WELDING OF DISSIMILAR MATERIALS WITH 1KW FIBER LASER

Paper 1908

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Abstract

The majority of applications in a range of industries i.e. automotive, electronics and medical, require welding of dissimilar materials. In principle, a laser can weld any material, which can then be joined by conventional processes.

When welding dissimilar metals, good solid solubility is essential for sound weld properties. The trends of welding dissimilar metals present considerable challenges. The weldability of dissimilar metals depends on many factors. The physical properties have a high influence on the amount of energy coupled in and the heat transfer.

When joining dissimilar materials, there may be certain advantages in using laser welding even though brittle intermetallics can form. Since the weld itself is narrow, the volume of intermetallics may be reduced to acceptable limits. Again, it may be possible to offset the beam in one direction or another, thus allowing some control over composition of the resulting alloy.

Although it may be possible to produce sound joints using these methods on a laboratory scale, it is more difficult to achieve similar controls under production conditions. This paper presents welding results achieved with a 1kW fiber laser for a range of materials.

Introduction

Many applications in various industry sectors such as electronics, medical, consumer goods, automotive, require joining of dissimilar metals. The trends of joining dissimilar metals present considerable challenges.

In principle, a laser can weld any material, which can be joined by conventional processes. The weldability of dissimilar metals depends on many factors. The physical properties have a high influence on the amount of energy coupled in and the heat transfer.[1]

Illustrated in Table 1 is the weldability of metal pairs. When welding dissimilar metals, good solid solubility is essential for sound weld properties. This is only achieved with metals that have compatible melting temperature ranges. If the melting temperature of one material is near the vaporisation temperature of the other, poor welds are obtained and often form brittle intermetallics.

Table 1: Weldability of metal pairs:

	Al	Ag	Au	Cu	Pt	Ni	Fe	Ti	W
Al	-	C	X	C	X	X	X	X	X
Ag	C	-	S	C	S	C	D	C	D
Au	X	S	-	S	S	S	C	X	N
Cu	C	C	S	-	S	S	C	X	D
Pt	X	S	S	S	-	S	S	X	X
Ni	X	C	S	S	S	-	C	X	X
Fe	X	D	C	C	S	C	-	X	X
Ti	X	C	X	X	X	X	X	-	X
W	X	D	N	D	X	X	X	X	-

Al: aluminium; **Ag**: silver; **Au**: gold; **Cu**: copper; **Pt**: platinum; **Ni**: nickel; **Fe**: iron; **Ti**: titanium; **W**: tungsten

C: Complex structures may exist
X: Intermetallics compounds formed; undesirable combination
S: Solid solubility exists in all alloy combination
D: Insufficient data for proper evaluation
N: No data available

When joining dissimilar materials, there may be certain advantages to using laser welding, even though brittle intermetallics can form. Since the weld itself is narrow, the volume of intermetallics may be reduced to acceptable limits. Again, it may be possible to offset the beam in one direction or the other, thus allowing some control over composition of the resulting alloy.

While it may be possible to produce sound joints by these methods on a laboratory scale, it is more difficult to achieve similar controls under production conditions. Mixing molten metal in a laser weld seldom produces a chemically homogeneous fused zone between two dissimilar materials.

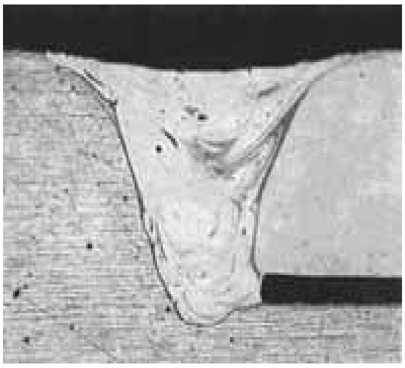
Although the average chemical composition of the weld may be acceptable, local heterogeneity can be responsible for the presence of brittle zones. It will also be apparent that minor variations in the beam position can significantly influence the relative proportions of the two main constituents in the weld zone.

