Applications of Laser Beam Welding in Automotive Sector-A Review

A. R. Biswas, N. Banerjee, A. Sen, and S. R. Maity

1 Introduction

Day-by-day automotive industry is adopting laser beam welding widely for various applications such as welding of body structures, door frames, auto hoods, chassis, and trunks [1–3]. It is also used for welding of different sub-components such as airbag initiators, electrical interconnection, motor coil windings, engine parts, transmission components, solenoids, air-conditioning equipment, fuel injectors, fuel filters, and alternators [4–7]. Electrification of motors is a new trend nowadays because of the increased demand for hybrid and electric vehicles. Fabrication of electric motor parts, including stator hairpins and power train connections, is the key requirements. Other additional applications in vehicle electrification are battery welding and connections. Laser beam welding is adopted to make the battery cell and join cells for creating a module. Besides, LBW helps to connect these modules to make a complete battery assembly. It is suited for the connections in the battery pack and electric motor [6–8].

Laser welding is also trending to fasten electronic components within vehicles at present. Laser welding of electronic connections gained a high safety record. These include the increase in vehicle safety equipment namely connecting sensor-based safety equipment and advanced driver-assistance system. Laser beam welding technology is also preferable for fast production lines like fiber lasers having no power degradation and no consumables [9]. Before the introduction of laser beam welding, industrial applications were running using conventional welding processes despite having several disadvantages.

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The first problem with such welding processes is the production of excessive toxic smoke and fumes which is not environment friendly. Again control of heat generated during welding is a big problem for those outdated processes. Welding quality and surface appearance may hamper due to spatter formation; thus, precision in weld dimension is under scanner. In the case of arc welding, high heat generated during operation may affect the grain size; thus, mechanical properties may change. Improper distribution of heat sometimes distorts the product shape. Larger HAZ is also responsible for the failure of the welded joint [10–14].

Laser beam welding eliminates most of the drawbacks of the traditional welding processes and is thus adopted by almost all industries nowadays. It is an environment-friendly process with less generation of fumes and gasses. Heat is pointed on a very narrow zone, which does not affect mechanical properties due to changes in grain size. Laser beam direction and position can be altered using a lens attached to the laser system. The process is suitable for welding pre-machined parts with minimal distortion and restricted heat. Laser welding imparts localized heat with a smaller HAZ, design flexibility, better accessibility, enabling approaches that are impossible with other processes [15, 16]. Different laser technologies have been adopted by the automotive sector, which includes pulsed ND: YAG for small components, blue direct diode lasers, pulsed disk lasers, and fiber lasers [9, 17]. A doping element ytterbium provides good conversion efficiency that matches well with existing laser delivery components. But fiber lasers have overtaken almost all applications in the automotive industry at present. Fiber laser offers ease of use, handling, and longevity. Fibers are economical and relatively cheap draws less electricity compared to YAG or pulsed disk lasers [18].

Researchers untiringly working hard to develop the process more advanced and effective from the application point of view by coupling this with other fabrication processes like gas metal arc welding, gas tungsten arc welding, and plasma arc welding. When laser welding is coupled with any arc welding process, then the system of welding is termed as hybrid laser welding. It improves weld bead pattern along with penetration as seen in Fig. 1. A start of art review has been done by Acherjee [19] about hybrid laser welding. The study indicates that hybridization has several advantages over individual arc welding and laser welding. These benefits are higher speed of welding, increased productivity, deeper penetration, higher process efficiency, better process stability, excellent gap bridging capability, etc. Sebestova et al. [20] have utilized TIG-assisted laser welding to join a 3 mm low-alloy and high-strength thick S460MC steel plate with DC01 to examine the effect of arc current rate on weld cooling rate, microstructure, and mechanical properties. A defect-free fully penetrated joint was the result. Also, it was found that during the increase in welding current, HAZ width increased strongly over FM dimensions. The weld microstructure was formed mainly of fine acicular ferrite and bainite. Casalino et al. [21] fabricated AISI 410 with AISI 304 stainless steel sheets using a fiber laser-assisted TIG welding. The FZ microstructure formed was predominantly martensitic with an increase of micro-hardness of about 350 HV. The crack was initiated near the weld root and distributed along the heat affected zone in the martensitic stainless steel. Song et al. [22] utilized TIG and laser-assisted TIG welding of cast magnesium alloy AZ80

