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The influence of position in overlap joints of Mg and Al alloys on microstructure and hardness of laser welds.

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Abstract

Structure and properties of laser beam welding zone of dissimilar materials, AZ31 magnesium alloy and A5754 Aluminum alloy, are investigated. The microstructure and quality of the Mg/Al weld were studied by metallography, microhardness and optical microscopy. Differences in physical and mechanical properties of both materials, magnesium and aluminum, affect weldability and resistance of this combination, and lead to the formation of intermetallic compounds in the welded metal.

Keywords: laser welding, dissimilar materials, AZ31 magnesium alloy, A5754 aluminum alloy, microstructure evolution.

1. Introduction

The procedures mostly described for obtaining quality welds in the literature have been elaborated for identical metals or, at least, for metals of similar compositions and properties. However, there are many applications in which assembly is made from metals of different compositions. This may be the case when one has to solve a mechanical wear problem, a high-temperature situation, or other conditions in which different properties are required from different parts of the same assembly. Therefore, the dissimilar-metal welding process has been identified as top priority for materials joining technologies recently [1].

Use of lightweight materials improves the energy efficiency and fuel economy of automotive vehicles. Thus, because of their extremely low weight in combination with their good castability and workability, the use of Mg alloys and Al alloys in specific structural applications has increased, replacing often the steels [2-3].

Welding of Mg and Al to form a compound structure can reduce the weight of the structure and the cost of the workpiece. However, it is difficult to obtain good dissimilar welds of these two kinds of alloys through conventional fusion welding techniques, such as arc and electron beam [4], since large intermetallic compounds, which have a strong negative effect on the mechanical properties of the weld, are easy to form in these processes [5].

In the past, the dissimilar combination of magnesium and aluminum has been realized by vacuum diffusion welding [6] or even by explosion welding [7]. These methods allow to obtain promising results but are difficult to implement in the context of industrialization. Other techniques, like friction stir welding [8] are particularly suitable for joining very dissimilar materials, by reducing the amount of interfacial brittle phases promoted by high temperature gradients. But again, the process used does not allow flexibility in the case of complex shapes or when the processing speed is a key factor in the success of the assembly.

Among the welding processes, laser techniques are now widely used for industrial production of homogeneous joints in the automotive industry because of a rather high flexibility of laser tool, and because of high welding speed. However, few studies have stated the limit of such techniques to join the Mg alloys to Al alloys [9]. So it is necessary to study the microstructure of laser welded joint Mg/Al.

The main objective of this research is to investigate the microstructure and the effect of the position in overlap joints of Al and Mg on the intermetallic compounds formation in the fusion zone. Experiments were conducted to provide a better understanding of the process. The microstructure and micro-hardness distribution were observed and analyzed by means of metallography and microhardness tests.

2. Experimental details

AZ31 magnesium alloy and A5754 aluminum alloy were selected as the base metal for welding experiments. AZ31 magnesium alloy was chosen due to its good rolling capabilities. 2 mm thick plates were hot rolled by several passes and then leveled and annealed at 300°C. The A5754 aluminum alloy belongs to the 5xxx series. This group includes magnesium as the major alloying element (up to 5.6%). These alloys derive their strength from the solid solution strengthening due to magnesium. The nominal alloying elemental compositions of AZ31 and A5754 alloy are shown in Table 1. The welding technological parameters are listed in Table 2.

Materials	Chemical Composition (Wt. %)						
	Mg	Al	Mn	Zn	Fe	Cu	Si
AZ31	96.67	2.65	0.17	0.52	-	-	-
A5754	2.68	96.63	-	-	0.4	0.14	0.13

Table 1. Chemical composition of test materials.

Joint	Laser power (W)	Velocity $m.s^{-1}$	Linear Energy $KJ.m^{-1}$
Al to Mg	2500	0.067	37.5
Mg to Al	4000	0.1	40

Table 2. Welding technological parameters used in test.

The sheet was cut and machined into rectangular samples, 160 mm long by 110 mm wide. Two kinds of assemblies were realized: (1) with aluminum placed upon magnesium and (2) with the magnesium placed upon aluminum in an overlap configuration, Fig.1 (a) and (b) respectively. For the investigation, the experiments were carried out with a 6kW diode-pumped disk laser TRUMPF 6002. The source is a Yb: YAG continuous laser with 1032 nm-wavelength. The spot size of the laser beam on the plates was 0.4 mm with a Gaussian intensity distribution. The workpieces are moved using a Computer Numerically Controlled table.

