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Laser welding.
LASERLINE® Technical.

Contents.

Introduction.

Fig. 1: Examples of 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 high-power 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 CO_2 lasers (2–10 kW) are used in the welding of car bodies, transmission components, heat exchangers and tailored blanks. For many years, low-power Nd:YAG lasers (< 500 W) 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 CO_2 laser welding, as CO_2 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 CO_2 laser welding, whereas it is less crucial in solid-state laser welding or direct diode laser surface modification.

The results presented here have to a large extent been obtained in projects carried out in The Linde Group's application laboratories or have been sponsored by the company.

The laser welding process.

Fig. 2: Laser welding head

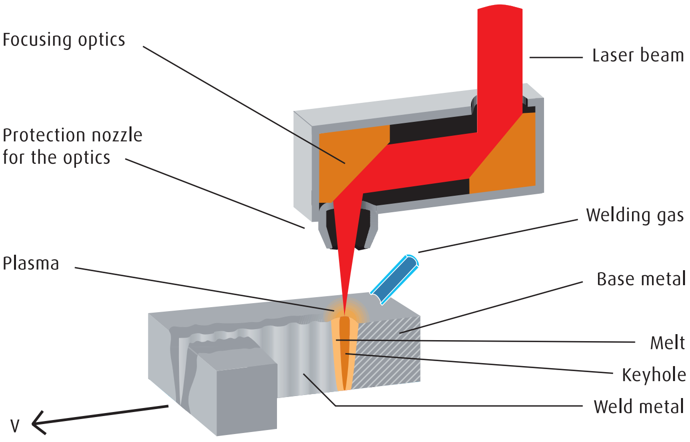
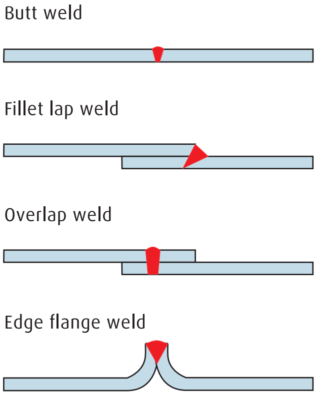


Fig. 3: The four main weld joint configurations



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 CO_2 laser.

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

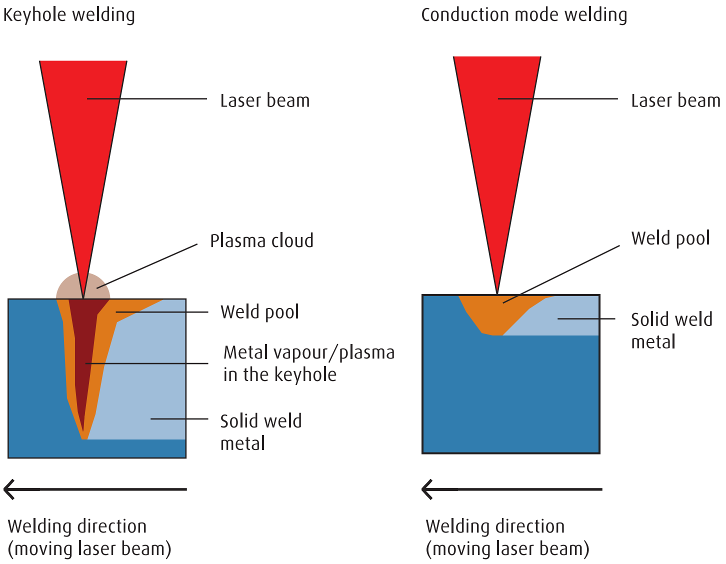
A butt weld is a configuration where the parts to be assembled lie on the same plane. Automotive tailored blanks are a typical application of this type of weld. The parts are joined by melting their edges, which are pressed together in order to minimise gaps. The edge fit-up is critical, especially in tailored blank welding applications (< 2.0 mm, respectively < 0.125 in): 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.

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 (0.05–0.2 mm, respectively 0.002–0.008 in) 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.

