Fracturing Behavior of Direct Bonded Ti with Mg Alloys by Solid State Bonding†

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Abstract

Ti and three Mg alloys (AZ61, AZ80 and AZ91) were directly bonded together by solid state bonding method in vacuum. These two materials appeared to be bonded well together although there was no intermetallic compound between Ti and Mg. Al element existing in Mg alloys seems to be an important factor involved in the bonding mechanism. The high bonding efficiency as 86% obtained from Ti bonded with AZ91 at 400 ºC for 1 hr by applying 40 MPa was guaranteed in the successful bonding.

KEY WORDS: (Ti), (Mg alloys), (Solid state bonding), (Spark plasma sintering)

1. Introduction

Ti is one of the famous structural materials applied in many industry fields recently. The remarkable properties of Ti such as light weight, high strength and good corrosion resistance made it suitable to apply for automobile or aerospace components. Many attempts to reduce a material cost and weight of these Ti components which lower fuel consumption were reported in the previous studies [1, 2]. One simple way to reduce Ti components weight is joining Ti with another light metal that possess lower density such as Al or Al alloys. Many methods were applied to join Ti with these materials by such as solid state bonding, transient liquid phase bonding (TLP bonding), and welding or brazing [3-5]. The effective method to join these two materials was solid state bonding because it can prevent the formation of brittle intermetallic compounds or heat affected zone (HAZ) [6, 7].

Mg is also an interesting material to bond with Ti because it possesses the lowest density among the conventional structural materials. The major problem to bond Ti and Mg together can be explained by their binary phase diagram since no intermetallic compound exists between them. Some researchers try to bond Ti and AZ31 (Mg alloy) together with inserting sheet such as Ni by TLP bonding [8]. However, the bonding material showed low shear strength with a smooth fracture surface. The objective in this study is to bond Ti and Mg alloys (AZ61, AZ80 and AZ91) by spark plasma sintering (SPS), which is one of solid state bonding methods, to prevent intermetallic compound layer formation. Three conventional Mg alloys were applied to study the effect of Al content on bonding strength and fracture surface of bonding material. Furthermore, an effect of bonding time on the UTS of each bonding couple was also studied.

2. Experimental

Pure Ti (Purity 99.5%) and cast Mg alloys (AZ61, AZ80 and AZ91) rod with diameter of 16 mm and 20 mm length were prepared. Mg alloys were solution treated in a muffle furnace at 400 ºC for 12 hrs, and subsequently quenched by water to eliminate β-Mg ($Mg_{17}Al_{12}$) and provide uniformly diffusion of Al at the surface of Mg alloys. The surface of Ti specimen was prepared by grinding with emery paper and polished with 0.05 μm Al_2O_3 colloid. A surface of Mg alloy was also prepared by grinding with emery paper and polished with 0.25 μm diamond paste. Ti and Mg alloys were inserted in a carbon container set in the SPS chamber as illustrated in **fig. 1**. Solid state bonding was performed at 400 ºC with a bonding pressure of 40 MPa in vacuum. Bonding couple was held at high temperature and pressure for 1 and 2 hrs before cooling in the SPS chamber. Tensile sample was machined from the bonding materials, and tensile test was performed at room temperature with testing speed of 0.05 mm/min. SEM and EDS were used to study fracture surfaces of bonding samples after tensile testing.

3. Results and Discussion

Figure 2 shows microstructures of pure Ti and Mg alloys after solution treated at 400 ºC for 12 hrs. Microstructure of pure Ti was an α-Ti matrix without other phases. β-Mg ($Mg_{17}Al_{12}$) usually observed in cast Mg alloys was dissolved into a matrix after long term solution treatment and formed homogeneous microstructures.

Figure 3 shows an original oxide layer of parent metals applied in this experiment. Figure 3a shows an oxide layer on a surface of Mg alloys after solution treated, and thickness of this layer could be measured at approximately 12 nm. Similarly, the thickness of oxide

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layer at the Pure Ti surface was also measured of 12 nm (fig. 3b).

