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Investigation into feasibility of hybrid laser-GMAW process for welding high strength quenched and tempered steel

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In this study, the feasibility of hybrid laser-gas metal arc welding process for replacement of conventional flux-cored arc welding procedure for welding high strength quenched and tempered steel was investigated. Experimental work focused on optimisation of process parameters to produce joint with desired properties. Hardness of the weld heat affected zone produced by both processes has been measured. Productivity and cost effectiveness of both processes were compared. It was concluded that hybrid laser-gas metal arc welding process is suitable for welding high strength quenched and tempered steel.

Keywords

strength, quenched, steel, high, tempered, welding, investigation, into, feasibility, hybrid, laser, gmaw, process

Disciplines

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Abstract

In this study, the feasibility of hybrid laser-gas metal arc welding process for replacement of conventional flux-cored arc welding procedure for welding high strength quenched and tempered steel was investigated. Experimental work focused on optimisation of process parameters to produce joint with desired properties. Hardness of the weld heat affected zone produced by both processes has been measured. Productivity and cost effectiveness of both processes were compared. It was concluded that hybrid laser-gas metal arc welding process is suitable for welding high strength quenched and tempered steel.

KEYWORDS: high strength quenched and tempered steel, flux-cored arc welding, hybrid laser-gas metal arc welding, heat affected zone, productivity.

INTRODUCTION

In manufacturing of heavy high strength steel structures innovative approaches are essential to satisfy the continuous drive to deliver improved quality and productivity outputs at a lower cost. To ensure better product performance and weight to strength ratio the manufacturer of quenched and tempered (Q&T) plate recently adopted novel improved alloy design. Another area of possible improvement is the welding process.

The chemistry and heat treatment of high strength Q&T steels are designed to deliver optimum properties, thus any microstructural changes during fabrication are undesirable. However, when steel is subjected to welding, the area surrounding the weld pool, known as the heat affected zone (HAZ), undergoes complex thermal cycles which alter original microstructure of the material. The extent and characteristics of these changes depend on nature and number of thermal cycles experienced, and may lead to such undesired effects such as HAZ softening (or hardening) and hydrogen assisted cold cracking (HACC). To preserve original properties of the steel plate, it is beneficial to employ welding procedures with optimised heat inputs and if possible, minimum number of weld passes.

Flux-cored arc welding (FCAW) is a widely used fabrication technique for joining high strength Q&T steel plates. The disadvantage of using flux-cored wires is that in multi-pass welding the slag formed on the surface of the bead needs to be removed before deposition of subsequent passes, this is ineffective in terms of both productivity and cost. What is more, the flux also has the potential to pick-up hydrogen from the surrounding atmosphere if the consumable is stored inappropriately or over a long period of time. This hydrogen may be absorbed in the weld pool, increasing the risk of HACC. Welding of thicker plates almost always requires multiple passes as the FCAW procedure gives relatively low penetration, the seam depth being a function of the heat conduction [1]. Welding of thicker sections with one pass would be possible by employing slower welding speeds, but this would result in even higher heat input and inadmissibly wide and soft HAZ.

The required deep penetration could be achieved by using the laser welding process. However, laser welding alone is not the most suitable option for welding of high strength Q&T steels in a production environment. Whilst it is a high productivity low heat input process, it produces narrow heat affected zones and steep spatial and temporal temperature gradients that often result in brittle microstructures susceptible to HACC. Laser welding also produces welds with a high ratio between welding depth and seam width. It consequently results in a slim weld seam and a poor gap bridging capability [2,3]. Due to this phenomenon, laser beam welding requires high precision during edge preparation and set-up.

Hybrid laser-gas metal arc welding (GMAW) which utilises synergy between laser beam and welding arc has the potential to offer the ideal solution for welding high strength Q&T steels. It couples the benefits and largely overcomes the disadvantages of the two individual processes [4]. During hybrid laser-GMAW process a smaller weld pool is formed in comparison with the FCAW technique. This results in lower heat input and consequently a narrower HAZ. The HAZ hardness of laser welded area (in laser welding alone possesses high hardness and has increased susceptibility to HACC) is tempered by subsequent GMAW pass [3]. The HAZ properties can be further improved by reduction of weld passes what would also lead to significant time and cost savings. Additionally, hybrid laser-GMAW process in utilises solid austenitic stainless steel consumable that according to data from weld hydrogen testing [5] results in zero weld diffusible hydrogen content, practically ruling out the risk of HACC, common defect experienced when welding high strength Q&T steels.

