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Laser Welding

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Abstract

Among novel techniques, laser welding is considered an adaptable and rapidly evolving method, finding innumerable applications in engineering industries. It is capable of welding narrow and impassable joints precisely, which can be operated under computer control. This chapter of the welding Handbook reviews the most recent developments in the field of laser welding, which are used for different applications. The first section provides an overview of laser welding basics and then moves on to the developments such as high-power CO₂ laser welding, laser micro-welding, and solid-state laser welding technologies. The second section underlines laser welding instruments used for joining different materials such as titanium, aluminum, and magnesium alloys, ceramics, and plastics. The third section highlights the advances in innovative laser welding methods with discussions on the applications of laser welding robots to improve the modeling and simulation of this technique. Lastly, the fourth section focuses on the use of laser welding technology in various industries including aerospace, automotive, railway, etc. The present Handbook is a practical reference for scholars, engineers, and professionals using laser welding techniques or requiring an understanding of the field of laser welding technologies.

Keywords: laser welding, CO₂ laser welding, laser micro-welding, solid-state laser welding

1. Introduction

Since 1962, there have been numerous reports on the metallurgical applications of lasers, including welding. The first laser welding operation was reported in 1963 for the butt welding of steel sheets using a pulsed ruby laser. In 1965, laser systems were developed to be used for welding electronic circuits, vacuum tubes interior, and other special applications that conventional technologies at the time could not provide. Due to the limited power source, until 1970, laser welding was limited to welding low-thickness materials at low speed. Later, high-power continuous laser sources were employed for welding procedures. In 1971, the presence of high-penetration welding or keyhole welding via laser beam welding (LBW) and electron beam welding (EBW) was reported. In other words, by this technique at high laser intensities (MW/cm³), it is possible to make keyholes in metals, which is not practical for pulsed laser welding because the formation of keyholes needs prolonged times to form and does not occur simply [1, 2]. Since 1972, the use of continuous CO₂ lasers changed this direction and

high-thickness stainless steel joints with full penetration were welded similar to those welded by the EBW process using the keyhole mode. These investigations were conducted in Japan, Germany, and the United Kingdom. Subsequent advances in CO₂ laser welding were focused on further optimization of laser resources, laser beam quality, and understanding the interaction of joint design, welding speed, radiation concentration, and the plasma effects on weldability. Studies in this field have continued using sources with the power of up to 12-15 kW. Using the neodymium-doped yttrium aluminum garnet (Nd:YAG) sources can be more applicable than CO₂ lasers due to their short wavelength and reduced radiance from the metallic materials (**Figure 1**). Currently, laser sources have many applications in the field of material processing. LBW as a new technology in recent years has found wide applications in various industries such as automotive, military, aerospace, shipbuilding, electronics, etc. Based on the assessments, it has been estimated that in the near future, the practice of diode lasers will have made great strides in LBW [3, 4].

The laser welding technique differs from conventional fusion welding methods in terms of equipment and operation. In laser welding, a thin and deep weld pool is achieved and the applied heat input to the joint is very low compared to conventional methods. This property allows the LBW to be used in certain applications where the welding depth requires a high width. The penetration depth and welding width can be

Figure 1.
Schematic of the laser beam production.

adjusted by controlling the laser power, changing the focal position of the beam, welding speed, distribution mode of energy transfer (pulsed or continuous mode), and shielding gas parameters. This enables the LBW to join and fabricate critical components with minimum risk. Features such as low welding width, high penetration depth, excellent joint strength, and low workpiece distortion in addition to fulfilling the need for low-weight joints with high corrosion resistance, proper weld appearance, low electrode consumption, eradicating machining process, and ability to weld unreachable areas have made industries interested in this technique.

There are two main methods for laser welding. The first is to move the workpiece rapidly underneath the beam to obtain continuous welding. The second route, which is more common, is to weld by irradiating a series of beams. Since during LBW both the melting and solidification processes occur in a few microseconds, almost no reactions take place between the melt and the surrounding atmosphere; therefore, generally using shielding gas is not necessary.

The most optimum joint design for LBW is the butt joint, however, due to the thickness limit, T-joints or corner joints are also desirable.

Hybrid processes that use a combination of laser and gas metal arc welding (GMAW) are also developed to be used in a fixed position. In addition, the equipment used to prepare the joint design is no longer needed. The alloys of the filler metals are specifically designed to make the joint physically uniform. In addition, the hybrid processes can significantly increase the production speed. Moreover, they also affect the penetration depth and sealing of the joint. Recent exclusive advances in the fabrication of laser diodes have provided a new opportunity to solve persistent industrial problems. These processes must be modified to be assimilated with the desired purposes [3, 4].

2. Laser welding process

LBW is one of the innovative methods of fusion welding. By irradiating a high-energy laser beam to the intended gap, the heat required to melt the edges and fill them is provided and the joining process is achieved. It should be noted that the equipment and operation of the LBW are dissimilar to the conventional fusion welding methods. In LBW, a thin and deep joint is achieved, and the heat input applied to the workpieces is so much lower than the conventional welding methods. This property allows LBW to be widely used in certain applications in which a high ratio of penetration depth to joint width is required [5–7].

LBW is a balance between heating and cooling in a certain volume of one or two solids, leading to the melting and solidification of a material. LBW is characterized by the creation of a molten region by the absorption of intensified radiation, which allows the molten pool to expand into the solid interface region, resulting in a continuous joint between the components. Failed joints occur when the molten area is too large, too small, or the material is excessively evaporated. Weld quality is analyzed according to the evaporation of alloying elements and the thermal gradient of the phenomena leading to the crack formation [8–11]. An imbalance in the volume and scale of the weld area leads to porosity. Achieving a balance between the heat input and output depends on the constant absorption of laser radiation and the uniform distribution of heat in the workpieces. The path of the laser beam to the weld pool is often disrupted by the accumulation of hot fumes at the beam focus point. In certain conditions, these hot fumes can turn into a plasma cloud that strongly affects the

Figure 2.
The keyhole formation and laser welding using keyhole mode.

beam and absorbs and disperses it (**Figure 2**). The first stage in studying LBW is to determine the parameters affecting the heating/cooling balance, molten pool, welding area, reproducibility of the process, and the development of methods to control these parameters [5–7].

