Analysis and Advantages of Welding Dissimilar Metals by Fiber Lasers

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Abstract -Welding of two dissimilar metals is the requirement projected by many industries for getting stronger, lighter, more efficient and cost-effective combined alloys. It is required in the new design of lighter, fuel efficient and environment-friendly automobiles. Similarly aerospace industry, electronics industry and medical industry require the welded dissimilar metals for various advantageous reasons. But there are many difficulties in welding dissimilar metals whose physical and chemical properties are far too different from each others'. There are stresses, porosity and cracks developed in such welding process. One of the solutions is the use of lasers to perform such welding. Out of many lasers, continuous wave (cw) and pulsed fiber lasers have proven to perform this task more efficiently than other lasers. To avoid the formation of inter-metallic compounds during welding of dissimilar metals, one of the many techniques is the use of suitable filler metal or filler wire. The details of these aspects are discussed in the present paper.

Keywords: Laser welding, dissimilar metals, fiber lasers, filler material.

I.INTRODUCTION

Dissimilar metal welding, as compared to the traditional welding, is the joining of two separate metals which wouldn't ordinarily weld together as they have differing chemical and mechanical properties. Some of the different properties of the metals to be welded are: their melting point, evaporation point, strength of each material, chemical composition, compatibility, and so on. Despite these limitations, there is a need for welding between such dissimilar materials for various purposes including the cost saving, weight reduction, increasing the efficiency of the devices, etc. Dissimilar metals are welded together in order to maximize on the benefits that each metal produces, while minimizing their drawbacks. Laser welding has been widely used in the aerospace, automotive, electronic, medical, shipbuilding and military defence industries due to excellent characteristics, such as small fusion and heat affected zones, low distortion, short cycle time and flexibility. [1, 2] Welding of dissimilar metals with the help of medium and high-power lasers, particularly fiber lasers, offers a practical, better and more precise solution. From smart phones to submarines, objects of all different sizes and from a variety of industries incorporate welding into their manufacturing process. This is done by physically melting the two metals together until they form one strong, connected joint. This fusion of metals is completed by using a high level of heat from the laser beam to cause the melting. Optimizing a product's finished properties, such as corrosion, wear, and heat resistance, while managing its cost, are the major motivations for dissimilar metal welding.

1.1 Need for Welding of Dissimilar Metals

Welding of dissimilar materials is always performed in response to a specific demand from industry. Several electronic, naval, aeronautic and automotive components are made by different materials joined together in order to improve mechanical and functional properties.
Following are some examples discussed to justify this need of welding dissimilar metals:

1.1.1 Automobile Industry:

In order to meet the current environmental regulations for better fuel efficiency and lower emissions of polluting gases from the automobiles, certain measures are needed. One of the practical solutions to tackle this problem is to reduce the weight of future vehicles by the substitution of heavy materials with lighter and stronger materials. High-alloyed Al-Zn alloys, for example, have very high strength-to-density ratio and are lighter in weight in comparison to the conventionally used steels and aluminium alloys. Aluminium alloys possess a density, which is approximately one-third of that of steel (so the lower weight), whereas their strength is maximal one-half of that of steel. Consequently, the specific strength of some aluminium alloys, such as Al-Zn alloys, can even exceed the values for ultrahigh strength steels, [1]

1.1.2 Aviation Industry:

It is an advantage to have the reduced weight in civil as well as military aircraft and yet perform more efficiently. The ability to leverage steel and aluminum alloys in mixed metallic components, for example, could dramatically reduce the weight of aircraft without sacrificing mechanical strength.

1.1.3 The battery and electronics industry:

The battery industry and the electronics industry are closely intertwined, and one would be unable to operate without the other. Further, it is predicted that the average household owns at least 24 electronic products or devices, and this number is only set to rise. This couldn't be possible without the use of dissimilar metal welding in the production of batteries and electronic products. Electric cars, a demand for the near and distant future, depend heavily on their efficient batteries. In consumer electronics, the requirements for lightweight structures with highly tailored thermal and electrical properties are constantly driving the need for more complex designs, often using thin foils and requiring joining of dissimilar metals, with aluminum with copper etc. As the use of electronics and batteries continues to rise, dissimilar metal welding is sure to continue growing as a vital process.