A comparison of weld seam geometries is shown for laser, laser hybrid and GMAW welding in Figure 1. Gao et al. [6] described characteristic laser hybrid weld as a ‘wine-cup’ shape which consists of wider (arc) zone above the narrow (laser) zone. These two zones differ from each other by alloying elements distribution, microstructure, hardness and the width of HAZ. Observed dissimilarities are attributed to the difference of temperature gradient, crystallizing and the effects of arc pressure on the molten pool between laser zone and arc zone.

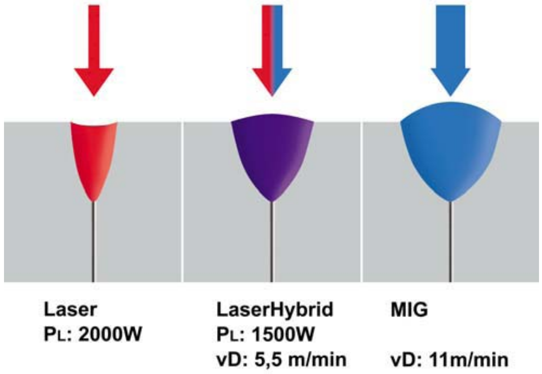

Figure 1 Comparison between the seam geometry of laser, MIG (GMAW) and hybrid laser-GMAW weld seams with the same penetration depth and the same welding speed [3].

Advantages of hybrid laser-GMAW process over currently used FCAW are summarised as follows:

- Reduction of the number of weld passes
- Reduction in the amount of used filler material
- Significantly improved cost effectiveness and production times
- Potential improvement of joint hardness and minimisation of HAZ
- Reduced risk of HACC

To achieve synergy between laser and arc to produce joints with optimal geometry and properties, process parameters such as laser to wire distance, welding and wire feed speed, welding torch angle have to be carefully selected. Work presented in this paper details the findings of feasibility testing and direction for future work to optimise and develop the hybrid laser-GMAW process for future replacement of currently used FCAW for welding high strength Q&T steel.

EXPERIMENTAL

Experimental equipment

This experimental work was completed using the robot controlled GMAW process to produce inner pass and hybrid laser-GMAW test bed to deposit outside cap pass. Hybrid laser-GMAW test bed utilises a 3kW diode laser power source, a GMAW power source and wire feeder, and a lathe bed capable of motion in 2 degrees of freedom. Lathe provides precise positioning system and movement of work piece during welding. A picture of the test bed is shown in Figure 2.

The laser beam is delivered through an optical fibre into a 50mm collimator and a 200mm lens. Significant practical advantage of utilising diode laser in combination with optic fibre is ability to easily position and move the laser torch making it ideal candidate for industrial use and automation.

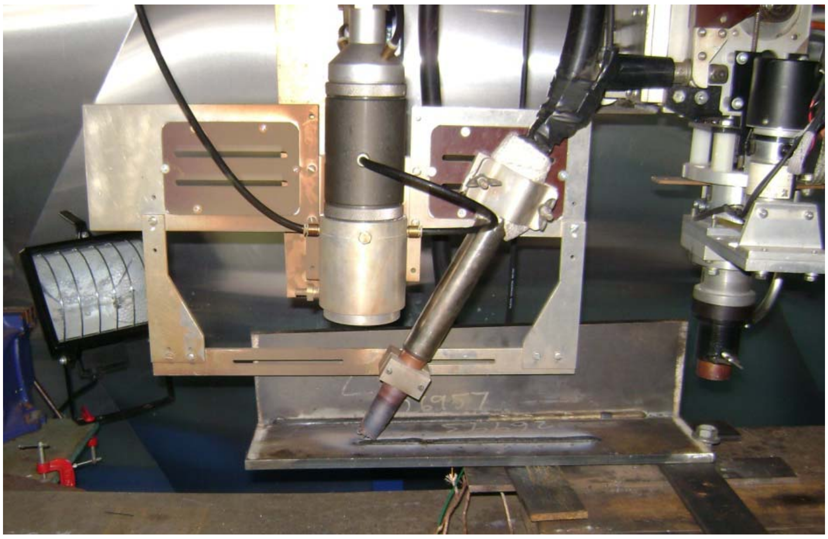

Figure 2 Hybrid laser-GMAW set-up.