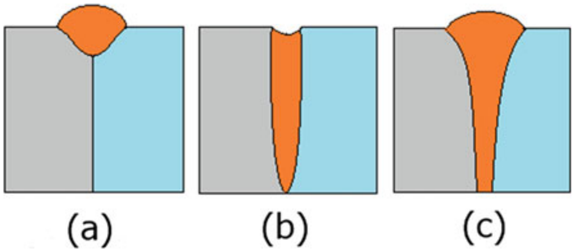


Fig. 1 Weld bead pattern and penetration for **a** arc welding, **b** laser welding, and **c** hybrid laser welding

with wrought magnesium alloy AZ31B. Results showed good weld formation with good tensile strength in both welding methods but hybrid welding possessed wider parameters than TIG welding, which makes it more reliable and flexible in industrial applications. Song et al. [23] joined a 1.6 mm AZ31 B sheet of Mg alloy with 1.0 mm Q235 steel using laser-assisted GTAW hybrid butt welding using AZ61 filler metal to determine the effect of welding heat on the interface bonding, morphology, fracture modes, and mechanical properties of the welded joints.

The maximum average tensile load (fracture) of the joints was 3265 Xue et al. [24] used laser-assisted MIG welding-brazing to join 6061-T6 aluminum alloy with 304 stainless steel to study the mechanical properties and microstructure of the welded joint. An excellent joint with good wettability was achieved on both sides of the stainless steel. Scanning electron microscopy, X-ray diffractometry, and energy-dispersive spectroscopy indicated an IMC layer at the 6061-T6/304 interface. Casalino et al. [25] joined DP/AISI316 with TWIP/AISI316 using fiber laser-MAG hybrid welding with austenitic steel filler. The heat affected zone at the TWIP side was austenitic in nature and showed a grain coarsening at the DP side. New martensitic grains were formed near the fusion zone. TWIP/AISI316 showed greater tensile strength than DP/AISI316. Zongtao Zhu et al. [26] butt welded AA6061 aluminum alloy with Ti-6Al-4 V titanium alloy of 3 mm thickness adapting laser-assisted MIG hybrid welding-brazing without a level. Cracks formed with a 0.2 mm laser-arc offset and an insufficient interfacial reaction occurred with the 1.2 mm offset in the lower region of the butt plane.

The present study shows the impact of LBW in the automotive industry, its recent development, its adaptation over traditional fastening processes, various processes of LBW used in the automotive sector, future aspects of the process, and a detailed survey of various applications of LBW in the automotive sector. As the study is strictly focused on automotive applications of LBW, thus it would be helpful for the budding researchers who are planning to work in this research domain in future.

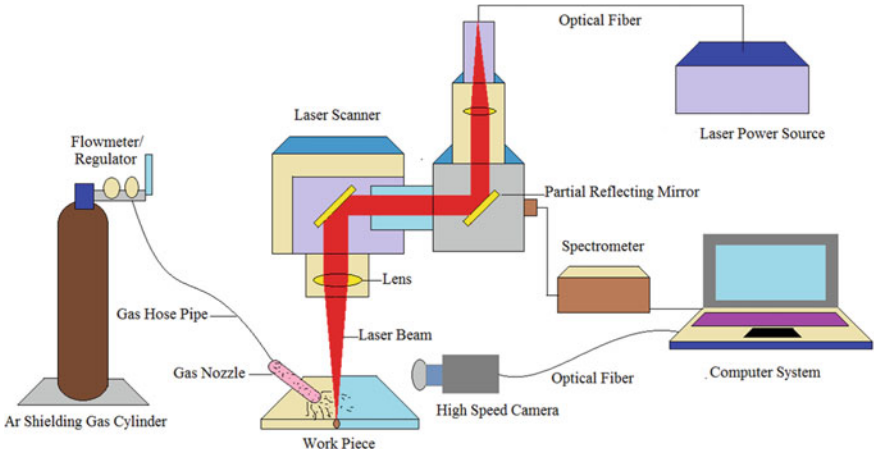


Fig. 2 Block diagram of laser beam welding setup

2 Laser Beam Welding

2.1 Experimental Setup

Figure 2 indicates a block diagram of the laser welding setup. Here, the laser beam can be controlled by the use of a focusing lens. Focal length, focal position, and even beam diameter before striking on the work pieces to be welded can be controlled. The shielding gas with various chemical compositions, flow rate, and density is used to make a defect-free welded joint. Most importantly, a wide range of parameters can be varied or analyzed in this process for a specific desired required output or response. A high-speed camera has been installed to take images and videos during the welding operation. Using a computer system with specific software, the whole system can be monitored and controlled. A spectrometer is installed to measure the property of light such as its wavelength, frequency, and energy.

