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Analysis of the Laser Welding Process

Abstract: The article discusses the basics of key-hole welding, melt-in welding, hybrid laser welding (laser + GMA) and laser welding with filler metal feeding as well as presents laser welding process applications in various industries. In addition, the article discusses advantages and disadvantages of laser welding as well as presents typical laser welding-related imperfections and possibilities of the real-time monitoring of laser welding process quality.

Keywords: laser welding, key-hole welding, melt-in welding, hybrid laser welding

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Introduction

Laser welding is increasingly common in various industrial sectors involving the making of welded structures such as car-making, shipbuilding, the construction of bridges, the production of steel structures of self-propelled cranes, the manufacturing of wind turbines etc. The growing popularity of the process results from its specific advantages including, high productivity, potential for the automation and robotisation of production as well as the high quality of joints characterised by the narrow heat affected zone (HAZ) and minimum welding stresses and strains [1–7]. Because the laser radiation beam is characterised by high power density, restricted within the range of 10^3 kW/mm^2 to 10^{11} kW/mm^2 (Fig. 1 and 2), the interaction between the laser beam and the material subjected to welding is intense, particularly as regards the key-hole welding of joints having a thickness > 6.0–8.0 mm (depending on the type of a material) [1, 2, 3, 6, 7, 13]. As a result, the online (real-time) monitoring of the welding process and the simultaneous joint quality-related control are indispensable for ensuring the high quality of laser welded structures. Tests concerned with the detection of welding imperfections formed during the welding process were performed as early as twenty years ago, yet test results were not widely used in industry, primarily because of the high price of sensors as well as due to the low accuracy and effectiveness of monitoring systems. On the other hand, industrial applications of laser welding were then very limited, which additionally restricted the interest in the online monitoring of the process [1–7].

Because prices of laser welding equipment are lower from year to year, laser welding technologies find increasingly many applications in industries making welded structures. During the high-volume production of welded structures, the effective on-line monitoring of the welding process reduces production costs and significantly improves the quality of production, including the achievement of

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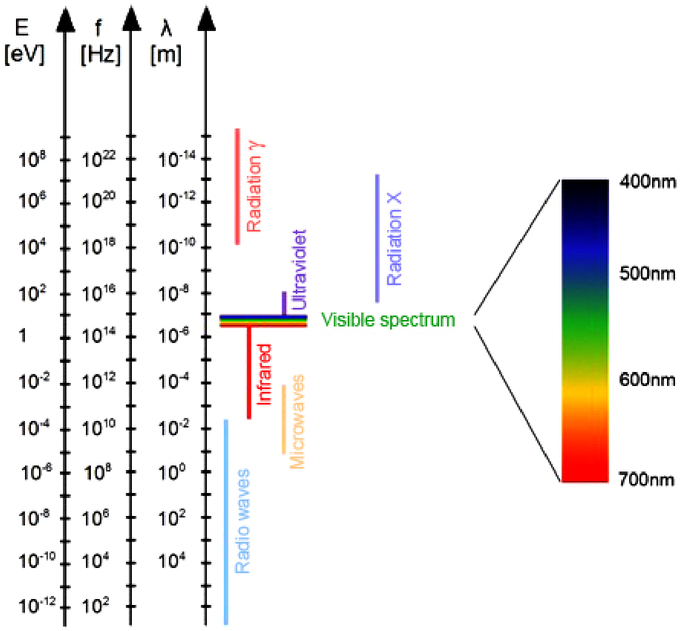


Fig. 1. Range of energy – E, eV, frequency – f, Hz and length of known electromagnetic waves λ, m; laser radiation used in welding engineering is restricted within the range of approximately 800 nm do 10,6 μm [1]

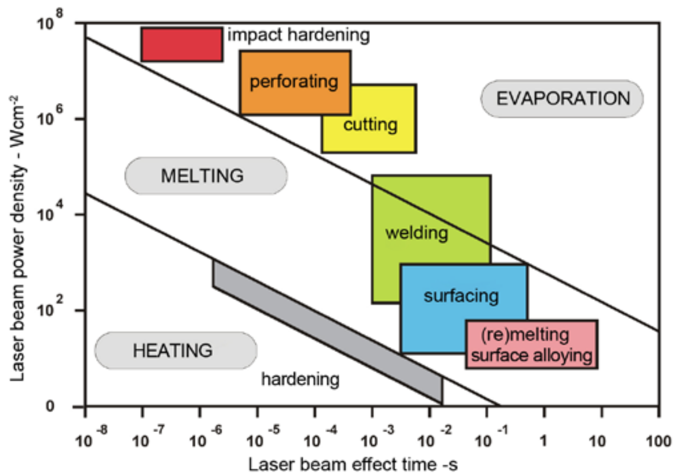


Fig. 2. Typical industrial applications of the laser beam in technological processes in relation to the power density of the laser beam and the duration of its effect [1]

the imperfection-free quality level.

