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An Analysis of Laser Welding Technology used for Joining Dissimilar Metals, Computational Parameters and Challenges

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Abstract:
Welding particularly joining dissimilar metals is new technology. Laser welding is a challenging task and most essential and reliable method of joining dissimilar metal used in various industrial area. Out of the modern welding laser welding is gaining its popularity due to its various unique features. Laser welding, is modern method of joining similar or dissimilar parts metal/non-metal by laser beam of very high power, high temperature source. Very good control on input factors, very small heat affected zone, precise accurate welding joint and high speed are some attractive features of this technique. This technology gives more flexibility to design engineer. Various kind of lasers such as Nd:YAG, Co2 laser, Diode laser, disk laser m/c are used in welding of automobile, aerospace and ships. All concept of laser welding depends on the key-hole phenomena. It is a cavity formed by recoil pressure and energy absorption is due to high temperature multi reflection of laser rays. So this gives deep Penetration of weld joint. This paper shows various Challanges of dissimilar metal welding and technique to over come this. In our use study We are going to use dissimilar metal plates of 3.5 mm thick of 16MnCr5 and 316 SS. This metal jonts are used in production of automotive cylindrical part in large quantity.

Keywords:. Laser Welding Technology, Industrial lasers, Laser Welded Joints etc.

1. Introduction

Industrial lasers are widely used for drilling, cutting, welding and surface remedy of ahuge variety of engineering metals from last decade [1]. In the automobile sectors, for example, the advantages of laser welding for joining of transmission additives, sheet frame panels and chassis components were found out in modern day manufacturing. Presently in manufacturing, food processing, chemical and spacetechnology commercial laser structures are in use.[17] Approximately 20 % are committed to welding joints among distinctive/dissimilar metals are especially used for chemical, power generation, electronics, nuclear fusion and petrochemical industries. Greater usability of different materials and alloys provides production anddesign engineers an extra flexibility with often results. Which has many advantages in technical and economic field over the components made of single material. Costly materials with unique and specified properties are used in critical locations, with low cost alloys that can be used in supporting or connecting roles. Laser welding is mostly preferred over conventional fusion welding/joining methods in specified factors such as quality of the weld, flexibility in production, increase in productivity and manufacturing opportunity. [16] The process parameters in laser welding such as, low energy input and high-power density etc. used for wide range of dissimilar material and applications. This present review work targeted understanding the concept of laser welding and its application for different field along its limitations over the conventional welding methods.

1.1 Area of Focus

A survey in 1992 revealed that about 20% laser machine setup were utilized in laser welding. In recent years adoption of this technique in automotive industries has takenboom. [12] In survey of Poona industrial area it is observed that in number of auto parts it is absolute essential to join different metals to join these dissimilar metals is challenging work. Currently research on laser welding of dissimilar metal is on broad level. Then also several research area in joining dissimilar metals is unexplored. [9] Magod is well known group in Laser welding, having number of units throughout the India. One of the job is a part of radiator of I.C. Engine. It has having two concentric cylindrical metal ring. Inner ring is of 316LSS and other is 16MnCr5. Job requirement is good quality peripheral welding joint. In literature review we found no systematic work (experimentation) is done for the above pair of material. Selection of proper types of laser, input parameter is area of focus. The goal is to evaluate optimum levelinput for best outcome.

