

Bi-materials of Al-Mg Alloy Reinforced with/without SiC and Al₂O₃ Particles; Processing and Mechanical Properties

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Abstract The bi-materials with Al-Mg alloy and its composites reinforced with SiC and Al₂O₃ particles were prepared by conventional powder metallurgy method. The Al-5 wt%Mg and composite mixtures were compacted under 150~450 MPa, and then the mixtures compacted under 400 MPa were sintered at 773~1173K for 5h. The obtained bi-materials with Al-Mg/SiCp composite showed the higher relative density than those with Al-Mg/Al₂O₃ composite after compaction and sintering. Based on the results, the bi-materials compacted under 400 MPa and sintered at 873K for 5h were used for mechanical tests. In the composite side of bi-materials, the SiC particles were densely distributed compared to the Al₂O₃ particles. The bi-materials with Al-Mg/SiC composite showed the higher micro-hardness than those with Al-Mg/Al₂O₃ composite. The mechanical properties were evaluated by the compressive test. The bi-materials revealed almost the same value of 0.2% proof stress with Al-Mg alloy. Their compressive strength was lower than that of Al-Mg alloy. Moreover, impact absorbed energy of bi-materials was smaller than that of composite. However, the bi-materials with Al-Mg/SiCp composite particularly showed almost similar impact absorbed energy to Al-Mg/Al₂O₃ composite. From the observation of microstructure, it was deduced that the bi-materials was preferentially fractured through micro-interface between matrix and composite in the vicinity of macro-interface.

Keywords : Ball-milling, Aluminum-magnesium alloy, SiC and Al₂O₃ particles, Macro- and micro-interface, Density, Compressive and impact properties.

1. Introduction

Since the 20th century, metal matrix composites (MMCs) have been noticed as potential structural materials due to their favorable mechanical properties such as high strength and stiffness.¹⁻⁴⁾ Among them, aluminum metal matrix composites can be fabricated by using conventional material manufacturing methods, which results in promising applications in aerospace, defense and selected automotive applications.^{5,6)} However, relatively high production cost for aluminum matrix composites must be an important problem. Therefore, they should be partially or selectively applied. The partially reinforced

components are made up of bi-materials with macro-interface, which is the most critical zones in the partially reinforced components, between unreinforced alloy and composites. According to the recently reported researches on such partially or selectively reinforced materials fabricated by casting,⁷⁻⁹⁾ such critical zones have a deleterious effect on the mechanical properties, resulting from that the micro-interfaces between reinforcements and matrix near macro-interface can be damaged and debonded during infiltration of the molten alloys. Accordingly, it might be desirable to produce the bi-materials using conventional powder metallurgy method that gives potential benefits for recycling of aluminum

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chips occurring during subsequent machining and for production of partially reinforced near net shaped components with the macro-interface consisting of relatively well-bonded micro-interfaces. In particular, it is of interest and importance to know deformation characteristics in the bi-materials with physically and mechanically critical zones prepared by such powder metallurgy method.

In this study, therefore, the aims are to establish the fabrication processing of bi-materials composed of Al-5 wt%Mg alloy and its composites reinforced with SiC and Al₂O₃ particles by conventional powder metallurgy method and to investigate the deformation characteristics based on the microstructure observation, compressive and impact tests.

2. Experimental Procedure

For bi-materials, the commercial Al and Mg powders with a size of below 100 and 500 m respectively, and SiC and Al₂O₃ particles with an initial size of ~40 m and ~10 m respectively were used. Fig. 1 shows SEM images of typical Al and Mg powders and reinforcements used. The Al, Mg powders and SiC, Al₂O₃ particles reveal the planar and irregular shape. The Al powders were mixed with 5 wt%Mg powders. And then, in order to produce composite powders mixture, each 30 wt% SiC and 30 wt%Al₂O₃ particles was added to the Al-Mg powders mixture. The prepared Al-Mg powders mixture, Al-Mg/SiC and Al-Mg/Al₂O₃ composite mixtures were separately ball-milled for 30h. The stainless steel ball and powders were in the ratio of 30 to 1. After drying and sieving, the ball-milled Al-5 wt%Mg powder mix-

