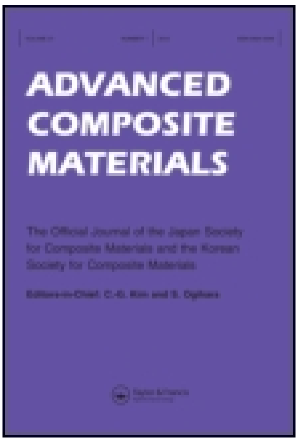

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Fabrication of aluminum borate whisker reinforced AZ91D magnesium alloy composites by semi-solid process and their mechanical properties

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Abstract—In order to develop a light weight piston for an automobile engine, aluminum borate whisker reinforced AZ91D magnesium alloy composites were fabricated by a semi-solid material process using squeeze casting. By controlling the solid fraction, f_s, and the rate of the infiltration into the preform, we succeeded in reinforcing a part of the cast alloy without deformation of the preform. The tensile strength of the alloy/composites interface fabricated by semi-solid (50% f_s, solid fraction in the semi-solid slurry) process was 120 MPa, and it was equal to the strength by conventional 0% f_s process. However, the flexural strength of the composite by the 50% f_s process was about 10% lower than the strength of that from the 0% f_s process, 498 MPa. After solid solution and aging treatment, the bending strength of the composites in both 0% and 50% f_s process was decreased. This might be caused by the notch effect of Mg_2Si compound produced between SiO_2 binder of the preform and magnesium during heat treatment.

Keywords: Metal matrix composites; semi-solid; squeeze casting.

1. INTRODUCTION

Recently, magnesium alloys have been used to reduce the weight of machine parts for automobiles. As for the application of the alloys to the piston in the engine, like a certain conventional aluminum alloy piston, suitable reinforcement of the piston-head is necessary to obtain high temperature strength nearly at 300°C. The aluminum borate ($Al_{18}B_4O_{33}$, shorted to AlBO) whiskers are utilized for the

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reinforcement of the MMC, because of their excellent mechanical properties and lower cost compared to SiC whiskers. On the other hand, semi-solid material processing has been developed. The remarkable advantages of this process are the lower amount of shrinkage cavity, macro-segregation and lower process temperature compared with conventional casting [1–3]. In this study, the conditions for fabrication of AlBO/AZ91D magnesium alloy by the semi-solid squeeze cast process was investigated in succession to our previous work [4, 5]. The mechanical properties of the AlBO/AZ91D MMC and the MMC/alloy joints were then examined.

2. EXPERIMENTAL PROCEDURE

2.1. Processing

To prevent the preform from deformation during the infiltrating process of semi-solid material, fabricating condition was examined in our previous work. The preform with 18% Vf. and 5 MPa compressive strength was then obtained by sintering AlBO whisker (Shikoku Kasei Co. Ltd., Alborex M12) with 5 mass% SiO_2 sol binder *vs* total amount of the whisker [6]. The preform which has dimensions of L100, H30, T10 was set in a cavity of the dies as shown in Fig. 1. The semi-solid AZ91D alloy was prepared by heating the master billet, which was produced by rapid solidification of the molten alloy [7]. The solid fraction f_s was controlled

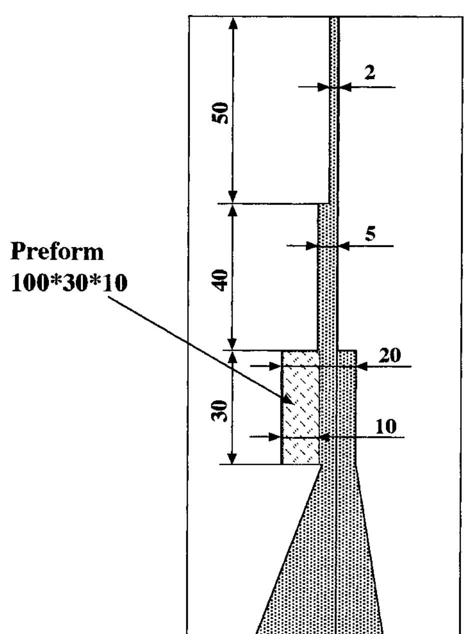

Figure 1. Dimensions of dies and the location of the preform in the cavity.

at 0% (750°C), 20% (590°C), 33% (580°C), or 50% (570°C) by controlling the temperature of the billet. The speed of the plunger with diameter of 60 mm and 309 mm stroke, was set at three levels 50, 100 or 200 mm/s. Approximately 100 MPa pressure was applied to the material at the end of squeeze casting.