To date, most joining of dissimilar metals has been carried out with pulsed lamp Nd:YAG lasers.[2-3] Lamp-pumped lasers are capable of producing long, multi-ms pulses with peak powers many times the rated average power of the laser, provided that the duty cycle is sufficiently low.

This ability stems from the flash-lamp itself, which is often more constrained by the maximum average thermal load than the peak power output. High peak power pulsed lamp pumped Nd:YAG lasers, coupled with pulse shaping, makes these lasers ideal for welding dissimilar materials.

The shaping of pulses is of great importance since the temperature has to be controlled where the two molten phases are mixed. Weld depths that are too deep can lead to defective joints. Insufficient weld depths can be avoided by adjusting the high starting power and the correct decreasing power to the joint geometry as well as the material properties of the pulse shape.

Figure 1 shows an example of a dissimilar material weld made with a lamp pumped Nd:YAG laser. This weld was made with a ramp down pulse (Figure 2).



Butt joint, 304 SS and Nitinol for medical applications

Butt joint: SS and bronze for spring inside a watch

Figure 1

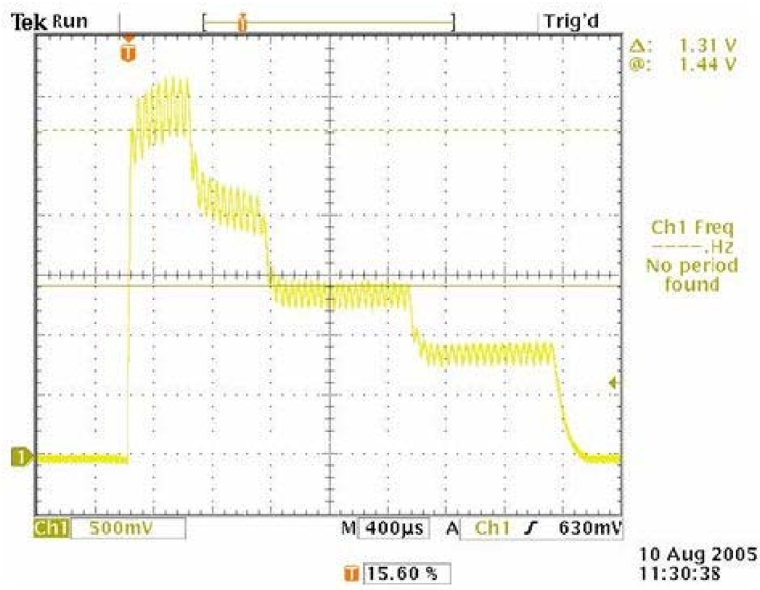


Figure 2: Example of a Ramp-down pulse shape which is very effective for welding reflective and dissimilar materials.

Compared to conventional lamp pumped Nd:YAG lasers, fiber lasers offer a number of advantages when welding dissimilar materials. The big advantage is the beam quality or focus-ability (understood to be the ability to achieve a small focus diameter with a given optical element). It is defined by the inverse beam product parameter (BPP):

Focus-ability = $1/BPP = 4/\Theta L \cdot dL$ (1)

The small focus diameter of fiber lasers offer a number of advantages during laser welding:

- High power density at the workpiece
- Reduced heat input
- Reduced heat-affected zone
- Reduced cycle time
- The volume of intermetallics may also be reduced to acceptable limits.

Fiber laser welding can be carried out using a single mode fiber laser with average power exceeding 2kW or a multi-mode fiber lasers with laser powers excess of 17kW. Multi-mode fiber lasers normally comprise several single mode fiber lasers, which are coupled into one fiber with reduced beam quality. However, the beam quality is still good enough to use small core diameter fibres, thus enabling very high power density at the workpiece.

From an applications perspective, both single and multi-mode fiber lasers have their advantages and disadvantages when welding dissimilar materials. This paper highlights welding results achieved for a range of dissimilar material combinations, using a 1kW multi-mode fiber laser.