3. Advantages of laser beam welding

Proper joining rate, excellent welding quality, very high accuracy, high automation capability, and exceptional appearance of the welded joint are included as beneficial factors, leading to the application of LBW in various industries. Economically, the reduced production costs and low consumption of consumables have made this method one of the finest joining methods. To recognize why LBW is one of the best welding solutions, the top five advantages of this technique are listed below [5–7]:

3.1 Ability to join complex joints and high accuracy

LBW can weld complex joints successfully, especially it can join dissimilar materials or areas very difficult to reach using traditional welding techniques.

One of the main advantages of LBW is that it can offer a high level of accuracy and control, i.e. it can be used to join the smallest workpieces together without damaging them.

Strong potentials can be proposed for weight reduction and joint design opportunities. Typically edge welding is carried out by direct fusion of two base metals. Using

Figure 3.
Joining of edge seams by LBW: (a) flanged butt joint and (b) flare-V groove.

this tactic, it is vital to maintain an almost zero gap between the workpieces to ensure suitable joining. Using the LBW, high fusion depth can be gained while reducing flange length by more than 50% of current standards. This can be obtained by employing hybrid features of integrated clamping, optical seam tracking, and beam oscillation capabilities (known as laser welding optic).

Like other welding processes, during LBW it is challenging to guarantee the accurate positioning of the energy at the joint. But a combination of process robustness, work-piece tolerances, and robot accuracy results in obtaining proper welds. Finding the joint by optical seam tracking and laser triangulation provides accurate positioning for the laser spot during the process. This seam tracking data is then sent back to the optic controller, translating the required data for repositioning of the head galvo motors to point the laser beam to the desired coordinates. The system is capable of providing several inclination angles to accommodate the adjustments of joint position for two and three-layer joints as flange heights variation relative to one another. By adding an integrated clamping unit to the head not only the workpiece can be fixed at the desired position, but also provides the tooling costs to clamp the seam can be reduced (**Figure 3**).

The clamping unit design allows the reaching into flanges openings or structures and rapid open/close clamping mechanism (200 ms), providing a good foundation for high-volume applications. The innovative technologies offer extra advantages to meet the welding requirements for base metals such as ultra-high-strength steels, aluminum, and boron. By utilizing oscillation motors along with those directly tied to beam location two-axis oscillation can be obtained at frequencies up to 1 kHz, which eliminates the oxide layers, extra time for the gas to exist the weld pool, or post-weld annealing of brittle microstructures. An instance of the cleaning of the welding area can be seen during the zero-gap welding of galvanized materials. To this end, a gap (-0.1 mm) is characteristically required to provide a place for evaporation of the zinc at temperatures higher than $0.5 T_m$ of the base material. If not correctly set up, the gas expulsion can be trapped within the solidifying melt and form porosity in the final weld. The oscillation feature grants a remelting phenomenon for the weld pool and allows the zinc to escape to the surface and leave the weld. For structural applications, it is frequently necessary to join dissimilar materials for example boron steels to electrolytically or hot-dipped galvanized steels. According to the beam location control feature using oscillation, a melt pool is formed, which floats on the workpiece.

However, a distortion in the workpiece is not essentially attributed to the adaptive nature of the process.

3.2 Low heat input

LBW method uses a low heat input rate that minimizes the joint distortion. Hence, it is the preferred method for those who wish to make luxury products such as custom jewelry. Laser sources employ tremendously localized energy and allow non-contact use, which applies lower heat input on the workpieces. This method is ideal for non-contact applications, which protects other areas of the parent material from the adverse effects of heat.

The feature 'line energy' is commonly used as a denominator to compare welding processes carried out in 1F and 2F positions. Moreover, heat input determines the joint geometry, which can be controlled via the modification of the welding parameters. In other words, the heat input is directly correlated to the laser power (or arc power) and the welding speed. The heat input for the LBW process is calculated according to Eq. (1).

$$Q_{laser} = PL/vt \quad (1)$$

where Q_{laser} is the laser heat input (kJ/mm), PL is the output power of the laser source (kW), and vt (mm/s) is the travel speed. The heat input of the hybrid laser-arc welding (HLAW) considers the additional energy delivered by the arc and is determined by Eq. (2).

$$Q_T = Q_{arc} + Q_{laser} = \frac{UI60}{vt} + (PL60)/vQt \quad (2)$$

where Q_{laser} is the LBW heat input (kJ/mm), PL is the source output power (kW), vt (m/min) is the travel speed, QT is the HLAW heat input (kJ/mm), Q_{arc} is the arc welding heat input (kJ/mm), U is the arc voltage (V), and I is the arc current (A).

3.3 Compatibility and replicability

LBW can provide continuous and repeatable component fabrication. This helps industries to reduce their manufacturing costs significantly. LBW is far more quickly and much more versatile than the conventional methods. Laser welding can also be used for cutting and drilling.

When a lap fillet is the functional joint, which should be processed, similar issues are apparent as well as the joint location and overlap. To resolve the issues optical seam tracking and beam oscillation are employed. However, gap bridging technology can also be used instead of clamping equipment. In most LBW applications, zero-gap is a similar challenge as well as the joint location and ideal fusion between sheets. In lap edge configurations gaps should be seen; hence, options are currently developed to produce sound joints in this configuration.

If a filler wire is required for modification of the chemical composition or other gap-related conditions, options are developed to use the tactile seam tracking system and utilize the filler metal to bridge the gaps (**Figure 4**). But, using remote laser welding, it is not practicable to insert the wire into the melting pool when optical seam tracking is employed for beam placement. Additionally, it is possible to weld the gap automatically without filler metal. Remote laser welding – adaptive (RLWA) is a unit, utilizing a

Figure 4.
 Laser welding using brazing filler metal.

real-time seam finding and tracking by internal controlling of the head, which is called gap bridging. The final result is the dynamic control of the laser spot position relative to the seam, not only irradiating a predetermined point in coordinates. When the beam is accurately placed into the seam, joining a lap point with high reliability is possible. This issue is attributed to gaps in the material, which typical laser processes struggle to accommodate. With gap bridging algorithms, which are predefined in the system controls, the LBW optic can identify gaps in the joint via the seam tracking package and adjust various conditions automatically to process the joint.

