Microstructure and properties of welds between 5754 Al alloys and AZ31 Mg alloys using a Yb:YAG laser

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ABSTRACT

Dissimilar laser beam welding between A5754 Al alloy and AZ31 Mg alloy with the plate thickness of 2 mm was investigated. Complex flow pattern characterized by a large volume of intermetallic compounds $Al_{12}Mg_{17}$ and Al_3Mg_2 is formed in the fusion zone. Microhardness measurement of the dissimilar welds presents an uneven distribution due to the complicated microstructure of the weld, and the maximum value of microhardness in the fusion zone is much higher than of the base materials.

Keywords: Magnesium alloys; Aluminum alloys; Laser welding; Microstructure characterization; Dissimilar materials.

1. INTRODUCTION

The growing demands for better fuel economy, reduction of exhaust gas emission and higher operating efficiency in transportation applications is prompting extensive research into lightweight structural materials [1]. Thus, the demand of dissimilar metals joint has increased.
Aluminum alloys are widely used in automotive, aerospace and ship industries due to the combination of mass reduction and high strength [2]. Magnesium alloys are also attractive in these fields due to their lower density and high specific strength with good damping capacity [3].
Therefore, it can be expected that the joining of aluminum and magnesium alloys EDX to be solved in industrial application. Until today the joining of dissimilar metals was realized by mechanical ways of assembling: screwing or roll bonding.
During the last years laser welding has become an important industrial process because of high degree of automation and high production rate, and so it is very advantageous in several applications. Laser welding is characterized by narrow weld width and high penetration. These advantages come from its high power density, which make the laser welding one of the keyhole welding processes [4-5]. Thus, the use of such technique to join magnesium alloys to aluminum alloy is a challenge due to significant differences in both physical and metallurgical properties [6]: for example, the large differences between thermal properties such as expansion coefficient and conductivity.
In the present study, the Yb:YAG laser beam was used to weld AZ31 magnesium alloy to A5754 aluminum alloy. Then the microstructure and microhardness distribution were observed and analyzed.

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2. EXPERIMENTAL DETAILS

2.1 Materials

AZ31 magnesium alloy and A5754 aluminum alloy were selected as the base metal for welding experiences. AZ31 magnesium alloy was chosen due to its good rolling capabilities. Two millimeters thick plates were hot rolled by several passes and then leveled and 300°C annealed. The A5754 aluminum alloy belongs to the 5xxx series. This group includes magnesium as the major alloying element (up to 5.6%). The nominal alloying elemental composition of AZ31 and A5754 alloys are shown in Table 1. The sheet was cut and machined into rectangular welding samples, 160 mm long by 110 mm wide (Fig 1).

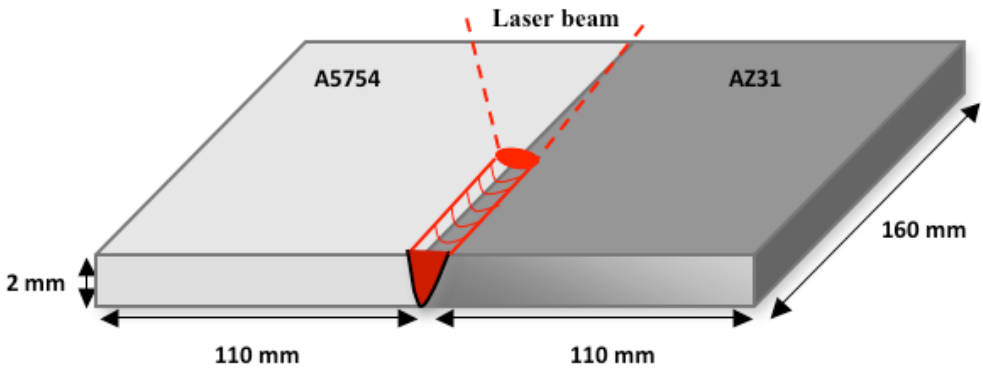

Fig 1. Laser welding of AZ31 Mg alloy with A5754 Al alloy

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. Material chemical compositions

2.2 Processing parameters and characterizations

For the investigations, the experiments were carried out with a 6 kW diode-pumped disk laser TRUMPF 6002. The source is a Yb:YAG continuous laser with 1030 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.

