Synthesis of Fe Based Metallic Glass–Pd Based Metallic Glass Composite by Slightly Pressured Liquid Phase Sintering*1

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To consolidate [(Fe0.5Co0.5)0.75Si0.05B0.2]60Nb metallic glass powder to full density, a pressurized liquid phase sintering was employed, which was intended to promote densification by an enhanced wetting of a liquid phase with solid particles. Pd42Ni57P30 metallic glass powder, which has been reported to have a high glass forming ability and the lowest critical cooling rate of glass formation of 0.067 K/s, was chosen as a liquid phase component. The melting point of the Pd42Ni57P30 metallic glass alloy of 763 K is lower than the glass transition temperature of the [(Fe0.5Co0.5)0.75Si0.05B0.2]60Nb metallic glass alloy of 808 K. However, the wettability of this alloy with the Pd42Ni57P30 alloy was revealed to be poor. Therefore, sintering pressure was applied to the compacts to promote a viscous flow deformation of solid particles and also to enhance the intergranular permeation of the liquid phase. A specially designed micro-hot press was devised for the pressure-sintering experiment. A pseudo-wettability was observed during pressure-sintering, and the liquid phase was found to fill completely the intergranular space of the powder compact. The relative density of 64–95%, as well as the sintering structure, could be controlled by the punch displacement to squeeze out a part of the liquid phase from the compact. The compressive fracture strength of the obtained metallic glass composite was found to be as high as 2051 MPa, and the fracture was observed to be intragranular type, suggesting a good bonding in the particle-binding phase interface. [doi:10.2320/matertrans.M2010197]

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1. Introduction

Fe-based metallic glasses have recently attracted much attention because of their rich resources, and extensive work is carried out worldwide for their practical applications.1) Fe-based metallic glasses exhibit a high mechanical strength and an excellent soft magnetic properties.2) However, the glass forming ability, as well as the thermal stability of the soopercooled liquid, of the Fe-based metallic glasses is low compared to the other metallic glasses such as Zr- and Pd-based alloys. Bulk samples of the Fe-based metallic glasses of the dimension of over 10 mm have not yet been prepared by conventional copper mold casting techniques,1,2) presumptively because of their difficulties in keeping a sufficient cooling rate throughout the casted sample to maintain glassy state. Powder metallurgy would be an alternative to the casting techniques to produce these metallic glasses with large dimensions and complex shapes because it starts with small-sized and thus thermally stable amorphous particles and the powder is well-consolidated by rapid hot pressing like Spark Plasma Sintering (SPS)6) or by warm rolling7) with keeping the amorphous state. Xie et al.8) for a Ni-based metallic glass consolidated by SPS method and Kim et al.7) for Cu-based metallic glass consolidated by warm rolling obtained a comparable compressive strength to those of the casted alloys. Yodoshi et al.9,10) reported the consolidation of Fe-based metallic glass of [(Fe0.5Co0.5)0.75Si0.05B0.2]60Nb4 powder to nearly full-dense compacts, keeping its amorphous state, but their compressive strength was found to be as less as a fourth of that of the casted alloy. Typical intergranular fracture was observed in this alloy, which suggests the weak bonding between consolidated grains.

In addition to this fact the cusp-shaped residual pores, presumably formed at inhomogeneous packing sites, remain in the compacts, which would also lower their strength. Normally these cusp-shaped pores can not be healed out because the hot pressing temperature, required to be between the glass forming and the crystallization points, is too low for the surface-tension driven pore closure. In order to obtain full-dense metallic glass compacts with strong intragranular bonding, we propose an application of a pressurized liquid-phase-sintering using a low-melting-point metallic glass as a liquid phase. In spite of the poor solid-liquid wettability in the metallic glass system the liquid phase is expected to penetrate in between solid particles under the influence of the applied pressure to form fully-densified two-phase compacts.