ture and each Al-5 wt%Mg/SiC and Al₂O₃ composites mixtures were compacted under a pressure of 150–450 MPa for 1 min, and then the mixtures compacted under 400 MPa were bonded by sintering at relatively high temperatures ranging from 773K to 1173K, which was used to obtain the well-bonding by chemical reaction at micro-interface of matrix/reinforcements, for 5h. Thus, the bi-materials of $\varnothing 9 \times 17$ mm were obtained. In order to estimate the soundness of bi-materials obtained, the density was measured by the Archimedes method, and the macro-structure was observed by naked eye and an optical microscope (OM). Based on the results, the specimens sintered at 873K for 5h were employed for micro-hardness and compressive tests. The micro-hardness was measured by Vickers micro-hardness tester and compressive test was conducted at a strain rate of 8.8×10^{-5} /s. Initial and deformed microstructures of bi-materials after compressive test were examined by a scanning electron microscope (SEM).

3. Results and Discussion

3.1. Fabrication of bi-materials by powder metallurgy method

The change of powder size with ball-milling time is shown in Fig. 2. The powders in the Al-Mg and composite mixture were well-distributed and became smaller with increasing the ball-milling time. They were also changed from planar shape to granular shape. The particle sizes of Al-Mg mixture and Al-Mg/SiC mixture drastically decreased up to about 20h in the ball-milling time, and they were saturated

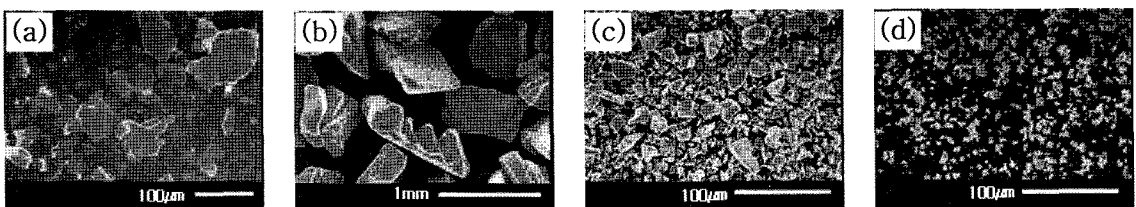


Fig. 1. SEM images showing powders employed in this study; (a) Al, (b) Mg, (c) SiC and (d) Al₂O₃.

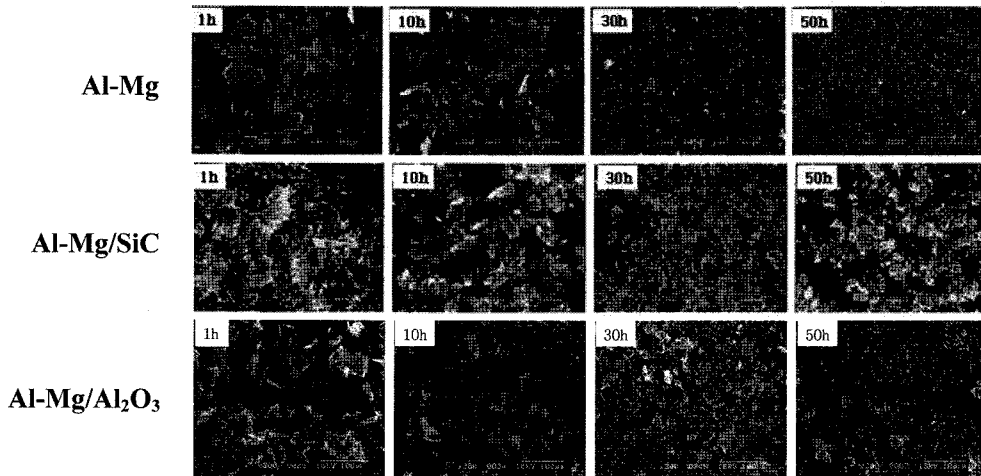
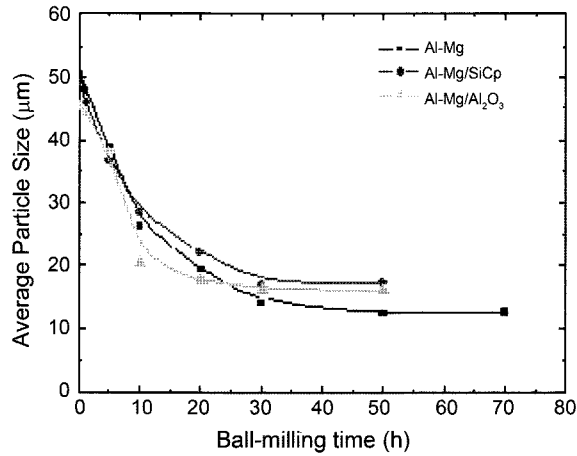