Experimental work

A multi-mode 1kW fiber laser (1000FL) with a maximum average output power of 1000W was used in this study. Beam product parameters (BPP) of this laser are $\leq$ 4 mm·mrad. The beam from the laser was transmitted in 100μm diameter fiber which terminated in right-angled output housing fitted with recoll and focusing optics. The calculated spot size at the workpiece was 150μm.

Laser welding experiments were performed on different metal combinations:

- Titanium alloy – aluminium alloy
- Copper – 304 stainless steel
- Copper – aluminium alloy

The most important thermo-physical properties of the corresponding metals are shown in Table 2. Although these values refer to pure metals and some properties are temperature dependent, the data provided is a basic reference for assessing weldability and deriving the welding strategy.

Metals	Coefficient of thermal expansion X10^{-6} K^{-1}	Latent heat fusion Jg^{-1}	Specific heat JK^{-1} kg^{-1}	Thermal conductivity Wm^{-1} K^{-1}	Melting point °C	Boiling point °C	Density gcm^{-3}
Aluminium	23.5 @ 0-100C	388	900 @25C	237@ 0-100C	660	2467	2.7
Copper	17.0 @ 0-100C	205	388 @25C	401@ 0-100C	1083	2870	8.96
Iron	12.1 @ 0-100C	272	444 @25C	81@ 0-100C	1535	2750	2.87
Titanium	8.9 @ 0-100C	365	523 @25C	21.9@ 0-100C	1660	3287	4.5

Table 2: Thermophysical properties of some metals

Parameters and welding speeds were adjusted to produce welds with consistent topbead and underbead, minimal spatter and undercut. Gas shielding for the weld topbead was supplied via a 10mm diameter pipe (Figure 3). In all cases, argon (10l/min) was used for shielding.

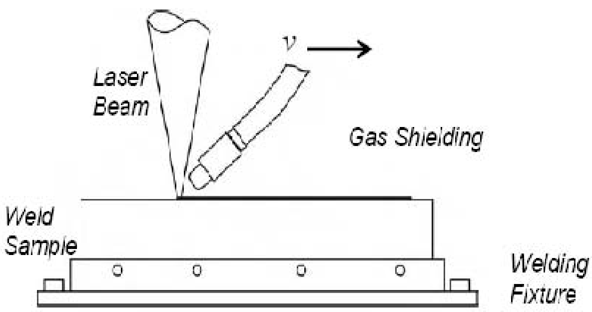


Figure 3: Gas shielding arrangement

Results and Discussion

Titanium/Aluminium Alloy

Recently, demand for dissimilar metal joints of titanium to aluminium alloy has risen in industry, especially in the transportation vehicle industry. However, it is well known that fusion welding of titanium to aluminium alloy is difficult because of the brittle intermetallic compound that is generated at the joint interface.

Figure 4 shows a photo-macrograph of the weld between Ti alloy and Al. The weld was very wide but the penetration into the lower aluminium sheet was very shallow.

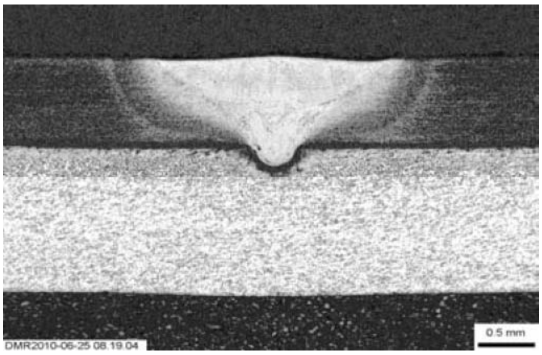


Figure 4: Photo-macrograph of the weld between Ti alloy and Al alloy. The specimen was etched with Kellers' reagent.

Figure 5 shows the bottom part of the weld where the two sheets were jointed. At the root of the weld there was a zone measuring approximately 150µm wide where aluminium had melted but not mixed with the remainder of the weld pool. The interface between the mixed molten metal and the melted Al was 'fluffy' with a lot of swirls where there was variable mixing of the melted sheets.

