Laser Welding of Aluminum and Steel alloys

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1.Introduction

The primary trend of modern structural engineering is the use of materials and structures with high strength and low specific gravity, which helps to reduce the weight of the final product [1]. An example of such materials is multi-materials or hybrid structures, consisting of several dissimilar metal alloys connected by welding, bolting, or brazing [2]. As a rule, the most processable and less labor-consuming connection type is welding, which provides the greatest strength and tightness. The weldability of dissimilar materials could be complicated by the difference in the physical properties of the materials being joined. It requires the use of technologies based on thermal and mechanical impacts on the joined workpieces. Additionally, welded joints from dissimilar materials are widely used in the aircraft building, shipbuilding, carriage building, aerospace, and electrical industries. Laser beam welding (LBW) is a welding technique used to join pieces of metal or thermoplastics through the use of a laser. The beam provides a concentrated heat source, allowing for narrow, deep welds and high welding rates. The process is frequently used in high volume and precision requiring applications using automation, as in the automotive and aeronautics industries. It is based on keyhole or penetration mode welding [3].

Aluminum and aluminum alloys with the characteristics of high specific strength, good formability, excellent corrosion resistance, and light weight, are widely used in the industrial sectors of aerospace, automotive, rail vehicles, shipbuilding, and household appliances. They are currently the most widely used light metals [1, 2]. Steel, with excellent mechanical properties, low cost, and ubiquitous use in many industrial sectors, is the most common and widely used heavy metal [3]. An emerging design concept is to produce functionally graded components via the joining of compositionally graded or dissimilar materials. There are a large variety of applications that would truly benefit from functionally graded components covering a range of mechanical, thermal, and corrosion properties in lightweight industrial machinery, reduction of fuel consumption, and emission of harmful gasses in automobile and aerospace. This paper focuses on technical laser welding processing to welding aluminum alloys and steels alloy[4].

Laser welding has many advantages, such as high energy density, high welding speed, small heat-affected zones (HAZ), low distortion, accurate control of heat input, and high levels of automation. In addition, laser welding can improve the microstructure and reduce segregation tendency in weld zone [5]. Simultaneously, laser welding can effectively control the nucleation and growth of brittle Fe-Al intermetallic compounds, leading to high-quality welding joints and offers excellent potential for further development [6].

2.1 Laser Welding

Within the last two decades, industrial lasers have advanced from exotic to state-of-the-art technology in many fields of manufacturing. While laser cutting is certainly the most popular application of highpower lasers, other processes such as laser welding and laser surface modification are also becoming the process of choice in their respective industries. Laser welding is increasingly being used in industrial production ranging from microelectronics to shipbuilding. Automotive manufacturing see (fig. 1), however, is among the industrial sectors which have proven to be most outstanding at developing applications that take advantage of the many benefits of this technology

- Low heat input
- Small heat-affected zone (HAZ)
- Low distortion rate
- High welding speed

These characteristics have made laser welding the process of choice for many applications that used resistance welding in the past. By adding the benefits of single-sided access, laser welding is given another strategic advantage, allowing it to open the door to a multitude of new applications. Hybrid processes involving a combination of laser and MIG arc welding are being developed to reduce fit-up requirements on the parts to be joined, thus improving the most critical aspects of laser welding. The addition of filler wire in GMAW substantially facilitates weld edge preparation. Alloying elements in the filler wire may be used to refine the mechanical properties of the seam. Beyond that, these combined processes can improve the welding speed of the individual processes, weld penetration depth and overall seam geometry High-power CO2 lasers (2–10kW) are used in the welding of car bodies, transmission components, heat exchangers and tailored blanks. For many years, low-power Nd:YAG lasers (< 500W) have been used to weld small components, such as medical instruments, electronic packages and razor blades. Nd:YAG, disc and fibre lasers with power levels in the multi-kW range benefit from beam delivery via optical fibres. These are easily manipulated by robots, thereby opening a large field of 3D applications, such as laser cutting and welding of car bodies. Welding gas plays an important role in laser welding. Apart from protecting the molten and heat-affected areas of the workpiece against the ambient atmosphere, it also increases the welding speed and improves the mechanical properties of the weld. The objective of this document is to give a general perspective of the technology and to provide guidelines for determining suitable gases and nozzle configurations for laser welding of mild steel, stainless steel, or aluminium, and for laser surface modification processes. The emphasis lies on gases for CO2 laser welding, as CO2 lasers are still the predominant type of laser used in the manufacturing industry, and in the higher power ranges in particular. The selection of the process gas is of critical importance in CO2 laser welding, whereas it is less crucial in solid-state laser welding or direct diode laser surface modification.