Laser welding involves interaction between the laser radiation beam and the material being welded. During the CO_2 laser welding process, the laser radiation beam is supplied by the laser radiation generator to the welding area with a system of mirrors and lenses. In turn, during welding involving the use of solid-state lasers, diode lasers, fibre lasers or disc lasers, the energy is supplied using optical fibres and lenses (Fig. 3 and 4) [1, 2, 3 and 7]. Because of this, the online monitoring of laser welding processes relies primarily on information based on the optical radiation of the welding area, where most sensors used in monitoring systems are optical. The particularly rapid development of systems enabling the online monitoring of laser welding processes has been observed over the past ten years and can be attributed to significant progresses in sensor technologies and the implementation of artificial intelligence in

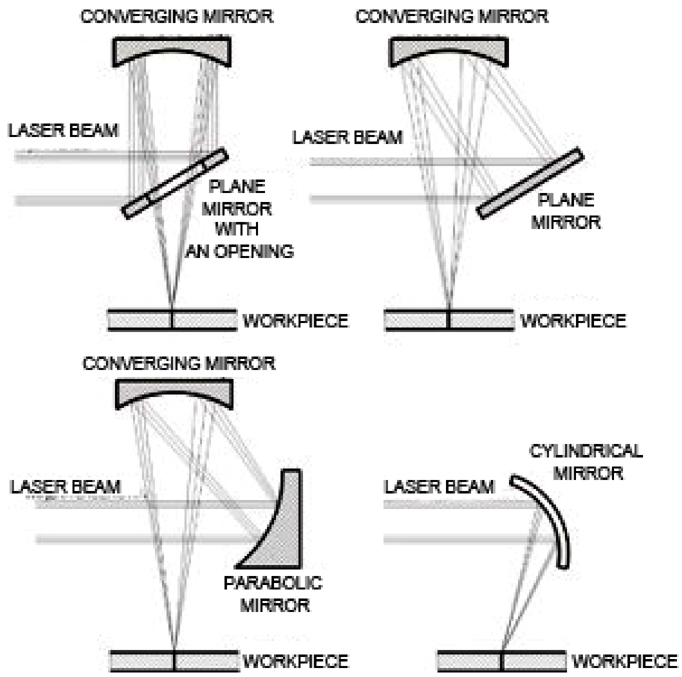


Fig. 3. Schematic design and operation of optical heads focusing the ring-shaped laser radiation beam generated by high-power CO_2 lasers [1]

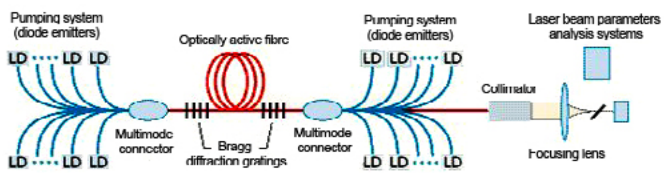


Fig. 4. Schematic design of a high-power fibre laser [1]

monitoring systems [2–24].

Basics of laser welding

Laser welding involves the gas-shielded melting of a structural joint area using heat generated by the concentrated laser beam radiation, characterised by very high power density restricted within the range of 10^2 W/mm² to 10^{11} W/mm² (Fig. 1–11) [1–5]. Depending on the type, design and the configuration of the laser resonator (the active element of the CO_2 laser or of the solid-state laser), a strong and constant electromagnetic field can be generated inside such a resonator. The shape of the aforesaid electromagnetic field affects the cross-sectional energy distribution of the laser beam, also referred to as ***Transverse Electromagnetic Modes*** (**TEM**) (Fig. 5 and 6). Additional designations of TEM_{mn} describe transverse modal lines in the cross-section of the laser beam on the surface of the laser beam focus. The beam is divided into two planes perpendicular to each other. The shape of the beam is described by means of the letters **m** and **n**, adopting the value of **0** or **1**. Typical distributions of electromagnetic radiation energy in industrial lasers used in welding engineering are the following:

- single-mode TEM_{00} type Gaussian distribution,
- multi-mode distribution, i.e. a few partially overlapping TEM_{01}, TEM_{10} and TEM11 type Gaussian distributions.

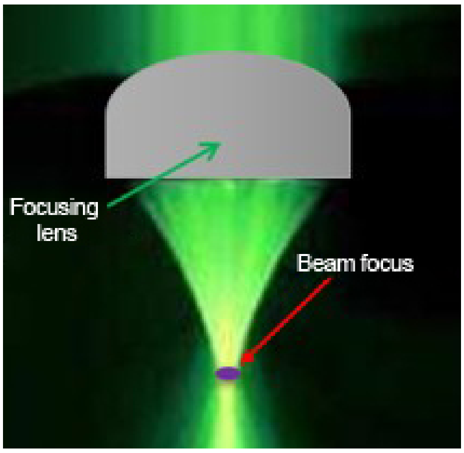


Fig. 5. Laser beam focused by the focusing lens [1]

