# Structural Connections for Lightweight Metallic Structures

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# Laser Welding of Structural Aluminium

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**Abstract** This chapter starts with an overview of the fusion welding processes used in aluminium welding and further progresses by analysing in detail the characteristics of laser welding of aluminium. Laser sources for welding are available for a few decades but new concepts are coming to the market. The chapter addresses the most commonly used lasers for materials processing, $CO_2$ and Nd-YAG (neodymium–yttrim aluminium garnet) and their interaction with aluminium alloys in welding applications. More recent laser types are also included, namely fibre lasers and disc lasers as, though only more recently available in the market, their potential is foreseen as being interesting for welding of aluminium. Hybrid laser MAG (Metal Active Gas) welding has proven to lead to good results in welding aluminium plates namely for long seam welding.

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# 1 Introduction

Welding of aluminum can be done using several different processes from fusion arc welding to solid state processes or brazing and soldering. The present chapter focuses on the use of laser in welding of aluminum. It starts with an overview of the fusion welding processes and further progresses with an analysis of the potential of different types of lasers used for welding of aluminum alloys.

Welding includes the joining process for metals and plastics where both the work pieces to be joined as well as the filler material used experience melting. A common method for welding metals is fusion welding, where a heat source is used to bring the parts to fusion temperature.

One of the heat sources most commonly used in fusion welding is an electric arc created by an electrical discharge between an electrode and the work pieces to be welded together generating enough heat to melt the material under the arc. The solidification of the melted material forms the weld.

Arc welding processes can use a consumable or a non-consumable electrode. In the first case, the molten metal from the electrode and the molten base metal mix together, solidifying to form a joint upon cooling. In order to protect the molten material from contamination or the surrounding atmosphere a flux or a shielding gas are used. In the second case, the joint is constituted by the base metal that melts and solidifies.

High temperatures generated by the welding process alter the microstructure in the welded areas creating a fusion zone associated with the molten metal and a heat affected zone (known as HAZ) which undergoes metallurgical transformations. This can change the mechanical behavior of the material. In aluminum alloys, these metallurgical transformations can lead to softening of the material in the HAZ, cracking and porosity. The process of fusion and solidification also generates residual stresses that can lead to distortion. These are important in aluminum welding due to the high thermal conductivity of this material and linear expansion coefficient which leads to large fusion and heat affected zones. For these reasons, the welding process must be optimized (heat input, metal composition and cooling rate) aiming at minimizing microstructural changes and residual stresses in welded joints.

Examples of fusion welding processes that can be used in aluminum are Oxygas, TIG/GTAW (Tungsten Inert Gas/Gas Tungsten Arc Welding) and MIG/MAG/GMAW (Metal Inert Gas/Metal Active Gas/Gas Metal Arc Welding).

Without a doubt, the use of aluminum as a welded structural material improved with the introduction in the 1940s of the inert gas welding processes. With a welding process that uses an inert gas to protect the molten aluminum during welding, it became possible to make high quality, high strength welds at high speeds and in all positions.

# 2 Arc Welding Processes

## 2.1 Oxygas Welding

Oxyfuel gas welding is a gas welding process where the heat is generated by an oxygen-fuel gas flame. An active flux is used when welding aluminum to remove the oxide and shield the weld pool. This was one of the earliest welding processes used for welding aluminum around 25 years prior to the development of the inert gas welding processes (GTAW and GMAW).

The problem with this welding process is that the flux used during the process is hydroscopic, absorbing moisture from the surrounding atmosphere and the flux becomes corrosive to aluminum. Therefore, after welding, the flux must be removed to minimize the chance of corrosion. Other disadvantages of using this process for welding aluminum are the wide heat affected zones created and respective deterioration of mechanical properties. Welding is only practical in the flat and vertical positions, but distortion is always significant.

The oxyfuel gas welding process was widely used for welding aluminum prior to the development of the inert gas welding process, but has limited use today.

## 2.2 Shielded Metal Arc Welding

Shielded metal arc welding (SMAW), also known as manual metal arc (MMA) welding is a manual arc welding process that uses an electric arc created through the flow of current between a consumable electrode coated in flux and the parent material to be welded (Fig. 1). The electric current, either alternative current or direct current, is provided by a welding power supply. As the weld is deposited, the flux coating of the electrode disintegrates, giving off vapors that serve as a shielding gas and provide a layer of slag, both of which protect the weld area from atmospheric contamination [1].

The versatility and simplicity of the process determine its wide use around the world, namely in the maintenance and repair. Prior to the development of the inert gas welding process (GTAW and GMAW) the arc welding of aluminum was mainly restricted to the Shielded Metal Arc Process (SMAW).

The core of the electrodes is in an aluminum alloy with a composition similar to that of the base material. The flux acts to dissolve the aluminum oxide on both the base alloy and the rod during welding. Some of the flux components vaporize in the arc to form shielding gases that help to stabilize the arc and shield the weld pool from the surrounding atmosphere.

One of the main problems with this welding process was corrosion caused by flux entrapment, particularly in fillet welds where the flux could be trapped behind the weld and promote corrosion from the back of the weld. Other problems were that welds from this process are prone to gross porosity.

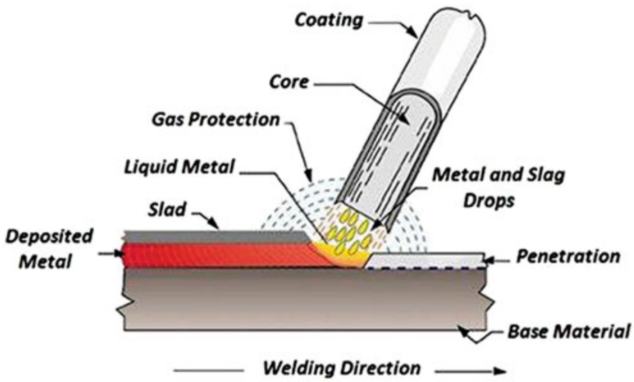



**Fig. 1** Shielded metal gas welding

The limitations of availability of electrodes with some alloys compositions as for the high magnesium content base alloys and the fact that the electrodes, once exposed to the air, begin to absorb moisture into the flux, which eventually corrodes the aluminum core and produces excessive porosity problems, has led to its substitution by gas shielded welding processes.

Current welding codes and standards for aluminum structures do not recognize this welding process as being suitable for production welding applications.

For repair welding, SMAW is quite often the solution due to limitations of the case, like accessibility. When this is the case, careful welding procedure specifications need to be developed to minimise the problems referred above.

## *2.3 Tungsten Inert Gas (TIG) Welding*

Tungsten Inert Gas (TIG) or Gas Tungsten Arc Welding (GTAW) process is quite often a viable option for welding aluminum. The processes uses an electric arc like in SMAW but established between a non-consumable electrode in tungsten and the material to be welded, under an inert shielding gas to protect the melted metal from atmospheric contamination (Fig. 2).

This process is widely used to successfully weld aluminum alloys. Aluminum alloys form refractory surface oxides which absorb the heat of the arc preventing the melting of the underneath material and thus creating difficulties for welding. In order to overcome this, alternating current (AC) is used for most applications. AC current provides a surface cleaning action while the electrode is positive (DCEP), due to the flow of electrons from the negative pole to the plate and reduced overheating of the tungsten electrode by dividing the arc heat about evenly between electrode and base material (Fig. 3).

