Progressive developments and challenges in dissimilar laser welding of steel to various other light alloys (Al/Ti/Mg): A comprehensive review

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ABSTRACT

In recent days, the utilization of lightweight alloys for various applications has been increased massively. Starting from the automobile industry, aerospace industry, and even in the biomedical field, there is a need for dissimilar precise joining of steel to other light alloys (magnesium alloy, aluminum alloy, titanium alloy). However, those alloys are characterized by different melting temperatures, machinability, strength, thermal conductivity, and oxygen reactivity. Considering this welding to challenge ongoing laser welding efforts to improve laser welding quality by altering the welding techniques, modes, proper use of shielding gases, using suitable process parameters, and even proper joint and surface preparations are discussed. The feasibility of implementing all those things in the industrial setup can be understood only after analyzing recent works. Changes in microstructure and the defects (solidification cracking, intermetallic components formation, porosity) arrived during and after laser welding of these materials are reviewed. The paper also highlights the effect of shielding gas, welding speed, laser power, defocusing position, etc. during laser welding of lightweight materials. The critical issues related to dissimilar laser welding of these combinations and some remedial measures are discussed. The purpose of this review is to emphasize and understand the recent trends of dissimilar laser welding and explore the scope of industry level applications.

1. Introduction

In the present day, welding of lightweight structural materials has become essential for many companies to reduce the weight of the components [1, 2]. It is also to be ensured that the properties of the materials and nature of the joining are fulfilling the essential criteria required for the product. In addition, the requirement of improving flexibility of design, dissimilar materials joining [3, 4, 5, 6, 7] has created its own place in industry even though it is complicated than similar materials joining. Mixed parts of steel and light alloys have that potential of reducing the weight of the components without compromising strength characteristics [8].

Steel is the most conventional and highly used raw material almost for all automotive and other related industries. Reducing weight can lead to a reduction in fuel consumption and CO2 emission, which can satisfy the green marketing criteria for automobile and aerospace sectors [1]. The hybrid of Steel/Titanium joint has the capability to reduce the cost in power generation and chemical industries [9, 10]. The use of the joint of high strength alloys and low strength alloys like Steel-Mg are much needed combination for reducing weight of structure in automotive sector [11]. Al-Steel hybrid combination is mainly used for the same reason of weight reduction of automotive bodies for reducing the fuel consumption [12, 13]. Therefore, the need to join steel with light alloys like Al, Mg, Ti is noticeable as it can't replace all the parts with similar
light alloys. However, it is not easy to achieve because they have completely different chemical compositions, melting points, mechanical and physical properties. Apart from that, thermal conductivities and the distinct value of thermal expansion coefficient makes the joining process more difficult. Besides, during the process, different stresses like residual thermal stresses are developed [14, 15]. Moreover, during the solidification process, the intermetallic compounds (IMCs) may generate, which gives a true challenge to the welding process [16, 17, 18].

Many fusion welding processes can be used for the joining of dissimilar materials. A process that enables less process time, high flexibility, and low heat-affected zone (HAZ), is desired. A method with low heat input is preferable than another arc based fusion welding processes. Therefore, laser welding is a suitable option. It is a process that uses the energy of a concentrated beam of monochromatic laser for producing fusion weld bead. The central processing parameters are focused on spot size, welding speed, and beam power. Inert gases like helium/argon are used to protect the weld bead from contamination and prevent the generation of absorbing plasma [19, 20, 21].

The paper aims to describe some challenges and some possible solutions to overcome these challenges considering its field of application. In the emerging world, the transportation industry approaches a step to replace steel as a significant structural material. Petrochemical and biochemical industries are also considering it because those light alloys also provide them high specific strength, high-temperature performance, excellent corrosion resistance, and biocompatibility.

The weldability of steel to other light alloys mainly depends on the crystal structure, atomic diameter, and solubility of composition in liquid and solid states. During the process, the IMCs forms are brittle and hard, which hampers the mechanical strength of the joint [17, 18, 22]. The reduction of IMCs formation is a significant challenge. Laser welding is a process where high cooling and solidification rates can be achieved. This property of Laser welding will reduce the risk of excessive formation of brittle intermetallic phases and the risk of segregation [23].

These reviews also try to highlight some proper laser welding techniques that might support the welding of those materials. The laser can be used mainly in two wave modes, i.e., pulsed mode and continuous mode. Pulse laser produces pulses of lasers, which leads to lower heat input and higher efficiency compared to continuous mode [24, 25, 26]. According to the intensity of the laser power and the melting temperature of the materials, laser welding can be carried out by conduction and keyhole mode. Conduction mode generally indicates a lower penetration. Keyhole laser welding results in a deep penetration as metal surface vaporized and traps more power by repeated reflection in keyholes [27, 28]. Laser welding can be done by autogenous or by using a wire metal. Laser offset [29, 30] also has a significant role in mechanical and microstructure during laser welding.

Moreover, the adaptation of proper process parameters [31, 32, 33] is essential as far as the welding quality and integrity are concerned. The shape of the weld bead is sometimes affected by the process parameters. This is the main reason to focus on the relations between weld bead and process parameters. It is also noticed that laser beam oscillating [34] welding can reduce the hot cracking sensitivity for some alloys. The selection of shielding gas [35, 36, 37] as per the type of laser source is significant to control the penetration of the welding. Plasma control is the main issue when considering CO₂ laser. Nd-YAG laser may suit different shielding gas for getting an improved penetration [38].

In some cases, edge preparation decides whether the welding process will be a single pass or multi pass process [39, 40]. All variations have their advances and drawbacks according to the material and other influencing conditions. Sometimes coating [41, 42, 43] on the welding metals may result in the desired output. However, it is essential to understand that the differences in steel properties and these alloys give challenges in every step of joining. This paper overall reviews these challenges and highlights the probable solutions tried so far to reduce it.

