Applying the Solid State Laser-GMA Hybrid Process for Single-Sided Full Penetration Welding of Bulb Bar Profiles in Shipbuilding

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Abstract:

Being one of the most welding-intensive sectors, shipbuilding is permanently striving for reducing costs, by increasing manufacturing preciseness. The Laser Gas Metal Arc (GMA) Hybrid Welding process supplies technological benefits to achieve this goal. Implementation of solid state lasers greater than 10 kW power is considered the main focus of current global research projects. Also subject of investigation is parent material and consumables. Even though CO_2-lasers are already applied, solid state lasers prove rather new, when it comes to high energy beam process utilisation. Combining the technological advantages of laser and arc is well-known to allow the user for improving quality and rise performance. It is thus the key aim, to employ Laser-GMA Hybrid Welding for single side full penetration joining of bulb bar profiles at high welding speeds. This paper deals with the effort, put in to providing the user with highly advanced process- and system technology.

1. Introduction

In shipbuilding, bulb bar profiles (see Fig. 1) are regularly used to increase stiffness of subassembly- and sectional parts. The average thickness of these profiles, often also referred to as stiffeners, lies between 4.0 and 8.0 mm. As yet, the most widely used joining process is Submerged Arc Welding (SAW). However, great drawbacks can be stated to be overcome. That is e.g. high heat input and low or moderate welding speed, resulting in warpage and distortion. This again may require an undesirable amount of rework, such as flame straightening. The optimal solution in this respect would be using the laser beam process only by its own. But tolerances, arising from preparation and pre-assembling, simply impede applying the laser alone. Laser-GMA Hybrid Welding however, is approved capable of solving the issues. This has already been confirmed industrially by an impressive CO_2 Laser-GMA Hybrid Welding system, installed and used since many years, with the German shipyard MEYER WERFT in Papenburg. Specific restrictions however, arising from the physical principle of CO_2-lasers (beam transmission via mirrors), often allow only for linear profile welding. Robotic applications are – practically – almost impossible. Due to their shorter laser wave lengths (1,03 µm for disc- and 1,07 µm for fibre laser), enabling the beam to be transmitted via a glass fibre cable, solid state lasers are not similarly constrained. This may lead to higher flexibility, also in non-linear welding.

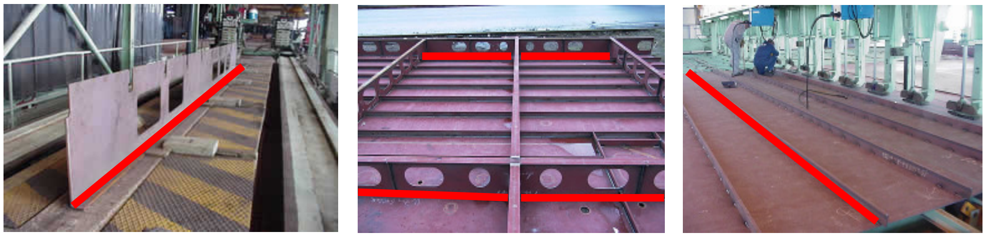


Figure 1: Bulb bar profiles [Rol]

2. CO_2 Laser-GMA Hybrid Welding with *MEYER SHIPYARD PAPENBURG*

A combination of four single 12 kW carbon dioxide Laser-GMA-Hybrid Welding systems, supplying a total power output of 48 kW, forms globally certainly one of the most impressive instances for successful field application. Adjusting GMAW torch and laser beam in distance and inclination angle to each other, leads to the characteristic common weld pool. The equipment is used for steel section prefabrication. These sections, showing dimensions of ≤ 20 m x 20 m, are produced fully automatically, which allows for further reducing operation time and cost. Several assembled steel sections again yield greater components, referred to as 'steel blocks'. Joining these, leads to the final ship hull. Being part of one superimposed automatic fixture- and handling device, Laser-GMA-Hybrid Welding is incorporated as a key process, governing quality and quantity. Panels, side walls and other specific parts (wall thickness 5.0 mm through 15.0 mm) are joined to each other obtaining one section. Both butt- and fillet welds are to be conducted. MEYER SHIPYARD has gained highest reputation with building cruising ships and knowing the extraordinary dimensions of these highly sophisticated constructions (e.g. length ~ 300 m for a modern cruising ship), leads to understand the total length of Laser-GMA-Hybrid welded joints, that is, approx. 400 km.