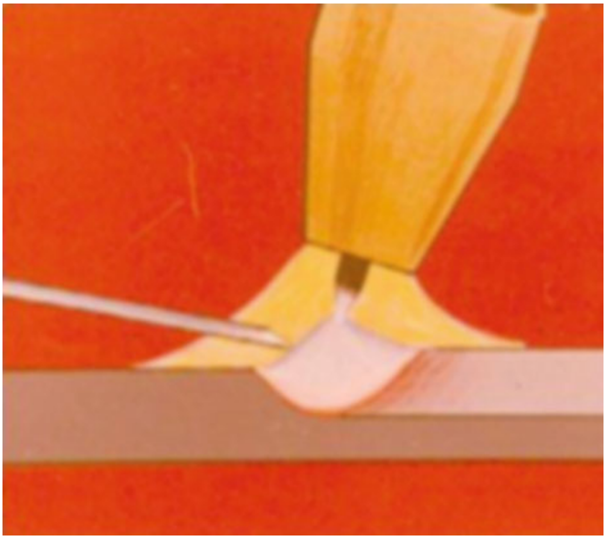


**Fig. 2** Gas tungsten arc welding- GTAW/TIG

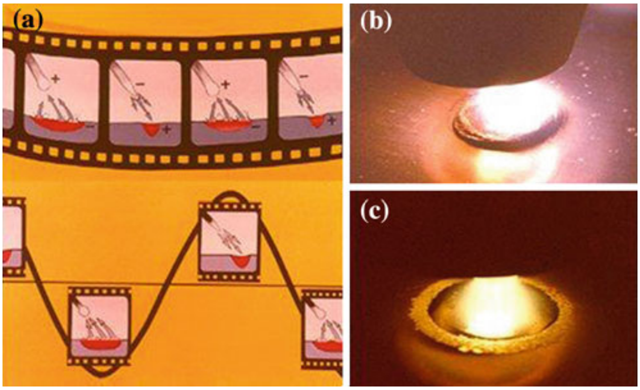



**Fig. 3** **a** Schematic representation of the effect of alternative current in GTAW of aluminum. **b** Positive electrode. **c** Negative electrode

GTAW power sources for AC welding, which allow for adjustment of the balance between polarities, enable the user to choose either enhanced arc cleaning or greater penetration capabilities.

Direct current (DC) power is employed for some specialized applications, as thin sheet welding because risks for burn through reduce since the plate heats less.

Argon shielding is generally used for welding aluminum with alternative current due to a better arc starting, cleaning action and weld quality when compared to helium. The cost of helium is also usually higher than argon.

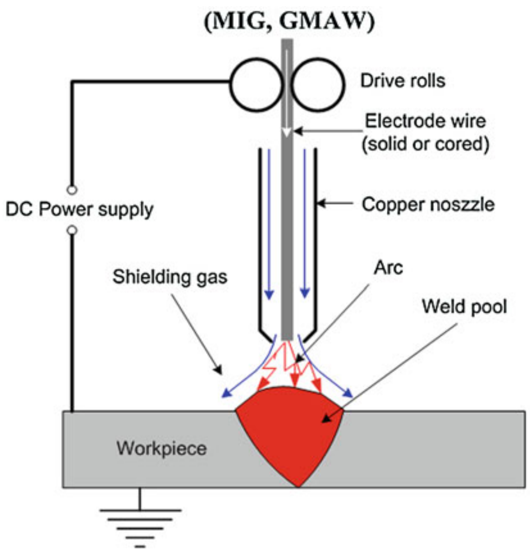



**Fig. 4** Gas metal arc welding (MIG/MAG, GMAW)

## *2.4 Metal Inert Gas/Metal Active Gas Welding (MIG/MAG)*

With MIG (Metal Inert Gas) or MAG (Metal Active Gas) welding also called Gas-Shielded Metal Arc Welding (GMAW), an arc is maintained between a continuous solid wire electrode and the base material of the work piece. The arc and the weld pool are shielded by a inert or active gas (Fig. 4).

A constant voltage, direct current power source is most commonly used in order to obtain a correcting arc. The MIG/MAG welding process operates on D.C. (direct current) usually with the wire electrode positive. This is known as "reverse" polarity. "Straight" polarity is seldom used because of unstable transfer modes of molten metal from the wire electrode to the work piece.

There are four primary methods of metal transfer in MIG/MAG, called globular, short-circuiting, spray and pulsed-spray, each of which has distinct properties and corresponding advantages and limitations. Short circuiting transfer occurs for low currents and low voltages and is desirable to weld thin plates and in positional welding due to the small dimension of the molten pool and the balance of forces actuating in the metal transfer, which allow for transfer against gravity (Fig. 5). Globular transfer is obtained with medium current and voltage levels and is characterized by big droplets detaching form the wire due to gravity force. This is usually associated with spatter and instability in the electric arc (Fig. 5). Spray transfer is characteristic of currents above the transition current and high voltages and is used in high productivity welding for thick plates in the down hand position (Fig. 5).

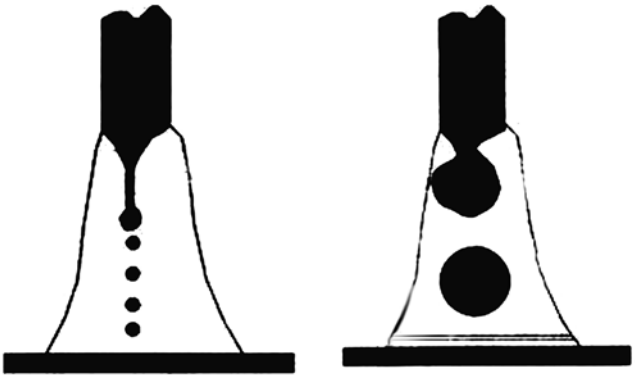


**Fig. 5** Spray (*left*) and globular (*right*) transfer modes

Pulsed spray is obtained with the use of pulsed current in MIG/MAG. Processes like GMAW-P (Pulse) also introduce additional complexity (with the need of defining supplementary variables such as peak current, base current, peak time, base time, frequency and duty cycle) which needs intense process knowledge for correct definition. For achieving good weld quality, one droplet should detach in every pulse to produce best weld quality with minimal defects and spatter. There are many power supplies in the market with embedded software for the most common ranges of applications, thus facilitating the choice of the welding procedure.

Aluminum can be welded with GMAW and GMAW-P with good results.

# 3 Laser Welding

## *3.1 Basic Considerations*

Laser beam welding is a fusion welding process where radiant energy is used to produce the heat required to melt the materials to be joined [2]. A concentrated beam of coherent, monochromatic light is directed by optical devices and focused to a small spot, for higher power density, on the abutting surfaces of the parts being joined (Fig. 6). Gas shielding is generally used to prevent oxidation of the melted material. Different parts and even different metals can be joined in a non-contact process. The required accessibility to the work piece being from one side only and the opportunity to abandon filling material completely are the main advantages of laser beam welding. Laser joining can be performed using either pulsed or continuous wave mode lasers.