2.2 Process Parameter

Figure 3 shows a fishbone diagram of laser beam welding parameters and responses. The process parameters of LBW are classified based on laser source and laser processing system. Parameters based on laser source are pulse wave mode, continuous wave mode, pulse frequency, spot size, pulse shape, laser power, etc. Now, parameters based on the laser processing system are welding speed, angle of ray inclination, focus depth, stand-off distance, focal length, focal position, beam diameter, etc. These parameters can be varied as per the requirement for a certain

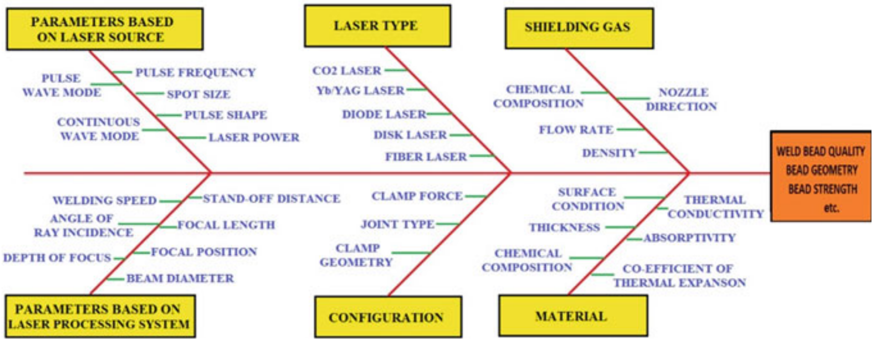


Fig. 3 Fish bone diagram of laser beam welding parameters and responses

response factor. The responses for LBW may be as follows: micro-hardness, residual stress, joint strength, grain size, penetration, etc. Researchers perform parametric optimization using different optimization techniques to see changes in these responses.

2.3 Shielding Gas

Shielding gas is useful in LBW for many purposes such as prevention of oxidation of molten weld pool, protection from atmospheric impurities, and stabilization of weld pool by creating a gaseous envelope. According to requirements, e.g., oxidation prevention capability, cost-effectiveness, penetration needed, plasma suppression, and limitations, shielding gas is selected. Table 1 shows different shielding gasses with specific features for LBW applications [27].

2.4 Types of Materials

LBW is suitable for a wide range of materials except for certain reactive materials, even some materials which are not weldable using conventional welding processes, easily weldable by LBW. It is a versatile process for welding both metals and non-metals. Some metals which are welded by LBM are stainless steel, carbon steels, HSLA steel, aluminum, and titanium [9, 28–31]. However, the high cooling rate is responsible for the problem of cracking during welding of high-carbon steels. Non-metals such as plastics and polymers are also using LBW technology [4, 5]. But at present, a wide variety of composites are laser welded for various applications in all fields of engineering. Before welding operation, certain material conditions must be considered such as surface condition, thickness, absorptivity, chemical composition, thermal conductivity, and coefficient of thermal expansion.

Table 1 Shielding gases used in LBW [27]

Shielding gas	Plasma suppression	Oxidation prevention	Relative cost	Flow rate (liter/min)	Penetration	Limitation
He	Excellent	Good	High	30–40	Deepest	None
Ar	Lower	Excellent	Medium	20–25	Wide	Plasma cloud reduces power density
N_2	Lower	Good	Low	20–25	Deep	Embrittlement of certain alloys (e.g., Ti)
CO_2	Lower	Poor	Lowest	30–45	Nominal	Not useful for reactive materials
Ar 80% He 20%	Good	Very good	Medium	30–35	Nominal	None

