Characteristics of AlSi11-AM60 bimetallic joints produced by diffusion bonding

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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 °C, the bonding zone had a thickness of about 50 μm and it was composed of Mg-Al intermetallic phases with irregularly distributed Mg2Si phase areas. When the heating temperature was 440 °C, the bonding zone was about 150 μm thick. Mg2Si 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.

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 °C. 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 °C 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 °C, (b) 440 °C.

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 °C. 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 Al3Mg2 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 Mg17Al12 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 Mg2Si 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 °C.

Figure 4 illustrates details of the microstructure of the joint fabricated at the higher temperature (440 °C). 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$_3$Mg$_2$ 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$_2$Si 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$_2$Si 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 °C: (a) area close to the AlSi11, (b) area close to the AM60.](image)

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

| Point | Mg % wt. | Mg % at. | Al % wt. | Al % at. | Si % wt. | Si % at. | Mn % wt. | Mn % 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 °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$_2$Si 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 Mg2Si 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 Al3Mg2 and Mg17Al12 intermetallic phases and irregularly distributed Mg2Si phase particles. The darker area adjacent to the AM60 was much thicker (about 110 μm) and the predominant phase was Mg2Si. 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.

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