By modulation of laser power, y offset of the beam relative to the joint edge, spot size, and using beam oscillation in the x and y directions, the melt can bridge the joint. Gaps with 50% or less of the upper sheet thickness can easily be addressed with both aluminum and steel materials, while recent studies show capabilities beyond that in certain situations (**Figure 5**).

3.4 High-strength joints

Since the heat input rate is significantly lower than the conventional methods, the heat affected zone (HAZ) of laser-welded joints is very small that allowing manufacturers to perform high-strength welds.

The laser beam machining (LBM) parameters such as laser intensity, beam distribution, scanning speed, spot size, and relative motion between the laser beam and workpiece can be adjusted according to different base materials. Currently, lasers are

Figure 5.
Different LBW gaps and RLAW equipment.

Figure 6.
Difference between the properties of (a) long-pulsed and (b) short-pulsed durations.

substituting conventional machining equipment because of their superior advantages. Major advances have been made in this area to shorten the pulse time for various machining processes. Prolonged pulse durations increase the HAZ and induce high thermal stresses, which result in the formation of cracks, voids, and surface debris. Short pulse times decline the thermal conduction, provide accurate machining operation, and proper surface finish. **Figure 6** reveals the difference between the properties of long and short pulse times [6].

3.5 Appearance, precision, and cleanliness

Since there is no need for filler metals in LBW, it provides an excellent welding quality and clean processing, so that it gains attention especially in the medical engineering industry where the quality of medical devices and components is very important.

The feature of weld optics focuses the beam down to a spot size range of 200-300 μm . On the contrary, larger spot sizes are rarely used, when low-shift welding

is desired. However, large weld spots are not beneficial since they require higher overall energy and a larger heat input rate. The weld heads function with a collinear charge-coupled device (CCD) camera. Different focal planes of the beam are corrected in the visible and infrared spectra. During this modification process, a sharp CCD image indicates the proper adjustment of the weld head to its correct focal position. Moreover, a projected crosshair is centered to the position of the weld spot to be perfectly superimposed with the beam (**Figure 5**). Thus, machine vision algorithms are employed for automated precise adjustment of the welding optics to desired coordinates so that the beam is exactly irradiated to the gap between the workpieces to be joined.

To keep the power density constant, LBW should be always carried out using the waist of the beam with an accuracy of 10 μm . If the irradiated beam is not focused, the power density rapidly increases and causes an uneven weld pool. Since the strength of the contact between the joining surfaces is one of the key parameters of low-shift welding, the welding design should be consistent with this parameter. To adjust cylindrical parts to the most parallel state, a dome-shaped air bearing is used. A preset force moves the parts in contact with each other, which are self-adjusted as floating on an air bearing. When the surfaces are positioned parallel to each other, the angular position is fixed to activate the alignment. Predetermined offsets can compensate for the predicted weld shift in a planar setup. By optimizing the tolerance of the parts, the accuracy of the offset can be improved.

If a welded component shifts during the nano-welding process, additional employment of the weld energy in an opposite direction bends the workpiece back into the desired location. During this process, the effect of the unavoidable shrinkage is exploited. Careful experimenting should be carried out to determine the proper power and time of the corrective pulse. This procedure is known as laser-induced micro-adjustment (LIMA). Forming nanostructured weld joints requires a weld design, which is optimized for LBW. The LBW system has to consider the specific aspect ratio of the workpiece. To obtain an optimal result, it is suggested that the nanostructure designer and the manufacturer of the welding system work together from the beginning.

4. Laser welding limitations

Although LBW can be an amazing technology, it also has minor limitations. One of the most common disadvantages of LBW is the high cost of the process. LBW machines are very expensive and complicated so they are not accessible to many manufacturers. The other disadvantage is that it requires a highly-skilled workforce. Otherwise, LBW is almost perfect [5–7].

5. Laser sources and stimulated emission

Laser is a monochromatic light source (sometimes visible) and coherent with very high orientation and brightness. A comparison of the conventional light source and laser light source is given in **Figure 7** [6, 7].

The energy levels used in the laser radiation process are generally of two categories of atomic and molecular energy levels. Under normal conditions, atoms are generally in the ground state until they are excited by an external stimulus (pumping system). Then they return to the ground state in a very short time (nano/microseconds) by

emitting a photon having an energy equal to the difference between the two levels. This return is possible in two ways [6, 7, 12], spontaneous emission and stimulated emission. Stimulated emission is considered in laser. When an atom is in the excited state, if a photon with an energy equal to its excitation energy passes by that atom, the photon induces it to be sunk. The photon is a laser photon if it is produced under the influence of another photon. Otherwise, it is the spontaneous emission [6, 7, 12].

6. Optical resonator

Each laser optical resonator consists of two mirrors and a pumping chamber, containing the active laser medium. Generally, one of the mirrors is a full reflector (input coupler), while the other is a partial reflector (output coupler). Photons, which are moving in the direction of the resonator axis are resonated to form the laser beam. Photons in other directions are destroyed by adsorption on the walls of the active medium (Figure 8) [3–7].

Figure 8.
The function of the optical resonator during laser beam production.

Figure 9.
The key components of laser welding procedure.