Fig. 4: Two different methods of laser welding


Keyhole welding

Conduction mode welding

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 ionised metal vapour

Conduction mode welding is typical of low-power lasers (< 500 W), 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 10^5 W/mm^2 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 (> 20 mm, respectively > 0.8 in) 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 10,000 K. The plasma absorbs portions of the laser beam, so that the plasma acts as an intermediary in the energy transfer:

Laser beam → Plasma → Workpiece

The evaporation pressure in the keyhole causes the plasma to expand above the keyhole. The CO_2 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 CO_2 laser radiation, is absorbed less in the plasma cloud.

Parameters in laser welding.

Table 1: Chemical behaviour and physical properties of different gases

Laser welding gas	Molecular weight (g/mol)	Thermal conductivity at 1 bar, 15 °C (W/m · K)	Ionisation energy (eV)	Dissociation energy (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

*CO_2 3 CO + O

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.

Role of the welding gas

The welding gas is directed to the workpiece 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 CO_2 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

Tendency to form a plasma

Plasma formation is most relevant in high-power CO_2 laser welding (> 3 kW) 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 CO_2 laser powers of over 3 kW.

Fig. 5: Gas nozzle designs used for laser welding

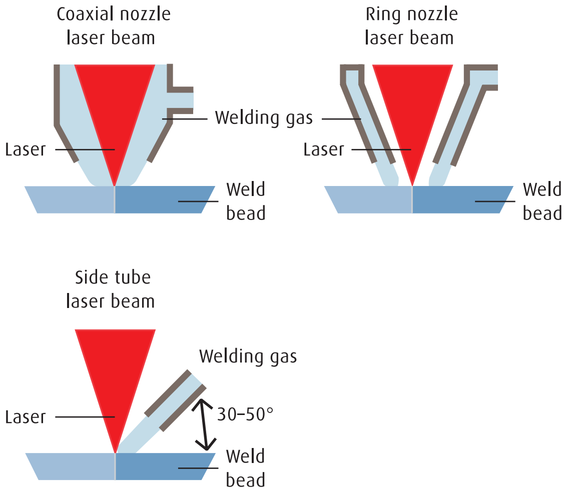


Table 2: Common nozzle diameters and stand-off distances for different types of nozzle devices

Nozzle device	Diameter (mm)	Stand-off distance (mm)
Coaxial	6–20	5–8
Side tube	5–9	2–8

Mechanical properties

In many cases, it is advantageous to use inert gases as welding gases because there is no reaction on the weld metal. Helium and argon are fully inert gases and do not affect weld metallurgy.

Carbon dioxide and nitrogen, on the other hand, are reactive gases which may react with the weld metal to form oxides, carbides, or nitrides and get trapped in pores. This can result in welds with deficient mechanical properties. As a result, pure carbon dioxide or nitrogen are unsuitable as welding gases in certain applications. In certain cases, however, reactive welding gases can be tolerated or may even be advantageous. In certain types of stainless steel, for example, the application of nitrogen as a welding gas component results in better corrosion resistance and a better microstructure of the weld.

Blanketing/shielding effect

Gas density is important for proper protection of the weld area. Low-density gases do not displace air as easily as high-density gases. Helium has a much lower density than air (see table 1), so that it rises quickly from the weld zone. Directed helium flow of either a high speed (small nozzle, high pressure) or a high flow rate (large nozzle, low pressure) is required for effective protection. Helium flow directed towards the pool centre may disturb the melt. Argon, on the other hand, has a high density and therefore replaces air more effectively (gravity position).

Helium/argon mixtures combining the benefits of both gases, i. e. the higher density of argon and the higher ionisation potential of helium, may be used to obtain better protection of the weld zone in CO_2 laser welding.

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 5 kW, where plasma formation is not yet a serious problem.