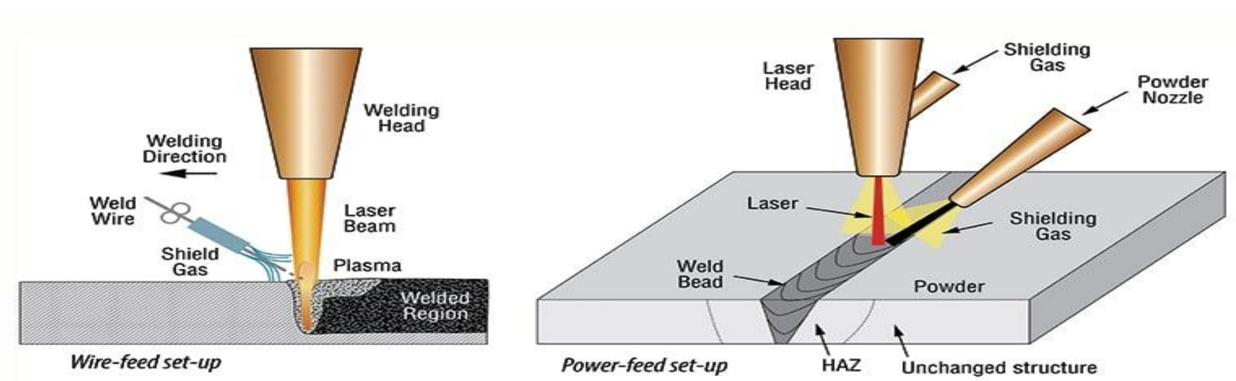

Figure 1: Schematic of laser welding set-up with filler material

Fig 1 : Laser welding

2.1.2 Principles of laser welding

The laser beam is focused onto the workpiece by a set of mirrors. These are used because they are much easier to cool than lenses, which are commonly used in lower-power cutting applications. When the laser beam is moved relative to the workpiece, the energy of the focused laser beam melts the metal so that a joint is formed. Fig. 2 shows the welding head of a high-power CO2 laser.

