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Experimental Studies of Fiber Laser Welding of a Range of Dissimilar Material Combinations

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Abstract

The capacity to produce a product utilizing various diverse metals and alloys greatly increases flexibility in design and production. Various properties such as corrosion, wear and heat of the product can be optimized, and cost saving in production are often gained. Joining of dissimilar material combinations, however, presents challenges owing to the big differences in physical, mechanical and electrical properties which are present and this can lead to premature failure of the welded joint due to the formation of intermetallic brittle phases.
In principle, a laser can weld any material, which can be joined by conventional processes. In the welding of dissimilar metals, good solid solubility is essential for sound weld properties. A sound weld between dissimilar materials is one that is as strong as the weaker of the two metals being joined, i.e., having sufficient mechanical properties i.e. tensile strength and ductility so that the joint will not fail in the weld.
At Prima Power Laserdyne detailed experimental studies have been carried to weld a range of different material combinations used in aerospace, electronics and medical industries with continuous wave (CW) and Quasi Continuous Wave (QCW) fiber lasers. Investigations including metallurgical and mechanical examinations were carried out by means of varying laser and processing parameters, such as laser power i.e. continuous wave or pulsed, power density, welding speed, etc.

Keywords: Fiber lasers; dissimilar material welding; aluminium alloys;, pure copper; pure nickel; titanium alloy; nickel alloy; stainless steel and low carbon steel

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1. Introduction

In recent years applications that involve joining dissimilar materials have increased in a number of industries i.e. electronics, medical, consumer goods, automotive, aerospace, because the process reduces manufacturing costs and offers design flexibility. However, the trends of joining dissimilar metals of components are offering high challenges for welding methods because of because their differences in physical and chemical properties, such as the melting and boiling points, thermal conductivity, density and coefficient of expansion, Klages et al., 2003 and Sun et al., 1995. The difference in the physical and chemical properties of the different materials during laser welding can often lead to the formation of brittle intermetallics phases, which are detrimental to the mechanical strength and ductility of the welded joints.

When joining dissimilar materials, there may be certain advantages in using laser welding even though brittle intermetallics may tend to form. Since the weld itself is narrow, the volume of intermetallics may also be reduced to acceptable limits. Again, it may be possible to offset the laser beam in one direction or the other, (butt joint configuration) thus allowing some control over composition of the resulting alloy. Although it may be possible to produce sound joint by these methods on a laboratory scale, it is more difficult to achieve similar control under production conditions. Mixing the molten metal in a laser weld seldom produces a chemically homogeneous fused zone between the 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 data a number of researchers have carried out in depth study of laser welding of dissimilar materials with different laser sources i.e. fiber, lamp pumped Nd: YAG and disk lasers to investigate the formation of the intermetallics during mixing of molten materials. The work included laser welding of aluminium to steel, Fan et al., 2011 and Sonia et.al., 2014; laser welding of copper to steel and copper to aluminium , Mai et.al., 2004; aluminium to titanium, Theron et. al., 2007; titanium to stainless steel, Anawa et.al, 2008; titanium to Inconel 718, Hui-Chi-Chen et.al., 2011.

This paper highlights the welding data achieved for different material combinations used in aerospace, electronics, consumer goods, medical etc. with both CW and QCW fiber lasers respectively.

2. Experimental details

The welding tests were conducted on Laserdyne 430 system with IPG 2kW CW and 9kW QCW multimode fiber lasers with the beam quality of ≤ 4 mm・mrad. Figure 1 shows Laserdyne 430 system together with the clamping fixture used during the welding tests. The beam from the laser was transmitted in a 100µm diameter fiber, which terminated in Laserdyne welding head nozzle fitted with focusing optics and the calculated spot size at the workpiece was 143µm. Laser welding experiments were performed on various material combinations i.e. aluminium to copper, titanium to Inconel, copper to stainless steel, aluminium to titanium and aluminium to stainless. The most important thermophysical properties of the corresponding metals are shown in table 1. Although these values refer to pure metals and some properties are temperature dependent, the data provided a basic reference for assessing the weldability and deriving the welding strategy.