Lasers are playing an important role in the joining of materials since the invention of high power solid state and gas lasers in 1964. In the first years, the main applications were resistance trimming of electronic circuits but with the

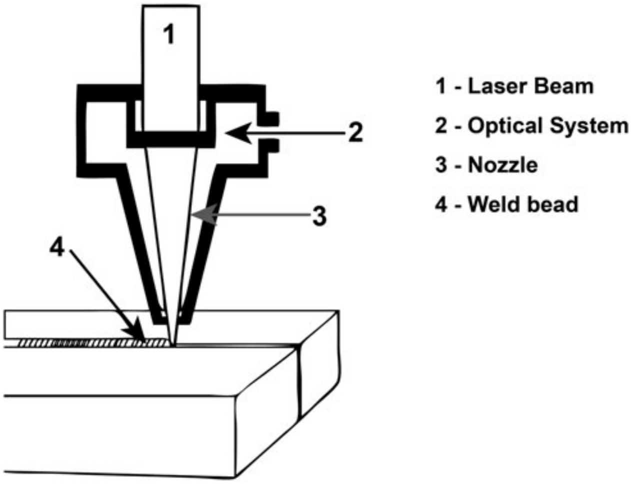



**Fig. 6** Laser welding

introduction in the market of a reliable high performance laser in the late 1970s, welding of sheet metal parts was possible.

Several types of lasers can be used in materials processing though the most common have wavelengths of 10.6 μm—$CO_2$ lasers (gas lasers), or 1.06 μm—Nd-YAG lasers (solid state lasers). The last decade has seen the rise of diode lasers and diode pumped solid state lasers. More recently, high power diode pumped fiber lasers and disk lasers were developed. These new lasers have been stated to be a serious alternative to solid state and carbon dioxide lasers for different materials processing applications.

Beam quality is of major relevance in materials processing with high power laser. The beam quality is defined by ISO 11146:1999 by the beam parameter product (BPP) or the $M^2$ factor, and these assess the ability to focus a laser beam.

The beam quality of a solid state laser is often specified by the beam parameter product (BPP) defined as follows:

$$BPP = \alpha . \omega_0 \quad \text{mm.mrad} \tag{1}$$

where $\omega_0$ is the radius of the beam waist and $\alpha$ is half the total divergence angle. Low values of BPP express good quality beams or the ability to focus a beam to a small spot.

Beam quality is also dependent on the laser radiation wavelength since the beam diameter at the focus is directly related to the wavelength (Eq. 2).

$$d_o = \frac{4\lambda}{\pi} \frac{f}{D} \tag{2}$$

where $d_o$ is the beam diameter at the focus, D the beam diameter before the focusing system with a focal distance f and $\lambda$ the wavelength.

**Table 1** Beam quality for different laser systems

| Laser type | Typical beam quality mm.mrad | Wavelength nm |
|---|---|---|
| $CO_2$ | 3.7 | 10,600 |
| Lamp pumped Nd:YAG | 25 | 1,060 |
| Diode pumped Nd:YAG | 12 | 1,060 |
| Yb Fibre laser (7,000 W) | 18.5 | 1,070 |
| Yb Fibre laser (IPG YLR 17,000 W) | 11.7 | 1,070 |
| Thin disc Yb YAG (1,500) | 7 | 1,030 |
| Yb Disc Lasers (40,000 N) | 10 | 1,030 |

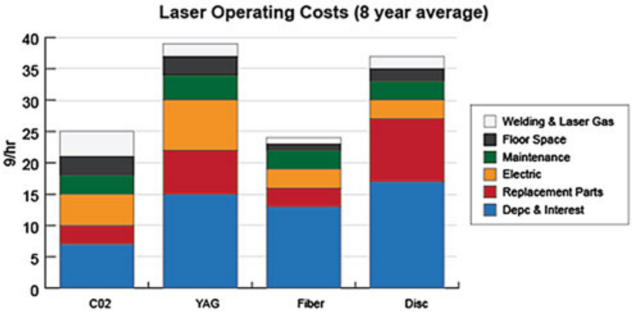



**Fig. 7** Estimated laser operating costs [6]

Generally, $CO_2$ lasers have very good beam quality, while solid state lasers are usually worse. However, fibre lasers have achieved significantly better beam quality, as shown in Table 1 [3–5].

It is well know that the use of laser welding requires high investment costs but it is wise not to forget that the running costs will also play an important part in the production costs. Figure 7 give a comparison of operating costs for different laser systems [6].

Laser welding of aluminium is widely used in industry, but there are nevertheless limitations which need to be addressed for each application. First, there is a poor coupling of the laser energy due in part to the high density of free electrons in the solid, making aluminium one of the best reflectors of light. In addition, many aluminium alloys contain magnesium or zinc, which are easily vaporized forming a plasma that blocks the incident beam.

Other issues that need to be considered when laser welding aluminium are low power absorption, alloy compositional differences and the importance of surface preparation. The power absorption changes dramatically at times, producing an unstable process with poor penetration control and a rough bead surface (it is commonly believed that the difference in the fraction of absorbed power is caused by melting of the metal) [7].

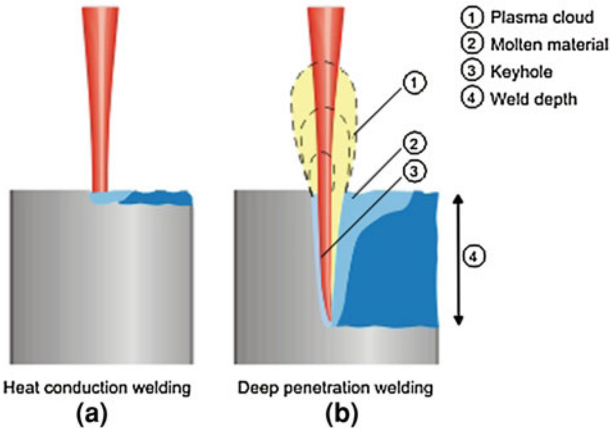
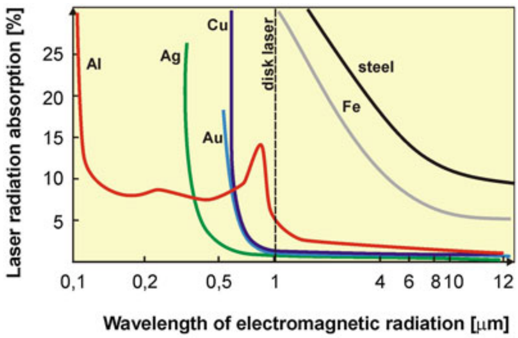



**Fig. 8** Sketches of conduction laser welding (**a**), and of keyhole laser welding (**b**) [7]

**Fig. 9** The radiation absorption of metals as a function of wavelengths of electromagnetic radiation




Welding aluminium alloys can be done both by conduction mode and keyhole mode (Fig. 8). Weld pool shapes in aluminium depend on the mean intensity of the laser beam and the laser pulse time.

The start of the laser welding process of aluminum is difficult in itself because of high reflection coefficient of laser radiation, Fig. 9. When the liquid metal appears, the radiation absorption increases (the reflection coefficient decreases), although it has remained on relatively low level.