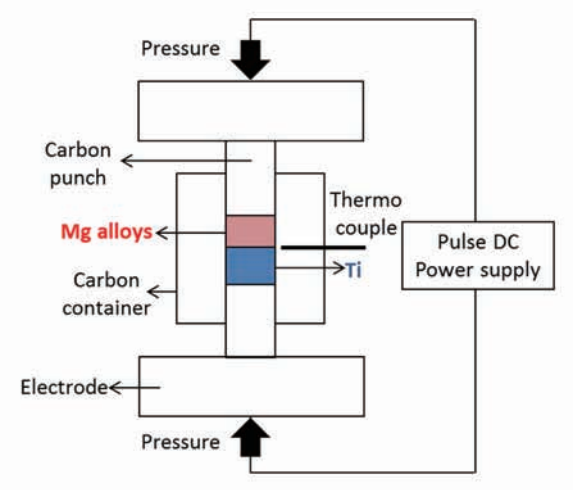

Fig. 1 Configuration of Mg alloys, Ti and carbon container installed in SPS chamber.

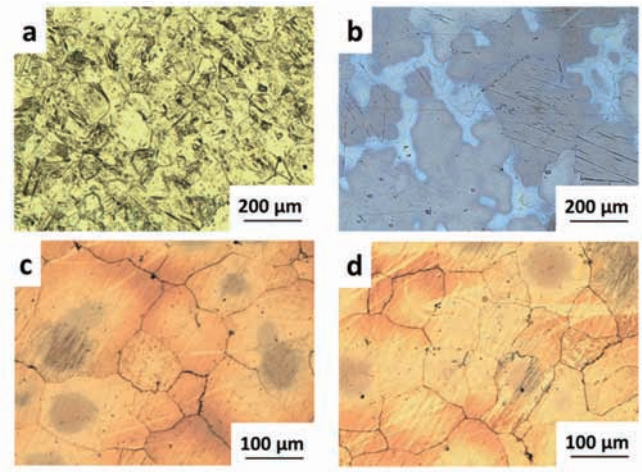

Fig. 2 Microstructures of a) Pure Ti and Mg alloys after solution treated b) AZ61 c) AZ80 and d) AZ91.

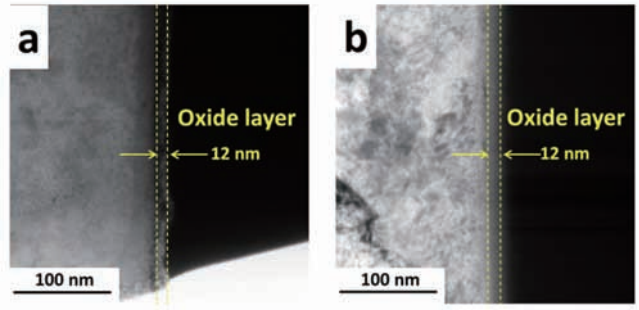

Fig. 3 Original oxide layer at the surface of a) Mg alloys after solution treatment and b) Pure Ti.

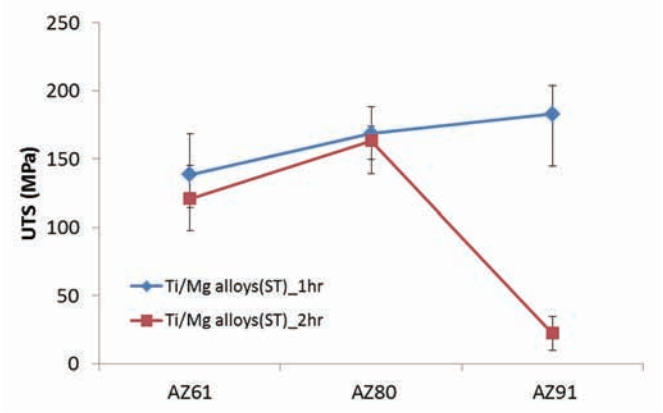

Fig. 4 UTS of Ti bonded with Mg alloys for 1 and 2 hrs.