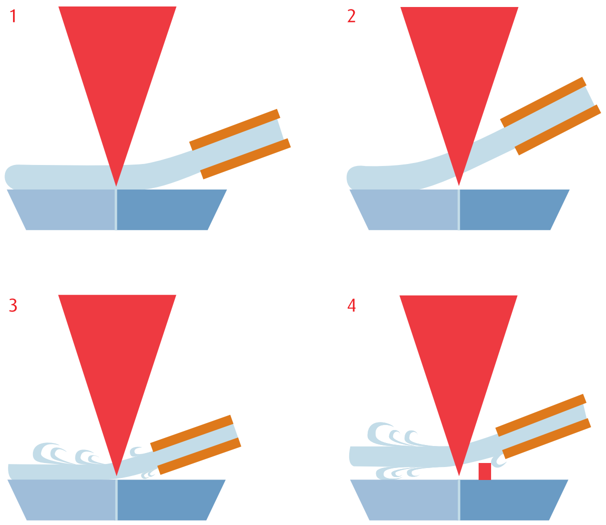
The size of the nozzles, i. e. the diameter of the orifice, should be relatively large so that a laminar, low-velocity gas stream can achieve good shielding against oxidation without disturbing the melt flow around the keyhole. The welding gas flows in the laser beam path and is affected by the laser 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 CO_2 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.

Fig. 6: Nozzle set-up and gas-flow adjustment



1. Correct nozzle positioning. Result: even shielding of complete seam
2. Wrong nozzle positioning. Result: improper shielding of seam and detrimental air injection
3. Nozzle too small, gas flow too large. Result: improper shielding of seam and detrimental air injection
4. Barrier between nozzle and seam (spatter etc.). Result: improper shielding of seam and detrimental air injection

Nozzle positioning

There are no strict rules applying to the use of nozzle devices. The side tube may, for example, trail behind the laser beam as shown in fig. 5, or it can be positioned in front of the moving laser beam. When using a CO_2 laser, trailing side tubes are less sensitive to variations in alignment parameters than leading side tubes. The tolerance window with respect to variations in nozzle parameters (angle to the workpiece, pointing direction etc.), however, depends on the type of welding gas used. Helium and argon/helium mixtures have large tolerance windows when used with CO_2 lasers.

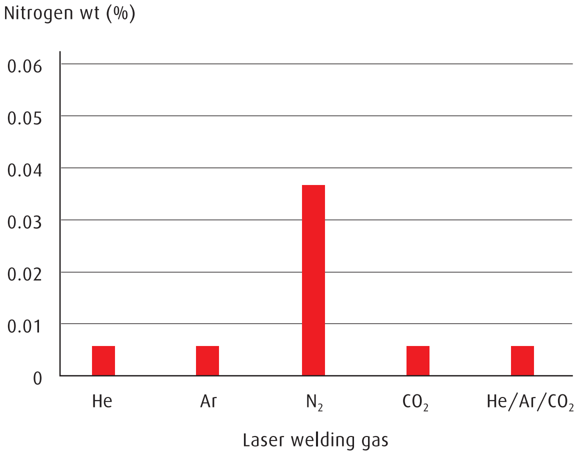
When using CO_2 lasers, one must make sure not to use welding gases containing carbon dioxide with coaxial nozzles, but rather only with side tubes and ring nozzles. In a coaxial nozzle configuration, the laser beam travels through the shielding gas, so that any carbon dioxide contained in a shielding gas will absorb the beam energy, and thereby cause plasma problems. Ultimately, this may lead to damage to the nozzle assembly.

The required welding gas flow rate depends on the nozzle design, the nozzle diameter, the type of laser and the laser power. The flow rate should be neither too low nor too high (see fig. 6). A low flow rate will not provide adequate shielding of the weld pool. A high welding gas flow rate affects the melt flow direction and results in a poor quality of the weld, such as an uneven weld bead and undercut. In addition, the welding gas stream should be laminar and even. Turbulence caused by an excessively high flow rate and barriers in the flow direction (see fig. 6) result in air being mixed with the welding gas, thereby impairing shielding. Suitable welding gas flow rates for coaxial nozzles and side tubes usually lie within the range of 10–50 l/min (20–100 cfh).

When using CO_2 lasers and argon as a welding gas, a high gas flow rate may be required to suppress plasma formation. Nevertheless, the argon flow rate must be kept low enough to avoid disturbing the melt.

Pressure and volume requirements for different materials.