2. Laser Welding

The use of laser as a source of welding was recognized immediately after the first practical laser was demonstrated in 1960. In the formative period, laser welding was performed with pulsed ruby rod glass lasers. It was first built laser. [5] Spot welding was carried out in most of the cases. Seam welding was also performed by overlappingspots. High quality welding in a no. of alloys was achieved with pulsed lasers. However,there was limitation in that penetration of welding was only up to a depth of approx. 1.5mm; carbon dioxide and Nd-YAG Lasers came handy for continuous seam welding. Therefore, without use of over lapping spots it is feasible to have continuous seam weld. By developing CO2 lasers with output in multi-kilowatts deep penetration welding was demonstrated. Meanwhile, the technology of laser welding has been evolving at a rapid pace. Various materials like nickel based alloys, low carbons steel, stainless steel, aluminum alloys, super alloys and titanium alloys etc. are welded using laser power welding method. With the help of Laser Direct Casting process it is now possible tolay down very narrow track of 0.8mmcomplexshape layer as rapid prototyping. [8]

Laser welding has a large number of positive points in its favor. They are [15][17]

a) With lasers, accurate, precise welding is possible

b) No need of filler material and hence contamination of the welded portion isavoided.

c) Since laser radiation does not possess the phenomenon of inertia, it facilitates thestart or stop of the welding instantly.

d) As in laser welding, the laser does not have any physical contact with work pieceand hence contamination of the weld does not occur.

e) Unlike electron beam welding, laser welding can be carried out in the normal workshop environment.

f) There is no need of using filler material and hence there will be no slag formation.

g) Materials for eg. Titanium, quartz etc., having tough properties are able to weld with lasers

h) Welding of intricate shapes can be done with lasers.

Although, these advantages make laser welding technologically superior to the conventional methods there of course are some disadvantages also [15]. They are:

a) If we use a laser of moderate power, i.e. easily available and inexpensive, the penetration depth is quite small. For large depth it would be quite expensive proposition.

b) If we do not control the laser pulse parameters precisely, there can be loss of material that occurs through vaporization.

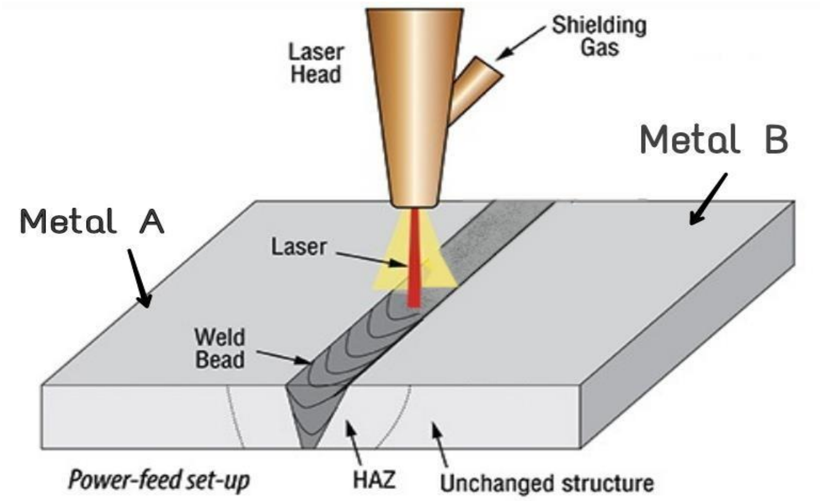

Fig.1 – Laser Welding System (Source: sme.org/technologies/articles/2020)

2.1 Laser Welding Process

A beam of light from laser of power densities of 10^6 W/cm^2 falls incident on the surfaces to be welded. The surface absorbs a part of laser radiation in short period oftime and material melts. [19] This leads to welding. In this process. Either the surfaceof the material or the laser beam can be moved relative to each other.

There are varieties of laser-welded joints. The Lap and Butt joints are typically weldedwith the help of CW or PW type lasers. Depending on laser irradiation period along with the power density a bead or spot-weld is developed in the structure of a keyhole type [19]. While the beam of laser is shot at the specimen plate, there is absorption of laser power due to interaction with free electrons within the metal. The switch from laser energy to thermal energy causes rise in temperature of the plate surface.