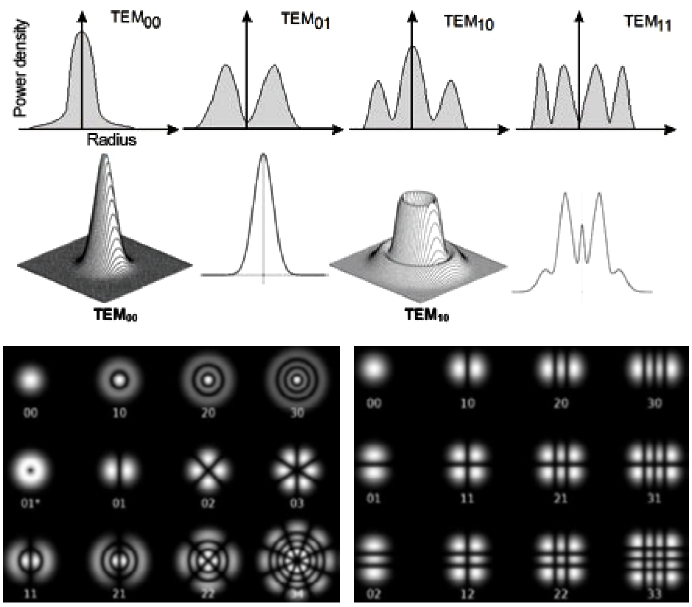
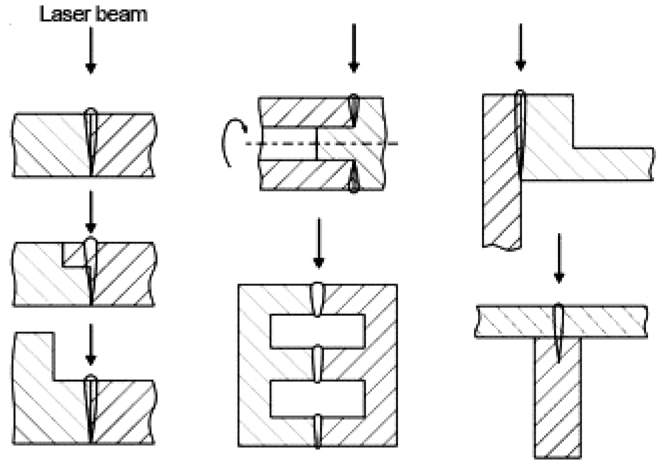


Fig. 6. Typical energy distribution in the laser beam focus: TEM01 energy distribution melted in a Plexiglas cube and laser beam energy distribution of cylindrical and polarised symmetry [1]

The laser welding of butt, T-shaped, overlap, angle, edge and flanged joints, i.e. basically all typical joints in structures made using weldable engineering materials (Fig. 7), can be performed without the use of the filler metal, using the keyhole technique (Fig. 8 and 9) or the melt-in technique (Fig. 10), identical as in the GTA or PTA welding processes. During the above-named processes, the weld metal is solely formed from the partially melted edges of materials being



Type of weld and joint	Schematic weld run	Laser welding technique
Continuous weld; all types of joints		Continuous beam welding, key-hole welding or melt-in welding of liquid metal
Segment welds; primarily thin overlap joints		Continuous or pulsed beam welding, key-hole welding or melt-in welding of liquid metal
Continuous overlap weld (composed of overlap spot welds); all types of joints		Pulsed beam welding, key-hole welding or melt-in welding of liquid metal
Spot welds; primarily thin overlap joints		Pulsed beam welding, key-hole welding or melt-in welding of liquid metal, thin overlap joints
Welds of various shapes; including girth welds, primarily thin overlap joints		Continuous beam welding, key-hole welding or melt-in welding of liquid metal, recommended for remote welding

Fig. 7. Primary types of joints makeable by means of laser radiation and recommended welding techniques [1]

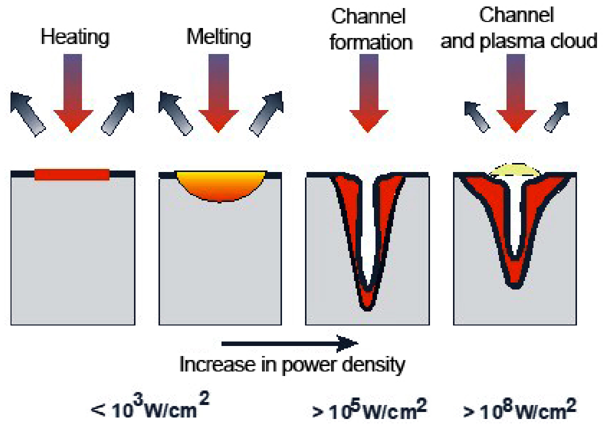
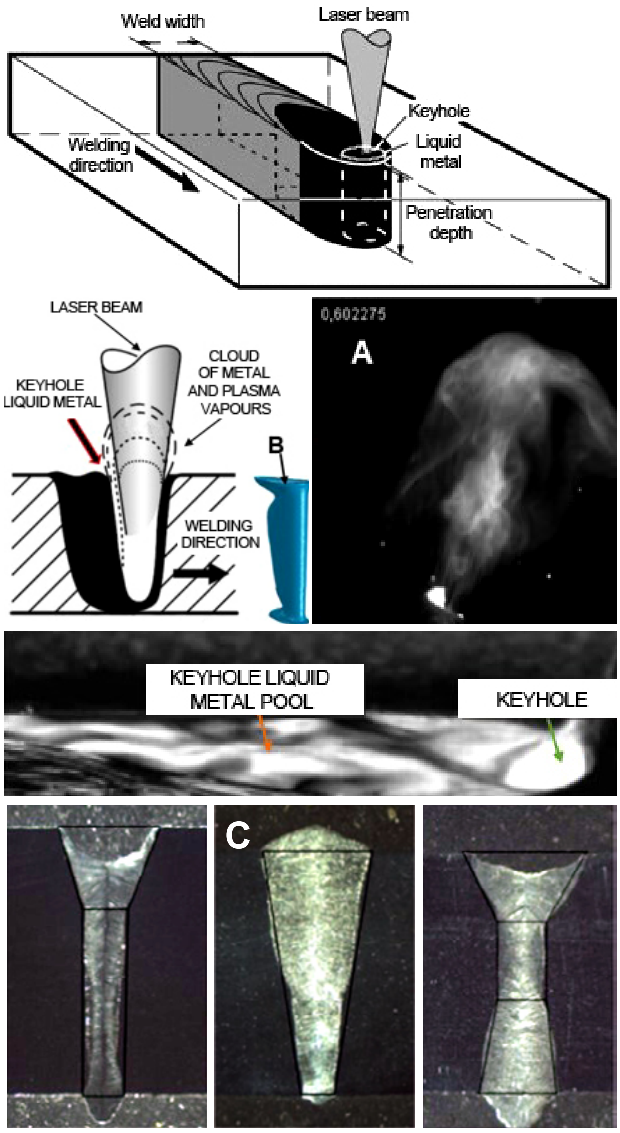


