Journal of JSEM, Vol.13, Special Issue (2013) s189-s193

Bonding Strengths of Interfaces between Cast Mg-Al Alloy and Cast-In Inserted Transition Metal Cores

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(*Received 11 January 2013; received in revised form 12 April 2013; accepted 20 April 2013*)

Abstract
The structures and strengths of the joining interfaces between Mg-10mass%Al alloy and cast-in inserted transition metal cores have been investigated. Three kinds of core materials were examined: S20C carbon steel, SUS304 stainless steel and titanium. The Mg-Al alloy specimen had higher shear strength than the pure Mg specimen for every core material. Molten Mg does not react with these core materials. On the other hand, molten Mg-Al alloy reacts with each core material and produces metallurgical joint with the core. The Ti core provided highest shear strength.

Key words
Bonding Strength, Cast-in Insertion, Magnesium-Aluminum Alloy, Transition Metal, Push-out Test

1. Introduction

In recent years, the constructional materials for metallic chassis of electromechanical products have been shifting to light metals such as magnesium alloys. Additionally, the light metal chassis in the near future may be required to have flow paths for energy, heat exchange media or information.

The sacrificial-core method, a powder-metallurgical microchanneling process, produces an arbitrary-shaped network of microchannels with a diameter of several tens or several hundreds micrometers in a sintered transition metal body.[1-5] Such a metallic microchannel device appears promising as a flow path for heat exchange media, *etc*.

A cast magnesium alloy member containing the microchannel devices can be produced by cast-in insertion. In this study, we investigated the structures and strengths of the joining interfaces between the magnesium alloy and cast-in inserted transition metal cores in order to select the optimum material for the microchannel devices.

2. Experimental Procedure

2.1 Cast-in insertion and heat treatment

Three kinds of core materials were examined: S20C carbon steel, SUS304 stainless steel and titanium. Mg-10mass%Al alloy and pure magnesium were used for the casting metal.

Figure 1(a) shows the constitution of the mold part of the apparatus for the cast-in insertion experiments. The mold part was composed of an aluminized low carbon steel mold and a graphite base to hold the core. As a preparative treatment, the core was buffed and then cleansed in an ultrasound bath.

During melting of the casting metal, the free surface of the molten metal was covered with a protective flux (10mass%$MgCl_2$-40mass%$CaCl_2$-30mass%NaCl-20mass%KCl) to prevent burning of the metal. The flux was also used for settling the oxide or nitride particles in the molten metal.

In the cast-in insertion experiment, the steel mold preheated at 1003 K was set on the graphite base holding the core. The base and the core were at room temperature. Immediately afterwards, the molten metal was top-poured at 1003 K into the mold. An additional experiment using the Mg-Al alloy and the Ti core was carried out in order to obtain the cooling curve during cast-in insertion. The layout of the thermocouples is illustrated in Fig. 2.

Some of the Mg-Al alloy specimens were solution heat treated (T4) according to JIS (H 5203:2006) and the others were examined in the as-cast condition (F).

2.2 Push-out tests and structure observation

The magnesium or Mg-Al alloy casting containing each transition metal core was cut for push-out tests and structure observation (see Fig. 1(b)). In the push-out tests, five test pieces were examined for each casting.