To verify this pressurized liquid phase sintering feasible for the consolidation of metallic glass powders into fully densified compacts with good intergranular bonding we chose the combination of [(Fe0.5Co0.5)0.75Si0.05B0.2]60Nb4 alloy and Pd42Ni57P30 alloy, both being a solid and a liquid phase, respectively. The latter, Pd42Ni57P30 alloy, as a liquid phase, was selected because its melting point is lower than the crystallization temperature of the solid constituent, which assures the solid particles keeping glassy state during hot pressing. In addition, this alloy has a high glass forming ability with cooling rate of 0.067 K·s−1, as well as a wide temperature range of supercooled liquid region.11) Therefore it is expected during cooling from hot pressing temperature the liquid phase will solidify into amorphous state thus forming an amorphous two phase alloy. This paper describes first the densification process of the liquid phase sintering of the present mixed system with particular interest in the penetration behavior of the liquid phase under the influence of the applied pressure, then discuss the phase formation during and after hot pressing. Finally the fracture strength will be mentioned in reference to the intergranular bonding.

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2. Experimental Procedures

2.1 Sample powders
The [(Fe_{0.5}Co_{0.5})_{0.75}Si_{0.05}B_{0.2}]_{0.7}Nb_{0.3} and Pd_{42.5}Ni_{7.5}P_{20-Cu_{30}} alloys were prepared by arc melting from the proper mixtures of the component metals. The alloys were remelted by induction heating and Ar gas-atomized to form spherical amorphous powders. The powders were sieved to under 125 μm, subjected to SEM observation, and XRD and DSC analysis. The two kinds of powders were mixed in a volume ratio of 64 : 36; here we assumed the random dense packing of spherical particles with a relative density of 0.64,\(^2\) therefore the liquid phase constituent may just fulfill the vacant volume of the solid particle packing to yield full dense two phase composite. The mixed powder was provided for the hot pressing experiment.

2.2 Measurement of wettability
Prior to sintering experiment the contact angle of the liquid Pd_{42.5}Ni_{7.5}P_{20-Cu_{30}} on the mirror-polished surface of the hot consolidated [(Fe_{0.5}Co_{0.5})_{0.75}Si_{0.05}B_{0.2}]_{0.7}Nb_{0.3} glassy alloy was measured by the sessile drop method, in which the contact angle was determined by an image analysis on the CCD camera images.

2.3 Pressurized liquid phase sintering
A specially designed micro hot pressing apparatus with a carbon die of 3 mm inner diam. was set up as shown in Fig. 1, which enables rapid heating and cooling of the powder compacts to avoid crystallization. The heating rate of the compacts was 200 K·min\(^{-1}\) by induction heating, and the cooling rate was as low as 150 K·min\(^{-1}\) by blowing gas directly to the hot pressing die. The powder was sintered in the pressure range of 0 to 75 MPa in argon at 833 K; this temperature is in the super-cooled liquid region of [(Fe_{0.5}Co_{0.5})_{0.75}Si_{0.05}B_{0.2}]_{0.7}Nb_{0.3} and above the melting temperature of Pd_{42.5}Ni_{7.5}P_{20-Cu_{30}}. The temperature was controlled with thermocouples directly inserted in the hot pressing die. Because of the poor wettability of the liquid phase on the solid particles, as will be described later, the pressure is indispensable to help the liquid alloy penetrate in the void space of the powder compact. The hot pressing time ranged from 60 to 300 s, within the incubation time for the crystallization; about 500 s at the present hot pressing temperature. It is to be mentioned here that by annealing for 10\(^3\) s at 700 K nanocrystalline grains are observed to appear in the glassy matrix, which may mean that at 700 K an appreciable atomic movement occurs for the structural modifications. We therefore assumed that the zero point of the time-temperature axes of the TTT curve, i.e. the zero time of the incubation period for the crystallization, is 700 K.\(^3,^{10}\)