The applied system proves beneficial due to:

- High welding speed
- Shorter lead time
- Fewer welding systems per section
- Less rework
- No lock plates for bushings
- Increased amount of prefabrication
- Excellent automation capabilities
- Fewer on-board installation joints
- Covering various sheet thickness- and material ranges ("tailored blanks")

Advanced technology is mandatory for producing the sections. One welding station is installed where the assembly takes place – the so-called 'panel line' (Fig. 2). Movable gantries, 20 metres in length and equipped with strong clamps and fixtures, are supplied with the single section parts as a variety of both different parent material grades and thicknesses. Despite the considerable final dimensions optical image processing, connected to the gantry system, permits the positioning to precisely remain within a tolerance range of ± 0.3 mm. This level is possible to be achieved using a high-performance milling head, applied to prepare the joint face prior to welding. That is, the two parts to be joined, are fixed and positioned in a way the milling head can process them simultaneously. Subsequently to machining, the opposing gantries, controlled in motion now to force the parts together, assuring the lowest possible gap to occur, as well as to maintain this condition throughout the whole welding sequence. Different wall thickness, lying within a particular section to be joined, is regular rather than being an exception. Hence, both the welding head's laser and GMA torch are needed to be permanently adjusted one to the other corresponding to the actual joining condition. This requirement is met using a welding head online control, consistently observing the process while in action.

Figure 2: Panel line at MEYER WERFT PAPENBURG [RoI]

As the separate produced '*shell plates*' have passed the assembly line, Laser-GMA Hybrid Welding is finally used to add variously shaped and sized bulb bar profiles in order to increase the part stiffness [MIE, SEY]. Picked up by one CNC roller conveyor, the profiles are first roughly, and then precisely positioned to the welding head using a camera controlled and specifically developed alignment trolley. Single-sided Laser-GMA Hybrid Welding is carried out. Joining complexity requires both welding head and mechanical equipment to be controlled entirely independently from each other. According to [MIE, SEY], up to 27 NC axes can be incorporated controlling the welding head, that is, the GMA welding torch related to the laser beam, and its position in dependence to the actual welding task. It appears understandable 'simple' trolleys to have the capability of significantly improving the degrees of freedom considerably vs. gantry systems. Hence, one of the main goals to achieve, is focused on further simplifying production by developing 'simple' but 'universal' solutions.

3. Laser-GMA Hybrid Welding Heads – Review and State of the Art

As mentioned great amount of effort is put in to industrial laser application research. One of the projects conducted is referred to as '*DockLaser*'. Being an important part of this project a tractor-guided Laser-GMA Hybrid Welding system (Fig. 3), based upon one 4 kW Nd:YAG and 10 kW fibre laser technology, had to be developed. The equipment concept developed by *DockLaser*, foresees a movable base station accommodating a high power solid state laser as well as the appropriate peripheral equipment. This base station is connectable to mobile devices for welding long linear joints, tack welding, as well as for manual welding- and cutting operation in outfitting areas. The maximum distance between base station and tools can reach up to 50 metres which gives sufficient flexibility for an efficient application in assembling large structures.

Solid state Laser-GMA Hybrid Welding was required to replace double-sided SAW, applied on site as yet achieving partial penetration joints. Additionally the bulb bar profiles were required to be single-sided-, but, due to crevice corrosion reasons, full penetration fillet welded as a regular Tee-joint. In other words, the weld metal, penetrating the material cross section, beneficially allows for 'sealing' the opposite root side.

The focus of the first project phase was laid on the establishment and evaluation of end-user requirements as well as on the definition of welding parameters in laboratory tests. As a next step, the integration of the equipment components has been done. Further on welding test has been carried out in the involved shipyards [Doc].

