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FACTS ABOUT Laser technology

Laser welding

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1. Introduction

Within the last decade, 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 for 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.

Recent breakthroughs in the field of laser diodes and fiber lasers present new opportunities for solving manufacturing tasks. They will, however, require thorough application-focused investigations in order to convert them into reliable manufacturing processes.

High-power CO_2 lasers (2 – 10 kW) are currently being 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 like, for example, medical instruments, electronic packages, and razor blades. Nd:YAG lasers with power levels in the multi-kW range benefit from beam delivery via optical fibers. 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 ambient atmosphere, it also increases welding speed and improves the mechanical properties of the weld.

The objective of this “FACTS ABOUT” 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 aluminum, 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. Selection of the process gas is of critical importance in CO_2 laser welding, whereas it is less crucial in Nd:YAG 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 sponsored by the company.

Fig. 1: Examples of laser welding

2. The laser welding process

2.1 Basic principles of laser welding

Fig. 2 shows the welding head of a high-power CO$_2$ laser. The laser beam coming from the laser resonator is transferred and focused onto the workpiece by a set of mirrors. These are used because they are much easier to cool than optical 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.

2.2 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 minimize 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, 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 gauges. 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 seam quality is not affected.

Fig. 2: Laser welding head

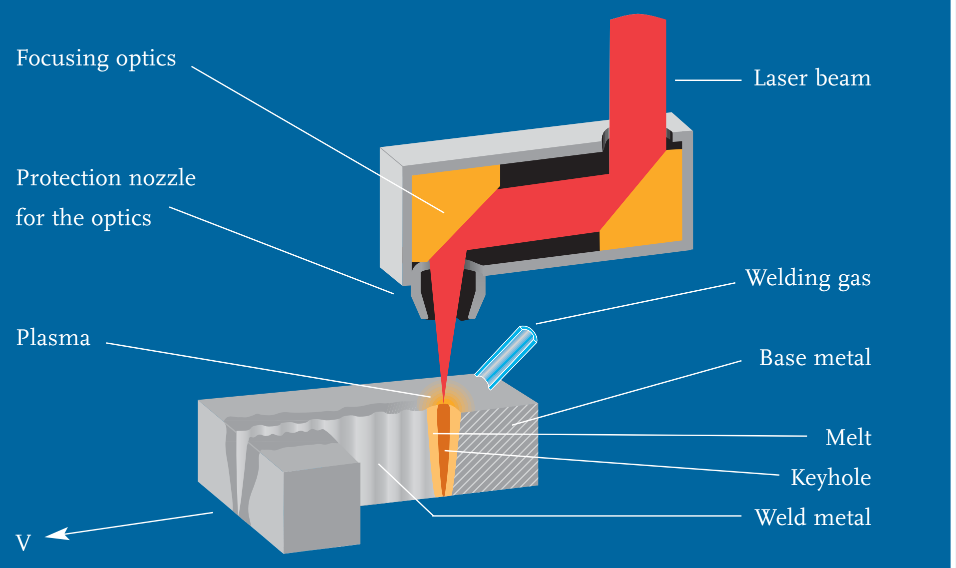
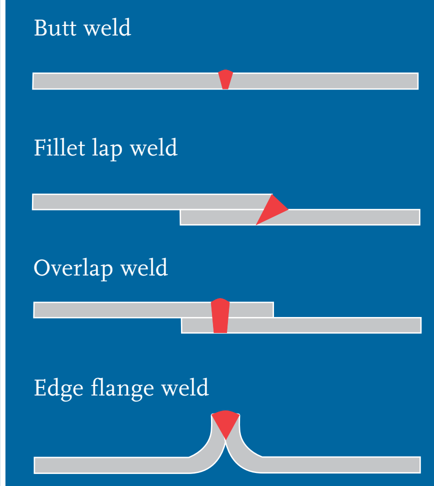


Fig. 3: The four main weld joint configurations



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, good fit-up is crucial.

2.3 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 via a cavity filled with metal vapor

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 characterized by a relatively wide and shallow profile.

High-power laser welding is characterized by keyhole welding. Laser power density in excess of 10^5 W/mm^2 melts and partly vaporizes the metal. The pressure of the vapor 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, to the effect that 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. ionized metal vapor 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:

