an additional 0.4% ~ 0.8% of the special lubricant. Unless mentioned, all lubricant content used in this study was 0.6%.

Mixed powder were heated at 175 ℃ for 15 min in air, then pressed into standard tensile test specimens by a pressure of 700 MPa in a steel mold heated to the pre-set temperature. The compaction temperature ranged from room temperature to 195 ℃ with a fluctuation controlled to be ±2 ℃. These samples were degassed at 750 ℃ for 2 h in the pre-heating chamber of a pusher type furnace, which protected with a reducing hydrogen-nitrogen atmosphere produced by an ammonia dissociator. Sintering was carried out at 1 120 ℃ (or 1 250 ℃) for 1.5 h in the sintering chamber then hold at 850 ℃ in the cooling chamber for 1 h and subsequently cooled to room temperature. Unless mentioned, all sintering temperature used in this study was 1 120 ℃. Green density, sintered density, tensile strength, impact toughness, hardness and elongation were measured.

3 RESULTS AND DISCUSSION

Table 1 compared the results obtained from warm compacted and conventionally cold compacted samples with 3% Al_2O_3 under different experimental conditions. As shown in Table 1, densities and mechanical properties of the compacts are not sensitive to the lubricant contents in the powder mixture. Compared with the other two samples, compacts with an admixed lubricant content of 0.6% show a slightly higher value in densities and mechanical properties. The benefit of warm compaction is obvious. There is about 0.3 g/cm^3 increase in both green and sintered density by using warm compaction at 175 ℃ instead of compaction at room temperature. The increase in tensile strength is more significant (about 20%). Table 1 also shows the effects of sintering temperature on densities and mechanical properties of the compacts. With higher sintering temperature of 1 250 ℃ instead of 1 120 ℃, there is practically no change in the sintered density, but the increase in tensile strength and elongation for both warm compacted and room temperature compacted samples are very significant. There are 8% increase in tensile strength and the increases in elongation are double. The reason for this is that the diffusion process becomes faster at higher temperature; and the alloying elements in the compacts are therefore closer to the equilibrium condition and can strengthen the alloy more effectively.

Fig. 1 shows the effect of compaction temperature on the green and sintered densities of samples containing 3% Al_2O_3. Densities increase with increasing compaction temperature and it reached a maximum at about 170 ℃ then decrease gradually. To obtain high density P/M materials, 175 ℃ was chosen as the compaction temperature in this study.

Fig. 2 shows the effect of Al_2O_3 content on green and sintered densities of samples compacted at 175 ℃ and at room temperature. The straight lines are the linear regression of data points. As shown in Fig. 2, the densities decrease linearly with the increase of Al_2O_3 content, and all four sets of data have the same slope. This is a reflection that the sample's density is a weighted sum of the density of the metal matrix, the

Table 1 Results of warm compacted and conventionally cold compacted samples containing 3% Al_2O_3 under different experimental conditions

w (Lubricant)/%	Compaction temperature/℃	Green density/($g·cm^{-3}$)	Sintered temperature/℃	Sintered density/($g·cm^{-3}$)	Tensile strength/MPa	Elongation/%	Apparent hardness (HRB)	Impact toughness/($kJ·m^{-2}$)
0.4	RT	6.76	1 120	6.68	442	1.0	91	–
0.4	175 ℃	6.98	1 120	6.86	497	1.2	94	–
0.6	RT	6.62	1 120	6.57	411	1.0	84	–
0.6	175 ℃	7.00	1 120	6.88	512	1.3	91	–
0.8	RT	6.60	1 120	6.53	406	0.7	83	–
0.8	175 ℃	6.97	1 120	6.86	511	1.0	87	–
0.6	RT	6.68	1 120	6.63	362	0.7	79	36
0.6	RT	6.68	1 250	6.59	389	1.4	71	34
0.6	175 ℃	7.02	1 120	6.90	499	1.2	83	46
0.6	175 ℃	7.03	1 250	6.92	537	2.3	82	38

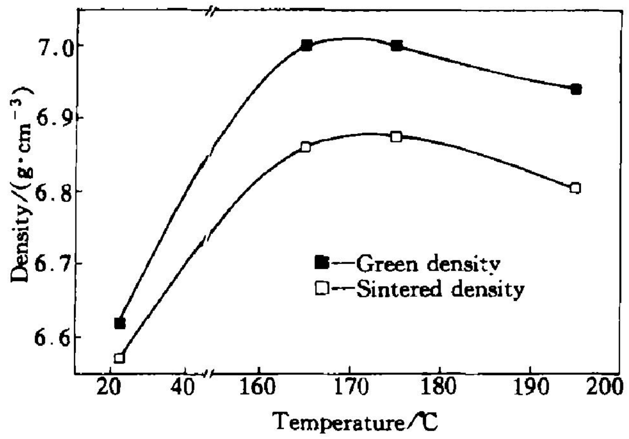

Fig. 1 Effect of compaction temperature on green and sintered densities of samples containing 3% Al_2O_3

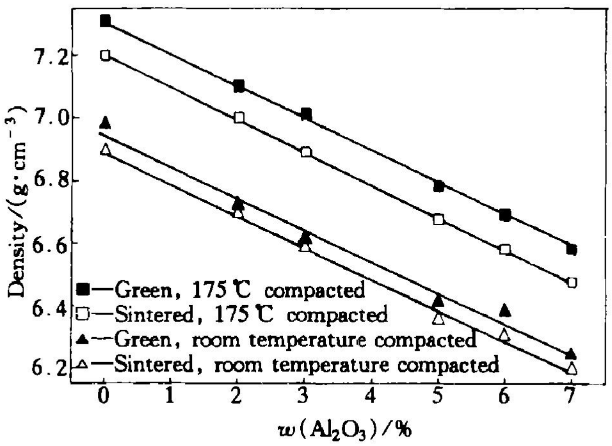

Fig. 2 Effect of Al_2O_3 content on green and sintered densities of samples compacted at 175 ℃ and at room temperature

reinforced Al_2O_3 and the pores. Compaction temperature and sintering process did not altered the weight ratio between the metal matrix and the Al_2O_3, while the weighted factor for the pores were increased. From this figure, we can also notice that the decrease in density after sintering for samples compacted at room temperature is less than those for samples compacted at 175 ℃. This is due to the fact that the residual stress in the warm compacted sample is higher than that in the cold compacted sample. During sintering the relaxation of these residual stress will make the compact expand and thus the drop in density is larger.

