Characteristics of AlSi11-AM60 bimetallic joints produced by diffusion bonding

R Mola, M Cieślik and K Odo

Kielce University of Technology, Faculty of Mechatronics and Mechanical Engineering, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland, UE

E-mail: rmola@tu.kielce.pl

Abstract. This paper demonstrates that the diffusion bonding method can be used to join AlSi11 alloy to AM60 alloy. The microstructure of the bonding zone in such joints was examined using optical and scanning electron microscopy. Its chemical composition was determined through energy dispersive X-ray microanalysis. The experimental results show that the microstructure of the bonding zone is dependent on the parameters of the diffusion bonding process. In an AlSi11-AM60 bimetallic joint fabricated at 420 ^{o}C, the bonding zone had a thickness of about 50 µm and it was composed of Mg-Al intermetallic phases with irregularly distributed Mg_2Si phase areas. When the heating temperature was 440 ^{o}C, the bonding zone was about 150 µm thick. Mg_2Si was the predominant phase and it was distributed more regularly over the Mg-Al phase matrix. The microhardness measurements of this joint showed that the bonding zone containing hard phases had much higher hardness than either of the alloys joined.

Keywords: magnesium alloy, aluminum alloy, diffusion bonding, microstructure, intermetallic phases, microhardness

1 Introduction

Lightweight alloys based on Al or Mg have been widely used in the automotive, aerospace, machine and defense industries for several decades. The materials are characterized by high strength-to-weight ratio (Rm/ρ). This property makes them desirable wherever it is necessary to reduce the structure weight in order to reduce energy and fuel consumption and, consequently, greenhouse gas emissions [1].

When Al alloys are compared with Mg alloys, differences in the physical and mechanical properties can be noticed. For instance, Al alloys have higher density, lower specific strength, lower machinability, and lower damping ability than Mg alloys. However, some properties of Al alloys are clearly superior to those of Mg alloys, e.g. higher tensile strength at elevated temperature, higher creep resistance, and higher plastic deformability at room temperature. Mg alloys, on the other hand, are characterized by low impact strength as well as much lower resistance to corrosion and abrasion than Al alloys [1].

The demand for lightweight and strong components has led to increased research into the fabrication of bimetals being a combination of these alloys. Because of their unique properties, Mg-Al bimetals are likely to become attractive materials, desirable in various industries. It is expected that Mg-Al bimetallic elements will have high strength while maintaining their low weight. The techniques used to join Mg alloys to Al alloys are: welding [2-4], soldering [5,6], friction welding [7,8], explosive welding [9], diffusion bonding [10-16], metal forming [17-20], and casting [21-23].

Diffusion bonding, also called diffusion welding, is a common method used to join both similar and dissimilar metals or alloys [24-26]. It is often used when traditional methods fail. The principal mechanism in this process is interdiffusion of atoms across the interface. The basic parameters of diffusion welding are heating temperature, contact pressure, and contact time. The process is carried out in a vacuum or inert gas environment.

This article analyzes the structure of the bonding zone in an AlSi11-AM60 bimetallic joint produced by diffusion bonding. The observations were conducted using optical and scanning electron microscopy. The chemical composition of the bonding zone was determined through quantitative EDS analysis. The microhardness of the bonding zone was also measured.

2 Experimental procedure

The chemical composition of the alloys joined is shown in table 1.

Table 1. Chemical composition of the alloys joined.

Alloy	Chemical composition, in wt.%							
	Al	Mg	Si	Fe	Zn	Mn	Cu	Ti
AlSi11	balance	0.15	10.97	0.26	0.01	0.43	0.15	0.07
AM60	5.97	balance	0.031	0.0023	0.035	0.269	0.0018	-

The procedure to prepare the materials for diffusion bonding was as follows. The specimens (20 x 10 x 50 mm) were cut from AlSi11 and AM60 ingots. The mating surfaces were first ground using up to 800 grit SiC abrasive papers, then cleaned with ethyl alcohol and finally dried. The diffusion bonding process was carried out in a Czylok vacuum furnace (figure 1 (a)). The AlSi11 and AM60 pieces were pressed against each other, heated from room temperature to a predetermined temperature for 30 min., kept at that temperature for another 30 min., and cooled back to room temperature. Two heating temperatures were used: 420 °C and 440 °C. During the heating process, the AlSi11 and AM60 specimens were under a pressure of 5 MPa. Figure 1 (b) shows a schematic diagram of the diffusion bonding process.

