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Laser Welding – New Applications in Welding of Pipelines and Rail Vehicles

Abstract: Laser welding and its combination with arc welding processes (laser-GMAW hybrid process) are obtaining an increasing importance for industrial applications. This paper gives an overview about the latest results of the development to qualify the laser welding process for tube welding, pipeline girth welding and welding of rail vehicles. Laser technologies are now available for tube production as well as for pipeline welding. There are technical solutions for production of longitudinal and helical welded tubes. Laser technologies are also applicable for pipeline welding in preproduction and under field conditions. Different procedures have been developed depending on tube diameters and wall thicknesses. The article contains examples of applications in gas and oil transport as well as in water pipeline transport. Laser welding of rail vehicles includes technologies for bogies and car bodies. Dependent on the application laser welding was used as a single process or in combination with GMAW. In the case of laser welding in the production of rail vehicles a close tie with the construction is necessary. The examples used demonstrate that laser welding is a safe technology used in highly sophisticated applications.

Keywords: Laser welding, Laser GMA hybrid welding, girth welding, pipelines, rail vehicles

Introduction

New generations of solid-state technological lasers are characterised by excellent laser beam quality obtained due to the efficient excitation of the laser active elements by means of semiconductor diodes which significantly affects material processing outcome, particularly during welding and cutting. The advantages of a high quality laser beam include nearly parallel weld junctions in the case of welds and parallel cut surfaces making a gap during the cutting process, very flat and almost linear courses of the boundary indicating penetration depth (dependent on welding rate and laser power) as well as the possibility of stronger beam focusing by long-focal-length optical systems making it possible to increase the working distance between the process head and the surface being processed.

Paradoxically, the high quality of a laser radiation beam is, to some extent, a disadvantage, particularly for welding processes, as it poses significantly more restrictive tolerance requirements for structural workpieces as well as for the precision and dynamics of radiation beam transmission systems in technological devices. This requires paying more attention to systems for moving a radiation beam and

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coupling it with a welding arc into a so-called hybrid welding process.

Present State of Laser Joining Technological Implementations in the Manufacture of Rail Vehicles

Laser welding in the production of car bodies [1]

Presently, the industrial production of side and roof sections of rail vehicle car bodies consists in joining pre-fabricated framework structures with sheet segments using resistance spot welding. A laser beam as a tool for making this type of overlap joints is an interesting alternative. The advantages of laser welding are mainly related to the possibility of performing non-contact processing with only one-sided required access to the workpiece. Due to the necessity of obtaining a proper penetration depth in overlap joints for the typical range of sheet thicknesses, the group of welding process parameters defined in initial tests was optimised, first, due to the smallest possible disturbance of the visible joint side, and second, due to the required weld shape. Finally, the welding process parameters were defined by verifying the repeatability and certainty of the process which ensured obtaining the required penetration depth in a specified overlap joint taking into consideration the combination of sheet thicknesses – the upper sheet: 4 mm and the lower sheet: 2 mm.

The implementation of the initial test results was performed on the segments of a complete side wall prepared as for resistance welding in real production conditions. Figure 1 presents a test rig used in the research-related tests. Making laser welded joints in such conditions requires planning the fixing and welding sequence. In doing so, on one hand it is necessary to take into consideration the possibly efficient utilisation of the robot operating area (as each change of the structural element position becomes the source of errors imposing the necessity of updating software and fixing system due to such a change), whilst on the other it is necessary to avoid "frozen gap tolerances", which cannot be compensated even by additional fixing-related labour. For this reason, coming out of an intended starting point S (Fig. 1), two different processing directions X and Y were established. The resultant processing operations (numbered 1–21) are the compromise arising from the boundary conditions specified above.