The keyhole technique is more widely used on aluminium. To this end, it is necessary to provide suitable power density of the laser beam, i.e., to reach the threshold value of power density, above which is formed the capillary filled with gases and metal vapors and surrounded with a thin film of molten metal. The laser radiation is absorbed by metal vapors in the capillary and by molten metal as a result of multiple reflections of the laser beam from the capillary walls covered with the liquid metal. For iron based materials, the threshold value of power density is about $10^6$ (W/cm$^2$). For aluminium and its alloys, on account of much higher thermal conductivity and high coefficient of laser radiation reflection, the threshold value of power density is about $1.5 \times 10^6$ (W/cm$^2$), while for a stable process it should be not less than $2 \times 10^6$ (W/cm$^2$) [8]. The above requirements bring about the necessity to use more powerful lasers than in case of welding of steel. In case of standard optical system enabling to focus the laser beam e.g., to the spot about 0.6 mm in diameter, the minimum power of the solid state laser of the Nd:YAG type should be more than 3 kW.

It should be kept in mind, however, that during welding with use of the low–power lasers there is danger of reflection of the laser beam from the workpiece surface back to the laser optical system. Thus, the welding head and the laser light cable can be damaged. The reflected radiation can also come back through the laser head and the laser light cable to the resonator. In extreme cases, the laser resonator can be damaged due to excessive thermal load that is due to exceeding the permissible power density inside the laser active element.

Laser welding of aluminium is used in industry with appropriate welding procedures that prevent the occurrence of defects. In case of aluminium, large trapped vapour pores near the root of keyhole-mode welds are common at higher power density. Due to the important difference (20:1) between hydrogen solubility values in liquid and solid aluminium, respectively, hydrogen remains trapped. The use of shielding gas is the common solution.

The pores are mainly due to hydrogen that can be significantly eliminated by surface milling and vacuum annealing [3]. Pores may also be produced by the vaporisation of the alloying elements, especially magnesium. An unstable keyhole with tendency to form “bottle neck” will increase the level of porosity. But the real danger generated by the presence of hydrogen is hot cracking susceptibility. Solidification cracks are more common in case of aluminium alloys containing copper.

The partially melted zone is defined as the HAZ sub-region in which a peak temperature between the liquidus and solidus was attained during welding. Localized melting occurs, accompanied by segregation at grain boundaries. A microstructure is produced that is unable to withstand the contraction stresses generated when the weld metal solidifies, rendering it susceptible to solidification cracking. Heat treatable aluminium alloys of the 6,000 series, for example, are susceptible to this type of cracking.

These aspects need to be taken into consideration when developing laser welding procedures.

## *3.2 $CO_2$ and Nd-YAG Lasers*

The two most industrially used lasers are carbon dioxide and Nd/YAG lasers. The former is a gas laser emitting at a wavelength of 10.6 $\mu$ with higher output powers, efficiencies around 20% (higher than Nd:YAG lasers), with a good beam quality, easy to focus but requiring complex and robust manipulation systems since the light cannot be transmitted via optical fiber. These lasers have high output powers

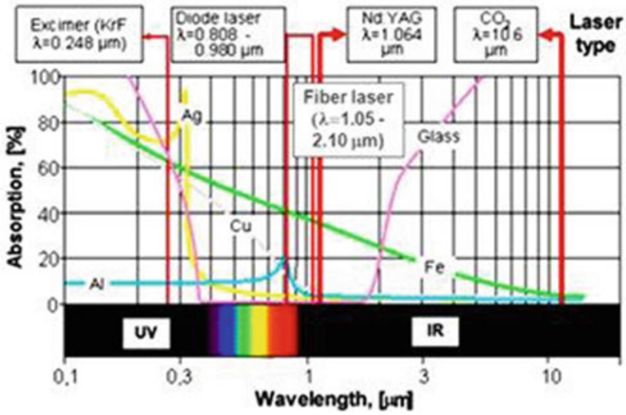



**Fig. 10** Variation of absorption over wavelength and type of material (TRUMPF courtesy) [24]

(up to 50 kW) which allows for keyhole welding modes in thick Al plate, despite the poor absorption of its wavelength [9].

Nd:YAG lasers are solid state lasers emitting at 1.06 $\mu$ in a range of wavelengths where the metallic materials are most absorbent, but have poor energy conversion efficiency (around 5%), limited output powers and high running costs specially due to maintenance. The possibility to be transported via optical fiber improves the system flexibility, but the most relevant advantage is the high absorption of Al alloys of its laser wavelength. That is, for the same weld penetration, the required power is lower for Nd:YAG laser than for $CO_2$ laser.

Diode lasers and diode pumped lasers have been the subject of innovative developments in the last decades. They use the same principles as a diode, so they are classified as solid state lasers and in recent years several developments have been performed by manufacturers. The resonator cavity is made of two coated bars to have the desired optical properties. They have good energy efficiencies in the range of 30–50% and can be transported via an optical fiber. Together with the low implementation area, they are easily integrated in manufacturing lines. Diode lasers are particularly adequate for laser welding of Al since they emit in the range of 800–900 nm (less than Nd/YAG lasers).

$CO_2$, Nd:YAG and diode lasers can be used for conduction mode welding (Fig. 8a) of metals and alloys; the absorptivity of the majority of metals increases as the wavelength decreases (Fig. 10). The use of $CO_2$ lasers will involve more absorption issues, since its wavelength is 10× higher than Nd-YAG beams. Conduction welding is normally used with relatively small components, with the beam delivered to the workpiece via a small number of optics; the use of optics instead of optical fibers is compulsory for $CO_2$ laser beam wavelength. Simple beam defocusing to a projected diameter that corresponds to the size of weld to be made, allowing for any gaps in the joint, is normally sufficient.

As referred before, keyhole mode welding (Fig. 8) is the most common for joining metallic materials by laser, aluminium included. Energy is absorbed by the material through two mechanisms, which determine the overall energy transfer efficiency. Inverse Bremsstrahlung absorption (transfer of energy from photons to electrons) takes place in the partially ionized plasma formed in and above the keyhole; it is the dominant mechanism at low welding speeds. Fresnel absorption by multiple reflections at the walls of the keyhole dominates at high welding speeds, and is dependent on the polarization of the beam. Plasma (ionized vapour) and plume (vaporized material) facilitate energy transfer from the beam to the material, but they also defocus and absorb the laser beam, reducing its power density. This absorption is more evident and must be avoided in case of higher wavelength (case of $CO_2$ laser, 10.6 μm), than in the case of wavelengths about 1 μm (Nd:YAG—1.064 μm). The deleterious influence of the plasma and vapours plume can be drastically reduced by using appropriate gas flow. The same gas is also used for shielding.

The keyhole is surrounded by molten material having a conical shape. The cavity is maintained through equilibrium between opening forces arising from material ablation and plasma formation, and forces caused by the surface tension and hydrostatic pressure of the molten pool, which act to close it. The requirement to maintain this balance leads to practical minimum and maximum travel speeds for keyhole welding—excessive speed causes the keyhole to collapse, whereas insufficient speed results in a wide weld bead that sags. Due to the phenomenon evolution inside the keyhole, the shape and size of the keyhole have a certain dynamic and fluctuate during welding and may negatively influence the constancy of penetration value.