2.4 Evaluation of the hot-pressed compacts
SEM observation and XRD measurement were made on the cross section of the hot pressed compacts. The relative density of the compacts was determined by Archimedes method. The volume fractions of the two phases involved in the composite were calculated by \(\rho_c = \rho_f V_f + \rho_p V_p\), where \(\rho\) and \(V\) are the density and the volume fraction, and the subscripts c, f, and p correspond to the hot pressed compact, the liquid phase, and the Pd_{42.5}Ni_{7.5}P_{20-Cu_{30}} phase, respectively. The \(\rho_c\) and \(\rho_p\) were those for the casted alloys, and 7.1 and 9.4 g/cm\(^3\). The mechanical properties of the hot pressed compacts were evaluated by compression test with a cross-head speed of 0.5 mm/min on cylindrical compacts of the dimensions of 3 mm in diameter and about 6 mm in height with both sides being parallel polished.

3. Results and Discussion
3.1 Powder characteristics
Figure 2 shows the SEM images of the Fe-based and Pd-based sample powders. The both powders exhibit spherical shape with smooth surface, and no crystalline structure is observed. The XRD patterns of these powders, as shown in Fig. 3, shows a simple hallow indicating single amorphous phases. Figure 4 shows the DSC results for the present powders. For the [(Fe_{0.5}Co_{0.5})_{0.75}Si_{0.05}B_{0.2}]_{0.7}Nb_{0.3} alloy, as has been reported in the previous paper\(^9,^{10}\), the glass-transition and crystallization temperatures are 808 K and 856 K, respectively, showing the supercooled liquid range of 48 K. The Pd_{42.5}Ni_{7.5}P_{20-Cu_{30}} alloy powders exhibit lower glass-transition and crystallization temperatures than those for the Fe-based alloys in the DSC curve. One can see a small endothermic peak at 763 K corresponding to onset melting behavior, and a large peak at 830 K corresponding to offset melting behavior. Table 1 summarizes the thermal characteristic temperature such as glass transition temperature (\(T_g\)), crystallization temperature (\(T_c\)), supercooled liquid region (\(\Delta T_g\)) and liquid temperature (\(T_l\)) which are confirmed to agree with the reported values.\(^5,^{11}\)

3.2 Wettability
Figure 5 shows the contact angle of the melted Pd_{42.5-Ni_{7.5}P_{20-Cu_{30}} alloy on the surface of [(Fe_{0.5}Co_{0.5})_{0.75}Si_{0.05}-B_{0.2}]_{0.7}Nb_{0.3} metallic glassy alloy. The contact angle is 150~160° in the temperature range of 800~830 K, the range just between \(T_g\) and \(T_c\) of the Fe-based alloy. The contact angle is found to decrease to as low as 130° when heated 270 s at 843 K, as shown in Fig. 6, however, this value is still

![Fig. 1 Schematic of micro hot press apparatus.](image-url)
too large to enhance densification by pressureless liquid phase sintering. This measurement has confirmed that pressure-assisted penetration of the liquid is indispensable for the liquid phase sintering of the present system.

![SEM images of gas atomized metallic glassy powder samples](image)

Fig. 2 SEM images of gas atomized (a) [(Fe₀.₅Co₀.₅)₀.₇₅Si₀.₀₅B₀.₂]₀.₉₆Nb₄ metallic glassy powder sample and (b) Pd₄₂.₅Ni₇.₅P₂₀Cu₃₀ metallic glassy powder sample.

![XRD patterns](image)

Fig. 3 XRD patterns of [(Fe₀.₅Co₀.₅)₀.₇₅Si₀.₀₅B₀.₂]₀.₉₆Nb₄ metallic glassy powder sample and Pd₄₂.₅Ni₇.₅P₂₀Cu₃₀ metallic glassy powder sample.

![DSC curves](image)

Fig. 4 DSC curves of [(Fe₀.₅Co₀.₅)₀.₇₅Si₀.₀₅B₀.₂]₀.₉₆Nb₄ metallic glassy powder sample and Pd₄₂.₅Ni₇.₅P₂₀Cu₃₀ metallic glassy powder sample.