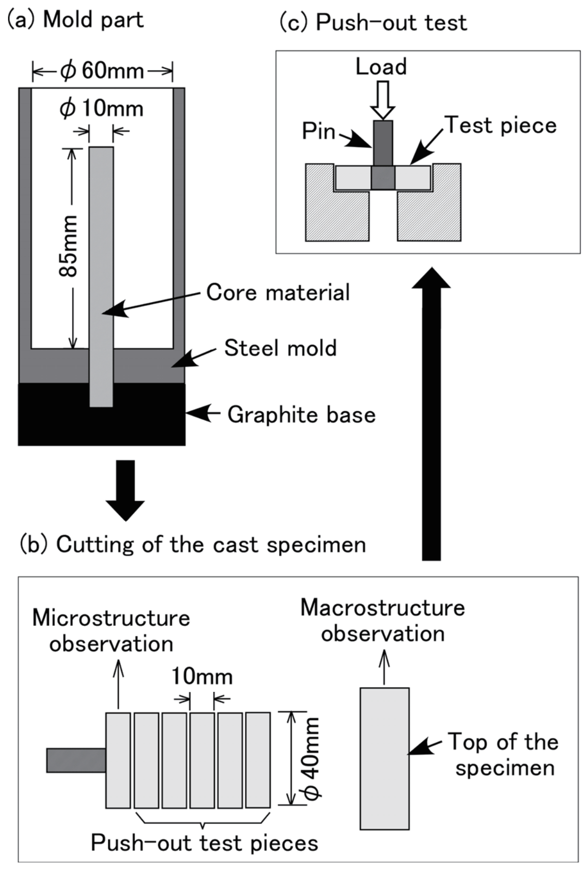

Fig .1 Experimental procedures. (a) Mold part of the apparatus. (b) Preparation of push-out test pieces and specimens for macro- and microstructure observation. (c) Set up of the jig for the push-out test

The pushing speed was set at 0.008 mm/s. The shear stress was calculated from the maximum load in each test, and the average value from the five test pieces was used as the shear strength, τ, to evaluate the strength of the joining interface between the cast metal and the core.

Macro- and microstructures were observed on the cross sections of the cast-in inserted specimens. Picric acid solution was used for the etchant to reveal the macrostructure. Microstructure observation and composition analysis of the reaction products at the joining interface were carried out by using SEM and EPMA.

In order to investigate the reactive properties between the molten Mg-Al alloy and the core materials, long-time immersion experiments were carried out. Tube-shaped core materials preliminarily cast-in inserted in Mg-10mass%Al alloy were used in these experiments. The size of the core was 10 mm in outer diameter, 8 mm in inner diameter and 40 mm in length. The Mg-Al alloy casting with each core material was remelted and held at 1003 K for 90 ks, and then the core was taken out of the molten Mg-Al alloy and cooled in a SO_2 gas atmosphere. Reaction products formed at the outer periphery of the cores were then examined by SEM and EPMA.

3. Results

3.1 Macrostructures of the cast specimens

Figure 2 provides four kinds of cooling curves measured at different positions during a cast-in insertion experiment using a Mg-10mass%Al alloy and a titanium core. Three characteristic points (the start of primary crystallization, the start of eutectic reaction and the end of solidification) are almost similar in these curves. This means a nearly isothermal solidification behavior. According to Fig. 2, the cast metal at the core surface continued to be liquid for 114 s, and the solidification time of the metal was 440 s.

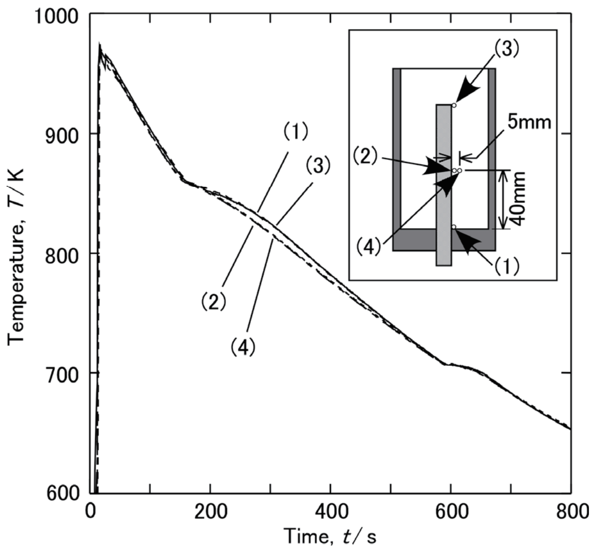

Fig. 2 Cooling curves measured at different positions during a cast-in insertion experiment using a Mg-10mass%Al alloy and a titanium core

Figures 3(a) and (b) depict cross-sectional macrostructures of the magnesium and Mg-Al alloy specimens, respectively. The core material was titanium in both specimens. The macrostructure varied remarkably with the composition of the cast metal. In the Mg-Al alloy specimen, fine equiaxed crystals were distributed over the entire region. In contrast, the magnesium specimen was composed predominantly of columnar crystals and equiaxed chill crystals were observed only near the core.