2. Challenges of dissimilar welding of steel with light alloys (Al, Mg, Ti): emerging developments

In last few decades’ automotive industry is realizing the need of reducing fuel consumption which results low CO₂ emission as well. Therefore, some light alloys have become an alternative in some components where replacement of steel is possible. There are various methods of joining two different parts whether it may be similar or dissimilar. Considering the permanent joints of materials riveting is always a good option but it again unable to fulfill the reason of replacing steel. A riveting is putting an additional weight and makes the entire process inefficient. Therefore, welding is the probable and may be suitable option an industry can go for. This paper focuses only on the most useful light alloys which already prove themselves as useful. The challenges [44, 45, 46] of Joining of steel with Mg, Al and Ti are further reviewed. The effectiveness of any welding process is greatly depending on the physical properties of the materials to be welded. Therefore, a general comparison of some properties is shown below in Table 1 [47].

Steel is widely used structural material as it has a high tensile strength and it is cost effective as well. In other hand Al has a very low density, High corrosion resistance, good strength to ductility ratio with sufficient availability. The combination of steel and aluminum can provide good formability, moderate strength, low density, a very good corrosion resistance at low material cost. The main technical challenge of joining Steel-Al [8, 23, 44] is formation of IMCs (mainly AlₓFeᵧ) during solidification [Table 2]. Apart from that these two materials have noticeable differences in thermal properties like melting point, thermal conductivity, Coefficient of thermal expansion, etc.

Figure 1a shows that Fe and Al has less solubility in solid state [44] so presence of IMCs in the welding interface is unavoidable. Among the AlₓFeᵧ compounds Al rich IMCs are more brittle than Fe rich IMCs. Differences in thermal properties generate thermal stresses in welding surface and generate a chance of brittle failure [48]. Al rich IMCs have very high hardness and low fracture toughness. For producing a reliable joint, the thickness of these Al rich IMC layer is one of the keys and probably the major challenge also [49, 50, 51]. It is also explored that IMC layer thickness increases with increase of heat input [52]. It is also studied that a higher

### Table 1. Comparison of properties [47].

| Properties               | Steel   | Stainless Steel | Aluminium | Magnesium | Titanium |
|--------------------------|---------|-----------------|-----------|-----------|----------|
| Density [g/cm³]          | 775-805 | 775-805         | 2.7       | 1.74      | 4.5      |
| Elastic Modulus [GPa]    | 190-210 | 190-210         | 69        | 46        | 100-120  |
| Thermal Expansion [10⁻⁶/K] | 9.15    | 9-20.7          | 23.1      | 25        | 8.4      |
| Melting point [°C]       | 1370    | 1454            | 660       | 650       | 1668     |
| Thermal Conductivity [W/m-K] | 26-48.6 | 11.2-36.7       | 237       | 156       | 17       |
| Electrical Resistivity [10¹⁶Ω-m] | 210-1251 | 75.7-1020       | 27.5      | 9.5       | 55       |
| Tensile Strength [MPa]   | 758-1882 | 515-827       | 110       | 135-285   | 1060     |
| Yield Strength [MPa]     | 366-1973 | 207-552        | 95        | 80-280    | 1480     |
| Hardness [Brinell]       | 149-627 | 137-595         | 245       | 260       | 716      |
melting pool diameter and lower welding speed can accelerate the IMC formation [53]. Fe and Al have different electrochemical potentials which lead to an unexpected corrosion behavior. A potential difference of 1.22 V is enough to create a corrosion rate flow between the two metals [54]. Mg is proved as a promising structural material like aluminum for its highest specific strength and lightest specific gravity. Steel and Magnesium (Mg) have a huge difference in melting point i.e., around 900 °C and very low solubility to each other which makes the joining process difficult [55]. The differences of other electrical/thermal properties between Steel-Mg are also significant as well. Usually, fatigue Strength of dissimilar welds is less than the similar welds of those materials. Apart from these Mg alloys have a high tendency to oxidize and low boiling temperature. Highly brittle intermetallic phases of TiFe, TiFe2, and Ti2Fe start forming in between the process. Dissimilarities in thermal properties generate thermal stress which leads to spontaneous cracking of joint. It becomes very difficult to control the molten pool of Ti–Fe in traditional fusion welding processes.

3. Advancements on the laser and laser welding

LASER is basically acronym for “Light Amplification by Stimulated Emission of Radiation”. Basically, it is a beam of stimulated photons of same phase and travelling in same direction. One of the major three laser components is an active medium of any laser active materials. The main difference of a laser active and laser non active material is the higher energy states of laser active materials are comparatively more stable than other materials [59, 60, 61]. Laser system also requires a pumping source of light which excites the molecules of the active medium. It may be coherent or incoherent light source. Once the molecules of active medium got excited, they move to higher energy level. Every ion tries to retain its lower energy state to become more stable. By any chance if one ion moves to lower energy state it releases energy as photon. One single photon stimulates another to come to lower energy state and to produce more photons. Finally, the most important task is done by the optical resonator [59, 60, 61]. Some optical mirror is placed in a way that complete reflection of photons is possible. Resonator also amplifies the lights and provides them a direction which is parallel to the axis. In every pass some amplified unidirectional monochromatic photons are released as laser beam by a transmitting window. The mostly used laser materials are carbon dioxide (CO2), neodymium-doped yttrium aluminium garnet (YAG; Nd: YAG), carbon monoxide (CO), neodymium glass (ND: glass), ytterbium-doped YAG (Yb: YAG) etc. [59, 60, 61]. Laser welding uses this power of LASER to join to materials of same or different properties by using the concept of fusion welding process. The photons released from laser beam transmitting window are focused on that place where joining is required and the arrangement is done in such a way that it covers the entire length as exhibits in Figure 2.

Laser welding process is performed generally by using two modes [62, 63, 64, 65]. They are conduction mode and keyhole mode [27, 28]. In conduction mode laser energy is distributed to base metals by conduction only. No evaporation takes place in this mode. In conduction laser welding only 20 % of beam energy is used for melting the material. A Part of the joint is melted by the laser beam and heat is then transferred by conduction to the other parts [27]. Naturally low penetration but wide area can be covered using this mode. Conduction mode welding results in a superior finish and almost free from porosity defect. This mode is suitable for joining of thin sheets. In case of keyhole mode power density is much higher, it uses almost 70–80% of the total beam energy. Due to higher energy, evaporation of base metals takes place. Narrow fusion zone and heat affected zone can be achieved with a high penetration and good welding efficiency. Only drawback happens with this mode is a poor porous surface finish which needs a further process [28, 66]. Figure 3 represents a fish bone diagram of laser weld process for dissimilar materials.

