A Review on Process Parameters of Ti/Al Dissimilar Joint Using Laser Beam Welding

K. Kalaiselvan, K. Sekar, S. Elavarasi

***Abstract*—**The use of laser beam welding for joining titanium and aluminum offers more advantages compared with conventional joining processes. Dissimilar metal combination is very much needed for aircraft structural industries and research activities. The quality of a weld joint is directly influenced by the welding input parameters. The common problem that is faced by the manufactures is the control of the process parameters to obtain a good weld joint with minimal detrimental. To overcome this issue, various parameters can be preferred to obtain quality of weld joint. In this present study an overall literature review on processing parameters such as offset distance, welding speed, laser power, shielding gas and filler metals are discussed with the effects on quality weldment. Additionally, mechanical properties of welds joint are discussed. The aim of the report is to review the recent progress in the welding of dissimilar titanium (Ti) and aluminum (Al) alloys to provide a basis for follow up research.

***Keywords*—**Laser beam welding, titanium, aluminum, process parameters.

I. INTRODUCTION

LASER Beam Welding (LBW) is widely used in welding of dissimilar metals due to high thermal conductivity, heat concentration, small thermal deformation, fast processing speed and low pollution [1]-[4]. In order to meet economic and environmental needs, modern industries have put forward higher requirements for new structures and processes [5]. Light weight metals can improve the utilization rate of whole structure due to the low density, good forming property, low cost [6] and high temperature resistance of titanium (Ti) and aluminum (Al) metal structures have a wide range of potential applications in aerospace, automotive and ship building industries [7].

Recently, many researchers have tried to use diffusion welding [8], brazing [9], friction welding [10], friction stir welding [11]-[13] and explosive welding [14]-[16] to connect Ti and Al alloys. However, these solid state welding methods are usually limited by the structure shape and size of the joints, so simple geometric shapes such as overlap and butt joints can be welded [17]. The LBW offers many features which make it an alternative to conventional processes. Laser source is characterized by coherent, collimated source of light, energy can be regulated and well monitored during welding. The laser welding process operates at very high speeds with low deformation, automated for a stable and repeatable in industrial applications. However, lasers can also join metals such as titanium, high carbon stainless steel and aluminum as well as dissimilar metals which are incompatible.

The quality of a weld joint is influenced by the welding input parameters. The common problem faced by the manufactures is the control of process input parameters to obtain a good welded joint. Therefore, in this literature review we carefully study the process parameters of laser welding such as laser offset, welding speed, laser power, shielding gas and filler metals to enhance the performance and to achieve better mechanical properties using titanium (Ti) and aluminum (Al) dissimilar combinations.

II. PARAMETERS

A. Laser Offset

Laser brazing of Ti6Al4V and A6061 T6 alloy is reported by focusing the laser beam on Al alloy side. The effect of laser offset distance on microstructures and mechanical properties of the dissimilar butt joint was discussed [18]. Laser offset has a significant influence on the thickness of interfacial intermetallic compound (IMC) layer and the mechanical properties of the joint. When suitable welding conditions are used, the thickness of interfacial IMC layer is less than 500 μm which increases the properties.

For the Ti and Al butt joint configuration, the focus spot of the laser beam was on the surface of the work pieces. The exact positioning of the spot was to realize a reproducible joining to produce Ti and Al welded structure, an appropriate thermal, laser based brazing process developed in a joint [19]. Additionally, parameter of laser focusing side also influences the properties and appearances of the weldment.

Ti6Al4V and AA6013 sheets of 1.0 mm and 1.6 mm thickness were joined by an Yb: Fiber laser [20]. Butt joints are conducted by varying the relative positioning of the laser beam toward Al alloy, from zero to 0.5 mm as shown in Fig. 1. The welding speed and the average laser power were fixed such as 3.0 m/min and 1000 W. The positioning of the laser beam has a pronounced influence on the quality of the joints. Between 0.2 and 0.4 mm, the Ti alloy was not melted. When the laser beam was positioned near the interface area, a melted region containing a mixture of Ti and Al was formed with the presence of some defects. Energy dispersive spectroscope (EDS) line scanning in the junction interface showed a decreasing of IMC layer in the joints without melted titanium

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alloy [20].

