Chapter 2

New Processing Routes for Functionally Graded Materials and Structures through Combinations of Powder Metallurgy and Casting

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Abstract

New processing routes for metal-matrix functionally graded materials (FGMs) and structures through combinations of powder metallurgy and casting are described in this chapter. Centrifugal mixed-powder method is introduced as a processing method for metal-matrix FGMs at first. The centrifugal mixed-powder method is a developed technique of centrifugal casting by setting predesigned mixed powder in a spinning mold in advance. As an example of processed FGMs by this method in our previous studies, Cu-based FGMs with dispersed diamond particles are shown. Graded structures in the Cu-based FGMs are investigated through scanning electron microscope (SEM) observations of microstructures. As the latest processing method for metal-matrix FGMs developed by our research group, centrifugal sintered-casting method is shown. The centrifugal sintered-casting method is a modified processing technique of the centrifugal mixed-powder method. In the centrifugal sintered-casting method, FGMs are processed by the combination of centrifugal sintering and centrifugal casting. Al–Si alloy and Cu-based FGMs with dispersed diamond particles are introduced as examples. Applications of metal-matrix FGMs processed by the centrifugal sintered-casting method are also described. Fabricated metal-matrix FGMs can be used as grinding wheel and applied to carbon fiber-reinforced plastic (CFRP) machining.

Keywords: Functionally graded materials (FGMs), Metal-matrix composite, Powder metallurgy, Centrifugal sintering, Centrifugal casting

1. Introduction

New processing routes for metal-matrix functionally graded materials (FGMs) and structures through combinations of powder metallurgy and casting are described in this chapter. FGMs are well known as a relatively new class of inhomogeneous composite materials having property gradient. The property gradient in the FGMs is caused by a position-dependent chemical composition, microstructure, or atomic order [1]. These FGMs are generally fabricated based on powder metallurgy, melt-processing technique, chemical vapor deposition, physical vapor deposition and so on.

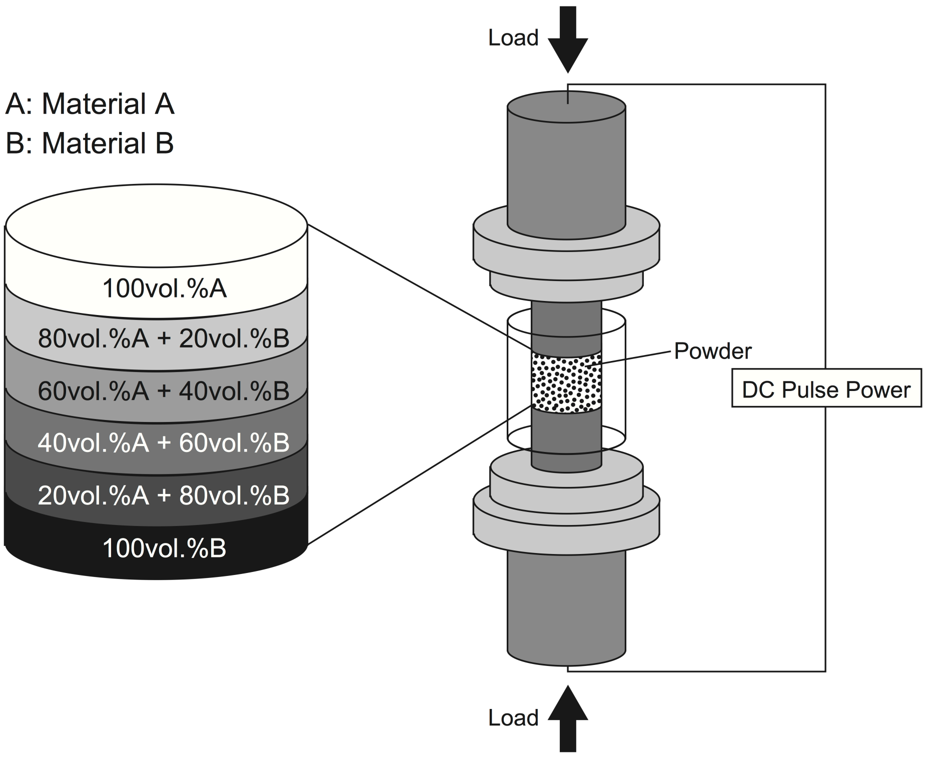

Figure 1. A schematic illustration showing a typical fabrication process of FGMs by the powder metallurgy method through spark plasma sintering (SPS).

Figure 1 shows a schematic illustration of a typical fabrication process of FGMs by the powder metallurgy method through spark plasma sintering (SPS). At first, mixed powders with various ratios of materials A and B are prepared. Predesigned mixed powders are stacked inside a die for the SPS as shown in Figure 1. The case of six-graded composition layers is shown in Figure 1. The number of graded layers can be freely chosen. Then, FGMs with stepwise graded structure can be obtained by sintering these powders with an SPS machine. Ti–ZrO_2 FGMs with stepwise graded structure were fabricated by this method in our previous study [2]. A continuous graded structure can also be obtained by this method with a green body having continuous graded composition. For example, Ti–ZrO_2 FGMs were fabricated by this method in our previous studies [3, 4].