Fig. 8. Effect of laser beam power on relative penetration depth and the shape of the beam energy absorption area on the surface of a metal object; focused laser beam [1]



P = 7.0 kW, V = 30 mm/s, FP = 0.0 mm; P = 5.7 kW, V = 25 mm/s, FP = + 20.0 mm; P = 8.0 kW, V = 20 mm/s, FP = - 4.0 mm

Fig. 9. Schematic diagram of the key-hole laser welding of butt joints as well as the key-hole (keyhole) and liquid metal drawn behind the weld keyhole, recorded using a high-speed camera; A – plasma cloud and metal vapours over the weld keyhole, B – shape of the weld keyhole determined on the basis of the melting point, C – three types of weld metal shapes in relation to laser welding parameters [1, 2, 12]

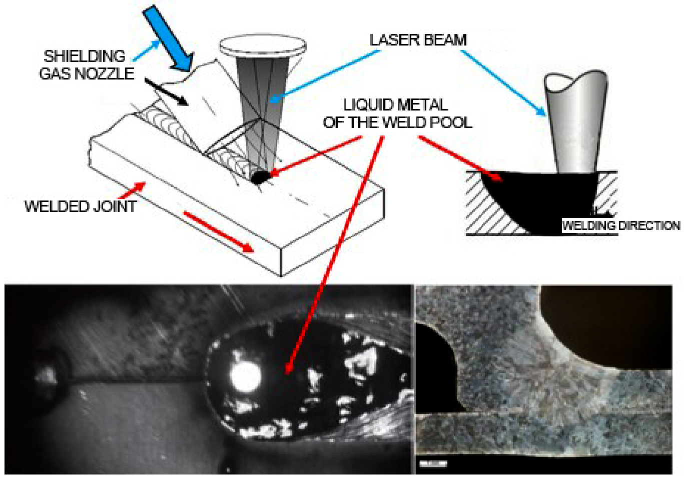


Fig. 10. Schematic diagram of the melt-in welding of butt joints, (a) liquid metal pool recorded using a high-speed camera (b) macrostructure of the melt-in HPDL diode laser welded joint of a nozzle unit ring (c) made of high-temperature creep resisting austenitic steel EI-835 (type 25-16-6) [1]

welded, nearly not differing from the base material in terms of the chemical composition.

Because of the small laser beam diameter and related difficulty directing precisely the laser beam along the welding path of a joint with square butt weld preparation, in order for the keyhole laser welding of thick butt joints (i.e. the thickness of which exceeds 15.0–20.0 mm) to ensure the complete penetration of joint walls and prevent the formation of imperfections (e.g. incomplete fusion), it is necessary to apply laser hybrid welding (LHW). The LHW process involves the combination of keyhole welding and GMA, GTA or PTA welding into one process (Fig. 11) [1, 6, 22, 23]. The combined effect of the laser beam and that of arc not only results in the complete penetration of the walls of a joint with square butt weld preparation but also requires less precision when controlling the movement of the laser head along the welding path without compromising the joint penetration depth. In addition, the LHW process enables the obtainment of higher welding rates and more favourable mechanical properties of joints (controlled by the chemical composition of a filler metal melted by GMA, GTA or PTA arc). To overcome the problem related to the precise control of laser beam movement along the welding path of butt joints or T-joints and control the chemical composition of the weld metal, it is also possible to use the laser welding process, during which the filler metal (in the form of a solid or flux-cored wire) is fed to the weld key-hole or the weld liquid metal pool (as in GTA and PTA welding) (Fig. 12) [1].

If the laser beam power density is low, i.e. in relation to steel below 1.0–1.5×10³ W/mm², whereas in relation to aluminium and copper below 0.5–1.5×10⁴ W/mm², laser radiation is intensively reflected against the material subjected to welding and, e.g. in the case of the CO_2 laser beam power density below 1.0–1.5×10³ W/mm² striking the steel joint, less than 30% of the beam energy is absorbed by the joint surface through direct Fresnel absorption [2, 3]. In the above-presented situation, the transport of energy from the laser beam focus area to the surface of the joint takes place through the conduction of heat deep inside the joint metal and the formation of the liquid metal pool (just as in cases of arc welding processes) (Fig. 8 and 10).

In turn, where laser beam power density exceeds the threshold limit of steel, i.e. approximately 1.5×10³ W/mm², aluminium and copper, i.e. approximately 1.5×10⁴ W/mm² and that of tungsten, i.e. approximately 1.5×10⁵ W/mm², the laser beam "drills" through a joint entirely, primarily as a result of the evaporation of the joint metal (Fig. 8 and 9). The above-named phenomenon leads to the formation of a gasodynamic vapour channel (keyhole) across the welded joint. The walls of the keyhole are covered with a thin layer of liquid weld metal, whereas the keyhole itself is filled with metal vapours and plasma. The laser beam partly reflected and absorbed by metal vapours and the liquid metal covering the walls of the keyhole. As a result of inverse Bremsstrahlung absorption (iB-absorption) [2, 3], charged atoms of metal vapours inside the keyhole can increase kinetic energy absorbed from laser beam photons.