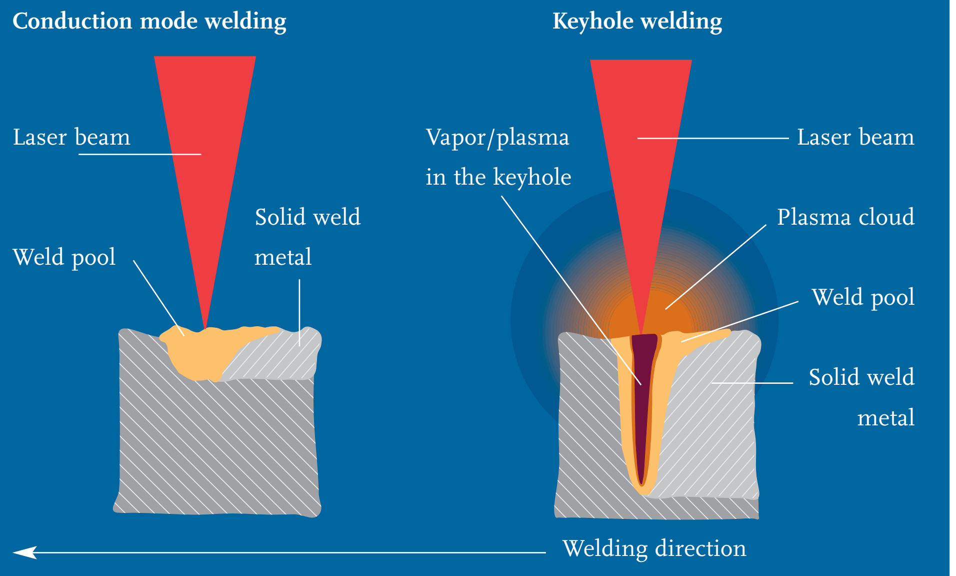
Laser beam → plasma → workpiece

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 characterized 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 is absorbed less in the plasma cloud compared to CO$_2$ laser radiation, and the lower beam intensity.

Fig. 4: Two different methods of laser welding



3. Parameters in laser welding

3.1 Role of the welding gas

The welding gas is flushed onto 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 cloud formation. The welding gas often plays 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

3.2 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 ionization energy. Molecular gases also consume dissociation energy before becoming ionized.

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 heat transfer from the plasma to the surroundings. This decreases the temperature of the plasma and hence its density.

Ionization 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 ionization energy.

Molecular weight, thermal conductivity, ionization energy, and gas density values are shown in Table 1 below.

Helium is a gas characterized by minimum molecular weight, maximum thermal conductivity, and maximum ionization energy, thereby making it the most suitable gas for suppressing plasma formation. Argon, on the other hand, becomes ionized relatively easily and is therefore more prone to forming excessive amounts of plasma, in particular at CO_2 laser power over 3 kW.

3.3 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. However, reactive welding gases can be tolerated or may even be advantageous in certain cases. For example, the application of nitrogen as a welding gas component results in better corrosion resistance and microstructure of the weld in certain types of stainless steel.

3.4 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 center 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 ionization potential of helium, may be used to obtain better protection of the weld zone in CO_2 laser welding.

3.5 Gas nozzle devices

Several common nozzle designs are shown in Fig. 5. Coaxial nozzles, ring nozzles, and side tubes are used for laser power 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 melt flow around the keyhole. The welding gas flows in the laser beam path and is effected by the laser radiation inside the coaxial nozzle. This, however, does not apply to the ring nozzle and the side tube.

A plasma jet of helium is frequently used when plasma formation becomes a serious problem, like, 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 standoff distances for coaxial nozzles, side tubes, and plasma jets are shown in Table 2 below.

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 via 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 1: Chemical behavior and physical properties of different gases

Laser welding gas	Molecular weight (g/mol)	Thermal conductivity at 1 bar, 15°C (W/m.K)	Ionization 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

*) $CO_2 \rightarrow CO + O$

Fig. 5: Gas nozzle designs used for laser welding

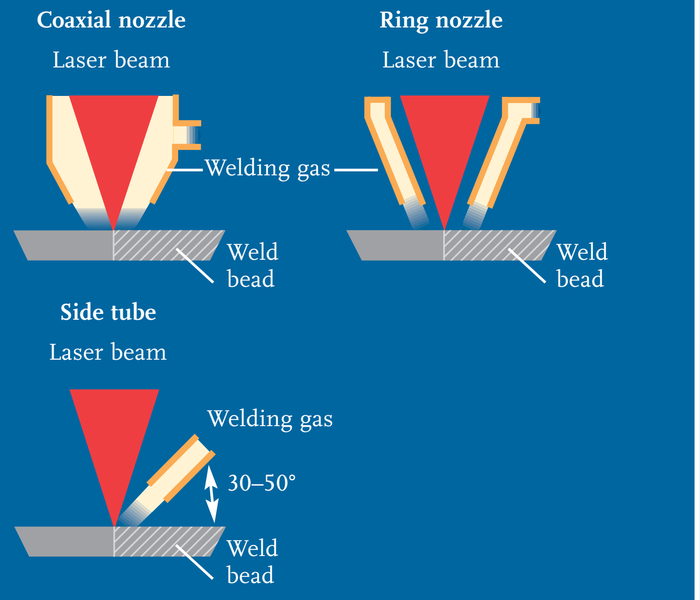


Table 2: Common nozzle diameters and stand-off distances for different types of nozzle devices

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

1 mm = 0.0394 in

3.6 Positioning of nozzles

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 lead the laser beam, i.e. it is attached in front of the laser beam in the welding direction. 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 related thermal destruction of the nozzle assembly.