1.1.4 Other uses:

Dissimilar metal welding is also used in common power plants, chemical plants and food processing applications, as it can join ferritic low alloy steel with austenitic stainless steel, a metal that is commonly used in these industries. Further, in medical industry there is a requirement for welding dissimilar metals for various purposes.

The move towards adopting lighter and stronger materials in everyday products, from automobiles to consumer electronics, has led to a number of significant challenges in welding these structures, especially in high-volume production environments.

II.FACTORS TO BE CONSIDERED FOR WELDING DISSIMILAR METALS

The development of versatile alloys has served many applications, but welding them together perfectly and repeatedly continues to be an difficult process. Given herebelow are some of the factors that should be considered before welding dissimilar metals.

2.1 Solubility

Solubility is the chemical property of a substance which determines its ability to dissolve in a solvent. Solubility of the two dissimilar metals must be mutual. If there is mutual solubility of the two metals, the dissimilar joints can be made successfully. If there is little or no solubility between the two metals to be joined, the weld joint will not be successful.

2.2 Inter-metallic compounds

The problem of making welds between dissimilar metals relates to the transition zone between the metals and the inter-metallic compounds formed in this transition zone. For the fusion type welding processes it is important to investigate the phase diagram of the two metals involved. Apriori analysis should be done about the inter-metallic compounds that will form within the transition zone between the two metals, investigating things, such as the crack sensitivity, how susceptible these are to corrosion and its ductile ability. In some cases, it is necessary to use a third metal that is soluble with each metal in order to produce a successful joint. This analysis can be useful to decide on using a filler material or a ‘buttering layer’ that is easily soluble with the two dissimilar metals.

2.3 Weldability

The level of weldability incorporating the solubility and inter-metallic compounds refers to the ability of the two metals in question to be successfully welded without resulting in cracks or any other defect. This will vary from metal to metal. Once we have determined the weldability of dissimilar metals, we can also appropriately select any other filling metals or buttering layers we shall use for a smooth transition.

2.4 Thermal Expansion

One must also consider the coefficient of thermal expansion of the two metals involved, which relates to how these metals will change shape in response to a change in temperature. If these are too different then the internal residual stresses can greatly reduce the operating life of the newly welded metals.

2.5 Melting Rates

Just as the two dissimilar metals may have different thermal expansion rates, they may also have different melting rates, which will cause an immediate problem between the two metals.

2.6 Corrosion

Corrosion can occur in between the transition area of the two dissimilar metals. If the two metals are on wildly different sections of the electrochemical scale, then this suggests a high level of susceptibility to corrosion, which is, of course, a damaging problem to the new weld.

Table 1 gives, at a glance, about pairing of suitable metals for welding.

TABLE 1. Weldability of metal pairs

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

Metals: Al: aluminum; Ag: silver; Au: gold; Cu: copper; Pt: platinum; Ni: nickel; Fe: iron; Ti: titanium; and W: tungsten.

Keys: C: Complex structures may exist; **X:** Inter-metallics compounds formed undesirable combination; **S:** Solid solubility exists in all alloy combination; **D:** Insufficient data for proper evaluation; and **N:** No data available.

Let us summarize the above-listed issues by giving an example of welding aluminum with steel. The low miscibility of aluminum alloys and steel is caused by very large differences in their thermo-physical, electrical, and chemical properties, mainly, the melting temperature difference between aluminum at 660°C and steel at 1538°C. The density of aluminum is also a third of that of steel, which means it will become liquid that much faster.

In addition to "floating" on the steel, liquid aluminum absorbs more laser energy than when in its solid state and results in laser-induced plasma. This often leads to porosity, hot cracks, and the formation of brittle Fe-Al inter-metallic compounds. These inter-metallic compounds greatly reduce the weld strength and reliability and are often hard to predict with most welding processes.