An increase in the kinetic energy of metal vapour atoms results in the further ionisation of metal vapours by high-energy electrons and the formation of plasma, an increase in plasma temperature and, ultimately, an increase in absorption coefficient iB. As can be seen, plasma plays a positive role in the keyhole laser welding process as it prevents the cooling of the keyhole by the surrounding atmosphere. In addition, plasma radiation inside the keyhole facilitates the evaporation of the liquid metal covering the walls of the keyhole. Metal vapours escape outside the keyhole, forming the cloud of metal vapours and plasma. The above-named phenomena are responsible for the fact that, in the keyhole, the laser absorptivity (absorption coefficient) of all engineering materials increases up to approximately 90%, regardless of the laser radiation wavelength. The transport of energy in the keyhole is characterised by significantly higher density and takes places through conduction and convection. The evaporation of the metal on the walls of the keyhole plays a fundamental role in the welding process (Fig. 5–7 and 9). The keyhole (gas channel) is supported by the pressure of weld metal vapours and the pressure of plasma flowing from both sides of the keyhole, where the proportion of the penetration depth to the run width may reach 100:1 (Fig. 10). The laser beam moving along the welding path (keyhole) enables the formation of the permanent butt joint of elements subjected to welding (i.e. usually in the form of butt joints or overlap joints) (Fig. 7–9).

During the keyhole welding process, the cloud of metal vapours and plasma formed in the keyhole is expelled outside, primarily towards the shielding gas feeding nozzle. The presence of the plasma cloud on the side of the weld root indicates the full penetration of the joint. The properties of the cloud of metal vapours and plasma depend on the type of the laser beam and the type of shielding gas. In terms of helium-shielded CO_2 laser welding, where helium is characterised by high ionisation potential (24,9 eV), the cloud is exclusively composed of emitted neutral metal atoms. Where the shielding gas is argon, characterised by the ionisation potential amounting to 15.7 eV or N_2 – 14.5 eV, because of the low ionisation potential of the gases, it is primarily gas plasma that is formed above the keyhole and makes up the cloud over the keyhole.

In diode, fibre or disc-laser based welding processes, the cloud above the keyhole contains low-ionised plasma. Nearly all maximum values of spectroscopic sensors of the cloud are based on the emission of neutral metal atoms, whereas emission based on argon plasma is difficult to detect. At the same time, because of high evaporation pressure inside the keyhole, significant metal spatter is expelled outside the keyhole (Fig. 13).

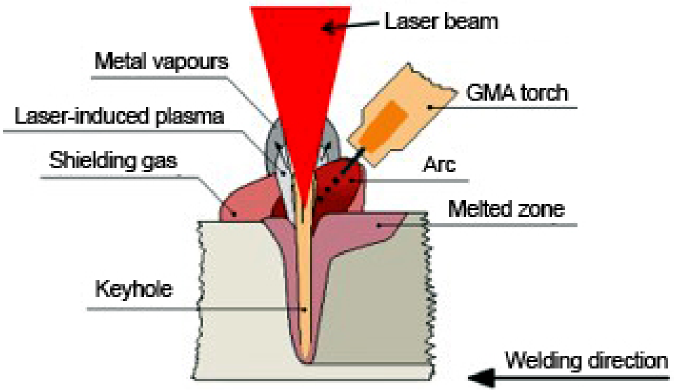


Fig. 11. Schematic diagram of hybrid laser welding (laser + GMA) [1]

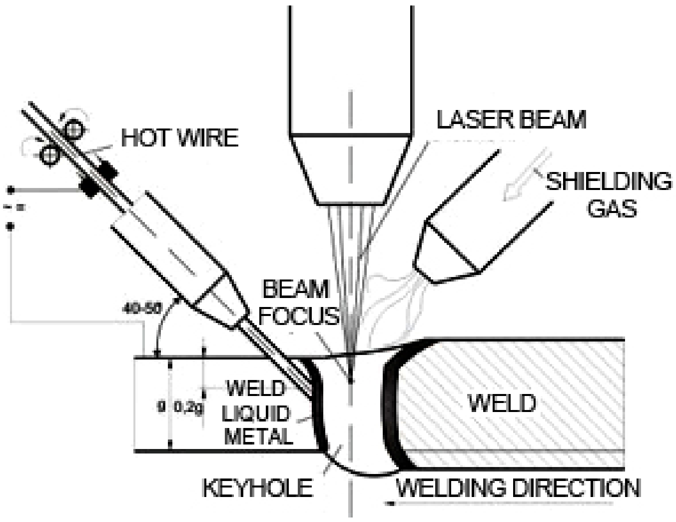


Fig. 12. Schematic diagram of the laser welding process with hot wire fed to the keyhole area, butt joint welded in one run using the keyhole welding technique [1]