The required welding gas flow rate depends on nozzle design, nozzle diameter, type of laser, and 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 weld, like, for example, 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) results 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.

4. Pressure and volume requirements for different materials

4.1 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

4.1.1 Plasma formation

Helium is the gas best suited for suppressing plasma formation and is therefore practically the only alternative in CO_2 laser welding with very high power, i.e. of approx. 10 kW and more. At lower laser power levels other welding gases can be used because plasma problems are less severe.

Argon is suitable for laser power of up to 3 kW. The plasma suppression properties of argon, however, may be improved by admixing helium, and, to a lesser degree, by admixing oxygen or carbon dioxide. Argon/30 % helium, therefore, provides good welds and high welding speeds at laser power of up to 5 kW and above, irrespective of the gas supply used. When using coaxial nozzles, argon/10 % oxygen also provides good welds and high welding speeds at laser power of up to 5 kW. Argon/20 % carbon dioxide yields relatively good results at laser power of up to 5 kW when side tubes are used.

4.1.2 Gas nozzle devices

As stated above, welding gases containing carbon dioxide can only be used in CO_2 laser welding with side tubes and ring nozzles (not with coaxial nozzles). One should take into account that welding gases containing helium, for example helium and argon/30 % helium, have large tolerance windows with respect to positioning of the welding gas device. Other welding gases, such as argon/20 % carbon dioxide and, in particular, argon/10 % oxygen only produce good welds within a more restricted range of side tube positions.

4.1.3 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 instability of the melt flow in the keyhole, which traps metal vapor 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. 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

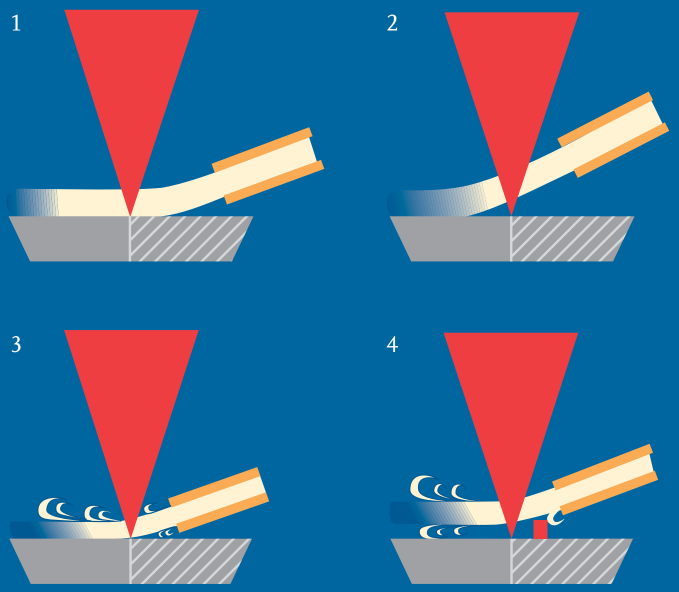
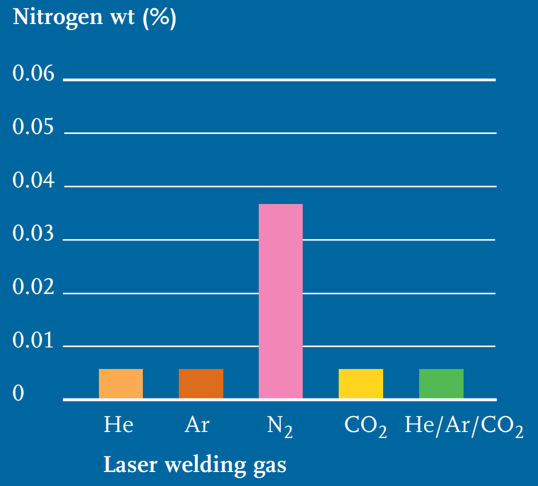
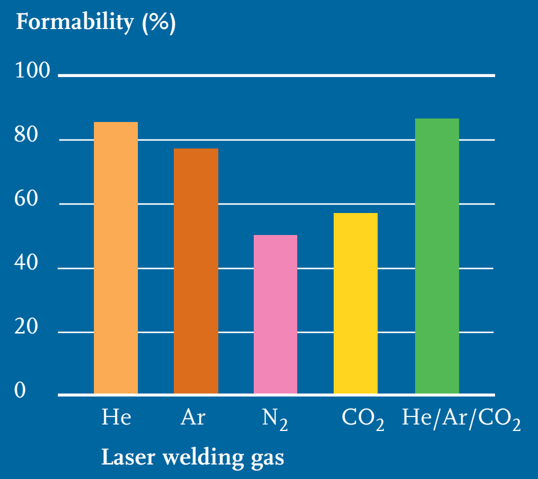