Titanium alloys like Ti-6Al-4V have been widely used in industry due to the excellent characteristics of good corrosion resistance, high strength and creep resistance. The largest use of Ti-6Al-4V alloy is in the aerospace industries, for example as static and rotating components in the turbine engines. Meanwhile, Inconel 718 nickel alloy, a high temperature material, is also widely used in the aerospace industries. Because of its superior mechanical properties and oxidation resistance at elevated temperatures, Inconel 718 is particularly suitable for components in the high temperature regions of aero engines and gas turbines.

III.ROLE OF FILLER MATERIAL IN WELDING OF DISSIMILAR MATERIALS

There are many types of materials which can be added at the interface of two dissimilar metals to produce a crack-free and strong joint. These welding materials are generally categorized under the term filler metals, defined as "the metal to be added in making a welded, brazed, or soldered joint." Generally, laser beam welding requires there to be no gap between the work-pieces. However, using filler metal increases the weld gap bridging ability, thus reducing the amount of work required to prepare the seam welding. Fillers have two functions: first, they are used to bridge wide or irregular gaps in the joint, reducing the amount of work required to prepare the seam. Second, the fillers add elements to the molten metal in order to alter the properties of the material in specific ways. Such properties include suitability for welding, strength, durability, and corrosion resistance etc. For example, the use of an appropriate filler material - namely vanadium has been reported for welding Al-Zn alloys [1]. In this regard, vanadium enables the manipulation of the material properties of the weld metal. As another example, if one is attempting to weld A514 low-alloy steel, with a minimum tensile strength of 110-KSI, with A36 steel that has a minimum tensile strength of 58-KSI, then it is advisable to choose a filler metal that has similar KSI levels to the A36 steel, such as a metal with a 70-KSI. On occasions, the filler metal can have a lower tensile strength than both the higher and lower strength of metals. For example, two metals with strengths of 100-KSI and 130-KSI could theoretically be welded with a 70-KSI filler metal. However, each metal is different, and one will need to check the welding specifications first. One should avoid over-matching the filler metal as this can result in a high level of stress, thereby reducing the usage life of the new weld.

Copper and copper-based alloys can be successfully welded to the low-alloy and mild-alloy steels and stainless steels. This can be done using high-copper-alloy filler for areas where the metal is thinner, and for thicker sections, the steel should have a buttering layer of the high-copper-alloy filler, and then welded to the copper.

IV.USING FIBER LASERS FOR WELDING OF DISSIMILAR METALS

4.1 Laser Welding Advantages

- **Weld strength:** The laser weld is narrow with an excellent depth-to-width ratio and has higher strength.
- **Heat affected zone:** The heat affected zone is limited, and due to rapid cooling, the surrounding material is not annealed.
- **Metals:** Lasers successfully weld carbon steel, high strength steel, stainless steel, titanium, aluminum, and precious metals as well as dissimilar materials.
- **Precision work:** The small, tightly controlled laser beam permits accurate micro-welding of miniature components.
- **Deformation:** Parts have minimal deformity or shrink.
- **No contact***:* There is no physical contact between the material and laser head.
- **Scrap:** Laser welding is controllable and generates low volumes of scrap.

4.2 Fiber Laser Welding Advantages

Different laser sources exist such as Nd: YAG, fiber, CO_2 etc. for welding of dissimilar metals. **The fiber laser produces a beam of outstanding optical quality for precise welding actions.** Due to the local heat input, deep welds can be produced at high heating and cooling rates. Modern fiber laser technologies have been evaluated successfully for their ability to weld two dissimilar metals. Unlike other welding technologies, these laser welding technologies are able to be pulsed, the pulses can be shaped and hence the temperature of the weld joint can be precisely controlled at the molten joint. Specifically, the small focus diameter of fiber laser technology offers enhanced power density, a smaller heat-affected zone, lower cycle time, and lower heat input, which can lead to a lower volume of inter-metallics and even controlled inter-metallic development. The difficulties associated with laser welding of materials such as aluminum and copper using 1-μm lasers can largely be overcome by using high-brightness fiber lasers. Dissimilar laser welding can be performed in a variety of different ways, and one of the preferred methods is the use of fiber lasers, as explained above. Fiber lasers are designed to be maintenance free with 'fit and forget technology', making them a reliable, efficient and effective solution to many other technologies.

