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Effect of Laser Welding Properties on Ti/Al Dissimilar Thin Sheets – A Review

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Abstract**—**Laser beam welding is an important joining technique for Titanium/Aluminum thin sheet alloys with their increasing applications in aerospace, aircraft, automotive, electronics and other industries. In this paper the research and progress in laser welding of Ti/Al thin sheets are critically reviewed from different perspectives. Some important aspects such as microstructure, metallurgical defects and mechanical properties in weldments are discussed. Also the recent progress in laser welding of Ti/Al dissimilar thin sheets to provide a basis for further research work is reported.

Keywords**—**Laser welding, Titanium/Aluminium sheets, microstructure, metallurgical defects and mechanical properties.

I. Introduction

LASER Beam Welding (LBW) of thin sheets is usually more difficult than welding thick sheet metal. Such aspects are usually related to high heat input similar to conventional arc welding process. This high heat input leads to various problems such as cutting, burn through, distortion, porosity, cracking, etc. Thus the selection of an appropriate welding process and procedure are important in order to prevent these problems. Compared with arc welding, laser welding and electron beam welding are excellent methods that offer many advantages such as narrow heat affected zone and impressive penetration depths. However laser beam welding is the best choice because it can be used at ambient pressures and temperatures. However the laser welding of thin sheet metals can still be problematic. Issues include the loss of material due to evaporation and inadequate control of heat which leads to cutting and melt through issues [1], [2]. There are plenty of reports on the welding of copper, stainless steel and aluminum alloys [1], [2] in thin sheets of less than 1 mm thickness but few studies have been published that focus on thin sheets of similar thickness in the case of Titanium/Aluminium alloys.

A. General Principle of Laser Beam Welding

Laser Beam Welding process as shown in Fig. 1 is a fusion joining process that produces coalescence of materials with the heat obtained from a concentrated beam of coherent and monochromatic light impinging on the joint to be welded [3]. In the LBW process, the laser beam is directed by flat optical elements such as mirrors and then focused to a small spot for high power density at the work piece using either reflective focusing elements or lenses. LBW is a no contact process and thus requires that no pressure be applied. Inert gas is generally employed as shielding to prevent oxidation of the molten puddle and filler metal may occasionally be used. The laser predominantly being used for industrial material processing and welding tasks are 1.0μm YAG laser and 10.6μm CO_2 laser with the active element most commonly employed in these two varieties of lasers being the Neodymium (Nd) ion and the CO_2 molecule respectively.

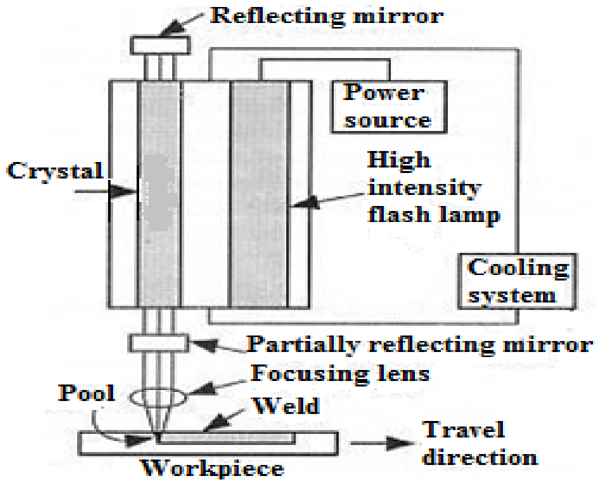

Fig. 1 Laser Beam Welding Process

In laser beam, welding bead geometrical variables are greatly influenced by the process parameters such as pulse frequency, welding speed, input energy and shielding gas [4].

II. Welding of Titanium and Aluminium Sheets

Ming Gao et al [5] developed fiber laser cold metal transfer which is a hybrid welding to join Titanium to Aluminium alloy butt joint configuration.

Fig. 2 shows the relationship between heat input and tensile strength. The optimal range of heat input for the accepted joint is 83–98 J·mm−1. The cross weld tensile strength is up to 213 MPa and 95.5% that of hybrid welded 6061-T6 Al alloy. Within the optimal range of heat input accepted joints are stronger than 200 MPa and fracture in the FZ. The heat input decreases to 71 J·mm−1 and tensile strength reduces to 138 MPa. It is found that both the bead shape formation and the interface growth depend on the downward and upward flow in the molten pool which is dominated by the laser power and the volume of liquid metal generated by heat input is shown in Figs. 3 (a) and (b).