Fig. 7: Nitrogen content in the weld metal of mild steel with various welding gases



Material thickness: 2 x 0.8 mm (0.032 in), lap joint, 4-kW CO_2 laser, ∅ 4-mm (0.16-in) side tube, welding speed 4.2 m/min (165 ipm)

The appropriate atmosphere at the weld pool depends on the material and the desired seam properties. The type of laser, the laser power and the gas feeding device must also be taken into account.

Welding gases for mild steels using CO_2 lasers

The selection of welding gases for CO_2 laser welding of mild steels is based on:

- → The need to avoid excessive plasma formation
- → The type of nozzle device used in the process
- → The metallurgical effect on the metal to be welded

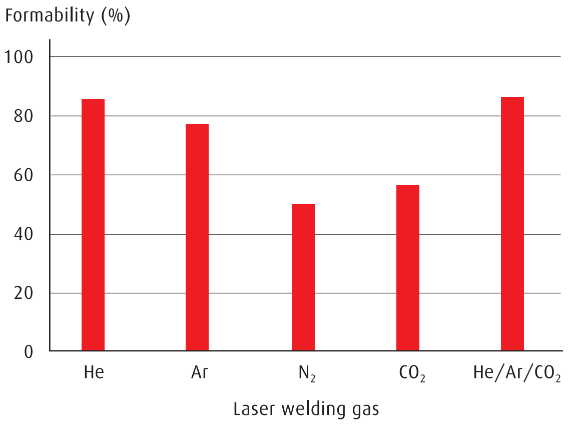
Welding gases using disc or fibre lasers

Plasma formation is not a major issue in solid-state laser welding (YAG, disc, fibre lasers) with laser powers of 1 to approximately 6 kW. However, fibre lasers with powers of more than 10 kW can generate extensive plasma formation leading to process problems; consequently, helium-based welding gases such as Ar/30 % He or Ar/50 % He may be applied. Please check with your BOC representative for the latest findings and the optimal welding gas for your application.

Metallurgical effect

Helium and argon are fully inert gases which do not react with the weld metal. By contrast, other welding gases or welding gas components, such as nitrogen, oxygen and carbon dioxide, are reactive. As a consequence, pores may be formed during laser welding. One of the reasons for this is an instability of the melt flow in the keyhole, which traps metal vapour and welding gas in the form of bubbles, which then form pores upon solidification. Fine-scale porosity may also occur when pure nitrogen is used as a welding gas. Nitrogen dissolves into the weld metal as shown in fig. 7. The solubility of nitrogen decreases when the metal solidifies. In this case, gaseous nitrogen is formed in the pores (slightly increased nitrogen content found with the other gases can be related to air injection from the gap in the overlapping area).

Fig. 8: Formability of joints in automotive-grade steel relative to the base metal



Material thickness: 2 x 0.8 mm (0.032 in), butt joint, 4-kW CO$_2$ laser, ∅ 4-mm (0.16-in) side tube, welding speed 7 m/min (275 ipm)

Reactive welding gases and gases that dissolve in the material affect the hardness and brittleness of the weld metal. Foreign atoms may enter and block the metal matrix, thus impeding weld ductility. They may also disturb the structural transformation process. The application of nitrogen increases the hardness of laser welds by means of nitrogen absorption into the weld pool. As nitrogen is an effective austenite stabiliser, more austenite is formed in the hot weld metal. Austenite is converted into martensite and bainite in the cooling phase. These hard phases make the weld harder.

Oxygen results in a softer weld, particularly in carbon-manganese steels. At high welding speeds, oxygen alters the grain structure, producing a more ductile material containing acicular ferrite. When laser welding is applied in shipbuilding, it is very important for the welds to be ductile. Welding gases containing oxygen additions, such as 96 % helium/4 % oxygen, increase ductility. Larger amounts of oxygen and slow welding speeds, on the other hand, provide enough time for the oxygen to react further and block the matrix with oxides. Consequently, the opposite effect is achieved, and the structure becomes embrittled.