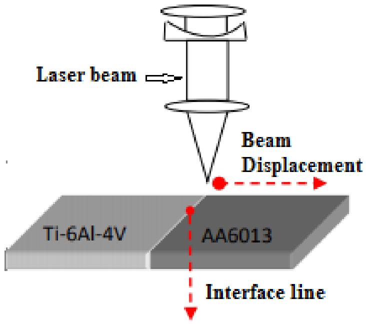

Fig. 1 Relative positioning of the laser beam toward Al alloy

AA5754 alloy and T40 joined in butt configuration by focusing a fiber laser onto the titanium side, close to the weld center line. The keyhole was made entirely of titanium side and the fusion of the Al achieved by heat conduction [21]. Filler metal was necessary to produce a sound dissimilar weld joint. The assembly was free from porosity formation and spatter defects. The mechanical properties were obtained. The energy input, the laser offset, and their interaction have significant effects on the ultimate tensile strength.

The feasibility of laser welding of Ti and Al have been reported via various auxiliary processes [22]. Fig. 2 shows that when the laser offset was on the side of the titanium metal side, more elongation was occurred in aluminum alloy side. In Ti metal side no deformation present but rupture was occurred in the fusion zone (FZ) that was close to the Ti alloy side [23]. The feasibility of laser penetration is demonstrated using Ti and Al alloys. The weld geometry and the formation of IMC could be regulated by process parameters.

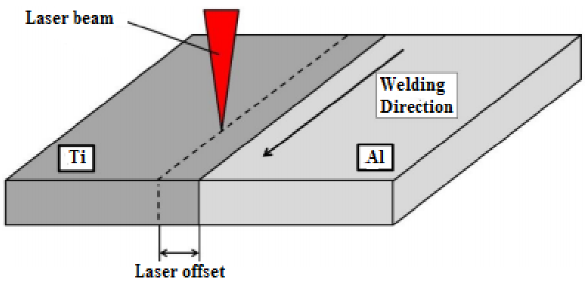

Fig. 2 Laser offset on Ti alloy side

AA5754/Ti6Al4V joint was performed by high-speed Yb:YAG laser welding. Observed morphology and phase content of dissimilar interface were formed between Al-rich and Ti-rich melted zones. Three types of contact interfaces were observed [24]. First one is the thin interface of TiAl formed under 0.2 mm beam shift to Al side and linear energy of welding ≥ 37.5 KJ/m. Second is cracked interface of 190-300 μm thick composed by Al_3Ti and other Al/Ti intermetallic formed under beam shift at 0.2 mm to Ti side and linear energy ≥ 37.5 KJ/m. Third is malaxated interface composed of layers and isles of Ti_3Al and TiAl forming in other tested conditions and favored by welding speed > 10 m/min. The maximal linear tensile force of 220 N/mm for 2 mm thick weld can attain when thin contact interface is formed.