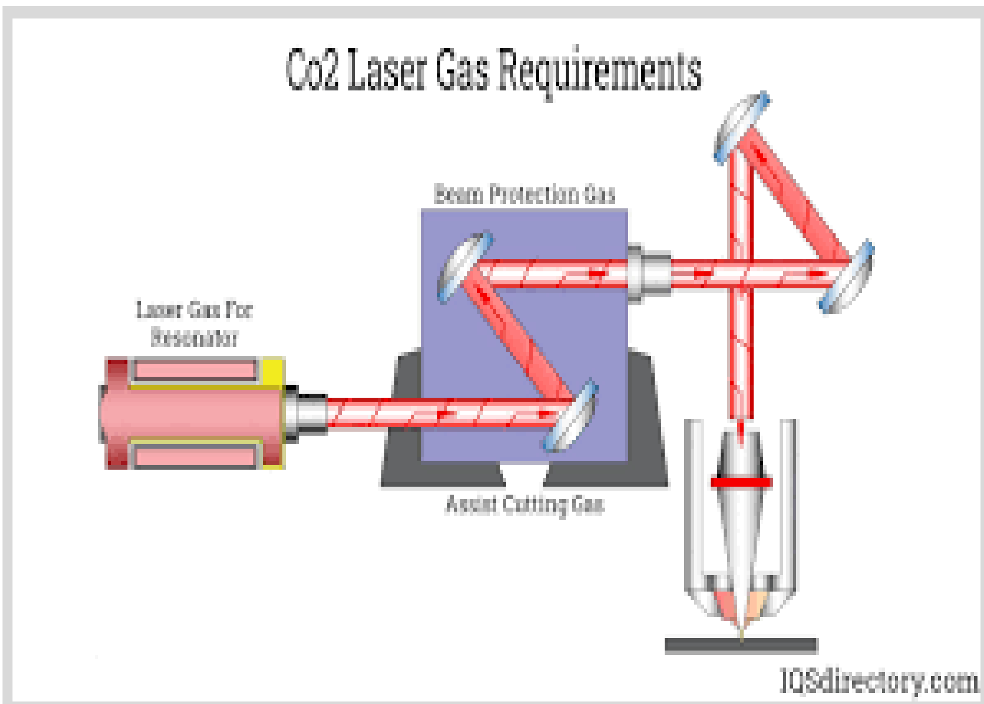

Fig. 2 The welding head of a high-power CO2 laser.

2.1.3 Weld joint configurations

As shown in fig. 3, there are four main weld joint configurations:

- Butt weld
- Fillet lap weld
- Overlap weld
- Edge flange weld

A butt weld is a configuration where the parts to be assembled lie on the same plane. Automotive tailored blanks are a typical application of this type of weld. The parts are joined by melting their edges, which are pressed together in order to minimise gaps. The edge fit-up is critical, especially in tailored blank welding applications (< 2.0mm, respectively < 0.125in): the beam passes through gaps exceeding approx. 10% of the material thickness, thus creating weld imperfections. Welding of coated materials does not cause any trouble as long as the edges are not coated.

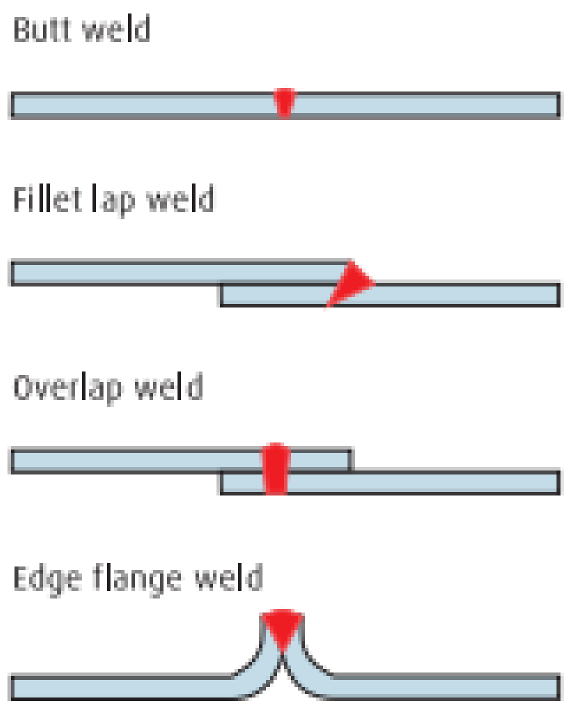

Figure 3: Four main weld joint configurations.

In fillet lap welds, the parts lie on top of each other, and the edge of one part is melted to bond with the surface of the other part. Weld edge preparation focuses on the joining of pure metal faces and requires removal of oxides and surface layers from the joining area. In an overlap weld, the parts lie on top of each other. Laser spot welding is a typical application of this type of weld. Most importantly, and similar to lap welds, the interface of the parts to be joined must be free from oxide and surface layers. The fit-up requirements are secondary. The beam must be powerful enough to penetrate a thickness equal to almost the total of the material thickness. Coating materials (zinc etc.), which cannot escape from the overlapping area, present major problems and may lead to pores and other inclusions in the weld. This may be prevented by leaving a small gap (0.05–0.2mm, respectively 0.002–0.008in) between the parts to be assembled. This gap allows for the coating to evaporate and escape from the weld zone so that the seam quality is not affected. In an edge flange weld, the parts to be welded are bent to provide a flange, which is then joined at the edge. Here again, a good fit-up is crucial.

2.1.4 Types of welding processes

As shown in fig. 4, there are two main methods of laser welding:

- Conduction mode welding, where the heat is transferred from the surface into the material by thermal conduction.
- Keyhole welding, where the laser beam energy is transferred deep into the material through a cavity filled with ionized metal vapour.