The melt-processing technique is also an effective way to fabricate continuous graded structure. In terms of melt-processing techniques to fabricate metal-based FGMs, various kinds of centrifugal method were developed: centrifugal casting [5–7], centrifugal solid-particle method [8, 9], centrifugal *in situ* method [10, 11], and so on. The centrifugal casting is a processing method that uses centrifugal force caused by rotation of a mold. By the centrifugal force in the rotating mold including molten metal and solid particles, compositional gradient due to the difference of the material densities between the molten metal and the solid particles is generated. By controlling these phenomena, FGMs can be fabricated. Basically, both the centrifugal solid-particle method and the centrifugal *in-situ* method are based on the centrifugal casting. The centrifugal solid-particle method can be conducted at a temperature of liquid–solid coexistence in alloy systems, such as Al–Ti [8, 9]. On the other hand, the centrifugal *in-situ* method can be made at a temperature of liquid phase in alloy systems, such as Al–Ni [10] and Al–Cu [11]. By using these processing techniques, various kinds of FGMs having specific graded distributions of reinforcement can be made.

As new melt processing techniques, centrifugal mixed-powder method [12–15] and centrifugal sintered-casting method [16, 17] have been recently developed. These two melt processing techniques are introduced in this chapter. Applications of metal-matrix FGMs processed by the centrifugal sintered-casting are also described. Fabricated metal-matrix FGMs can be used as grinding wheel and applied to carbon fiber-reinforced plastic (CFRP) machining [17].

2. Materials processing

2.1. Centrifugal mixed-powder method

Many attempts to fabricate FGMs have been done by the centrifugal casting [5–7]. Generally, the finer dispersed particle size becomes, the more difficult to disperse them into molten matrix. The equation for velocity of a solid particle in a viscous liquid can be written as:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \frac{\left|\rho_\mathrm{p} - \rho_\mathrm{m}\right| G g D_\mathrm{p}^2}{18\eta} \tag{1}$$

where ρ_p is density of particles, ρ_m density of molten matrix, g gravitational acceleration, D_p particle diameter, and η viscosity of melt [7]. Since the velocity of a solid particle in a viscous liquid is dependent on the square of the particle diameter D_p, it is quite difficult to control graded distributions of dispersion nanoparticles in FGMs in the case of the conventional centrifugal casting. As a new processing technique for metal-matrix FGMs, the centrifugal mixed-powder method is proposed by Watanabe et al. [12] for overcoming these problems. The centrifugal mixed-powder method could give us fine particle-dispersed FGMs by using a combination of high centrifugal force and mixed powder. This new method is a developed technique of the centrifugal casting by setting predesigned mixed powder in a mold in advance [12].

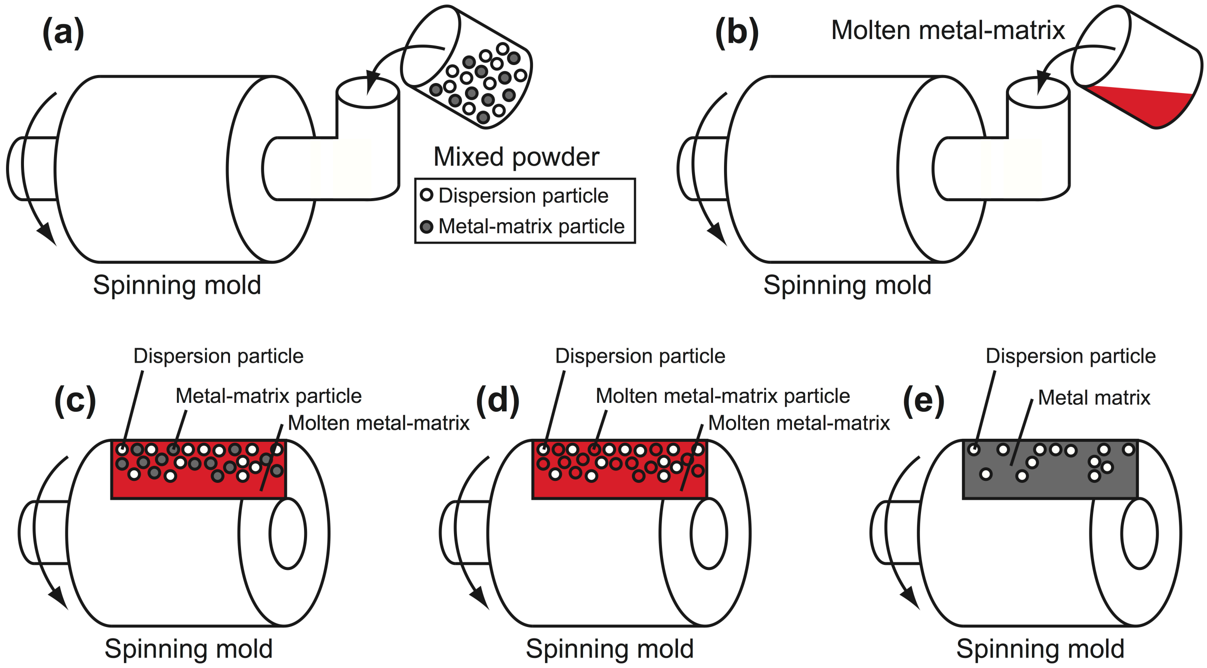

Figure 2. A schematic illustration showing the process of the centrifugal mixed-powder method [12].