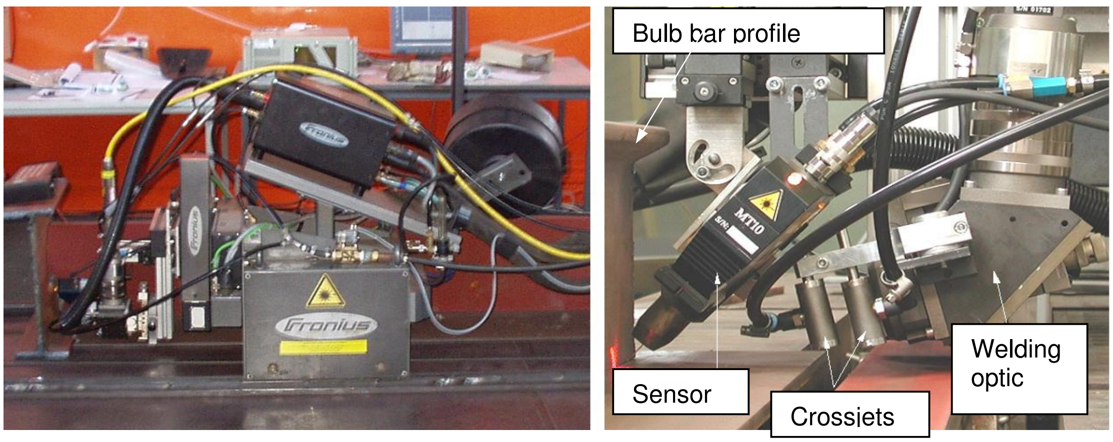


Figure 3: Tractor-guided Laser-GMA Hybrid Welding system (left); Laser-GMA Hybrid welding head (right)

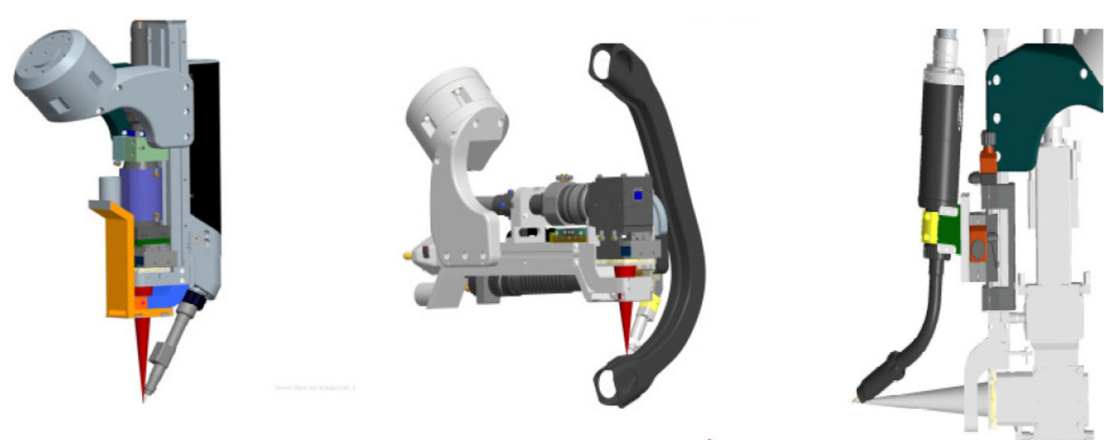
Figure 4 (A through C) shows three different FRONIUS developed Laser-GMA Hybrid welding heads, applicable for solid-state lasers ≤ 10 kW.

Type A: Considerable the first commercial Laser-GMA Hybrid welding head, developed mainly for butt welds, as well as for partial penetration fillet welds. The unfitting adjustment angle between laser beam and horizontal plate impedes bulb bar single-sided full penetration welding. That is, laser optics and GMA welding torch, lying in the same dimensional plane, prevent setting the laser beam incidence to 12° and the GMAW torch at 35° - 40°, necessary basically to fully penetrate the workpiece.

Type B: Accessibility reasons were the main driving force to make the laser beam incidence separately adjustable from the welding torch to 10° through 14°, leading thus to obtain type 'B'. Achieving an electrical current load of 250 A (100% duty cycle) and including beneficial features, such as wire guidance and wire straightener, allows the head to be industrially employed particularly within the automotive industry, e.g. for welding car axle carriers (see Fig. 4 B). Appropriately adapting a GMA welding torch of 300 mm in length (350 A at 100 % duty cycle) and simultaneously increasing the focal length enables this head to be exceptionally also applied to single-sided bulb bar welding. However, the geometrical arrangement of laser beam and GMA torch, situated in the same orthogonal plane relatively to the welding direction, needs to be well recalled.