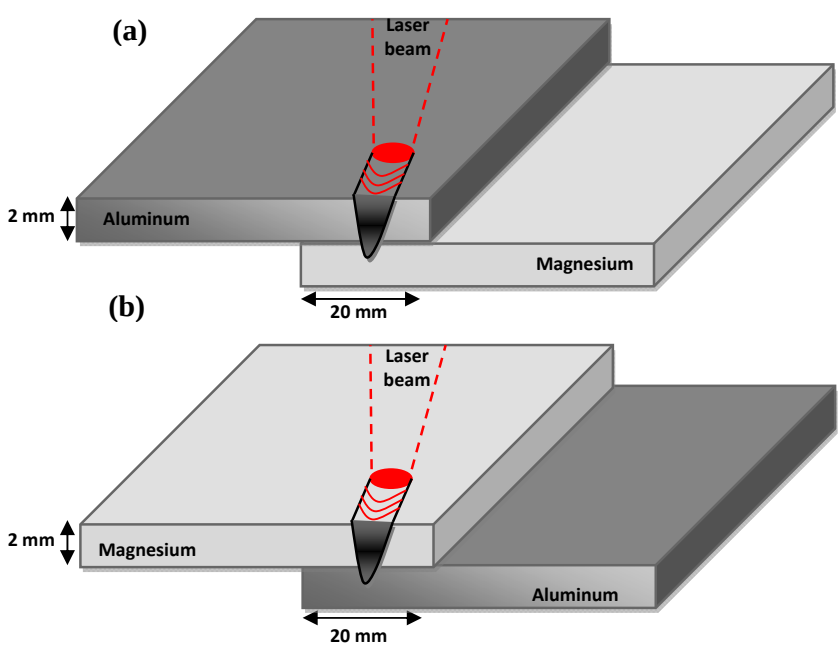


Fig.1. Laser welding of Mg alloy AZ31 to Al alloy A5754.

As magnesium and aluminum are highly susceptible to oxidation, a protective atmosphere is required during welding. The use of shielding gas is also used to protect the optics from metal slag. It is well known that the choice of the shielding gas has an influence on the formation of the plasma. Three types of shielding gases are commonly used in laser welding: helium, argon and nitrogen. Many authors have investigated the effectiveness of these three shielding gases and have reported that an argon gas flow was a good choice for these two materials, in case of Nd:YAG welding [10]. The use of a back shielding gas can reduce the sag, which often occurs due to the low viscosity and surface tension of magnesium.

The influence of gas flow rate on weld width was also studied and it was reported that increasing gas flow up to 20 l/min is needed to affect the susceptibility to oxidation [10]. Next to these works, we decide to use 20 l/min argon gas flow to protect the molten pool of the top and back from oxidation. The focal point was fixed on the surface of workpiece.

After welding, the laser-welded joints were ground with abrasive paper, mechanically polished with a final polishing step, comprising use of a 0.3 μm diamond paste.

Microstructural characterizations of welded samples were performed on their cross-sections by using both Optical Microscopy (OM, Leitz RZD-DO) and Scanning Electron microscopy (SEM, Jeol JSM-7001F) accompanied by Energy Dispersive X-ray Spectroscopy (EDX, Oxford). The measurement of hardness was performed on a Leica VMHT digit hardness tester with a load of 1.96 N and dwelling time of 15 s to estimate mechanical properties of dissimilar welds.

3. Results and discussion

Fig.2 shows an optical macrograph of a transverse section of dissimilar welds. The mixing of the two metals was very clear. It could be seen that the molten metal of upper sheet penetrated in the lower sheet in the two welded samples, the penetration depth of the weld pool within the lower sheet was 0.45 mm and 2 mm, Fig.2 (a) and (b) respectively.

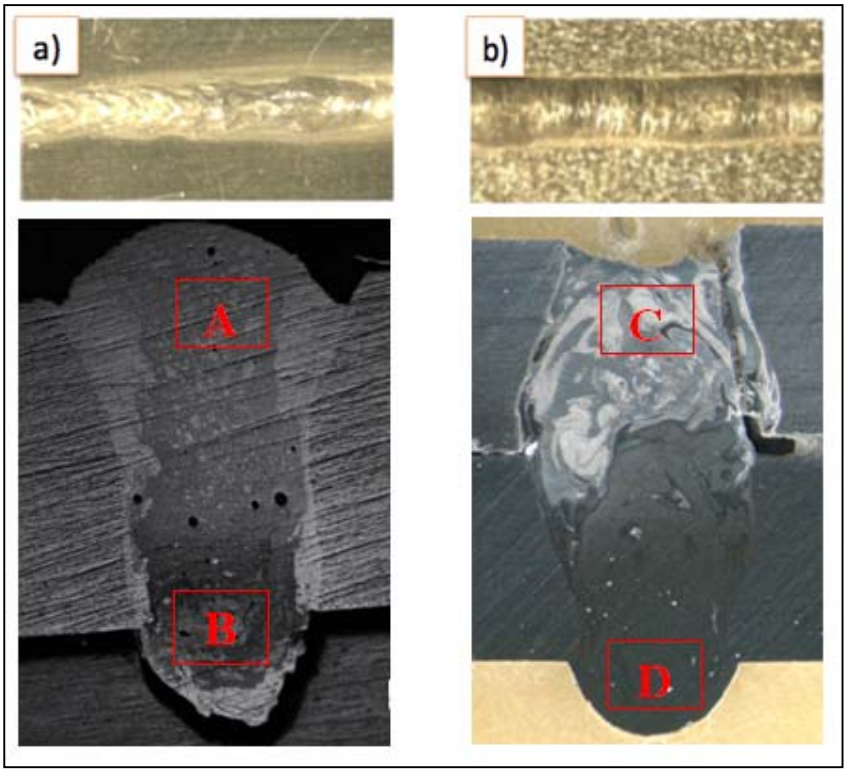


Fig.2. Optical macrographs of cross-section of dissimilar welds, (a) A5754 on the top, (b) AZ31 on the top.