Figure 2 shows the experimental procedure of the centrifugal mixed-powder method. At first, a predesigned mixed powder is prepared. This mixed powder consists of metal-matrix particles and dispersion particles. Basically, the melting point of dispersion particles should be higher than that of metal-matrix particles to form FGMs. Particles such as ceramics, metals, and alloys that have higher melting points compared with metal matrix can be chosen as dispersion particles for metal-matrix FGMs. The mixed powder including metal-matrix particles and dispersion particles is inserted into a spinning mold as shown in Figure 2(a). After that, a metal-matrix ingot is melted in a crucible. This molten metal matrix is poured into the spinning mold as shown in Figure 2(b). The poured molten metal matrix penetrates into the space between the particles due to the applied centrifugal force as shown in Figure 2(c). The heat from the poured molten matrix melts the metal-matrix particles as shown in Figure 2(d). Finally, ring- or disc-shaped FGMs or structures having dispersion particles distributed in the outer part of the cast sample can be obtained as shown in Figure 2(e). FGMs, such as Cu/SiC [12], Al/TiO_2 [12], and Al/Al_3Ti/Ti [15], were obtained with this processing method in our previous studies.

The centrifugal mixed-powder method can also be performed by using centrifugal casting machines which are commercially available. Figure 3 shows a typical appearance of vacuum centrifugal casting machine supplied by Yasui & Co, Japan. This centrifugal casting machine has a heating coil, a straight arm, a crucible, a mold, and a balancer inside the casting chamber [18]. By setting predesigned mixed powder in the mold in advance, FGMs can be obtained. By using this processing method, Cu/diamond [13], Al alloy/diamond [14], and the other FGMs

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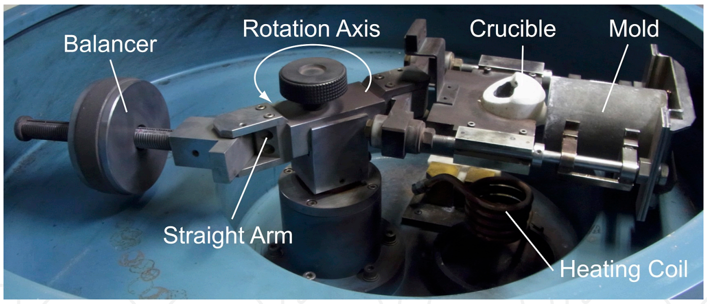

Figure 3. A typical appearance of vacuum centrifugal casting machine.

were fabricated in our previous studies. Detailed processing method and microstructural characterization of fabricated Cu/diamond FGMs are shown below.

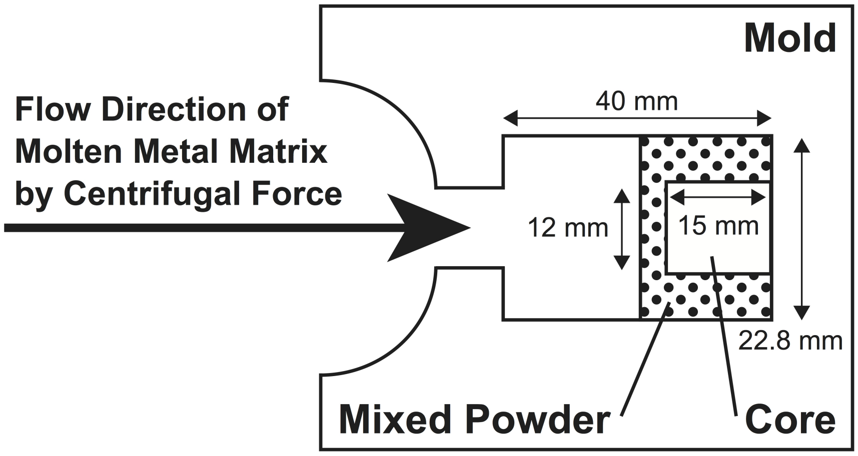

Figure 4. A cross-sectional drawing of a mold for centrifugal casting.

A cross-sectional drawing of a mold for centrifugal casting is shown in Figure 4. The mold has a cylindrical casting pattern with 40 mm width and 22.8 mm diameter. A cylindrical core with 15 mm width and 12 mm diameter is also attached in the mold as shown in Figure 4. Since fabricated FGMs can be applied to grinding wheel for mechanical machining as described in Section 3, these pattern and core are required. Dendritic-shaped Cu particles in the mean particle diameter of approximately 22 μm and 100/120 mesh diamond particles (149 μm in JIS B 4130) were used. Both the particles were mixed in a mortar. The volume fraction of diamond to Cu was chosen as 25 vol.%. The mixed powder was inserted into the mold as shown in Figure 4. Then, molten Cu was cast into the spinning mold by applying centrifugal force with the vacuum centrifugal casting machine in vacuum at 1473 K and 1573 K. The mold was spun for 99 s. The calculated applied G number (ratio of centrifugal force to gravity) at the top of mold along the direction of centrifugal force was about 36 G.