The welding experiments have been performed in the range of incident laser power from 2.5 kW to 5 kW and with a welding speed from 5 to 9 m/min corresponding to a linear energy from 17 KJ/m to 38 KJ/m.

Magnesium alloys and aluminum alloys being highly susceptible to oxidation, we used a shielding gas flow (Argon, 20 l/min) to protect the molten pool of the top and the back weld. The samples were mechanically clamped on the moving table.

After welding, the laser-welded joints were ground with abrasive paper, mechanically polished with a final polishing step, comprising use of a 1µm 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 Spectroscopy system (EDX, Oxford Instruments). The hardness measurements were performed on a Leica VMHT digit hardness tester with a load of 1.96 N and indenting time of 15 s.

3. RESULTS and DISCUSSION

3.1 Microstructure of dissimilar fusion zone

Fig 2 (a) and (b) shows the cross-sections of joint at different conditions. From Fig 2 (a) and (b), we can see that no obvious welding defect was found in the joint, indicating that sound weld of A5754 Al alloys and AZ31 Mg alloys can be obtained by laser welding.

Microstructures of the fusion zone of Mg–Al joint are shown in Fig 3 (a) and (b). The mixing of the two metals could be clearly seen. The laser beam affects the weld metal zone directly, which will be melted completely. So, the temperature of the fusion zone is above the liquidus temperature. As a result of the rapid solidification of the laser-melted zone, finer grains were formed in the surface and columnar crystals were produced along the heat-flow direction near to the base metal. Thus, we can see that an intermixed structure existed in the top and in the bottom of the joint. Also, from Fig 3 (a) and (b), we observed some big particles distributed unevenly in the fusion zone, which may be ascribed to the stirring effect resulted from strong convection in the welding pool under the action of high power laser. Moreover, the difference in physical and chemical properties of these dissimilar metals might produce different mixing regions, which made it possible that the metals could be joined.

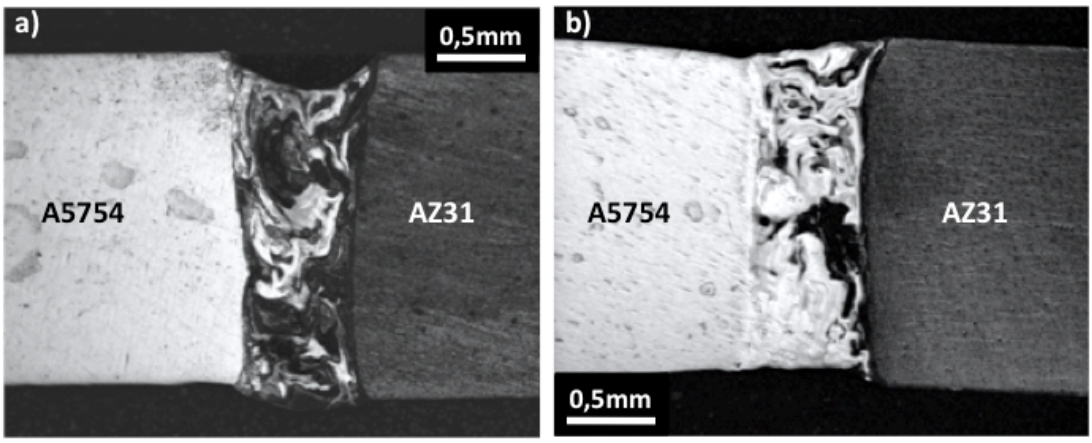

Fig 2. Optical macrograph of cross-section of dissimilar welds: (a) P=2.5kW, V=5m.min^{-1}, (b) P=5kW, V=8m.min^{-1}