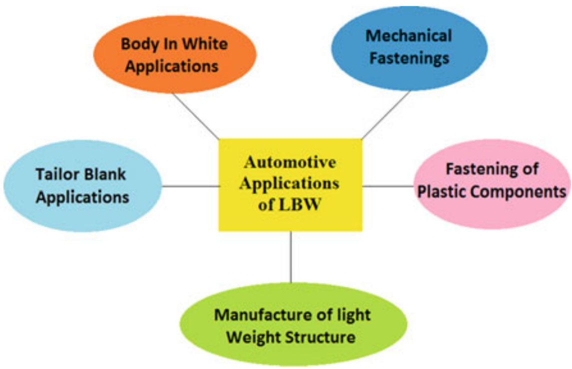
3 Applications of LBW in Automotive Sector

There are several applications of laser beam welding in the field of automotive sector which includes multi-thickness welded blanks, car assembly components, body in white applications, and mechanical fastening of different components [1–3, 6, 28]. The automotive applications are divided into a few categories as shown in Fig. 4.

3.1 Tailor Blank Applications

Tailor blanks are used to reduce material consumption and cost. Some applications are inner door panels, floor panels, cross rail bumpers, inner panel tailgates, wheel housings, etc. [1]. For the reduction of car costs and fuel consumption, innovative

Fig. 4 Automotive applications of LBW



design is the only solution. In this regard, Assunção et al. [2] made a comparative study to show the effectiveness of fiber laser over Nd: YAG and CO_2 laser. According to the study, welding speed was higher in the case of the thicker plate. The study result also showed the failure of the thin section outside the weld and cracks initiated in the case of the thin plate. A study has been made for the development of tailor blank for Nissan automobile company by Shibata [3]. The author addressed various issues of tailor blank application during vehicle production.

3.2 Body in White Applications

Body in white applications is the welding of various components for making final structure such as welding of car roof to the body side. To make a lightweight as well as a good strength car body, laser welding of DC 04 low carbon steel to a 6016 aluminum alloy was done using a fiber laser. Qianqianet et al. [32] showed optimal parameter values such as 0 mm defocusing value, 1400 W laser power, 40 mm/s welding velocity, and 35 L/min shielding gas flow for sound welding performance. High welding power and slow welding speed resulted in the formation of island solute which leads to internal crack formation. Higher weld strength was achieved with shorter Fe-Al reaction time and faster welding speed. A model has been developed by Franciosa et al. [33] for the selection of process parameters to control the volume of the molten weld pool and achieved the gap bridging with the application of remote laser welding of aluminum components. The model reduces the process parameter selection time which leads to a reduction of the number of physical experiments. The author suggested further development of the model by investigating the effect of welding speed on weld quality loop. Using remote laser welding, joining of selective laser melting (SLM) steels (made of 316L and 18-Ni 300) with conventional cold-rolled steels has been done for automotive application by Fieger et al. [34]. The result showed that the combination of boron steel and maraging steel should be considered only when 22MnB5 was on the top to ensure a high-quality assembly. A study has been done by Ribolla et al. [17] on laser beam welding of steel roof and side panels for an automobile body. For large-scale production of the car body, a continuous 4 KW power was ideal.

Steels have a property like high strength which is desirable for a car not only for the body but also for the main structure. Agarwal et al. [35] welded advanced high-strength automotive steel for automotive application to study solidification cracking. The result indicated the transverse strain near the fusion boundary to predict the cracking behavior as shown in Fig. 5. With the decrease in heat input, susceptibility to solidification cracking decreased. Both for the passengers' safety and fuel consumption, high-strength and low-alloy steel HC340LA, dual-phase steel HCT600X, and multi-phase austenitic steel RAK40/70 were laser welded by Evin et al. [36] for making car structures. The high-quality joint is produced with high strength without porosity.