During aluminium welding in keyhole mode, the absorption process is much more unstable than in the case of steel welding. The molten metal conical wall of the keyhole and the resulting seam are wider than in case of steel. Even if the vaporisation temperatures (of the keyhole walls) for steel and aluminium are close, the fusion temperature of aluminium is about 900 K, whilst for steel is about 1,800 K, while thermal conductivity of aluminium is higher than steel. Due to the increased volume of molten metal and to its lower viscosity, the aluminium welding process is characterised by important flow of molten metal. Moreover, there is a trend of flowing through the root, generating excess of penetration and "drop", whilst the lack of material at surface may generate undercut. Root flaws may be prevented by assuring a support (gas, flux, or other) at root or by an appropriate design of the groove.

## *3.3 Fiber Lasers*

Fiber lasers date back from the early 1960s, in low power applications [10, 11]. In 2000, the first 100 W fiber laser was produced [12] and in past years increasingly multi-kilowatt fibre lasers have been introduced for materials processing up to 30 kW, and the technology is available to produce systems of higher power.

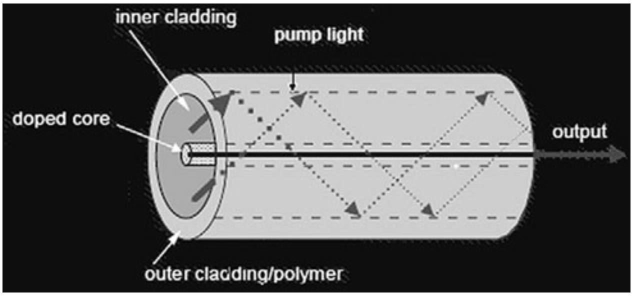



**Fig. 11** Double-clad fiber laser [3]

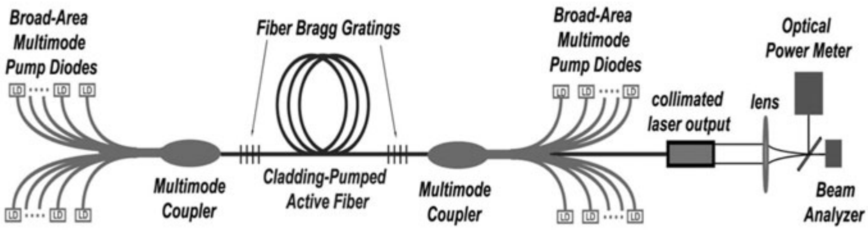



**Fig. 12** Schematic presentation of a fiber laser architecture [15]

High power fiber lasers have multiple advantages, including: high efficiency; very compact design with minimum footprint area; good beam quality with small beam focus diameter; and a robust setup for mobile applications [13].

The active medium is the core of a silica fiber doped with a rare earth: erbium, ytterbium, neodymium or thallium. The pumping process uses multimode diodes rather than diode bars. The laser beam is emitted longitudinally along the fiber. Two Bragg gratings inscribed on the fiber limit the wavelength of the emitted beam. The resonator cavity is thus constituted by the fiber itself, either the core, as in single-mode lasers or the inner cladding around this core as in double-clad fiber laser, as shown in Fig. 11 [14]. The outer cladding is made of a polymeric material with low refraction index to minimise attenuation (Fig. 12) [15]. The resulting laser beam is essentially diffraction limited and when fitted with an integral collimator, produces a beam that is extremely parallel.

Figure 13 shows the beam wavelength for different rare earth doping agents. Typically, ytterbium-doped multi-clad fiber has an emission wavelength of 1.07–1.08 $\mu$. The diode pumped energy is delivered to the active medium via multimode fibers that are spliced to the multi-clad coil.

Fiber lasers are modular so, for example, a 1 kW unit can be made up of ten individual fiber lasers integrated into a common cabinet. Although the beam is no longer single-mode, the resulting beam quality is better than for the same power in Nd-YAG lasers. A 6 kW laser can deliver a beam via a 200–300 µm fiber.

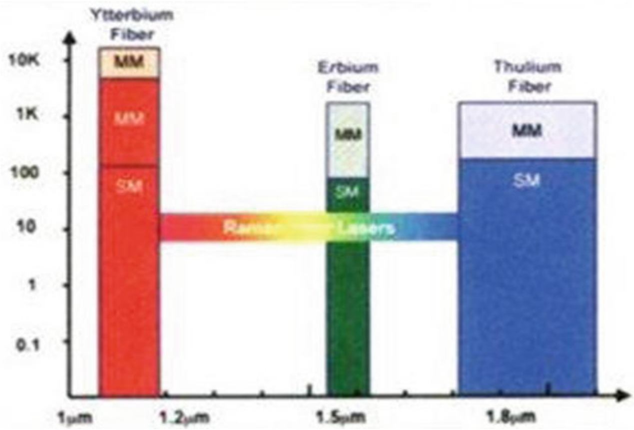



**Fig. 13** Fiber laser spectral ranges [15]

Ytterbium fiber laser has a wall plug efficiency of 16–20%. Though erbium and thulium fiber lasers demonstrate lower wall plug efficiencies, they are still more efficient than typical YAG lasers. Additionally, the lifetime of the pumping diodes exceeds the lifetime of other diode pumped lasers [13], reducing costs.

Fiber laser welding of aluminium has been developed and, as with $CO_2$ and Nd-YAG lasers, provided a correct welding procedure is used, sound welds with no porosity or cracking are obtained [25].

## *3.4 Disk Lasers*

Disk lasers are of the newest generations of solid state lasers. The scheme of the disk laser is shown in Fig. 14.

The active element of disk lasers is YAG crystal in the form of a disk, 150–300 μm in thickness and approximately 12–15 mm in diameter. Usually, the crystal is ytterbium–doped (Yb:YAG). The laser disk is mounted on the copper radiator carrying away the heat produced during generation of the laser beam. The active element –Yb:YAG disk—is optically excited by lighting it with diode laser radiation focused on the disk to form a spot, several millimeters in diameter. The application of diode lasers makes it possible to match closely the wavelength of pumping radiation to the Yb:YAG crystal pumping absorption. Because the disk is very thin, only a part of the pump radiation passing the disk is absorbed. The remainder is reflected by the rare side of the disk and is directed back to the disk through the mirror system. When it is focused again, a part of its energy is turned over to the disk in order to excite it. Nowadays, in case of one disk, up to 20 optical paths are used for pump radiation enabling to achieve optical efficiency of the laser on the level of above 60%. This, in turn, means that the wall plug

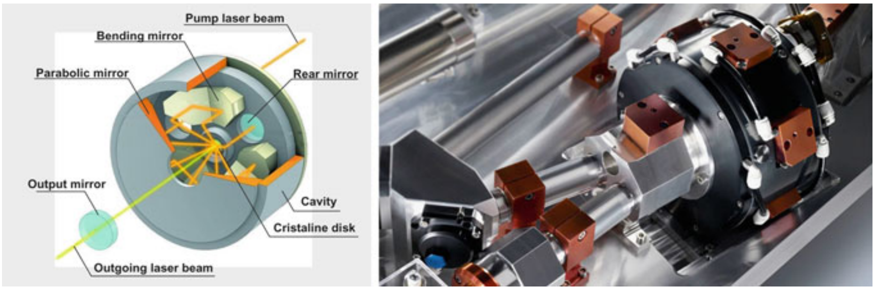



**Fig. 14** Scheme of Yb:YAG disk laser (on the *left*) and resonator of the TruDisk Laser (on the *right*) (*source* Trumpf GmbH + Co. KG)