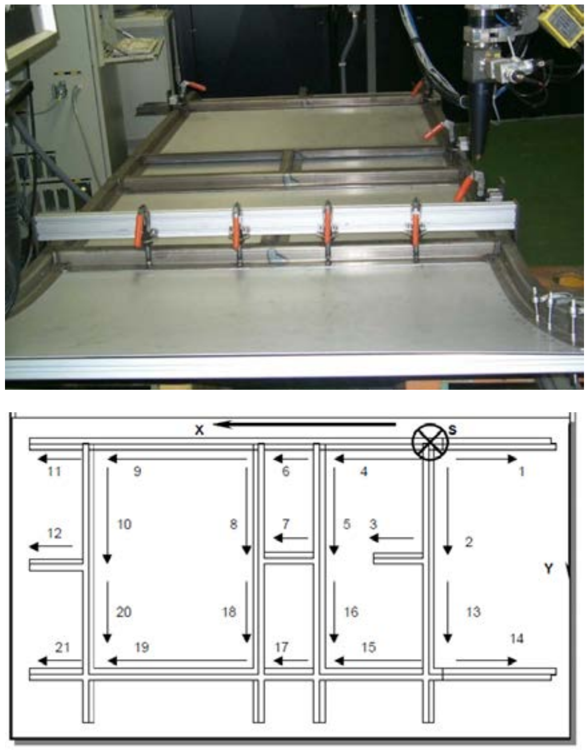


Fig. 1. Test rig and welding sequence on the side wall demonstrator

In order to technically assess the joints, the bent part of the wall segment was sampled for test pieces which next underwent both static and dynamic shear tests. The remaining part of the side wall segment was subjected to material examination carried out on a ready-made structural element. On the segment, in specific places extensometers (strain rosettes) were used in order to determine strains, and thus stresses, under the maximum load of 40 kN (Fig. 2).

It was finally determined that with assumptions related to the fixing system adjusted and optimised for the laser welding process, this

Fig. 2. Station for extensometric measurements of the side wall segment

Fig. 3. Positioning for making the filler weld in the overlap joint and the head for hybrid welding with integrated welding process control sensors

welding method can be used successfully for the production of side walls similar to those subjected to the tests.

Tests of (laser-GMA) hybrid welding of car bogies

Coupling the laser radiation beam with the welding arc has given rise to a welding heat source of new possibilities. The interaction of both heat sources triggers a synergic effect which, to a significant extent, eliminates the disadvantages of welding processes performed using each of the aforesaid heat sources separately. The main economic result of welding a T-joint is obtaining complete penetration without the necessity of bevelling sheet edges, using one-sided welding at a rate of 40-60 cm/min. The maximum thickness of sheets joined using presently available laser welding machines with one-sided access to the joint and a fillet weld thickness a = 5 mm amounts to approximately 10 mm, where the welding rate is limited by the fillet weld thickness and not by laser power.

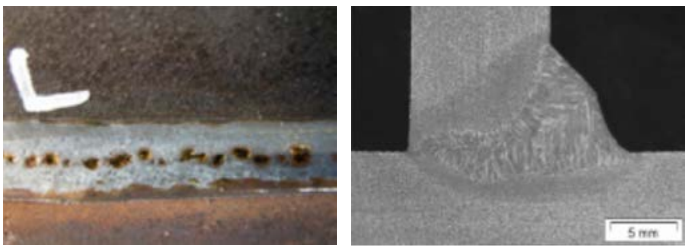
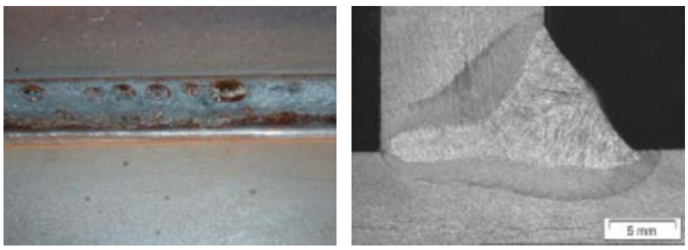
Process heads for Laser-GMA hybrid welding

Adopting the initial tests as the basis, various tooling variants were developed in conjunction with industrial partners. Using the necessary range of movement freedom degrees, the system can be easily adopted for welding various types of joints. An important issue related to the tooling was its integration with sensors monitoring the Laser-GMA hybrid welding process. Figure 3 presents the example of such integration on the basis of various heads for hybrid welding.

The purpose of the tests described below was to adapt the Laser-GMA hybrid welding for the manufacture of selected bogie components with the following assumptions related to the course of the tests:

1. reduction of the number of beads for obtaining full penetration,
2. reduction of the amount of filler metals/welding consumables used,
3. reduction of pre-welding labour.

Table 1 – View of welds for the 10 mm and 12 mm thick sheets

	
t = 10 mm	t = 12 mm

The first stage involved the development of the process parameters for welding 10 mm and 12 thick sheets made of the S355J2G3WC+N steel. The laser beam source was a fibre laser (4.5 kW). The technological test results were documented in the form of the external view of the weld and the cross-sectional macrographic metallographic specimen. Table 1 presents the results for the T-joints of 10 mm and 12 mm thick walls.

Another important test stage involved the investigation of conditions determining the spatial movements of the hybrid welding process head by means of an industrial robot taking into consideration the access and possible collisions with the workpiece.