Fig.3 shows SEM micrographs at the interface between the fusion zone and the Mg substrate, Fig.3(a), and between the fusion zone and the Al substrate, Fig.3(b). The microstructure consists of three different areas: base metal, heat-affected zone and fusion zone. From the microstructure analysis, the heat-affected area could be identified only between fusion zone and Mg substrate, Fig.3(a), however no difference could not be observed between the heat-affected zone and the Al substrate, Fig.3(b). Also, it can be seen from the Fig.3(a) that the structure close to the weld metal was columnar crystals which grew into the base metal.

Fig.4 shows the micrograph of Mg-Al interface. The welded metal is mainly composed of dendrite crystals, which were eutectic in structure formed during the laser beam welding [11]. From this figure, it can be observed that the microstructure of the fusion zone is composed of a rather complex and heterogeneous solidification structure. This microstructure was promoted by hydrodynamic movements in the Mg-Al interface. A recrystallization phenomenon was also evidenced in the fusion zone of dissimilar laser welds, with a grains refinement generated during cooling thermal cycles.

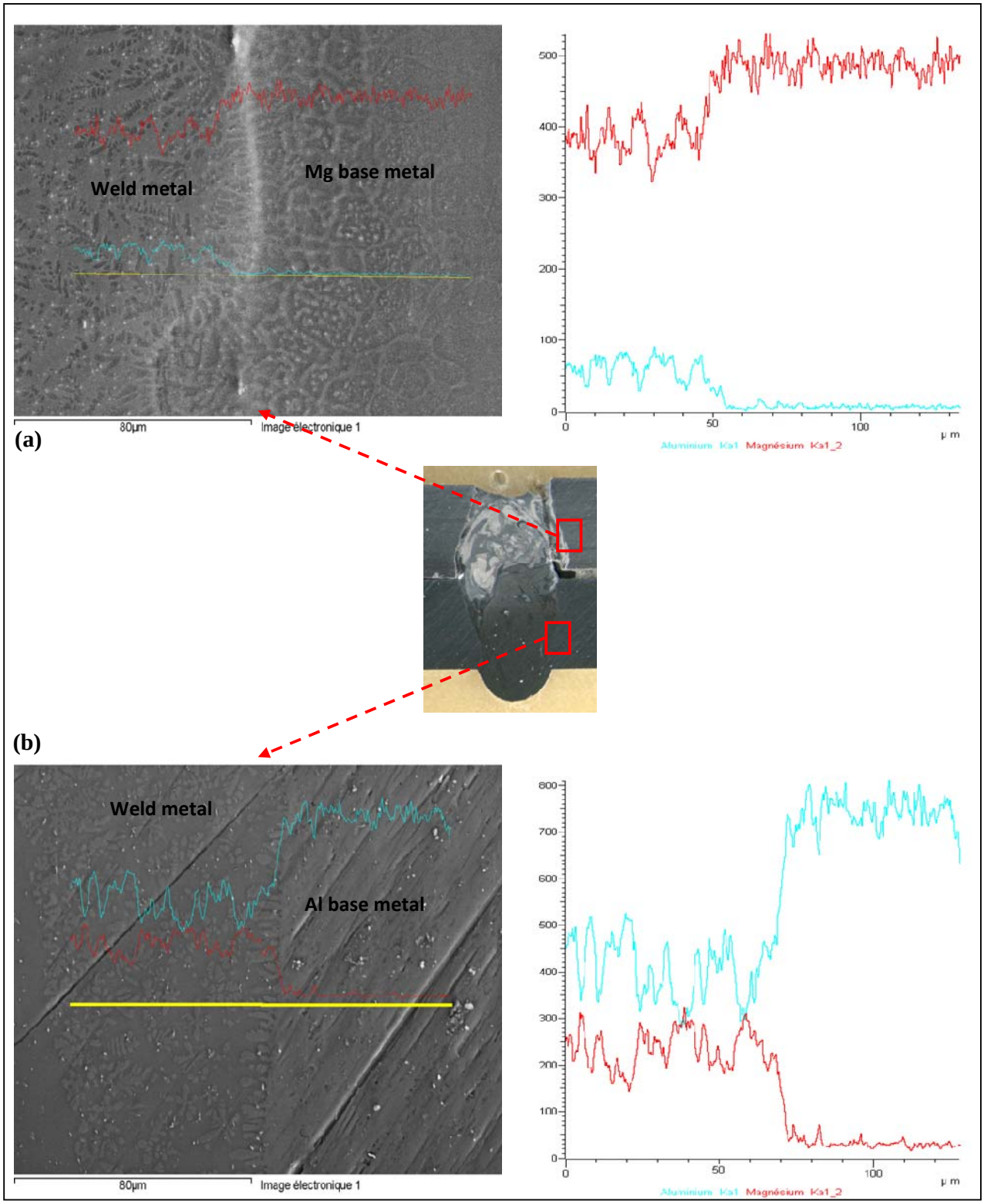


Fig.3. The SEM image and the distribution of Mg, Al, in the joint, with magnesium placed upon aluminum.

Quantitative analyses of the Mg and Al elements were done in different areas (A, B, C and D) of the joint, Fig. 2(a) and (b). For convenience of discussion, the binary Al-Mg phase diagram [12] is shown in Fig.5. The analysis results of the chemical composition of various representative areas of the welds are given in Table 3.