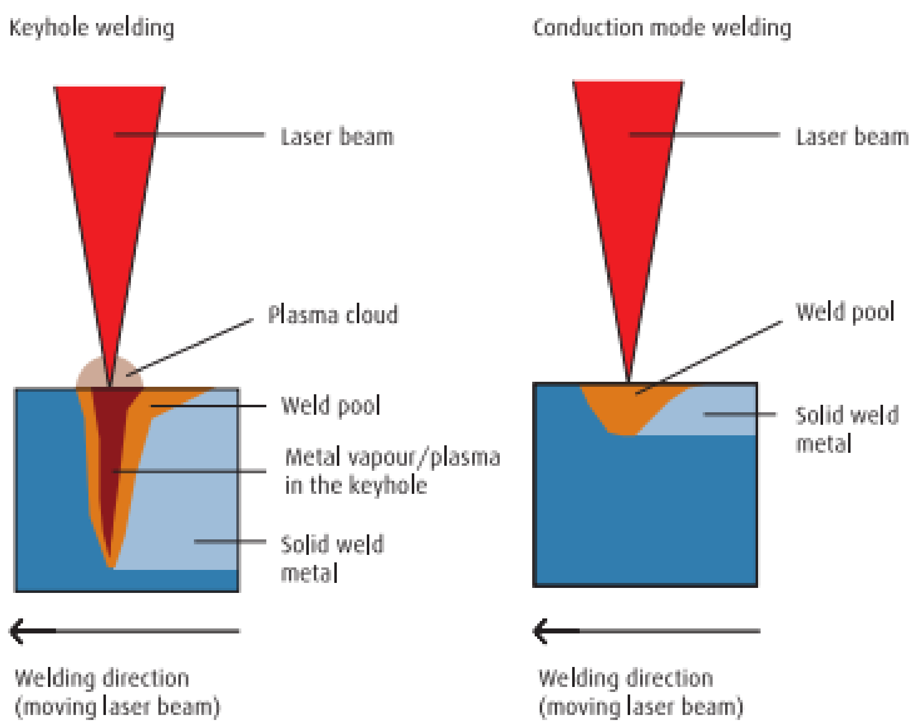

Figure 4: two main methods of laser welding

Conduction mode welding is typical of low-power lasers (< 500W), where power density is normally not sufficient to create a keyhole. The resulting weld is characterised by a relatively wide and shallow profile. High-power laser welding is characterised by keyhole welding. Laser power density in excess of 105W/mm2 melts and partly vaporises the metal. The pressure of the vapour displaces the molten metal so that a cavity is formed – the keyhole. Inside the keyhole, the absorption rate of laser radiation increases due to multiple reflections in the keyhole. Whenever the beam hits the wall of the keyhole, a part of the beam energy is absorbed by the material. Keyhole welding hence allows very deep (> 20mm, respectively > 0.8in) and narrow welds, which is why it is also called deep-penetration welding. During deep-penetration laser welding, the temperature in the keyhole becomes so intense that a physical condition similar to a plasma is achieved, i.e. ionised metal vapour and temperatures far above 10,000K. The plasma absorbs portions of the laser beam, so that the plasma acts as an intermediary in the energy transfer.

The evaporation pressure in the keyhole causes the plasma to expand above the keyhole. The CO2 laser beam is then defocused and scattered by the plasma cloud, leading to a larger focus diameter and a change in the focus position and energy density. Laser radiation is also absorbed in the plasma cloud. The extended plasma cloud causes the penetration depth of the weld to decrease. The weld assumes a nail-head shape due to the energy absorption in the cloud. If plasma formation is extensive, the welding process may even be interrupted entirely. The plasma cloud, which is characterised by the emission of a bluish light, is generally composed of a mixture of metal atoms, ions, electrons and components of the ambient gas atmosphere. In some cases, plasma may also be ignited in the welding gas itself, particularly when argon is used as a welding gas. During high-power Nd:YAG laser welding, the effect of plasma formation is only of secondary importance. This is due to the shorter wavelength of Nd:YAG laser radiation, which, compared to CO2 laser radiation, is absorbed less in the plasma cloud.

Laser beam → Plasma → Workpiece

3.1.1 Parameters in laser welding

Table 1 shows chemical behavior and physical properties of different gases in leaser welding.