Fig. 7: Nitrogen contents in the weld metal of mild steel with various welding gases



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

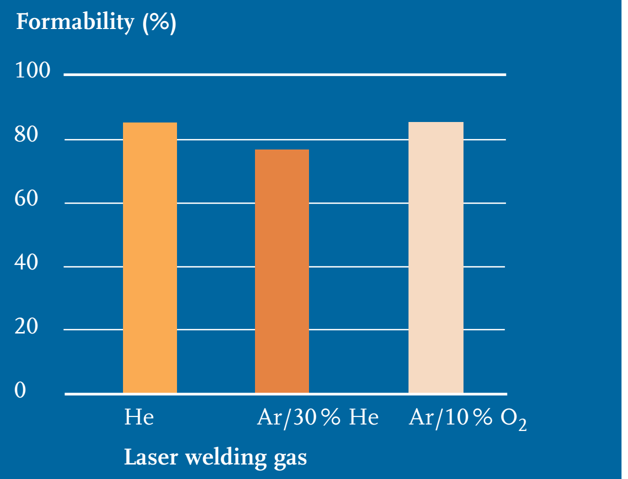
Fig. 8: Formability of joints in automotive grade steel relative to the base metal



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

Fig. 9: Laser-welded tailored blanks

Fig. 10: Formability of joints in mild steels, relative to the base metal



Material thickness: 2 x 0.8 mm (0.032 in), butt joint, 4 kW CO$_2$ laser, ø 5 mm (0.20 in) coaxial nozzle, 7 m/min (275 ipm) welding speed

Reactive welding gases and gases that dissolve in the material affect 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 stabilizer, 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, like, for example, 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 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.

4.1.4 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, like, 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 on butt-welded 0.8 mm (0.032 in) steel sheets. 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 benefits of the single gases, resulting in superior formability and smooth weld edges.

Good formability may also be obtained with helium and argon mixtures, as shown in Fig. 10.

This example shows how the performance requirements for an application dictate which type of gas should be used in order to meet these requirements.

Technically, helium is the most suitable welding gas for CO$_2$ laser welding of mild steels in terms of process reliability, efficiency, and structural integrity. Helium may be applied for coaxial nozzles, side tubes, and plasma jets. Helium is characterized by a very large tolerance window with reference to 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 power and even for welding thick plate.

Argon can serve as an alternative shielding gas for laser power up to 3 kW. It tends to form excessive plasma above 3 kW, which results in a loss of productivity and quality. 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 compared with pure argon.

Argon/30 % helium is an inert gas mixture that may be used for both coaxial nozzles and side tubes. As far as side tubes are concerned, this mixture has a large tolerance window for variations of nozzle positioning. The weld quality and, in particular, the formability of the welded sheets are almost as good as those with helium or Ar/10 % oxygen (see Fig. 10). The mixture is therefore suitable for tailored blank welding.

Argon/10 % oxygen may be used with coaxial nozzles (laser power of up to 5 kW). It produces welds with good mechanical properties, e.g. good formability, and is therefore suitable for tailored blank welding. However, argon/10 % oxygen should not be used for orbital welds, as defects may occur at the overlap point of the weld seam.

Argon/20 % carbon dioxide may be used with side tubes (laser power of up to 5 kW). The tolerance window with respect to the positioning of the nozzle is smaller than for helium or argon/30 % helium. The mechanical properties and the formability of welded thin sheets are acceptable for certain applications. These can be improved markedly with helium additions.

A summary of welding gases suitable for CO$_2$ laser welding of mild steel is shown in Table 3 of Chapter 6.

4.2 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. However, reactive welding gases, such as carbon dioxide, argon/10 % oxygen or argon/20 % carbon dioxide, may be considered as alternatives for certain applications.

4.3 Welding gases for stainless steels using CO_2 lasers

The same considerations applying to mild steels, like, for example, plasma formation and nozzle arrangement, also apply to welding gases for stainless steels. The metallurgical impact of welding gases on the weld metal, though, 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 oxidizes the weld and may increase the risk of inter-crystalline corrosion.

4.3.1 Austenitic stainless steel

Austenitic steels are the most common types of stainless steel. Austenitic steels 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; however, it has a higher alloy content, particularly with reference to molybdenum and nitrogen, than ordinary austenitic steels.