Materials	Chemical Composition (Wt. %)				
	Mg	Al	Zn	Fe	Si
Area A1	20.12	79.88			
Area A2	32.71	66.94		0.35	
Area B1	63.59	36.13	0.28		
Area B2	66.66	32.92	0.42		
Area C1	66.21	30.73	0.64		2.41
Area C2	82.69	16.29			1.02
Area D1	36.62	63.38			
Area D2	20.88	79.12			

Table 3. Chemical composition in the different areas representative of the welds.

Areas A and B relate to the configuration in which the Al alloy A5754 is above the Mg alloy AZ31. From the EDS analysis, Fig.6, in the A area which is at the top of the fusion zone, parts A1 and A2 have an aluminum concentration well above the concentration of magnesium. These results suggest that the area A consists of intermetallic compounds Al_3Mg_2 and of a α-Al solid solution, in proportions that vary depending on the location of the measurement and thus from the cooling of the melted zone. In the B area, which is at the bottom of the fusion zone, analysis of part B1 indicating that this location may contains $Al_{12}Mg_{17}$ intermetallic compound, while part B2 is composed of a mixture of intermetallic compounds $Al_{12}Mg_{17}$ and of a α-Mg solid solution. It may be noted that the area A contains iron, an element present in the aluminum alloy in similar proportions.

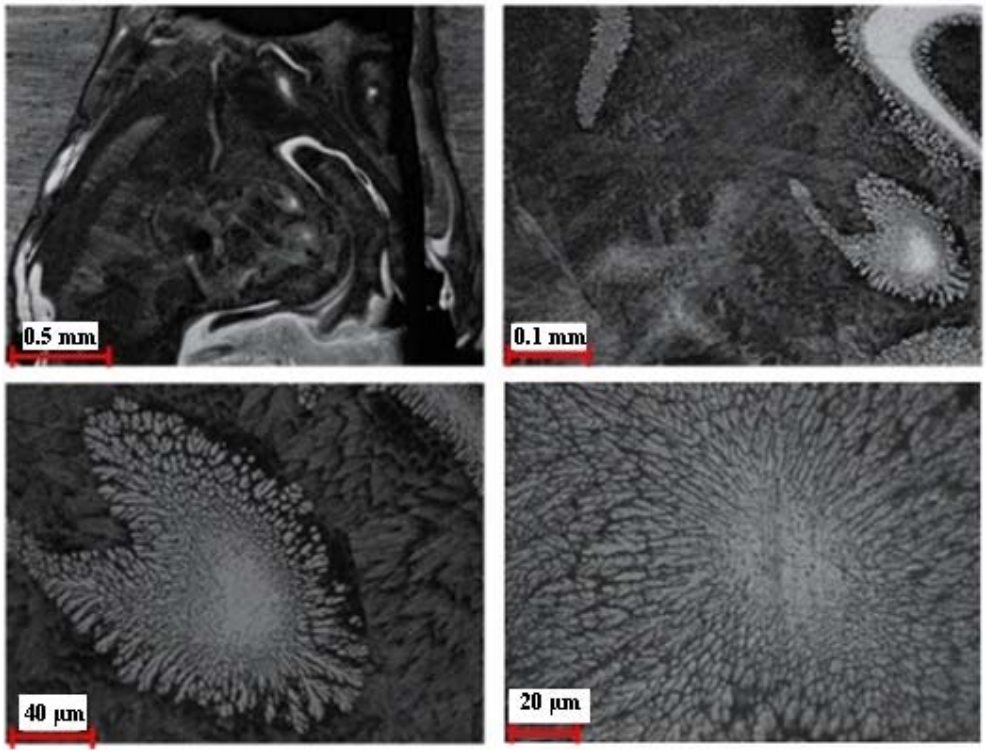


Fig.4. Microstructure of fusion zone in dissimilar weld when Mg was on the top.