Laser welding gas	Molecular weight(g/mol)	Thermal conductivity at 1 bar,15°C(W/m.k)	Ionisation energy(eV)	Dissociation(eV)	Density relative to air (rel.)
Helium	**4**	**0.15363**	**24.6**	**0**	**0.14**
Argon	**40**	**0.01732**	**15.8**	**0**	**1.38**
Nitrogen	**28**	**0.02550**	**15.6**	**4.3**	**0.96**
Carbon dioxide	**44**	**0.01615**	**13.8**	**2.9**	**1.52**

Table 1: Chemical behavior and physical properties of different gases

The local atmosphere at the weld pool has a decisive effect on the welding result and can be used to tune seam properties. The atmosphere depends on the species of gas supplied and also on the design and position of the gas nozzle.

3.1.2 Role of the welding gas

The welding gas is directed to the work piece through a nozzle system in order to protect molten and heated metal from the atmosphere. However, the welding gas has other functions, too. It protects the focusing optics against fumes and spatter and, in the case of CO2 lasers, also controls plasma plume formation. The welding gas can be made to play an active role in the welding process, such as increasing the welding speed and improving the mechanical properties of the joint.

Gases have different chemical reactions and physical properties, which affect their suitability as assist gases for different welding tasks. At least three important points must be considered:

- Tendency to form a plasma
- Influence on mechanical properties
- Blanketing/shielding effect

3.1.3 Tendency to form a plasma

Plasma formation is most relevant in high-power CO2 laser welding (> 3kW) because high intensities are needed to create plasma. The tendency to plasma formation is determined by the atomic/molecular weight of the gas, its thermal conductivity and its ionisation energy. Molecular gases also consume dissociation energy before becoming ionised. Low molecular weight increases the recombination rate between metal ions and electrons of the plasma, so that the plasma becomes suppressed or less dense. High thermal conductivity of the welding gas increases the heat transfer from the plasma to the surroundings. This decreases the temperature of the plasma and hence its density.

Ionisation energy constitutes the most important factor here. This energy is required to remove an electron from the gas molecule/atom, so that a free electron and an ion are formed. The tendency of a welding gas to ignite into a plasma of its own is therefore reduced by high ionisation energy. Molecular weight, thermal conductivity, ionisation energy and gas density values are shown above, in table 1.

Helium is a gas characterised by minimum molecular weight, maximum thermal conductivity, and maximum ionisation energy, thereby making it the most suitable gas for suppressing plasma formation. Argon, on the other hand, becomes ionised relatively easily and is therefore more prone to forming excessive amounts of plasma, in particular at CO2 laser powers of over 3kW.

3.1.4 Gas nozzle devices

Several common nozzle designs are shown in fig. (5). Coaxial nozzles, ring nozzles and side tubes are used for laser powers of up to 5kW, where plasma formation is not yet a serious problem. The size of the nozzles, i.e. the diameter of the orifice, should be relatively large so that a laminar, low-velocity gas stream can achieve

good shielding against oxidation without disturbing the melt flow around the keyhole. The welding gas flows in the laser beam path and is affected by the laser radiation inside the coaxial nozzle. This, however, does not apply to the ring nozzle and the side tube. A plasma control jet of helium is frequently used when plasma formation becomes a serious problem, for example when welding thicker parts

using high-power CO2 lasers see (fig. 5). The plasma jet nozzle has a small diameter and the resulting high-velocity gas stream displaces the plasma cloud from above the keyhole. A plasma jet nozzle is often combined with a coaxial nozzle in order to obtain better shielding of the weld pool. Common nozzle diameters and stand-off distances for coaxial nozzles, side tubes and plasma jets are shown in table (2). When a side tube or a plasma jet nozzle is used, the focusing optics, i.e. mirrors or lenses, must be protected against fumes and spatter. This can be achieved by feeding a protection gas stream through a coaxial nozzle. Alternatively, a cross-jet providing a high-velocity gas stream across the laser beam may be used to keep away fumes and spatter.

Table (2): Common nozzle diameters and stand-off distance for different type of nozzle device.