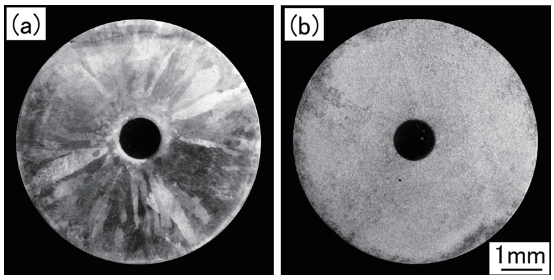

Fig. 3 Macrostructures of the cast specimens containing the titanium cores. (a) Magnesium, (b) Mg-10mass%Al alloy

3.2 Shear strengths of the joining interfaces

Figure 4 illustrates the results of the push-out tests. The Mg-Al alloy specimen had higher shear strength than the pure Mg specimen for every core material. Among the Mg-Al alloy specimens in Fig. 4, the Ti core provided highest shear strength. In the case of the Mg specimen, on the other hand, the shear strength was comparable in the

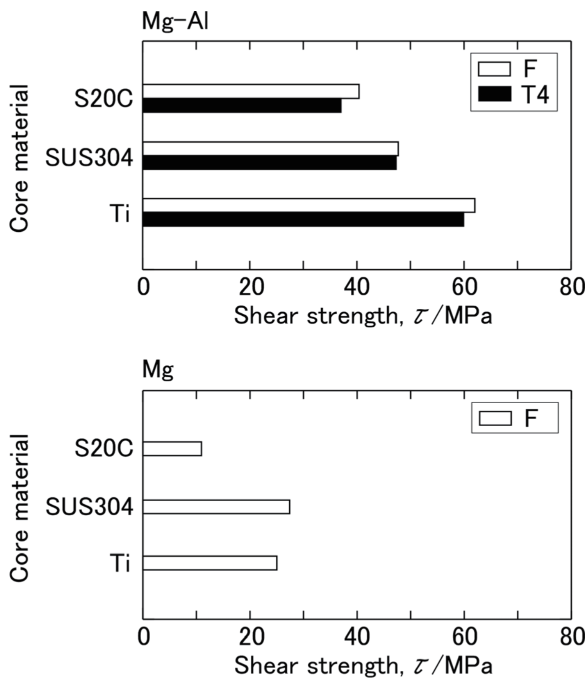

Fig. 4 Results of the Push-out tests

specimens with the SUS304 core and the Ti core. It is also noteworthy that the solution heat treatment had little effect on the shear strengths. In general, the solution heat treatment contributes to improvement of tensile strength of the cast Mg-10mass%Al alloy. The above result indicates that the strength of the cast alloy was not the dominant factor for the joining strength.

Molten magnesium does not react with S20C carbon steel or Titanium. In such a case, shear strength depends on the mechanical joint properties. Only nickel, which is contained within SUS304 stainless steel, can produce intermetallic compounds with magnesium.[6] Table 1 lists the linear expansion coefficients of the materials, α, and compares the difference of those between each cast metal and each core material, $\Delta\alpha$ (= $\alpha_{\mathrm{Cast\ Metal}} - \alpha_{\mathrm{Core}}$). In Table 1, every $\Delta\alpha$ value is positive. Therefore, thermal contraction of the cast metal can contribute to mechanical joining. However, it was not the dominant factor for the shear strength because it did not correspond to the results shown in Fig. 4. Wettability between the core material and the molten cast metal may also affect the shear strength. Especially in the case of reactive wetting, in which the wetting process influenced by reaction between them [10], alteration of interface and formation of intermetallic compounds can produce metallurgical joint. Molten Mg-Al alloy generally reacts with each core material and provides metallurgical joint with the core. However, wetting data necessary for comparison with the results in Fig. 4 were not available in literature. Hence we focused on the structure of the joining interface, especially on the reaction products.