Fig. 2. Change of powder size in bi-materials with milling time.

after 30 h. However, the particle size of Al-Mg/Al₂O₃ mixture rapidly decreased up to 10h. Consequently, Al-Mg/SiC and Al-Mg/Al₂O₃ powders showed the average particle size of about 17 m and the size of Al-Mg particles was approximately 13 m after ball-milling for 50h.

The relative density of green compact with compacting pressure is shown in Fig. 3(a). The density of bi-materials increased with depending on the compacting pressure. At higher pressure than 400 MPa, the green density of bi-materials did not increase any more. The change of density after sintering at 773K~1073K for 5h is plotted in Fig. 3(b). The sintered bi-

materials revealed high density compared to as-compacted one. Among them, one sintered at 873K appeared the highest density of approximately 90%. There is better green and sintering density in the bi-materials with Al-Mg/SiC composite rather than Al-Mg/Al₂O₃ composite.

Fig. 4 shows macroscopic views of bi-materials obtained by compaction under 400 MPa (a), followed by sintering at 873K (b) and 973K (c) for 5h. As compacted bi-materials showed well bonding between Al-Mg and composite side with naked eyes. And also, we could obtain sound samples for test by sintering at 873K for 5h. However, the bi-materials

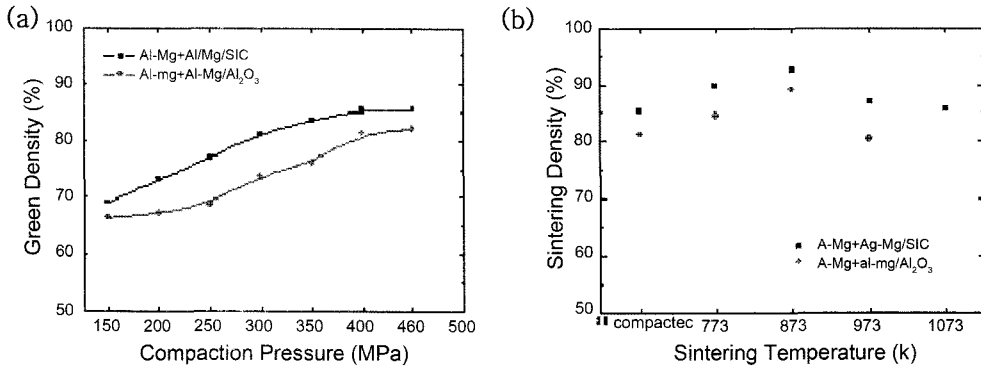


Fig. 3. Change of density in bi-materials with (a) compaction pressure and (b) sintering temperature.

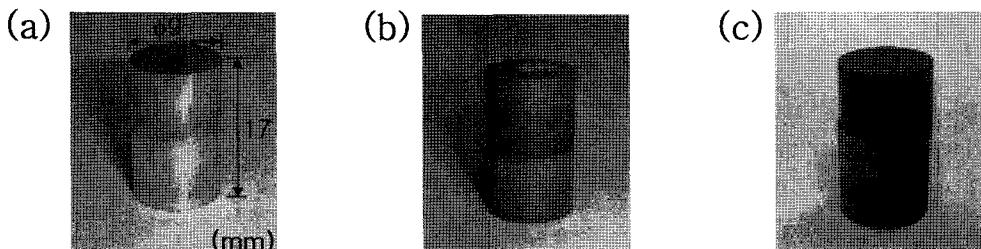


Fig. 4. Macroscopic views of bi-materials after (a) compaction under 400MPa, sintering at (b) 873K and (c) 973K for 5h.