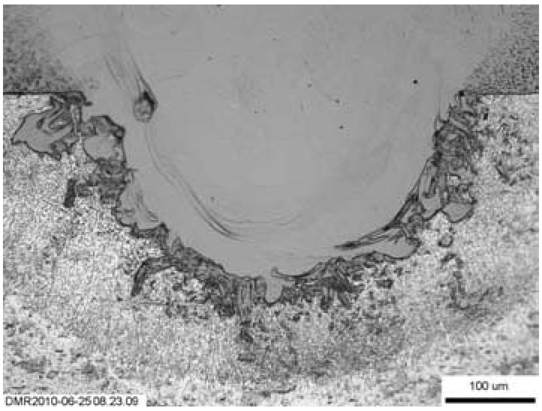


Figure 5: The root of the weld between Ti alloy and Al alloy. The specimen was etched with Kellers' reagent

Figure 6 shows an SEM micrograph with the location of EDX analyses. The Ti sheet was consistent with the Ti--6Al-4V alloy and the Al contained a little Fe, Mn and Mg, consistent with a 3000 (Al-Mn) series Al alloy.

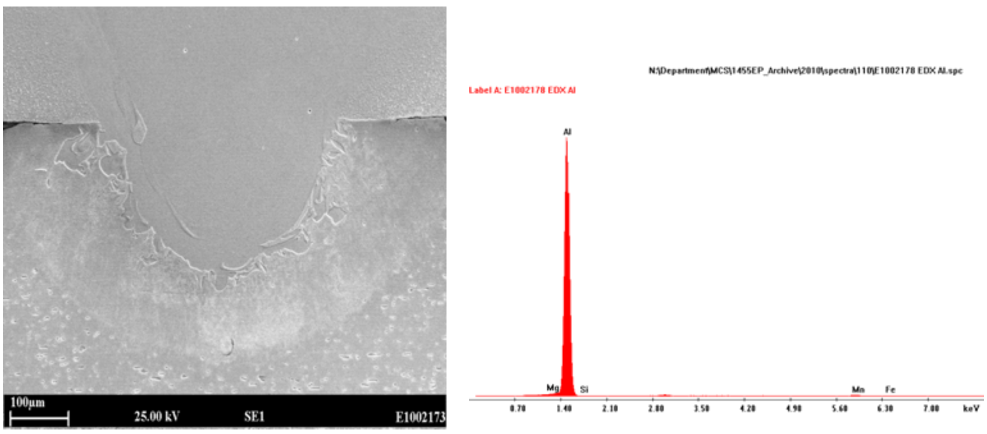


Figure 6: SEM micrograph of the root of the Ti-Al weld and EDX analysis spectra

A few, isolated, micro pores can be observed in Figures 4-6. The compositions in locations 1, 3 and 5 were similar, consisting mainly of the Ti alloy with only a small dilution with Al.

Stainless Steel/Copper

In the field of power generation and transmission, cryogenics, electrical and electronics, copper–steel combinations are often used due to their high electrical conductivity and stiffness. However, the high thermal conductivity of copper tends to rapidly dissipate heat away from the weld, leading to difficulties in reaching the melting temperature.

The major problem in welding copper to steel is hot cracking in the heat-affected zone of steel due to copper melting and penetrating into the grain boundaries of solid steel. Figure 7 shows the weld of stainless steel to copper. This was a fully penetrated weld. The bottom part of the weld had an inhomogeneous structure but the top part was relatively uniform.

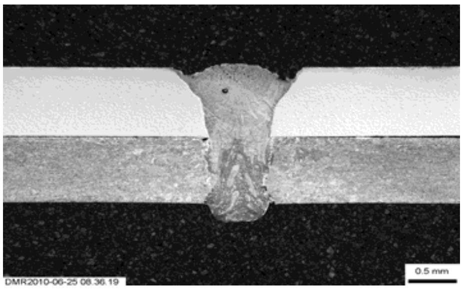


Figure 7: Photomacrograph of the weld between 304 stainless steel and Cu etched electrolytically in 20% H_2SO_4 + 0.1 g/l NH_4CNS and by immersion in ferric chloride

Figure 8 shows an SEM image of the weld and EDX analysis that was conducted for the sheets. It was confirmed that the copper sheet was pure Cu. The composition of the 304 stainless steel sheet was also confirmed.