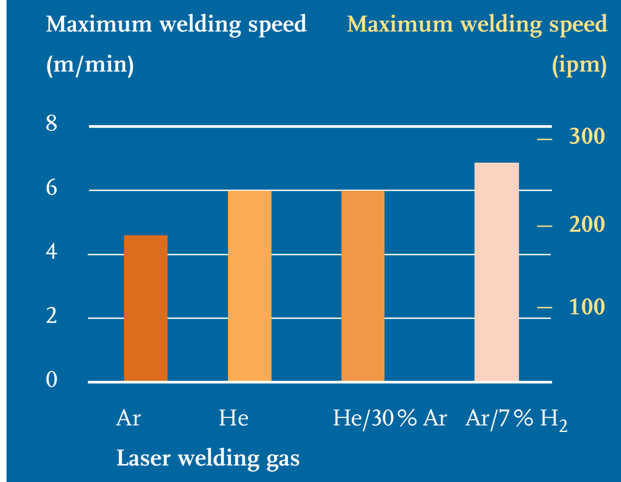
Helium, argon, and argon/helium mixtures (argon/30 % helium and argon/50 % helium) are frequently used when working with austenitic steels. The higher the laser power, the higher the helium content that the welding gas must have in order to reduce plasma formation.

By contrast, with ferritic steels, welding gases containing hydrogen, like, for example, argon/6–10 % hydrogen, can be used when working with austenitic steels, as there is no risk of hydrogen embrittlement. 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 also obtained with argon/7 % hydrogen.

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.

Fig. 11: Welding speeds for various welding gases



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

4.3.2 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 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.

4.3.3 Austenitic-ferritic stainless steel

Austenitic-ferritic steels are also known as duplex or superduplex stainless steels. They are characterized 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-stabilized austenitic steels, as there is a risk of titanium nitride formation. Hydrogen-free backing gases like, for example, 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 summarized in Table 3 of Chapter 6.

4.4 Welding gases for stainless steels using Nd:YAG lasers

Laser beam absorption and scattering due to plasma formation is of secondary importance in Nd:YAG laser welding in contrast to CO_2 laser welding, see explanations in Chapter 4.2. As a result, helium and helium mixtures are not particularly useful 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. Argon has been used as a welding gas for low-power Nd:YAG laser welding (less than 500 W) of small stainless steel components for many years. 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. It is likely that the same considerations as in CO_2 laser welding of stainless steel will apply in this respect.

Suitable welding gases and backing gases for Nd:YAG laser welding of stainless steels are summarized in Table 4 of Chapter 7.

4.5 Welding gases for aluminum using CO_2 lasers

CO_2 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 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 aluminum and to thus form a keyhole. CO_2 laser welding of aluminum therefore requires markedly higher power and beam quality than CO_2 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. However, as shown in Fig. 12, solubility decreases when the aluminum solidifies, so that hydrogen is precipitated in the form of small and round pores. The sources of hydrogen are oxide/hydroxide surface layers on the workpiece and humidity from the ambient air. Obviously, welding gases with hydrogen content should be avoided in the laser welding of 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, so-called cavities, and material may be ejected from the keyhole, a phenomenon commonly called humping. This is due to instability of the keyhole in the turbulent melt pool, leading to collapse of the keyhole. In order to stabilize 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 stabilizing the keyhole.

Nitrogen is a reactive welding gas when used with aluminum, as particles of aluminum nitride may be formed in the weld metal. Some caution is therefore advisable when nitrogen or compressed air are selected as welding gases for aluminum.

The most suitable welding gases for CO_2 laser welding of aluminum and aluminum alloys are mixtures of helium and argon. These allow better coupling of the laser radiation into the workpiece and lead to better weld quality. Figure 13 shows the penetration depth and welding speed obtained with 3, 4, and 5 kW laser power and the required composition of the welding gas. As an example, 3 mm (0.12 in) penetration depth is achieved at a welding speed of 3 m/min (118 ipm) and 4 kW beam power if the welding gas consists of 80 % argon plus 20 % helium. A much higher amount of argon than mentioned would result in intensive plasma formation and enclosed beam power losses in the plasma. A much higher helium content, on the other hand, would result in process instabilities and reduced weld quality.

Laser welding of aluminum sometimes requires an inert backing gas to protect the root side of the weld against atmosphere. 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 aluminum and aluminum alloys are summarized in Table 3 of Chapter 6.

4.6 Welding gases for aluminum using Nd:YAG lasers

The infrared radiation of Nd:YAG lasers is better absorbed by aluminum and aluminum alloys than that of CO_2 lasers, due to the shorter wavelength of Nd:YAG lasers. Nd:YAG laser welding of aluminum 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 aluminum are helium and helium/argon mixtures. Helium has been shown to cause 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 atmosphere, in particular humidity. Both argon and helium are suitable for this purpose.

Suitable welding gases and backing gases for Nd:YAG laser welding of aluminum and aluminum alloys are summarized in Table 4 of Chapter 7.