Table 1 Linear expansion coefficient of each material (α) and the difference of α between the cast metal and the core material ($\Delta\alpha = \alpha_{\mathrm{Cast\ Metal}} - \alpha_{\mathrm{Core}}$)

Material	α / 10^{-6}K^{-1}	$\Delta\alpha$ / 10^{-6}K^{-1} (Mg)	$\Delta\alpha$ / 10^{-6}K^{-1} (Mg-Al)	Ref.
Mg	27.0	–	–	[7]
Mg-Al	25.2	–	–	[7]
S20C	12.7	14.3	12.5	[8]
SUS304	16.5	10.5	8.7	[8]
Ti	9.1	17.9	16.1	[9]

* Temperature range: Room temperature - 473 K

3.3 Reaction products at the joining interfaces

Figure 5(a) presents the structure (a back-scattered electron image) of the joining interface between the cast Mg-Al alloy and the S20C core. (The combination of the cast metal and the core material is abbreviated as "Mg-Al/S20C", for example, from here.) Figure 5(b) shows the structure of the reaction product formed on the surface of the S20C core during the long-time immersion experiment. Figures 6(a) and (b) depict the EPMA results measured across the reaction products seen in Fig. 5(a) and (b), respectively. In Fig. 5(a), some spotty areas of a reaction product are observed. The concentration profiles in Fig.

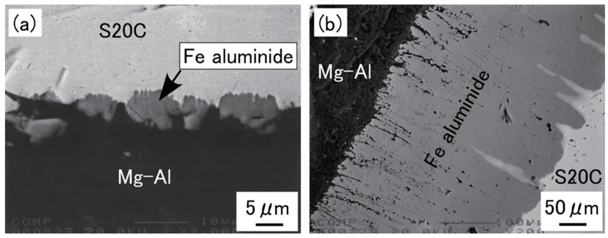

Fig. 5 Structures near the contact interfaces between the Mg-Al alloy and the S20C core. (a) Cast-in insertion experiment. (b) Long-time immersion experiment

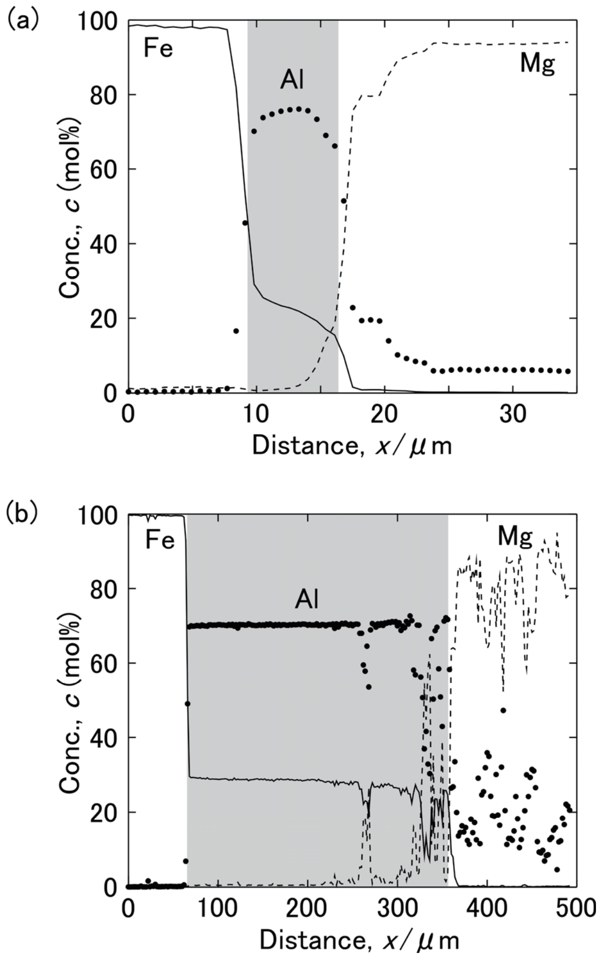

Fig. 6 Concentration profiles measured across the reaction products in the Mg-Al/S20C specimens. (a) Cast-in insertion experiment. (b) Long-time immersion experiment. Each gray band indicates the reaction product region

6(a) indicate that the composition of the spotty reaction product corresponds to iron aluminide Fe_2Al_5 or $FeAl_3$. On the other hand, a notably thick layer of Fe_2Al_5 is seen in Fig. 5(b).