Regardless of the thickness, or how different the chemical and mechanical properties of two dissimilar metals are, successful welding can be achieved using fiber lasers. Fiber lasers can work with all of the key metals including aluminium, brass, copper, and various types of steel. CW fiber lasers can weld everything from thin steel to thick carbon steel and stainless steel. This makes them the perfect solution for dissimilar metal welding whether this is for medical devices, or other larger industrial solutions found in the automotive or aerospace industries. The use of pulsed fiber lasers represents another direction for dissimilar welding, offering both commercial and technical benefits. Fiber laser welding thus provides unique benefits.

Given herebelow are some of the additional features and capabilities of using fiber lasers for efficient weldability of dissimilar metals.

Fiber lasers offer excellent flexibility in tailoring weld dimensions and the best penetration per watt performance, which enables high speed seam welding. A 300-W fiber laser can seam weld 0.01-inch thick airbag detonator casings at 2 inches per second, while a 20-W pulsed fiber laser can produce a 0.001-inch diameter spot welds in 0.001-inch thick foil. The architecture of the fiber laser is scalable, with laser powers available at multi-kilowatt levels used for penetration welding applications up to and beyond 0.25-inch thickness. Fiber lasers use power modules that are made up of individual modules ranging from 200 to 2000 watts. For example, a 4 kilowatt (kW) laser is made up of multiple modules, with the option of adding an additional module for redundancy. Fiber lasers are very compact, with power up to 1kW offered in rack-sized formats. They can be air-cooled up to 500 W.

The small focus diameter of fiber lasers offers a number of advantages during laser welding. Other advantages of fiber lasers are:

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

V.FILLER MATERIAL/WIRE USED IN LASER WELDING OF METALS

5.1 Filler wire and filler material is sometimes used in the laser welding of metals. For example, 6A02 aluminum alloy was welded by fiber laser welding with two different filler wires (ER4043 and ER5356). [3]

5.2 Stainless steel usually presents a satisfactory corrosion resistance in many environments, but they tend to suffer from poor surface hardness, which can be detrimental when wear resistance is required. When adding a filler material, the laser welding–brazing method can help suppressing the growth of brittle inter-metallic compounds at the joint site. Hence, mechanical properties of the joint obtained by laser welding–brazing can be enhanced, and the same applies to corrosion resistance. [4] In one such case, joining of dissimilar materials was performed using a Fiber Ytterbium (YAG) laser source which emits light with a wavelength of 1.064 µm. The parameters set were: average power of 150 W, peak power up to 10.5 kW, pulse energy up to 70 J, pulse duration 6.8 ms, spot size 1 mm, frequency 8 Hz. Both direct joining with no filler material and with filler material have been tested, varying the laser source parameters in order to optimize the joint quality. When no filler material was used, the base materials was preheated at 350°C, while for laser brazing tests, two different filler materials (one Fe-based, i.e. AISI 316L and one Ni-based , i.e. modified Inconel 625) were tested. It was found that the laser brazing with Ni-based filler material was better in performance to obtain multi-material parts made of AISI 420 stainless steel and Stellite 6.

5.3 During welding of Ti-Ni metals, three inter-metallic phases, Ti_2Ni, TiNi and $TiNi_3$, are formed. Ti_2Ni and $TiNi_3$ phases have been recognised as the brittle phases which can increase hardness and reduce strength. Conversely, the TiNi phase has properties of high ductility, non-magnetic, good corrosion resistance and good toughness at low temperature. For these reasons, TiNi titanium alloy has been widely used in the medical industry, such as dental applications, stents and surgical devices. Considering the welding of titanium and its alloys to nickel and its alloys, Fiber laser welding of Ti-6Al-4V titanium alloy to Inconel 718 nickel was used with TiNi filler [2].