Fig. 12: Hydrogen solubility in pure aluminum

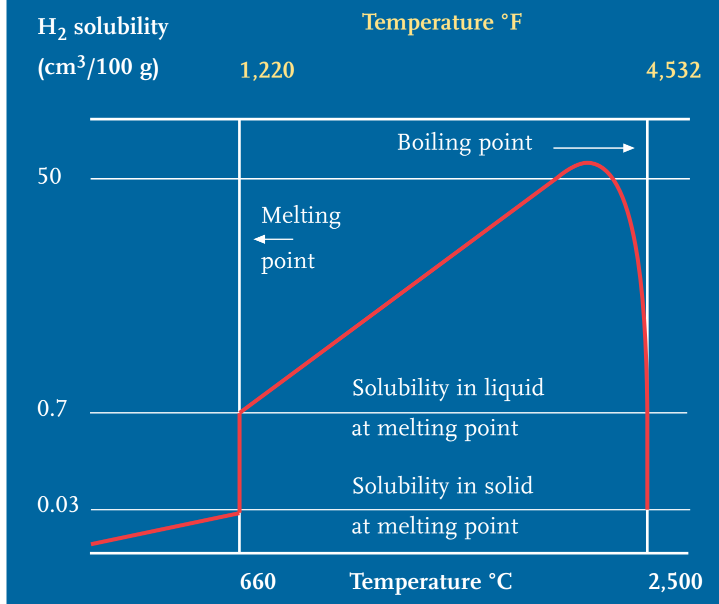
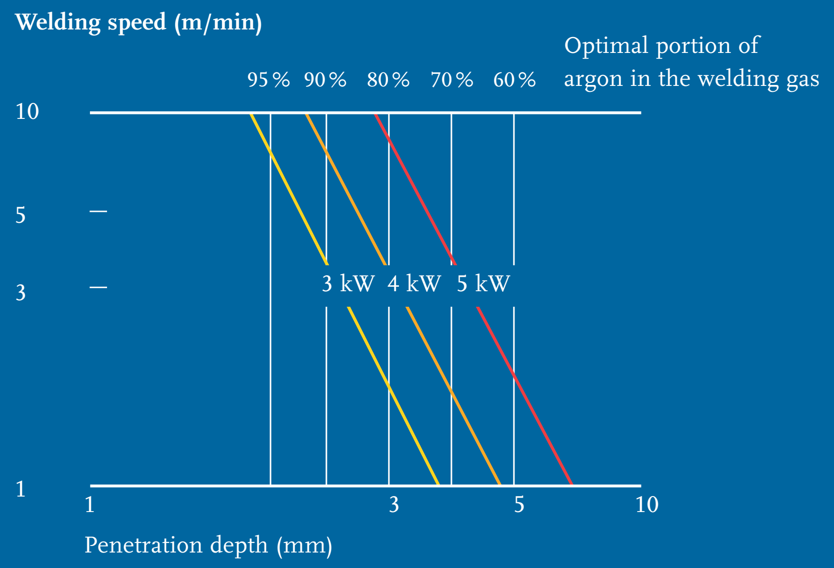
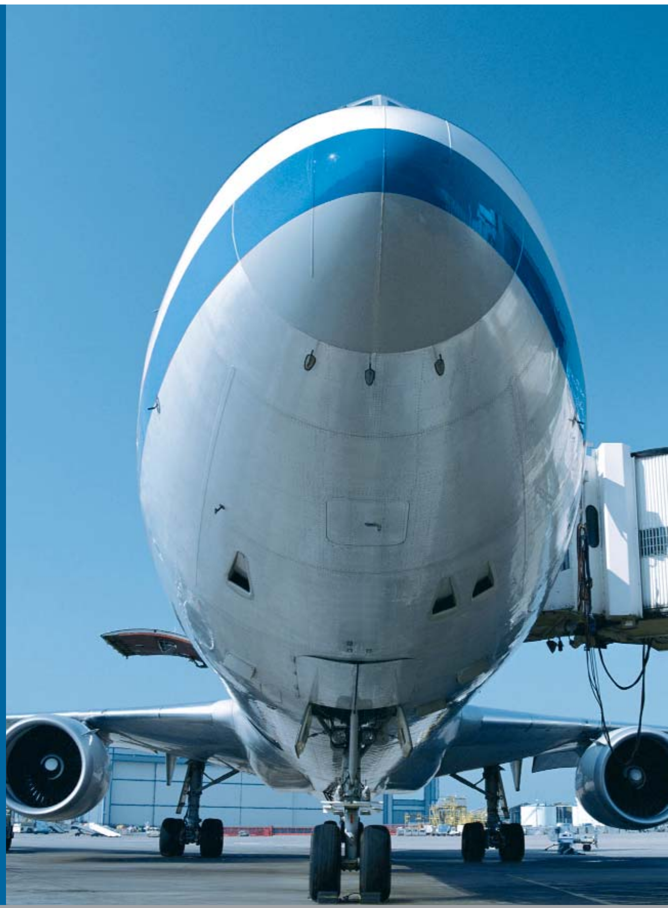


Fig. 13: Penetration depth and welding speed during laser welding of aluminum with various laser power and optimum welding gas composition



Welding gases are argon/helium mixtures with varying portions of argon in helium. CO_2 laser welding with 3 kW, 4 kW and 5 kW laser power, coaxial gas feeding, according to [4].