3.1. Modes of operation

Laser can be used by two operational mode named pulse mode [67, 68] and continuous mode [61, 68] that means lasers can be emitted either pulsed fashion or continuously. The wattage calculated for the pulse mode is the product of energy per pulse and no of pulses per second (Hz). In other hand in continuous mode, we can consider the average power. During pulse laser welding of stainless-steel control of weld temperature is comparatively easier as it absorbs laser photons in a good manner but it becomes difficult for aluminum and magnesium as it melts in very narrow temperature range and melting point is low as well. Since the duration of typical pulse laser is very short i.e., 1–10 milli seconds, so it becomes very difficult to measure the welding temperature during the process [69]. The weld result can only act as a good estimator. Pulses of short duration and high peak power can create good penetration but

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**Table 2.** The most common intermetallic compounds (IMCs) are found in the steel/Aluminum fusion joints [44].

| Alloys | Composition |
|-------|-------------|
| Fe (wrought alloys) | AlFe, AlFe2C, Al3Fe, Al3Fe2, Al2Fe3 |
| Fe (Cast or wrought Al alloys) | Al2Fe,AlFeSi, Al3FeSi, Al2Fe3Si |
| Fe (excessive Zn)/Fe | Al2Fe2Zn3 |

**Figure 1.** (a) Al–Fe binary phase diagram [57] (b) Ti–Fe binary phase diagram [58].
chance of spatter increases [67]. In other hand pulses of long duration and low peak power produce a shallower weld with lesser spatter. In a study of Al–Mg–Si and Al–Mn aluminium alloys [70] The molten pool formed in a continuous type [Figure 4(a)] [70] and had a porosity distribution less than 0.05 mm from crack end on the dissimilar metal bonding interface with major porosity formed in the left side of A6062, in the bottom joint of the welded portion the crack has been formed, mainly due to structural problem. Though when the mode of welding is pulse [Figure 4(b)] of 500 Hz frequency, the porosity portion is distributed along the small molten zone. The possible reason is the air inside the weld bead unable to escape from the system. Pulse width also plays a crucial role in a laser welding process of carbon steel and austenitic stainless steel. HAZ width decreases with increase of pulse width [71] but it has no effect at all in a mechanical property like ultimate tensile strength. Assuncao et al. [72] have tried to compare the material interaction of both CW and PW mode keeping the other conditions similar. Results shown that due to higher spatial peak power density, PW mode gives a good penetration in Al sheet. Moreover, keeping same heat input in CW mode increases the IMC formation. Under controlled and optimal processing condition in pulse mode it is possible to reduce the thickness
of IMC layer. Micro hardness testing of the welding zone shows slightly more hardness compared to the base metal in the aluminium section though for steel portion it shows a satisfactory and almost defect free result [73]. For titanium CW mode is mostly used for its lower operating cost, excellent beam quality and higher efficiency. In other hand when thin sheet is concerned, pulsed wave mode is dominating for its properties like lower heat input, narrow weld bead rather narrow HAZ and less solidification time [74, 75, 76].

3.2. Laser heat input source

Any laser joints either for similar or dissimilar materials are done mainly using CO₂ and Nd: YAG laser heat sources. Recently fiber lasers are also used in different industrial applications. It is noticed that for the thin sheets of aluminium and magnesium YAG based lasers are more advantageous from the viewpoint of controlling the heat input [21]. Fiber laser welding of steel and Mg gives near about a strength of 100 MPa and many drawbacks of joining this combination can be avoided [56]. In some occasions CO₂ laser and fiber laser are used for joining of steel-Ti, Steel-Al/Mg by applying a specific method of laser roll welding. A good result can be achieved by controlling welding speed, laser power and roller pressure. Interlayer thickness and production of intermetallic metals can be minimized [77, 78, 79]. However, Nd: YAG laser is suitable for Ti alloy for good weldability and performance compared to the other two heat input sources [80].

3.3. Welding parameters

There are many important factors which decide the quality of a laser welding. Quality is not only an external matter of the weld. A good quality welding has to be internally up to the mark. Welding speed, laser power and defocusing distance. All these are the deciding parameters for a laser welding. Defocusing distance is the distance between the focal plane of laser and work piece surface. It helps to get the power density on the work surface and the spot diameter as well. Figure 5 [81] reflects the effects of the welding parameter (focus length) on penetration depth for two dissimilar steel alloys. It is important to generalize the effects of these parameters irrespective of material and some other factors. Though for the laser welding of steel to Al, Mg or Ti the impacts may vary according to the particular case. Zhang. M et al. [82] examined the effects of these parameters of fiber laser welding for the new hot-rolled nano scale precipitation-strengthened steel of thickness 4.5 mm. It is observed that increase in laser power increases the downward flow of molten metal which produces more root humping. With the increase of welding speed, the width of the weld seam decreases and also hardness of the weld seam and HAZ increases. This study concluded with some optimum values (laser power 3KW, welding speed 1.2 m/min, and defocusing distance -2mm) for 4.5 mm thick NPS steel. Another study [83] concluded the same thing for laser welding. Up to a certain limit of welding speed the weld width decreases and produces less HAZ but further increase in speed may result in insufficient melting. Aluminium alloys face a major problem of porosity for any type of fusion welding. A study with two dissimilar aluminium alloys [84] concluded that weld geometry is affected by welding speed, laser diameter and laser power. In micro-structure study the similar effect is not noticed that much. The hardness is also less dependent on these parameters though it gives poorer result than friction stir welding.