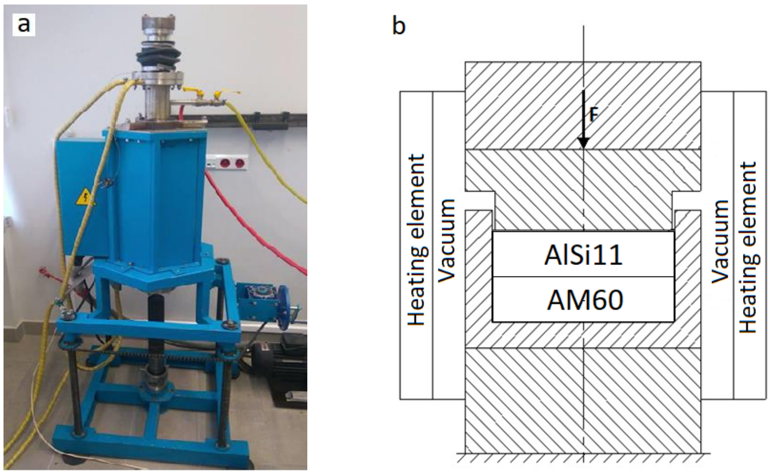

Figure 1. (a) Vacuum heat treatment furnace with an integrated pressing unit, (b) schematic diagram of the formation of a bimetallic joint using the diffusion bonding technique.

Metallographic examinations were conducted to analyze the structure of the bonding zone formed between the two alloys. A Nikon ECLIPSE MA200 optical microscope and a JEOL JSM-5400 scanning electron microscope were used. The chemical composition of the bonding zone was determined by means of an Oxford Instruments Link ISIS-300 energy dispersive spectroscopy (EDS) system coupled with a scanning electron microscope (SEM). The microhardness tests were performed at a load of 100 g using a MATSUZAWA MMT micro Vickers hardness tester.

3 Results and discussion

The microstructure of the bonding zone in the AlSi11-AM60 bimetallic joints fabricated at two different temperatures is shown in figure 2. Figure 2 (a) shows the AlSi11-AM60 joint produced at 420 ^oC. As can be seen, the bonding zone is thin (about 50 µm) with a lighter matrix and some darker areas. The darker areas are adjacent to the Si crystals occurring in the microstructure of the AlSi11 alloy close to the bonding zone. As observed from figure 2 (b), applying a temperature of 440 ^oC while keeping the other parameters unchanged resulted in the formation of an AlSi11-AM60 bimetallic joint with a much thicker bonding zone (about 150 µm). The area closer to the AlSi11 alloy was lighter and thin (about 40 µm thick) while the area adjacent to the AM60 alloy was darker and approximately 110 µm in thickness.

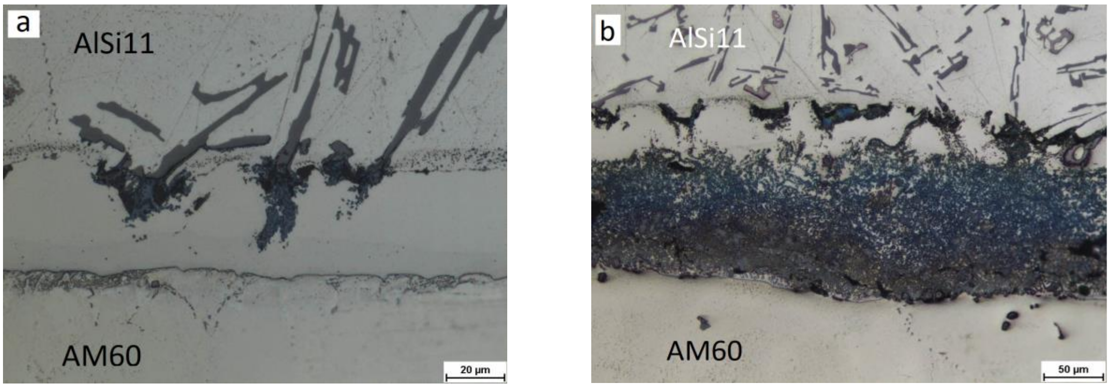

Figure 2. OM images of the microstructure of the bonding zone in the AlSi11-AM60 joints fabricated by diffusion bonding at: (a) 420 ^oC, (b) 440 ^oC.