The project co-partners provided laser-GMA hybrid welded test structural elements. Due to the required positioning accuracy as well as in order to limit preparation-related labour and to reduce structural element tolerances imposed by the production technology, it was necessary to use the possibility of applying a laser sensor controlling the movement of the process head in conditions close to those typical of manufacturing. The interface of workpieces was first traced by a laser sensor fixed on the process head in the proven configuration for the Laser-GMA hybrid welding process with a lead of approximately 25 mm and an inclination angle of 200. All the fixing and adjustment-related works were followed by test welding with the laser beam switched on slightly later. Due to increased light and fume emission during the hybrid welding process the possibility of recognising the interface of workpieces by the sensor was so deteriorated that the precise tracing of the interface could not be ensured. Due to this it was necessary to increase the sensor lead up to 50 mm leaving the same inclination angle. The increase in the sensor lead in relation to the welding area created negative boundary conditions as at the same time the sensor disturbance contour increased and, as a result, tracing the interface gap of a small radius and width was impossible or extremely problematic to perform. Figure 4 presents the test structural element and the sensor-led hybrid head.

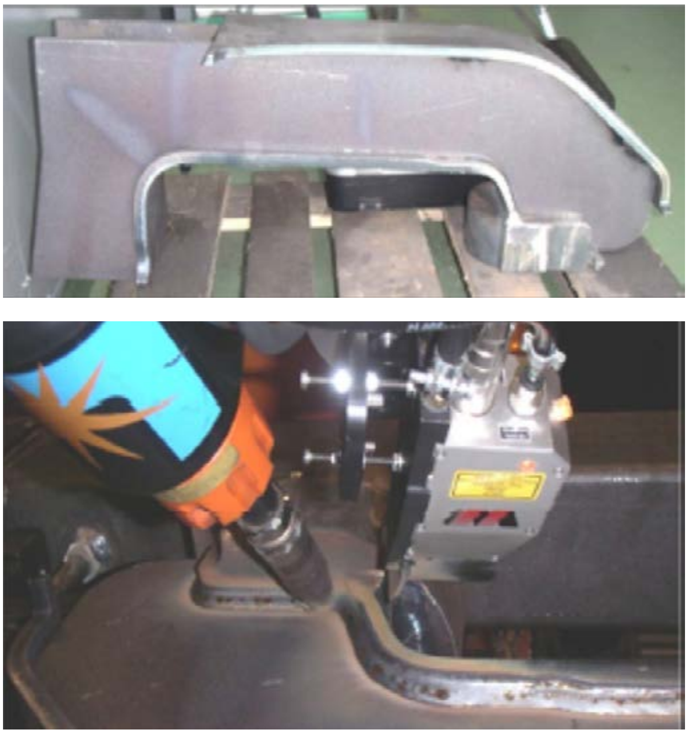


Fig. 4. Test structural element and the hybrid welding head with the sensor

It was ascertained that the very good results obtained in laboratory tests could not be fully obtained during welding of the selected structural units. The reason for this could be the overly low welding laser power (approximately 4.5 kW). The modified heat offtake conditions on the real structural element negatively affected the possibility of obtaining the required penetration depth expected on the basis of sheet welding results obtained during the initial tests. Another aggravating factor was the increased lead of the sensor in relation to the welding area, resulting in significant fluctuations of the laser beam position in relation to the weld, which, particularly in the curved areas, resulted in the formation of unacceptable joints caused by improper positioning.

Laser-GMA hybrid welding of Pipe Joints in Construction Site-like Conditions

Objectives and technological conditions

The objective of the technological and equipment-related tests described below was to use the state-of-the-art related to the Laser-GMA hybrid welding in making pipe joints taking into consideration all necessary aspects present in this case, i.e. tolerances, the influence of surrounding conditions, tooling mobility and welding performed in restricted positions under construction site-like conditions. The mobility-related possibilities of laser equipment have been particularly well demonstrated by fibre lasers of the past five year used, among others, in shipbuilding and pipeline welding [2].

From technological point of view the essence of the tests was the use of the deep penetration effect, typical of laser welding, for making high-quality root runs, with the weld groove height being between 6 and 10 mm. In this case the possible setting variants for the laser beam and welding arc were compared in relation to various methods of the preparation of workpiece edges during the hybrid welding of butt joints. The strategy used for making girth pipe joints involved making two welds on the pipe circumference using the up-down technique. This is a typical technique used in pipeline welding as it reduces the existence of necessary freedom degrees of the laser beam-welding arc system necessary for the optimum weld formation technology. Next, after determining the technological parameters for the hybrid welding of the first bead, the test rig was integrated with the second, i.e. the following MAG welding process. The purpose of this action was to obtain the full cross-section weld for 12 mm thick sheets in one cycle. It was assumed that

a) fibre laser 4.5 kW b) fibre laser 10 kW

Fig. 5. Fibre lasers used in the tests

the MAG process following the hybrid process would positively affect the mechanical-technological properties of the weld.