Sintering temperature	773K	873K	973K	1073K
Al-Mg+Al-Mg/Al ₂ O ₃				X
	△	O	△	
Al-Mg+Al-Mg/SiC				
	O	O	△	△

※O: Relatively sound, △: Many pores in Al-Mg side, X: Failed.

Fig. 5. Cross sections of bi-materials obtained by sintering at 773K-1173K for 5h.

with the sound macro-interface between Al-Mg and its composites could not be obtained at higher temperatures than 873K.

Fig. 5 shows the cross sections of bi-materials sintered at various temperatures. It is apparent that macro-interfaces of bi-materials with SiC and Al₂O₃ particles are macroscopically well-bonded by sintering at 873K, whereas there are numerous pores in the Al-Mg side after sintering at 773K, 973K and

1073K even if the bonding of macro-interface seems to be good. Consequently, the sound bi-materials with well-bonded interface could be obtained at 873K, which was used for the observation of micro-structure and mechanical test in this study. In addition, the debonding of the macro-interface occurred by sintering for only 1h at all temperatures, and it disappeared after sintering for 3h and 5h at the higher sintering temperatures than 873K.

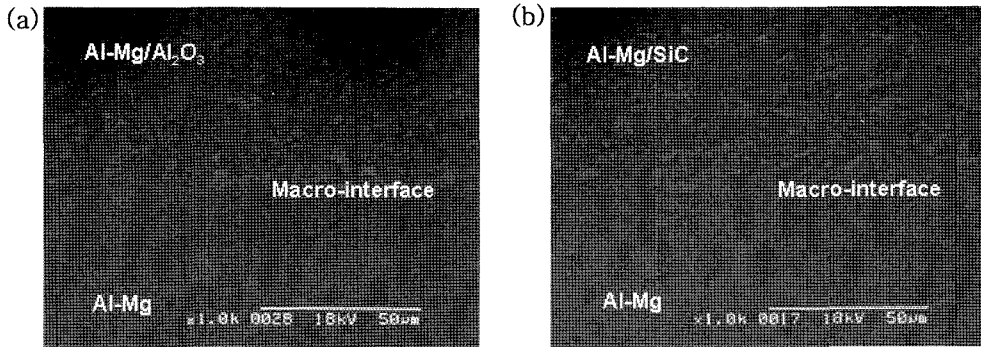


Fig. 6. SEM images showing microstructures of bi-materials sintered at 873K for 5h; (a) Al-Mg+Al-Mg/SiC and (b) Al-Mg+Al-Mg/Al₂O₃.

3.2. Microstructure and mechanical properties

Fig. 6 shows microstructures of the bi-materials sintered at 873K for 5h. The bi-materials were composed of the unreinforced Al-Mg, composite and clear macro interface between Al-Mg and its composite. The SiC particles were densely distributed a little bit compared to the Al₂O₃ particles in the macro-interfacial region. The bi-materials with SiC particles rather than Al₂O₃ particles showed more evident macro-interface, resulting from a larger size of SiC particles compared to Al₂O₃ particles.

The micro-hardness of bi-materials is listed in Table 1. The micro-hardness of each part in the bi-materials with SiC had apparent tendency to increase with increasing sintering temperature from 773K to 873K, indicating the improvement of bonding in micro-interface of Al-Mg/composites. The unreinforced Al-Mg alloy side showed the micro-hardness

Table 1. Micro-hardness of bi-materials sintered at 773K and 873K for 5h (Hv)

Bi-materials	Al-Mg+Al-Mg/ Al ₂ O ₃	Al-Mg+Al-Mg/SiC	
	873K	773K	873K
Sintering temperature	873K	773K	873K
Al-Mg alloy side	99	94	105
Interface area	124	161	197
Composite side	169	208	246

of approximately 100Hv in both bi-materials and higher micro-hardness at higher temperature which causes to better bonding between Al-Mg particles. The micro-hardness of macro-interface area demonstrates in between the Al-Mg and composites. The composite and macro-interface area with SiC particles rather than Al₂O₃ particles showed higher micro-hardness, resulting from that the hardness of SiC particles was higher than that of Al₂O₃ particles.