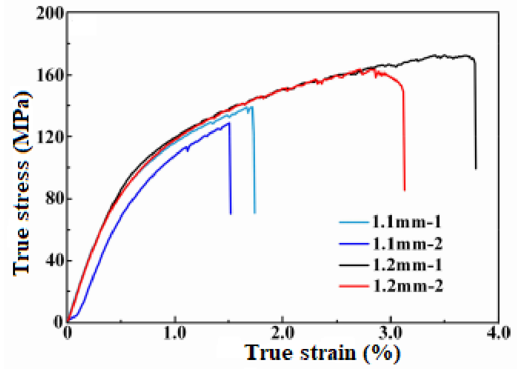

Fig. 3 True stress–strain curves

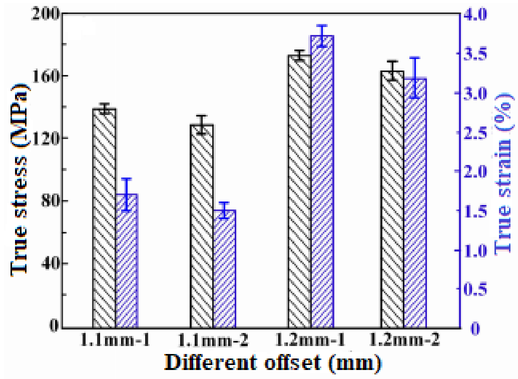

Fig. 4 Tensile strength and fracture elongation

The true stress-strain curves of the Ti/Al welding–brazing joints are shown in Fig 3. The tensile properties of the welded joints were found to be sensitive to the laser offset [25]. The thickness and distribution of the IMCs was quite different for different laser offsets. It is evident from the figure that joints had a lower tensile strength of 139 and 128 MPa for oscillation frequencies of 28 and 30 Hz, respectively for a laser offset of 1.1 mm, whereas the tensile strength significantly increased to 173 and 164 MPa for oscillation frequencies of 28 and 30 Hz, respectively in the Fig. 4. As discussed earlier, with a 1.1 mm laser offset, the TC4 alloy underwent micro melting, which resulted in a large number of IMCs with uneven thickness during welding. IMCs with large size or uneven thickness significantly reduced the mechanical performance of the brazed joint, whereas in the fusion zone the porosity defect was the main cause of reduced mechanical properties. With a laser offset of 1.2 mm, the IMCs were distributed with uniform thickness of and had less porosity defects. These two factors resulted in a significant increase in tensile strength.

The T40 and 5754 Al alloy plates were welded by using Yb–YAG laser welding [26]. The laser offset was kept constant at 0.75 mm in order to assess the effect of the linear energy on the weld characteristics. The micro hardness at the middle-thickness of the transverse cross section of weldment as shown in Fig. 5. The Al fusion zone showed a micro hardness that was slightly higher than the base material. The micro hardness rose slightly because the grain was refined during the rapid solidification. Molten Ti produced local hardening. The hardness was greater in the FZ than in the Ti base material (250–300 HV0.2 versus 180–200 HV0.2). Because of the 1 martensite phase, the Ti hardness increased up to 50% of that of the base metal (175 to 260 HV0.2).

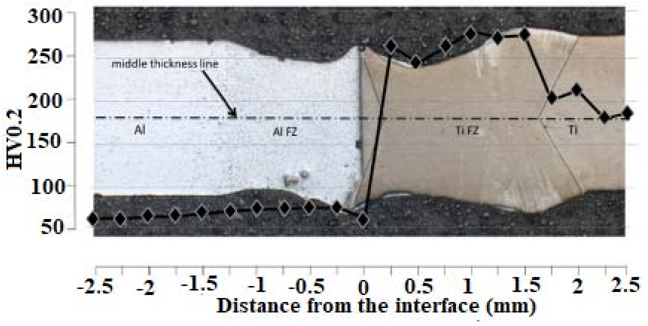

Fig. 5 Micro hardness of weldment

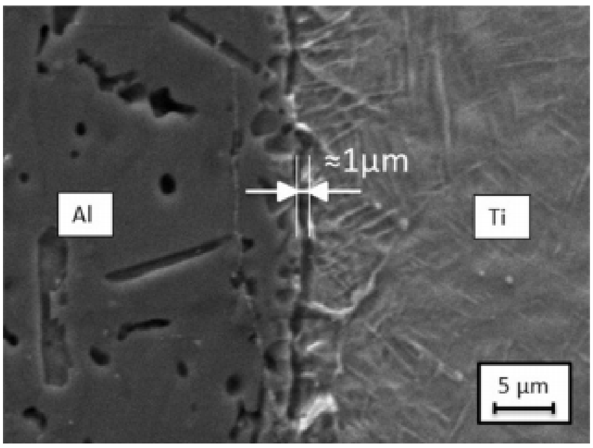

Fig. 6 Microstructure and interface of weldment

Measurement of the micro hardness within the intermetallic layer was impossible because the dimension of the impression was larger than the IM layer itself, which was ~1 μm. Fig. 6 shows the metals microstructure close to the intermetallic layer. Al FZ was made up of small-size grains with an inter-granular Mg precipitate. The microstructure of Ti was α1 martensite, which produce during fast cooling. The intermetallic interface presented discontinuities.