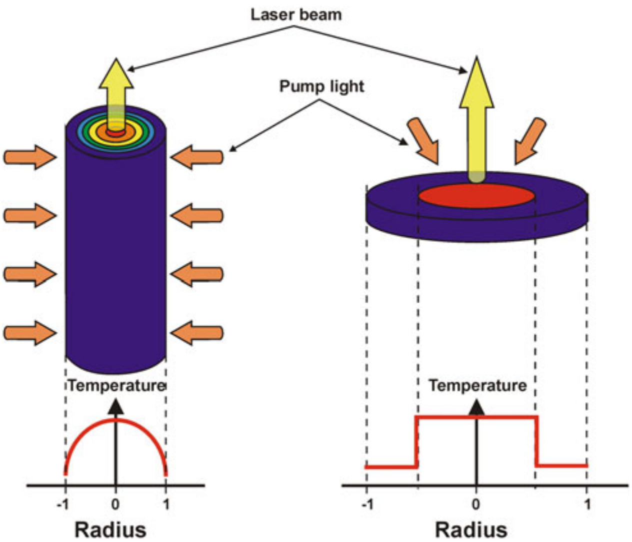



**Fig. 15** Temperature profile on the cross-section surface of the active element of conventional Nd:YAG lamp-pumped laser (on the *left*) and disk laser (on the *right*) (*source* Trumpf GmbH + Co. KG)

efficiency is about 25%. On account of the crystal geometry, the heat flow occurs in one direction only, i.e., along the resonator optical axis. The temperature on the disk cross-section surface is constant—isothermal lines are perpendicular to the laser optical axis. Lack of temperature differences on the disk cross-section surface results practically in elimination of unfavourable phenomenon of crystal deformation on this surface which happens in conventional, lamp-pumped Nd:YAG lasers, Fig. 15. Owing to that, the laser beam quality depends only to a low degree on the power of emitted radiation. The rear side of the disk adjacent to the heat

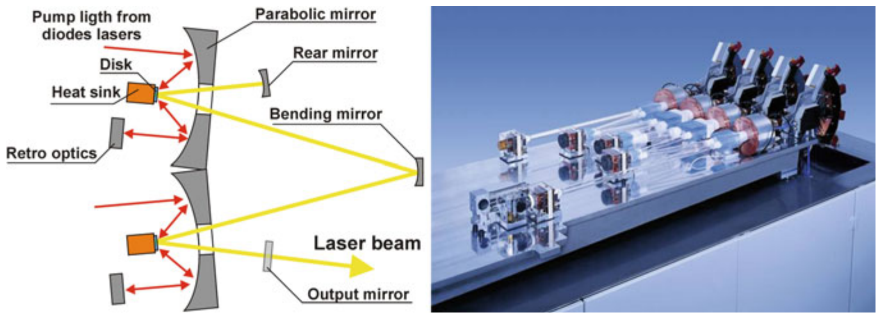



**Fig. 16** Scheme of the coupling of several disks in one resonator (on the *left*) and an example of disk laser resonator composed of four disks (on the *right*) (*source* Trumpf GmbH + Co. KG) [24]

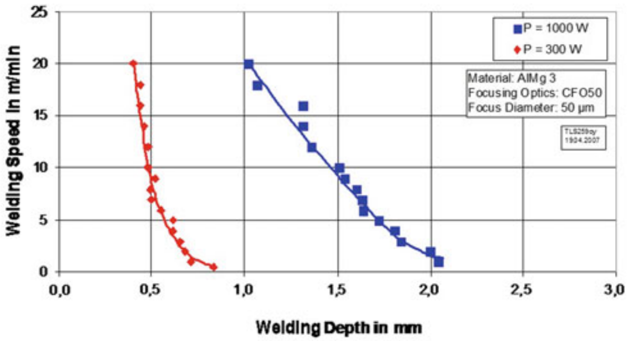



**Fig. 17** Relation between welding speed and penetration depth in disk laser welding (*source* Trumpf GmbH + Co. KG) [24]

exchanger, to which the crystal is mounted, has a reflective surface, which reflects laser beam and pump light.

Disk laser fabricators are incessantly striving after the increase in laser beam power from single disk. Now (in 2010), it is possible to obtain about 5.5 kW laser beam power per disk. Calculations show that there is no fundamental limitation up to 30 kW per disk [16, 17]. The laser beam power depends directly on that of the pump radiation, i.e., on the power of diode lasers generating the pump radiation. A further increase in laser power can be obtained by setting-up of several disks on one optical path. Theoretically, it is possible to set-up any number of disks. In practice, more than four disks are not used in one resonator, (Fig. 16).

The time of failure-free operation between replacements of pumping elements has been extended significantly in comparison to lamp—pumped solid state lasers—the life of diode lasers used for pumping is estimated at about 20,000 h. The designs used at present enable to exchange the single diode pack in 3 min without the necessity of aligning of the pumping system. Planned replacements of pumping systems have not an essential influence on the production continuity.

Nevertheless, in order to protect the welding head and the laser light cable transmitting the laser radiation, it is recommended to incline the head about 5–15° in relation to the axis perpendicular to the material under welding so that the reflected laser beam, if any, does not meet again the optical system. The welding process can be carried out with both positive and negative incident angle of the beam.

In many cases, when welding by conventional single beam laser technique, it is possible to obtain quality joints while high welding speed is achieved simultaneously, (Fig. 17).

As with fiber lasers, disc laser welding of aluminium alloys has been tested with promising results.

### *3.5 Hybrid Laser MAG Welding*

If two welding processes, such as laser welding and MIG welding are coupled in one common process zone this is called a "Hybrid Process", a Laser-MIG-Hybrid welding process, (Fig. 18). The laser beam and the MIG arc are interacting in the process zone; they are coupled via the molten metal and in the majority of cases via the common process plasma.

Generally, the use of filler material may work out not only bead geometry issues, but also metallurgical and joint strength problems. Besides the bad appearance of the bead, an inadequate geometry introduces stress picks that multiply the local loading several times. On the other hand, the losses caused by burning of alloying elements (mainly those with low vaporisation temperature, namely Mg and Si) may be appropriately compensated by using filler metal. Reports have also indicated the stabilisation of the keyhole dynamic when filler metal is used. Definitely, the best solution becomes the use of laser-GMA hybrid welding, that provides very stable process and combines in a holistic way the advantages of these two welding processes.

The coupling of both methods results in process-specific advantages which are called synergistic effects: deep penetration, high welding speed, low heat input and low distortion, Figs. 19 and 20.

In Laser-MIG-Hybrid welding, the addition of filler material is carried out via the MIG arc process. The application of the MIG technology entails the advantage that the filler wire can be molten with relatively inexpensive energy while the high-quality laser beam energy is maintained in an almost undiminished form for the penetration and the material transport into the depth. The positioning of the wire to the laser beam is relatively easy compared to cold filler wire feeding as by the common plasma a guidance of the arc towards the keyhole can be observed.