A study [85] with dissimilar fiber laser joining of Al and Steel of a lap configuration. A constant laser power of 400 W is used and 12 different combinations of speed and defocusing distance are considered for investigation. After the metallographic examinations the papers come out with an optimum welding speed of 0.5 m/min and -2 mm defocus. Some kind of problem arises with steel and Mg laser dissimilar welds. Due to differences in thermal property a very high-power laser with a low speed can do the work for the steel but Mg portion gets a very large HAZ and weld width. Similarly, for Steel portion did not get the required penetration if welding speed increase or laser power decrease much [86]. Optimal values with some other strategy implementation can provide a comparatively satisfactory result. In general, high welding speed can reduce the formation of IMCs in the fusion zone as it affects the solidification rate directly [87]. Higher welding power and reduction in welding speed are the effective parameters than the others which result in increase of entire dimension of molten pool i.e. width and depth [88]. Welding power has a significant role in thickness of IMCs and interfacial temperature. These two responses have shown higher value in higher laser power [89]. Apart from welding speed and laser power nozzle distance is another powerful parameter for fiber laser welding. Reduction in nozzle distance reduces the tensile strength and significant increment in tensile strength (almost 20%) has been noticed with the increase of nozzle distance [90]. In other hand porosity decreases with the decrease of nozzle distance as the depth of weld bead increases [90]. In pulsed mode welding along with all these welding parameters one another impactful parameter is pulse duration. Tensile strength, elongation and related temperature gradient. Higher peak power indicated higher temperature and short cooling span. This increases the chance of the welded joint to be brittle but elongation decreases [91]. Figure 6 [89] shows the effect of heat input in fracture strength of Steel/Al laser welded lap joint. The figure indicates that the fracture strength increases with laser power up to an optimum level and then it started decreasing. Some modern optimization techniques can be adopted for choosing suitable parameter values [92, 93, 94].

3.4. Shielding gas

The atmospheric welding has a very obvious economic advantage but oxygen contamination in the welds produces porosity, spatter and slag of
undesired level. Sometimes it affects other mechanical properties too. Helium and argon inert gases and generally used as shielding gas. Ar is mostly used commercially for its low price compare to the He gas. In modern application some reactive gases like N₂ and CO₂ is partially mixed with those inert gases if that does not create such noticeable metallurgical defect. It is important to consider the effect of the shielding gas as it takes a vital role in solidification behind the weld pool [95]. The use of pure N₂ is also noticeable in recent days for his lesser cost even from Ar gas. Elmer. J.W et. al [96] have shown that steel and Stainless steel the results hardly differ when using N₂ instead of Ar. The welds are almost porosity free. But in another study [97] it is found that for Al and Mg welds quality is improved by using He as inert gas than Ar. A study for these two materials the load carrying capacity is also improved in case of He. A study of a high power laser welding of AISI 304 concluded [98] that N₂ is giving more porous free welds than Ar. N₂ shielding gas helps to produce a deep welding seam and narrow molten width. Ar as shielding gas forces to reduce the welding speed than N₂ shielding gas for CO₂ laser welding whereas mixture of N₂, He and Ar gives a satisfactory result [99]. He, Ar or mixture of He–Ar proves to be effective for the welding of titanium weld. According to the combination of the base metals the selection of shielding gas is to be done and it must be economically advantageous as well. Table 3 has exhibited a comparative effect of shielding gas for different process and demand conditions.

3.5. Surface preparation

The formation of IMCs can be suppressed by controlling the time of liquid/solid interfacial reaction or the temperature. Noticeable difference in melting temperature of steel to these light alloys leads to uneven penetration which reduces the quality of mechanical properties of the joint. Surface preparation is an integrated part of dissimilar welding. Various investigations have been done for realizing the effects of surface preparation [Table 3] and to improve the quality of welding. In a study of steel-aluminum overlap joint [107] using laser welding with/without Ni foil concluded that by using Ni foil formation of crack in the interface can be suppressed. Ni foil can improve the tensile property of joint and decreases the micro hardness of the IM regions. Ni coated steel and Mg joint can provide a joint efficiency of 88.50 % relative to Mg base metal [108]. Maximum tensile-share fracture load of 230 N/mm can be achieved with a coating thickness of 20 μm. In a laser welding brazing process, the weld strength of Mg to Zn coated steel can be improved by at least 20 N/mm compare to the Mg to non-Zn coated steel [109]. A clear reaction layer is visible in the interface of Mg and Zn coated steel which is not present in case of non coated steel. Ni coating in laser welding of steel and aluminium acts as a barrier of direct mixing of Al and Fe which reduces the formation of Fe₂Al₅ for the very obvious reason [110]. The fracture load can be improved up to 200–250 N by using Ni coating and micro hardness can be reduced up to 150–200 HV as well. In a study of continuous laser joining of Steel and Ti alloy through 1 mm vanadium foil [104] has come out with a result that two pass welding is giving

Table 3. Effect of shielding gas and transition material.