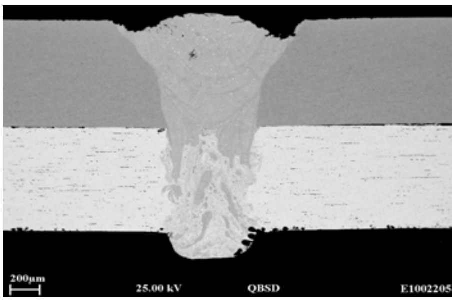


Figure 8.a SEM micrograph of the profile of the weld between stainless steel in the as-polished condition and Cu

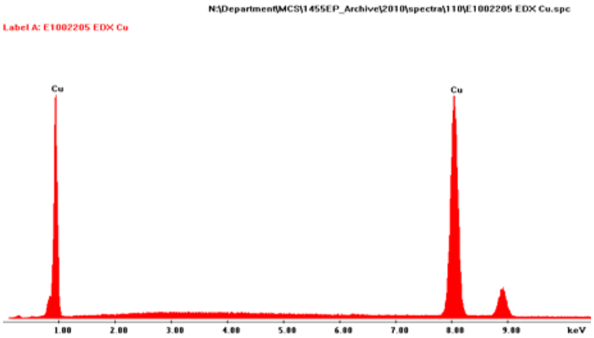


Figure 8.b EDX spectrum from the Cu sheet

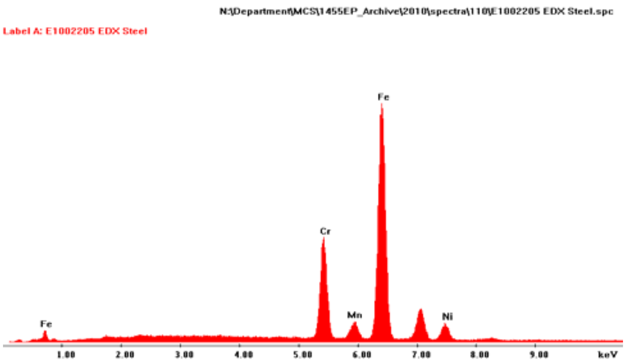


Figure 8.c EDX spectrum from the stainless steel sheet

At higher magnification, Figure 9 shows a small region of solidification cracking in the centre of the weld surrounded by many steel-rich spherical particles in a copper rich matrix.

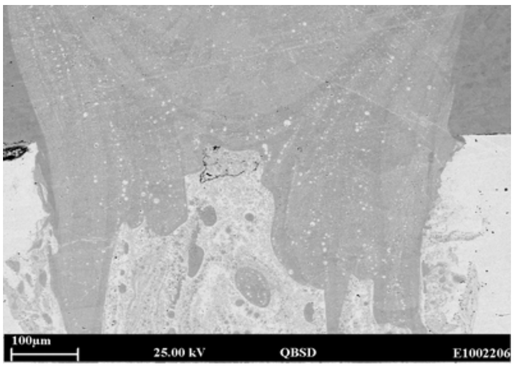


Figure 9.a: A low magnification SEM micrograph of solidification cracking in the centre of the weld between 304 stainless steel and Cu in the as-polished condition.

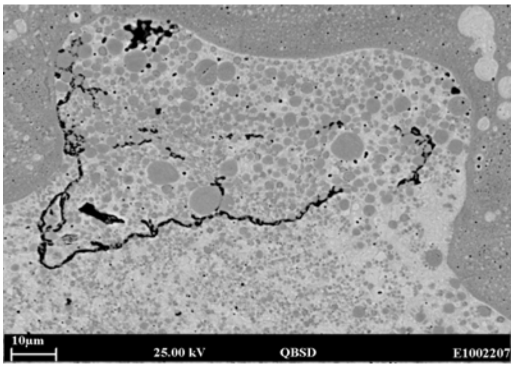


Figure 9.b: A high magnification SEM micrograph of solidification cracking in the centre of the weld between 304 stainless steel and Cu in the as-polished condition.