The laser radiation source was composed of two different fibre lasers. The first test stage, focused on making the first bead for the edge of the joint having the height of up to 6 mm, involved the use of the fibre laser having the output power of 4.5 kW (Fig. 5a), whereas at the second stage the edge having the height of 8 mm was made using the test rig integrated with the laser having the output power of 10 kW (Fig. 5b).

The fibre laser having the power of 4.5 kW and manufactured in 2003 was one of the first of this class of fibre lasers used for welding. It has proved its long-term stability in numerous applications.

In order to obtain the full cross-section of the weld the hybrid welding head was provided with an additional torch for arc welding (Fig. 6a). Due to this it became possible to make the full cross-section of the pipe girth

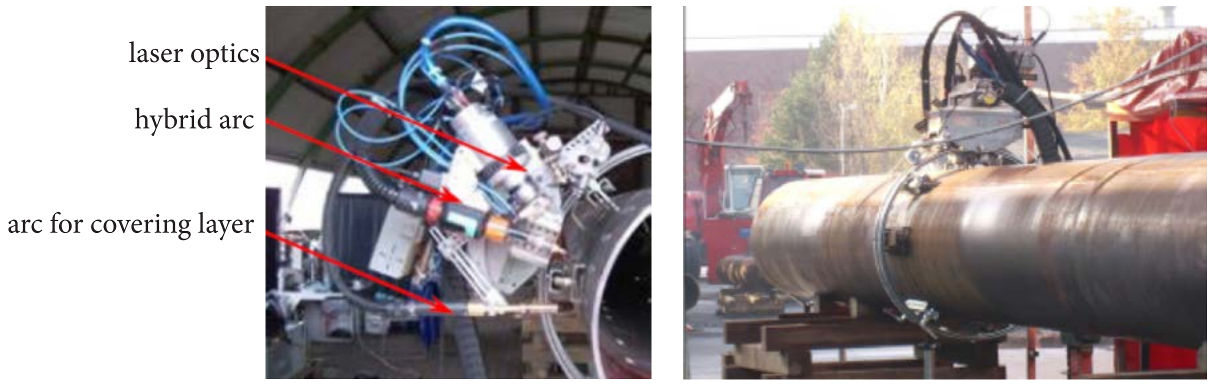


Fig. 6. Hybrid welding head with two arc welding torches (welding of the root and of the weld covering layer) and the whole test rig on the pipe

weld by means of two welds made using the up-down technique. By integrating the units described above the complete test rig presented in 6b was made.

Welding was performed on 6-meter long pipe sections. In this case the required pipe tolerances if compared with a pipe with calibrated ends are higher particularly in relation to the quality and thus the joggle of pipe edges.

Technological test results

As mentioned above, the tests were conducted using two laser beam sources of various powers. At the first stage the fibre laser was used for carrying out a number of basic tests in order to define the hybrid welding output parameters and to determine the range of tolerances for pipe edge position changes with the ever-changing position of pipe girth welding which can be tolerated by the hybrid process.

The second stage of the tests aimed to assess the hybrid welding potential for a higher power laser and the increase in the edge height for a root run from 6 mm to 8 mm. In this case a fibre laser having a power of 10 kW was used. The stage finished with the determination of hardness in the weld root area as this area can reveal slight hardening (partial martensitic transformation) susceptibility due to obvious dependence on the laser beam used for making the root run. The comparison involved hybrid welded root runs and full cross-section welds made with the additional covering run using the welding arc. The results are presented in Figure 7.