The Laser-MIG-Hybrid process allows avoiding the substantial disadvantages of laser beam welding without filler material. The process offers excellent gap bridging ability and allows to influence the weld pool metallurgy without

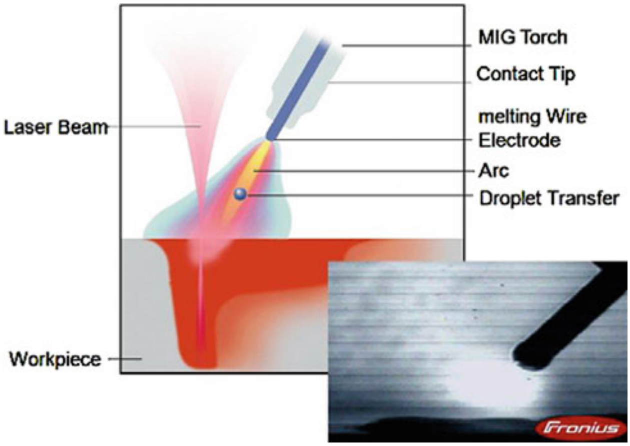



**Fig. 18** Laser MIG hybrid welding process

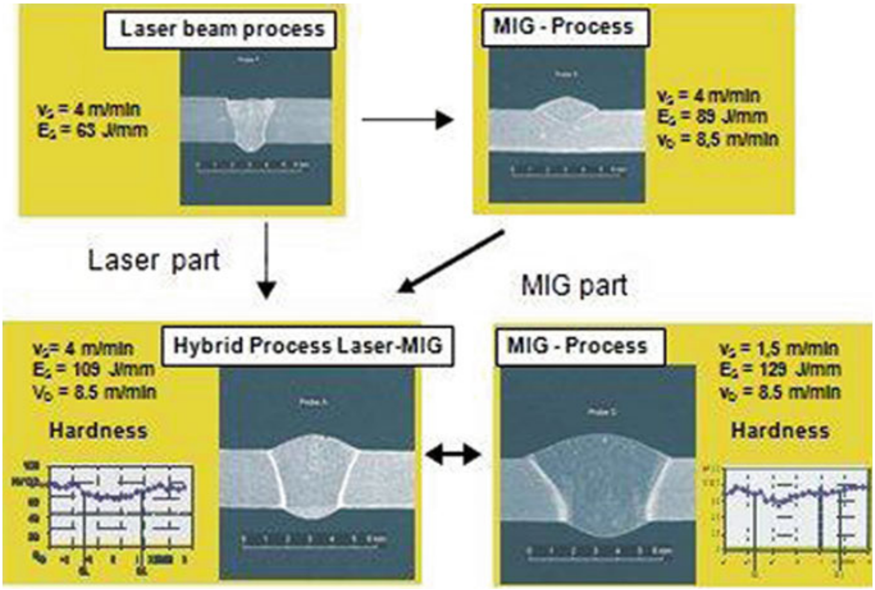



**Fig. 19** Laser MIG hybrid welding of aluminum alloys, contribution of laser and MIG process

abandoning the main advantages of laser beam welding—the deep penetration and the high welding speed.

The MIG arc is either pulsed arc or is triggered by direct current arc, in the most cases a spray arc via commercial MIG welding power sources. The shielding of the welding zone is realised through pure helium or helium-argon gas mixtures. Low argon contents in the shielding gas exert positive influence on the material

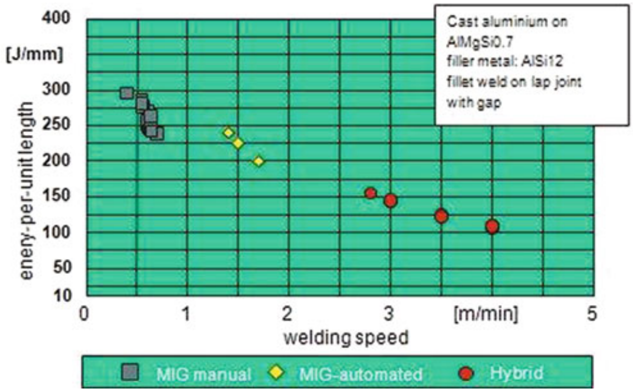



**Fig. 20** Laser MIG hybrid welding, increase of welding speed and reduction of heat input

transition and the arc stability. The applicable gas mixture is a compromise between high plasma shielding and arc stability. Welding filler materials are mainly commercially available solid wires which are also used for MIG welding of the aluminium alloys.

The advantages of the Laser-MIG-Hybrid welding processes can be summarised as followed:

- High process speed
- Low heat input
- Low thermal distortion
- Good gap bridging ability
- Excellent weld properties
- Good process stability

Despite all the advantages of Laser-MIG-Hybrid welding the fact still remains that, caused by two coupled welding processes, the number of setting variables increases. For a reliable and stable hybrid welding process and excellent weld properties, the exact setting of the parameters is mandatory.

## 4 Advantages, Limitations and Trends

The main advantages of laser welding reside in the shape of the weld and good penetration, high precision, high mechanical properties of the weld, high welding speed, low heat input, high flexibility and possibility of automation and robotising. In general, there is no need to machine the weld/joint after welding.

The case of beam transmission and directional control permits multi-station operation. Nearly 100% duty cycle is possible by switching the beam from station to station. The high energy density beam enables narrow welds and narrow heat affected zones, and therefore good retention of metal properties and relatively low distortion of the work piece.

The main disadvantages are the relatively high cost of investment and the important requirements related to the machining of the parts to assure a precise groove (reduced dimensional tolerances). Most of the multi-kilowatt laser systems operate at only about 10–20% efficiency for converting electrical power into a focused infrared laser beam.

Higher productivity is possible in laser welding through: a reduction in processing time because of the low inertia of laser welding; a reduction in the use of materials; the use of a wide range of materials; a reduction in labour costs; a reduction in scrap; a reduction in process cycle time through the minimization of post treatment working; a reduction in response time to orders; the high equipment availability time. Higher product quality, in terms of improved in-service properties, can be achieved through: improved tolerances; accurate control of process parameters; selection of new materials; and product redesign. Laser welding is environmentally friendly; it uses clean energy and few contaminating materials [2].

Hybrid welding processes combine the characteristics of their constituent techniques: a laser beam is highly penetrating, but intolerant to variations along the joint line; these can be accommodated by more forgiving arc fusion processes. Hybrid processing enables technical problems to be overcome as well as reducing the requirements placed on the laser, leading to a reduction in capital investment. This type of reasoning can be applied to most thermal mechanisms of laser processing, presenting opportunities for novel application of an existing technology [18].

Laser welding of aluminium is commonly used on many applications through procedures for keyhole welding, and quality standards must be generated and approved by classification societies, particularly for thick section materials. Both are currently obstacles to greater application. Equipment for on-line process monitoring and quality control is continually being sophisticated. This will enable rugged systems to be made, which will increase process automation, and make the process more attractive to a wider range of industry sectors.

Weldability of aluminium alloys depends in great part on the alloy grade, i.e., on the alloy chemical composition. Some of them, due to increased susceptibility to hot cracking, need to be welded with the use of additional material modifying the chemical composition of welds.

Three joint designs (butt, tap, and flange) are best suited for laser welding of aluminium [7].

Butt joints with sheared edges are acceptable provided they are square and straight. A fit-up tolerance of 15% of the material thickness is desirable. Misalignment and out-of flatness of parts should be less than 25% of the metal thickness.