| Laser type                          | Materials                                      | Design of joints | Thickness | Shielding Gas | Transition material | Remarks                                      | References |
|------------------------------------|------------------------------------------------|------------------|-----------|---------------|--------------------|-----------------------------------------------|------------|
| CO₂ Laser/CW mode (maximum power 15 kW) | Aluminum alloy A5083/ Stainless steel type 304 | Butt             | 6–10 mm   | (i)He         | (i)N₂              | He shielding gas produces more porosity than N₂ under same welding conditions | 100        |
| Fiber Laser/CW mode (maximum power 650W) | DXS4 Zn coated steel/ EN-AW-5754 Al alloy | Lap              | 1 mm/1 mm | (i)Ar        | Zn                  | (i) Degree of corrosion reduces with higher density of Gas. Therefore, welds by Ar give better result. (ii) N₂ results in Less hardness variation and better strength | 101        |
| Diode laser/CW mode (2.2 kW laser power) | AZ31B–H24 magnesium alloy/Steel sheet | Lap              | 2 mm/0.6 mm | He           | Sn coating on steel sheet and Mg–Al–Zn brazing alloy wire filler | Porosity or cracks were not observed in the joint. the tensile shear strength of the interface was greater than 27.5 MPa | 102        |
| disc laser/CW mode (5 kW maximum laser power) | AZ31B magnesium alloy/ Zn-coated and uncoated steel | Lap              | 3 mm/1.2 mm | Ar gas       | (i) Zn Coated (ii) Uncoated | Uncracked steel produces 1.5 times more strength than coated steel (average load of 6182 N) in keyhole mode. | 103        |
| (i) Yb: YAG laser (CW mode) of 6 kW maximal power | (ii) Nd:YAG laser (pulsed mode) of 1.05 kW average power | (i) AISI316L/Ti6Al4V (ii) Ti–6Al–4V/301L stainless steel | Butt (i)2mm/2mm (ii)0.8mm/0.8mm | Ar gas (i)mentioned (ii) Not | (i)1.06 mm vanadium foil (ii) Copper inter layer | (i) Single pass produces 130 Mpa Maximum strength and double pass produces 367 Mpa maximum strength. Joint is almost crack free (ii) Average tensile strength 350 Mpa. | 104,105   |
| Nd: YAG laser/Pulsed mode (peak power 4.5 kW) | Commercially pure titanium/304 stainless steel | Lap              | 0.25 mm/0.25 mm | Ar           | NA                  | Average hardness Fe rich islands are 429 Hv and Ti rich islands are 284 Hv. Maximum strength got 70% of the pure Titanium | 106        |
satisfactory weld strength. This joint has a has tensile strength of 367 MPa which is 92% of the annealed V. Nd-YAG pulsed laser welding of Steel and Ti alloy by using copper interlayer [105] has a joint tensile strength of near 350 Mpa. Cu layer reduces the brittleness and improves the mechanical properties. It is also noticed Ti-Cu intermetallic layer is continuous and has a fix thickness in the Titanium alloy side.

3.6. Joint preparation and filler materials

Joint design is considered as an important step of laser welding. A proper joint design can fulfill the requirements of any particular application which might not make possible without it. Joint preparation shows its value mostly when the thickness of the materials is more than usual. It decides whether the laser welding process would be a single pass process or a multi pass process [39]. In other hand filler materials helps to improve the mechanical properties of the joint and reduces the chance of under fill. Filler can be used in a form of wire or powder as well. Joints can be done in form of butt [111, 112, 113], T joint [114], lap joint [107, 115]. The most commonly used configuration is butt joint configuration. It can be performed by both autogenously and with the help of filler. M.M. Atabaki et. al [111]. has investigated a narrow gap butt joint of a structural steel (A36) with the help of high laser power. Full penetration and defect free welds were achieved at the optimum condition of 7KW laser power with the help of cold filler wire. It is noticed that autogenous welding produces more brittle welds than the other. Some wire filler was used in between the two plates which had a gap of 2.5 mm in between. By using this technique double sided I joint of 50 mm thick plates can be achieved. S. Chen et al. [116] investigated the overlap joint of steel and aluminium with controlled laser power and got a satisfactory result. Apart from joint preparation, selection of filler gives added quality assurance of the joint. R. Cao et. al [117] were investigated and tried to make a proper selection of filler wire for 3 mm thick Mg AZ31-to-1 mm thick galvanized steel. That study revealed that use of Ni based wire can produce more weld strength than Cu base wire for that particular materials and process. Ni powder in dissimilar welding resulted in reduction of micro hardness of the weld zone and made the composition more homogenous [118] compares to the Ni foils. H. Li et. al. was investigated on TiNi alloy and stainless steel by using Co and Cu as filler materials [119, 120]. At a thickness of 20 μm Co filler the joint strength is maximum (347 MPa), further increase in thickness decorates the mechanical property. Although Cu filler metal has an ability to raise the mechanical strength of the joint up to 520 Mpa at a thickness of 80 μm. In addition, filler powder has an ability of increasing the utilization of laser power which reduces power requirements [121, 122]. When investigating the effects of filler wires in dissimilar welding M. Mohammadpur et. al [123], has concluded that Zn based wire produced highest mechanical resistance and Al based filler wire offered a good surface finish.

3.7. Effects of groove geometry

Effects of different type of grooves [124] like V groove, square groove, J groove, Y groove etc are also there. L. Li et. al [124]. nicely concluded the effects of the different groove shapes on laser welding brazing of steel and aluminium. The best spreading of filler metal was achieved in bottom surface with half V groove shape. The fractured path for different groove shapes was different [Figure 7]. Even 25 mm thick steel plates can be joined by hybrid laser welding in single pass with square groove butt joint [124]. A. Huang et.al [125]. noticed that for the thick and medium plates, the latter bead welding process should properly increase the heat input to reach sufficient width of weld to keep away from the lack of fusion in the side wall for V grooves. In case of L-type groove, the width of the weld of latter bead would comparatively increase with the decrease of groove constraint and as a result of it the heat input can be reduced during the process which results in low energy consumption. Symmetric V-grooves has capability to increase the apparent look of the weld and in some extend it has also an effect on tensile strength of joint [126]. The impact of Y-groove angle [127] is also noticeable for getting ideal weld bead shape. A Y-groove angel in between 20°-30° is suitable medium and heavy plate.

3.8. Offset position

The meaning of laser offset [29, 30, 56] is the biasing of laser focus by a certain distance either side of the welds. Offset can be an effective technique while the welds are not similar material. The primary aim of laser offset is to reduce the temperature of the welding interface. The offset amount will determine how much the interface temperature will decrease and most importantly in which side with respect to the interface the focus is shifted. It is normal that the maximum temperature will be reached at the focus point line but it should be remembered the welding happens in the interface only. Now the situation is, there are two dissimilar materials to join having differences in thermal properties but it has to be joined smoothly. The initial part of concern is the melting of two working material. One must be having higher melting point than the other. Now in a situation when the laser is focusing on the interface, one of them will reach the melting point fast and will melt more at a higher temperature as long as other attains its melting temperature and start melting. If the difference is nominal, then offset might not necessary for that occasion. The entire scenario may differ if the configuration of joint is lap.