![Contact angle of metallic glassy alloy surface](image)

Fig. 5 Contact angle of [(Fe₀.₅Co₀.₅)₀.₇₅Si₀.₀₅B₀.₂]₀.₉₆Nb₄ metallic glassy alloy surface by Pd₄₂.₅Ni₇.₅P₂₀Cu₃₀ molten alloy as a function of the specimen temperature.

![Contact angle of molten alloy as a function of holding time at 843 K](image)

Fig. 6 Contact angle of [(Fe₀.₅Co₀.₅)₀.₇₅Si₀.₀₅B₀.₂]₀.₉₆Nb₄ metallic glassy alloy surface by Pd₄₂.₅Ni₇.₅P₂₀Cu₃₀ molten alloy as a function of the holding time at 843 K.

### Table 1

<table>
<thead>
<tr>
<th>Powder composition</th>
<th>T₉ (K)</th>
<th>Tₓ (K)</th>
<th>ΔTₙ (K)</th>
<th>Tₗ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[(Fe₀.₅Co₀.₅)₀.₇₅Si₀.₀₅B₀.₂]₀.₉₆Nb₄</td>
<td>808</td>
<td>856</td>
<td>48</td>
<td>—</td>
</tr>
<tr>
<td>Pd₄₂.₅Ni₇.₅P₂₀Cu₃₀</td>
<td>569</td>
<td>666</td>
<td>97</td>
<td>830</td>
</tr>
</tbody>
</table>

![Exothermic curve](image)

Fig. 4: Exothermic curve for [(Fe₀.₅Co₀.₅)₀.₇₅Si₀.₀₅B₀.₂]₀.₉₆Nb₄ and Pd₄₂.₅Ni₇.₅P₂₀Cu₃₀ metallic glassy powder samples.

![Contact angle vs. temperature](image)

Fig. 5: Contact angle vs. temperature for [(Fe₀.₅Co₀.₅)₀.₇₅Si₀.₀₅B₀.₂]₀.₉₆Nb₄ metallic glassy alloy surface by Pd₄₂.₅Ni₇.₅P₂₀Cu₃₀ molten alloy.
3.3 Microstructure

Without pressure no penetration of the liquid occurs as shown in Fig. 7, and the liquid phase seems to remain in its original position while being slightly depressed between solid particles keeping its high contact angle. Figure 8 shows the cross-sectional microstructures of the compacts sintered 270 s at 833 K by applying the pressures up to 35 MPa; the liquid alloy penetrated in-between the solid particles and distributed evenly throughout the void space of the compact. The elimination of the residual pores is seen to be enhanced with increase in applied-pressure. The densities of the compacts (a)∼(d) in Fig. 8 are 7.64 g/cm³ (relative density

\[
[(\text{Fe}_{0.3}\text{Co}_{0.3})_{0.75}\text{Si}_{0.05}\text{B}_{0.2}]_{96}\text{Nb}_4\quad \text{Pd}_{42.5}\text{Ni}_{7.5}\text{P}_{20}\text{Cu}_{30}
\]

Fig. 7  SEM images of the surface of specimen pressureless liquid phase sintered at 833 K, holding time 160 s.