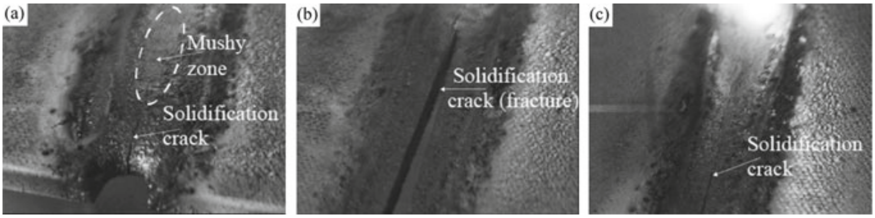


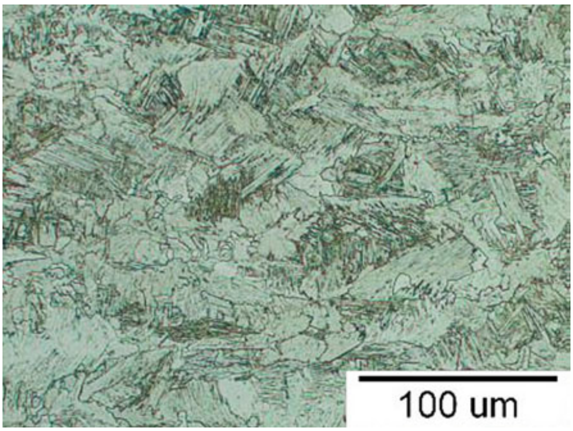
Fig. 5 High-speed camera images showing solidification cracking during welding. **a** solidification crack initiating at the trailing edge of the mushy zone (5 mm); **b** full fracture observed (5 mm); **c** the solidification crack ceases propagating beyond (7 mm) [35]

The result also indicated the highest work hardening for multi-phase steel RAK40/70 because of the formation of austenite to martensite structure as shown in Fig. 6. For the same purpose, a dual-phase advanced high-strength steel (DP600) was welded by Fernandes et al. [15] using laser welding. The hardness at the weld zone HAZ dropped significantly after the heat treatment. Due to the automotive applications, 304 L steel and carbon steel st37 of 1.4 mm thickness were welded by Kumar et al. [37] in butt-joint configuration.

At the fusion zone, coarse recrystallized grains were found. The change of heat affected zone width was negligible in austenitic stainless steel and in case of st37 decreased with an increase in pulse width. Passengers' safety is the priority for car manufacturers; thus, they promote researches to gain a new domain of knowledge. For making a strong and safe car structure, a high-strength galvanized steel sheet was joined by Mei et al. [38] using laser welding. The high-quality joint was made without porosity and cracks.

The hardness was achieved due to high welding speed and recrystallized fine grain structure. Laser welding has been performed on DP980 dual-phase and high-strength and low-alloy steels by Westerbaan et al. [9] for automotive applications.

Fig. 6 Fusion zone microstructure of laser welded steel HC34OLA-HC34OLA [36]



The weld concavity of DP980 and HSLA steels was due to reduced power and increased welding speed. The result indicated higher concavity while reduction of tensile strength of the DP980 welds without affecting the HSLA welds.

3.3 Manufacture of Lightweight Structure

As the price of fossil fuel is increasing day-by-day so it is essential for car manufacturers to cut down the overall weight of the car to reduce fuel draining. The most popular combination of materials for this purpose is steel and aluminum. Steel possesses high strength, and aluminum is corrosion resistant with lightweight. A 1.5 mm thick aluminum 5182 sheet and a 590DP steel sheet with Zn coating were remote laser welded by Kotadia et al. [28] to form a lightweight structure. The research pointed out that for a thin sheet dissimilar welding keyhole formation was undesirable due to uncontrolled mixing in the weld pool, formation of porosity, and defects. Due to their lightweight, aluminum and its alloys are trending in the automotive sector for the lightweight vehicle. Using laser welding, 5754 (AlMg3) alloys were fabricated by Çevik et al. [29], and the experiment showed that tensile strength was unaffected by welding speed. Another experiment was done by AlShaer et al. [39] to weld AC-170PX (AA6014) aluminum for lightweight automobile vehicles. The study showed that the filler with higher Mn and Mg content leads to a significant decrease in porosity compared to 80% porosity with the silicon rich wire. A 6 mm thick AA5754 aluminum alloy sheet was welded by Casalino et al. [40] in butt welding configuration with varied speed and shielding gas to get a high-quality weld bead. An ANN optimization technique was adapted to establish the relationship between process parameters and bead characteristics.