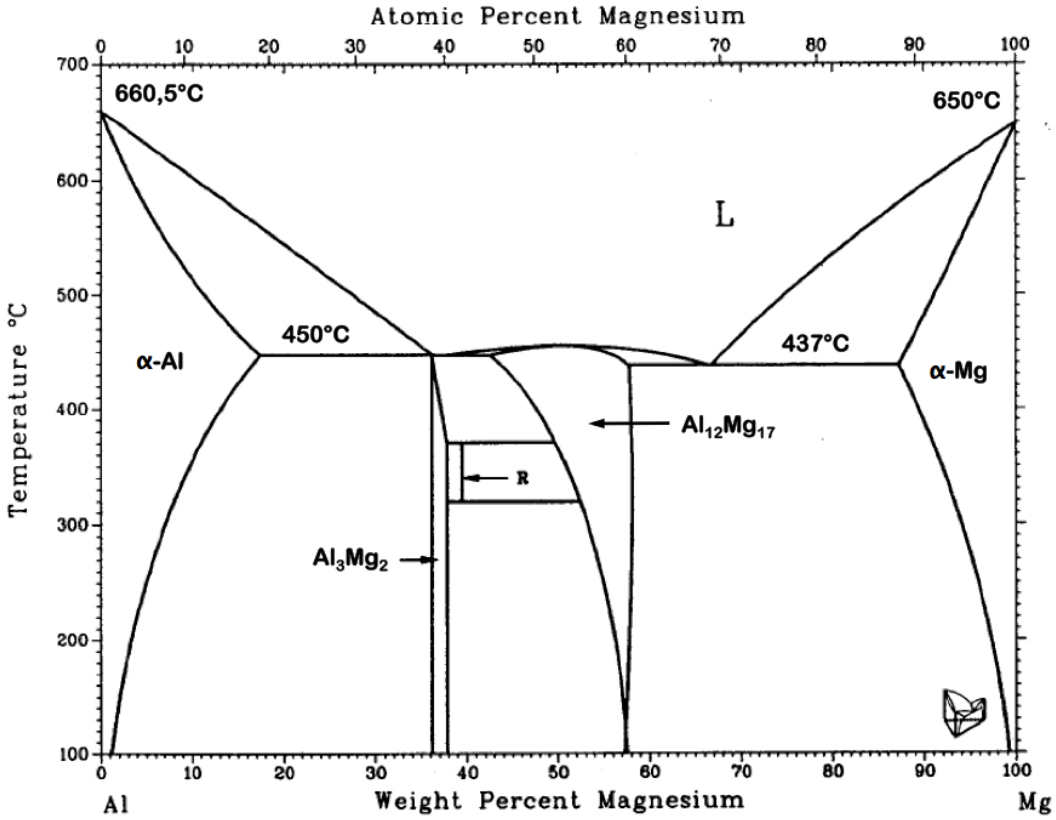
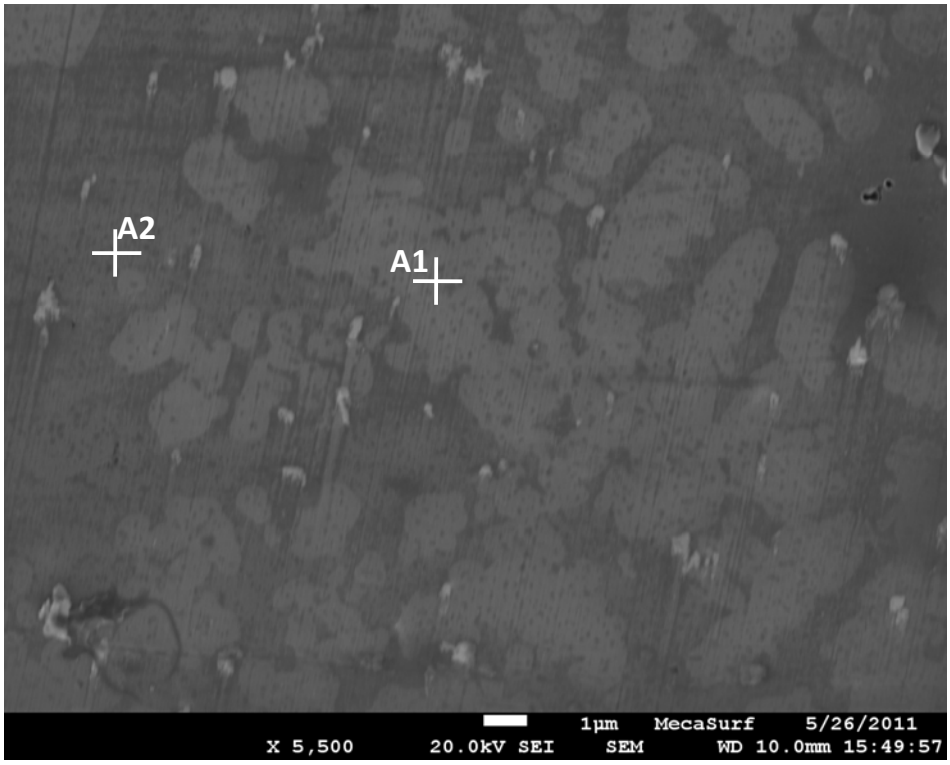
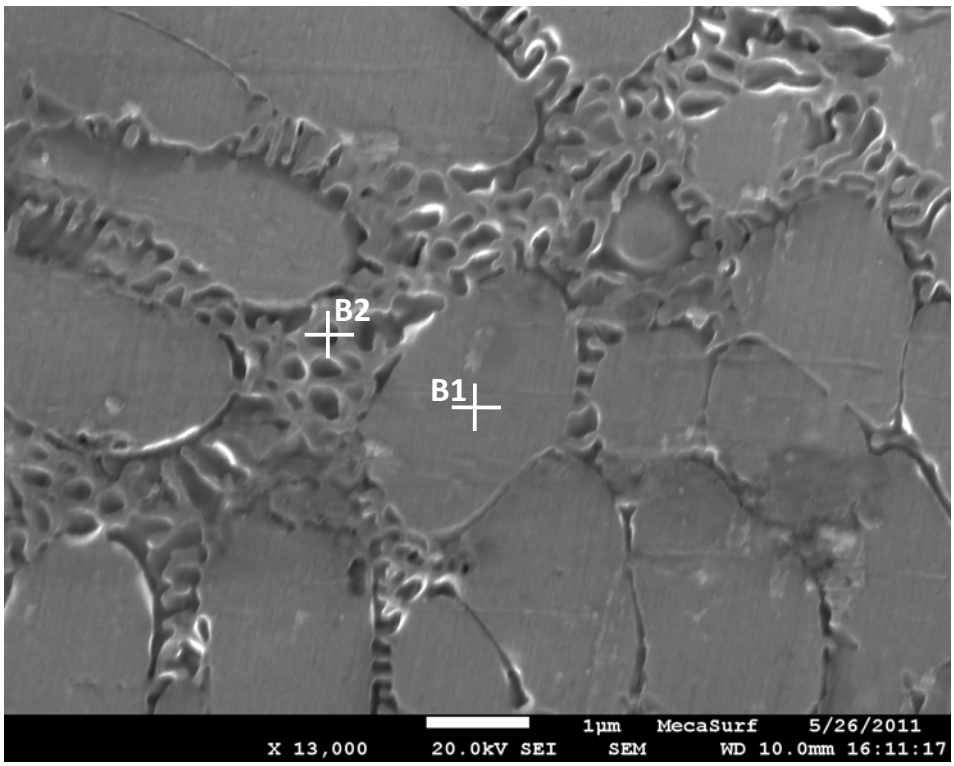