Figure 4 shows the UTS of Ti bonded with each Mg alloy at bonding times of 1 and 2 hrs. For the samples that bonded at 1 hr, UTS gradually increased when the Al content increased from 6 (AZ61) to 9 wt% (AZ91). However, in the case of 2 hrs bonding, UTS was drastically decreased when the Al content increased from 8 wt% (AZ80) to 9 wt% (AZ91). In a trial experiment where Pure Ti and Pure Mg was bonded with same condition, results showed that this bonding couple could not be bonded together. This suggests that Al was a key element that related to a bonding mechanism.

A bonding efficiency of each bonding material shown in **fig. 5** can be calculated by following equation.

$$\text{Bonding efficiency} = \frac{UTS\ of\ bonding\ material}{UTS\ of\ solution\ treated\ Mg\ alloy}$$

Ti bonded with AZ91 at 1 hr shows a highest bonding efficiency of 86.4%. That of Ti bonded with AZ61 and AZ80 for 1 hr was a little higher than bonding for 2 hrs. A great difference was detected in Ti bonded with AZ91 where bonding efficiency was decreased from 86% to 11% when bonding time increased to 2 hrs.

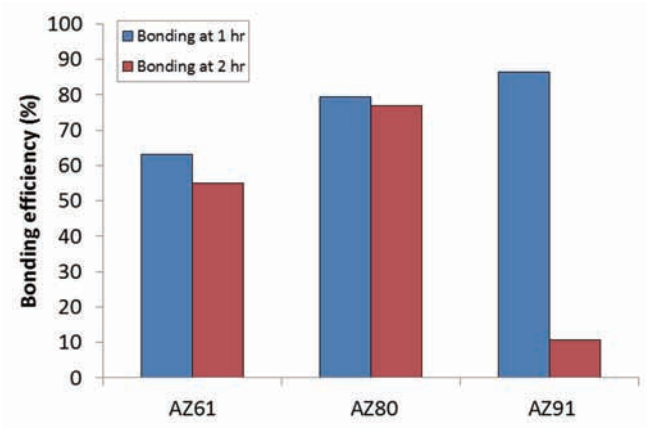

Fig. 5 Bonding efficiency of Ti/Mg alloys bonding materials.

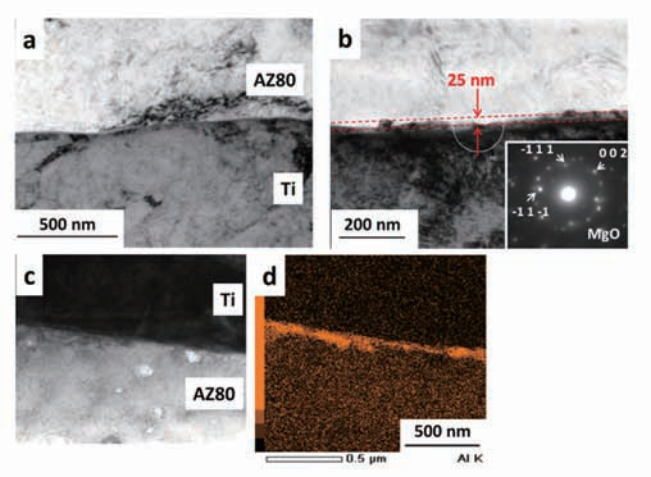

Fig. 6 Bonding interface observation by TEM a) Ti/AZ80 bonded at 2 hrs b) Ti/AZ91 bonded at 2 hrs c) Bonding interface of Ti/Mg alloys and d) TEM-EDS analysis of Al from c).