Aluminium/Copper

Joints between aluminum and copper are often required in electronic and automotive market sectors. The battery for hybrid cars is mainly constructed from a combination of aluminium alloys (3003 series, AL-Mn alloy) and pure copper. Joining these materials pose particular challenges. The battery has to operate safely and reliably for the whole of the life cycle stipulated by the manufacturer, and that's at least ten years.

Figures 10 and 11 show the weld between Al alloy and Cu and an SEM micrograph is shown in Figure 12. It can be seen that the penetration into Cu was low and there were many cracks in the lower part of the weld.

Figure 13 shows detail of the crack morphology and the locations for EDX analyses. The cracks were brittle in character and all stopped at the interface between the weld and the Cu parent metal. The analyses suggest (Figure 13b) a number of phases are present i.e. very close to $CuAl_2$.

Another similar analysis (figure 14) was carried out at the edge of the weld near the interface between the sheets, where a long interfacial crack extended into the lower part of the weld. This crack was also brittle in character, similar to the cracks in other locations of the weld. However, there were no cracks observed in the upper part of the weld, where dilution of the Al by Cu was low.

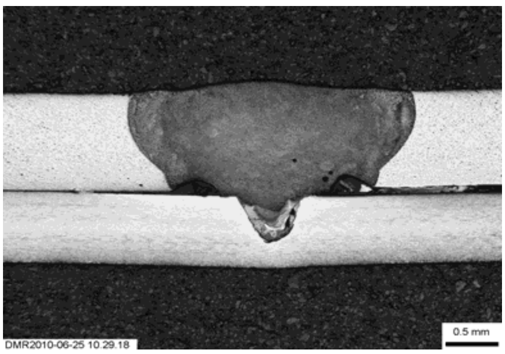


Figure 10: Photomacrograph of the weld between Al alloy and Cu, etched in Kellers' reagent + ferric chloride

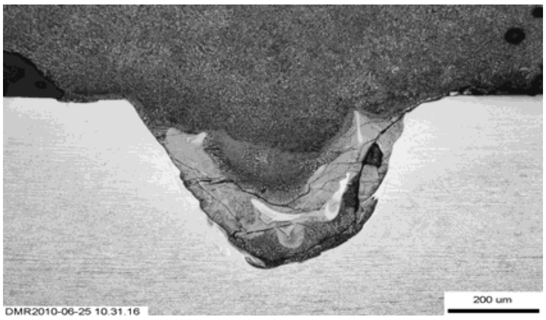


Figure 11: The root of the weld between Al alloy and Cu, etched in Kellers' reagent + ferric chloride