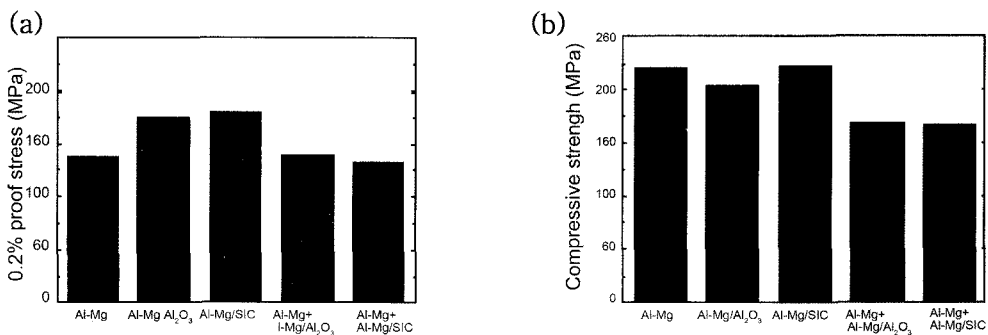


Fig. 7. (a) 0.2% proof stress and (b) compressive strength of Al-Mg alloy, Al-Mg alloy based composites and bi-materials sintered at 873K for 5h.

From the above results, it can be concluded that SiC particles are desirable to produce the bi-materials.

Fig. 7 reveals 0.2% proof stress and compressive strength of Al-Mg alloy, Al-Mg matrix composites reinforced with SiC and Al₂O₃ particles and bi-materials sintered at 873K for 5h. The bi-materials showed lower compressive strength than Al-Mg alloy and composite reinforced with SiC and Al₂O₃ particles, while the 0.2% proof stress is compatible with that of Al-Mg alloy.

The impact absorbed energy in bi-materials sintered at 873K for 5h, together with alloy and composites, is represented in Table 1. The impact absorbed energy of bi-materials is lower than that of composites. The bi-materials with composite reinforced with SiC have higher impact absorbed energy than Al-Mg alloy, and their impact absorbed energy capacity is more excellent than the bi-materials with Al₂O₃, which is same with Al-Mg/Al₂O₃ composite.

3.3. Deformation characteristics

Fig. 8 shows macroscopic views of bi-materials sintered at 873K for 5h after compressive test, along with Al-Mg alloy, Al-Mg/Al₂O₃ and Al-Mg/SiC composites also sintered at 873K for 5h. The Al-Mg alloy and composites fractured without a large change of shape and size. However, the fracture in bi-materials occurred macroscopically in the unreinforced Al-Mg alloy side, concurrent with shrinkage. From this result, it is considered that the 0.2% proof stress is preferentially dominated by the deformation of Al-Mg alloy side in bi-materials, resulting in nearly same proof stress with Al-Mg alloy as shown in Fig. 7(a).

The deformed microstructures in the vicinity of macro-interface in bi-materials sintered at 873K for 5h after compressive test were shown in Fig. 9. Many debondings of micro-interface and cracks are shown in the macro-interface region, indicating that

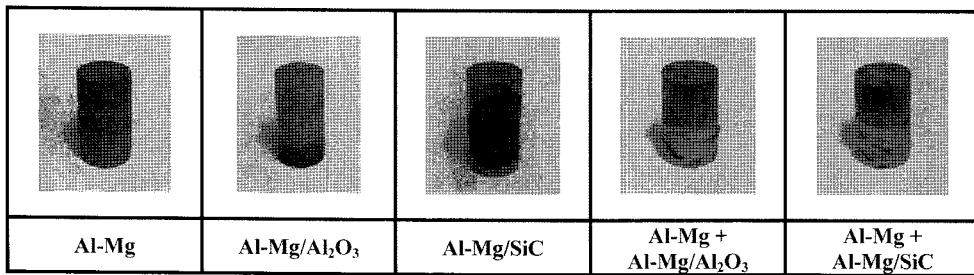


Fig. 8. Photographs of specimens after compressive test.