Fig. 3 depicts the variation of tensile strength and elongation of the sintered samples compacted at 175 ℃ and at room temperature as function of Al_2O_3 content. Fig. 4 depicts the variation of impact toughness and apparent hardness of the sintered samples compacted at 175 ℃ and at room temperature as function of Al_2O_3 content. The curves in these two figures are binomial fits of mechanical property data points obtained from samples compacted at room temperature and at 175 ℃; while the straight lines in Fig. 4 are the linear fit of the hardness data. They all show a decrease as the Al_2O_3 content increases. This is as expected since density of the sintered compacts decreases with increasing the Al_2O_3 content also. Except for the hardness data, effect of warm compaction diminishes as the Al_2O_3 content increases. As shown in Fig. 3 and 4, tensile strength, elongation and impact toughness of samples with 7% Al_2O_3 compacted at 175 ℃ are very close to those of samples compacted at room temperature. As we know tensile strength, elongation and impact toughness are not only sensitive to the pores and reinforced particle content, but also sensitive to the inter-granular bonding strength. It is obvious that the bonding strength between metallic particles is much stronger than that between metallic particle and alumina particle, therefore, as Al_2O_3 content increases, tensile strength, elongation and impact toughness decrease. At a critical Al_2O_3 content (approximately 7% Al_2O_3 in this case), the benefit gained by warm compaction is neutralized by the increasing effect of weak bonding between metallic particle and alumina particle.

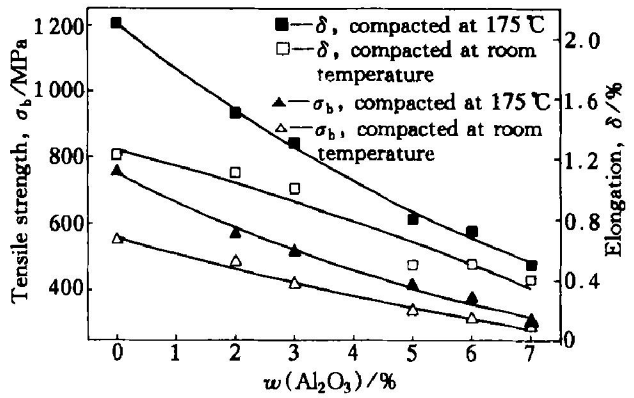

Fig. 3 Effect of Al_2O_3 content on tensile strength and elongation of samples compacted at 175 ℃ and at room temperature, respectively

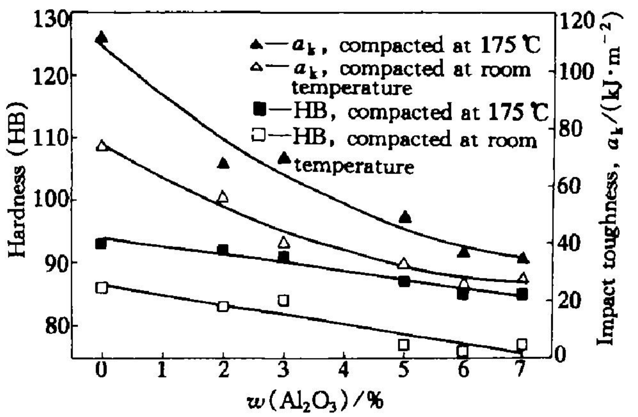

Fig. 4 Effect of Al_2O_3 content on apparent hardness and impact toughness of samples compacted at 175 ℃ and at room temperature, respectively

Although no data beyond 7% Al_2O_3 are presented in this study there is no reason to expect the mechanical properties obtained from warm compacted sample has a lower value than those obtained from conventional cold compacted sample. Hardness of a P/M composite material is sensitive to pores and reinforced particle content. It is not very sensitive to the inter-granular bonding strength. Warm compacted sample always has higher density than those of conventionally cold compacted sample, which means warm compacted sample always has lower porosity. Therefore hardness data obtained from samples compacted at different temperature decrease monotonically with increasing Al_2O_3 content, but the warm compacted samples always show a significant higher hardness.

4 CONCLUSIONS

1) 0.6% was found as optimal lubricant content in the fabrication of alumina particulate reinforced P/M iron-base composite.

2) The optimal compaction temperature ranges from 160 ℃ to 180 ℃.

3) A 3% alumina particulate reinforced iron-base composite with a green density of 7.0 g/cm^3 can be obtained by pressing the powder with a pressure of 700 MPa at 175 ℃. The sintered materials have a density of 6.88 g/cm^3 with a tensile strength of 512 MPa and an elongation of 1.3 %.

4) Density and mechanical properties of the composite decrease as the alumina content increases.

5) Effect of warm compaction diminishes as the Al_2O_3 content increases. At a critical Al_2O_3 content, approximately 7% in this case, the benefit gained by warm compaction is neutralized by the increasing effect of weak bonding between metallic particle and alumina particle. The tensile strength, elongation and impact toughness of samples with 7% Al_2O_3 compacted at 175 ℃ are approximately as same as those of samples compacted at room temperature.

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