The laser absorption rises barely with a boom in the temperature of solid which considerably goes above the melting temperature. Also, the temperature of laser- irradiated area increases up to the boiling temperature. A cavity or a keyhole is shaped through spring back pressure caused by evaporation. Since the absorption of laser energy is extraordinarily excessive because of multi-reflection in the event of akeyhole formation. This keyhole type deep penetration welding is seemed as an efficient joining method. A shiny plume of evaporated vapors is emitted through laser-irradiated part or a keyhole. Spattering of melt droplet caused by a robust jet of the ejected plume, every now and then occurs from inlet of a key hole.[13]

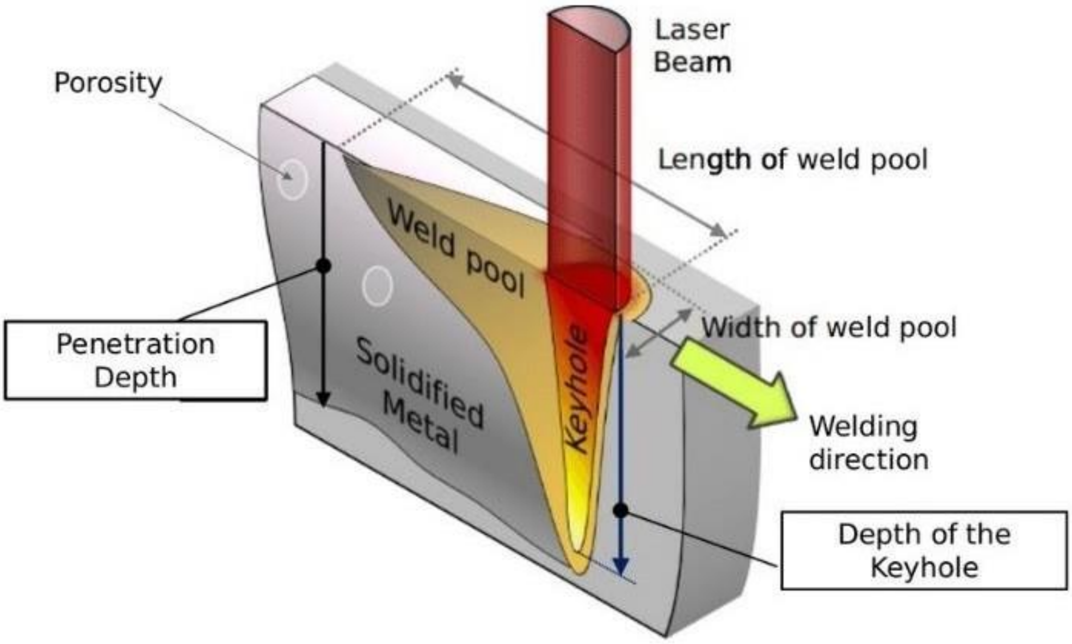

Fig.2 – Laser Welding Phenomenon (Source: alliedscientificpro.com)

2.2 Parameters Affecting Laser Welding Process

The penetration depth and the efficiency of laser are governed by factors such as absorptive of the work-piece, beam diameter, laser power etc. The effects of these on the laser output, are discussed below:

a) Absorptive:

Laser welding is usually done with Nd -YAG and CO_2. Both these lasers have emissionin the infrared area/region of the spectrum. Hence, the reflectivity of the materials to be welded in this region has to be considered, in metals absorption not infrared depends to a great extent on the conductive absorption by free electrons. [14] Nd:YAG pulsed laser welding can achieve better absorptivity.[22]