5. Lasers in surface modification

Laser surface modification processes are still the least popular among all industrial laser applications. When taking the cost of subsequent operations into consideration, the apparently higher cost of laser processing may lead to overall lower manufacturing costs. This will ultimately be the driving factor 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 traits (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 having a high carbon content.

5.1 Laser surface transformation hardening

This process is the most common among all surface treatment applications. The laser beam is used to rapidly heat the surface of the part to a temperature just below the melting point at which the microstructure of the material changes from ferrite to austenite. During cooling, the matrix changes again from austenite to hard martensite.

Subsequent quenching of the part is not necessary, as the same effect is performed by the surrounding material and shielding gas. Another purpose of the shielding gas is to protect the hot material from reacting with the environment. In most cases, argon and nitrogen are used for this task (rarely helium). However, one must be aware that nitrogen may also react with the material and lead to increased hardness.

It is interesting to note that laser hardening may be carried out on both steel and cast iron. In comparison with traditional hardening processes, it can be applied locally to reduce overall distortion (see Fig. 14).

The shielding gas flow rate (typically 20 l/min, res. 40 cfh) is a function of the processing spot size and the feed rate. Increasing spot sizes and feed rates lead to a larger work area, which requires higher gas flow rates.

5.2 Laser surface modification

The laser surface modification process allows a modification of localized characteristics on a component. This is usually performed on cladded or cast materials in order to anneal or temper a specific area. As melted materials exhibit a higher absorption rate for gases than do solid materials, the shielding gas needs to be selected carefully. In most cases, inert gases, such as argon or helium, are used for this task, and sometimes nitrogen, too. However, once again, one must be aware that nitrogen may also react with the material, thereby increasing hardness.

If the base material has a high gaseous content and a remelting process is performed in order to reduce the content, a shielding gas, which will not interfere with this process, should be selected.

5.3 Laser alloying

In this process, the base material is melted and gaseous/solid alloy elements are added to the melt pool in order to modify the mechanical properties of the surface layer, such as wear or corrosion resistance, hardness, chemical resistance, etc.

Depending on the type of material and the specific application, a multitude of metallic powders or gases may be considered. Nitrogen is a major gaseous alloy element. However, the application of CH_4, CO_2 and other gases (e.g. fluorinated gases) is possible.melting

Solid alloy elements are blown into the melt pool in the form of powder by an inert gas (usually argon) which then performs both the carrier and the shielding function.

5.4 Laser cladding

Laser cladding is used to deposit a layer onto the surface of a material, e.g. to improve wear or corrosion resistance. During the laser cladding process, the surface of the substrate is melted slightly and a cladding material is deposited onto the substrate. The cladding material is usually in the form of wire or powder, which is melted to bond to the substrate.

Adjustment of energy input is critical in laser cladding. The base material should be melted as little as possible, as melting dilutes the deposit. At the same time, the base material and the deposited material must form a strong compound.

If the cladding material is provided in the form of wire, the shielding gas is normally argon, nitrogen, or helium. Powder material is delivered by an inert carrier gas, mostly argon, which also functions as the shielding gas.

As this requires a relatively high flow rate, an additional shielding gas nozzle may be used. However, it is important that the second nozzle does not interfere with the powder deposit process. Feeding the power material and carrier gas coaxially may result in undesired plasma disturbance. Helium or hydrogen additions can solve this problem with suitable materials, especially with respect to hydrogen.