B. Welding Speed

The main difficulty is the control of intermetallic phase formation, which occurs during thermal joining of Ti and Al alloys. Through locally restricted energy input and high welding speed, the thickness of these phases can be reduced to below 2 μm. This fibrous structure results in good tensile strength [27]. Nd:YAG pulsed laser welding of dissimilar metals, titanium grade 2 with 1 mm thickness and 3105-O Al alloy with 0.5 mm thickness are welded by using AlSi5 filler metals and investigated experimentally [28]. The weldment of Ti to Al was narrow and the parameters selected are pulse energy 11 J, pulse duration 6 ms, pulse frequency 20 Hz, argon gas flow rate 20 l/m and welding speed 4 mm/s. A tactile seam tracking pulses with the circular path that leads to laser spot joining was better method for welding of Al to Ti with increasing welding speed.

Welding of Al and Ti dissimilar metal using single mode fiber laser with more welding speed was tried [29]. Single mode fiber lasers have initially developed for communication, but nowadays they are widely applied to the industrial production process of welding. Single mode fiber laser is compact and has a long life. The research results suggested an excellent configuration possibility of a strong Ti/Al dissimilar weld with IMC reduced by using a single-mode fiber laser under the condition of an extremely high welding speed shown in Fig. 7.

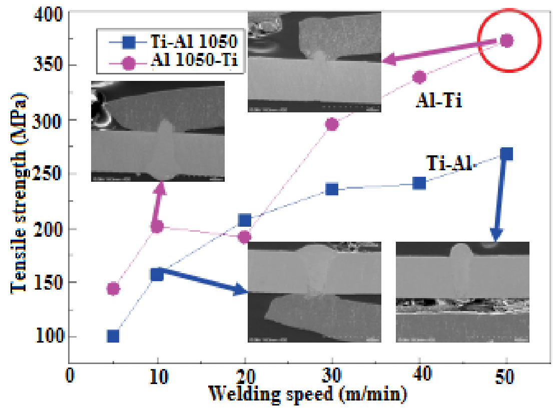

Fig. 7 Tensile shear tests

Two main difficulties encountered when welding sheet metals are distortion and burn through. Each of the processes is discussed along with feature characteristics that mitigate these problems [30]. The welding process commonly employed to improve the quality of thin sheet metal welding includes precisely preparing joints for a tight fit, using many short and closely spaced tack welds, carefully clamping the base materials, positioning, precise control of heat input and welding with the highest possible uniform travel speed. The processes discussed include Gas metal arc welding (GMAW), laser welding and resistance spot welding. It ascertained the possibilities limited by metal surface cleanliness, thickness and parameters during welding. Additionally, knowing the boundaries, it is useful for selecting a welding method and further improvements in advanced welding technology.

The effectiveness of the crack repair depends on low-speed fiber laser welding as a preparation step for composite patch repair using aluminum alloys AA7075-T6. The process design needed to overcome challenges related to alloy strength recovery, focusing position, crack tracing, welding speed, plate flatness, shielding gas, thin sheet factors and cracks. A thick layer, partial penetration model, is first used to determine the starting point of laser welding conditions [31]. 74% of the alloy strength was recovered for the single-pass repair and

68% for the double-pass repair. Successful crack fusion is the most challenging factor related to the metal flatness which affects the location and relative position of the laser focusing point during welding.

Dissimilar welding of Ti and Al metals was carried out under the Al-Ti and Ti-Al combinations at various welding speeds using single mode fiber laser having high power density. The results of the tensile test indicated that Al-Ti dissimilar weld joints had greater than Ti-Al joint and high welding speed has stronger tensile shear loads. It was confirmed that the high welding speed of 50 m/min could reduce the formation of brittle IMC such as Al_3Ti and Al_2Ti. Mainly, Al_3Ti IMC were generated in Al-Ti and Al_2Ti was produced in Ti-Al. A needle-shaped martensitic Ti phase was provided under Al-Ti condition at 50 m/min welding speed [32]. On the other hand, martensitic Ti phase was not generated on the Ti-rich side of a FZ and small size dendritic phases and island type phases of IMC formed from Ti phase under Ti/Al condition at 50 m/min welding speed. Dissimilar welding of Al and Ti sheets using a single-mode fiber laser at extremely high welding speeds suggests the possibility of sound and strong dissimilar welds as shown in Fig. 4.