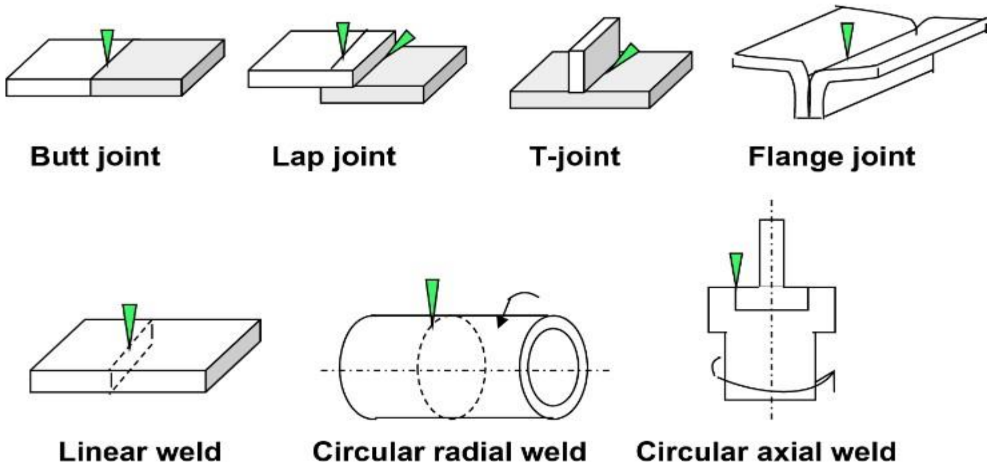

Fig.3 – Laser Welded Joints (Source: Handbook of Laser Welding).

b) Beam Diameter:

The diameter of the laser beam determines the power density. This therefore is an important parameter However, very little is known about the fact that it is very difficult to measure the diameter of high-power laser beams. The beam diameter is defined on uniquely. For instance, the diameter of Gaussian beam can be defined in two ways. One is, as the beam diameter at a point, where the power has dropped to$1/e^2$ of the central value containing about 80% of the total power. The second is, as the diameter at a point where the power has dropped to 1/e of the central value, which contains about 60% of the total power, for welding with laser beam diameter of $1/e^2$ is adequate. [14]

c) Laser Frequency:

It is also seen that, for an increase in power, frequency increases. Also, it has an effecton beam spread such as if the frequency is kept low the beam spread is greater and when the frequency increases the diameter also increases which reduces the beam spread. [15]

d) Laser Power:

If the diameter is constant, penetration increases almost linearly with rise in power. Demonstrations have also shown that for a given thickness of the material to be welded by the laser beam a minimum threshold power is essential [14]. More powermay increases number of pores. This is because of more power increase in the formation of metal vapour accelerate metal vapour formation. [24] In pulsed laser welding low average power and high peak power will decrease width of heat affectedzone.[22] Average power is important parameter than beam diameter. [21]

e) Welding Speed:

It is also seen that for a specified material thickness to be welded and with a given laser power, there always in an optimum speed of welding [1]. The rate (speed) of welding is inversely proportional to the desired depth of weld penetration. If we apply speeds over the optimum speed, pipe welding occurs. On the other hand, if thespeed is less than the optimum, there will be excessive melting, loss of material andperforations in the weld [4]. Shorter wave length laser improve welding quality at higher welding speed [6]. Hot cracking defects may occur at high welding speed (4.8to 6 m/min) during solidification in joining Aluminium alloys [25].

f) Reflectivity:

If the reflectivity of the materials is of a high order, then the energy absorbed is muchless. However, the reflectivity may not be the same throughout the duration of the laser pulse. It has been experienced that during the first part of the laser pulse, the material melts. This obviously results in considerable increase in the energy absorbedby the material [15].

High reflectivity (e.g. pure copper) is one of the cause for low welding efficiency. Number of methods are suggested to improve laser weld ability. First coating of low reflective layer of alloys on the top of the surface. But in this case there is chance of changing mechanical properties of the weld. Second method is to use oxygenated (o_{2-Ar}) gas jet in laser welding . The energy absorption increases from 4.89%- 16.10%.Reflectivity can be reduced by using dual laser beam or by using laser of short wave length. [23]

g) Type of Shield Gas:

It also influences the penetration and hence the bead width. Helium gives more penetration and narrower bead whereas argon gives less penetration and a wider bead. This is because of helium reduces the plasma size and hence allows more energy to reach the welding point [6].

h) Wire Feeding:

Surface finish, weld dimension control and good quality LBW joint can be obtained by proper wire feeding technic. Front feeding, rear feeding, and wire feeding angle are the area of concern as per situation [7].

i) Focal Position:

Focal Position is a distance between surface of work piece and optical focal point of laser. The focal position is more beneficial if it is below work piece surface. It is found that welding penetration increases gradually while focal point moving down the surface level. The penetration is maximum when focal point is 0.4 mm below work piece surface. i.e. at this position deepest penetration depth is obtained[24].