7. Laser welding procedure

The principles of the LBW process are not complicated. The procedure schematic is presented in **Figure 9**. (1) A pump, which is the energy source provides the energy required for the process. The pump stimulates the laser to such an extent that the electrons held by the atoms are moved to higher energy levels. (2) Electrons reduce their energy levels dramatically, releasing photons. The spontaneous emission of photons is what leads to the production of the laser beam. (3) Spontaneously emitted photons collide with the ones having higher energy levels. The collision reduces the energy levels of the electrons, leading to the emission of another group of photons. Both groups are now having the same wavelength and moving at the same speed. (4) Photons are emitted in all directions. However, they are all limited to travel in the same medium and hit the resonator before reflecting from the medium. The intensifying mirror then determines the level and direction of emission. To perform any type of amplification, the fraction of atoms must be higher than that of low-energy photons. (5) The laser beam is targeted and focused on the workpieces to be welded. Highly-focused light energy is converted to heat energy at the workpiece surface. (6) During a process known as surface conductivity, the generated heat melts the material surface. The generated heat is controlled to be below the boiling point of the parent material. This technique is an ideal solution when welding materials that have high thermal conductivity. Apart from welding, other procedures such as drilling, cutting, and stripping can be carried out using laser beam energy [3, 13–16].

By combining the LBW and GMAW techniques, the laser-GMAW hybrid welding is developed. This combination is an attractive tool with a great potential for welding lightweight structures, especially aluminum alloys. This hybrid welding technique is generally acknowledged for its efficiency, robustness, and flexibility. By combining a

deep-penetrating laser beam with high filler feeding of GMAW the primary applications of LBW and GMAW can be improved significantly. The main benefits of this technique are high gap-bridging ability, deep and stable weld penetration, facile addition of the filler metal, and low distortion. This hybrid method allows much wider groove tolerance in comparison with LBW of specific alloys such as aluminum alloys. Furthermore, the distortion reduction decreases the required post-welding treatments and facilitates the assembling process because the hybrid-welded components are more dimensionally precise. Moreover, if very accurate metallurgical factors are needed, the hybrid process can be easily balanced with the filler metal, which declines the susceptibility to hot cracking, especially for specific aluminum alloys. This combined process can also enhance the weld bead shape appearance and quality (e.g. by elimination of undercut), reducing the porosity and increasing the welding speed.

Since hybrid laser arc welding (HLAW) apparatuses are influenced by each of the two processes, the weld geometry of HLAW is controlled by the heat input of each process as presented in **Figure 10**. For instance, by increasing the power of GMAW, the width to depth ratio of the weld is increased. Nevertheless, due to the contribution of both techniques, the HLAW-welded joints are usually similar to LBW at the bottom and similar to GMAW on the top of the joints.

In addition, due to the involvement of a high-density laser beam, keyhole formation is a characteristic of the HLAW process in most cases. On the other side, a

Figure 10.
Hybrid laser GMAW welding process.

conduction-like process without the formation of the keyhole is obtained if the beam is not focused or its power is insufficient. A previous study regarding the aluminum LBW showed that initially, the Nd:YAG laser beam absorption by the base metal surface could be as low as 10%. But, when the base metal was molten, the beam absorption greatly increased up to almost 100%, especially when the keyhole was formed. Interestingly, it has been reported that the arc stability of GMAW is increased when it is coupled with a laser beam. This enhancement is achieved when the arc is close enough to the beam and they share the same melting pool. For example, since the aluminum melt has a lower electrical resistance than that of the solid-state or oxide layer, the arc favors the path with the lower resistance. Besides, the interaction between the keyhole and arc plasmas increases the arc stability. The energy from the formed keyhole creates a metal plasma, ionizing the shielding gas of the GMAW process that facilitates the strike and stabilizes the arc. Furthermore, the HLAW arc has a finer geometry, a higher electrical conductivity, and a higher current density (up to 500% of the GMAW arc). On the other side, since in HLAW, the metal plasma is originated from both the base metal and the filler metal, more metal vapor is produced than that of the LBW. Consequently, the keyhole formation is much easier and process failure is prevented. The penetration of this technique is higher than the LBW due to the higher plasma pressure. Since the molten pool is larger during this process, the weld pool is in the liquid state for a longer time compared to the LBW. This is beneficial in the case of welding aluminum alloys due to the high hydrogen solubility in the molten aluminum. Hence, a larger melting pool gives more time to hydrogen bubbles to escape from the weld, resulting in the formation of fewer gas pores.

Because of the interaction between the two processes, the advantages are more than the drawbacks. For welding aluminum alloys, these advantages depend on the welding parameters, the alloy composition, and the joint type. A majority of the authors stated that the welding speed is increased by using the hybrid technique. Moreover, it improves the penetration of the weld seam, which is 10-20% and 20-50% higher than the LBW and GMAW, respectively. Additionally, many studies have expressed that the stability during aluminum welding is higher in comparison with LBW or GMAW processes. Additionally, the applied heat input is lower due to the elevated speed and high energy density of HLAW. By lowering the heat input the distortion of the welded components is directly decreased. Since the GMAW process generates a large welding seam, gap bridging is improved during HLAW compared to the LBW. It has been reported that the HLAW can increase the gap bridging from 1.05 to 1.19 mm compared to the GMAW, while the maximum gap tolerance of the autogenous LBW is around 0.3 mm. Another benefit of this process is its higher wire feed alignment compared to the LBW. Since in the HLAW process the feeding wire does not have to intersect with the laser beam and the weld pool, the addition of filler metal is more facile than that of the cold wire fed LBW. The reduction in the component distortion, high gap bridging, filler application, and wire misalignment tolerance are the main important aspects of automated HLAW that increase the robustness of this process for industrial applications compared to the primary original processes of LBW and GMAW.

8. Types of laser welding based on laser sources

Several types of lasers can be utilized for LBW. These include fiber lasers, Nd:YAG pulsed lasers, and Nd:YAG continuous-wave lasers. However, one should know that the type of employed laser source for LBW depends on the application [3, 6, 7, 13, 17].

Solid-state lasers	Gas lasers	Semiconductor lasers	Liquid dye lasers
Ruby	ArF	AlGaInP	Stilbene
Alexandrite	KrF	AlGaAs	Coumarin 102
Ti-sapphire	XeCl	InGaAs	Rhodamine 6G
Nd-YLF	XeF	InGaAsP	
Nd:YAG	Argon		
Nd:glass	Krypton		
Er-YAG	HeCd		
	Copper vapor		
	Gold vapor		
	HeNe		
	CO ₂		

Table 1.
Solid-state, semiconductor, gas, and liquid dye lasers.