Figure 5 shows Cu/diamond FGMs cast at 1473 K (Fig. 5a) and 1573 K (Fig. 5b) [13]. As these samples were fabricated for an application as grinding wheel, these cast samples have hollows for attaching pulley. It was observed that consolidated mixed-powder area kept leaning to the

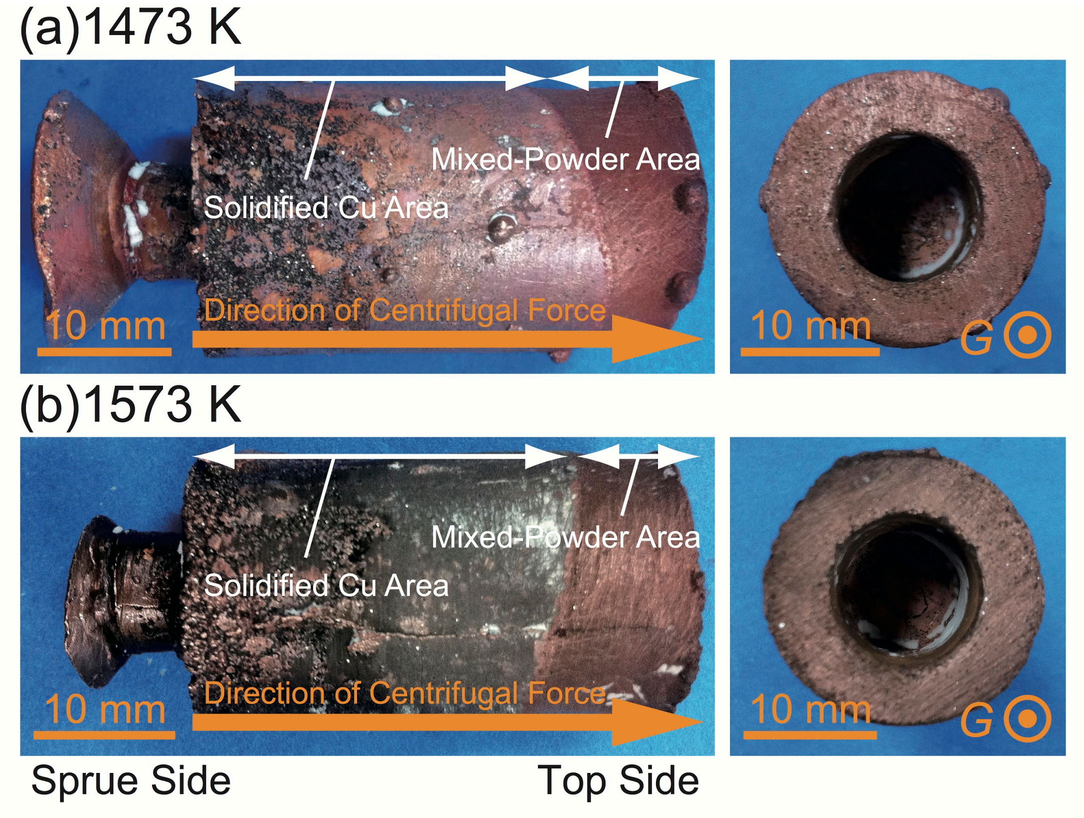

Figure 5. Cu/diamond FGMs fabricated by the centrifugal mixed-powder method. Casting temperatures were 1473 K (a) and 1573 K (b) [13].

right side of the cast sample, that is, the position of maximum centrifugal force as shown in Figure 5. Since density of diamond (3.52 Mg/m^3) was smaller than that of molten Cu (8.00 Mg/m^3), a little amount of diamond particles were distributed around surface at sprue side due to the molten metal flow. A graded structure should be made by this difference of density between diamond and Cu.

Cross-sectional observations were carried out with scanning electron microscope (SEM) to investigate diamond dispersion behavior after casting at 1473 K. Figure 6 shows a backscattered electron compositional image showing a cross section of the Cu-based diamond graded cast sample fabricated without pulley hollow [13]. Diamond particles were distinguished from Cu matrix as black colored area in the sample. It should be noted that the distribution of diamond particles in the inner part of the cast sample also biased to the top side (right side) as shown in Figure 6. It was also confirmed that obvious traces or boundaries of Cu particles were not observed although voids were seen around some diamond particles. Therefore, Cu particles in the predesigned mixed powder were fully melted and fused each other due to heat transfer from the poured molten Cu.

The number of diamond particles and the mean diameter of diamond particles at each divided area along the direction of centrifugal force were measured. The results are shown in Figures 7 and 8, respectively. These data were taken from the cross-sectional image of the cast sample

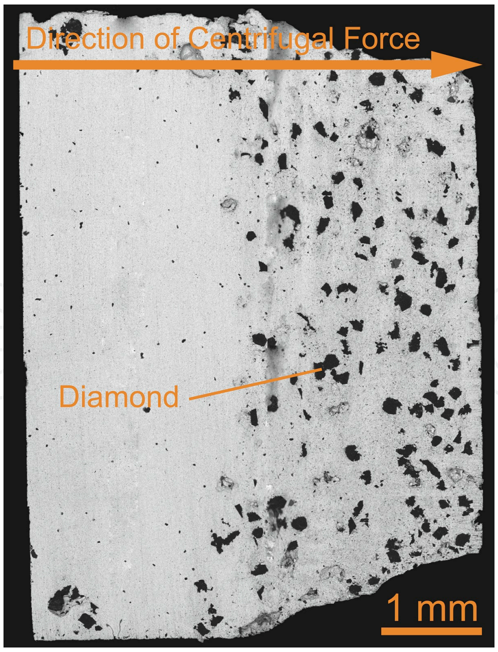

Figure 6. A backscattered electron compositional image showing a cross section of the Cu-based diamond graded cast sample obtained by the centrifugal mixed-powder method [13].