If it lowered below this point laser spot diameter on the work piece surface becomeslarger and intensity of it decreases and weld penetration reduces. So 0.4 mm is threshold value for deep penetration.

Design of Experiment (DOE) technique is very useful tool to identify various parametersassociated with selected process. To find correct level of parameters for a process by trial and error method for any material is very time consuming and cost increasing. Toovercome this difficulty and to find out exact output parameters for variable input parameters can be predicted by developing the model. By using DOE technique, we can reduce experimental run [3].

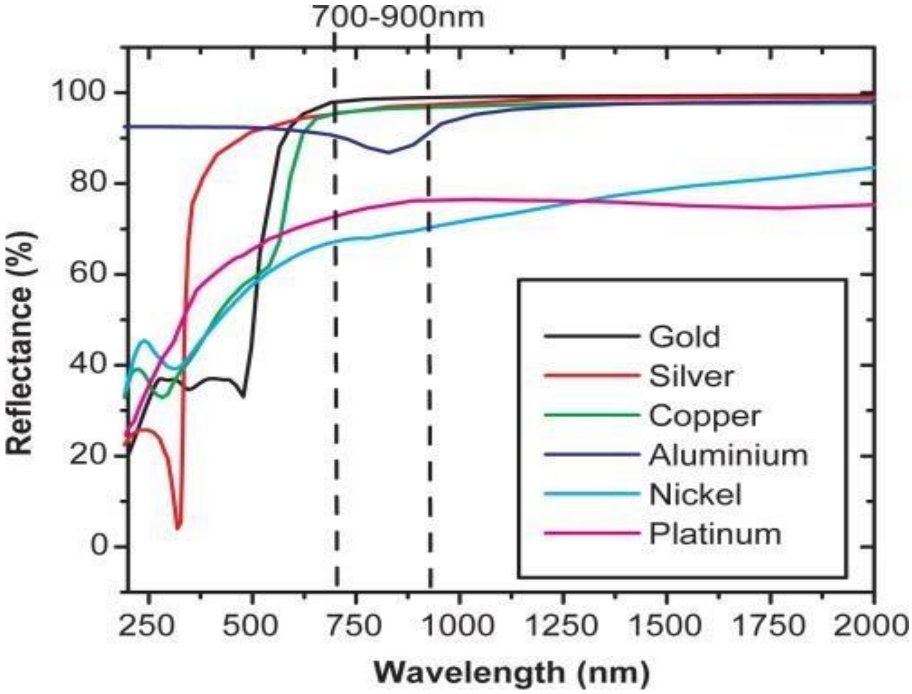

Fig: 4 Reflectivity of Materials

2.3 Challenges in Welding Dissimilar Materials

a) High Thermal Conductivity

If any one of the couples of the metal has high thermal conductivity effect in rapid heat transfer across the joint, this creates important drawback in LBW joint. As the heat of laser beam diffuses to large area of whole welding piece, avoids accumulationof energy in weld zone and automatically vanishes unique advantage of LBW. Higherthermal conductive metal requires higher fluencies to attain the melting temperature. High conductivity is main reason of small keyhole, in the case of stainless steel in conduction mode, the heat absorption is around in 20%, while in case of keyhole mode it will improve up to 60%. [20]