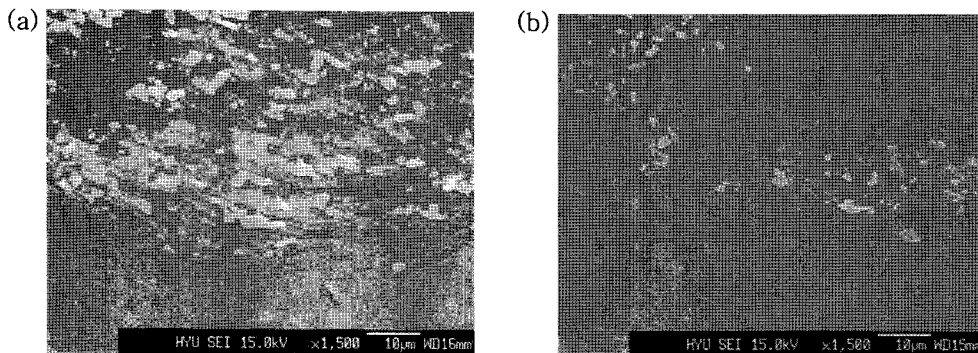


Fig. 9. SEM images showing the deformed microstructures after compressive test in the vicinity of macro-interface in bi-materials sintered at 873K for 5h; (a) Al-Mg+Al-Mg/SiC and (b) Al-Mg+Al-Mg/Al₂O₃.