Fiber lasers can be used for a wide range of applications, from joining very small components used by medical engineering and electronics industries to welding thick components in the automotive and aerospace industries. Fiber lasers are versatile and inexpensive, which are suitable for achieving high-quality spot welds [3, 6, 7, 13, 17].

Laser sources are generally classified based on the state of matter of their active medium and their temporal modes. Hence, according to physics, lasers are categorized into solid-state, semiconductor, gas, and liquid dye lasers [4]. According to the temporal modes, they are classified into two modes of continuous-wave (CW) and pulsed mode. In the CW mode, the beam is continuously irradiated without interruption, whereas in the pulsed mode the beam is irradiated periodically. **Table 1** displays the laser types and their wavelengths.

These medium-power lasers use continuous-wave mode during the welding process. Therefore, the average power of the source must be higher than a certain limit. Continuous-wave lasers are ideal for high-speed and deep penetration welding. They produce joints with a very low heat input rate. Hence, they create a smaller HAZ [3, 6, 7, 13, 17]. Nd:YAG pulsed lasers generate discrete pulses of controllable energy that can be used for ideal welds. Although the average power of these lasers is often low, they employ high-power peaks for welding. They can be properly utilized for joining large spot welds as well as deep spot and seam welds.

The laser active medium is doped by a few numbers of impurity ions in solid-state lasers. Among the solid-state lasers, Nd:YAG lasers are mostly employed for LBM applications. The solid-state sources (e.g. Nd:YAG, ruby, and Nd-glass lasers) are vastly utilized for the machining of metals. However, Nd:YAG lasers can also be used for ceramic materials. Gas lasers are categorized into three types according to their composition (i.e. neutral atom, ion, and molecule). In general, gas lasers can be used in either CW or pulsed modes. They are also used with the transverse flow, axial flow, and folded axial flow for construction applications. Among them, CO₂ lasers are most commonly employed for machining ceramics, plastics, nonmetals, and even organic materials.

Although semiconductor lasers are made of solid materials, their functioning principles are different from solid-state sources. The function is based on the radiative

recombination of charge carriers. These sources can produce wide beam divergence angles (around 40°).

In comparison with other lasers, liquid-state sources are easier to fabricate. Their main advantages are the simple cooling procedure and replacement of the laser cavities. Unique properties of liquid organic molecules allow the liquid dye lasers to be adjusted over a wide range of wavelengths (200-1000 nm).

9. Types of laser welding based on welding method

LBW is divided into three types of welding, conduction mode, conduction/penetration mode, and penetration or keyhole mode (**Figure 11**) [5].

9.1 Conduction welding

During the conduction mode of LBW, heat is transferred to the metal through thermal conductivity. In this mode, low energy is transferred per unit area ($\sim 0.5 \text{ MW/cm}^2$), which is often used for shallow joints to create a wide and shallow weld (**Figure 8**). Due to the low penetration depth in this mode, the gas absorption in the weld pool is low. It is also completely soundless. Typically, this mode can be utilized for applications, which require a high-quality weld e.g. battery sealing applications. The conduction mode is carried out in four steps [3, 5–7, 13, 17], (I) heating of the workpiece surface by the laser radiation, (II) formation of the molten pool, (III) no melt evaporation during the process, and (IV) determination of weld pool shape by the thermal conductivity (**Figure 12**).

9.2 Conduction/penetration welding

This mode occurs at medium energy density per unit area ($\sim 1 \text{ MW/cm}^2$) and leads to greater penetration than the conduction state (**Figure 11**) [3, 5–7, 13, 17]. In this case, the keyhole exists with shallow penetration that provides a characteristic aspect ratio (depth/width) of ~ 1 . This mode is carried out almost exclusively via pulsed Nd:YAG laser for various spot and seam welding applications.

Figure 11.
Different modes of laser welding.

Figure 12.
The effect of thermal conductivity on the weld pool shape (a) heating, (b) surface melting, (c) surface vaporization, (d) plasma formation, and (e) ablation.

9.3 Keyhole welding

By increasing the peak power density ($>1.5 \text{ MW/cm}^2$) the welding mode is shifted to the keyhole, i.e. deep narrow welds with an aspect ratio higher than 1.5. The laser beam heats up and melts the material quickly upon irradiation. If the intensity is high enough, a key-shaped cavity filled with the base metal vapor is formed, reflecting the generated heat into the material bulk that is sealed by the molten material behind the laser beam (**Figure 13**). In this case, welding is often performed by high-energy laser sources to join thick workpieces or fill cavities. This mode is called keyhole welding and it is accompanied by a muffled sound [3, 5–7, 13, 17]. Keyhole formation improves the laser heat absorption via two major mechanisms; first, through Fresnel absorption mechanism, absorbing the beam by successive reflections of the beam on the keyhole walls (**Figure 13**), and second, through the absorption of the laser energy into a vapor-filled cavity caused by a phenomenon called inverse Bremsstrahlung process [5, 17].

In the keyhole mode, the weld can be accomplished at either very high travel speeds (up to $20''/\text{s}$ with short depth welds, or very deep welds (i.e. up to $0.5''$). The high-power density of the laser beam forms a thread of vaporized material, called a keyhole, extending into the bulk and providing a channel for the beam to be efficiently delivered into the joint. This direct energy delivery into the workpiece maximizes the weld depth and minimizes the heat input to the base metal, minimizing the HAZ and workpiece distortion. This mode is used for the production of many automotive and train components such as torque converters and gearboxes, which require up to $0.25''$ penetration. The keyhole is surrounded by the melt, which tries to close it. Under steady-state conditions (optimized welding), the vapor pressure confined

Figure 13.
Absorption of the laser beam due to successive radiations from the wall of the keyhole.

within the keyhole prevents the melt from collapsing in on itself permanently, which would interrupt the welding. But even during an optimized weld localized collapses of the keyhole may take place.

The main difference between these modes of LBW is that in the first mode the surface of the weld pool is not broken, but in the case of penetration welding, the surface of the weld is opened so that the laser beam penetrates the molten pool. Conduction welding is not prone to gas absorption during the process, which is due to the lack of penetration of the laser beam into the material bulk. In penetration welding, discontinuous closure of the keyhole increases the susceptibility to porosity formation in the weld pool (**Figure 14**) [3, 5–7, 13, 17].