Figure 6 shows a bonding interface as observed by TEM. Fig. 6a shows a bonding interface of Ti/AZ80 bonded for 2hr which gave high bonding strength, the bonding interface was clean without any reaction layer. On the other hand, a diffraction pattern indicated that MgO layer existed at an interface of Ti/AZ91 bonded for 2 hrs (fig. 6b) and this sample gave a very low bonding strength. Compared to an original oxide layer, thickness was increased from 12 nm to 25 nm. It could be assumed that an oxide layer from AZ91 side was grown during long time (2 hrs) bonding, and the existence of oxide layer was reduced bonding strength. This oxide layer seemed to prevent a diffusion of Al element to Ti side and inhibited its reaction with Ti. However, a mechanism that activated this oxide film growth was still unknown. TEM-EDS analysis of Al element at bonding interface of Ti/Mg alloys was shown in fig. 6c and d. This Al diffusion layer was detected after bonding and it supported an assumption that Al element was very essential to bond pure Ti with Mg alloys. The real bonding mechanism could not be explained clearly because no reaction layer between Al and Ti existed at bonding interface even observed by TEM.

Figure 7 shows fracture surfaces at the Mg alloy side of Ti/Mg alloys bonded for 1 hr. Figure 7a shows a fracture surface of AZ61 in which small tearing damages could be seen. Tearing damages became larger and could be observed at fracture surfaces of AZ80 (fig. 7b). Amount of these large tearing damages was further increased on fracture surface of AZ91 compared to AZ80. This showed a good relationship between bonding efficiency (shown in fig. 5) and damages on the fracture surface. For example, a sample giving high UTS shows severe damages.

Figure 8 shows fracture surfaces at Mg alloy side of Ti/Mg alloys bonded for 2 hrs. They are similar to Ti/Mg alloys bonding for 1 hr, and the fracture on AZ80 surface became more severe compared to AZ61 by increasing of bonding efficiency.

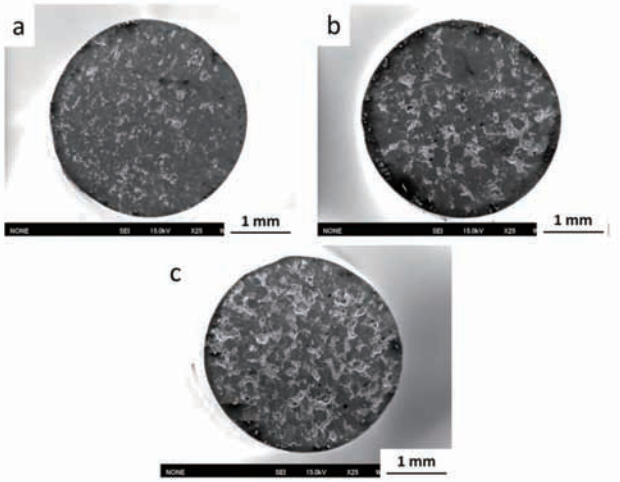

Fig. 7 Fracture surfaces of Ti/Mg alloys bonded for 1 hr (Mg alloys side) a) AZ61 b) AZ80 and c) AZ91.

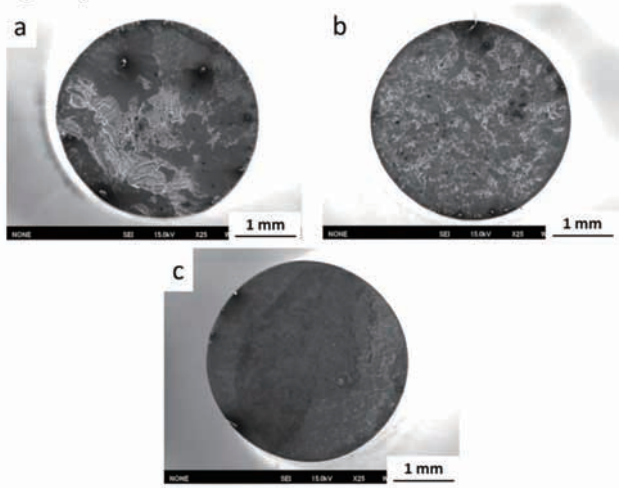

Fig. 8 Fracture surfaces of Ti/Mg alloys bonded for 2 hrs (Mg alloys side) a) AZ61 b) AZ80 and c) AZ91.