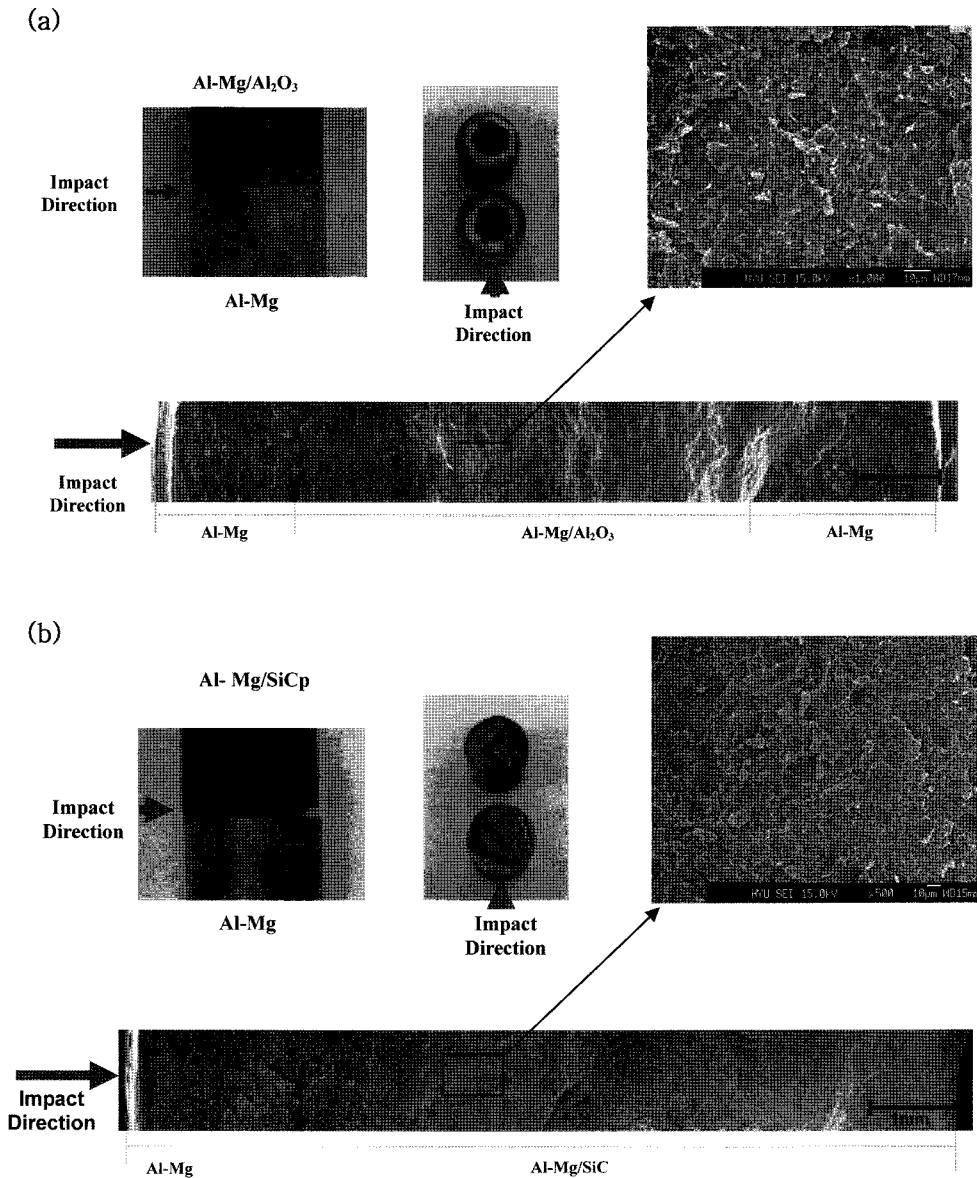


Fig. 10. Photographs and fractured surfaces after impact test in bi-materials sintered at 873K for 5h; (a)Al-Mg+Al-Mg/SiC and (b)Al-Mg+Al-Mg/Al₂O₃.

the fracture occurs along the micro interface in the macro interface. Consequently, this leads to the lower compressive strength compared to the Al-Mg alloy and composites as shown in Fig. 7.

The fracture of bi-materials during impact test occurred macroscopically in the region of macro-interface as shown in the photograph of Fig. 10(a)

and (b). In addition, the observation of fracture surface indicates that the onset of fracture is from Al-Mg alloy side but it propagates through the macro-interface. In the fracture surface of bi-materials with Al₂O₃, relatively many voids and pores are measured compared to bi-materials with SiC, which corresponds to difference of impact absorbed energy as

Table 2. Impact absorbed energy of Al-Mg alloy, Al-Mg based composites and bi-materials sintered at 873K for 5h

Specimen	Al-Mg	Al-Mg/Al ₂ O ₃	Al-Mg/SiC	Al-Mg + Al-Mg/Al ₂ O ₃	Al-Mg + Al-Mg/SiC
Impact absorbed energy (J)	1.32	1.59	1.99	1.02	1.58

shown in Table 2. This might be due to the difference of sintering density, approximately 5% as shown in Fig. 3.

The nature of the micro-interfaces between reinforcements and matrix in the physically critical zone, macro-interface, has a crucial effect on the mechanical properties of bi-materials. The micro-interfaces often have deleterious effects because of solute segregation, enhanced dislocation density, precipitation reactions, and reinforcement clustering. These can lead to imperfections at micro-interfaces that facilitate nucleation of cavities and cracks. Furthermore, the SiC and Al₂O₃ particles used in this study are not perfectly round but planar or irregular shapes. Such sharp corners constitute geometric imperfections that can promote damage initiation and growth.^{10,11} Additionally, the SiC and Al₂O₃ particles near macro-interface could be preferentially damaged by high pressure compaction. Plastic flow is concentrated near such a region. In this study, we could observe many debondings and cracks in the macro-interface after compressive test as shown in Fig. 9. Goni *et al.*⁷⁾ and Chang *et al.*^{8,9)} had reported that such macro-interface had a significant influence on the mechanical behavior of bi-materials produced by casting. Accordingly, it is reasonably deduced that the debondings and cracks in the macro-interface causes the low compressive strength in bi-materials compared to Al-Mg alloy and composites as shown in Fig. 7(b).

4. Conclusions

Al-5 wt%Mg mixture, Al-5 wt%Mg/30 wt%SiC and Al-5 wt%/30 wt%Al₂O₃ composites mixtures were separately ball-milled for bi-materials, and were

subjected to compaction under 150–400 MPa and sintering at 773K~1173K for 5h. The bi-materials compacted under 400 MPa and sintered at 873K for 5h showed the highest density and the well-bonded macro-interface between Al-Mg alloy and composites. The compressive strength of bi-materials sintered at 873K for 5h appeared relatively lower than Al-5 wt%Mg alloy and its composites, while they showed almost the same value of 0.2% proof stress with Al-Mg alloy. Based on the observation of the deformed microstructure, it was obvious that the fracture of bi-materials occurs along the micro-interface in the macro-interface region, concurrent with the limited deformation in Al-Mg alloy region, leading to the lower compressive strength.

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