A similar phenomenon occurs when CO_2 is admixed to the welding gas. A small proportion of CO_2 reduces the surface tension of the weld pool, which results in smooth weld interfaces. A high proportion, on the other hand, increases the carbon content in the weld metal. The additional carbon uptake may become a serious problem in steels with more than 0.25 % of carbon, as these steels are prone to cracking during laser welding. Assist gases without carbon dioxide are therefore preferred for these steels. It is important not to use welding gases containing hydrogen in laser welding of mild steel or other ferritic steels. Hydrogen dissolves into the weld pool and embrittles the metal matrix.

Examples of applications

The formability of the weld is an essential criterion in tailored blank welding. A tailored blank is a flat sheet made of two or more pieces of steel, which are butt-welded (see fig. 9). The steel sheets may have different thicknesses and different steel grades, and they may be coated or uncoated. After welding, the blanks are press-formed into components, such as, for example, ground plates or inner door panels for automobiles.

The formability of laser-welded butt joints is frequently tested with a stretch-draw test. In this test, a punch stretches the seam area until it cracks. The distance the punch travels is then compared to that of the base material. Fig. 8 shows results for different pure welding gases and one special mixture on butt-welded 0.8-mm (0.032-in) steel sheets. All gases were applied through a side tube. The formability achieved with nitrogen or carbon dioxide is evidently inferior to that achieved with helium or argon, due to the presence of pores in the joint. If air is applied as a welding gas, the result is just as bad: the nitrogen content is absorbed in the molten pool and then trapped in pores. In addition, seam imperfections may appear in the overlap area of circular welds. Welding gases containing helium, argon and CO_2 combine the benefits of the single gases, resulting in superior formability and smooth weld edges.

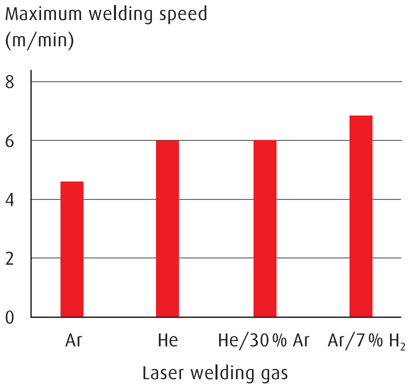
A summary of welding gases suitable for CO_2 laser welding of mild steel is shown in table 3 on page 18.

Fig. 9: Laser-welded tailored blanks

In terms of process reliability, efficiency and structural integrity, helium is the most suitable welding gas for CO_2 laser welding of mild steels. The gas may be applied for coaxial nozzles, side tubes and plasma jets. Helium is characterised by a very large tolerance window for variations in the positioning of side tubes. The formability of welded sheets is relatively good, and helium is therefore well suited for tailored blank welding. Helium has very good plasma suppression properties and may also be used for all laser powers and even for welding thick plates. Helium, however, is a finite natural source, and its availability is limited. Therefore, alternatives for pure helium are increasingly being demanded for laser welding.

Argon can serve as an alternative shielding gas for laser powers of up to 3 kW. It tends to form excessive plasma above 3 kW, which results in a loss of productivity and quality. Compared with pure argon, argon mixtures (such as argon/30 % helium, argon/10 % oxygen and argon/20 % carbon dioxide) have better plasma suppression properties at specific laser power levels.

Fig. 10: Welding speed for various welding gases



Austenitic steel (AISI 304): 2 mm (0.08 in), 2.2-kW CO_2 laser, ∅ 8-mm (0.315-in) coaxial nozzle

Welding gases for mild steels using Nd:YAG lasers

There are considerably fewer problems with plasma formation in Nd:YAG laser welding than in CO_2 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.

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.

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. Fig. 11 shows 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, a LASGON® H 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.

Nitrogen is a suitable welding gas component for those austenitic and superaustenitic steels that are alloyed with nitrogen. Nitrogen as a welding gas compensates for loss of nitrogen in the weld metal, which

would otherwise occur, thereby reducing the pitting corrosion resistance of the welds.

However, nitrogen should not be used as a welding gas for austenitic steels alloyed with titanium and niobium. Nitrogen forms nitrides with these elements, so that there is less free titanium and niobium available for prevention of chromium carbide formation and intercrystalline corrosion.

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 CO_2 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.