Type C: The latter to overcome was the cause creating the type 'C' welding head, excellently suitable for the shipbuilding application discussed. In order to fully cover the specific bulb bar welding conditions it was found optimal to adjust the welding torch 30° backhand relative to the workpiece. Hence, the weld bead, GMAW deposited, is followed by the laser beam which fully penetrates the stiffener profile. Type 'C' is capable of processing wire electrodes of 1.0 mm through 1.6 mm in diameter, differently to type 'B', being able to only operate ø 1.0 mm based upon the highly precise wire guidance and straightener system. Also as a beneficial addendum the 'C' type is produced adaptable with a second GMA torch to significantly reducing operation time. This due to both welding directions may be covered without returning the welding head to its original starting position. Unneeded to mention actually, however, the wire electrode tip is exactly adjustable within all Cartesian directions, for achieving the widest extent of process stability and reproducibility.

A B C



Focal length:	200 – 300 mm
Current load:	250 - 350A 100%
Laser power:	4 - 10 KW
Focal diameter:	0.45 - 0.9 mm

Figure 4: Laser-GMA Hybrid welding heads for solid state lasers rated up to 10 kW

4. Applicability Test – Experimental Setup

Laboratory applicability trials were conducted. The system consisted of one FRONIUS TPS 5000 GMAW inverter power source (360 A / 100% duty cycle) connected to an 8 kW solid state disc laser (*TRUMPF 'TruDisc 8002'*). A conventional six axes industrial robot (ABB 4400) was equipped with the new developed Laser-GMA Hybrid welding head, see Fig. 5, for both high reproducibility and flexibility reasons. Laser focal diameter is well-known to play an important part and was also found crucial with the tests conducted. Basically it was considered using an optical fibre (ø 0.3 mm), 200 mm collimation- and 300 mm focal length, for obtaining a 0.45 mm focal diameter. Practical estimations however, involving the regularly given manufacturing tolerance scatter in shipbuilding applications, have led to the final decision to use ø 0.6 mm optical fibre (similar imaging ratio) for obtaining a focal diameter of 0.9 mm. Optimal laser incidence was found 12°. Greater values were found deteriorating process stability and considerably increasing the risk of partial lack of fusion.

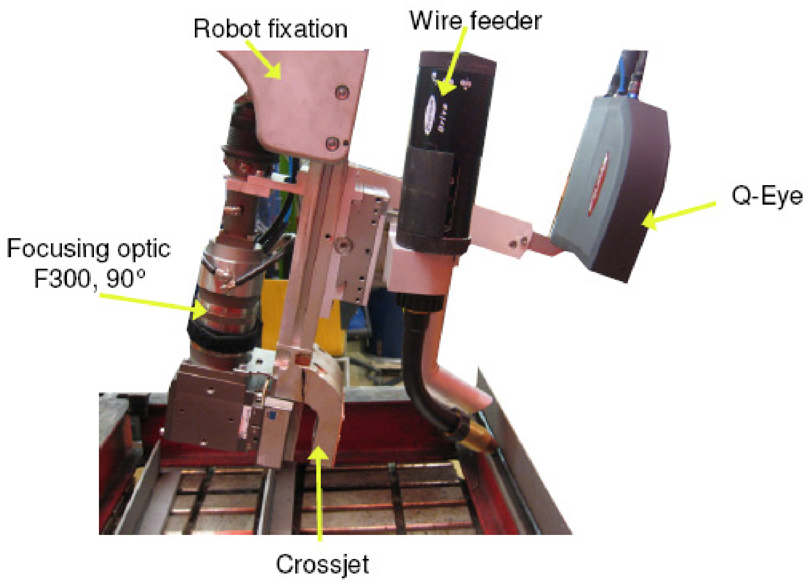
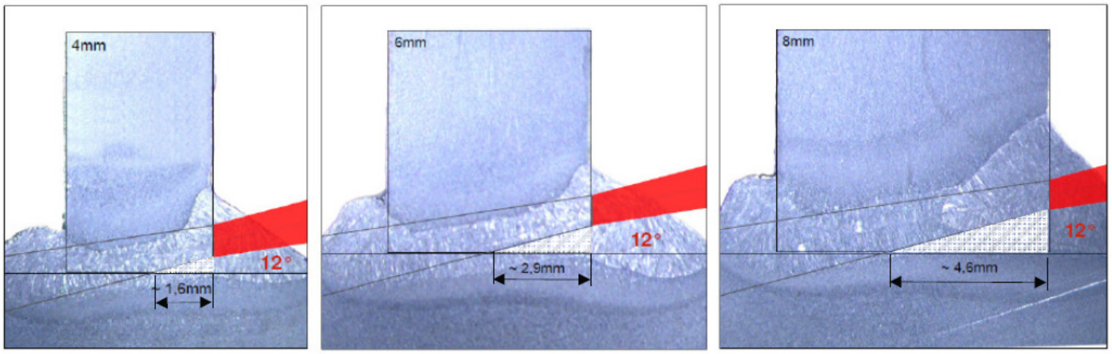