Parameters and welding speeds were adjusted to produce welds with consistent topbead and underbead with minimal spatter and undercut. Gas shielding for the weld topbead was supplied coaxially through the welding nozzle. This welding nozzle (patent pending) has a number of unique features which improves the weld quality during laser welding of difficult materials. The nozzle (figure 2) is integrated with high pressure air cross jet. The cross-jet provides a high velocity gas barrier that prevents molten metal spatter and fumes from the weld zone and from contaminating the protective lens cover slide. Critical to this design is that the cross-jet does not contaminate or otherwise interfere with the welding shield gas. The cross-jet nozzle can be used with the entire range of shield gas delivery devices including welding shoe and coaxial gas nozzle tip. The shielding gas shoe provides a controlled atmosphere for the weld zone while it is molten and while it is cooling at a temperature which won't be compromised by the ambient atmosphere. This is particularly important when trying to minimize porosity in the weld. An important benefit of the design of the focusing lens/shield gas assemblies for laser welding is that they can be changed quickly in order to vary the focused spot size.

Fig.1. Experimental set-up; (a) 430 6-axis machining centre; (b) clamping fixture which produces constant pressure along the length of weld

Fig.2. Laserdyne welding nozzle (patent pending)

Table 1: Thermophysical properties of materials tested

Properties	Pure Al	3003 Al alloy	5083 Al alloy	Pure copper	304SS	Ti-6Al-4V alloy	In 718 alloy
Hardness (Hv)	20	29	95	50	200	350	410
Melting point (°C)	650	655	570	1083	1400	1670	1340
Boiling point (°C)	2467	2500	2485	2870	2890	3325	2920
Density (g/cm)	2.71	2.73	2.65	8.96	8.03	4.40	8.90
Specific heat (J/kg °C)	900	910	900	388	400	610	435
Coefficient of expansion (10−6 °C−1)	22.9	23.2	23.1	17.5	12	8.2	13
Latent heat (kJ/kg)	388	385	386	205	272	290	274
Thermal conductivity (W/m°C) @ 20°C	24	25	23	40	8.1	5.8	11.4

After welding, the samples were sectioned across the weld and polished down to 1 μm surface finish and etched with the appropriate etching regent for optical and scanning electron microscopy examination. Some the samples were also used for mechanical testing.

3. **Results and discussion**

3.1. Titanium – aluminium

Recently, the demand for dissimilar metal joints of titanium to aluminium alloy has arisen in industry, especially in the transportation vehicle industry. However, it is well known that fusion welding of titanium to aluminium alloy is very difficult because the crystalline structure of titanium and aluminium is different as well as big difference in the physical properties of both materials i.e. melting point, thermal conductivity, thermal expansion of coefficient .The large variation in both physical and mechanical properties can lead to the formation of the brittle intermetallic compound at the weld joint interface. Figure 3 shows a photomacrograph of the weld made with 1.7kW CW fiber laser between Ti alloy (T-6Al-4V) and 3003 aluminium alloy. It can be seen from the weld profile that the weld was very wide but the penetration into the lower aluminium sheet is very shallow. Figure 4 shows the bottom part of the weld where the two sheets were joined. At the root of the weld there was a zone 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 shows an EDX spectrum from the root of the weld. The Ti sheet was consistent with the Ti--6Al-4V alloy and Al contained a little Fe, Mn and Mg, consistent with a 3000 (Al-Mn) series Al alloy.

The Ti-Al binary equilibrium phase diagram is shown in figure 6, Luis Augusto RochaI, et.al, 2003. It can be seen from the diagram that on Al- rich side, there is virtually no solid solution of titanium and they form various intermetallics compounds such as Ti_3 Al, Ti Al, Ti Al_2 and Ti Al3. These intermetallics compounds are formed the joint interface are very hard and brittle at room temperature and often can lead to very poor tensile strength of the welded joint. It is possible to produce to weld joint with adequate tensile strength, provided the thickness of the intermetallic compounds layer at weld interface is kept to very small level i.e. 10-20μm, Chen, et al, 2010. The welds made with QCW laser had slightly better tensile strength numbers compare to CW output, which may suggests that the thickness of intermetallics compounds at the weld interface with pulsed laser pulsed laser parameters is smaller compare to CW parameters.

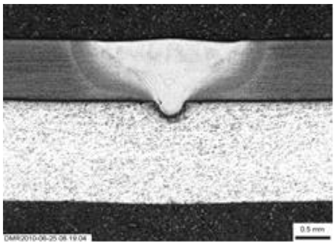


Fig.3. Photomacrograph of the weld between Ti alloy and Al alloy The specimen was etched with Kellers' reagent

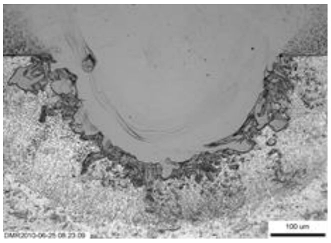


Fig 4.The root of the weld between Ti alloy and Al alloy, etched with Kellers' reagent