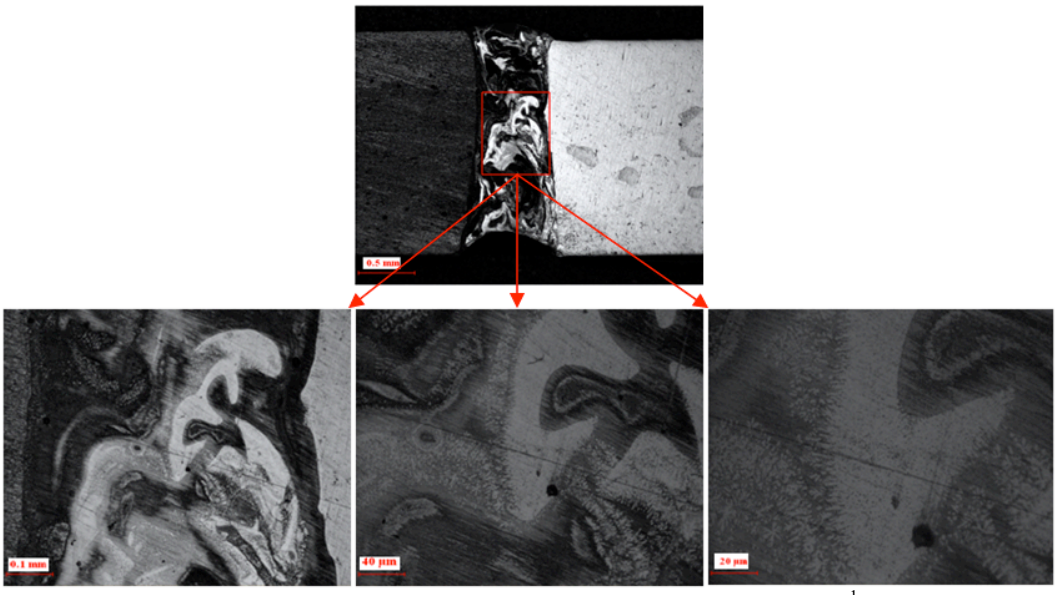

Fig 3 a) Optical microstructures of fusion zone, P=2.5kW, V=5m.min^{-1} (30kJ/m)

3.2. Elemental distribution of the joints

For convenience of discussion, we refer during our analysis on the binary Al-Mg phase diagram cited in reference [7]. Al has the main influence on the formation of particles. The maximum solubility of Al in Mg ranges from 2.1 wt% at 25°C to 12.6 wt% at the eutectic temperature of 437°C. There are two eutectics. The first one is between the Al-rich phase (Al) and Al_3Mg_2, and the second between the Mg-rich phase (Mg) and $Al_{12}Mg_{17}$. Both eutectic temperatures, 450°C for the former and 437°C for the latter, are far below the melting points of Al (660°C) and Mg (650°C). The eutectic temperatures 437°C and 450°C are more than 200°C below the melting point either during Al-to-Mg laser welding to form liquid films along the interface between Al and Mg. Upon cooling, the two eutectic reactions are reversed, and Al_3Mg_2 and $Al_{12}Mg_{17}$ are formed.

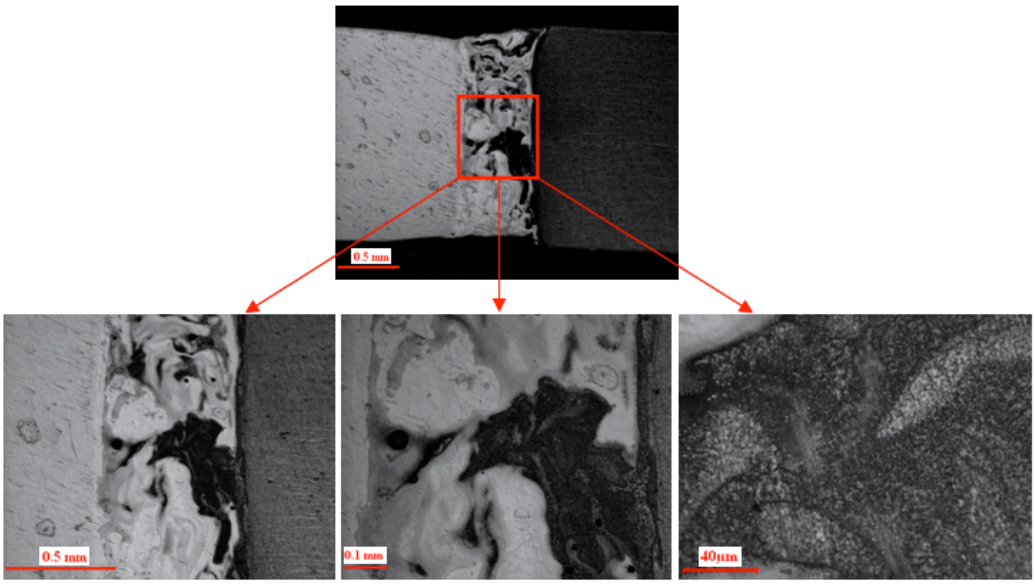

Fig 3 b) Optical microstructures of fusion zone, P=5kW, V=8m.min^{-1} (37.5kJ/m)