Figure 5: Laboratory set-up of Laser-GMA Hybrid Welding for single-sided full penetration of bulb bar profiles

5. Web Plate Thickness Variation – Measurable Effects

Figure 6 depicts bulb bar macro sections applying 4.0; 6.0 and 8.0 mm stiffener wall thickness. Particular consideration must be given to the brightly marked area within the fusion zone. Depending on the stiffener thickness, at given conditions (see table below the images) this area varies, as the laser beam (focal ø 0.9 mm) proves only restricted (focal diameter, -length and position) for wholly covering the full cross section. The area, representing the unit volume, actually would be needed to be melted by the GMAW process, but could also be reduced expanding the laser beam focal diameter. As well-known however, the latter may reduce both fusion depth and/or welding speed, requiring a rising laser power for compensation. A balanced relationship between laser power, GMAW deposition rate and welding speed is necessary thus, to be established and maintained throughout the welding sequence.

According to this, it is recognisable from Fig. 6 the GMAW power decreases as the stiffener thickness increases. The welding speed however, can be seen to decrease, correspondingly.



Thickness [mm]	4 / 12	6 / 12	8 / 12
Welding speed [m/min]	2.0	1,5	1.0
Wire feed speed [m/min]	7,5	6,5	5,5
Current [A]	220	200	180
Voltage [V]	19.0	19.0	20.0
Laser power [kW]	7.0	8.0	8.0
Laser incidence [°]	12	12	12
Shielding gas	96 Ar / O2	96 Ar / 4 O2	96 Ar / 4 O2
Gas flow rate [l/min]	20	20	20

Figure 6: Laser GMA Hybrid fillet welding – filler metal G3Si1 (EN 440), ø 1.2 mm and laser incidence of 12°

Figure 7 plots welding- (red solid line) and wire feed speed (blue dashed line) over profile thickness (t_{web}). Although showing a linear relationship welding speed shows one significantly greater inclination (50%) vs. wire feed speed (27%), resulting in greater weld metal volume rates with rising wall thickness.