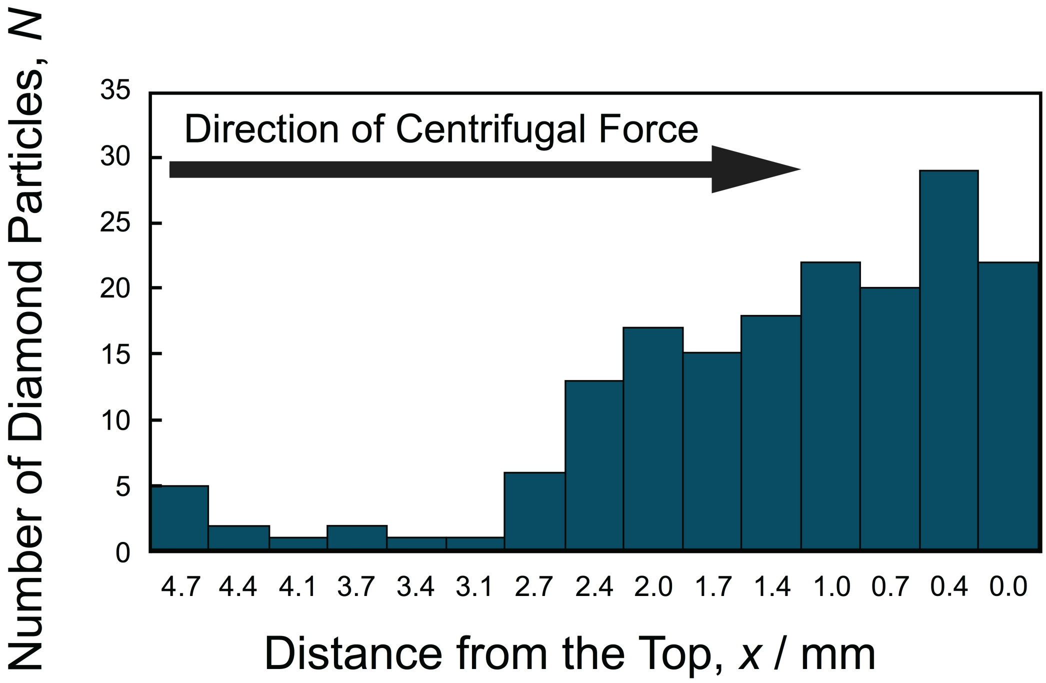

Figure 7. The number of diamond particles as a function of distance from the top of Cu/diamond cast sample [13].

as shown in Figure 6. In Figure 7, the number of diamond particles was drastically decreased at around 3 mm from the top, where the mixed powder was inserted before the centrifugal casting. The result indicates that the mixed powder was compressed and immobilized by pressure of molten metal due to centrifugal force. Whereas diamond particles were sufficiently

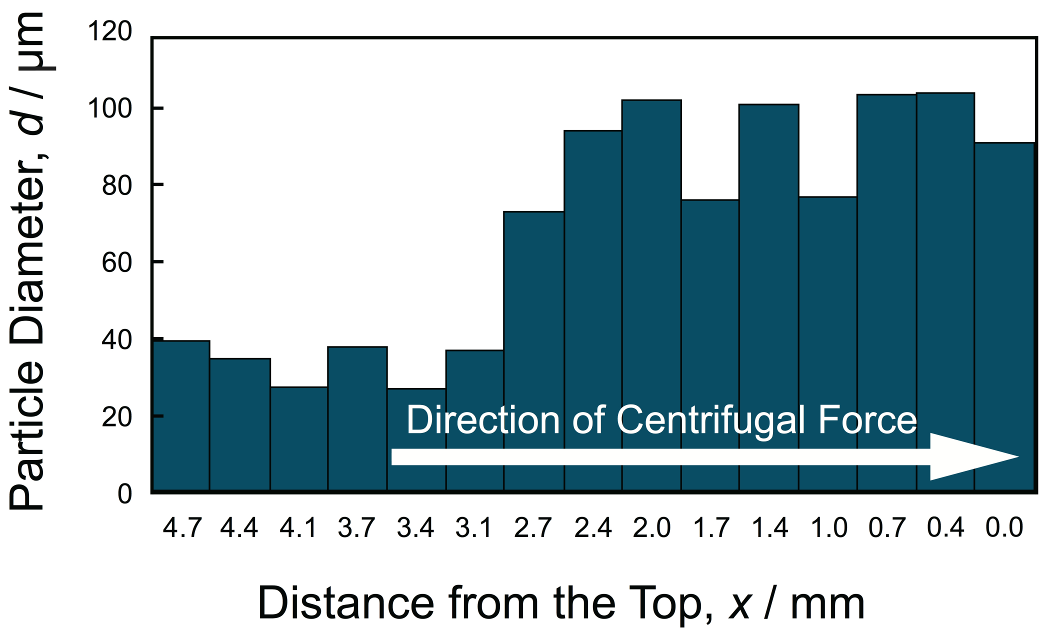

Figure 8. The particle diameter as a function of distance from the top of Cu/diamond cast sample [13].

immobilized by Cu particles between diamond particles, graded distribution of diamond particles was successfully obtained. Within the diamond particles densely dispersed region between 0 and 3 mm from the top of the Cu/diamond cast sample, the number of diamond particles increased with approaching to the top of the Cu/diamond cast sample. Thus, the Cu/diamond FGMs were successfully fabricated by the centrifugal mixed-powder method. On the other hand, the particle diameter distribution between 0 and 3 mm is almost homogeneous as shown in Figure 8. The mean diameters of diamond particles in this range are 80–100 μm. In the distance from the top, between 3 and 5 mm, particle diameter distribution is also homogeneous. However, the mean diameters of diamond particles in this range are 30–40 μm. These results may suggest that collision of Cu molten metal with the mixed powder at surface of the powder area washed away part of the diamond particles, and molten Cu flow sent it to the surface at the sprue side. This phenomenon is not appropriate for production of FGMs. To overcome this problem, a modified processing method is described in the next section.