Fig 4 shows lines scan of element magnesium and aluminum in the top of weld (L1), middle of weld (L2) and bottom of weld (L3). Mg contents on the top and on the middle of weld was higher than that at the bottom; while the Al contents on the bottom was higher than that on the top and middle of weld. This can be explained by the difference between the physical properties of magnesium and aluminum. Indeed, the melting temperature of magnesium is a little bit lower than that of aluminum. At the beginning of the process, the reflectivity of Al (more than 90%) is higher than that of Mg (70%). The thermal conductivity is lower for Mg than Al. Thus, on the top of weld, the magnesium will be heated more rapidly and melted more than aluminum. Moreover, the stirring effect resulted from strong convection and hydrodynamic flows in the welding pool under the action of high power laser can lead to an inhomogeneous repartition of magnesium and aluminum alloys in the weld pool and to heterogeneous structures favored also by positive Marangoni effect.

On average, we can found that, on the top of the weld, there is 60-80 % of magnesium, in the center 70-90 %, finally and at the bottom only 20-25 %.

Fig 5 shows Al and Mg distributions in the irregular shaped region analyzed by EDX. In each EDX map, points with the higher concentration are shaped with a lighter shade of gray. A SEM micrograph of the fusion zone (discontinuous black rectangle in Fig 5) is shown in Fig 6.

Quantitative chemical compositions analysis results from position A1 to A4 by EDX are shown in Table 2. ***Point A1*** composition indicates that this location may contain a mixture phase composed of intermetallic compound ($Al_{12}Mg_{17}$) and solid solution (α-Mg). Combining with the phase diagram of the binary Al-Mg systems, the ***A2 zone*** was estimated to consist of intermetallic compound (Al_3Mg_2) and solid solution (Al). ***Point A3*** is a mixture of magnesium and aluminum, which should be the Mg-Al intermetallic phase ε [7]. ***Point A4*** composition indicates that this region may contain Al_3Mg_2 intermetallic compound.

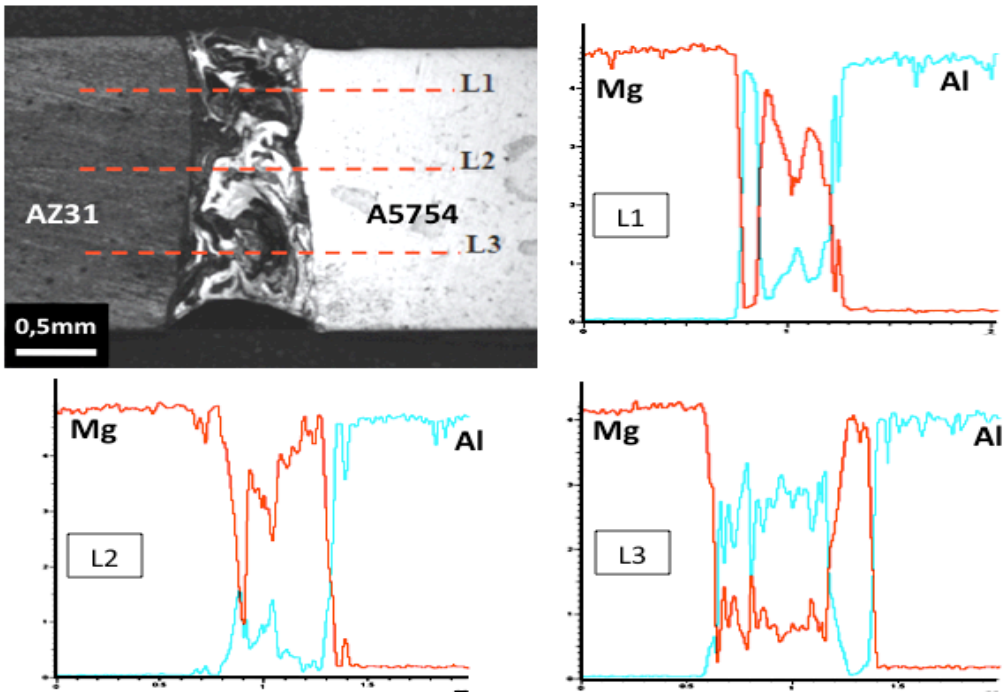

Fig 4. SEM image and EDX lines scan of magnesium and aluminum in the joint (2.5kW; 5m.min^{-1})