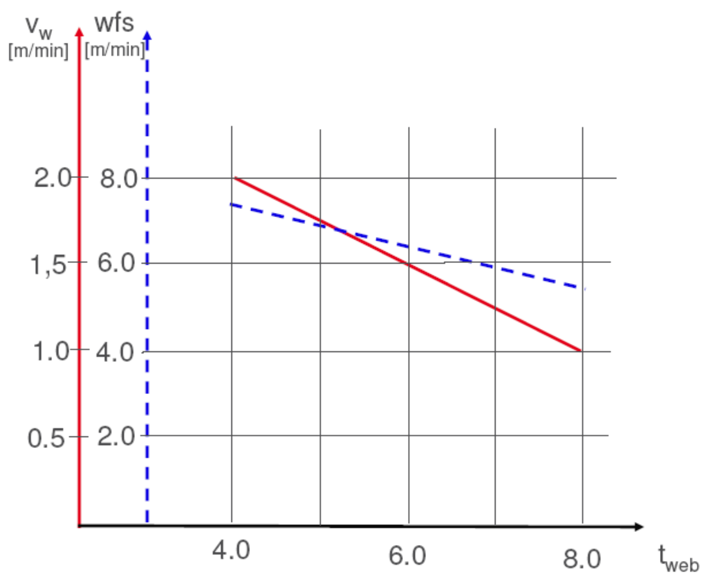
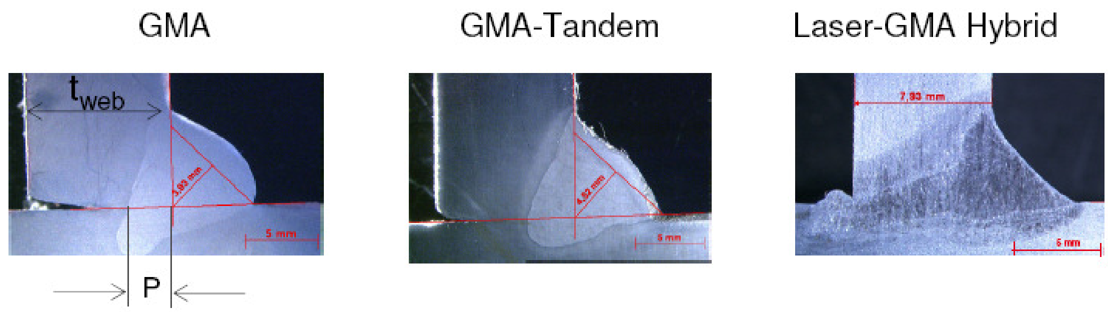


Figure 7: Relation of welding- and wire feed speed vs. web profile thickness

6. Comparing Laser-GMA Hybrid- to Conventional Welding Processes

In order to understand process performance data, it was decided to additionally incorporate a comparative analysis of Laser-GMA Hybrid Welding versus single- and tandem wire GMAW into this investigation. Figure 8 represents single-sided welded Tee-joint macro sections. Showing adequate penetration '*P*' into the web plate (t_{web} = 8.0 mm), i.e. ~ 28% with single- and ~ 35% with tandem wire GMAW, the open arc processes operate at lower or appropriate high welding speed (v_w). That is, 0.6 m/min for single- and 1.2 m/min for tandem wire GMAW, respectively. Understandably heat input (*Q*) shows higher values for single wire GMAW (1.04 kJ/mm), reducible applying tandem wire GMAW (0.84 kJ/mm). Full penetration however, meeting thereby explicitly one of the main requirements, with simultaneously lowest heat input (lowest distortion) and adequate welding speeds, could be obtained whereas applying Laser-GMA Hybrid Welding.



	GMA	GMA-Tandem	Laser-GMA Hybrid
v_w:	0.6 m/min	1.2 m/min	1.0 m/min
Q:	1.04 kJ/mm	0.84 kJ/mm	0.74 kJ/mm

Figure 8: Fillet weld penetration ratio applying different welding processes

Primer coatings are a permanent subject to deal with in shipbuilding. Considering this fact, both primer- and non-primer coated parts were welded. It was found high amount of spatter- and fume generation with all processes, degrading their stability. Removing primer coatings from, and adjacent to, the joint area prior to welding appears thus stringently recommended.

7. Hardness profiles

Figure 9 shows hardness lines and welding parameters on a section of AH 36 structural shipbuilding steel. Filler metal was G3 Si 1 according to EN 440 (ø 1.2 mm). Maximum hardness in the weld seam was 380 HV10, and measured in all three cases on the fusion line adjacent to the thicker material (girth plate). Depending on the code requirements this may exceed however, the parent material maximum hardness values. Hardness line 1 was captured two (2) millimetres into the stiffener profile and no considerable difference could be found between the three (3) hardness lines taken. It can be seen whereas, the hardness gradient within the stiffener profile (t = 6.0 mm) proves shallower vs. the 12.0 mm girth plate. This is suggested to arise from higher cooling rates into the thicker girth plate, which was, however, no further subject of this investigation.