2.2. Centrifugal sintered-casting method

As the latest processing method for metal-matrix FGMs developed by our research group, centrifugal sintered-casting method is shown in this section. The centrifugal sintered-casting method is a modified processing technique of the centrifugal mixed-powder method. In the centrifugal sintered-casting method, FGMs are processed by the combination of centrifugal sintering and centrifugal casting [16, 17]. As described in Section 2.1, the centrifugal mixed-powder method enables us to fabricate metal-matrix FGMs. Especially, the centrifugal mixed-powder method is an effective way to fabricate metal-matrix FGMs reinforced with nanoparticles [12]. However, predesigned powder mixtures tended to flow away during the centrifugal casting in the case of some combinations of powders in the centrifugal mixed-

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powder method. As an attempt to overcome this problem, the centrifugal sintered-casting method is developed through the combination of centrifugal sintering and centrifugal casting.

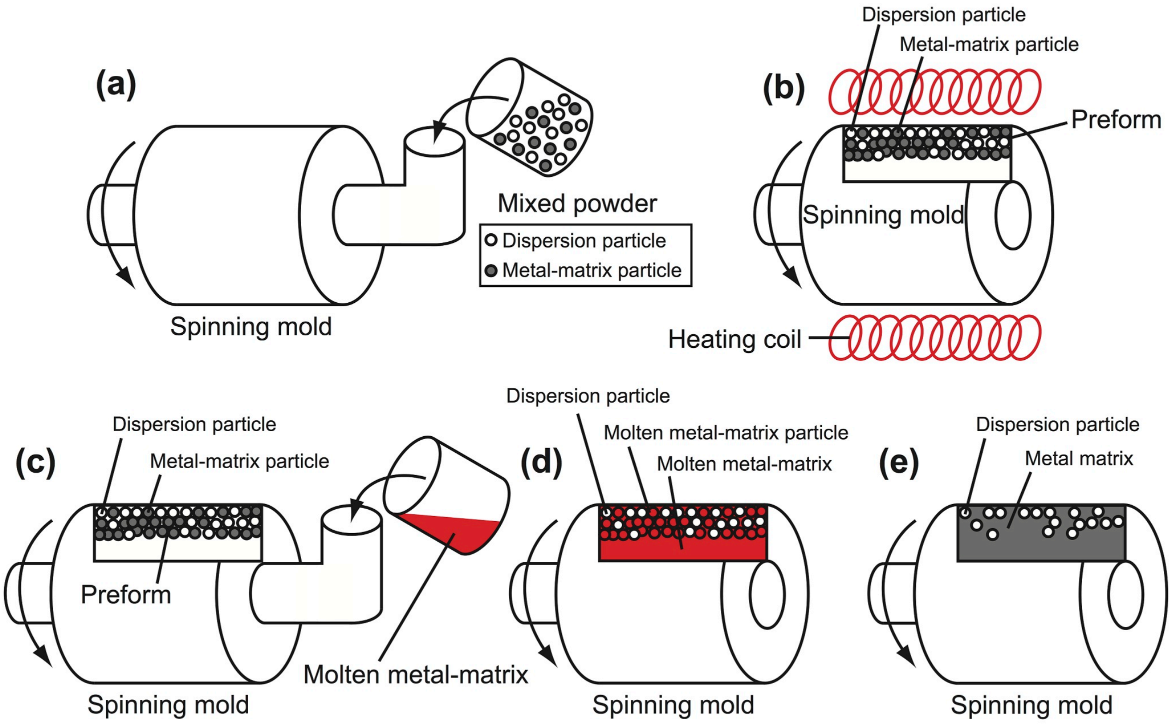

Figure 9. A schematic illustration showing the process of the centrifugal sintered-casting method [17].

Figure 9 shows a schematic illustration of the process of the centrifugal sintered-casting method [17]. In the centrifugal sintered-casting method, a ring-shaped metal-matrix preform with dispersed particles is produced by the centrifugal sintering at first. Predesigned mixed powder of dispersion particles and metal-matrix particles is inserted into a spinning mold as shown in Figure 9(a). Basically, the melting point of dispersion particles should be higher than that of metal-matrix particles to form FGMs in this method as well. Subsequently, the mixed powder is sintered under centrifugal force by heating coils to fabricate a preform as shown in Figure 9(b). Then, molten metal matrix is poured into the fabricated preform by the centrifugal casting to obtain metal-matrix FGMs as shown in Figure 9(c). The molten metal matrix penetrates into the space between the particles by the applied centrifugal force as shown in Figure 9(d). At the same time, the metal matrix particles are melted by the heat from the molten metal matrix. Finally, ring- or disc-shaped FGMs with dispersed particles distributed in the outer part of the samples can be obtained as shown in Figure 9(e).