Fig.5. Al-Mg phase diagram [12].



(a)



(b)

Fig.6. Chemical analyses of Al and Mg distribution in (a) region A and (b) region B, figure 2(a).

Figures 7 and 8 show the element spatial distribution at the top and the bottom of the fusion zone, respectively, in the configuration in which the Mg alloy AZ31 is above the Al-alloy A5754.

From EDS analysis of C area, measurements results suggest that the grey phase (part C1) and black phase (part C2) could be composed of the mixture of the intermetallic compound $Al_{12}Mg_{17}$ and the α-Mg solid solution. Also, a large number of precipitated particles containing Mn (white dots) are observed in the fusion zone.

The microstructure of the area D is shown in Fig.8. The structure showed some precipitates containing Fe. From the EDS analysis, it is noted that the composition of the interdendritic part D1 corresponds to the intermetallic compound Al_3Mg_2. The element analysis of part D2 is consistent with a mixture of the intermetallic compound Al_3Mg_2 and the α-Al solid solution.

We can conclude from qualitative and quantitative EDS micro-analyses that during the lap welding process of aluminum-base alloy A5754 and magnesium-base alloy AZ31, the α-Al solid solution and Al_3Mg_2 phase were the first intermetallic compounds formed adjacent to Al side. However, the α-Mg solid solution and $Al_{12}Mg_{17}$ phase were the first intermetallic compounds formed adjacent to Mg.

Particular attention is also given to the mechanical properties of dissimilar welds by monitoring the hardness in the different zones (Fusion zone and base metals). The microhardness distribution of the fusion zone has an effect on the performance of the weld.

Fig.9 shows the hardness profile of the dissimilar weld AZ31/A5754. As can be seen, the hardness of the fusion zone is significantly higher than that of Mg substrate (65 HV) and Al substrate (64 HV). The microstructure of the fusion zone of dissimilar weld AZ31/A5754 depends on the chemical composition of both AZ31 and A5754 base metals. So, the structure transformation may be reflected by the microhardness distribution.

According to previous observation, Fig.6 and Fig.7, the fusion zone was characterized by complex vortex flow so this enhances the intermetallic compounds formations, which were composed of the brittle phases, Al_3Mg_2 and $Al_{12}Mg_{17}$, as confirmed by much higher hardness in the fusion zone relative to the base metals, Fig.9 (a) and (b). It was shown that the phases Al_3Mg_2 and $Al_{12}Mg_{17}$ can reach hardness levels greater than 220 Vickers [13]. These important hard phases, combined with a refinement of the grain, can explain the values reached in the melted zones.