Ideal Joint Geometry

The target of this work is to develop the hybrid laser-GMAW process to produce joints with geometry as shown in Figure 3.

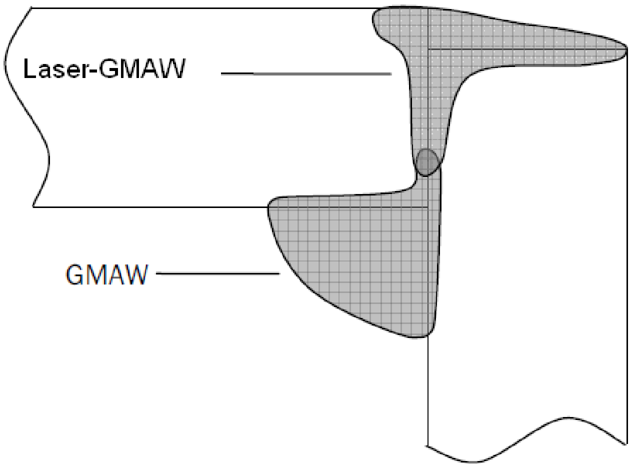

Figure 3 Ideal geometry of the hybrid Laser-GMAW joint.

Weld test sections were prepared by tacking 300x100x8.5 high strength Q&T test plates, with the specified geometry parameters, on the inside corner. It is to be noted that test plates were sectioned using water jet cutter and no edge preparation was done prior to welding. The inner pass was deposited first followed by the outer cap pass.

Initial testing was conducted to understand the capability and limits of the testing infrastructure. Following work focused on optimisation of process parameters to obtain full penetration and good fusion in the welded joint. Welding parameters common to all trials are presented in Table 1.

Table 1 Parameters common to all welding trials

Welding parameter	**Value**
Laser power	3 kW
Hybrid Laser-GMAW filler material	ø1.2 mm solid austenitic stainless steel wire
Hybrid Laser-GMAW shielding gas	1.5% O_2 in Ar at 20 l/min
Hybrid Laser-GMAW voltage	30 V
Laser focal point	2 mm under plate surface
GMAW filler material	ø1.2 mm solid austenitic stainless steel wire
GMAW shielding gas	1.5% O_2 in Ar at 20 l/min
GMAW voltage	26.3 V
GMAW wire feed speed	9.5 m/min

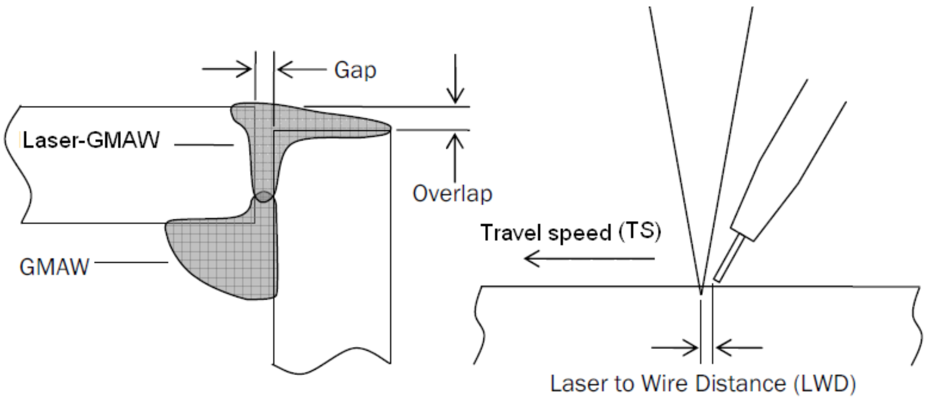

Figure 4 Diagram of experimental parameters.

RESULTS

Gap between plates

During initial testing (Test 1-3, Table 2), it was concluded that 3kW laser does not have sufficient power to achieve required penetration through test plates tacked tight against each other. As a result of that, the gap dividing the test plates was introduced to aid the penetration. Series of trials carried out determined the optimum width of the gap to be 1.5mm. Literature [6] suggests that full penetration of bead-on-plate weld on 7 mm plate of mild steel is possible employing a higher power laser.