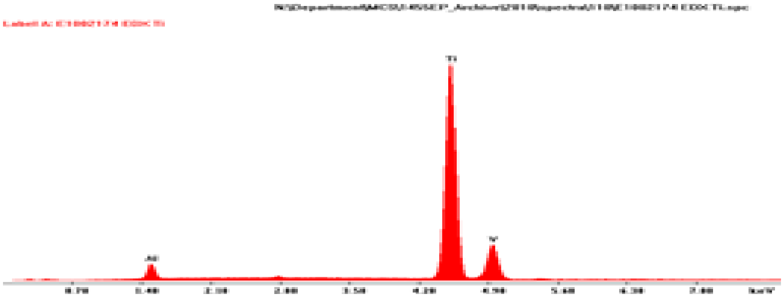


Fig.5. EDX spectrum from the root of weld, which shows very little mixing of the two materials has taken place during welding

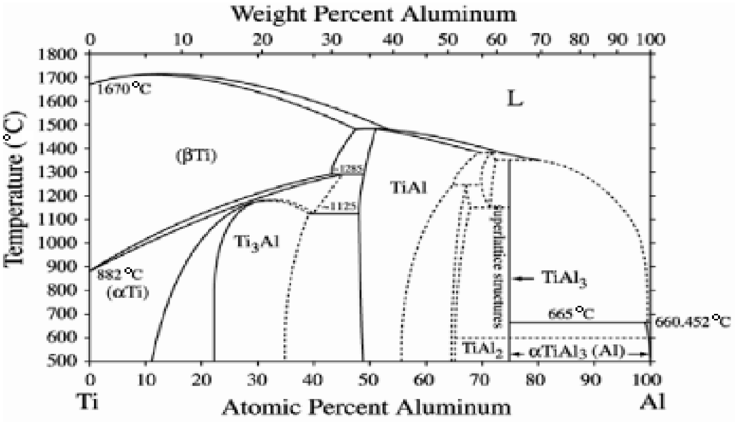
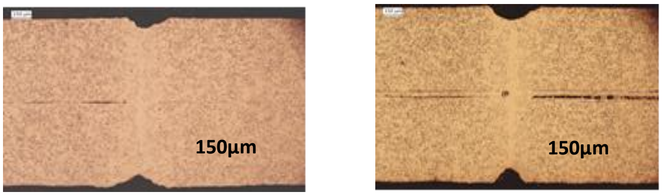


Fig.6. Ti-Al binary equilibrium phase diagram, Luis Augusto Rocha et.al. 2003

3.2. Aluminium- copper

Joints between aluminium and copper are often required in electronic and automotive market sectors. The battery for hybrid car is mainly constructed from a combination of aluminium alloys (3003 series, Al-Mn alloy) and pure copper to produce electrical contact to the positive and negative outside terminals. These materials pose particular challenges to be joined together. 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. The main welded joints are overlap because these joints are less demanding to part fit up and tolerances. Under optimum laser and processing it was possible to crack and porosity free welds in pure copper and 3000 aluminium alloy. Typical cross sections of the copper and aluminium alloy welds with CW output power are highlighted in figure 7-8 respectively.



2x1.0 mm thick overlap joint

0.75+50µm foil+0.75mm overlap joint

Fig.7. C101 pure copper; 1.6kW CW power, N2 shield gas

2x1.0mm overlap joint

2x1.5mm overlap joint

1.0+1.0mm butt joint

Fig.8. 3003 Al alloy, 1.6kW CW average power, N_2 shield gas

Welding tests carried out with aluminium to copper has highlighted that no single parameter controls weld quality whereas it is a combination of both laser and processing parameters which has a significant effect on the weld quality of these joints i.e.

- Laser output modulated output from high power continuous wave lasers (figure 9) can help with cracking and porosity. Modulation produces welds with controlled heating and cooling. This reduces the freezing range of the weld metal minimizing tendencies for solidification cracking in aluminium alloys while reducing formation of brittle intermetallics during the dissimilar material welding process.
- Power density, an optical power per unit area, is another important parameter which controls the weld quality during the welding of highly reflected materials. The high initial reflectivity of reflective materials can be overcome provided the intensity of the laser focused beam is sufficiently high. The absorption rate increases remarkably as the temperature of the material rises. Both aluminium and copper require higher power intensity compare to steels for laser weld initiation. Whereas welding with reduced power density can lead to problems with the back reflection.
- Finally the third parameter which had significant effect on the weld quality was the laser spot position with respect to the workpiece. It is possible to offset the laser beam in one direction or the other, thus allowing some control over composition of the .resulting alloy.