High intensity of laser beam vaporized the Mg alloys by direct irradiation while joining with a combination of Mg-steel alloy [56]. Offset welding is useful to overcome this drawback. Laser beam focuses on the steel side at a parallel line with interface and melts it, then heat is conducted and convected and makes the Mg surface wet. A lower offset may result in cracking as the solubility of Steel-Mg in normal atmospheric pressure in liquid state is very less. In other hand a larger offset has

Figure 7. Fractured path for different joints: (a) square-shape groove at steel side, (b) half Y-shape groove at steel side, (c) half V-shape groove at steel side [124].
created an incomplete welding as the interface temperature was not enough to wet the Mg base metal.0.6 mm laser offset was found as the optimum one [128, 129]. Similar kind of situation arises for joining steel with aluminum in butt configuration. At an offset of 0.2 mm the spontaneous crack was formed due to excessive production of brittle IMCs. Offset of 0.4 mm and 0.6 mm gives a good result and nominal IMC formation comparatively, further increment in offset distance results in incomplete welding though IMC formation decreases [130, 131, 132]. The shifting of laser beam should be towards titanium side for joining it with steel alloy when no interlayer is used. The fracture occurred in SS side when the offset distance is 0. 25mm. Offset of 0.35 mm comes with a very effective result with a nominal Ti–Fe IMC formation while 0.45 mm offset can also generate a fusion weld zone but the strength reduces due to insufficient wetting of SS. When the laser offset was 0.55mm, the laser spot was too far away from the interface, and the weld zone could not be formed properly [133]. By using single Cu interlayer and composite Cu–Nb interlayer in between Steel and Ti alloy and offset the laser beam toward Steel side significantly reduces the production of brittle IMCs. At a range of Offset distance of 0.4–0.6 mm results in improved quality of welding [134, 135].

4. Scientific discoveries and novel advances in the mechanical properties of welded-joints

The metallurgical structure of welds has the most influence on mechanical properties of welding. Microstructural observations are essential for identification and improvements of some mechanical properties like hardness, tensile strength etc. Some specific micro level observations become more impactful when the joining occurs between two dissimilar materials with differences of thermo-mechanical properties. Mechanical property after Joining of steel and aluminium is mostly depends on the type and thickness of IMCs. Keeping it in mind other conditions need to be modified. This is applicable for other dissimilar joints also as in all cases there are some certain constraints which hampers mechanical properties of joints. Researchers are trying to get probable solution on particular case wise. A Comparison [Table 4] of joint strength and micro hardness of dissimilar laser welds under different conditions:

The interface should get the sufficient power so that the surface gets sufficiently wetted. Power density takes a vital role in determination of the thickness and IMC layer; similar laser spot energy results in thicker IMC formation for higher density of power [136]. Laser welding of Steel/Al [65] the best tensile shear strength of 130 MPa was observed for an IMC layer thickness of 10 μm when the materials are welded using copper backing bar and, in all conditions, the minimum tensile strength is higher than the strength of the weakest materials. The loss of alloying element should be avoided for Mg/steel combination also. Direct irradiation of high-power laser needs to avoided [56]. Low power fiber laser produces higher strength [139] in case of butt joint of Mg/Steel alloy than high power disk laser source [56]. Use of vanadium foil nano powders and Cu interlayer has a positive response for improving the joint strength of Steel alloy/Ti alloy [104, 138, 141].

5. Residual stresses

The most significant feature of laser welding process is rapid heating and cooling. During this process with dissimilar metals nonuniform expansion and contraction weld pool and base metal region results in distortion and finally develops residual stresses within the joint even in no loading condition. The most granted property which is responsible for this residual stress is coefficient of thermal expansion. There are also differences in yield strength which limit the magnitude of it that can exist in the materials. Generation of excessive residual stresses can lead to distortions, premature failures, fatigue cracking and many other severe problems. Residual stress generated in a weld joint can be measured by some surface based techniques [142] named centre-hole drilling [143], magnetic methods and X-ray diffraction [144] or by some volumetric techniques such as the inherent strain method, deep hole drilling, the contour method, neutron diffraction method. Laser welding of steel/Mg faces a faster exposure of weld region and narrow volumetric weld zone which is beneficial if comparison is made with the other fusion welding processes. The nature of stress on the fusion zone is tensile and on the base metal it is compressive which is very normal. The residual stress on the steel plate is lower than that on the magnesium plate which could be lesser up to 60 MPa, not only that the deformation on magnesium plate is about 2.8 mm

| Laser type | Materials | Design of the joint | Thickness | Transition material | Strength of the joint | Max Micro hardness | References |
|------------|-----------|---------------------|-----------|---------------------|---------------------|-------------------|------------|
| Fiber Laser/CW mode (8 kW maximum power) | XF350/AAS5083-H22 | Lap | 2mm/6mm | No | 31.3 kN (Max share load) | 1145HV | 136 |
| Fiber laser/CW mode (8kW maximum Power) | DCO4 steel/6111-T4 aluminium alloy | Lap | 1mm/1mm | No | 130 Mpa (Max) | 968 HV | 65 |
| Nd: YAG laser/Pulsed mode (average power 6kW) | DP1000 steel/aluminium alloy 1050 | Lap | 1mm/1mm | No | 140 Mpa (Max) | Not reported | 5 |
| Fiber laser/CW mode (maximum power 5kW) | DF590 dual phase steel/A6061 aluminium alloy | Butt | 2mm/2mm | ALSi12 wire filler | 196 MPa (Max) | Not reported | 137 |
| Nd: YAG laser/Pulsed mode (average laser power 300W) | 316L stainless steel/1060 pure aluminium alloy | Lap | 0.8mm/0.8mm | No | 46.2 N/mm | 700 HV | 138 |
| Nd: YAG laser/Pulsed mode (average laser power of 1.05 kW) | TC4 titanium alloy (Ti–6Al–4V)/3011 stainless steel | Butt | 0.8mm/0.8mm | Cu interlayer | 350 MPa (Avg) | Specific value not mentioned | 105 |
| Disk Yb:YAG laser/CW mode (maximum available power of 10 kW) | AZ31B magnesium alloy/316 stainless steel | Butt | 3mm/3mm | No | 100 MPa | Not reported | 56 |
| Fiber laser/CW mode (6kW maximum power) | AZ31B Mg alloy/304 stainless steel | Butt | 3mm/2mm | No | 211 MPa | Not reported | 139 |
| Nd: YAG laser/CW mode (4 kW maximum power) | AZ31 magnesium/22MnB5 steel | Lap | 1.5mm/1.5mm | AZ61 welding filler | 213 MPa | Not reported | 140 |
| CO2 Laser/CW mode (4 kW maximum power) | Ti–6Al–4V titanium alloy/201 stainless steel | Butt | 1mm/1mm | No | 150 Mpa | Not reported | 116 |
| CO2 Laser/CW mode (2.35 kW maximum power) | VT1–0 titanium alloy/12Kh18N10T stainless steel | Butt | 2mm/2mm | Nano Powders | 335 MPa | 420HV(Avg) | 141 |
| Yb: YAG Laser/CW mode (3 kW maximum power) | A15316L stainless steel/Ti6Al4V titanium alloy | Butt | 2mm/2mm | Vanadium foil | 367 MPa | 440HV(Avg) | 104 |
which is greater than that of steel plate [145]. The reason behind the above two statement is justified as the Mg plate will achieve a higher temperature gradient than the steel plate. Figure 8 [145] plotted and compared the residual stresses from XRD result and simulated result on middle cross section and on the top surface for steel and Mg alloy.