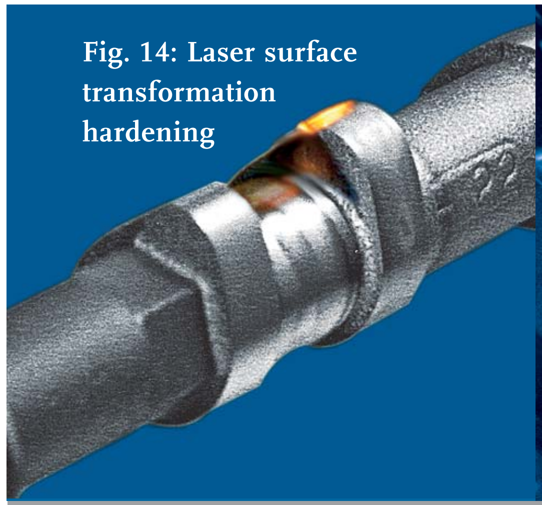
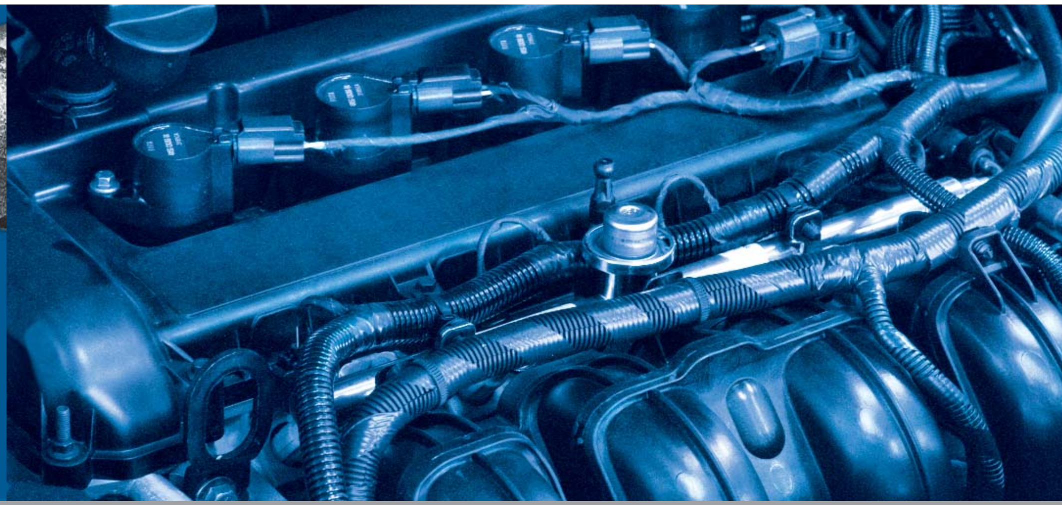


Fig. 14: Laser surface transformation hardening



6. Welding gases for CO_2 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 power, coaxial nozzles, and side tubes, high weld quality, good formability	Argon
	Argon	Laser power up to 3 kW, coaxial nozzles, and side tubes	
	Argon/30 % helium Argon/50 % helium	Coaxial nozzle and side tubes, high weld quality, good formability	
	Argon/10 % oxygen	Laser power up to 5 kW, coaxial nozzles, good formability	
	Argon/20 % carbon dioxide	Laser power 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 power up to 8 kW, side tubes, high weld quality especially with coated material	
Austenitic and superaustenitic stainless steels	Argon/6–10 % hydrogen	Laser power up to 5 kW, coaxial nozzles, and side tubes, high welding speed, shiny weld surface	Argon and nitrogen/hydrogen mixtures
	Argon	Laser power up to 3 kW, coaxial nozzles, and side tubes	
	Argon/30 % helium Argon/50 % helium	Coaxial nozzles and side tubes	
	Helium	All laser power, coaxial nozzles, and side tubes	
	Nitrogen	Coaxial nozzles and side tubes, steels alloyed with nitrogen	
Ferritic stainless steels	Argon	Laser power up to 3 kW, coaxial nozzles, and side tubes	Argon
	Argon/30 % helium Argon/50 % helium	Coaxial nozzles and side tubes	
	Helium	All laser power, coaxial nozzles, and side tubes	
Austenitic-ferritic stainless steels (duplex)	Nitrogen	Coaxial nozzles and side tubes, steels alloyed with nitrogen	Nitrogen
	Argon/nitrogen mixtures	Coaxial nozzles and side tubes	
	Helium/nitrogen mixtures	High laser power, coaxial nozzles, and side tubes	
Aluminum and aluminum alloys	Argon/30 % helium Argon/50 % helium Helium/30 % argon	Side tubes and coaxial nozzles, high weld penetration, good weld quality	Argon and helium
	Helium	All laser power, coaxial nozzles, and side tubes	

*Values listed in the Tables are indicative and may vary depending on the welding system.

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7. 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 power, inert gas, good weld quality	Argon
	Carbon dioxide	Special applications	
	Argon/carbon dioxide	All laser power, good weld quality especially with coated material	
Austenitic and superaustenitic stainless steels	Argon	All laser power, inert gas, good weld quality	Argon and nitrogen/hydrogen mixtures
	Argon/6–10 % hydrogen	All laser power, shiny weld surface	
	Nitrogen	Steels alloyed with nitrogen	
Ferritic stainless steels	Argon	All laser power, inert gas, good weld quality	Argon
Austenitic-ferritic stainless steels (duplex)	Nitrogen	All laser power	Nitrogen
Aluminum and aluminum alloys	Helium	All laser power, good weld quality	Argon and helium
	Helium/10–30 % argon	All laser power, good weld quality	
	Argon	All laser power, weld spatter	

*Values listed in the Tables are indicative and may vary depending on the welding system.

8. Literature

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