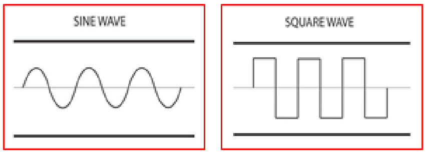


Fig.9. Example of laser outputs from CW fiber laser

Welding tests carried out with copper to aluminium alloy showed it was possible to weld these together in both overlap and butt joint configuration respectively (figure 10). However, under close examination of the partial penetration of overlap joint, it appears there are some micro cracks at the lower part of the weld (figure 11). The Cu–Al phase diagram (figure 12), from the Metals Handbook, shows a wide range of Cu–Al phases that may be formed during welding. In addition, during non- equilibrium cooling conditions are known to promote the formation of $CuAl_2$ Naeem, et.al. 2010. Figure 13 shows EDX spectra near the bottom of the weld. These cracks are brittle in character, which drastically reduces the tensile strength (table 2). Tensile strength data for the QCW laser welded samples was higher compare to CW output. It is not surprising that the tensile strength numbers were higher with QCW laser output, because the pulsed laser parameters can be refined more accurately to control the mixing of the two materials and hence reduced the formation as well the thickness of the intermetallic compounds.

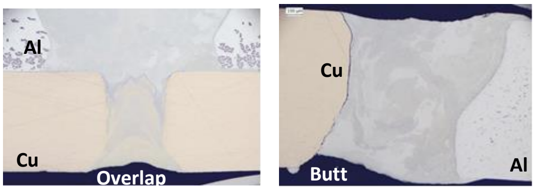


Fig.10. 1mm Al 3003+ 1mm pure Cu, 1.6kW power, N_2 shield, unetched micrograph

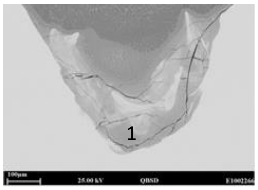


Fig.11. SEM micrograph of the root of the partial penetration weld between A' alloy and Cu

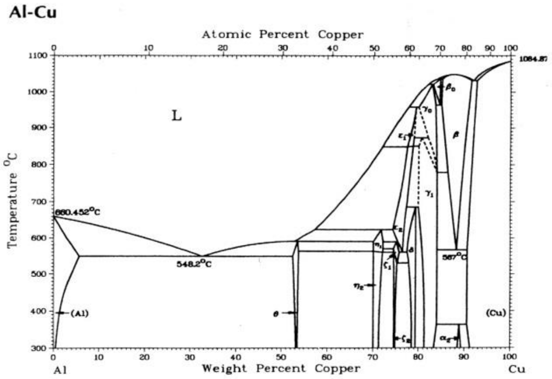


Fig. 12 Al-Cu phase diagram

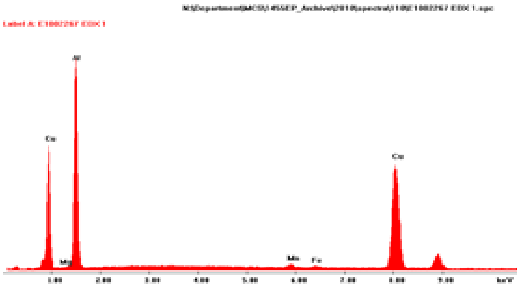


Fig.13. EDX spectra near the bottom of the weld (location 1 in Fig. 11)

Table 2: Tensile strength data of welds made with CW and QCW fiber lasers respectively

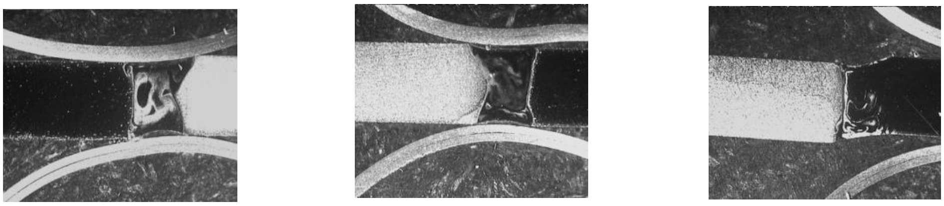
Material	Joint type	Tensile strength (MPa)	
3003 Al	Overlap	CW	QCW
		150	160
3003 Al	Butt	170	180
C101 Cu	Overlap	220	210
C101 Cu	Butt	210	230
Al+ Cu	Overlap	60	110
Al+ Cu	Butt	65	120