In dissimilar metal welding of the two metal plate to be joined having large differencein coefficient of thermal conductivity gives two different effect. Metal which has highthermal conductivity gives low coupling efficiency, slow process and high input power means more distortion while the metal having low conductivity gives keyhole effect which is more preferable Thermal conductivity of metal can be reduced by adding alloying element in pure metal for example aluminium and silicon in steel reduces thermal conductivity considerably. Chromium, Vanadium, Tin in alloy with steel reduces thermal conductivity moderately. But this information is not available in caseof number of metals [17]

b) Solubility of Substance

Firstly, solubility is the chemical asset of a substance which determines its capacity todissolve in a solvent, of the two distinct metals want to be welded, if the metals are incapable to be dissolved together, then the welding device will fail. To keep away from the formation of inter-metallic compounds in the process of welding of diverse metals, one of the many strategies is the usage of appropriate filler metallic or filler wire. When welding diverse metals, appropriate strong solubility is critical for a soundweld. This is best done with metals which have suitable melting temperature ranges [15].

c) Melting Temperature

If one material's melting temperature is similar to the other's vaporization temperature, low quality welds are received and frequently form brittle inter-metallic.While joining different materials, there can be benefits to the use of laser welding, despite the fact that brittle inter-metallic can form. Since the weld itself is narrow, thequantity of inter-metallic can be decreased to applicable limits. Again, it is able to be feasible to offset the beam in a single path or the other, for that reason permitting a few controls over configuration of the subsequent alloy.[15] Laser roll welding is one solution to join these type of dissimilar metals.[10] In lap welding laser is focused from the metal having high melting temperature.[18]

d) High Reflectivity

From the previous two decades researchers are focusing the adverse effect of reflectivity of alloys and metals in LBW. Reflectivity of some aluminium alloys is higherthan 80% at the wavelength of 800nm its reflectivity is 87%. The difference in reflectivity of two dissimilar metals creates problem of local heating of one side whichhaving high reflectivity. Reflectivity depends on surface finish so one way to reduces the reflectivity is to decrease the surface finish of the plates to be joined. One of the way is sand blasting on the area near weld length second method is bare coating, nearweld length. This method is used for laser weld of small length. Fibre laser has small wavelength than CO2 laser. The reflectivity of laser radiation is more for longer wavelength [11].

2.3 Lasers for Welding

The kinds and features of the main lasers used for welding are encapsulated in Table

1. CO2 lasers with 10.6 µm wavelength are technologically advanced with excellent beam quality and easy attainment of higher power. The maximum laser power approaches approximately 50 kW of which 1-15kW power levels are certainly employed in welding of ships, airplanes, automotive components, steels, etc. Nd:YAGlasers having 1.06 µm wavelength can be operated in CW or PW mode and are transported through an optical fiber. Pulsed Wave (PW) lasers are mostly consideredin welding of small and medium sized components such as glass frames, electric components, battery cases, as well as dissimilar metal plate joining.[28]. ContinuousWave (CW) lasers are employed for laser welding of stainless-steel tanks and pipes, aluminium chassis, galvanized steel plates, etc.

The main drawback of this lamp-pumped Nd:YAG lasers is its low electrical efficiencyof not more than 4%[4].To overcome the drawbacks of CO2 and YAG lasers new laser-diode (LD)-pumped solid-state (YAG) lasers is been developed with capacity of 6-10 kW. But due to some higher technical requirements the productions of these lasers have been stopped. Lately, expectations from fiber and disk lasers in terms of greaterefficiency, high power and magnificent beam quality is increased as compared to lamp or LD-pumped YAG lasers. Currently, trends of lasers with higher power and beam quality have been focused upon laser diodes (LD), LD-pumped fiber, disk type lasers high power fiber laser.[20]

Fig.5 -Types and Characteristics of laser for welding

(Ref: Chapter1, Handbook of laser welding technology, Edited by Seiji Katayama)

Laser Diodes have greater electrical efficiency up to 60%. Fiber-delivered and Direct LD are automated to robots for performing welding of few mm sized sheets [2] of stainless steels, aluminium alloys, plastics, etc. They are also used brazing of galvanized steels. The drawback of LD is low quality beam. Higher efficiency, high power and refined beam quality are accomplished by disk [14] and fiber type lasers [29]. This fiber and disk lasers with improved electrical efficiency up to 20-25% and power approx. to 16 kW and 100 kW[14], respectively, are industrially available for producing deep penetration work.[29] Fiber and disk lasers are both brought into service as heat sources for remote welding.