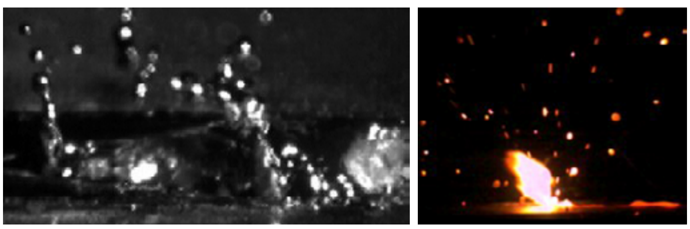


Fig. 13. Significant metal spatter recorded using a high-speed camera, during the keyhole welding process performed using a disc laser [18, 21, 22]

Laser welding – advantages and disadvantages

Laser welding processes are characterised by enormous, yet not fully exploited, industrial potential. The aforesaid potential is particularly impressive in comparison with conventional arc welding processes and characterised by the high quality and efficiency of welding processes, easy automation and robotisation, production flexibility, the possibility of performing simultaneously welding, surfacing, alloying, remelting, heat treatment or cutting of structures using laser beams powered by one laser radiation generator, significant depths of the penetration in joints with square butt weld preparation, narrow HAZ as well as low welding stresses and strains [1–11]. In terms of metallurgical, technological and structural weldability, laser welding technologies make it possible to obtain high-quality joints in hard-to-weld materials or materials impossible to weld using arc welding technologies (Fig. 7–12) [1, 2, 10, 15].

The more extensive application of laser welding technologies is still limited by relatively high equipment-related investment costs, difficulties welding structural materials characterised by low laser radiation absorptivity (e.g. copper, aluminium, magnesium and their alloys), the necessity of ensuring high accuracy and purity when preparing joints, the susceptibility to porosity formation or the formation of dangerous and poorly detectable internal incomplete fusions, particularly during keyhole welding [1–18].

The development of electronic and computer-aided control systems combined with developments in materials engineering result in the gradual reduction of welding equipment prices, i.e. one of the primary barriers restricting industrial applications of laser welding technologies. However, laser welding as such is a complex process, highly sensitive to the stability of primary welding parameters including the power and the type of the laser beam, welding rate, the diameter and the position of the beam focus, the length of the beam focus as well as the type and the flow rate of shielding gas [1–24].

The instability of any of the above-named parameters or the presence of joint impurities or surface irregularities as well as the unprecise preparation of elements to be joined (e.g. improper gap or the misalignment of sheets/plates etc.) and poorly detectable material defects (altering welding process parameters) result in the formation of internal and external welding imperfections of the joint. The most typical welding imperfections of laser welded joints include cracks, porosity, incomplete fusion, lack of penetration, weld face irregularities, burn-throughs, weld face and weld root undercuts and metal spatter (Fig. 13–16) [1–19].

To provide the high quality of laser welded joints, particularly as regards robotic welding, it is necessary to apply systems making it possible to monitor the quality of joints on an online basis. The above-named systems utilise sensors recording signals of dynamic changes in physical phenomena present in various joint areas, i.e. keyhole, liquid metal pool of the weld, the cloud of plasma and metal vapours above the keyhole or weld pool, emitting electromagnetic radiation and acoustic waves. Electromagnetic radiation generated in the laser welding area constitutes a source of specific quality-related features of the welding area. The radiation of the laser welding area is composed of ultraviolet radiation, visible radiation, radiation generated by the cloud of plasma and metal vapours,

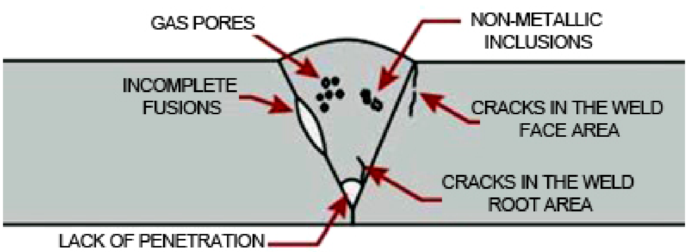


Fig. 14. Typical imperfections in laser welded joints [1, 5, 14–21]