Asymmetric stress distributions, welding distortion noticed for laser welding brazing of Steel/Al alloy. Al has a high temperature range than steel so it is obvious Al side will have larger tensile stress distribution but deflection of the steel side is larger. Thus, laser welding brazing has now a relevant approach when the dissimilar metals have larger differences in properties like Steel and Aluminium [146, 147]. In a laser welding process of Steel and Ti alloy shows the similar pattern of compressive and Tensile strength and by using copper/vanadium interlayer/Ni powder the stability of the joint has been improved [104, 118, 148]. The difference of melting point of Ti6Al4V and steel is around 200K and for this the difference in the average compressive strength generated in base metals is very nominal. The tensile stress generated in weld pool region have a higher value than the base metal compressive stress [148]. In addition, development of thermal model in any FE software for predicting temperature distribution [149] and residual stress is important and assessment of optimum laser parameters are to be done by using any optimization technique.

6. Metallurgical observations

6.1. IMCs formation

One of the big challenges and probably the biggest challenge of dissimilar welding is formation of brittle IMC layer which directly affects the mechanical property of the welding. The thickness and the compounds of the IMC layer should be analyzed with the change of different input parameters or processes. Sometimes IMCs formation depends on the specimen location for dissimilar lap welding. Different specimen location produces different type, size and amount IMCs [87]. It is investigated those IMCs which Fe richer are ductile and tough for dissimilar joining of steel to other alloys. It also suppresses the hot cracking and produces good strength [150]. It is also noticed in a study that laser power influences the thickness of the IMC layer [151]. Figure 9 [151] has shown the formation of IMC layer thickness at a laser power of 1800 W in an input laser power of 1800W of a butted weld joint of steel/Al has shown a 2 μm average IMC thickness layer which is less than the thickness noticed in 2200 laser power. Considering sound welding as most important criteria, an optimum balance between the other parameters needs to be maintained. R yuan et. al [147] has found almost the similar kind of outcome during their study of laser welding of Steel/Al in lap joint configuration. In both the cases maximum strength of the joint is achieved at an optimum value of laser power in between the maximum and minimum input power considered for study. Filler materials like Si and Zn can suppress the growth of interfacial reaction layer and brittleness of the reaction layer [152, 153]. Use of Cu interlayer in dissimilar laser welding of TC4 Titanium alloy and 301L steel alloy reduces the brittleness of the of the IMCs as it gets the diffuse distribution. It also helps to reduce the Ti–Fe IMC formation. Uneven microstructure distribution developed due to fast heat and solidification process in pulsed mode [105]. Role of IMCs in the interface layer for Mg and Steel could be different. Low solubility of Mg and Steel in liquid state creates a need of bonding compound which has a good solubility of both materials. In a Laser welding brazing of magnesium alloy and Sn plated steel alloy with

Figure 8. Residual stress distribution on hybrid butt weld, (a) on middle cross-section and (b) on the weld top surface [133].

Figure 9. [151] IMC layer of steel side in laser power of 1800 W a) upper portion of weld bead b) Bottom portion of weld bead.
Mg–Al–Zn alloy filler metal, IMC Al₆(Mn, Fe)₂ plays the role of common bonging material [102]. Offset laser welding of Mg-Alloy-Steel in butted configuration proved to be effective in reducing the thickness of IMC layer [56].

6.2. Cracks and pores

Formation of micro cracks and in some cases excessive micro pores affects the quality of welding. Scanning Electron Microscopy (SEM) analysis is needed for revealing the crack initiations. It is impossible to remove these defects completely from dissimilar welding but it can be kept in control definitely. The main reason of generating micro pores near the fusion zone is the gases trapped in the solidifying weld pool. One other reason may be collapse of unstable keyholes of laser welding process. H. Chen [101] et al. has observed that the porosity cannot remove completely in welding of steel alloy and aluminium alloy. The pores are mainly around the fusion zones. It is reduced up to a certain level by applying another defocused laser beam. Hydrogen has a good solubility in magnesium which indicates that hydrogen pores are less part of concern for Mg alloys than Al or Ti alloys. Another interesting observation has made by X Gao [154] et al. that overlapping factor value of than 75% can be very fruitful for reducing porosity of Ti alloy in pulsed mode. Even high-power CO₂ laser welding in the presence of N₂ shielding gas can suppress the porosity formation effectively [100]. Autogenous offset welding of Mg alloy and 316 Steel alloy of 3 mm thickness with a disk Yb-YAG laser of maximum power 10 kW has found porous free [56].