Laser to wire distance

Tests 1-3 (Table 2) also revealed that the depth of penetration is significantly affected by varying laser to GMAW wire distance. The best penetration was obtained employing 1mm laser to wire distance. Test 6 (Table 2) indicates that the optimal laser to wire distance will change depending on wire feed speed.

Travel speed

After experimental parameters for geometry with 5 mm overlap were optimised to deliver full penetration the overlap was decreased to 3 mm increasing the thickness to be penetrated. Travel speed affects the overall energy delivered into the weldment. The penetration improved when the travel speed was decreased from 380 to 300 mm/min and Test 9 (Table 2) showed that it is possible to create a hybrid laser-GMAW joint with close to ideal geometry when the travel speed was reduced to 250 mm/min and 1.5mm gap was present between the plates. A macro of the weld cross-section of this trial is shown in Figure 5.

Table 2 Summary of the test parameters subjected to optimisation and obtained results.

Test number	Experimental test parameters					Notes
	Overlap [mm]	Gap [mm]	WFS [m/min]	TS [mm/min]	LWD [mm]	
1	5	0	5	380	**0**	Very poor penetration
2	5	0	5	380	**1**	Improved penetration
3	5	0	5	380	**2**	Very poor penetration
4	5	**1**	5	380	1	Improved penetration
5	5	**1.5**	5	380	1	Full penetration
6	5	1.5	**6**	380	1	Poor penetration
7	**3**	1.5	5	380	1	Insufficient penetration
8	3	1.5	5	**300**	1	Improved penetration
9	3	1.5	5	**250**	1	Satisfactory penetration

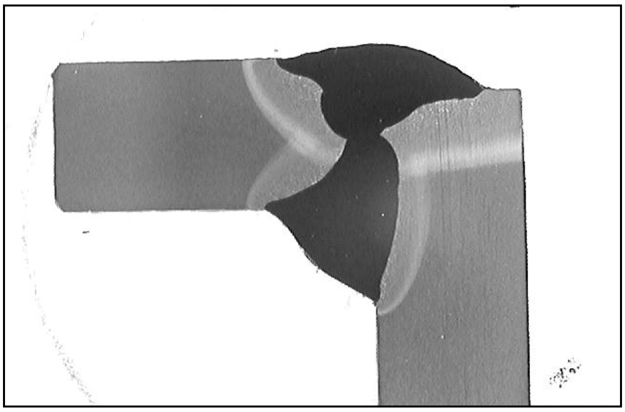

Figure 5 Macro of the weld cross-section produced with parameters detailed in Table 2 – Test 9.

Comparison with current procedure

A comparison between the current FCAW multi-pass and the investigated hybrid laser-GMAW two pass procedure has been made in

Table 3. The time, consumable length, and weld volume has been calculated per one meter of the joint and does not account for preheat time, time needed to remove the slag from the surface of the bead or time waiting to achieve interpass temperature. These values suggest that a 36% decrease in welding time and a 56% decrease in the amount of consumable used would result from using the hybrid laser-GMAW process for deposition of the outer cap pass.

Table 3 Comparison of the time spent in deposition, consumable usage and total wolume of the weld for current FCAW and investigated hybrid laser-GMAW procedure.

Process	Welding time [s]	Consumable usage [m]	Volume of the weld [mm^3][1]
FCAW	608	99.4	95400
Hybrid laser-GMAW	390	43.8	49500
Difference	**218**	**55.6**	**45900**

[1] 85% efficiency for flux-cored wire and 100% efficiency for solid wire were assumed.

Comparison of the HAZ size has also be made. For reference, the cross section of a weld produced with the current FCAW procedure as shown in Figure 6. An outline of the base material, weld material, and HAZ is shown in Figure 7. From the diagrams it can be seen that weld produced with hybrid laser-GMAW has a much smaller HAZ in the base material shown in the vertical direction. This is offset by a larger HAZ in the base material shown in the horizontal direction. The HAZ from the inner passes is of similar size.