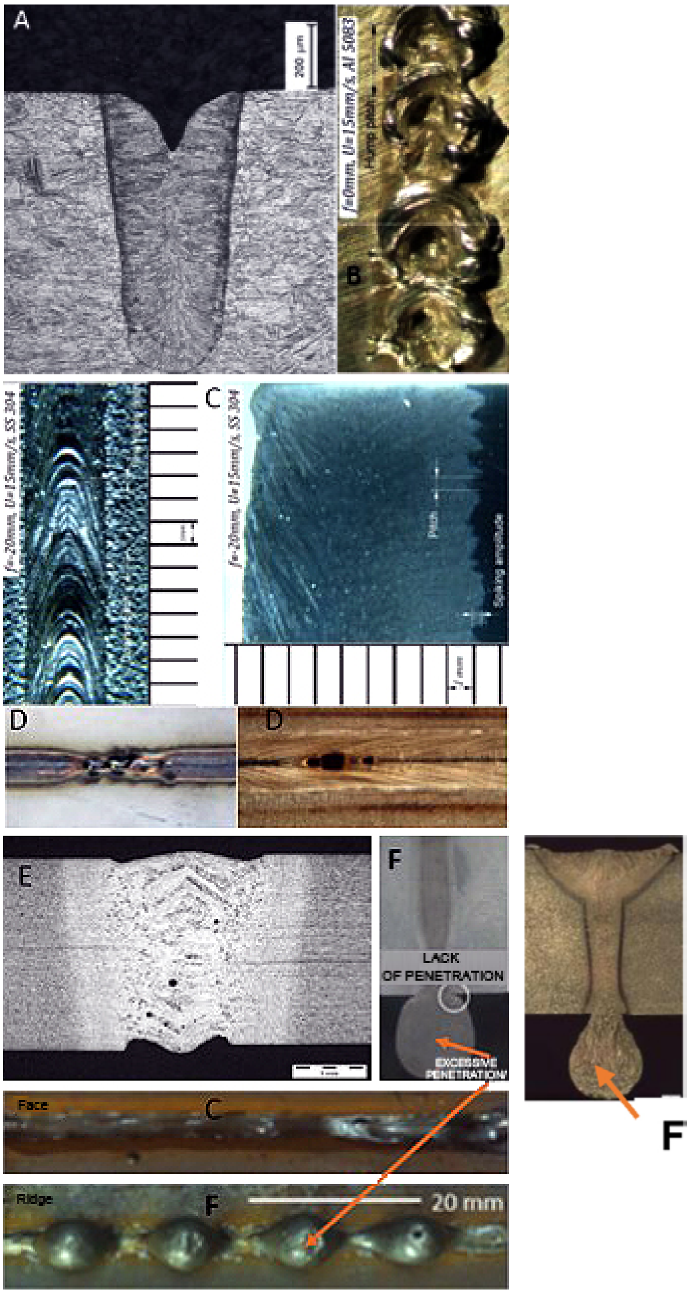


Fig. 15. Typical external imperfections in laser welded joints: A) significant blow-out (weld face concavity), B) metal spatter and significant weld face irregularities, C) weld face irregularities – humping (corrugated excessively large face reinforcement, D) burn-throughs, E) weld face and weld root undercuts, F) significant excessive penetration of the weld metal in the root of the joint and the lack of penetration in the weld root [1–5, 17]

the emission of laser radiation reflected against the welding area as well as thermal (infrared) radiation (Fig. 1).

Monitoring systems connected to laser heads, equipped with systems of photodiode and optical sensors, spectrometers, pyrometers, plasma cloud electric charge sensors or acoustic sensors, providing significant amounts of data in the form of signals or images of laser welding areas and integrated in adaptive control systems involving the use of artificial intelligence, neural networks and fuzzy logic make it possible to control the quality of welded joints on an online basis [3, 4, 15, 17, 19–24].

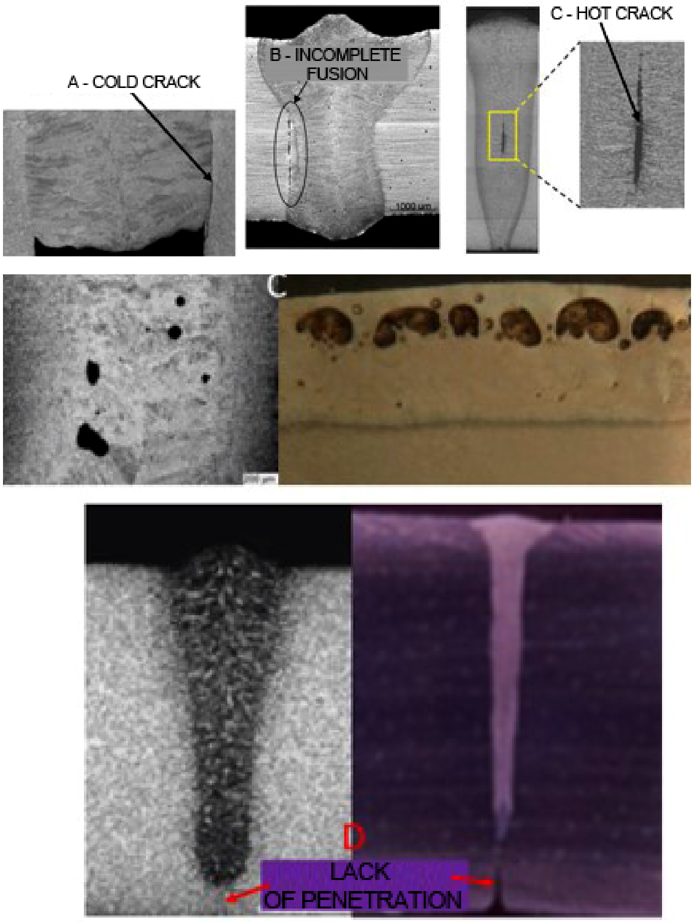


Fig. 16. Typical internal imperfections in laser welded joints: A) cold crack, B) incomplete fusion – lack of fusion with the wall of the joints with square preparation, C) hot crack, D) gas pores in the melted area of the weld and under the weld face, E) lack of penetration [1, 5, 19]

Summary

The global tendency where various industries are implementing increasingly many automated and robotic production (particularly welding) processes, is responsible for the fact that laser welding, characterised by high production efficiency, high quality of welded joints, narrow HAZ as well as minimum welding stresses and strains, is more and more often used in the production of welded structures [1, 4, 6,10, 15]. Laser technology-based production processes are characterised by high flexibility manifested by the possibility of performing simultaneously several processes, including welding, surfacing, alloying, heat treatment or the cutting of structures with laser beams generated by one laser radiation generator. At the same time, it is possible to notice the quick reduction of laser welding equipment-related investment costs and an increase in the power (significantly above 10 kW) of laser generators, particularly those used in the solid-state lasers, i.e. disc, fibre and YAG lasers [1, 4, 9, 10, 15]. As a result, it is possible to perform the fast (at a rate above 1.0–3.0 m/min) keyhole laser welding of butt joints and overlap joints having a thickness exceeding 10.0–15.0 mm. The application of hybrid laser welding techniques heightens the above-named limit above 15.0–20.0 mm [1, 2, 3, 6].