Dissimilar welding of Ti and Al using single mode fiber laser with high welding speed and microstructural characteristics of the interlayer in the Ti and Al weldment were observed [33]. Full penetration welding was tried. The welded areas and formation of intermetallic phases were observed by the scanning electron microscope (SEM) and analyzed by using X-ray diffractometer (XRD). The results suggest a formation possibility of a strong Ti and Al dissimilar weld with IMC reduced by a single mode fiber laser under the condition of high welding speed.

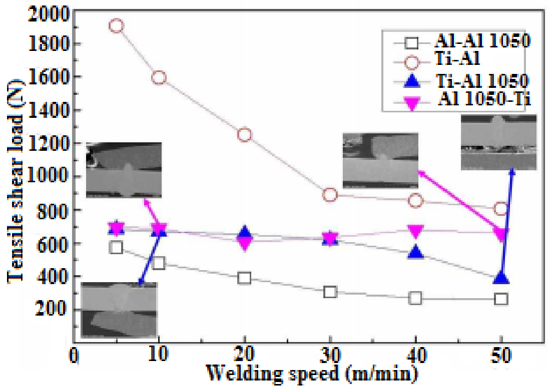

Fig. 8 Tensile shear tests using single mode laser

C. Laser Power

In pulsed Nd:YAG laser welding process, metal melts and solidifies consecutively by a peak high power laser beam [34]. The solidification time in this process is less as compared to that of the conventional welding process. The mode of the welding method is governed by the process parameters like laser energy, pulse duration, pulse frequency, power and welding speed. It is necessary to examine the influence of laser power on weld bead geometry and performance parameters such as duty cycle, energy density, pulse overlap and bead diameter. It is found from the experimental and analytical approach that laser powers significantly affect weld bead geometry, variation in bead diameter from pulse to pulse, duty cycle and active pulse energy.

Laser assisted joining of dissimilar materials, like aluminum alloys–steel, aluminum alloys–titanium and hard metals–steel have been examined with high power Nd:YAG and diode lasers. Joining of aluminum alloys from 5XXX and 6XXX groups and titanium have been investigated. Titanium and aluminum have been welded using a 3kW Nd:YAG laser with resulting very uniform and homogeneous intermetallic phase (IMP) with a thickness of less than 10 µm as shown in Fig. 5. Additionally, butt joints between hard metals K40 and carbon steel C75 have been examined and no formation of brittle η-phases was noted. Laser assisted joining of aluminum and steel samples in a butt joint have been welded leading to thin IMP with a thickness of less than 10 µm. Results indicated that laser welding produces competitive joints without cracks or pores in the weld seam between dissimilar metals joints [35].

Fig. 10 shows the spreading length of Ti6Al4V and 5A06 alloy plate weldment. The top and back side increased first and then decreased as the laser power increased. The length of the back side was greater than the top side. When the laser power was less than 1230 W, the spreading length of top and back side increased to 1471 and 1602 µm at 1230W [36]. The laser power increased more than 1230 W, the spreading length of the molten metal stopped suddenly. When the laser power increased, spreading length of Al molten liquid was higher because of the increasing molten Al liquid. From these practical experiments, the laser power exceeded 1230 W, more heat is diffused in the atmospheric air, resulting in the rapid solidification of molten Al liquid and a sharp decrease in spreading length.

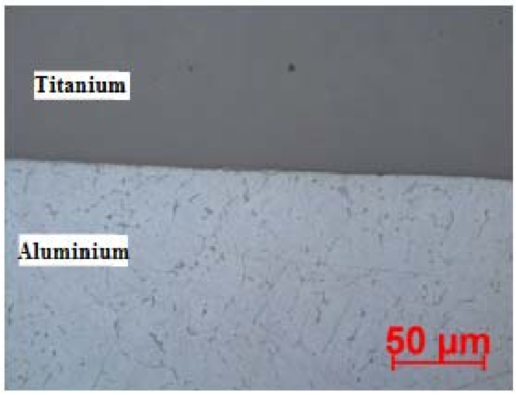

Fig. 9 Intermetallic layer thickness

The tensile strength of the weld joint is up to 213 MPa as shown in Fig. 11. The strengths are above 200 MPa when laser power is at the range of 2.0-2.5 kW, but decrease rapidly when laser power deviates from this range [36]. This indicates that tensile strength is more sensitive to laser power. When laser power is inadequate, lack of fusion appears at the root of interface and the IMC layer is too thin. During the tensile test, the crack prefers to initiate at the gap caused by lack of fusion due to stress concentration.