2.2. Characterization of the material

The tensile strength of the MMC/Alloy joints and three-point bending strength of the MMCs were measured at room temperature by an autograph (Shimadzu, AG-5000D). After squeeze casting, some specimens were heat-treated in the condition of T6 (two steps solution treatment: 390°C, 43.2 ks, 410°C, 57.6 ks, aging hardening: 170°C, 57.6 ks). In order to examine the damage of the whisker after squeeze casting, distribution of the whisker length was measured by SEM observation of the extracted whisker by etching of dilute HCl solution. The products of chemical reaction between AlBO and alloy were determined with XRD.

3. RESULTS AND DISCUSSION

3.1. Optimization of the squeeze cast process

The suitable process area between plunger speed and solid fraction is shown in Fig. 2. At the conditions of ring-mark on the map, the semi-solid alloy was completely infiltrated into the preform without the deformation, as shown in Fig. 3.

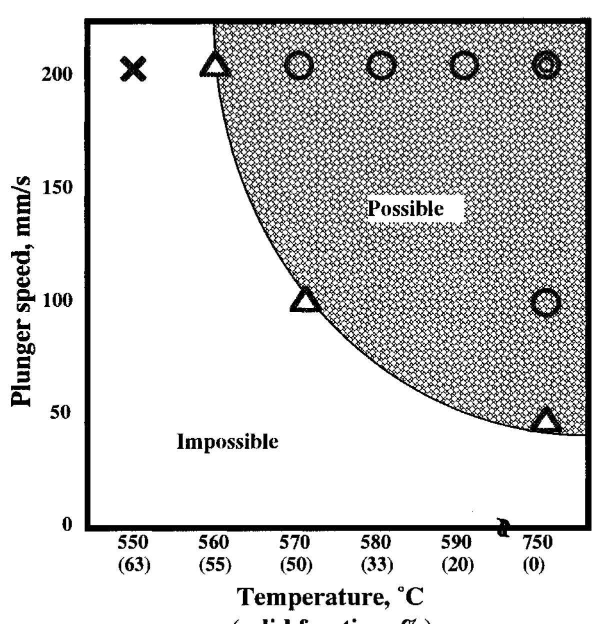

Figure 2. Suitable process area between plunger speed and solid fraction.