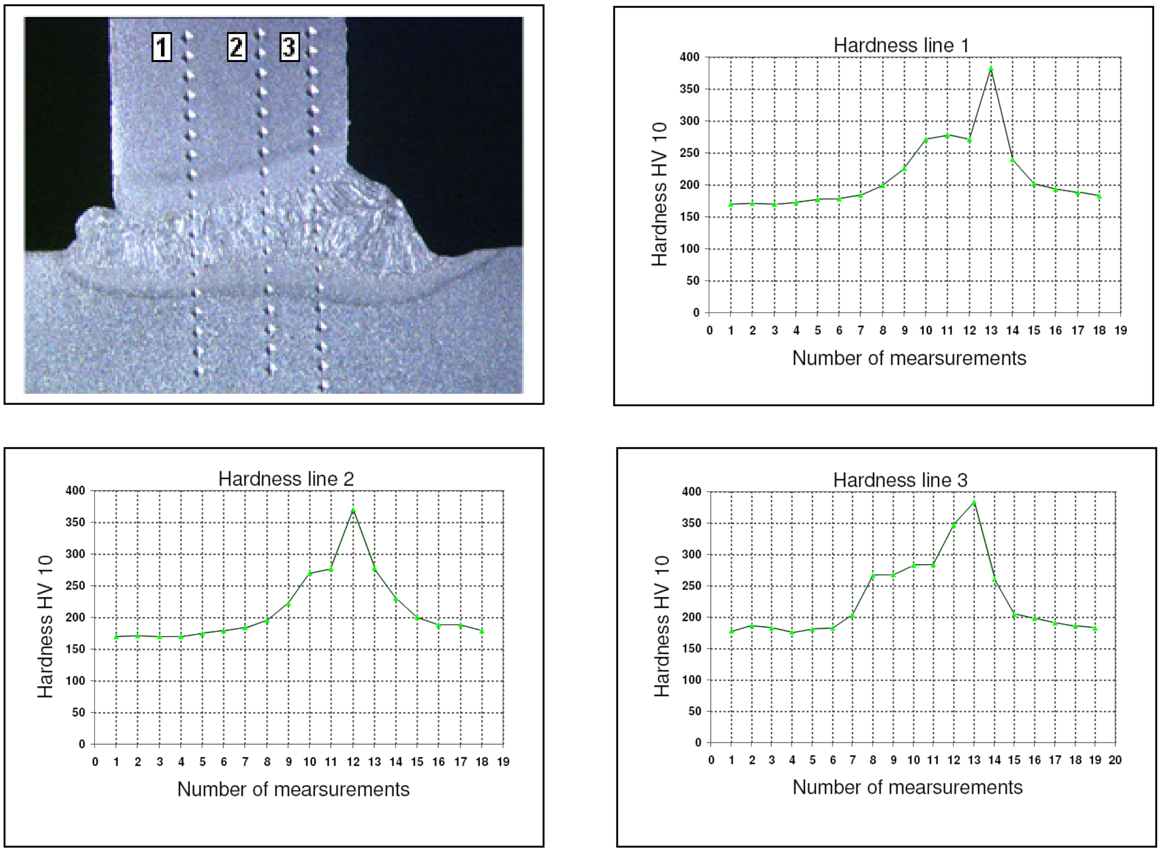


Figure 9: Hardness lines for single-sided fillet weld: indentations (top left); line 1 (top right); line 2 (bottom left); line 3 (bottom right); experimental data (table below)

Thickness [mm]	6.0 / 12.0
Welding speed [m/min]	1.5
Wire feed speed [m/min]	6.5
Welding current [A]	200
Arc voltage [V]	19.0
Laser power [kW]	8
Shielding gas (EN 439)	96 Ar / 4 O_2
Filler wire (EN 440)	G3 Si 1
Preheating temperature [°C]	-
Parent material grade (ASTM A 131M)	AH 36