Austenitic-ferritic stainless steel

Austenitic-ferritic steels are also known as duplex or superduplex stainless steels. They are characterised by a two-phase microstructure containing austenite and ferrite. As a rule, the volume fractions of austenite and ferrite are equal. The main alloying elements are chromium, nickel and molybdenum. Duplex stainless steels are usually also alloyed with small amounts of nitrogen. Superduplex steel is a higher alloyed variation of austenitic-ferritic steels.

One of the problems in welding duplex steels is that the content of austenite in the weld bead is reduced considerably in comparison with the parent metal. This impairs the mechanical and corrosion properties of the joint. Using nitrogen, argon/nitrogen mixtures, or helium/nitrogen mixtures as welding gases can increase the austenite content in the weld bead, as nitrogen absorption into the weld metal promotes the formation of austenite.

Welding gases with hydrogen content should be avoided when working with duplex steels. These materials contain significant amounts of ferrite, which is susceptible to hydrogen embrittlement.

Laser welding of stainless steels sometimes requires additional protection against oxidation of the weld and/or backing gas for the root side. As a result of the high welding speed, the hot weld metal may leave the protection zone before cooling down to an uncritical temperature and may consequently react with the ambient air. In this case, an additional gas shroud can afford extra protection for the top bead.

Argon and nitrogen/hydrogen mixtures are used as backing gases for austenitic steels. However, nitrogen/hydrogen mixtures are not recommended for titanium-stabilised austenitic steels, as there is a risk of titanium nitride formation. Hydrogen-free backing gases such as argon are recommended for ferritic steels, in order to avoid the risk of hydrogen cracking. Nitrogen is suitable as a backing gas when working with duplex steels and superduplex steels, because it generates a higher amount of austenite in the weld metal.

Suitable welding gases and backing gases for CO_2 laser welding of stainless steels are summarised in table 3 on page 18.

Welding gases for stainless steels using Nd:YAG lasers

In contrast to CO_2 laser welding, laser beam absorption and scattering due to plasma formation is of secondary importance in Nd:YAG laser welding (see explanations on page 12). As a result, helium and helium mixtures do not offer significant advantages as welding gases in Nd:YAG laser welding of stainless steels.

The selection of welding gases for Nd:YAG laser welding of stainless steels is largely determined by the need to provide protection against oxidation. For many years, argon has been used as a welding gas for low-power Nd:YAG laser welding (less than 500 W) of small stainless steel components. Argon may also be applied in high-power welding (1–5 kW). When welding austenitic steels, argon/6–10 % hydrogen may be used to reduce surface oxides in order to obtain shiny weld surfaces. In some cases, active welding gases, such as nitrogen, are used to enhance corrosion resistance and to obtain a suitable microstructure of the weld. The same considerations as in CO_2 laser welding of stainless steel will apply in these cases.

Suitable welding gases and backing gases for Nd:YAG laser welding of stainless steels are summarised in table 4 on page 19.

Welding gases for aluminium using CO_2 lasers

CO_2 laser welding of aluminium and aluminium alloys is considered to be difficult due to the high reflectivity and thermal conductivity of aluminium. The high reflectivity makes it difficult for CO_2 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. CO_2 laser welding of aluminium therefore requires significantly higher power and a better beam quality than CO_2 laser welding of steel.

Porosity is a typical phenomenon in laser welding of aluminium. 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 aluminium. 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 CO_2 laser welding of aluminium and aluminium 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 aluminium 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 CO_2 laser welding of aluminium and aluminium alloys are summarised in table 3 on page 18.

Welding gases for aluminium using Nd:YAG lasers

Due to the shorter wavelength of Nd:YAG lasers, their infrared radiation is better absorbed by aluminium and aluminium alloys than that of CO_2 lasers. Nd:YAG laser welding of aluminium is hence easier than with CO_2 lasers. Problems associated with energy coupling and plasma formation are less critical.

The most suitable welding gases for high-power Nd:YAG laser (1–5 kW) welding of aluminium are helium and helium/argon mixtures. It has been shown that helium causes less weld spatter than argon. Good welding results with helium/argon mixtures have also been obtained with argon contents in the 10–30 % range.

Backing gases are sometimes needed to protect the root side of the weld against the ambient air, in particular against its humidity. Both argon and helium are suitable for this purpose.