The structure of the bonding zone in the AlSi11-AM60 joints was studied using a scanning electron microscope. Figure 3 shows the bonding zone obtained at 420 ^oC. The EDS results for points 1-3 (figure 3) are given in table 2. The chemical composition of the lighter area of the bonding zone closer to the AlSi11 (analysis at point 1) indicates the presence of an Al_3Mg_2 intermetallic phase. The Mg to Al ratio in the lighter area of the bonding zone closer to the AM60 alloy (analysis at point 2) suggests the $Mg_{17}Al_{12}$ intermetallic phase. The irregularly distributed darker areas adjacent to the Si primary crystals in the AlSi11 alloy have a high content of Si. The EDS data suggest the Mg_2Si phase (analysis at point 3).

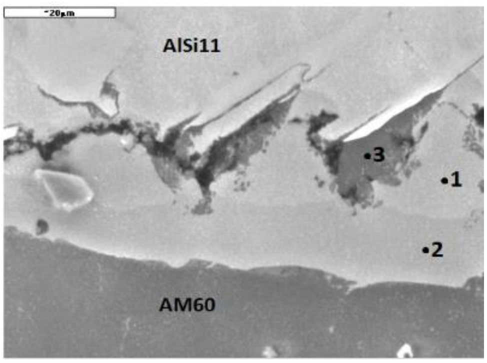

Table 2. Results of the quantitative EDS analysis corresponding to the points in figure 3.

Point	Mg		Al		Si	
	% wt.	% at.	% wt.	% at.	% wt.	% at.
1	38.42	40.92	61.58	59.08	-	-
2	58.97	61.47	41.03	38.53	-	-
3	64.02	67.27	-	-	35.98	32.73

Figure 3. SEM image of the microstructure of the AlSi11-AM60 joint fabricated by diffusion bonding at 420 ^oC.

Figure 4 illustrates details of the microstructure of the joint fabricated at the higher temperature (440 ^oC). The EDS results obtained at points 1-6 (figure 4) are provided in table 3. Figure 4 (a) shows the microstructure of the bonding zone close to the AlSi11 alloy. As can be seen, there are gray phase particles in the lighter matrix. The elemental analysis of the lighter matrix close to the AlSi11 alloy (point 1) revealed the presence of the Al_3Mg_2 intermetallic phase. The chemical composition of the lighter matrix closer to the central area of the bonding zone (point 2) is different; it is the $Mg_{17}Al_{12}$ intermetallic phase. From the elemental analysis of the gray particles in the lighter matrix (point 3) it is clear that they are the Mg_2Si phase. Figure 4 (b) illustrates the microstructure of the bonding zone adjacent to the AM60 alloy. This area has a more uniform structure. The gray phase particles (point 4), which are regularly distributed over the lighter matrix, are the Mg_2Si phase. The EDS data obtained for the lighter area of the bonding zone adjacent to the AM60 alloy (point 5) suggest the $Mg_{17}Al_{12}$ intermetallic phase. As can be seen, light particles are present in the bonding zone both close to the AlSi11 and the AM60. Those occurring closer to the AM60 alloy (point 6) indicate a multi-component phase consisting mainly of Mn and Al but also Si and Mg. The EDS analysis shows that the white multi-component phase observed close to the AlSi11 alloy contains also Fe.

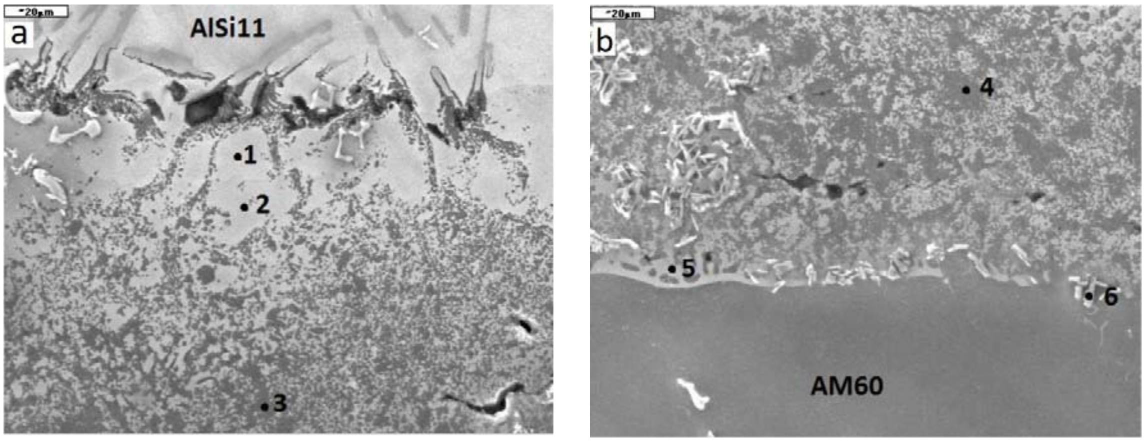

Figure 4. SEM images of the microstructure of the AlSi11-AM60 joint fabricated by diffusion bonding at 440 ^{o}C: (a) area close to the AlSi11, (b) area close to the AM60.