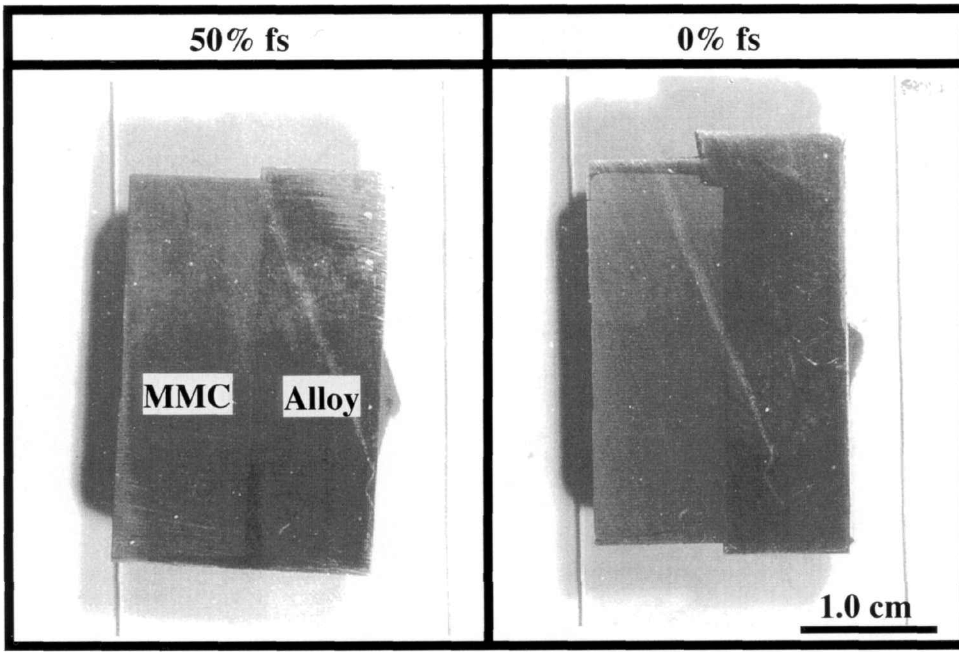

Figure 3. Cross-section of the specimen after squeeze casting.

Regarding the conventional squeeze casting process, the preform tends to deform at higher infiltration rate. However, this result reveals the opposite tendency. In this process, decrease in the temperature of the billet must be inevitable during the stroke of the plunger, especially as a cold sleeve is used. Then the lower plunger speed will lead to a larger decrease in the billet temperature before the infiltration of the semi-solid alloy is complete. This tendency will be more obvious than in the semi-solid process of aluminum alloy because of the smaller specific heat of magnesium alloy. The hot-sleeve system should be effective to enlarge a suitable process area. Hereafter, the maximum solid fraction in the map, 50% f_s at 200 mm/s is chosen to fabricate composite materials. Samples were also fabricated by conventional 0% f_s process at 200 mm/s plunger speed for comparison of microstructure and mechanical properties of 0% f_s process with 50% f_s process.

3.2. Microstructure

Optical microscope images including the MMC/alloy interface are shown in Fig. 4. It is found that α-Mg solid phase piles up on the preform in the as-cast 50% f_s specimen during the infiltration process of the semi-solid material, as reported in the previous work [4]. After T6 treatment of the 50% f_s specimen, a mosaic structure was formed, which was composed of α-Mg grains (white grains) and black color grains. The black grains contain $Al_{12}Mg_{17}$ intermetallic compound, which is precipitated from α-Mg solid solution. On the other, with regard to the 0% f_s specimen, a more uniform morphology was obtained than with the 50%