Figures 7 and 8 provide the results of the combination Mg-Al/SUS304. The spotty shape of the reaction product in Fig. 7(a) is similar to that in the Mg-Al/S20C specimen seen in Fig. 5(a), and it is mainly composed of Fe_2Al_5 according the EPMA result in Fig. 8(a). In the Mg-Al/SUS304 specimen prepared by the long-time immersion experiment, the composition of the reaction product is similar to the case of the combination Mg-Al/S20C, but its thickness is much smaller.

Presumably, an anchor effect by the spotty reaction products contributes to the improvement of the shear strength of the cast-in inserted specimens in addition to the effect of metallurgical joining. However, oversize reaction products may lose the effects because of the brittle nature of the iron aluminides.

The results of the combination Mg-Al/Ti are shown in Figs. 9 and 10. No reaction product was detected in the cast-in inserted specimen (see Fig. 9(a)). However, a thin aluminide layer was formed on the surface of the Ti core during long-time immersion in the molten Mg-Al alloy as seen in Fig. 9(b). This result indicates the possibility of metallurgical joint between the cast Mg-Al alloy and the Ti core even in the case of shorter-time contact in the cast-in insertion experiment.

4. Conclusions

We investigated the structure and shear strength of the joining interfaces between the Mg-Al alloy and the cast-in inserted transition metal cores (S20C carbon steel, SUS304 stainless steel and titanium) in order to select the optimum material for the microchannel devices embedded in the magnesium alloy members. The results of our investigation are summarized as follows.

(1) The Mg-Al alloy specimen had higher shear strength than the pure Mg specimen for every core material.

(2) In the case of the Mg-Al alloy with the S20C or SUS304 core, iron aluminide formed at the joining interface.

(3) In the Mg-Al alloy specimen with the Ti core, which provided highest shear strength, no reaction product was detected by SEM. However, titanium aluminide was formed on the surface of the Ti core when the core was immersed in the molten Mg-Al alloy for a long time, 90 ks or longer. This result indicates the possibility of metallurgical joint between the cast Mg-Al alloy and the Ti core.

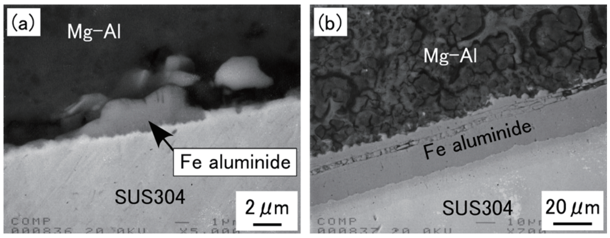

Fig. 7 Structures near the contact interfaces between the Mg-Al alloy and the SUS304 core. (a) Cast-in insertion experiment. (b) Long-time immersion experiment