Nozzle device	Dimeter(mm)	Stand – off distance(mm)
Coaxial	5-20	5-8
Side tube	5-9	2-8

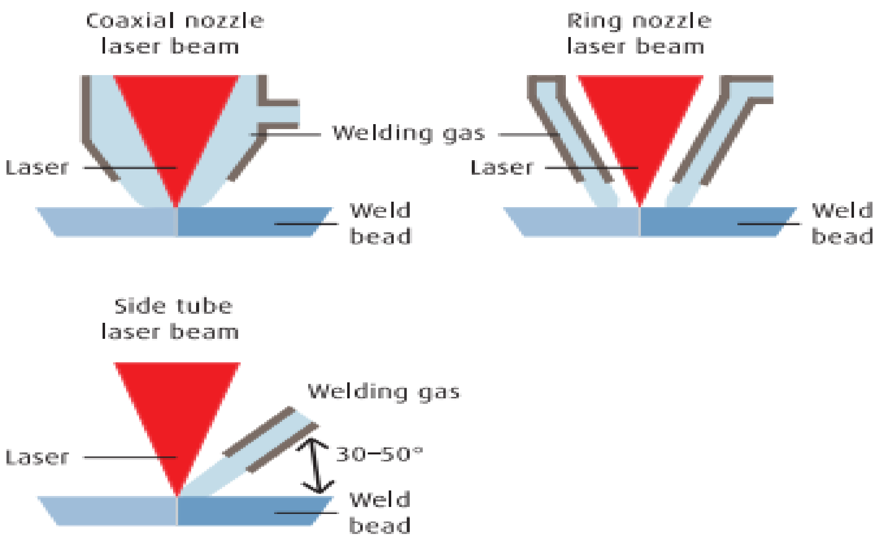

Fig (5): Gas nozzle design used for laser welding.

4. volume and pressure requirements for welding different materials

4.1.1 Welding gases for mild steels using Nd:YAG lasers

There are considerably fewer problems with plasma formation in Nd:YAG laser welding than in CO2 laser welding. This is related to a large extent to the difference in the wavelengths and intensity of their laser radiation. When using mild steel, Nd:YAG laser radiation is readily absorbed by the workpiece. There is no real need for welding gases with a helium content. Argon, an inert gas, is therefore a suitable welding gas for Nd:YAG laser welding of mild steel. For certain applications, however, reactive welding gases such as carbon dioxide, argon/10% oxygen or argon/20% carbon dioxide may be considered as alternatives.

4.1.2 Welding gases for stainless steels using CO_2 lasers

The same considerations applying to mild steels, such as plasma formation and nozzle arrangement, also apply to welding gases for stainless steels. The metallurgical impact of welding gases on the weld metal, however, differs from that on mild steels. This is due to the fact that stainless steels contain considerably larger amounts of alloying elements.

The selection of welding gases depends on the type of stainless steel – austenitic steel, ferritic steel, or austenitic-ferritic steel – and its specific alloying composition. Welding gases containing oxygen and carbon dioxide should generally be avoided. Oxygen leads to oxide inclusions in the weld metal and on the surface, which may decrease corrosion resistance. Carbon dioxide oxidises the weld and may increase the risk of intercrystalline corrosion.

4.1.3 Austenitic stainless steel

Austenitic steels are the most common types of stainless steel. They contain chromium and nickel as their main alloying elements. Small amounts of nitrogen are sometimes added to improve mechanical strength and pitting corrosion resistance. Superaustenitic steel is an example of an austenitic steel that has a higher alloy content, particularly with reference to molybdenum and nitrogen, than ordinary austenitic steels. Helium, argon and argon/helium mixtures (argon/30% helium and argon/50% helium) are frequently used when working with austenitic

steels. The higher the laser power, the higher the helium content that the welding gas must have in order to reduce plasma formation. Welding gases containing hydrogen, such as argon/6–10% hydrogen, can be used at lower laser powers. Besides controlling plasma formation, hydrogen also reduces surface oxides and affects the viscosity of the melt. welding speeds for some welding gases applied to

2-mm (0.08-in) austenitic steel. In these tests, the argon/7% hydrogen mixture leads to the highest welding speeds in comparison with helium, argon, or helium/30% argon. Shiny metallic weld surfaces were obtained in lower-power CO_2 laser welding. For reduced plasma formation with high-power CO_2 lasers. Mixture can be used consisting of 8–10% hydrogen and 20–40% helium in argon. A mixture based on hydrogen, argon and helium provides shiny metallic weld surfaces in higher-power CO_2 laser welding.