Fig. 8  SEM images of the surface of slightly pressured liquid phase sintered specimen at 833 K, holding time 270 s with the relative densities, applied pressure (a) 92.0%, 7 MPa, (b) 92.1%, 14 MPa, (c) 94.0%, 28 MPa, (d) 95.6%, 35 MPa.
Microstructural observation, a dense amorphous compo-
phases to be detected by XRD. From this fact together with
amorphous structure and the compact contains no crystalline
diffraction curve has a broad peak characteristic to an
cross-sectional surface of the fully densified compact. The
necessary to obtain full-dense compacts for the present alloy
shown in Fig. 9, which was sintered at a pressure of 50 MPa,
was obtained by higher pressure and prolonged time, as
compaction (Fig. 9) the solid particles are not observed to be
deformed, and their packing fraction is 0.71, which may be
sintering. It is further to be noted that in the fully densified
compact (Fig. 9) the solid particles are not observed to be
deformed, and their packing fraction is 0.71, which may be
compared to the packing density 0.64 of the random dense
packing (RDF)\(^{12}\) of equal-sized particles. Because of a size
distribution, the present powder is to have a larger packing
density than that of the RDF. Further pressurization with
higher pressure causes the glassy solid particles to deform at
the contact points, thus decreasing the interparticle space,
and the redundant liquid volume is squeezed out from the
compact. Figure 11 shows this squeezed liquid metal exuded
from the gap of the die and punch. We describe in the next
section a possibility of controlling the two phase micro-
structure by excess pressurization and the melt squeezing.

3.4 Control of liquid phase content

Figure 12 shows the microstructure of the compact
sintered at 833 K, the solid particles of which are deformed
presumably by viscous flow to a denser packing state with a
greater contiguity; the volume fraction of the solid phase is
0.71, 0.87 and 0.95. This observation shows that by a proper
pressurization and the resulting liquid squeezing we can
control both packing state of the solid particles and the liquid
volume fraction. Figure 13(a) and (b) show two compacts
having similar liquid volume fraction of 0.17, 0.13 respect-
ively, sintered with and without liquid squeezing. The
compact (a) was produced from a powder premix whose
mixing ratio of the solid and liquid constituents was 83 : 17,
and sintered 160 s at 833 K and 75 MPa nearly to full density
yet without squeezing. Its volume fraction of the liquid phase
is 0.17 as is the same as the original mixing ratio. The
compact (b) had the initial volume ratio of 64 : 36, sintered
at the same temperature and pressure as in the compact (a),
but with prolonged time of 252 s, causing squeezing of
liquid to the liquid volume fraction of 0.13. The complete
elimination of residual pores and a viscous deformation of
the solid particles with their denser packing are attained by
squeeze-pressurization.

3.5 Mechanical properties of the composite

Figure 14 shows the compressive stress-strain curve of
the consolidated sample included [(Fe\(_{0.5}\)Co\(_{0.5}\)Si\(_{0.75}\)B\(_{0.2}\)]\(_{96}\)Nb\(_{4}\), liquid phase
sintered at 833 K, holding time 220 s with the applied pressure of 50 MPa.

92.0\%), 7.65 g/cm\(^3\) (92.1\%), 7.81 g/cm\(^3\) (94.0\%), and 7.94
g/cm\(^3\) (95.6\%), respectively. A nearly full-dense compact
was obtained by higher pressure and prolonged time, as
shown in Fig. 9, which was sintered at a pressure of 50 MPa,
for 220 s at 833 K. It was confirmed that at least 50 MPa is
necessary to obtain full-dense compacts for the present alloy
system. Figure 10 shows the XRD pattern taken from the
cross-sectional surface of the fully densified compact. The
diffraction curve has a broad peak characteristic to an
amorphous structure and the compact contains no crystalline
phases to be detected by XRD. From this fact together with
the microstructural observation, a dense amorphous compo-
site of [(Fe\(_{0.5}\)Co\(_{0.5}\)Si\(_{0.75}\)B\(_{0.2}\)]\(_{96}\)Nb\(_{4}\) and Pd\(_{42.3}\)Ni\(_{7.5}\)P\(_{20}\)Cu\(_{30}\) alloys can be produced by the pressurized liquid phase
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distribution, the present powder is to have a larger packing
density than that of the RDF. Further pressurization with
higher pressure causes the glassy solid particles to deform at

Fig. 9 SEM image of the surface of full densed specimen with solid phase
[(Fe\(_{0.5}\)Co\(_{0.5}\)Si\(_{0.75}\)B\(_{0.2}\)]\(_{96}\)Nb\(_{4}\), volume fraction of 71\%, liquid phase
sintered at 833 K, holding time 220 s with the applied pressure of 50 MPa.