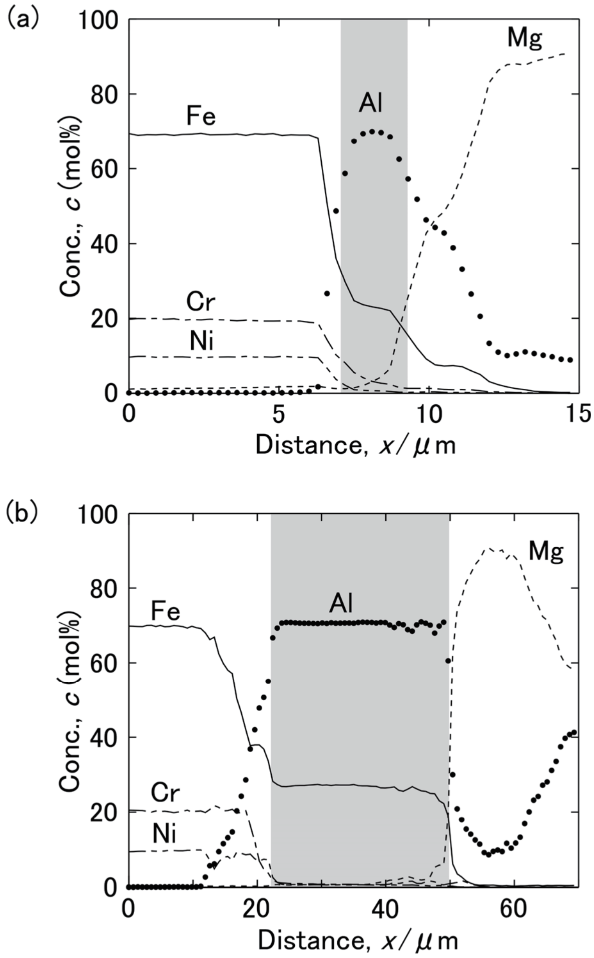

Fig. 8 Concentration profiles measured across the reaction products in the Mg-Al/SUS304 specimens. (a) Cast-in insertion experiment. (b) Long-time immersion experiment. Each gray band indicates the reaction product region

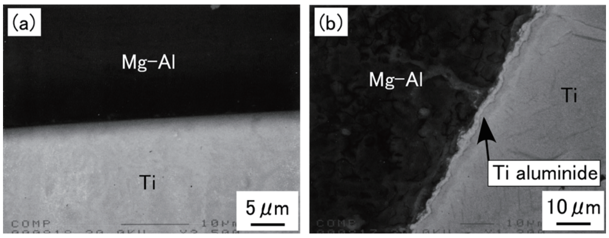

Fig. 9 Structures near the contact interfaces between the Mg-Al alloy and the Ti core. (a) Cast-in insertion experiment. (b) Long-time immersion experiment

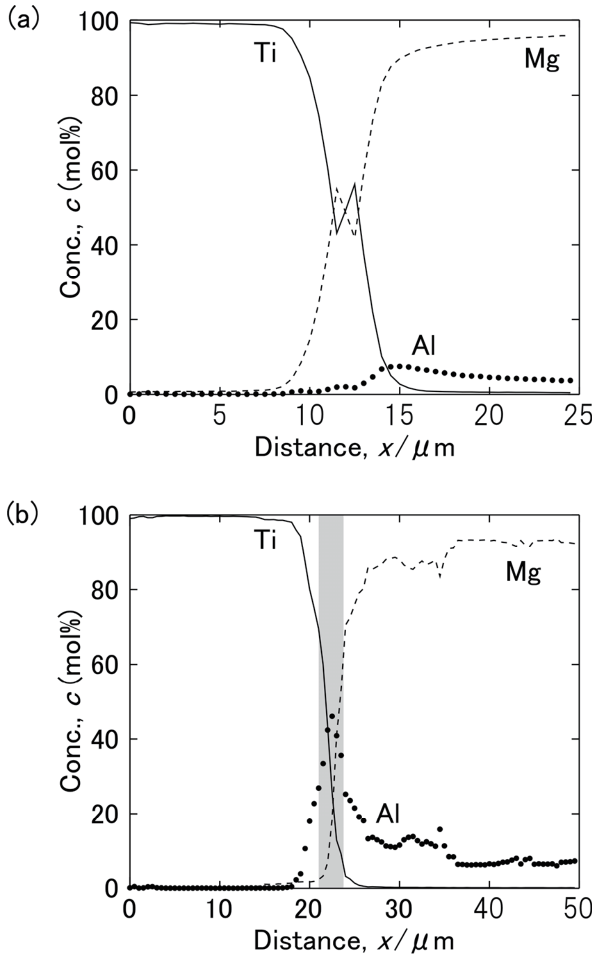

Fig. 10 Concentration profiles measured across the interfaces in the Mg-Al/Ti specimens. (a) Cast-in insertion experiment. (b) Long-time immersion experiment. The gray band indicates the reaction product region

Acknowledgement

We would like to express our appreciation to Mr. Takamitsu Baba (formerly a graduate student of Hokkaido University) for his assistance in the experiments.

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