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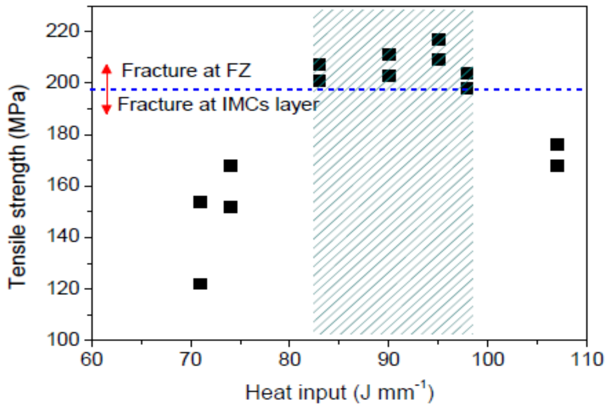


Fig. 2 Tensile strength as a function of heat input

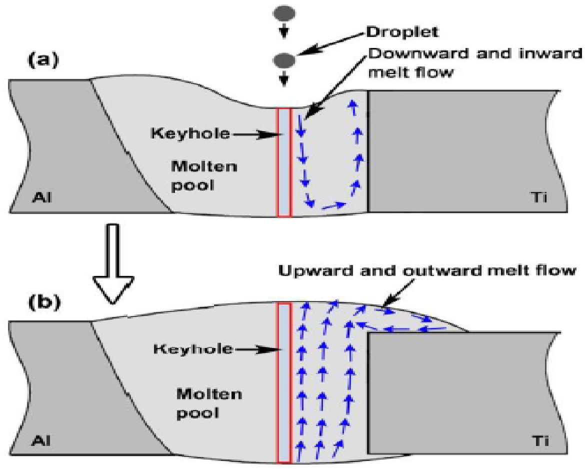


Fig. 3 Molten pool of welding (a) Initial stage (b) Stable stage

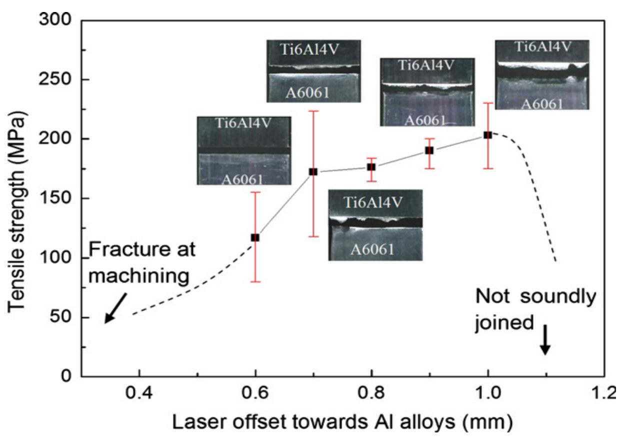


Fig. 4 Tensile strength and fracture analysis with various laser offsets

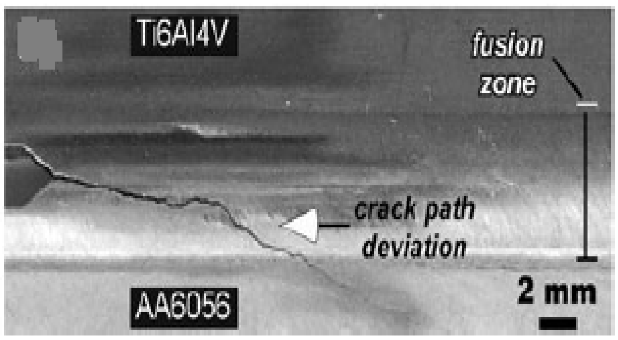
When the laser power is too small lack of fusion appears at the root of the titanium sheet due to insufficient liquid metal and shallow flow. When the laser power or the heat is excessive a too thick Inter Metallic Compounds (IMCs) layer forms at the top corner of the titanium interface. The IMCs layer of accepted joint is thin and thickness is about 1µm.

Zhihua Song et al [6] highlighted the welding of Ti6Al4V/A6061 dissimilar alloys with 2 mm thickness by laser beam without filler metal can produce sound brazing joints with good appearance under welding conditions of 4 kW laser power, 4 m/min welding speed and 0.8–1.0 mm laser offset at aluminum alloy side.

Laser offset has a great influence on the thickness of inter facial IMC layer and the mechanical property of joint. With increasing laser offset the thickness of interfacial IMC layer decreases and the tensile strength of joint increases as shown in Fig. 4. When the laser offset is 1.0 mm thickness, the interfacial IMC layer is about 0.26 mm and the average tensile strength of joint is about 64% of the aluminum alloy base metal. The interfacial intermetallic phase is $TiAl_3$. When the thickness of interfacial IMC layer is decreased by increasing the laser offset the dissimilar joints tend to fracture in the fusion zone of aluminum alloy.