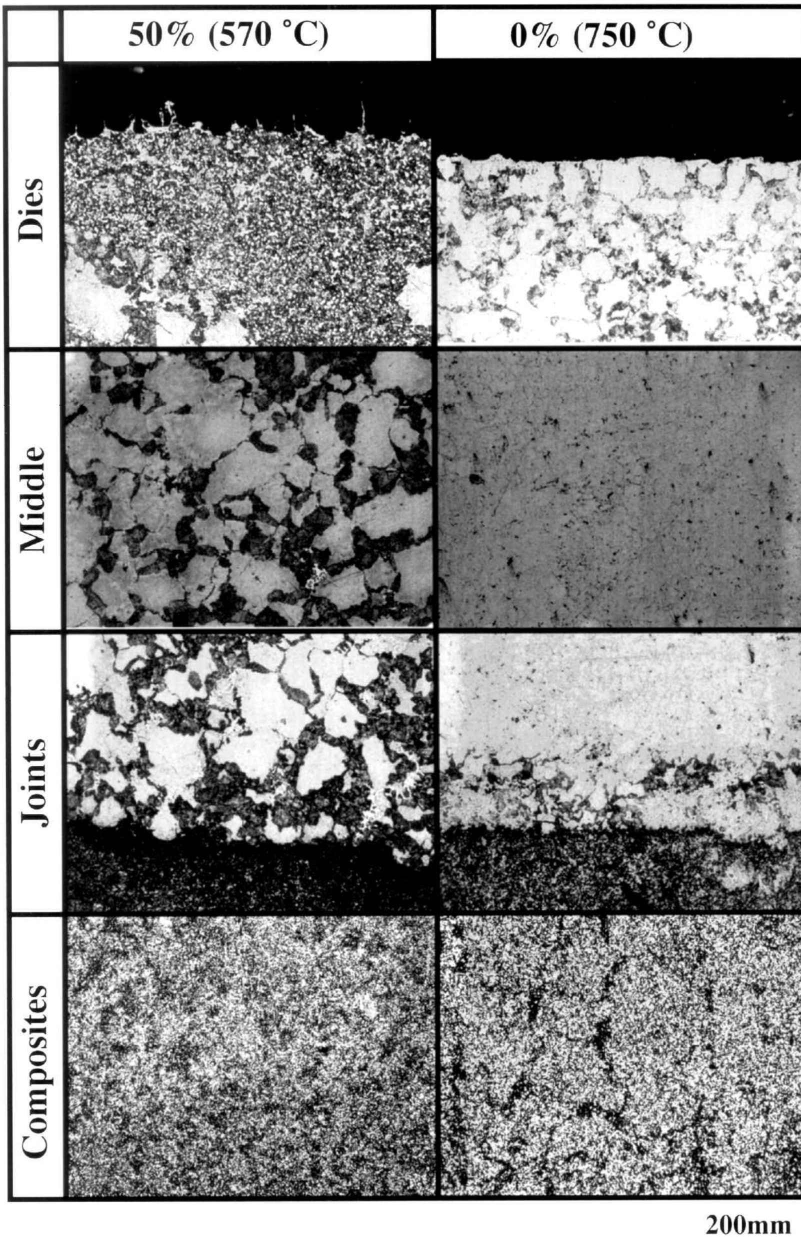

Figure 4. Microstructure of the specimen including MMC/alloy interface.

f_s specimen. Therefore, in order to disperse precipitates uniformly, longer solid solution treatment is necessary for the material by semi-solid process than that for the conventional 0% f_s process.

3.3. Mechanical properties

To examine the bonding strength of the MMC/alloy interface, a tensile test was carried out. The result is shown in Fig. 5. All specimens ruptured at the interface. It was found that the average bonding strength of 50% f_s specimens are equal to the strength of 0% f_s specimens. However the range of tensile strength of the specimens (T6, 50% f_s) is wider than that of as-cast specimens. This would be due to growth of the grain by the T6 treatment, as mentioned, above. The bending strength of the composites is shown in Fig. 6a. In our previous work, the aluminum content in the matrix of the composites fabricated by 50% f_s process is higher than that in the matrix of 0% f_s specimens [4]. This led to the higher Vickers hardness than that of 0% f_s specimens. However average bending strength of the 50% f_s specimen is 12% lower than that of the 0% f_s specimen. The distribution of the whisker length (Fig. 7) reveals that the average length in the 50% f_s specimen is 5 μm, which is 37% lower than that in the 0% f_s specimen. This will be caused by the higher pressure of the semi-solid process to the preform during the infiltration of liquid phase than the pressure of the conventional process. Furthermore, after T6 treatment, regardless of the solid fraction, the flexural strength decreased by 16% (in 50% f_s) or 26% (in 0% f_s). In order to investigate the reason for this reduction, preforms without inorganic binder such as SiO_2 were prepared. As the result of the squeeze cast, the preforms were compressed and deformed by the pressure of the infiltration; however, the reduction in the strength after T6 treatment become minor in both 50% f_s (13%) and 0% f_s (4%) specimens (Fig. 6b). The result of the XRD for the composites (0% f_s) implies the chemical reaction between SiO_2 sol on the surface of the whisker and magnesium in molten alloy produces a Mg_2Si intermetallic phase. This phase was identified in both as-cast and T6 treated materials. The formula of the reaction should be written as follows. The Gibbs free