4.1.4 Ferritic stainless steel

Chromium is the main alloying element of ferritic stainless steel. Inert welding gases, such as helium, argon, and argon/helium mixtures, are suitable for CO2 laser welding. Nitrogen used as a welding gas increases the nitrogen content in the melt. Therefore, nitrogen has the same effect as carbon when working with ferritic steels, i.e. it increases the quantity of martensite in the weld metal and therefore also the brittleness of the weld. Welding gases with a hydrogen content are unsuitable because ferritic stainless steels, similar to mild steels, are susceptible to hydrogen embrittlement.

4.1.5 Welding gases for aluminum using CO2 lasers

CO2 laser welding of aluminum and aluminum alloys is considered to be difficult due to the high reflectivity and thermal conductivity of aluminum. The high reflectivity makes it difficult for CO2 laser radiation to be absorbed by the workpiece; the high thermal conductivity makes it easy to conduct the absorbed heat away from the focal spot. As a result, it is harder to overcome the threshold for deep-penetration welding, i.e. to reach the high temperatures necessary for evaporating aluminium and to thus form a keyhole. CO2 laser welding of aluminum therefore, requires significantly higher power and a better beam quality than CO2 laser welding of steel. Porosity is a typical phenomenon in laser welding of aluminum. To a large extent, porosity may be related to hydrogen, which is easily dissolved in the molten pool. Obviously, welding gases with hydrogen content should be avoided with aluminum. In addition, the gas supply system for the welding gas must be diffusion-tight against hydrogen permeation. Pores may also become large and deep (resulting in so-called cavities) and material may be ejected from the keyhole, a phenomenon commonly called humping. This is due to the instability of the keyhole in the turbulent melt pool, leading to the collapse of the keyhole. In order to stabilise the keyhole, the laser beam can be split up into two beams with a special mirror (twin focus technique). The foci of the beams are placed close to each other, thus widening and stabilising the keyhole.

The most suitable welding gases for CO2 laser welding of aluminum and aluminum alloys are mixtures of helium and argon, such as Ar/30% He. These allow better coupling of the laser radiation into the workpiece and result in good weld quality.

Laser welding of aluminum sometimes requires an inert backing gas to protect the root side of the weld against the ambient air. Humidity, for example, may lead to hydrogen-induced porosity in the weld. Argon and helium may be used as backing gases. Suitable welding gases and backing gases for CO2 laser welding of aluminum and aluminum alloys are summarized in table (3).

Table (3): Welding gases for CO2 laser welding.

Material	Welding gas	Comments*	Backing gas
Mild steels and C-Mn steels	Helium	All laser powers, can be applied through coaxial nozzle or side tubes, results in high weld quality, good formability	Argon
	Argon	Laser powers of up to 3 kW, coaxial nozzle or side tubes	
	Argon/30 % helium Argon/50 % helium	Coaxial nozzle or side tubes, high weld quality, good formability	
	Argon/10 % oxygen	Laser powers of up to 5 kW, coaxial nozzle, good formability	
	Argon/20 % carbon dioxide	Laser powers of up to 5 kW, side tubes, limited tolerance to changes in nozzle parameters, acceptable weld quality for low-carbon steels	
	LASGON® C: argon/helium/ carbon dioxide	Laser powers of up to 8 kW, side tubes, high weld quality (especially with coated material)	
Austenitic and superaustenitic stainless steels	Argon/6–10 % hydrogen	Laser powers of up to 5 kW, coaxial nozzle or side tubes, high welding speed, shiny weld surface	Argon and nitrogen/ hydrogen mixtures
	LASGON® H: argon/helium/ hydrogen	Laser powers of up to 8 kW, coaxial nozzle or side tubes, high welding speed, shiny weld surface	
	Argon	Laser powers of up to 3 kW, coaxial nozzle or side tubes	
	Argon/30 % helium Argon/50 % helium	Coaxial nozzle or side tubes	
	Helium	All laser powers, coaxial nozzle or side tubes	
	Nitrogen	Coaxial nozzle or side tubes, steels alloyed with nitrogen	
Ferritic stainless steels	Argon	Laser powers of up to 3 kW, coaxial nozzle or side tubes	Argon
	Argon/30 % helium Argon/50 % helium	Coaxial nozzle or side tubes	
	Helium	All laser powers, coaxial nozzle or side tubes	
Austenitic-ferritic stainless steels (duplex)	Nitrogen	Coaxial nozzle or side tubes, steels alloyed with nitrogen	Nitrogen
	Argon/nitrogen mixtures	Coaxial nozzle or side tubes	
	Helium/nitrogen mixtures	High laser powers, coaxial nozzle or side tubes	
Aluminium and aluminium alloys	Argon/30 % helium Argon/50 % helium Helium/30 % argon	Side tubes or coaxial nozzle, high weld penetration, good weld quality	Argon and helium
	Helium	All laser powers, coaxial nozzle or side tubes	