Vaidya et al [7] has studied the grain size in the fusion zone is reduced and the intermetallic phase formed at the interface is thinner. Specimens could be mechanically tested without formation of cracks in the reaction zone and premature pullout or debonding. In this sense the weld coupons are sound in both configurations. Hardness and tensile strength are slightly higher in the modified joint whereby the fracture occurred in the hardness dip on the side of AA6056–T6 and the interface remained intact in both cases. Typical crack morphologies in the modified joint specimens are shown in Figs. 5 (a) and (b). In some joint specimens the crack deviated away from the interface into the Al-side as in Fig. 5 (b) and indicates the interface had better properties than the surrounding.

(a) Crack path in the modified joint



(b) Crack path deviation away from the interface

Fig. 5 (a) Crack path in the modified joint and (b) Crack path deviation away from the interface

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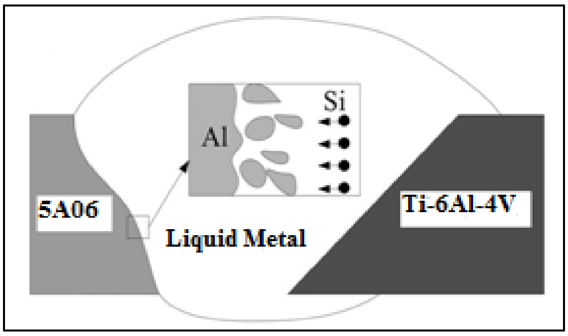
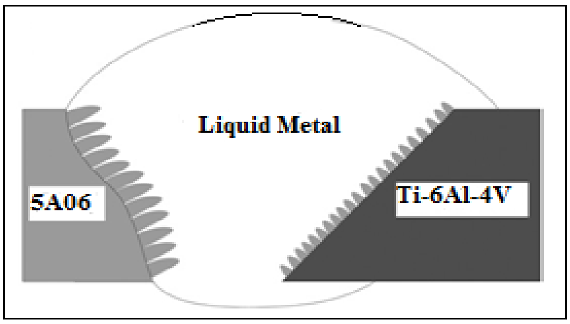
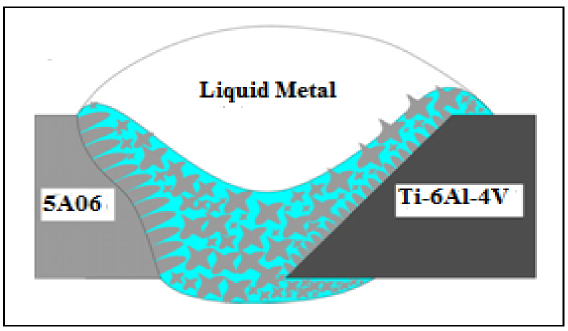
Laser offset has a great influence on the thickness of inter facial IMC layer and the mechanical property of joint. With increasing laser offset the thickness of interfacial IMC layer decreases and the tensile strength of joint increases. During fatigue crack propagation partly intercrystalline fracture occurred in the fusion zone of the unmodified joint specimens. This absent in the modified joint specimens and completely transcrystalline fracture and striations are observed not only for the interface adhering Al particles in the fusion zone. Moreover ductile tearing occurred after a longer crack length. In such fractographic differences, the improvement brought about by the joint modification is a genuine effect. In addition to the decrease in the interfacial area the modified configuration is inferred to have induced a faster cooling rate. This has most likely decrease the reaction zone, improve the interfacial binding, reduce the grain size in the fusion zone, avoid grain boundary segregation and retain solute for hardening.



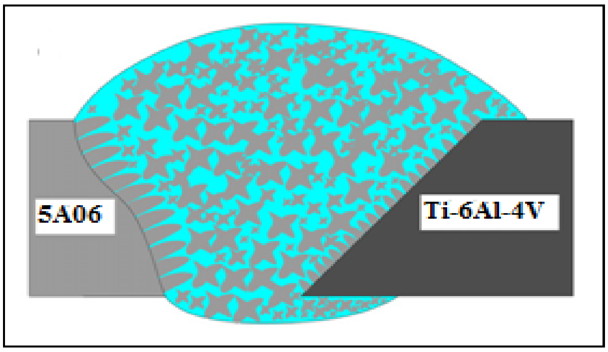
(a) Formation of weld pool and diffusion of element Si



(b) Formation of columnar crystal zone



(c) Solidification of the seam



(d) Formation of the joint

Fig. 6 Crystallization behavior of fusion welding joint, (a) Formation of weld pool and diffusion of element Si, (b) Formation of columnar crystal zone, (c) Solidification of the seam and (d) Formation of the joint

Shuhai Chen et al [8] have explained the fusion welding zones as fusion line (FL), columnar crystal zone (CCZ) and equiaxed crystal zone (ECZ).