In lap joints, air gaps between pieces to be welded severely limit weld penetration and/or weld travel speed. For round welds in aluminium, no gap can be tolerated unless inert gas coverage can be maintained over the entire weld area.

Flange joint geometry is especially suited for aluminium because of the aluminium's high shrinkage rate. Square edge and good fit-up are also necessary.

Shipbuilding and aerospace are industries where the application of laser welding of aluminium can be often found. Although the first aircraft made by Boeing was partially welded, mechanical fastening methods such as riveting have dominated because of the difficulties associated with fusion welding of the common aluminium aerospace alloys 2024 and 7075. Laser welding can reduce joining costs relatively to adhesive bonding and riveting by about 20%. EADS Airbus has invested heavily in laser welding as a replacement for riveting in non-critical applications. One application involves joining stiffening stringers to the skin of the fuselage. The damage-tolerant alloy 6013 is the base material and 4047 the filler material. The stringers are welded from two sides at 10 m/min, using two 2.5 kW $CO_2$ laser beams. The joint is designed such that the HAZ is contained in the stringer, and does not impinge on the skin. The process was first used in series production of the Airbus 318, and was then implemented in other aircraft types.

High power fiber lasers can be used for deep penetration welding in a diversity of materials since the low wavelength that characterizes these lasers allows its absorption by almost all metals and alloys and the fiber delivery system provides the necessary flexibility for beam manipulation and positioning especially when 3D is required for processing.

Micro-welding was done in medical equipments [19]. The Bremer Institute in Germany studied fiber laser welding in AA6056 aluminium alloy 6 mm thick, with a 6.9 kW laser and a welding speed of 50 mm/s [20] with excellent results.

Quintino et al. performed successful experiments in high power laser welding of AA7150 aluminium alloy, for pipeline application [21, 22] with a 8 kW fiber laser installed in Cranfield Institute in UK.

Laser welding of aluminium has important applications in automotive industry since aluminium started to be used not only for gear box, but also for structural parts. The new concept of aluminium integrated car body involves the use of extruded high strength elements jointed in nodal points. Both laser welding and laser-GMA hybrid welding are used, besides classical arc welding and brazing processes.

Laser-GMA hybrid welding has much more volume of applications in industry when compared with laser welding [23]; e.g., from about 500 km of weld in case of a cruiser, about 250 km are made by laser-GMA welding, but in this case the major part of the structure is made of naval steel.

Laser-MIG-Hybrid applications of aluminium-alloys in the manufacturing industry, especially in the car industry, show the high potential of this method, Figs. 21 and 22. Through the development of innovative laser systems, as, for example, fibre laser and disc laser, which excel with their compact design, high efficiency, high precision and high flexibility new possibilities for the Laser-MIG-Hybrid welding methods present themselves. The increasing power and beam quality of solid state lasers will emerge new possibilities especially for welding light metals.

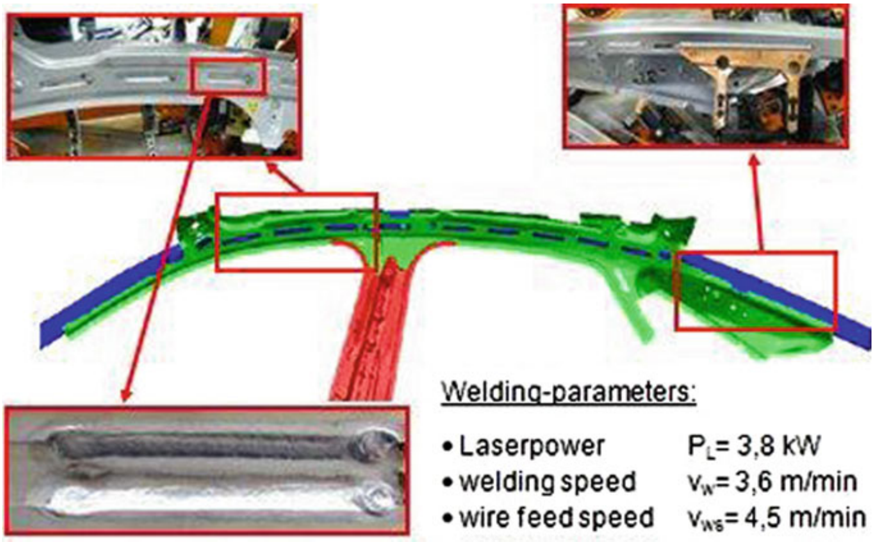



**Fig. 21** Laser-MIG-hybrid welding, industrial application, reduction of distortion, audi A8 roof rail

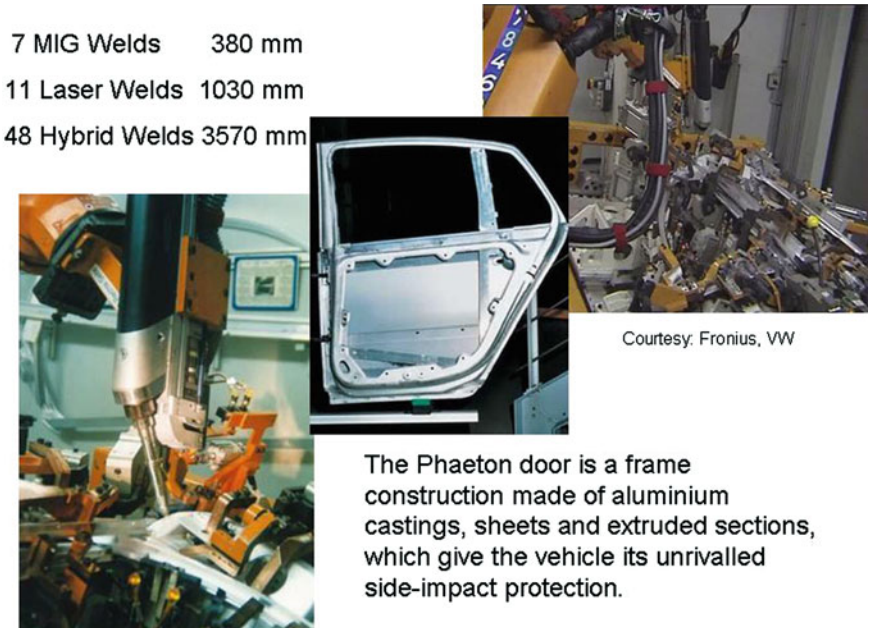



**Fig. 22** Laser-MIG-hybrid welding, industrial application, lightweight aluminium car door, VW phaeton

## 5 Conclusions

Lasers have a good potential for welding aluminium namely in deep penetration welds, where the high power of the beam combined with a sharp focus, can penetrate comparatively thick joints, while producing a very narrow weld, and a correspondingly narrow HAZ, when compared to arc welding processes.

The current understanding of the important physical processes occurring during laser welding of these alloys such as energy absorption, fluid flow and heat transfer in the weld pool, and alloying element vaporisation create a sound platform to use this process.

The market presents quite a few options of different types of lasers and combination of laser and arc welding for the user to choose from.

Whichever the part or construction to be welded and whichever the laser equipment to be used, care must be put in the definition of the welding procedure to assure sound welds with mechanical properties matching the base material.

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