To have a lightweight automobile structure, Al alloy and Zn coated steel were welded by Chen et al. [41] adapting laser welding. The experimental result showed that nitrogen acted as the shielding gas. The corrosion resistance and the surface finish could be improved during double pass welding with argon as the shielding gas. Another investigation was done by Kim et al. [42] to have a lightweight car body by welding of aluminum (AA5182) alloy with AA5356 filler wire. The authors found optimal welding conditions with laser power of 4 Kw, filler wire feed rate of 2.7 m/min, and welding speed of 7.95 m/min. For manufacturing car body, zinc-coated steel sheets with aluminum sheets have been joined by Liedl et al. [43] in a butt-joint as well as in a lap joint configuration. The experimental results indicated that the laser welding of aluminum and steel samples produced narrow and well-defined IMPs with 10 μm thicknesses. Lap joint as well as butt-joint weld configurations showed good reproducibility.

Laser welding was adopted by Long et al. [44] to join 6016 aluminum alloy to DC04 steel with pre-placed metal powders in a lap joint configuration to reduce the weight of the car structure. The combined Taguchi-response surface method optimized process parameters for good quality weld as shown in Fig. 7 as 30 mm/s welding speed, 1344.73 W laser power, defocus distance −2 mm, and shielding gas flow rate of 30 L/min. For the same purpose, AA5182 aluminum alloy with AA5356 filler wire was welded by Park et al. [45] with wire feed rate, laser power, and welding speed as control parameters. A genetic algorithm tool was used for parametric optimization which showed optimal process variables as 2.3871 m/min wire feed rate, 4 kW laser power, and 8.4762 m/min welding speed. Aluminum welding is challenging because of pore formation which weakens the joint. An investigation was done by Pastor et al. [46] to weld 5182 and 5754 automotive aluminum alloys using Nd: YAG laser welding. The researchers concluded that an unstable keyhole was responsible for pore formation in an aluminum structure.

Even Mg alloy in combination with Al alloy can create a lightweight car body but is tough to weld because of brittle intermetallic phases. Laser welding of Mg alloy to Al alloy has been done by Scherm et al. [30] using ZnAl as filler material which showed that strength was affected by Al content of filler. Due to lightweight and good mechanical properties, Mg alloys are also adopted by car manufacturers. Abderrazaka et al. [31] determined the bead width and the penetration depth as a function of both the welding speed and the incident laser power.

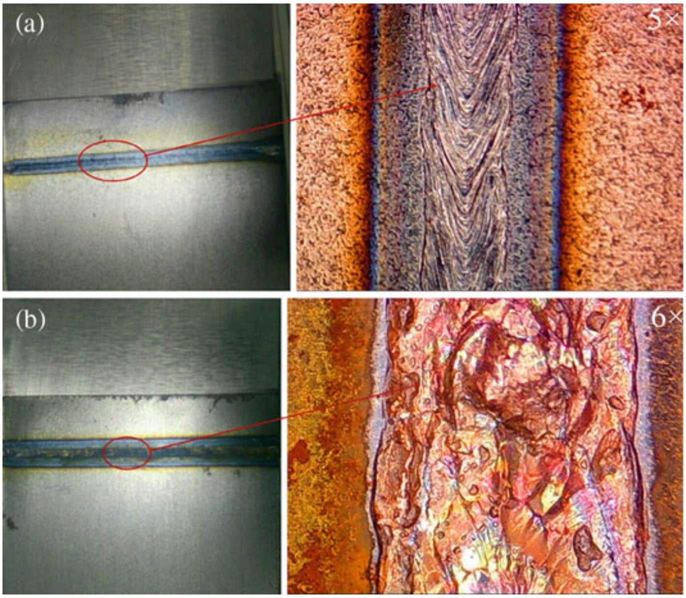


Fig. 7 **a** Bead appearance of aluminum alloy to steel with metal powder and **b** without metal powder [44]

3.4 Fastening of Plastic Components

The use of molded plastics has been adopted by the automotive industry for different car components. Most of them are simple components such as headlights and taillights [4]. But for welding of complex geometrical shapes, laser welding is suitable over traditional welding processes. Another popular application of laser beam welding is car keys [5]. Other applications are sensor housings, under hood components, instrument panels, etc.