The microstructures of welding joint consist of Al grains and ternary near eutectic structure including Al, Si and Mg2Si. Fusion line with fine hypoeutectic microstructure is formed by diffusion of element Si from weld pool to semi molten zone at solid and liquid interface. The columnar crystal formed due to obvious directionality of heat conduction is shown in Figs. 6 (a)-(d). Equiaxed crystals are formed in the weld pool due to the stir by filler wire and high degree of super cooling. The microstructures of brazing zone are orderly from Ti alloy to the seam consists of Ti nano size granular Ti7Al5Si12 and serration shaped TiAl3. Apparent stacking fault structure of intermetallic compound TiAl3 is found. During the interfacial reaction at solid and liquid interface the formation of Ti7Al5Si12 depended on the dissolution of Ti alloy and the segregation of Si atoms and intermetallic phase TiAl3 is formed by the crystallization. Growth of brittle reaction layer could be suppressed because dissolution of Ti alloy is weakened by formation of ternary compound Ti7Al5Si12.

CHEN Shu-hai et al [9] have studied the interrelationship between Al alloy to Ti alloy Si element diffuses to the interface and enriches there with the mode of Ti dissolution or melting. It is found that Si diffusion behavior plays an important role in forming those interfacial compounds. Chemical potential prediction model of the ternary alloys is established based on MIEDEMA model of solution enthalpy. The influence of Ti molar fraction and temperature on Si chemical potential is analyzed according to calculated results. It is found that the influence of Ti molar fraction is far higher than that of the temperature on Si chemical potential. The minimum value of Si chemical potential is approximate 0.5 of Ti molar fraction, which presents a good agreement with experimental data. In the case of Ti dissolution mode the dissolution of Ti alloy in liquid filler induces the reduction of the Si chemical potential. In the case of Ti melting mode element Si not only gets together at the interface but also further diffuses to liquid Ti due to slight melting of Ti substrate.

Tadamalle et al [10] have analyzed the weld bead geometry, effective pulse energy, energy density, duty cycle, percentage of overlap and pulse off time. The bead width, depth of penetration decreases as the welding speed increases. Depth of penetration is more sensitive to the welding speed than bead width over range of speed. The weld bead dimensions are more sensitive to the peak power input up to 1700 W and less sensitive beyond 1700 W. Laser welding machine cannot be loaded beyond 98.38 % of duty cycle.

Michael Kreimeyer et al [11] developed a process for joining aluminum to titanium in butt joint configuration. For the production of this kind of tailored blank a conventional CO_2 laser working head is used. By the integration of a shielding gas nozzle positioned above the weld seam, it is possible to join aluminum to titanium under local gas protection. Joints with minimal intermetallic phase layers <2μm can be realized through process adjustment using the deep penetration effect. The process parameters are pre determined by FEM simulation allowing a sufficient estimation of the process parameters with respect to temperature time control and beam positioning with a constant energy input per unit length as shown in Fig. 7.

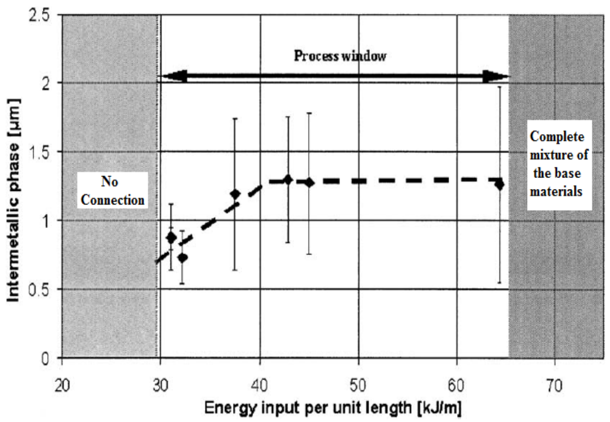


Fig. 7 Process window for joining Titanium - Aluminum welding using FEM analysis

The growth of the intermetallic phase has ($TiAl_3$) only a minor dependence on the energy input per unit length probably due to the limited diffusibility of aluminum in the titanium aluminide phases. Therefore areas with three phases aluminum, intermetallic phase and titanium are formed. These three phase areas depend heavily on the energy input per unit length. Static tensile strengths of about 200MPa are reported. This is equivalent to 80% of the aluminum base material.