Figure 14.
The schematic of different modes of laser welding (a) conduction mode, (b) transition keyhole mode, and (c) keyhole/penetration mode.

Since LBW is a high energy density method, it does not require thermal conduction to achieve a deep penetration, which is in contrast to the conventional methods of arc welding and gas welding that obtain penetration via increasing the heat input. In conduction LBW, the weld width is often greater than the depth and the heat input is greater than the amount required for penetration. Moreover, in penetration or keyhole welding, the laser heat is transferred from the surface into the joint and creates a deep and thin weld pool (**Figure 14**) [4, 18].

10. Variables affecting laser welding

Achieving optimal conditions is a necessary and sufficient condition to achieve an ideal weld with a suitable appearance. Therefore, it is necessary to study the variables and parameters affecting LBW [3–7, 13, 17, 19–21].

10.1 Parameters

10.1.1 Parameters related to the laser source

- The type of laser source that determines the laser wavelength (CO₂, Nd:YAG, etc).
- Continuous (CW) or pulsed laser
- Medium laser power
- The energy of each laser pulse
- Pulse time width
- Pulse frequency

- Laser beam quality
- Optical specifications of the laser beam focusing system in the focus

10.1.2 Parameters related to the operation of the system and the welding process

- The parent material and its chemical composition
- The distance from the center of the beam to the surface of the workpiece
- Welding speed
- Conditions for starting and finishing welding
- Gas shielding type
- Gas discharge
- Nozzle geometry
- The geometry of the joint of the two sheets includes the distance between the two edges and the matching of the two edges
- Plasma plume or bubble formation when laser radiation on the metal surface

10.2 Effect of laser source type

The function basis of a laser source is depended on the state of matter of the source active medium (gas or solid-state). The most well-known gas lasers are CO₂ lasers, employing a combination of helium, nitrogen, and carbon dioxide gases with a ratio of 1:1:18. The sources operate based on the molecular energy levels of the gas. Hence, they are considered molecular lasers. The most important factor in optimizing the performance of a CO₂ laser is efficient cooling of the gas and prevention of decomposition and failure of the gas molecules. The new generation industrial CO₂ lasers are fabricated with low-power ranges (10-20 watts) to high-power ranges (about 6000 watts), using radio frequency (RF) waves as the pumping source called RF-excited lasers. The advantage of these lasers over other gas lasers is the possibility of operating in high-frequency pulse mode and the extended life span of the sealed-off tubes. Another type of gas laser is the gas dynamic laser. Since the function of these lasers is based on the sudden decrease of the gas pressure, the gas type of the source is very determinative during the pressure reduction and the sudden cooling mechanism of the active medium. This type of source is widely used for military purposes.

Nd:YAG lasers are the most widely used solid-state sources, having higher optical and physical properties, and greater efficiency compared to gas lasers. In Nd:YAG lasers, the active medium is a Y₃Al₅O₁₂ crystal, where some of the Y³⁺ ions have been replaced by Nd³⁺ ions, resulting in the formation of Nd:YAG crystal and providing a promising active medium with several high-intensity wavelengths in the infrared region. Another solid-state source is used in diode lasers (semiconductor lasers),

Figure 15.
Different pulse modes.

resulting in the fabrication of sources with ultrahigh efficiency and great tunability. However, the main limitation of these lasers is their high divergence.

Nd:YAG laser welding can be used more than CO₂ due to its shorter wavelength (1.06 mm) which allows displacement using optical fibers and also reduces the reflection of metal surfaces [3–7, 13, 17, 19, 20].

10.3 Pulse shape

In most cases, LBW uses a square pulse shape (**Figure 15**). But two other types of pulse shapes are also used in special welds. The first type (Spike pulse) is used for light-reflecting materials such as copper and aluminum (**Figure 15**). The second type (Annealing pulse) is used to minimize the radiant heat cycle during welding for crack-sensitive materials (**Figure 15**) [3–7, 13, 17, 19, 20].

It should be noted that the capability of pulse shaping in some lasers such as Nd:YAG sources can facilitate operations such as drilling and cutting. So that a chain of very short pulses with a higher peak power than the main pulse is descended immediately after the main pulse to form a quick coupling by the laser beam or numerous pre-pulses with a lower peak power before the main pulse (a pre-pulse should have lower power than the main pulse) are descended on thin foils to prevent the welding area from being punctured.

10.4 Peak power

The peak power of a laser source is the maximum power that the source can provide in either continuous welding (CW) or pulsed welding modes. It is measured in watts (W) or kilowatts (kW).

One of the important parameters of pulsed laser welding is pulse peak power. In fact, with this peak power, penetration welding can be created with a low-power laser. The peak power of a square pulse (P_p , (J/ms)) is equal to the pulse energy (J) divided by the pulse time or width (Pulse duration (ms)) (Eq. (3)) [3–7, 13, 17, 19, 20].

$$P_p = \frac{\text{Pulse energy}}{\text{Pulse duration}} \quad (3)$$

Obviously, by significantly reducing the pulse time in a low-power laser, a high pulse peak power can be achieved to create penetration welding.

An optimum peak power creates the deepest penetration in the given energy without the expulsion of materials. Welded joints, which are made with high peak power and short pulse widths are narrow and deep and require a high heat cycle.

10.5 Time width or pulse width

Pulse width is the duration of each laser pulse (ms). During the pulse on time, the workpiece senses the pulse power, and in the distance between the two laser pulses (pulse off), the parent material is cooling. The pulse width controls the heat input to the workpiece, the welding width, and the heat cycle. Increasing the pulse width expands the welding and HAZ dimensions due to the increased heat transfer time (Figure 16) [3–7, 13, 17, 19, 20].

In other words, the pulse width is a fine-tuning parameter, which is used to adjust the penetration and width of the weld and, if necessary, to stabilize the weld. By increasing the pulse width and prolonging the thermal transfer time, the weld dimensions (penetration, width, and HAZ). To increase the weld width, reduce the thermal cycle, and minimize depth variation, the pulse width must be increased.