*The listed values are indicative and may vary depending on the welding system. Linde's LASERLINE® programme includes optimised gases, tailor-made gas supply systems and comprehensive services.

5. Safety in laser welding.

Lasers are associated with potential sources of hazards, such as laser radiation, electric power supply and by-products, resulting in laser materials processing that requires special care and appropriate safety systems. The gas cylinders, cylinder bundles and tanks normally used for gas supply also need to be handled carefully and require appropriate accident prevention measures.

5.1.1 Laser radiation

Lasers used for welding and surface treatment applications radiate in the infrared or ultraviolet spectra, which are not visible to the human eye. This is why an HeNe laser or a laser diode, both low-power lasers that radiate in the visible spectrum, are switched into the beam path when equipping a laser machine. The intensive laser light of the materials processing laser is especially dangerous to the eye. CO_2 laser radiation is absorbed by the cornea, YAG and fibre laser radiation penetrate through to the retina which can be destroyed irrevocably by relatively little radiation.

Misdirected laser radiation can come directly from the laser and threaten the eyes as a result of a faulty parameter setting, an opened cover, a displaced mirror etc. Other hazards include skin burn or inflammation from combustible materials as a result of misdirected laser radiation. The greatest hazard, however, usually stems from reflected laser radiation: the major share of the laser radiation is reflected by cold material first. To this we can add reflections of work piece edges, as a

result of turbulence in the weld pool etc. Misdirected radiation and reflections must be blocked off. That is why the law stipulates that the laser beam and the work zone must be in an enclosure. Beyond that, all those present, and the machine operators in particular, should wear protective goggles that are appropriate for

the laser radiation being used. YAG and fibre laser radiation are very dangerous to the eye and require special protective measures and approved safety goggles. Standard protective goggles made of glass or acrylic glass are not suitable at all, as glass and acrylic glass allow YAG laser radiation and fibre laser radiation to pass through.

5.1.2 Welding emissions

Depending on the materials being welded, laser welding may generate fumes that are hazardous to health. Therefore, it is important to always provide sufficient extraction and fresh air.

5.1.3 Gases and gas supply

Gases for laser welding are supplied in gaseous form in gas cylinders or cylinder bundles, or in liquid form in cryogenic vessels, or, as applicable, in a tank. Gas cylinders and cylinder bundles shall be stored in well-ventilated places only. Cylinders must always be secured, so that they cannot fall over as this can cause injury or damage to the cylinder valve. When gas is being withdrawn, its pressure must be decreased to operating pressure, which can be done using the corresponding cylinder pressure regulator and/or point-of-use regulators provided.

These must be suited for the respective purity of the gas being used and opened slowly in order to avoid a pressure shock that would damage subsequent installations. The cylinder must be resealed when the work is finished. Pressure regulators should only be connected and replaced by authorised personnel. Safety valves settings and safeguards may not be changed at all. The gases themselves are contained in the air we breathe, which is harmless as such. Carbon dioxide, however, is a heavy gas that can collect in basins and basement rooms and then displace respiratory oxygen. Therefore, attention should be paid to effective extraction or, as applicable, good ventilation when carbon dioxide is being used as a process gas or part of process gas.

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