3. Laser Welding of Dissimilar Metals

Number of applications in variety of industry such as automobile, shipbuilding, electronics, artificial human part making requires joining of different metals and showing large potential to counter at the high speed, more flexible, better performance requirements of modern industry[14]. Any two of different metal which can be coupled by conventional methods can be coupled by laser welding technology also. With sound and deep weld and with high speed then those of others. Main response factor to join the dissimilar metals are solubility of different metals, wide difference in melting temperature[12], wide difference between reflectivity of the metal plate to be joined, excessive thermal conductivity of one of them or both metal plates or parts., wide differences in coefficient of thermal expansion. All these create variety of defects and imperfection in the joints. These defects may be in geometrical or in appearance, or internal invisible. To avoid this defect and for high speed and performance result laser welding is best solution. This is possible because of different types lasers such as diode lasers, fiber lasers, co lasers, Nd-YAG lasers, disk lasers andsolid-state lasers with different merits are now developed [15]. Due to this development range of dissimilar metals like copper-aluminium, stainless steel- titanium alloy – aluminium alloy, magnetic material (16mncr5), non-magnetic material (316LSS). Can be successfully joined. This laser-based process is becoming more desirable due to fine control of heat input at weld joint. These are possible due to number of input parameters in case of laser welding. These parameters are welding speed, laser power, laser beam and diameter, etc.

3.1 Possible Dissimilar Metal Arrangements

It is feasible to carry out laser welding experiments on various metal combinations: We will see combination, difficulties in welding with laser welding and solution on them of few of them.

1. Aluminium alloy& Titanium alloy
2. 304 Stainless steel& Copper
3. Aluminium alloy& Copper

It will consider the most significant thermo-physical properties of the correspondingmetals although these values apply to pure metals and some characteristics are a fundamental reference for weld ability temperature dependent evaluation, the dataserve as a reference for weld ability temperature dependence and deriving the welding technique.

1) Aluminium alloy & Titanium alloy:

Demand for different titanium to aluminium alloy metal joints has recently increased, especially in the transport vehicle industry. It is widely known thataluminium alloy to titanium fusion welding is hard due to the brittle inter-metallic compounds that are formed at the joint interface. When the aluminium combinations are uncovered to a laser beam, the relatively high thermal conductivityvalues induce quick heat transfer. This impact is an imperative drawback for laser welding, as the warm heat diffuses to the entire segment of the weld, avoiding the vitality concentration in the weld pool. Hence, aluminium combinations have need of advanced laser energies than other alloys to be fused. [26] The element Si, Mg,, Zn in alloy of Aluminium reduces thermal conductivity.

Another important factor limiting LBW of Al alloys is high reflectivity. It is less for short wavelength so to use laser of short wave length is good solution. Surface treatment such as sand blasting or dark coating is also used to decrease the reflectivity of Al alloys.

Third factor in welding of Al alloy is low viscosity of the weld pool. Till date there is no solution for this problem.