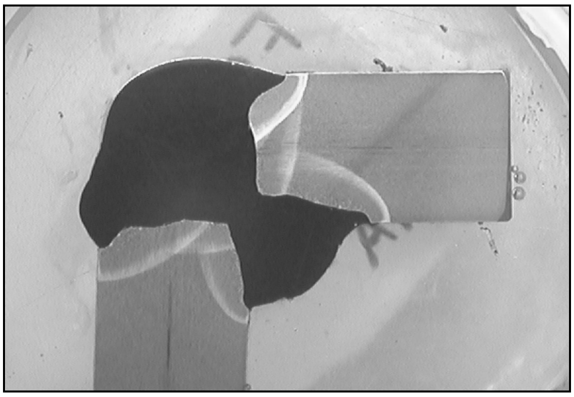

Figure 6 Weld cross-section of the joint produced by current FCAW procedure.

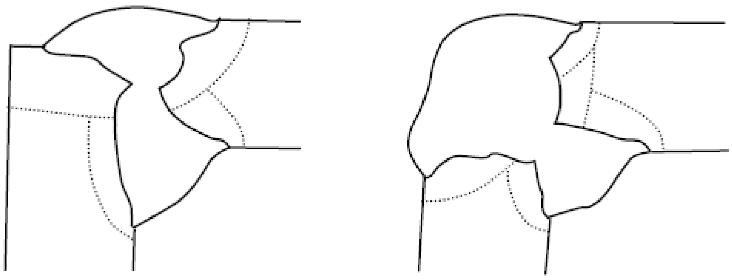

Figure 7 Comparison of weld cross-sections of current FCAW and investigated hybrid laser-GMAW procedures outlining areas of the weld metal and HAZ.

Hardness testing

Hardness of the samples produced with both procedures was measured 2 mm under plate's surface. Figure 8 presents hardness profile of the cap area. It can be seen that the HAZ resulting form hybrid laser-GMAW process was 1 mm wider compared to FCAW procedure. The hardness profiles were almost identical and the the unaffected parent material was distant 12 mm from the fusion line for both procedures. Hardness profiles measured in the area of inner pass are presented in Figure 9. Hardness of the HAZ of both samples is very similar with slightly wider over tempered region produced by GMAW resulting form higher welding current.

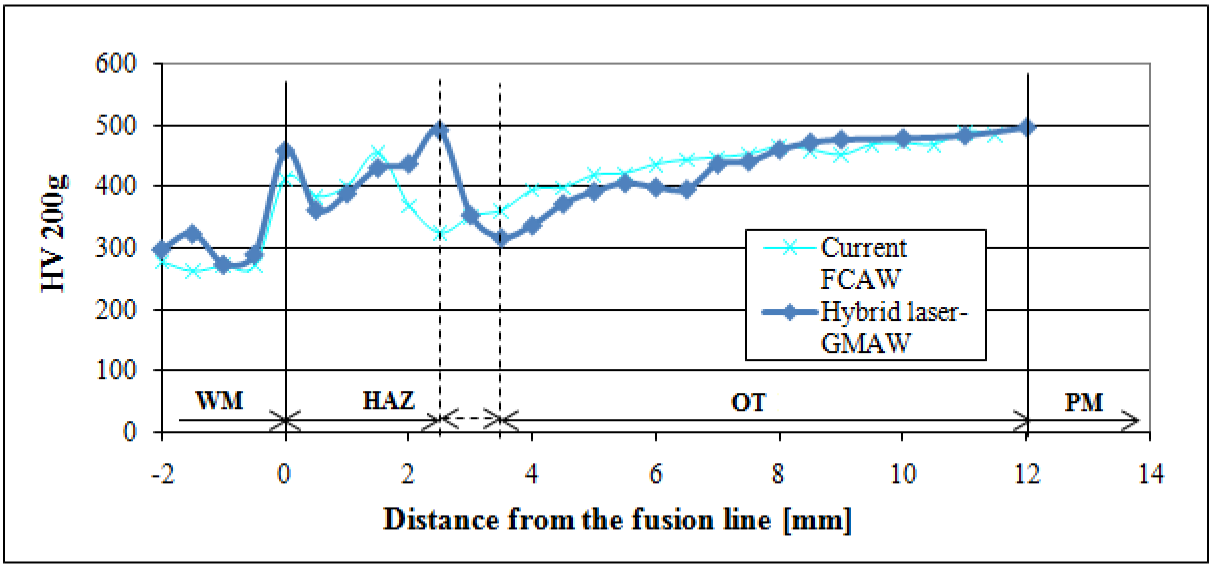

Figure 8 Weld hardness profiles measured on the outer surface of the cap passes.