Table 3. Results of the quantitative EDS analysis corresponding to the points marked in figure 4 (a) and (b).

Point	Mg		Al		Si		Mn	
	% wt.	% at.	% wt.	% at.	% wt.	% at.	% wt.	% at.
1	37.68	40.16	62.32	59.84	-	-	-	-
2	57.51	60.03	42.49	39.97	-	-	-	-
3	61.18	64.43	4.9	4.65	33.92	30.92	-	-
4	63.42	66.7	-	-	36.58	33.3	-	-
5	65.21	67.53	34.79	32.47	-	-	-	-
6	3.14	5.05	33.9	49.18	1.34	1.87	61.62	43.9

Figure 5 shows indentations left after Vickers tests for the joint fabricated at 440 ^{o}C. The microhardness of the AlSi11 varied from 60 to 63 HV, while that of the AM60 ranged from 63 to 65 HV. The microhardness of the bonding zone in the lighter area closer to the Al alloy, where the predominant phase was Mg-Al, reached 227-247 HV. The microhardness of the darker area observed closer to the AM60 alloy was 287-308 HV; the higher values were due to the presence of the hard Mg_2Si phase.

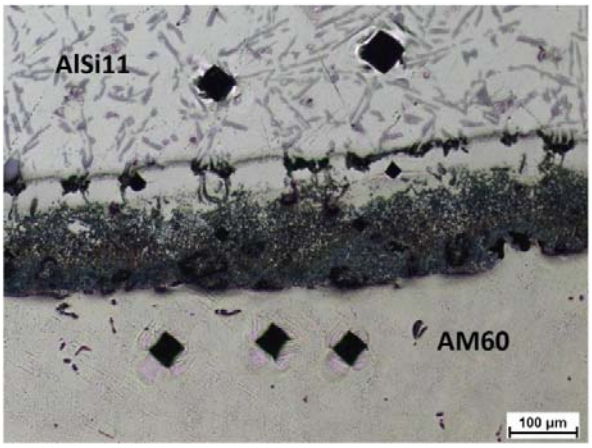

Figure 5. OM image of the joint fabricated at 440 °C with indentations left after the Vickers microhardness tests.

4 Conclusions

The experimental results showed that the microstructure and thickness of the bonding zone in the AlSi11-AM60 joints under study were dependent on the heating temperature. The joint fabricated at 420 °C had a thickness of about 50 µm and it was composed of Mg-Al intermetallic phases with irregularly distributed Mg_2Si phase areas. When the heating temperature was 440 °C, the bonding zone had a thickness of about 150 µm and two main areas could be distinguished. The lighter area closer to the AlSi11 was about 40 µm thick; it consisted of Al_3Mg_2 and $Mg_{17}Al_{12}$ intermetallic phases and irregularly distributed Mg_2Si phase particles. The darker area adjacent to the AM60 was much thicker (about 110 µm) and the predominant phase was Mg_2Si. The microhardness tests conducted for that joint revealed that the hardness of the bonding zone was several times higher than that of either of the alloys joined.