8. Weld Pool Observation applying '*Q-Eye*'

Laser beam wavelengths are known capable of damaging particularly the human eye, and, according to EN 60825 (part 1-5), it is not permitted remaining in the welding cell throughout processing. Weld pool monitoring provides an approach to transfer both essential parameters and visual images to an operator situated outside the cell, preventing thereby any hazardous affects [FRO]. Different methods are known meanwhile to be applicable. One of which, a stroboscopic camera system referred to as '*Q-Eye*', was also incorporated into this investigation and shall be described hereafter. Both camera and illumination are energy supplied via an especially developed high-voltage device. A conduit, connecting device and camera, installed next to the welding head, transmits energy, process data and cooling air. A second data lead, connected to one personal computer allows for data transfer and visualisation. Utilising Ethernet, the data may be also distributed across further connected personal computers. Data acquisition is begun and finished switching a simple "Arc-On/Off" signal, routed either via the welding power supply's internal 'LocalNet'-RS 232 or 'LocalNet'-Ethernet interface. Optical images and weld data, after real time transmission, are stored upon the PC hard drive memory and can be analysed until the next weld sequence begins. Even though technically possible, the amount of captured data may prove exceeding; it is recommended rather to avoid their permanent storage. Welding current, arc voltage and wire feed speed are captured each 100 ms in order to compute their arithmetical average value. Weld pool visualisation additionally allows the operator to react upon any process irregularities, by introducing corrective means. Figure 10 schematically represents the '*Q-Eye*' application e.g. to observing the weldments' rear side. Showing image 'A' and 'C' of Fig. 10 not complying with the required penetration requirements (deviation in z-axis direction), image 'B' whereas meets the given demands. Allowing the operator to currently correct these deviations just manually, it is future planned to implement these corrections automatically connecting adaptive control to mechanical means.

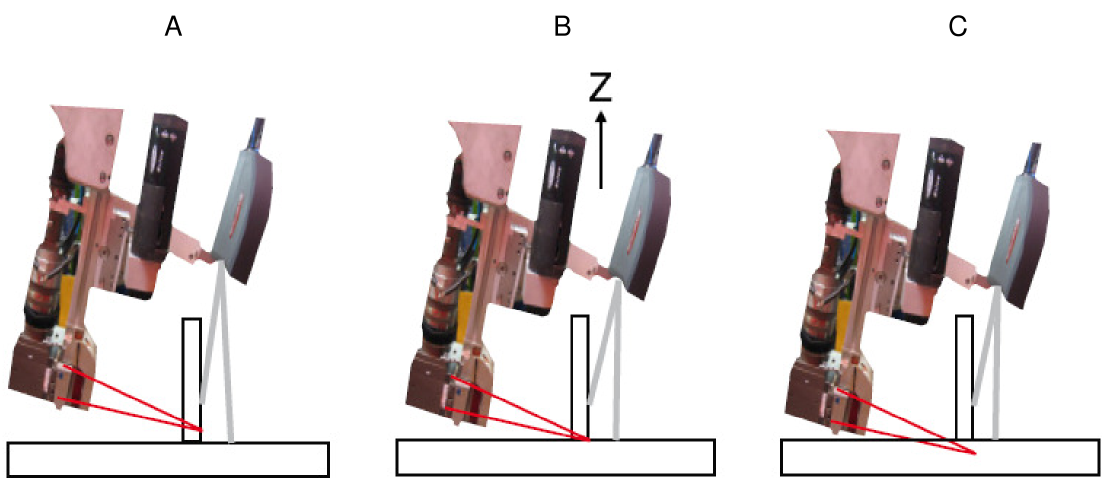


Figure 10: Schematic '*Q-Eye*' application for root side observation

Summary

A specific shipyard welding application, i.e. joining bulb bars as stiffener profiles to web plates, was described in this paper. The usually employed Submerged Arc partial penetration welding often leads to undesirable drawbacks such as distortion and warpage, necessary to be exceedingly reworked by e.g. flame straightening. This generates additional cost. An approach for both reducing cost and improving quality is to use solid state Laser-GMA Hybrid Welding, capable of covering the whole range of joints to be carried out. International research activities such as the '*DockLaser*' project focus on developing and investigating tailored manufacturing components to be employed in shipbuilding. The hybrid welding head is estimated a crucial key for successful implementation of high power (≤ 10 kW) solid state Laser-GMA Hybrid Welding. Three commercially available welding heads were reviewed and discussed. It could be shown that incorporating the special shipbuilding considerations into the development process can finally lead to a tailored product, capable of fully meeting the particular requirements. Practical welding trials implementing original structural shipbuilding steel grades and parts, could prove the solid state Laser-GMA Hybrid Welding process able to supply both highly reproducible results and high quality output. Hence, solid state Laser-GMA Hybrid Welding employing highly advanced hybrid welding heads is considered cost reducing and an efficient and quality improving alternative to SAW.

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