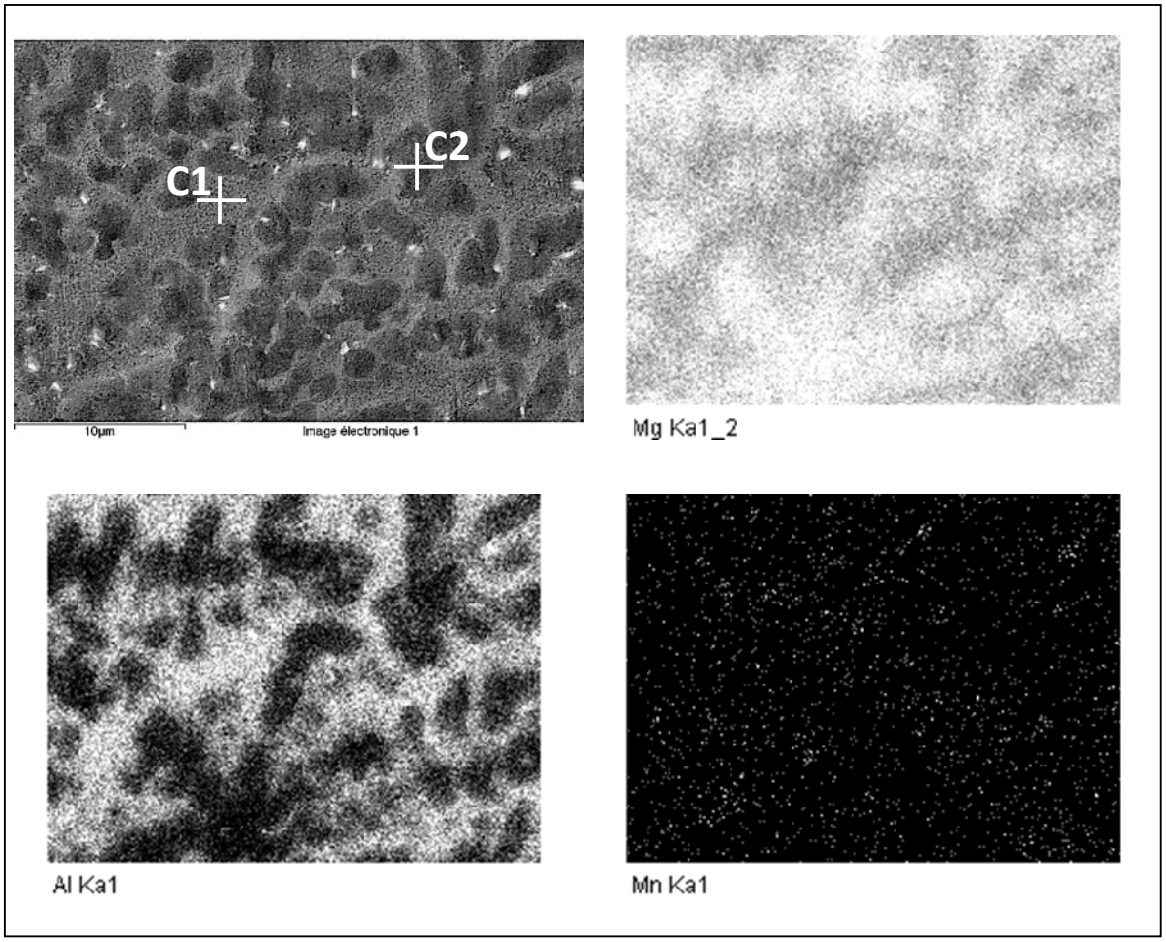


Fig.7. Quantitative EDS maps of Al, Mg and Mn distribution in region C, figure 2(b).

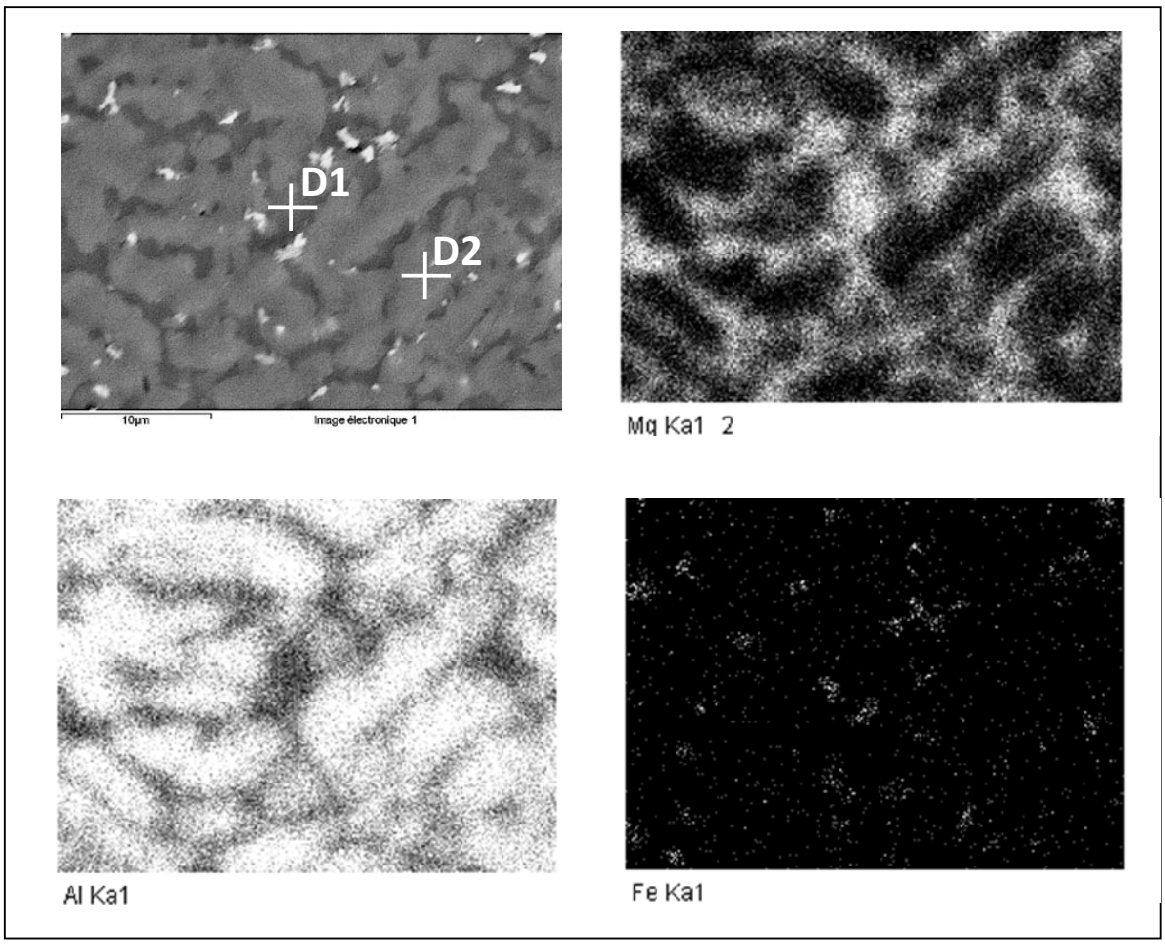


Fig.8. Quantitative EDS maps of Al, Mg and Fe distribution in region D, figure 2(b).