References

[1] Dziadoń A and Mola R 2013 Magnesium-trends of development of mechanical properties *Metal Forming* **24** 253-77
[2] Liu L, Liu X and Liu S 2006 Microstructure of laser-TIG hybrid welds of dissimilar Mg alloy and Al alloy with Ce as interlayer *Scripta Materialia* **55** 383-6
[3] Borrisutthekul R, Miyashita Y and Mutoh Y 2005 Dissimilar material laser welding between magnesium alloy AZ31B and aluminum alloy A5052-0 *Science and Technology of Advanced Materials* **6** 199-204
[4] Liu L, Ren D and Liu F 2014 A Review of dissimilar welding techniques for magnesium alloys to aluminum alloys *Materials* **5** 3735-7
[5] Wang Z, Wang H and Liu L 2012 Study on low temperature brazing of magnesium alloy to aluminum alloy using Sn–xZn solders *Materials & Design* **39** 14-9
[6] Liu L M, Tan J H, Zhao L M and Liu X J 2008 The relationship between microstructure and properties of Mg/Al brazed joints using Zn filler metal *Materials Characterization* **56** 479-83
[7] Somasekharan A C and Murr L E 2004 Microstructures in friction-stir welded dissimilar magnesium alloys and magnesium alloys to 6061-T6 aluminum alloy *Materials Characterization* **52** 49–64
[8] Sato Y S, Park S H C, Michiuchi M and Kokawa H 2004 Constitutional liquation during dissimilar friction stir welding of Al and Mg alloys *Scripta Materialia* **9** 1233-6
[9] Mróz S, Stradomski G, Dyja H and Galka A 2015 Using the explosive cladding method for production of Mg-Al bimetallic bars *Archives of Civil and Mechanical Engineering* **15** 317-23
[10] Zhao L M and Zhang Z D 2008 Effect of Zn alloy interlayer on interface microstructure and strength of diffusion-bonded Mg–Al joints *Scripta Materialia* **58** 283-6

[11] Liu P, Li Y, Geng H and Wang J 2005 A study of phase constitution near the interface of Mg/Al vacuum diffusion bonding *Materials Letters* **59** 2001-5
[12] Somekawa H, Hosokawa H, Watanabe H and Higashi K 2003 Diffusion bonding in superplastic magnesium alloys *Materials Science and Engineering* **339** 328-33
[13] Li Y, Liu P, Wang J and Ma H 2007 XRD and SEM analysis near the diffusion bonding interface of Mg/Al dissimilar materials *Vacuum* **82** 15-9
[14] Liu P, Li Y, Geng H and Wang J 2006 Investigation of interfacial structure of Mg/Al vacuum diffusion-bonded joint *Vacuum* **80** 395-9
[15] Zhang J, Luo G, Wang Y, Shen and Q Zhang L 2012 An investigation on diffusion bonding of aluminum and magnesium using a Ni interlayer *Materials Letters* **83** 189-91
[16] Dziadoń A, Mola R and Błaż L 2011 Formation of layered Mg-eutectic composite using diffusional process at the Mg-Al interface *Archives of Metallurgy and Materials* **56** 677-84
[17] Zhang X P, Castagne S, Yang T H, Gu C F and Wang J T 2011 Entrance analysis of 7075 Al/Mg–Gd–Y–Zr/7075 Al laminated composite prepared by hot rolling and its mechanical properties *Materials & Design* **32** 1152-8
[18] Liu X B, Chen R S and Han E H 2009 Preliminary investigation on the Mg-Al-Zn/Al laminated composite fabricated by equal channel angular extrusion *Journal of Materials Processing Technology* **209** 4675-81
[19] Zhang X P, Yang T H, Castagne S and Wang J T 2011 Microstructure; bonding strength and thickness ratio of Al/Mg/Al alloy laminated composites prepared by hot rolling *Materials Science and Engineering* **528** 1954-60
[20] Binotsch C, Nickel D, Feuerhack A and Awiszus B 2014 Forging of Al-Mg compounds and characterization of interface *Procedia Engineering* **81** 540-5
[21] Mola R, Bucki T, Dziadoń A 2017 Microstructure of the bonding zone between AZ91 and AlSi17 formed by compound casting *Archives of Foundry Engineering* **17** 202-6
[22] Hajjari E, Divandari M, Razavi S H, Emami S M, Homma T and Kamado S 2011 Dissimilar joining of Al/Mg light metals by compound casting process *Journal of Materials Science* **46** 6491-9
[23] Hajjari E, Divandari M, Razavi S H, Emami S M, Homma T and Kamado S 2012 Characteristics and mechanical properties of Al 413/Mg joint in compound casting process *Metallurgical and Materials Transactions A* **43** 4667-77
[24] Konieczny M and Szwed B 2016 Effect of cooling rate on titanium and stainless steel joints performed with copper interlayer METAL 2016: 25rd International Conference on Metallurgy and Materials (Brno) 1456-61
[25] Shao X, Guo X, Han Y, Lu W, Qin J and Zhang D 2015 Characterization of the diffusion bonding behavior of pure Ti and Ni with different surface roughness during hot pressing *Materials & Design* **65** 1001-10
[26] Aleman B, Gutierrez L and Urcola J J 2013 Interface microstructures in diffusion bonding of titanium alloys to stainless and low alloy steels *Material Science and Technology* **9** 633-41