Möller et al [12] stated that the heat conduction welding process is a feasible process for joining aluminium- titanium hybrid structures. Moreover it is demonstrated that the deformation prior to welding influences the deformation after welding. The thermo mechanical simulation gives information about distortion and residual stresses of the specimens. The height distortion is caused by an occurring longitudinal plastic compression zone in the titanium component part and extends nearly over the total length of the specimen.

Woizeschke et al [13] have highlighted the aluminum-CFRP (Common Fiber Reinforced Composites) joints of the novel foil concept competing failure modes. However, failing of the Al-Ti interface at the front side of the titanium laminate has been detected at all specimens. Hence a modification of the Al-Ti joining zone would be necessary to make the entire specimen suitable for higher seam loads. Additionally a buckling of the external titanium foils of the laminate occurred next to the Al-Ti transition at several specimens. Prospectively such local plastic deformations of the joint should be avoided at an early stage of loading even though the buckling has not influence on the seam strength.

Mohammed Naeem et al [14] welded between Titanium and Aluminium. The weld is very wide but the penetration into the lower aluminium sheet is very shallow as shown in Fig. 8.

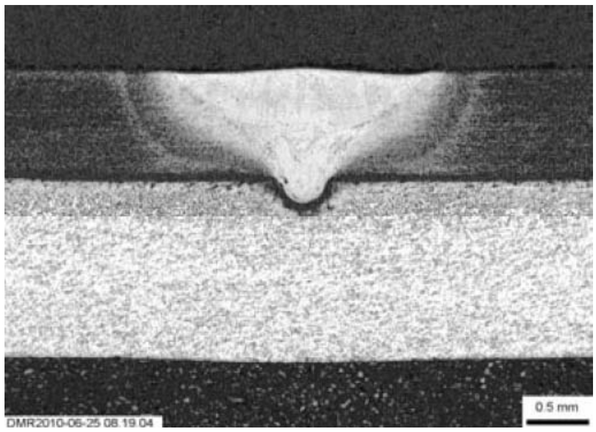


Fig. 8 Photo-macrograph of the weld between Ti and Al alloy

Fig. 9 shows the bottom part of the weld where the two sheets are jointed. At the root of the weld there is 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 Aluminium is a lot of swirls where there is variable mixing of the melted sheets.

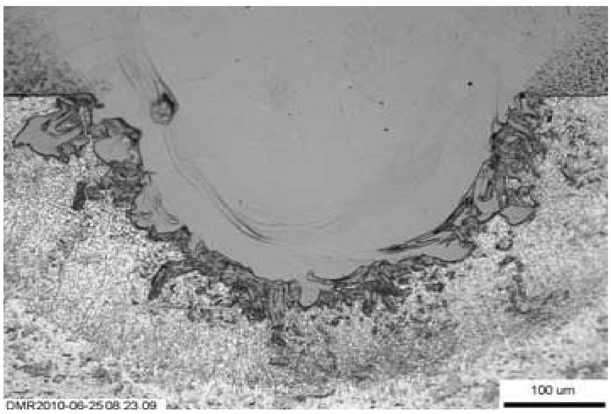


Fig. 9 The root of the weld between Ti and Al alloy

Large differences in melting point between the sheets of Ti and Al are reported. These are the region within the lower melting point sheet, which had melted but not mixed with the main weld pool. And also titanium to aluminium weld which is 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.

III. Conclusion

1. The LBW of thin sheets are focusing laser beam on aluminum alloy side. The effect of laser offset on the microstructure, mechanical properties and formation of interfacial IMC layer of the dissimilar butt joint are discussed.
2. When the laser power is too small lack of fusion appears at the root of the Ti6Al4V sheet due to insufficient liquid metal and shallow flow. When the laser power or the heat input is excessive a too thick IMCs layer forms at the top corner of the FZ/Ti6Al4V interface because the substrate is melted and the solidification rate is slowed by heat accumulation.
3. Laser offset has a great influence on the thickness of inter facial IMC layer and the mechanical property of joint. With increasing laser offset, the thickness of interfacial IMC layer decreases and the tensile strength of joint increases.
4. During fatigue crack propagation partly intercrystalline fracture occurred in the fusion zone of the unmodified joint specimens. These are absent in the modified joint specimens and completely transcrystalline fracture and striations are observed not only for the interface adhering Al particles but also in the fusion zone. Moreover ductile tearing occurred after a longer crack length.
5. Si diffusion behavior plays an important role in forming those interfacial compounds. The bead width and depth of penetration decreases as the welding speed increases.
6. The thermo mechanical simulation gives information about distortion and residual stresses of the specimens. Also height distortion is caused by an occurring longitudinal plastic compression zone in the titanium component part.

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