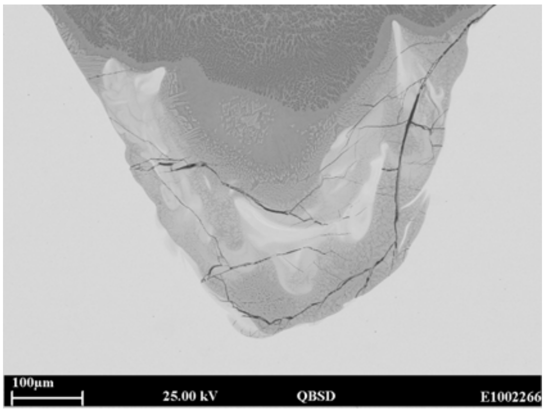


Figure 12: SEM micrograph of the root of the weld between Al alloy and Cu

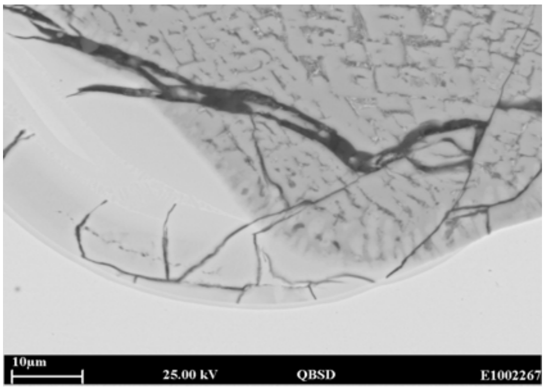


Figure 13a: SEM micrograph of the interface between the weld and Cu sheet in the weld between Al alloy and Cu

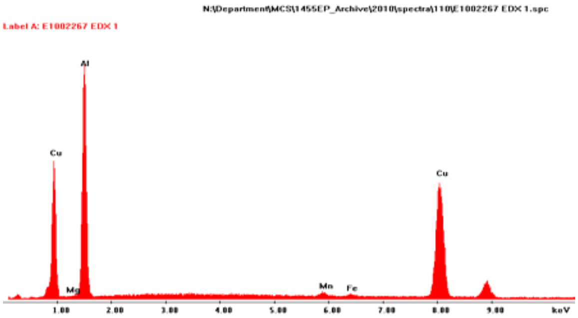


Figure 13b: EDX spectra near the bottom of the weld

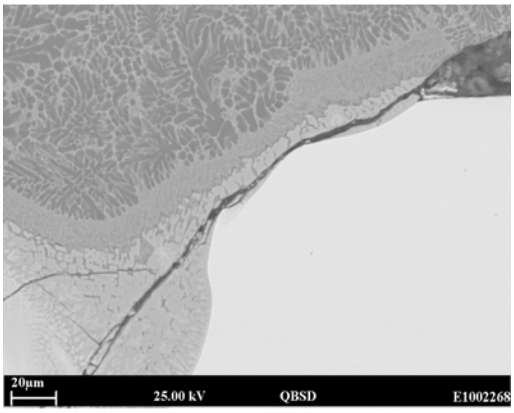


Figure 14a: SEM micrograph of the interface between the weld and Cu sheet in the weld between Al alloy and Cu.

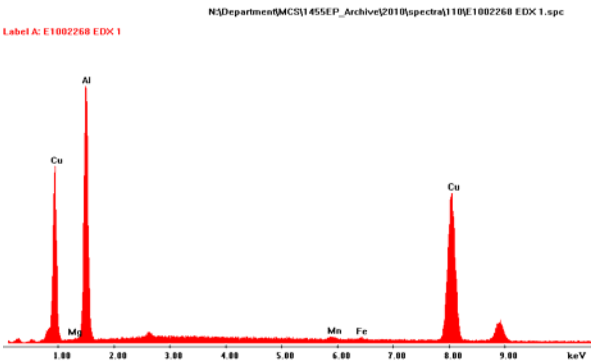


Figure 14b: EDX spectra near the bottom of the weld.

Summary

The presence of dissimilar materials highlighted differences in the behaviour of laser welding, compared to other fusion welding processes such as arc welding. Thus, mixing in the weld pools was relatively poor and there were usually two distinct regions in each weld cross section, corresponding to where the pool was surrounded by each sheet.

Where there were large differences in melting point between the sheets, e.g. Ti and Al, there was a region, within the lower melting point sheet, which had melted but not mixed with the main weld pool.

Few problems would were anticipated with joints between dissimilar copper alloys, and this generally proved to be the case. Although austenitic stainless steel and copper alloys were characterised by a mixture of copper and iron-rich phases, these welds were mostly sound.

However, the joints with the aluminium alloy sheets contained significant cracking. Both welds to copper and stainless steel-plated copper contained at least some regions where brittle intermetallic phases were present and cracks were observed in these regions. Even the titanium to aluminium weld - which was sound in the aluminium-rich region - contained a few small micro-cracks in the small root area where high dilution with titanium had created brittle intermetallic phases.

References

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