In our previous studies, Al–Si and Cu were selected as metal matrix to fabricate Al–Si alloy/diamond and Cu/diamond FGMs, respectively [16, 17]. Al–Si alloy particles and Cu particles were uniformly mixed with diamond particles, respectively. The volume fraction of diamond particles in mixed powder was chosen as 10 vol.%. The predesigned mixed powder was set in the cylindrical mold having a rotational axis of 20 mm diameter and 30 mm length, respectively. The mixed powders were sintered in the spinning cylindrical mold under the centrifugal force of about 280 G at 843 K in argon atmosphere for Al–Si alloy/diamond particles [16] and 1100 G at 1273 K in vacuum for Cu/diamond particles [17], respectively. Then, the centrifugal casting was performed under the centrifugal force of about 78 G at 1373 K with pouring molten Al in the case of Al–Si alloy/diamond preform [16]. In the same way, molten Cu was poured into the Cu/diamond preform in the mold under the centrifugal force of about 34 G at 1393 K [17].

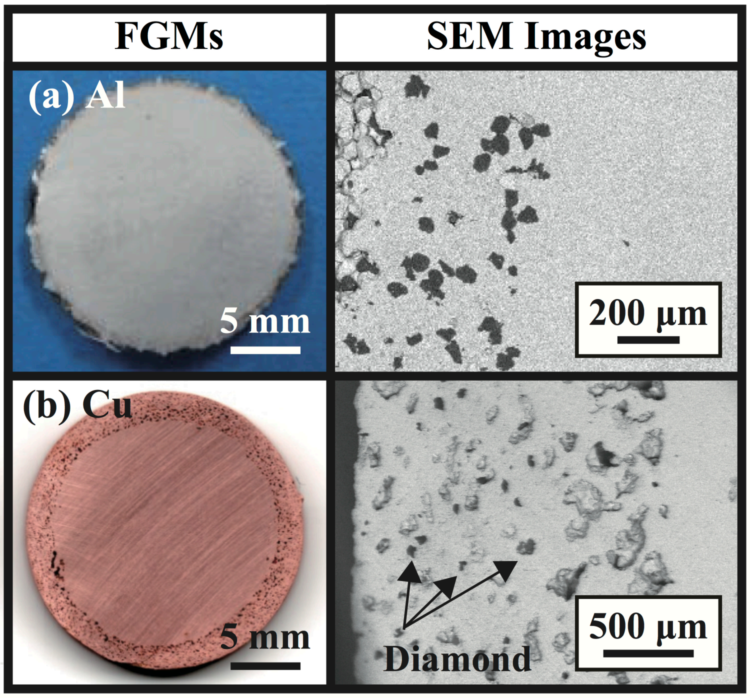

Figure 10. Macrographs of Al–Si alloy based (a) and Cu-based (b) FGMs with dispersed diamond particles fabricated by the centrifugal sintered-casting method and SEM images showing the microstructures of the outer part of the cast samples [16, 17].

Figure 10 shows macrographs of Al–Si alloy and Cu-based FGMs with dispersed diamond particles fabricated by the centrifugal sintered-casting method. SEM images showing the microstructures of the outer part of the Al–Si alloy and Cu-based FGMs are also shown in Figure 10. It should be noted that the diamond particles were distributed at only outer part of the cast samples as shown in Figure 10. The centrifugal sintered-casting method is an effective way to fabricate metal-matrix FGMs.

3. Applications of FGMs processed by the centrifugal sintered-casting

In this section, applications of metal-matrix FGMs processed by the centrifugal sintered-casting method are introduced. As described in Section 2.2, Al–Si alloy/diamond and Cu/

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diamond FGMs were fabricated by the centrifugal sintered-casting method. Diamond plays important role as abrasive in the field of mechanical machining. Recently, CFRP is widely used as main structural parts for aircraft due to its high strength, stiffness, and lightweight [19]. However, some issues about occurring defects, such as fiber pullout, delamination, burrs, and splintering, have become problems in machining CFRP by common drills. These technical issues have led numerous researchers to seek solutions for precision machining of CFRP [20–23]. The key issue of precision machining of CFRP has been obtaining good hole quality in the aircraft industry. In addition, tool change is frequently required in drilling CFRP in many practical situations. Therefore, the improvement of tool life for machining CFRP is important subject since high-priced diamond grains have been widely used as abrasive.

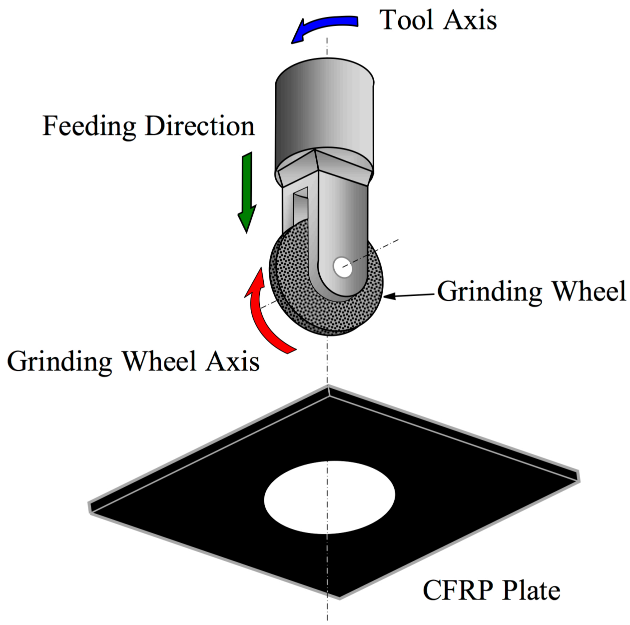

Figure 11. A schematic illustration of the gyro-driving grinding wheel system [24].