3.3. Titanium- Inconel alloy

Titanium alloy (Ti-6Al-4V) with its unique properties i.e. good corrosion resistance, high strength, good creep and fatigue is widely used in aerospace industry for example as static and rotating components in the turbine engines, Boyer 1999. Whereas Inconel 718 nickel based alloy offers excellent mechanical properties at elevated temperatures as well very good oxidation resistance at high temperatures (900 deg. C) temperatures, which makes this alloy suitable for manufactured components in the high temperature regions of aero engines and gas turbines, Gobbi et al, 1996. Limited amount of research had been carried to successfully weld these materials. The work carried at the University Manchester with single mode fiber laser by Hui-Chi Chen et al, 2010 showed that the formation of intermetallic brittle phases and welding defects could be effectively restricted at welding conditions produced by the combination of higher laser power, higher welding speed and shifting the laser beam from the interface to the Inconel 718 alloy side. Similar results were achieved during the present studies with multi-mode CW and QCW fiber lasers. Crack free and reduced porosity welds were produced by optimizing a number of laser parameters i.e.

- Average power (CW)
- Pulse shaping
- Shield gas
- Focus position respect to the workpiece
- Focus position respect to weld joint
- Pulsed parameters (peak power, pulse energy, pulse frequency etc.)
- Weld speed

Figure 14 shows three welds produced with different laser spot position with respect to the weld joint between two materials.



50/50 spot; crack in the centre

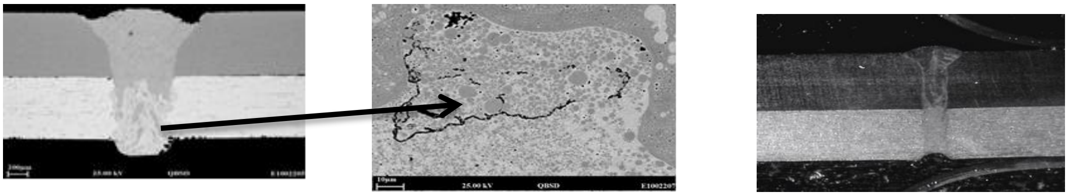
Laser spot 200μm towards In 718 plate

Laser spot 200μm towards Ti plate, no weld

Fig.14. Butt joint between 1mm thick T-6Al-4V and 1mm Inconel 718 alloy, 1.6kW average power, 4.5m/min, argon shield gas

3.4. 304 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. 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. In this good quality welds produced with both CW and QCW fiber lasers. Figure 15 shows overlap joints between 304 stainless and copper. There were very few micro cracks at center of the welds. These micro cracks were more apparent with CW output than QCW output. The work has shown that these two materials can be welded with reasonably good tensile strength.



CW, average power 1.6kW, N_2 shield gas

SEM micrographs of solidification cracking in the centre of the weld

QCW laser, N_2 shield gas

Fig.15. Overlap joint between 304 stainless steel (1.5mm) and pure copper (1mm)

3.5. 304 stainless steel- aluminium alloy

Laser welding of steel to aluminum is difficult due to the formation of different types of Fe-Al intermetallics during mixing of the molten materials, which produces welds with very little or no strength. There are various techniques that can be used during laser welding to reduce the formation of these intermetallics and hence produce strong welds. Some of these techniques are currently being evaluated i.e. conduction mode welding, laser brazing with wire, optimization of laser parameters i.e. laser power, pulse duration, overlapping etc. to control the heat input etc. Early results looks promising in terms of producing sound welds. This work was customers' development work and due to confidentiality it is not possible to share the welding data here.

4. Summary

The work has highlighted that the fiber lasers with its high beam quality, it is possible to weld difficult material combinations. To produce sound welds (good tensile strength), it is essential to control the mixing of the dissimilar materials in order to reduce the formation of brittle intermetallic compounds which can lead to cracking and produce welds with low mechanical properties. This studies shows that heat input and cooling rate has major influence on the type and thickness of the intermetallics. Laser and processing for both CW and QCW lasers which control the heating and cooling cycle during welding of different material combinations are listed below and it is important to note that no single parameter controls the formation of intermetallics i.e.

4.1. Parameters for CW laser welding

- Average power
- Power density
- Laser output i.e. CW or modulated
- Laser focus position with respect to workpiece
- Laser focus position with respect the weld joint
- Welding speed
- Type of shield gas

4.2. Parameters for QCW laser welding

- Pulse energy
- Pulse width
- Pulse frequency
- Overlapping of the pulses
- Welding speed
- Spot size
- Laser focus position with respect to workpiece
- Laser focus position with respect the weld joint
- Type of shield gas

It is also worth pointing out that it very important have a very good welding jig which can clamp the plates tightly together in order to reduce the air gaps in the joints, as well as misalignment of the plates, because both of these can significantly affect the weld quality of the joints.

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