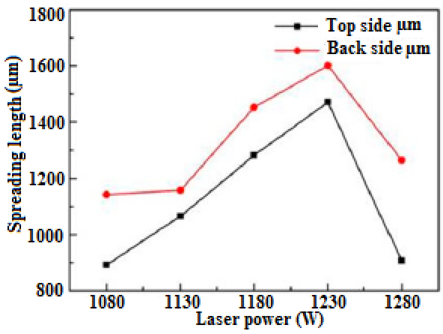

Fig. 10 Spreading length

Heterogeneous interfacial reactions are easily found along the Ti/Al interface due to high-temperature gradient during laser welding brazing of dissimilar metals. To increase uniform energy distribution of laser beam, nonhomogeneity and appropriate welding groove were conducted [36]. Experimental validation investigated the effects of these efforts on the nonhomogeneity of interfacial reactions. The rectangular spot laser can further improve homogenization of the interfacial reaction along the interface in comparison with circular spot laser.

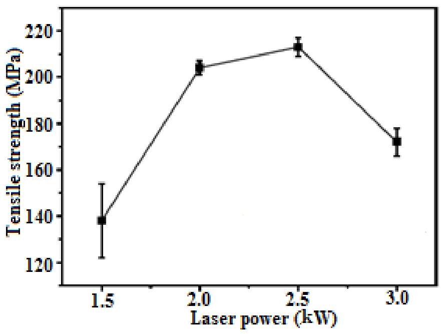

Fig. 11 Tensile strength

The test results show that the combination of spot laser welding brazing and V-shaped groove can control the joints in the seam in a broad processing parametric window.

The main problem created with the welding of Ti and Al alloy is the crack that is formed immediately after the solidification with sound during the cooling cycle [39]. A detailed experimental investigation is carried out to understand how these cracks are formed in the weldment. Fig. 12 shows a representative cross-sectional microstructure of a sample welded at a speed of 0.5 m^{-1} min and with an incident power of 2 kW. The laser offset is kept towards the titanium side during welding. One observes a frozen convection swirl in the FZ that is asymmetric with respect to the weld joint. This convection is common in many dissimilar joints [40], [41] when a concentrated heat source is applied. This is probably because the very fast cooling does not allow the elements to mix properly.

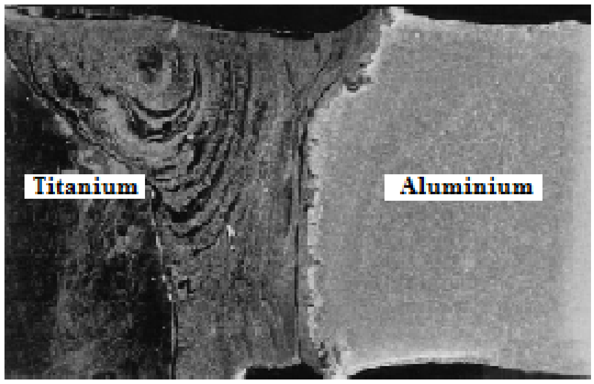

Fig. 12 Weldment cross section

Long cracks originating from the surface are present in the FZ. It is observed in all experiments that cracks propagate only along the region close to the aluminum side of the interface and these are transgranular in nature. A sharp interface is observed between the Ti alloy and the FZ, whereas a diffuse interface exists between the FZ and the Al alloy side.

Fig. 13 shows the microstructure of the specimen welded at a higher speed (2.00 m min^{-1}). The laser offset is towards the Ti side. It is revealed that the crack intensity as well as the size of the resolidified zone in the Al alloy is reduced.