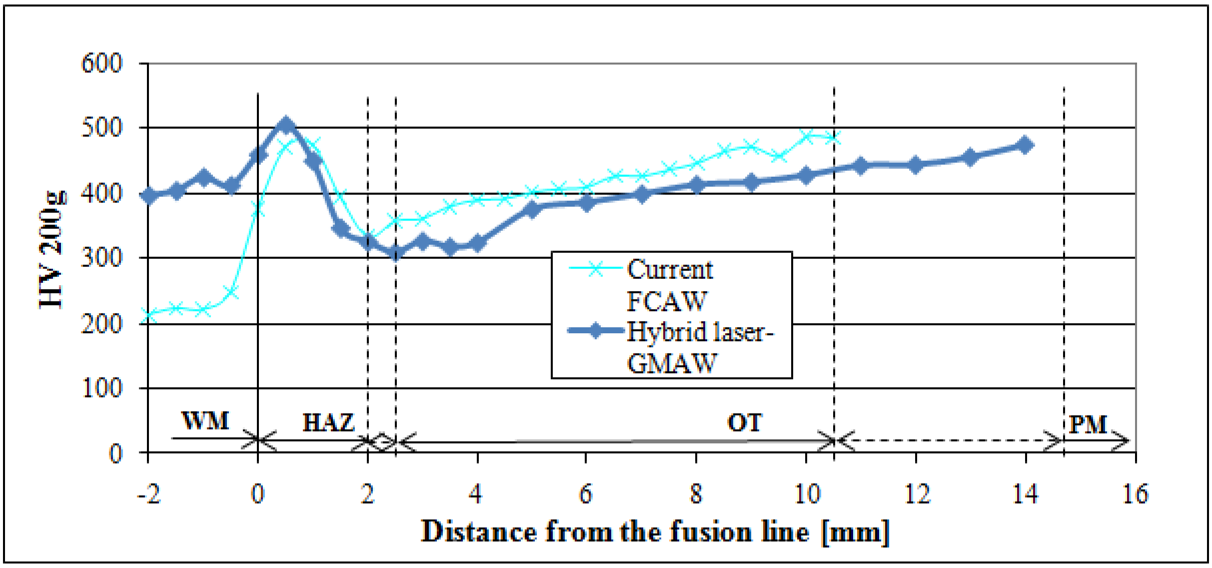

Figure 9 Weld hardness profiles measured on the inner surface of inner pass.

CONCLUSIONS AND RECOMMENDATIONS

Feasibility testing of hybrid laser-GMAW process on high strength Q&T plate has been conducted and the following conclusions have been made:

1. It is possible to produce a hybrid laser-GMAW on high strength Q&T plate at close to the ideal geometry using a 3 kW diode laser.
2. The distance between the laser focal point and the wire affects the penetration depth of the resultant weld significantly.

4. The hybrid laser-GMAW joining process reduced welding time by 36% and consumable usage by 56% over the current FCAW procedure. (Note: Only time spent in actual deposition of the weld is considered.)
5. The HAZ of the hybrid laser-GMAW weld showed an increase in size in the direction perpendicular to the laser, and smaller in the direction of the laser.
6. Hardness profiles measured in the area of both cap and inner pass are almost identical. Inner pass deposited with GMAW process possesses slightly wider over tempered region.

To be able successfully implement hybrid laser-GMAW process into industry practice yielding all the potential benefits this process offers, further work is required. Additional testing will be completed on this process to understand limits of operating parameters and optimisation for industry use. Areas for further investigation include:

- Offsetting the GMAW bead from the laser to minimise the size of the HAZ produced in the direction perpendicular to the laser.
- Minimising the plate gap required by the process to obtain full penetration welds.
- Investigate the effect of using a higher power laser.
- Implementing welding robotic arm to carry the hybrid laser-GMAW set-up.

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