Suitable welding gases and backing gases for Nd:YAG laser welding of aluminium and aluminium alloys are summarised in table 4 on page 19.

Lasers in surface modification.

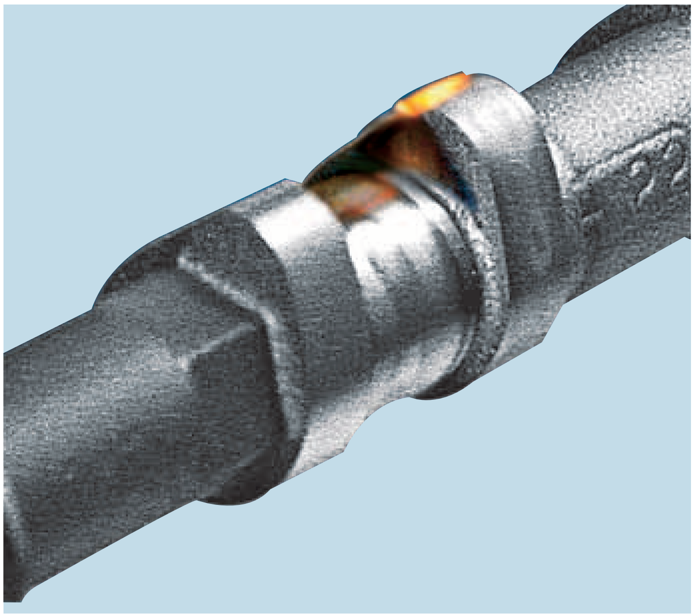


Fig. 11: Laser surface transformation hardening

Lasers are well suited for surface modification processes such as hardening, alloying, cladding etc., as these provide a highly controllable heat source that can be applied precisely.

Laser surface modification processes are still the least popular among all industrial laser applications, however when taking the cost of subsequent processes into consideration, the apparently higher cost of laser processing may lead to overall lower manufacturing costs.

This will ultimately be the driving force for a more common application of these technologies, which include:
→ Laser surface transformation hardening
→ Laser surface modification
→ Laser alloying
→ Laser cladding
→ Others

Since high power levels are required, most systems currently use CO_2 lasers. Unlike cutting and keyhole welding applications, these processes require a defocused beam in order to process large surfaces per unit of time. Ideal processing conditions can be achieved by using special optics to shape the laser beam. The resulting linear or rectangular shapes are better suited for consistent surface processing.

It is worth mentioning here that these requirements match the current characteristics of direct diode lasers. The properties (shape and size of the beam) that currently keep those lasers away from applications such as laser cutting and which limit their suitability for laser keyhole welding are ideal for surface modification processes.

Thanks to their high flexibility, these compact systems will find many applications in surface modification technologies.

Absorption on the surface to be processed is often increased by coating the part with a thin layer of material with a high carbon content.

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.

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.

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.

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.

Welding gases for CO2 laser welding.

Table 3: Welding gases for CO_2 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.

Welding gases for Nd:YAG laser welding.

Table 4: Welding gases for Nd:YAG laser welding

Material	Welding gas	Comments*	Backing gas
Mild steels and C-Mn steels	Argon	All laser powers, inert gas, good weld quality	Argon
	Carbon dioxide	Special applications	
	Argon/carbon dioxide	All laser powers, good weld quality (especially with coated material)	
Austenitic and superaustenitic stainless steels	Argon	All laser powers, inert gas, good weld quality	Argon and nitrogen/ hydrogen mixtures
	Argon/6–10% hydrogen	All laser powers, shiny weld surface	
	Nitrogen	Steels alloyed with nitrogen	
Ferritic stainless steels	Argon	All laser powers, inert gas, good weld quality	Argon
Austenitic-ferritic stainless steels (duplex)	Nitrogen	All laser powers	Nitrogen
Aluminium and aluminium alloys	Helium	All laser powers, good weld quality	Argon and helium
	Helium/10–30% argon	All laser powers, good weld quality	
	Argon	All laser powers, weld spatter	

*The listed values are indicative and may vary depending on the welding system.

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