3.5 Mechanical Fastenings

For the manufacturing of distributed windings of electrical drives with high-power density for battery-operated electric vehicles, an element called hairpins is assembled by the use of the laser to the stator lamination and contacted afterward to produce the winding [6]. Aluminum alloys such as AA6060-T6, AA6063-T6, and AA6008-T7 have been used for the construction of the battery tray. Sun et al. [7] used filet lap joint coupled with power modulation and beam oscillation to avoid centerline cracks. For making a low resistance battery module connection, aluminum Al 99.5 and copper Cu-ETP were laser welded by Hollatz et al. [8]. For aluminum on top of the copper, the oscillation leads to a wider connection width. Due to the growing demand for electric vehicles, lithium-ion battery cells are being increasingly used as energy storage devices. Fabrication of CuSn6 sheet with a battery, which consists of nickel-plated DC04 steel in an overlapping welding configuration were done by Mehlmann et al. [47]. The copper sheet was effectively connected with the steel sheet of the battery by the laser beam micro-welding. During laser welding of copper, small spot size along with keyhole welding leads to a small contact area between the two joining components which has been rectified using additional parameters such as amplitude and oscillation frequency, in conjunction with spatial power modulation. Haeusler et al. [48] showed that the maximum penetration depth decreased while using higher oscillation amplitudes compared to a conventional laser weld. The reduction of the surface roughness was indicated a more stable behavior of the weld pool and the solidification. No spattering was detected during the process with the use of spatial power modulation. A 99.5% aluminum ribbon (Al H11) with a cross-section of 300 $\times$ 2000 μm^2 was welded by Helm et al. [49] with a 2 mm AlMgSi1 plate designed to minimize the contact resistance of the connection area. The metallographic study showed a correlation between the width of the connecting zone and the number of lines. The batteries having limited terminal thickness would not be penetrated during welding to avoid damage to the cell.

The investigation of the influence of spatial power modulation on the weld seam geometry and intermetallic mixing of copper and aluminum was done by Hollatz et al. [50]. Stainless steel was selected to study the behavior and the stability of developed data processing strategy and the resulting depth values. Low melting point and high thermal conductivity of copper make poor weld which leads to low-energy utilization. A 1064 nm wavelength Nd: YAG laser to improve weld efficiency and welding quality was proposed by Maina et al. [51] for good surface quality and deep penetration enhancing absorption rate. The study showed good surface quality and deep penetration achieved for transitional processing conditions between keyhole and heat conduction welding with enhanced rate of absorption. For safety, it is important to seal the battery can as many failures occurred in recent years. The weld area of aluminum and copper was investigated by Mian et al. [16] via SEM and energy-dispersive spectroscope to understand the microstructural and physical characteristics. The scanning speed did not affect heat affected zone as the samples were observed from the aluminum side as the laser power and spot size were same for both of the scanning speeds.

For joining of pressure sensors and battery cells, the small processing time is economical; thus, thin metal sheets like nickel, stainless steel, titanium, and aluminum of thickness below 100 μm are worthy. Seiler et al. [52] studied the humping effect during LBW of thin metal sheets. The author showed the way to avoid the generation of the humping effect, and the indicator was the ratio of laser power to weld seam cross-sectional area for the materials.

4 Conclusions

In the present research work, the advantages of the laser beam welding over other welding processes have been discussed along with various applications in the automotive sector. Discussions on the making of the fuel-efficient lightweight car body, multi-thickness weld blank, car assembly components, body in white elements, mechanical fastening in case of electrical, and electronic elements have been zeroed in this paper. In most cases, for making a lightweight structure, aluminum and its alloys have been utilized. But the most used dissimilar material combination, i.e., aluminum and steel have been adopted as aluminum makes the car body light and steel adds strength.

Mechanical fastening of electrical lighting elements and electronic sensors has been increased nowadays as the automotive sector is keeping eye on electric and hybrid vehicles. The ultimate target is to make a good quality welded joint with desired mechanical properties and fatigue strength with a low overall cost; thus, further study in this field must go on.

5 Future Scope

Parametric optimization has been done based on few parameters; thus, a vast study can be done in this domain using several newly developed optimization techniques such as MACONT, Pythagorean fuzzy DNMA method, and ant colony optimization.

Even study can be done with variation of shielding gasses or mixture of two or more shielding gasses with right proportion and a comparative study then may be done on weld quality, weld strength, micro-hardness, etc. For example, Corgon is used in arc welding applications for its numerous advantages. Though a number of papers have been published on identifying various welding defects but for future prospective, further study is required to find ways to reduce pores, various forms of cracks, and other welding defects as quality matters. For making the overall process cost effective, research must be done to design and develop new setup.

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