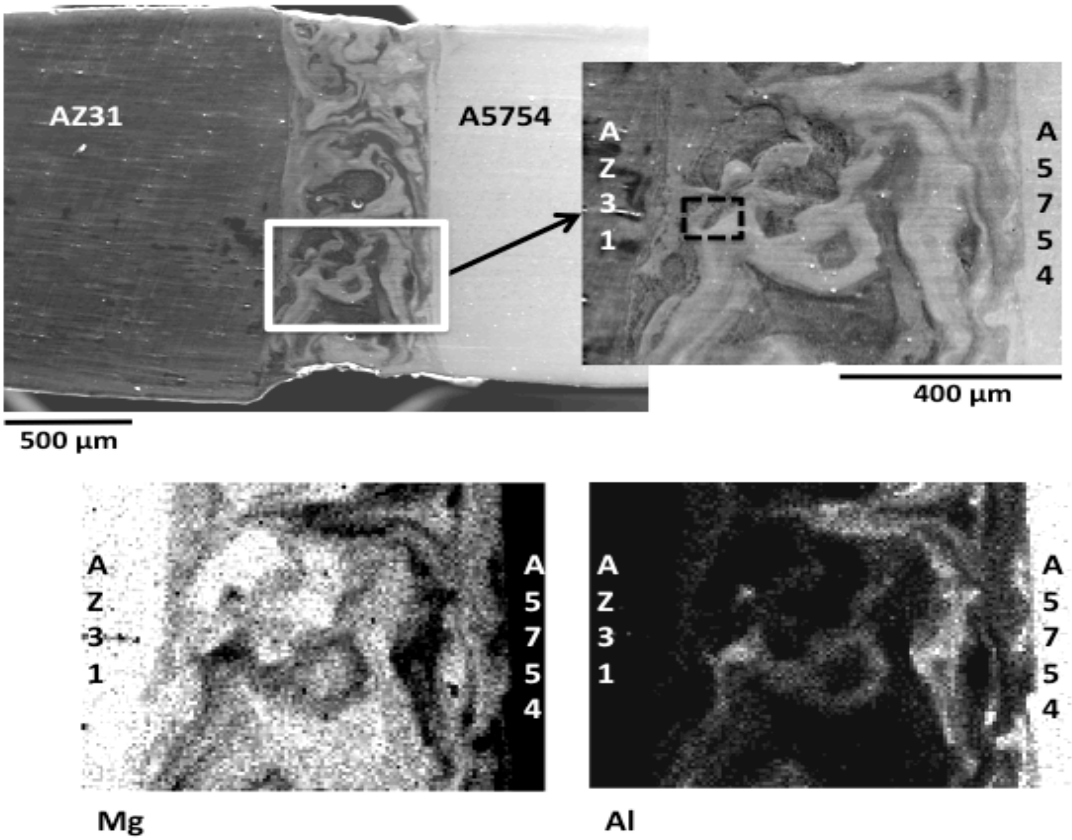

Fig 5. Qualitative EDX distribution of magnesium and aluminum in fusion zone

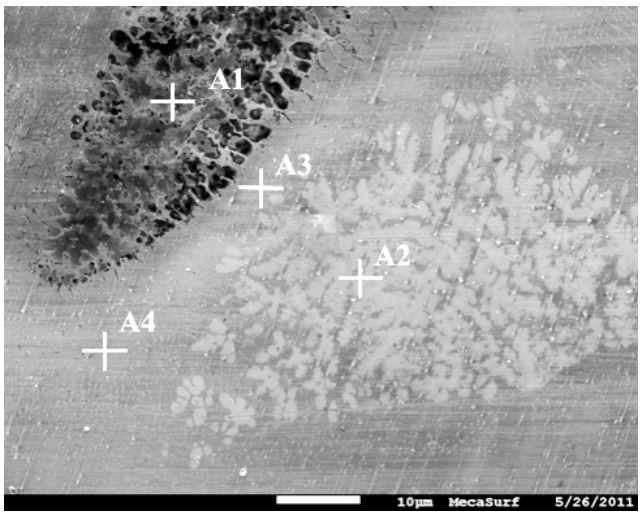

Fig 6. EDX points analysis of Al and Mg distribution in region A

Element (wt.%)	***Position***			
	A1	***A2***	***A3***	***A4***
Mg	82.28 +/-0.16	21.29 +/-0.18	48.97 +/- 0.24	38.36+/- 0.13
Al	16.94 +/- 0.14	78.08 +/- 0.13	51.03 +/- 0.24	61.30+/- 0.13
Zn	0.54 +/- 0.08			
Mn		0.27 +/- 0.07		
Fe		0.36 +/- 0.08		0.34+/- 0.08
Si	0.25 +/- 0.05			

Table 2. Chemical compositions of points marked by A1 to A4 in Figure 6

3.3. Microhardness testing

The hardness profile across the contact region of AZ31 magnesium alloy and A5754 aluminum alloy, which was measured from magnesium to aluminum along the lines marked in Fig 4, is shown in Fig 7. We can see that micro-hardness measurements showed an uneven distribution, and the hardness on the fusion zone was much higher than of the base material. Base materials of aluminum alloy and magnesium alloy had average hardness values of 65 $HV_{0.2}$ while some fairly large micro-hardness values were noticeable in the weld zone, of which the largest was 260 $HV_{0.2}$.

The hardness measured along the three lines, L1, L2 and L3, present the same profiles due to that the intermixing between AZ31 magnesium alloy and A5754 aluminum alloy occurred in the total of the fusion zones. Microstructure study of the fusion zone revealed the presence of intermetallics compounds, such as $Al_{12}Mg_{17}$ and Al_3Mg_2 phases, responsible of the sharp variations of microhardness in the weld zone [8]. Fig 8 shows some micro cracks formation in the dissimilar weld. This can be explained by the characteristic of the Mg-Al intermetallic phases that appears in the fusion zone. At the interface, the hardness gradient is the sharpest, thus in can lead to formation of a few cracks.