2) Stainless steel - Copper:

Copper's high thermal conductivity appears to throw away heat farther and farther from the weld rapidly, leading to difficulties in achieving the melting temperature. Hot cracking in the heat-affected zone of steel due to melting of copper andpenetration through the grain limits of solid steel is the main challenge in welding copper to steel.[11] Melting temperature of Copper is 360^0 C less than the steel. To overcome this situation butt joint were created by focusing laser beam offset on steelside. Defect free joint in above material can be obtained by reducing amount of copper in melted zone. Another challenge in joining these materials is infiltration of melted copper between the grains of solid steel. This leads to cracks in heat affectedzone. [27]

Materials	***Aluminium(Al)***	***Iron (Fe)***	***Titanium(Ti)***	***Copper(Cu)***
Density (g/cm^3)	2.7	7.85	4.5	8.92
Melting temperature (°C)	660	1563	1668	1357
Heat conductivity (W/mK)	238	75	22	400
Coe. of Thermalxpansion (1/K)	2.3×10^{-6}	12.3×10^{-6}	10.8×10^{-6}	16.5×10^{-6}
Modulus of elasticity (GPa)	72000	210000	105000	130000
Absorptivity (%)	9	40	-	3
Magnetic Properties	Absent	Present	Absent	Absent

Aluminium - Copper:

In the electronic and automotive market sectors, joints between aluminium and copper are frequently needed. The hybrid car battery is primarily made from a mixture of aluminium alloys (3003 series, AL-Mn alloy) and pure copper. Special tasks are raised by mixing these materials. The heat energy is carried out by copper over 10 times quicker than steel. Copper and aluminium are also highly reflective with respect to steels. Very small quantity of laser energy is absorbed into both copper and aluminium, and this energy dissipates quickly into the majority material, making it impossible to sustain a molten pool. A high pulse peak power and a short pulse length enable the efficient welding of copper and aluminium.[11]

1. Proposed Material

Alloy steel (16MnCr5) - Stainless steel (316LSS)

Material	**C**	**Mn**	**P**	**S**	**Si**	**Cr**	**Ni**	**Mo**	**N**
316LSS	0.08	2.00	0.045	0.030	0.75	16-18	10-14	2-3	0.10
16MnCr5	0.14 to 0.19	1 to 1.30	0.035	0.035	0.040	0.8 to 1.1	*	*	*

Materials	***316LSS***	***16MnCr5***
Melting temperature (°C)	1390 – 1440	1450 – 1510
Heat conductivity (W/mK)	14.6	25
Coe. of Thermal expansion (1/K)	9.4×10^{-6}	10×10^{-6}
Modulus of elasticity (GPa)	193000	$(190 – 210) \times 10^{3}$
Absorptivity (%)	-	-
Magnetic Properties	Absent	Present

In our study, we are going to use 316LSS and 16MnCr5 material plate of 3mm thickness. We have studied the above two materials out of which alloy steel has high tensile strength and hardness but is magnetic in nature while stainless steel is highly resistant to corrosion and oxidation and is non-magnetic. The joint of above is used to make automotive cylindrical part which is non-magnetic from inside (stainless steel) and having good strength and hardness (alloy steel) to make gear on outer periphery. These two can make good welding joints since both havemelting temperatures in the range of 1390-1570oC and coefficient of thermal expansion in the range of $9.4*10^{-6}$ to $10*10^{-6}$ /K also both materials have low rangeof thermal conductivity in range of 15W/m°C to 25W/m°C. One of the main problem in joining these materials is porosity after joining. The main reason is of joint is bad edge preparation.[30] For edge preparation we have option ofmechanical cutting (milling) , surface grinding with coolant , shear cutting , wirecutting EDM , laser cutting and water jet cutting . We preferred water jet cutting for the edge preparation due to no heat effected zone with good accuracy good surface finish, low cost and fast method of cutting.

Conclusion

Current research on laser welding of dissimilar metals has broad scope as it is usedin industry. In traditional welding process in put parameters are few and cannot controlled finely. But in Laser Beam Welding process, input power, frequency, welding speed, beam diameter, focal position are the different parameters. These parameters are more in numbers and can control finely. Focus of study is to findbest possible set of parameters for the joint of 16 Mn Cr5 and 316LSS.

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