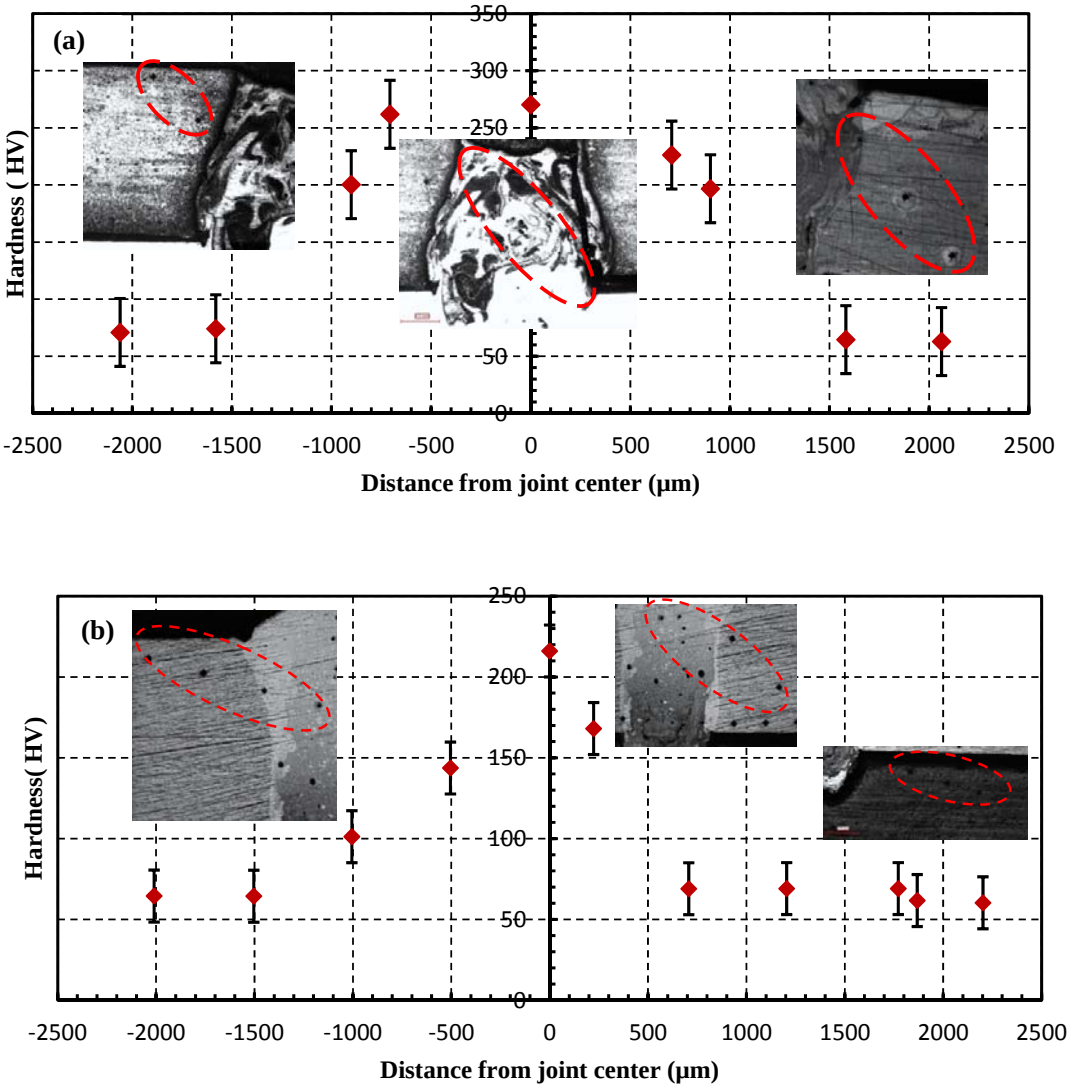


Fig.9. Microhardness profiles of microstructure from (a) Mg to Al and (b) Al to Mg.

4. Conclusion

This study could be a helpful document to understand the microstructure and the performance of a Mg/Al laser beam weld, when the aluminum is placed above the magnesium and also when the magnesium is placed above the aluminum.

1- The microstructure in the fusion zone of dissimilar welds between Mg/Al was observed and analyzed. The welded metal was mainly composed of dendrite crystals.

2- A variety of Al-Mg intermetallic compounds, $Al_{12}Mg_{17}$ and Al_3Mg_2, was generated in the irregular shaped region in the welded zone.

3- The microhardness measurements in the fusion zone were higher than that in the base metals. The test results indicate that the Mg-Al intermetallic with high hardness could be formed near the fusion zone, and this caused much higher hardness in the weld metal.

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