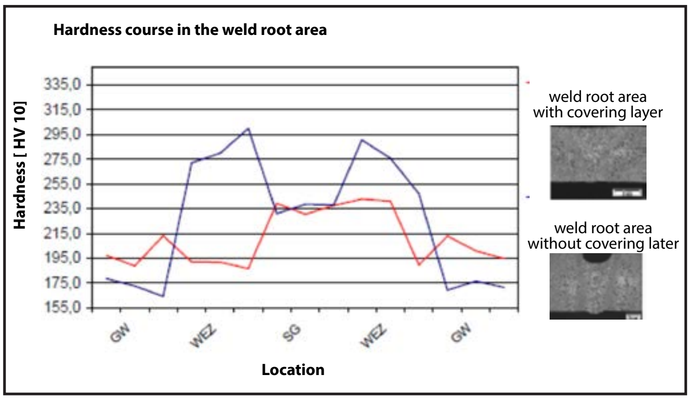


Fig. 7. Effect of the final welding arc on hardness courses GW = parent metal, WEZ = HAZ, SG = weld

An important objective of the tests was to define the typical tolerances used in pipeline welding and to determine the effect of these tolerances on the possibility of applying the hybrid welding process. In order to determine the real situation for all the weld groove edges it was necessary to measure the pipe wall thickness, edge height, edge gap, gap width (on the joint) and the joggle of pipe edges.

The quality of welds was assessed in destructive and non-destructive tests. Previously, the pipe segment underwent ultrasonic examination (phased-array technique) and radiographic tests. The purpose of these tests was to determine the possibility of detecting internal imperfections by means of NDT in order to compare them with real imperfections, their size and location, determined by means of metallographic examination. The data obtained were used to develop various graphs in order to demonstrate extreme points and compare them directly with the welding results as well as with previously established tolerance-related requirements.

Further technological and equipment-related tests

The objective of the tests presented was to verify the technology and equipment for hybrid girth welding of pipes taking into consideration the impact of climate [3]. In this way it was possible to obtain important information related to still existing imperfections. The information obtained greatly contributed to the development of equipment design. The following process faults were indicated:

- obtained welding rates were overly low; the target rates should be 3 m/min,
- it is necessary to adjust the laser power to the welding position,
- tooling reassembly for changing direction or position is excessively time consuming and is the source of defects caused by many setting operations,
- present technique with its mechanical properties fails to meet process requirements.

Taking into consideration the conclusions mentioned above it was possible to develop and build an advanced device free from the faults enumerated above. On this basis a special prototype was developed (Fig. 8a), also for further research aimed to implement the girth Laser-GMA hybrid welding of the following properties:

- technological rates:
  - positioning - up to 6 m/min,
  - welding - up to 3 m/min;
- pipe diameters processed - 500 – 700 mm;
- change of welding parameters dependent on the welding position;
- tracing the weld and performing the process according to the weld.

The integrated laser head can be coupled with all fibre solid-state lasers having the power of up to 20 kW. The objective of the tests was to optimise the welding process in relation to pipe wall thicknesses from 10 mm up for various edge heights in the hybrid welding of the root run using a fibre laser having the power of 12 kW, operated since January 2009 at SLV Halle GmbH (Fig. 8b).

Fig. 8. Specialised prototype of a device equipped with the YLS-12000 fibre laser

Specified weld areas were subjected to metallographic tests for the presence of internal imperfections. Typical pipe-related tolerances were taken into consideration in order to enable the determination of performing the process for even higher laser power values and higher welding rates in the case of specified range of pipe tolerances. Figure 9 presents the weld of a 10 mm thick pipe from the welding position corresponding to three o'clock.

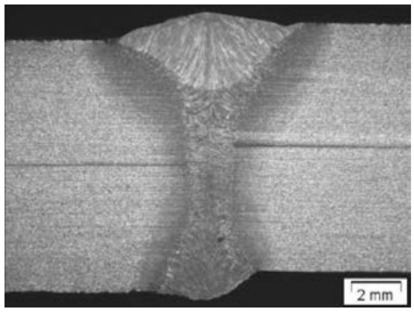


Fig. 9. Macroscopic metallographic specimen of the weld made for 1 mm pipe joggle

Summary and Prospects

The research works presented emphasize two issues related to the technical equipment and the welding technology. First of all, due to the fast development of laser technologies, the operational properties of laser equipment have improved significantly. The range of possible welding-related laser applications has also increased considerably. It can be anticipated that, particularly in the thickness range inclusive of and above 6 mm, hybrid laser welding (coupling a laser beam with an GMA welding arc) will be the only technology enabling the introduction of a high-power and high-quality laser beam to welding processes without compromising the acceptable amount and sizes of welding imperfections.

The works presented show laser beam welding to have entered a wide range of economic applications New laser equipment and technological development open up new application areas with efforts being made to eliminate economic barriers and, in competition with other joining processes, gain a greater market share. The progress in hybrid laser welding technologies is particularly visible, especially as regards solid-state lasers, which due to the possibility of laser beam transmission by means of optical fibres offer almost unlimited freedom of process head movements and, in consequence, improve and facilitate robotic production processes.

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