Depending on the thickness of a joint and the type of a material subjected to welding, the small laser beam diameter (required during keyhole welding and amounting to between 10.0 mm and 800 mm) is responsible for the fact that it is necessary to very precisely control the movement of the laser beam along the welding path as well as to ensure very high purity and accuracy when preparing edges of a joint with square butt weld preparation. Each failure to ensure necessary precision may be responsible for the formation of significant internal welding imperfections including weld face irregularities, weld face blow-out, weld face and weld root undercuts, the lack of penetration (Fig. 14 and 15) and, particularly dangerous and poorly detectable, internal imperfections

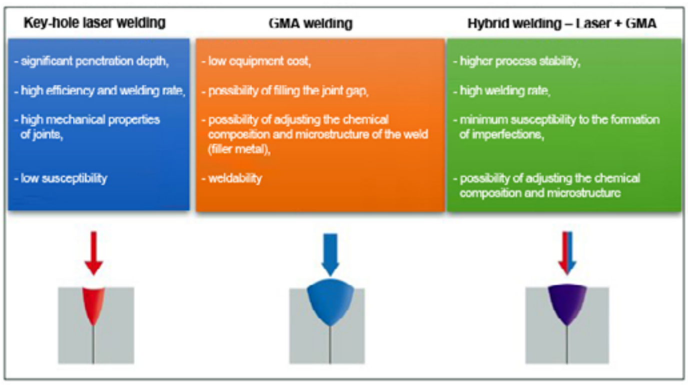


Fig. 17. Comparison of advantages of key-hole laser welding, GMA welding and laser hybrid welding (LHW) – laser + GMA, (Fig. 11) [1]

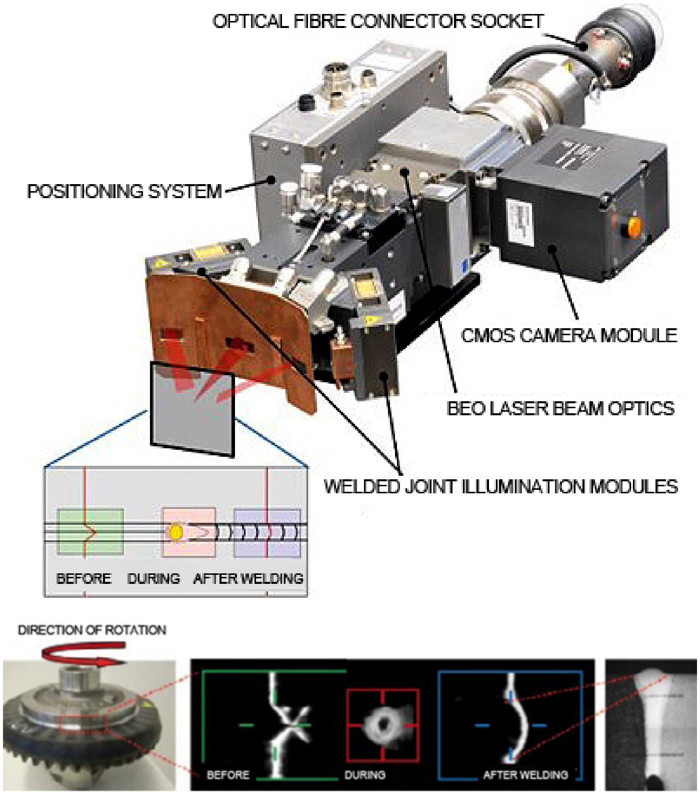


Fig. 18. Laser head equipped with an online monitoring system (SeamLine Pro) containing three optical sensors (NIR camera and two visible radiation cameras) monitoring the quality of joints BEFORE, DURING and AFTER the laser welding process; exemplary application in the welding of a butt joint of the hub and the rim of a toothed wheel; the position of the joint of the hub and the rim is precisely measured in the window concerned with the stage BEFORE welding, the keyhole is monitored DURING welding and the width of the weld face is measured AFTER the completion of the welding process [14]

in the form of internal incomplete fusions (Fig. 16). In turn, because of problematic metallurgical weldability, the improper adjustment of linear welding energy may trigger the formation of hot cracks, usually in the weld metal crystallisation axis or the formation of cold cracks, usually in the fusion area or in the HAZ (Fig. 16). Particularly in cases of butt welded joints having a thickness exceeding 15.0–20.0 mm, the use of hybrid laser welding makes it possible to reduce the requirements connected with the precise control of the laser beam movement along the welding path and the accuracy of pre-weld joint preparation. In addition, through the appropriate adjustment of the chemical composition of the filler metal and the adjustment of laser beam and GMA welding parameters, the hybrid laser welding process enables the control of metallurgical weldability [1, 6]. A technologically advanced solution enabling the obtainment of high-quality laser-welded joints, in terms of the keyhole, melt-in or hybrid laser techniques (already implemented by some laser equipment manufacturers) involves providing the laser head control system and the laser generator with a system tasked with the online monitoring of welded joint quality (Fig. 18) [3, 4, 14, 15, 17, 22–24].

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