It should be mentioned that the optimization of maximum power (peak power) and pulse width during LBW highly affect the joint quality. So that a very high maximum power causes spraying and improper joining. On the other hand, very small pulse width can cause spraying or lack of penetration.

Figure 16.
Schematic of the pulse width and power peak effects on the weld shape.

Figure 17.
Visual relationship between the frequency, pulse width, and energy level.

10.6 Pulse energy

From the point of view of the irradiated material, each laser pulse acts as a package of energy called pulse energy (pulse energy, (E, J)) and its relationship with the power peak (P_p , (J/ms)), and pulse width (T , (ms)) (pulse width or pulse duration) (Eq. (4)) is in **Figure 17** [3–7, 13, 17, 19, 20].

$$E = P_p \times T \quad (4)$$

10.7 Frequency

Frequency (f) indicates the number of pulses of the flash lamp and therefore the number of laser pulses per second (Eq. (5)). Frequency is expressed in Hertz (Hz) or pulse per second (PPS) as given in Eq. (1). On the other hand, the frequency inverse ($1/f$) is equal to the interval between two consecutive pulses. By knowing the amplitude of the laser pulse (T), we can estimate the time between two pulses, i.e. the laser extinction time. It also controls the heat input to the workpiece and the heat cycle [3–7, 13, 17, 19, 20].

$$f = \frac{1}{\text{Pulse period}} \quad (5)$$

10.8 Average power

The importance of this parameter is for welds using more than one pulse. In fact, the average power (P_{ave}) of a laser source is obtained by multiplying the energy of each pulse by its frequency (Eq. (6)) [3–7, 13, 17, 19, 20].

$$P_{ave} = E \times F \quad (6)$$

Medium power is applied when more than one pulse is required for welding. As the average power increases, the heat input rate increases; hence, with increasing the heat input, the penetration depth and weld width increase. In general, at constant power, the smaller the beam diameter, the more concentrated the heat and the smaller the weld pool. The diameter of a laser beam output can be increased by increasing the power. For instance, lasers with 1, 5, 10, and 25 kW powers have

diameters of 10, 25, 40, and 70 mm, respectively. The average power density of these diameters is between 6 and 13 W/cm².

10.9 Power intensity or density

The density or power intensity (I) at any given moment is equal to the amount of direct power equal to the cross-sectional area of the beam (D) at the parent material surface (Eq. (7)). The diameter of the laser spot in the focus depends on the type of laser and its beam quality and the beam focusing system. Power density is a function of the beam focusing tool and the maximum laser output power [3–7, 13, 17, 19, 20].

$$I = \frac{\text{Power}}{\pi \frac{D^2}{4}} \quad (7)$$

In short, the amount of beam intensity determines the state of the welding process and the formation or non-formation of the keyhole. On the power peak, the penetration rate of the weld, the pulse width usually controls the heat input to the workpiece, and the power density controls the penetration rate of the weld.

10.10 Optical specifications of the laser beam focusing system in the center

The choice of laser beam focusing system depends on the type of process, the type of laser, and the workpiece material. In fact, the cross-sectional area of the laser beam at the focus, which is one of the two main factors in determining the laser intensity at the focus, depends on the choice of the focal length of the laser beam focusing system. The relationship between the laser spot diameter at focus (D_F) and the focal depth or Rayleigh length (R_L) with the focal length of the beam focusing system is given in Eqs. (8) and (9).

$$D_F = M^2 \left(\frac{4}{\pi} \right) \lambda \left(\frac{f}{D_L} \right) \quad (8)$$

$$R_L = D_F \left(\frac{f}{D_L} \right) \quad (9)$$

where f is the focal length of the beam focusing system, λ is the laser wavelength and M^2 is the quality factor of the laser beam. Rayleigh length is the distance at which the laser intensity reaches 70.7% of the maximum intensity at the focus and is considered as the focal depth or effective focal length. The larger the focal length of the focus system, the smaller the diameter of the laser spot in the focus (**Figure 18**) [3, 4, 6].

The intensity distribution due to the optical nature of lasers depends on the properties of the resonator, active medium, and pumping system. Although the intensity distribution at the cross-section of the beam is not uniform, it can be predicted according to the properties of the resonator, active medium, and pumping system and is considered as an intrinsic feature of each source. The best mode for intensity distribution is Hermite-Gaussian mode or TEM₀₀, having the highest intensity in the center of the beam with an M^2 factor of 1. High-power industrial lasers usually have a combination of TEM₀₀ mode and higher modes in the beam. Therefore, the higher the share of higher modes, the larger the M^2 factor, the greater the divergence, and the

Figure 18.
Schematic of the laser beam focusing system.

lower the optical quality of the laser beam. To reduce the divergence and correct the beam of lasers with low optical beam quality, such as solid-state Nd:YAG sources, a special optical tool called a beam expander is used.

11. Joint and adaptation design (fit-up)

LBW is in most cases without metal fillers. Therefore, to have an ideal laser weld, the edges must fit perfectly at the joint. If the distance between the weld surfaces is too great, there will not be enough melt to fill the gap and an undercut will be created on the weld surface. To create the desired weld, the gap distance must be very small. Normally it should not be more than 10% of the material thickness [3, 4, 6].

12. Seam welding

Sequential irradiation of laser pulses on the workpiece, while the workpiece is moving at a slight velocity perpendicular to the axis of the radiation, creates a continuous chain of welding cones. Sometimes their overlapping extends to the lower sections and the depth of the workpiece (**Figure 19**). The percentage of overlap is a function of the speed, frequency, and diameter of the laser spot. This parameter is used to determine the most suitable laser conditions for work and to determine the total time of the welding cycle [3, 4, 6].