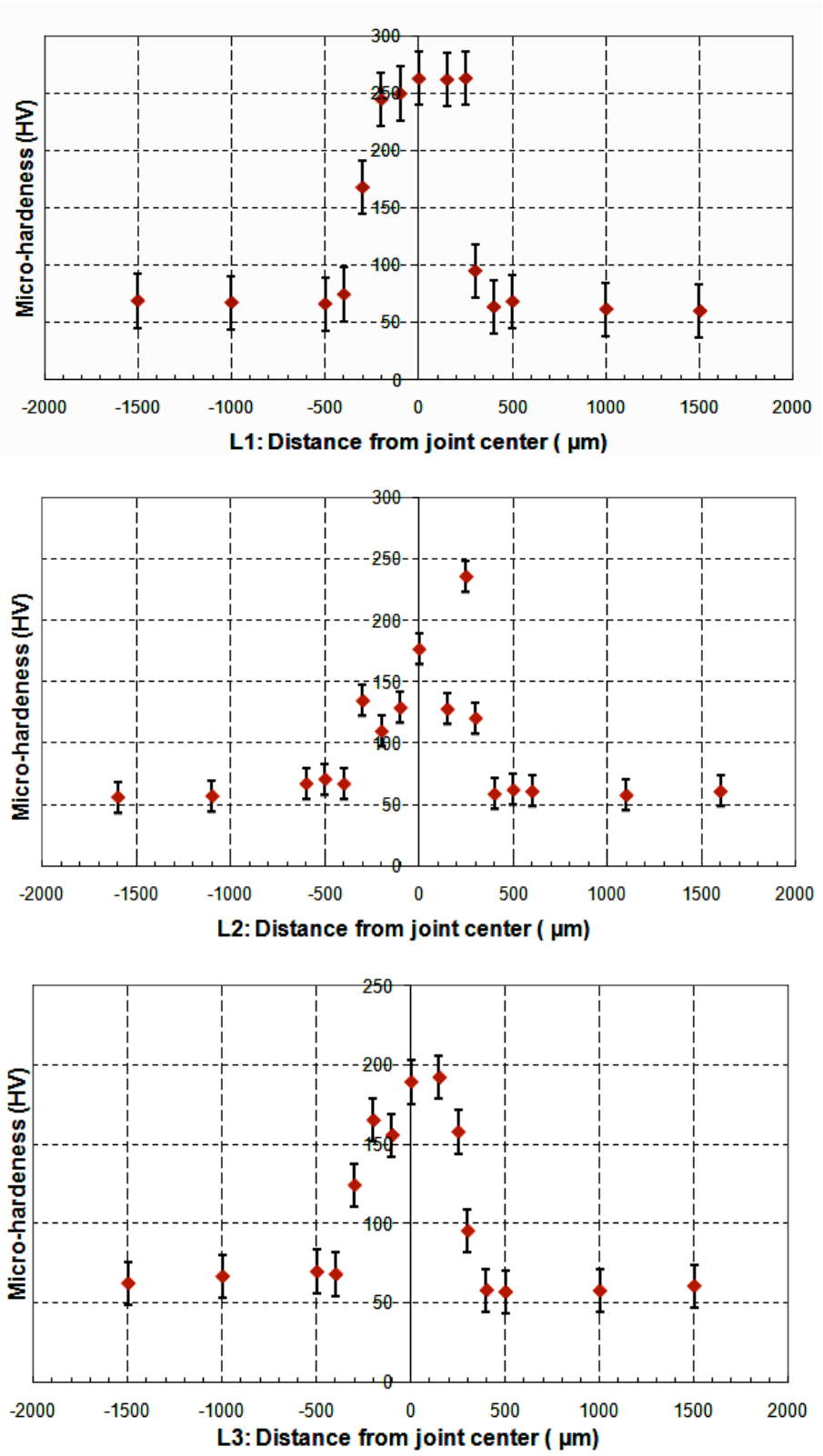

Fig 7. Microhardness profiles of the dissimilar weld with different locations

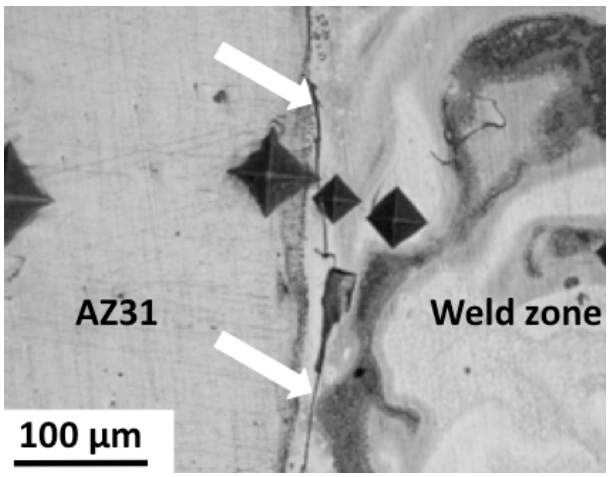

Fig 8. Micro-cracks at the interface between weld zone and AZ31 base material

4. CONCLUSION

In summary, A5754 aluminum and AZ31 magnesium alloys have been joined using a laser welding process. We conclude as follows:

- Dissimilar laser beam welding of A5754 aluminum and AZ31 magnesium alloys produced an irregular shaped region in the fusion zone.
- The areas of the welded joint are composed of a mixture of magnesium or aluminum solid solution and intermetallic compounds, mainly Al_3Mg_2 and $Al_{12}Mg_{17}$.
- Microhardness profiles presented uneven distributions and the maximum value of micro hardness in the fusion zone was too higher compared with that of the base materials. The intermetallic compounds are responsible for the hardness increase of in the molten zone.
- The hardness gradient is responsible for the creation of micro cracks at the interface between the molten zone and the base material.

To overcome the hardness gradient, it would be interesting to study the possibility of reducing the presence of compounds with a suitable heat treatment. In addition, it could reduce the residual stress field that must exist at the interface between the weld zone and the base material, as we have shown in previous work [9]. Another solution could be the use of a process that avoids the complete fusion of the two materials during assembly. Thus, the friction stir welding can be used to make welds with properties more uniform with respect to the base materials.

Acknowledgements

The authors wish to thank Mr. Henri ANDRZEJEWSKI for his technical assistance in laser experiments. The authors wish to place their sincere thanks to Professor Philippe BOURNOT and Dr. Eric VALERIO for helpful discussions.

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