5.4 Chopde et al [5] studied the laser welding of aluminum and copper. The aluminum and the copper utilized were Al3003-H14 and Cu110-H00, respectively. It was observed that copper and Aluminum needed filler material to create fusion weld and minimize inter-metallic structure. From studies it was found that the filler in the powder form will help create better fusion joint allowing both copper and aluminum to fuse together. The aluminum base alloys are highly crack-sensitive because they contain approximately 1.0% Magnesium Silicide (Mg_2Si), which falls close to the peak of the solidification crack curve. To reduce crack sensitivity, filler alloy 2036 was added to all welds during welding for better results. Laser welding of aluminum and copper using the filler is displayed in Fig. 1.

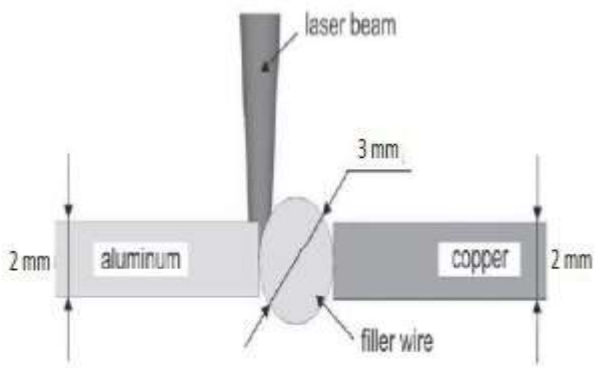

Fig. 1: Laser welding of aluminum and copper using the filler wire [5]

5.5 Welding of dissimilar magnesium and aluminum alloys is an important issue because of their increasing applications in industries. Welding of dissimilar Mg and Al is challenging due to the formation of brittle inter-metallic compound such as $Mg_{17}Al_{12}$ and Mg_2Al_3. In this approach, employing filler metals was used in laser welding. Laser hybrid friction stir welding was used to join Al alloy to Mg alloy with Ni foil as filler material [6]. The strength of the weld thus increased due to the presence of less brittle Ni-based inter-metallic phases instead of $Mg_{17}Al_{12}$. Ni was distributed well at the interface of the Mg and Al alloy and the distribution considerably reduced the formation of brittle inter-metallic compounds.

5.6 Dissimilar material joining of aluminum alloy to steel has been paid great attention in automotive industries because the application of light material like aluminum alloy can improve the fuel efficiency and control air pollution by reducing the weight However, due to large differences in thermo-physical properties like melting points, thermal and electrical conductivities, and thermal expansion rates between the two materials, joining of aluminum to steel becomes very challenging. The main issue is the formation of Fe_xAl_y inter-metallic compounds at an elevated temperature, which may result in poor mechanical properties of the joint and therefore influence the usability of the whole component. In one experiment, Butt joining of aluminum alloy to steel of 2.5 mm thickness was conducted by a 10-kW fiber laser with ER4043 filler metal [7].

CONCLUSION

In this paper we have discussed the importance of welding two dissimilar metals for getting lighter material in weight, corrosion-resistant, cost-effective, stronger and more efficient materials. This is based on the demands made by many industries including automobile, aviation, electronic, medical and other industries. But the welding between two dissimilar metals is a challenging issue due to widely different chemical, electro-mechanical and other physical properties of each metal to be welded. This leads to cracks, stresses, porosity, corrosion, brittle and weak joints. A number of inter-metallic compounds are formed during this type of welding. Many solutions to tackle this problem have been suggested in this paper. Laser-based welding is one such solution. Out of many lasers such as Nd:YAG, CO_2, and fiber lasers, cw and pulsed fiber lasers have demonstrated remarkable capability in welding two dissimilar metals. In some cases, filler materials or filler wires have been used to prevent the formation of inter-metallic compounds and thus leading to crack-free, stress-free, corrosion-free, longer-lasting, cost-effective and stronger joints.

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