Fig. 10 XRD pattern of full densed specimen liquid phase sintered at
833 K with the applied pressure of 50 MPa.

The contact points, thus decreasing the interparticle space,
and the redundant liquid volume is squeezed out from the
compact. Figure 11 shows this squeezed liquid metal exuded
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sintered 160 s at 833 K and 75 MPa nearly to full density
and sintered 225 s. From this figure, the compressive fracture strength, Young’s
modulus, yielding strain are 2051 MPa, 237 GPa, 8.7 \times 10^{-3},
respectively. Figure 15 shows the SEM image of the fracture
surface of this sample. As you can see, fracture occurs inner
particle of [(Fe\(_{0.5}\)Co\(_{0.5}\)Si\(_{0.75}\)B\(_{0.2}\)]\(_{96}\)Nb\(_{4}\) metallic glass and no fracture traces of inter particle can be seen. Although
the consolidated sample of [(Fe\(_{0.5}\)Co\(_{0.5}\)Si\(_{0.75}\)B\(_{0.2}\)]\(_{96}\)Nb\(_{4}\) metallic glassy powders without any additives shows the compressive fracture strength as high as 900 MPa\(^{8,10}\) because of intergranular fracture type, metallic glass dual phase
composite prepared by slightly pressured liquid phase sintering in this study shows the twice as high compressive strength.

Generally, it is known that the effect of preventing the progress of the slip shear band by second phase and the effects of multi axial stress field and stress concentration by the mismatch of two phases Young’s modulus is occurred for the mechanical properties of dual phase metallic glassy composite. In this study, the areas around \([(Fe_{0.5}Co_{0.5})_{0.75-Si_{0.05}B_{0.23}N}_{0.75}]\) metallic glassy particles also seem to play a role as a priority site of shear bands.

In any case, interface state of the two phases is one of the important factors for mechanical properties, and three types of mechanism can be considered to achieve the good
bonding in the particle-binding phase interface; One is that \([\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}_{0.05}\text{B}_{0.2}\text{Nb}_{0.96}]\) metallic glassy particles directly bonds each other. Another one is that the thin film like \(\text{Pd}_{42.5}\text{Ni}_{7.5}\text{P}_{20}\text{Cu}_{30}\) metallic glassy phase exists as an agent of each solid phase particle and it keeps good bonding. The other one is that the reaction layer exists between \([\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}_{0.05}\text{B}_{0.2}\text{Nb}_{0.96}]\) metallic glassy particles and \(\text{Pd}_{42.5}\text{Ni}_{7.5}\text{P}_{20}\text{Cu}_{30}\) metallic glassy particles and it prevents from peeling each particle. It should be revealed, by the further observation of interface, which type of these three mechanisms occur this result of this study. It is another important issue to discuss in detail that the structure dependence of the strength, and deformation behavior of liquid phase network structure during the densification process.

4. Conclusions

(1) Fully densified metallic glass composites can be obtained by a pressurized liquid phase sintering in the combination of \([\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}_{0.05}\text{B}_{0.2}\text{Nb}_{0.96}]\) and \(\text{Pd}_{42.5}\text{Ni}_{7.5}\text{P}_{20}\text{Cu}_{30}\) alloy powders, keeping both alloys amorphous state during processing.

(2) By pressurization the liquid phase is forced to penetrate in between the void space of the solid particle packing and distributes evenly through the compact.

(3) Extra pressurization causes squeezing of the liquid metal out of the powder compact and a viscous deformation of the solid particles at the particle contacts to form a denser packing state with higher contiguity. This is an alternative possibility of controlling the microstructure of this metallic glass composite.

(4) Fracture strength of the present metallic glass composite is as high as 2051 MPa and the fracture is of intergranular type, which suggests a good bonding between the particle interfaces.

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REFERENCES