A novel CFRP machining equipment, that is, gyro-driving grinding wheel system for machining CFRP was recently developed [24–26]. The gyro-driving grinding wheel system was developed for overcoming problems related to defect issues during mechanical machining. Figure 11 shows a schematic illustration of the gyro-driving grinding wheel system [24]. In the gyro-driving grinding wheel system, a grinding wheel is used instead of drill bits for drilling CFRP. The equipped grinding wheels required toughness as a desirable mechanical property as the grinding wheel was subjected to the torsion force in the gyro-driving grinding wheel system. In the previous studies [17, 24], holes with good quality in CFRP plates have been obtained without defects by this machining system equipped with our fabricated metal-matrix FGMs.

CFRP drilling tests were performed with the gyro-driving grinding wheel system equipped with fabricated Cu/diamond FGMs as a grinding wheel. Cu was selected as metal matrix for its mechanical properties and high thermal conductivity. Diamond particles were used as abrasive in Cu matrix for machining CFRP. CFRP drilling tests were carried out with feed rate of 5 mm/min, peripheral wheel speed of 7000 rpm, spindle speed of 2800 rpm, and dry machining. Bidirectional CFRP composite laminates having thickness of 5 mm were used as workpiece material. Photographs of a hole having diameter of 20 mm drilled by the gyro-driving grinding wheel system equipped with fabricated Cu/diamond FGMs as a grinding wheel (Fig. 12a) and the one having diameter of 10 mm drilled by a conventional drill bit (Fig. 12b) in CFRP plates are shown in Figure 12. Delamination and burrs were seen in the drilled CFRP plate in the case of the conventional drill bit. It should be noted that precision drilling of CFRP plate without burring and delamination were achieved by the gyro-driving grinding wheel system equipped with fabricated Cu/diamond FGMs as grinding wheel. In this way, FGMs fabricated by the centrifugal sintered-casting method have been attempted to apply for the practical use.

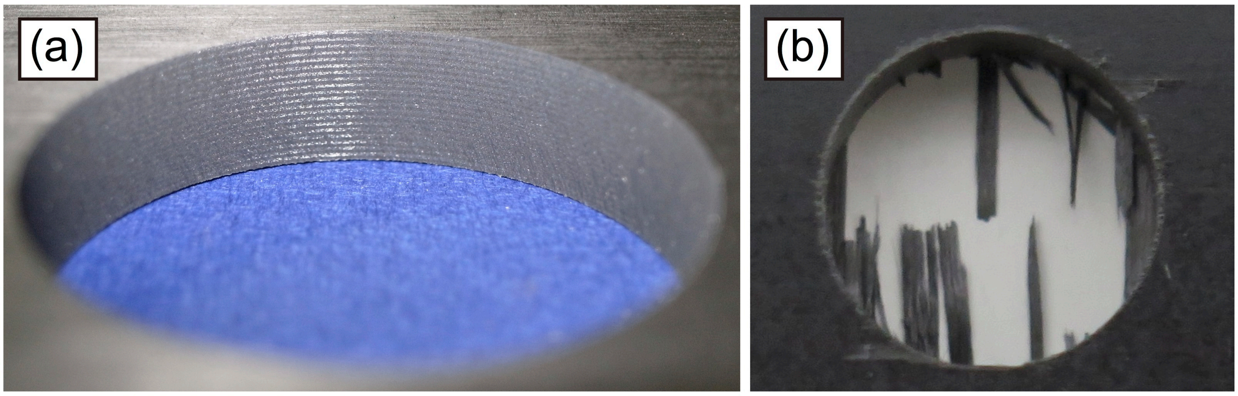

Figure 12. Drilled hole having diameter of 20 mm made by the gyro-driving grinding wheel system equipped with fabricated Cu/diamond FGMs as a grinding wheel (a) and the one having diameter of 10 mm made by a conventional drill bit (b) in CFRP plates [17].

As the other possibilities for application of FGMs, materials for heat sink can be considered as candidate. Nowadays, thermal management materials such as heat sink for microelectronics and semiconductors have been investigated, extensively [27–30]. The materials currently used for heat sinks are Al and Cu due to their high thermal conductivity in metals and alloys. The thermal conductivities of Al and Cu are about 250 and 400 W m^{-1} K^{-1}, respectively. On the other hand, diamond is well known as the material having the highest thermal conductivity in materials. To enhance the thermal conductivity of heat sink materials, Al/diamond and Cu/diamond composites are promising materials. Our Al alloy/diamond and Cu/diamond FGMs fabricated by the centrifugal sintered-casting method might work as well in this field.

4. Summary

Two kinds of new processing routes for metal-matrix FGMs through combinations of powder metallurgy and casting were developed: the centrifugal mixed-powder method and the centrifugal sintered-casting method. Metal-matrix FGMs were obtained by these two methods. These processing methods enable us to overcome existing problems in the conventional fabrication process of FGMs. Fabricated FGMs were also applied to machining CFRP as an attempt for the practical use. Continued studies for fabrication processes of FGMs and the gyro-driving grinding wheel system are still required to put them into practical use in the future. Further investigations should open up a new field of and a market for FGMs.

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