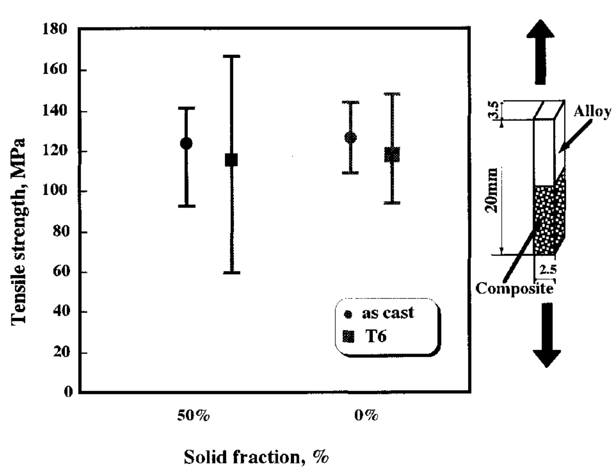

Figure 5. Tensile strength of the MMC/alloy interface.

energy change indicates that this reaction is possible thermodynamically:

$$SiO_2 + 3Mg(\text{liquid}) \leftrightarrow 2MgO + Mg_2Si.$$

It is well known that the precipitation of intermetallic compound such as Mg2Si or existence of primary crystal such as primary Si phase in the Al-Si alloy between whisker and matrix causes the notch effect to the whisker. This leads to a reduction in the strength of the composites [8]. In this case, during the solid solution treatment for aging treatment, the particle of the produced Mg_2Si phase grows by the 'Ostwart

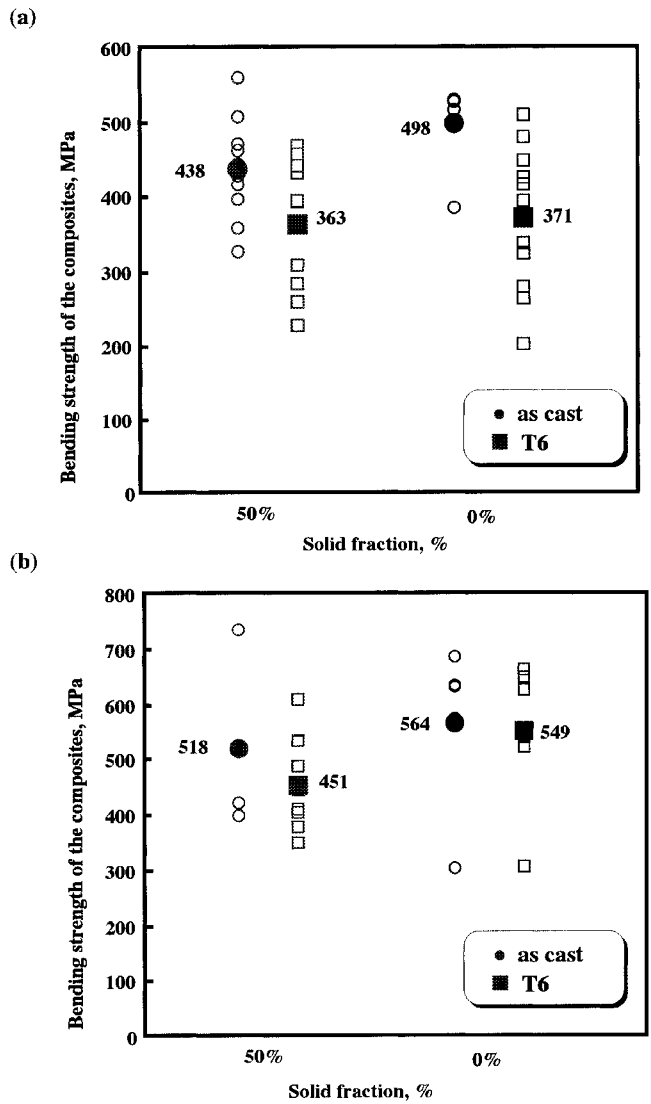

Figure 6. Bending strength of the composite, (a) with SiO_2 binder, (b) without inorganic binder to prepare the preform.