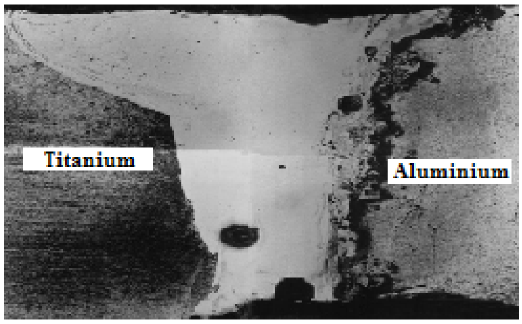

Fig. 13 Micro crack

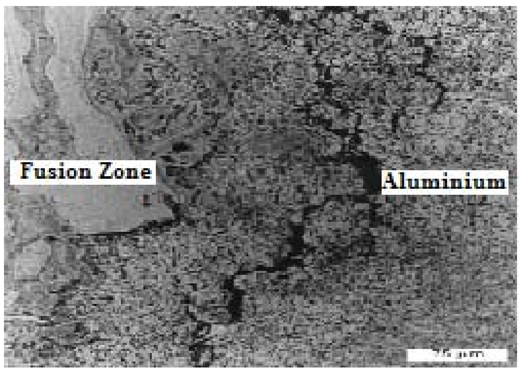

Fig. 14 Microstructure of the FZ Al alloy interface

The interface roughness is more prominent than the specimen with lower velocity. In this case the micro-cracks at the surface as well as internal cracks are developed instead of a pronounced long crack. One also observes the presence of porosity in both the fusion and the aluminum remelted zone. It can be noted that the intensity of porosity decreases with the lower velocity and is almost nil for the velocity of 0.5 m min^{-1}.

Fig. 14 shows the microstructure of the FZ Al alloy interface for the specimen welded at a speed of 1 m min^{-1} and with the laser power of 2 kW. One observes a solidification crack in the zone of resolidified Al alloy. The crack is intergranular in nature and perpendicular to the solidification direction. Porosities are also observed in the sample. The crack in this region is found occasionally and the occurrence of it could not be generalized with laser parameters used for the study. Solidification cracks and porosity are very often found in laser welded Al alloys [42]. It is noteworthy that in this specimen, there is no longitudinal crack in the weld near the Al alloy interface. This gives an evidence that cracks in the FZ are formed after the solidification of Al alloys. In this case, the solidification crack acts as a sink for the relaxation of the stress in the FZ.

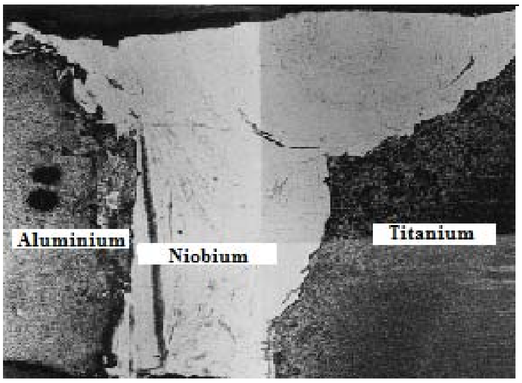

Fig. 15 Cross-section of the specimen welded with the addition of niobium plate

Fig. 15 shows the microstructure of the sample that is welded with Niobium (Nb) placed between Ti alloy and Al alloy. The laser offset is between Ti and Nb. It is interesting to note that no crack is observed in the FZ. Nb melts partially from the two sides of the plate. The average Al content in the FZ is 11 at% which is within the range of Ti solid solution according to the phase diagram [43]. Nb also partially dissolves in the FZ, leading to the formation of Ti solid solution. The high-magnification microstructure around the interface between the Nb plate and the Al alloy reveals that it consists of Al_3Nb globular particles in an Al matrix.

D.Shielding Gas and Filler Metals

In laser welding, the shielding gas is used to stabilize the welding process, to improve weldment features and to protect the seam against oxidization. Besides the type of shielding gas used, the nozzle parameters play a significant role. The chemical compositions of the shielding gas and the flow geometry are key factors limiting the size of the plasma, its contamination by the atmosphere and affecting the final quality of the weld joints. An experimental study of the physical phenomena such as interaction between the plasma plume, shielding gas and laser beam direction using by a spectroscopic investigation under various operating conditions were discussed [44]. A correlation is found between the spectral features and the oxide layers on the surface of the welding seam, caused by poor shielding gas and by the vaporization of elements.