If a balance is struck between the parameters of pulse penetration, welding speed, and pulse frequency, seam welding has reached the desired state. Usually, at first, the laser parameters such as pulse width and power are selected and the welding speed is determined by considering the spot diameter and the overlap required (**Figure 20**). The overlap factor (Q_F) is given in Eq. (10) [3, 4, 6].

$$Q_F = [1 - (V/f)/(S + VT)] \times 100 \quad (10)$$

where V (mm/s) is the travel speed of the workpiece (Travel speed) below the welding head, f is the working frequency of the laser (Hz), ϕ is the beam spot size (mm) and T is the pulse width of the laser (ms) [3, 4, 6].

Figure 19.
Schematic of linear welding with a pulsed laser.

Figure 20.
The effect of overlap on penetration depth in seam laser welding.

The best conditions are obtained when complete and defectless welding is created with the least energy and number of pulses and with a reasonable speed [3, 4, 6].

13. Applications of laser welding

The application of laser beam welding (LBW) in the industry is increasingly expanding, from microelectronics to shipbuilding can use this welding process. This user potential can be attributed to the following factors [3–7, 13, 17, 19–21]:

- Limited heat input
- Small accepted heat area
- Slight unevenness
- High welding speed
- Potential of dissimilar joining

Some of these features make LBW the preferred option for some industries that have previously used the resistance welding process. The LBW process can also be combined with an electric arc welding process with a wire used in neutral shielding gas or the MIG welding process. These process combinations are designed to be placed on the surface to be welded. In addition, the special equipment used significantly reduces the tools needed to prepare the desired edge for welding. The existing filler wires with the appropriate chemical composition have provided the necessary conditions for the uniformity of the mechanical properties of the welding area. In addition, the combined processes can significantly increase the speed of work, are also effective in deep penetration and the overall sealing. Recent advances in laser diodes have provided a new opportunity to solve industry problems.

Powerful CO₂ lasers (2-10 kW) are currently used in automobile structure welding, heat exchangers, etc. For years, ruby lasers less than 500 W have been used to weld small workpieces such as small, delicate parts of medical instruments, electronic packs, and even razors. High-power ruby lasers use optical fibers to transfer the beam. This was done simply by robots and made possible a wide range of 3D applications such as cutting and laser welding automobile structures.

The laser beam is focused on a small point and creates at that point, it causes the metal to melt and even evaporate. To focus the power of powerful CO₂ lasers, water-cooled mirrors are used instead of lenses.

Fiber laser welding stands out as a robust technique when the joining of dissimilar materials is considered using the LBW in medical devices, electronics, automotive, and aerospace applications. It can simultaneously reduce manufacturing costs and offer design flexibility.

Theoretically, any material that can be joined by conventional methods, can be also welded by LBW. However, when welding dissimilar materials due to their different physical and chemical properties (e.g. melting point, boiling point, density, thermal conductivity, and coefficient of thermal expansion) various difficulties can occur, which makes the joint unacceptable. Moreover, good solid solubility is vital for the production of sound welds of dissimilar metals. This is only achieved when the materials have compatible melting points. If the vaporization temperature of a material is close to the melting point of the other one, the weldability is low, which results in low-quality joint and/or formation of brittle intermetallic phases.

Formerly, most dissimilar welds were performed by flashlamp pulsed Nd:YAG lasers. Lamp-pumped sources can produce multi-millisecond pulses, which have peak powers much higher than the average source power (with a low duty cycle). High peak power of the lamp-pumped Nd:YAG sources along with the pulse shaping capabilities results in an ideal option for welding dissimilar materials. Penetration depth is too deep during this technique, which may lead to defective joints. However, insufficient weld depths can be prevented by adjusting the initial and final powers based on the base metals and the joint geometry.

Researchers have developed various pulse shapes to improve weld quality and decrease cracks and porosity. These attempts have provided valuable solutions to join dissimilar materials in the absence of welding defects.

LBW is a versatile method that can be used for various types of metals (**Table 2**). Some of the metals commonly used in LBW are:

- Carbon steel [44, 55–57]
- Aluminum [26, 58, 59]

	Al	Cu	Mo	Ni	Fe	Ti	Mg
Al	[22]	[23, 24]		[25]	[26, 27]	[28–32]	[33, 34]
Cu			[35]		[36, 37]	[38]	[39]
Mo					[40]		
Ni				[41]	[42]	[43]	
Fe					[44–49]	[50]	[51, 52]
Ti						[53]	[54]
Mg							

Table 2.
Recent reports on dissimilar LBW joints.

- Titanium [60–64]
- Nickel [65–68]
- Stainless steel [18]
- Molybdenum [40]
- Kovar [69, 70]

Further advances have been made in this technology to expand its scope. It can now be used for many other types of metals and even dissimilar materials.

14. Conclusions

This chapter is focused on the fundamentals, parameters, and applications of laser beam welding. Currently, laser sources have many applications in the field of material processing. Laser beam welding as a new technology in recent years has found wide applications in various industries such as automotive, military, aerospace, shipbuilding, electronics, etc. An energy source provides the energy required for laser production. This source stimulates the electrons held by the atoms to move to higher energy levels. Electrons reduce their energy levels dramatically, releasing photons. The spontaneous emission of photons is what leads to the production of the laser beam. In LBW, a thin and deep joint is achieved, and the heat input applied to the workpieces is so much lower than the conventional welding methods. This property allows LBW to be widely used in certain applications in which a high ratio of penetration depth to joint width is required. LBW has a great power density (in the range of megawatts per cubic centimeter), which offers a very small HAZ due to its high heating/cooling rate. The weld pool size may vary between 0.2 and 13 mm. though only smaller sizes are used for welding. Different sources include fiber lasers, Nd:YAG pulsed lasers, and Nd:YAG continuous-wave lasers are used for LBW based on the application. LBW employs three types of modes including conduction mode, conduction/penetration mode, and penetration or keyhole mode to join the materials. The main difference between these modes is in the type of heating mode, weld pool filling, depth of penetration, and shape of the weld pool. Different parameters affect the LBW process

such as the chemical composition of the parent material, welding gap, welding speed, gas shielding type, beam shape (geometry), joint type, etc. Many equations are suggested to determine the LBW parameters, pulse energy, frequency, power and power density, and beam focusing adjustments, which are described in detail in the chapter.

Conflict of interest

The authors declare no conflict of interest.

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