Fracture surface of Ti/AZ91 bonded for 2 hrs was very smooth. This is related to its low UTS. EDS analysis was applied on the surface of AZ91 before bonding and fracture surface of AZ91 bonded for 1 and 2 hrs. **Figure 9** shows oxygen contents that could be measured from a surface of AZ91. Low oxygen content was measured from the initial and fracture surface of sample bonded for 1 hr as 0.18 wt%. This corresponded to a very thin original oxide layer and clean bonding interface for original surface of AZ91 and fracture surface of AZ91 bonded at 1hr, respectively.

Oxygen content measured from the fracture surface of sample bonded for 2 hrs shows very high level of oxygen content at 2.8 wt% corresponding to an existence of MgO layer which growth and remained at the bonding interface. These results also suggest that long time bonding of 2 hrs for AZ91 could be activated an oxide film growth between Ti and AZ91 interface which was harmful to UTS of bonding material. Moreover, the increment of UTS by increasing the Al content in Mg alloys suggests that Al was an effective element related with bonding mechanism of Ti/Mg-Al alloys.

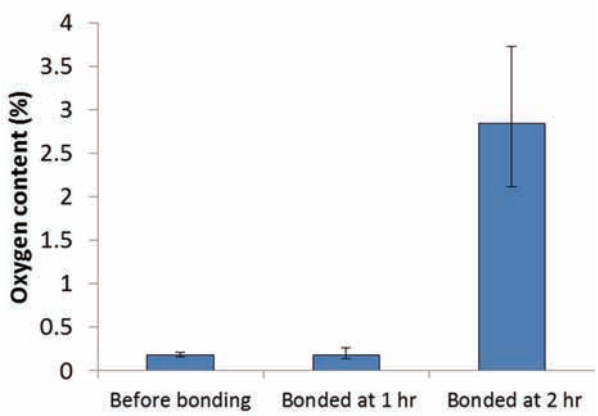

Fig. 9 Oxygen content measured from initial surface and fracture surface of AZ91.

4. Conclusion

- Bonding between Ti and Mg could be achieved by applying Mg-Al alloys. Solid state bonding by applying high temperature and pressure during a process was a promising method to bond these two materials together.
- Oxide film formation could occur in AZ91 with long term bonding for 2 hrs, this phenomenon strongly reduced the UTS of bonding material and changed the characteristic of fracture surface.
- Highest bonding efficiency which can be obtained from Ti bonded Mg alloys was 86.4% in Ti/AZ91. The suitable bonding condition was bonding at 400 ºC for 1 hr at 40 MPa.

5. References

1) Y. Wei, W. Aiping, Z. Guisheng, R. Jialie, Mater. Sci. Eng. A 480 (2008) 456–463.
2) L. Xu, Y.Y. Cui, Y.L. Hao, R. Yang, Mater. Sci. Eng. A 435–436 (2006) 638–647.
3) S. Chen, L. Li, Y. Chen, J. Huang, J. Alloys Compd 509 (2011) 891–898.
4) X.Y. Nie, J.C. Liu, H.X. Li, Q. Du, J.S. Zhang, L.Z. Zhuang, Mater. Design 63 (2014) 142-150.
5) S.P. Gupta, Mater. Charact 49 (2003) 321-330.
6) X. Li, W. Liang, X. Zhao, Y. Zhang, X. Fu, F. Liu, J. Alloys Compd. 471 (2009) 408–411.
7) G. Mahendran, V. Balasubramanian, T. Senthilvelan, Mater. Design 30 (2009) 1240–1244.
8) Anas M. Atieh, Tahir I. Khan, Maters. Sci 48 (2013) 6737-6745.