Cracks formation during solidification is very common defect for any kind of welding process. Thermal stresses developed during the process initiates hot cracking as well. In some alloys of Aluminum and Magnesium high dissolution of hydrogen makes the hot cracking more severe. In homogeneous microstructure in the weld zone a major cause of crack initiation. Brittle IMC formation malbalances the distribution of fracture driving force which generates micro cracks in the welding surface. High welding speed for laser welding enhances the probability of solidification cracking of steel. It is investigated that the critical strain for solidification crack initiation decreased with the increase of welding speed in laser welding. It is noticeable that dissimilar welding of aluminium alloy and steel with high laser power makes the joint more brittle and forms micro cracks. Reduction in heat input up to a moderate level improves the welding quality as well as formation of micro cracks [155, 156, 157, 158, 159]. Crack formation of laser welded butt joint of AISI304 and Ti6Al4V can be reduced by using copper deposition technique. Presence of copper in the welding interface makes the joint compatible from different point of views [148, 160, 161, 162, 163]. Coating can play different role for different laser welding processed for Steel-Mg dissimilar joint. Enrichment of Zn in Mg fusion zone develops thermal stresses which lead to crack formation [103]. Coating in steel is not good option for keyhole mode than use of bare steel. On other hand for conduction mode Zn coating is proved to be useful as bare Steel-Mg is almost impossible to join in conduction mode in lap configuration.

6.3. SEM analysis

Scanning Electron Microscopy (SEM) is useful tool which uses a focused electron beam for getting a magnified view of sample for better analysis of surface topography. Characterization of the quality of weld melts is done by SEM micro structure analysis. SEM images changes its color with the change of composition. In of laser welding of Steel and Aluminium the parts which are comparatively [157, 164, 165, 166]. The thickness of the IMC layer [56, 151, 158] and the area of the bonded zone can be calculated from SEM analysis. Figure 10 [56] shows the SEM images of two different magnification of Steel-Mg intermetallic edge and eutectic. For a lap joint configuration, it is cleared from the SEM images that the IMC formations occur mainly in the edges of the weld zone [159, 167, 168, 169]. The morphological structure of the welding zones i.e., welded zone, heat affected zone and unaffected zone, and topography of fracture surface can be clearly determined from SEM images [160, 161, 162, 163]. The presence of micro voids and dimples in the fracture zone confirms the ductile mode of the fracture that occurred during the laser welding process. Figure 11 [164] indicates the visible difference observed by any SEM image among welding zone, HAZ, and base metal zone. Yan et al., 2010 [164] confirms from SEM image that dual beam laser forms more void less surface than single beam laser for dissimilar lap joint. Yang et al. observed that dissimilar laser welding of Steel-Al forms needle like phase near the fusion zone and lamellar phase near steel [165, 166]. PW mode able to form a root shape structure on welding surface observed from SEM study where as CW mode didn’t [170, 171, 172].

7. New regulatory approaches

Process based regulatory approaches are already discussed in every section as per requirement. Apart from that some monitoring based or numerical model based or assistance based approaches are there which can improve the quality of laser welding in lesser time and costing [173, 174, 175]. Some cognitive assessment method has been introduced for quality checking of laser welding. This system corresponds the monitoring system with predicted images from thermal model [167, 176, 177, 178]. G. Pastras et al., have been introduced new numerical approach of energy efficient laser welding processes [168, 179, 180, 181]. Determination of critical power and critical scanning speed have been suggested. Close loop adaptive control or feedback control based laser welding has been introduced to ensure targeted quality in short period of training time [169, 182, 183, 184]. Any of the quality criteria may be taken as reference for verifying adaptive control responses. A Papacharalamopoulos et. al [170]. have considered penetration depth as quality
control criteria. Laser welding process is an expensive one [185, 186, 187]. Wide range of experiment is not feasible all the time. The technique of achieving experimented quality data is very important. Artificial Neural Network (ANN) seems to be very useful for predicting quality data, Z Zhang et. al. studied [171]. Real time penetration state monitoring by convolution neural network (CNN) [172, 188, 189] could be a good alternative of ANN. Almost 95% of similarity with real time and post process study has been achieved using CNN [190–191].

8. Concluding remarks

Above studies suggested that dissimilar laser welding of Steel to those alloys has a good scope for fabrication industries according to the demand of the market. The main conclusions are summarized as follows:

i. The literatures revealed that process parameters of laser welding have a good impact on the quality of welds and on some desired property. It may differ with the combinations of the base metals as the concerns are not same. Scientific observation and identification of the defects and to try different parameter values for getting the optimum one is required. It should be kept in mind that these dissimilar metals should be joined in optimum processing conditions keeping all consequences in mind.

ii. The combinations of Steel/Ti, Steel/Al and Steel/Mg have been studied for the mechanical and metallurgical benefits with the requirements keeping the economic benefits in addition with it. Different techniques or methods have been applied or introduced for improving the mechanical strength of the welds within favorable conditions.

iii. Though as far as these dissimilar joints are concerned, use of laser can decrease the process time and HAZ but in most of the cases the weld strength is less than the strength of the base metal. The main reason behind than is formation of IMCs.

iv. Porosity and cracks are also issues in some cases. Though all these defects cannot be removed completely but more studies are going on to control them up to a satisfactory level.

9. Future trends

Development of science and technology creates the scope of using new combination of materials according to the need. Specific industry demands specific features of materials which suit with the condition. Light materials are become essential for reducing the weight of the entire structure. Steel is commonly used structural material for many industries. Light material but high cost of raw material or fabrication processes often reduces the need where light weight structure is not at the top of the priority list. Some essential properties of any specific material force science and technology to develop something new. There are differences in the type of challenges faced for different materials. The nature of probable solutions may also have variations. The future prospects are briefed as follows:

i. New techniques are required to develop by focusing on Industrial demand. Proper modeling and simulation should be carried out for the Optimization of laser welding parameters.

ii. Future research should give more focus on fiber laser welding for different dissimilar combinations and with different grades of the same material as it has a low tendency of plasma plume formation.

iii. Some very common but rarely studied mechanical properties like corrosion resistance, fracture toughness is to be studied more in future studies for welding of steel and other light alloys.

iv. Another important section is the simulation of temperature distribution and from these a clear idea of residual stress generation is to be validated. There are so many simulations software is available for validation of experimented data with proper modeling. Above all defect free quality welds within budget are always appreciated in industrial aspect.

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