A comparative study has been carried out on the influence of two different shielding gas systems on autogenous laser welding process of AA5083. Bead on plate tests have been performed by using a 2.5 kW CO_2 laser source with shielding gas helium, supplied respectively by a coaxial conical nozzle and a two pipe nozzle. The influence on process parameters of gas flow rate, travelling speed, laser focusing position, and bead details were observed [45]. Several sets of parameters able to produce acceptable welds were selected. The results have presented on the laser butt welding of 3 mm thick plates are very competitive if compared with the state of the art.

A novel approach is presented using filler wire and a highly focused laser beam transverse to the welding direction. The process development for welding in a butt joint configuration was made [46]. The influence of the welding speed, wire feed speed, parameters on wire melting behavior and the welding results was observed. Process windows for joining the sheet metal of 1 mm thickness with 1 mm joint gap, allowable tolerances for laser, wire and gap misalignment were identified. Additionally, the reached gap bridging ability of 1.9 mm for a constant gap and 3.15 mm for an opening gap configuration was utilized for aluminum alloys.

An important feature of laser welding is the ability to use filler metals, which may be introduced during processing in the form of powder or continuous wire feeding [47]. Tolerances of the quality of edges can be widened and the chemistry of weld metal can be controlled. The use of filler metal in laser welding is not currently widespread, principally because of the high degree of control required over the process variables and the lack of knowledge concerning properties of the weldment.

Good mechanical property of the welds with desired appearance was obtained by Ti6Al4V and 5A06Al alloys laser welding-brazing using AlSi12 filler metal [48]. Three types of fractures occur in the FZ, in the interface and the FZ of a mass of the porosities when different heat inputs were used as shown in Fig. 12. Tensile strength of the fracture in the FZ with low heat input is higher than that in the interface and porosities with high heat input.

Joining of titanium T40 and aluminum AA5754 metals with Al-Si filler metals were practically carried out by using laser beam [49]. The important mechanical properties of tensile strength of the joint were observed. LBW brazing of AA 6061 aluminum and Ti6Al4V titanium alloys with Al-5Si filling wire was experimentally conducted [50]. It is found that the influence of Si content on mechanical strength of the joint was indistinctive.

The disk laser welding brazing of an AW5083 to a titanium grade 2 alloy with 5087 aluminum alloy filling wire was investigated [51]. Additionally, laser beam offset distance 300 µm was used toward the aluminum alloy sheet during welding. The highest tensile strength was observed in the weld joint and well refined grain size in the FZ were observed using microstructural observation.

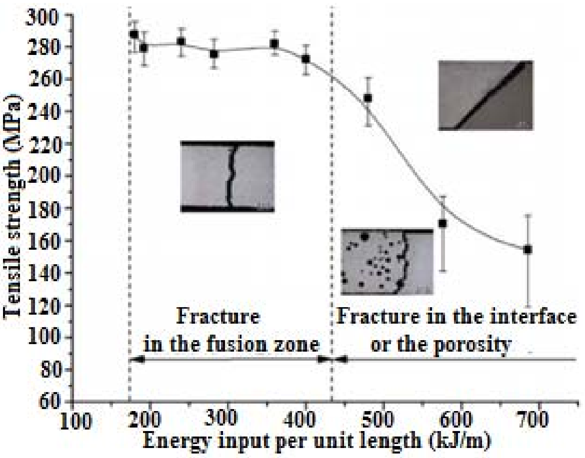

Fig. 16 Tensile strength

III. Conclusion and Future Scope

Followings are the conclusion of this literature review:

1. LBW parameters play a significant role in determining the quality of Ti/Al weld joint.
2. The dissimilar joint quality can be defined in terms of properties such as weld bead geometry and mechanical properties.
3. It has also been observed that the offset distance, welding speed, laser power, shielding gas and filler metals are the most effective parameters followed by depth of penetration.
4. Further, the development of dissimilar welding has come a long way in the past decade, still LBW process is at the experimental stage. The applicability of Ti/Al dissimilar LBW process for industrial purposes is constrained by several key technical issues that need to be further investigated.
5. Research is mainly focused on similar metals. Only few researches have worked on laser welding of dissimilar metals. Still, more studies on the effect of process parameters need to be addressed a better understanding on the Ti/Al dissimilar metal combinations.

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