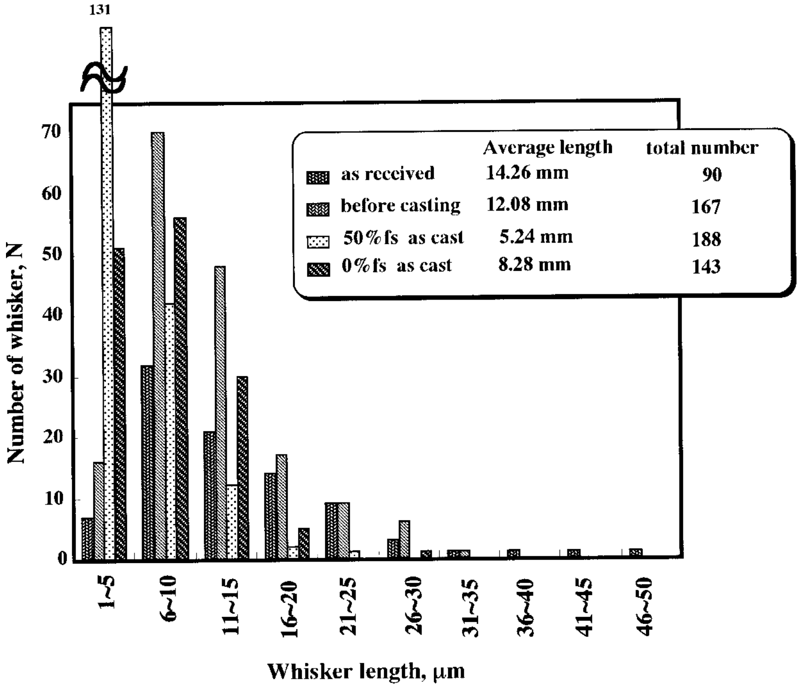

Figure 7. Distribution of the whisker length.

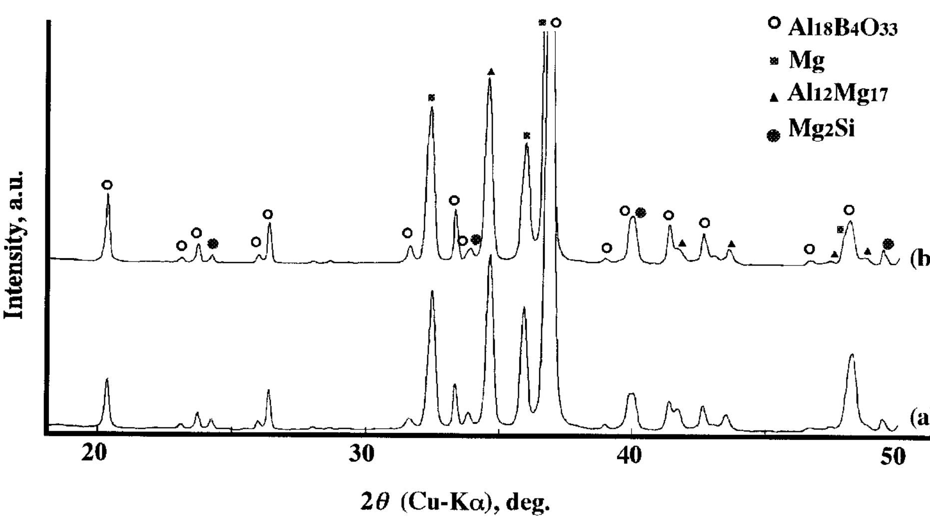

Figure 8. XRD patterns of AlBO/AZ91D composites, (a) as-cast, (b) T6 treated. (solid fraction = 0% process).

ripening', then the notch effect will become obvious. Therefore, it will be necessary to select an alternative inorganic binder which is chemically stable to the magnesium and is effective in strengthening the preform.

4. CONCLUSIONS

Aluminum borate whisker reinforced magnesium alloy matrix composites was fabricated with semi-solid material process by the squeeze casting.

(1) Without deformation of the preform, it is possible to fabricate MMC/alloy jointed material by squeeze casting up to 50% solid fraction.

(2) The average bonding strength of the MMC/alloy interface of 50% f_s specimens is 120 MPa, which is equal to the strength of 0% f_s specimens.

(3) The average flexural strength of the composite, fabricated by squeeze casting of 50% f_s material, was 438 MPa. However as the result of heat-treatment, the strength decreased to 368 MPa. This will be caused by the notch effect of Mg_2Si phase produced by the chemical reaction between SiO_2 sol and magnesium.

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