LASER-MIG Hybrid Welding of Thick Plates of Mild Steel in Single Pass

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ABSTRACT

Laser hybrid welding combines the deep penetration capability of laser beam and edge gap bridging capability of an arc welding process such as MIG/MAG. In the present work, a 3.5 kW slab CO_2 LASER -MIG hybrid welding system was used to carry our laser hybrid welding studies with an aim to achieve butt welds of 12mm thick mild steel plates in single pass. Bead-on-plate studies were carried out to first understand the effect of parameters such as laser power, focal plane position of the laser, MIG wire feed rate, composition of shielding gas, distance between laser and MIG arc on the weld penetration. The optimized parameters were then applied on butt welds with Y-groove edge preparation with varying root face height and groove angle to identify suitable joint design. Combining the results of bead-on-plate experiments and butt welding experiments, welding of 12 mm thick mild steel plates in single pass could be achieved. The LASER-MIG hybrid butt welds so fabricated showed 100% joint efficiency and high bend ductility.

Keywords: LASER hybrid welding, 12 mm thick mild steel plate, single pass weld

1.0 INTRODUCTION

LASER welding process is a well-known power beam process owing to its advantages such as high weld aspect ratio, high welding speeds, narrow weld and small weld/heat affected zone (HAZ) resulting in good mechanical properties and high productivity [1,2]. However, laser welding demands high joint fit-up accuracies which are difficult to maintain in large scale production and in thick sections. To overcome this limitation, LASER-MIG hybrid welding (LHW) process has been developed and is becoming popular in the recent times with applications in many fields such as aerospace, automotive, ship building, pipelines, pressure vessels etc. LHW is a fusion welding process which combines laser and arc sources in such a way that the benefits of both welding processes are effectively utilised. [3-8] Schematic of laser hybrid welding set up is shown in **Fig. 1a** and the actual laser hybrid arrangement at ARCI is shown in **Fig. 1b**. Primary purpose of hybrid process is combining the deep penetration capability of laser and edge bridging capability of laser. There are other advantages as well.

Such as, possibility to change the fusion zone chemistry etc. when compared to laser welding and higher welding speeds and less usage of filler compared to MIG welding. Consequently, the laser hybrid welds are deeper than MIG welds and broader than laser welds. **Fig. 2** compares cross section macrographs of beads-on-plate produced by arc, autogenous laser and hybrid welding on 12mm thick mild steel plate. The arc weld shown in **Fig. 2a** is shallower than both the laser and hybrid weld pools shown in **Fig. 2b** and **Fig. 2c**, respectively. The width of the hybrid weld is comparable to that of the arc weld. Hybrid welding also provides enhanced productivity and capabilities in excess of what can be achieved by either laser or arc welding alone. While the process has

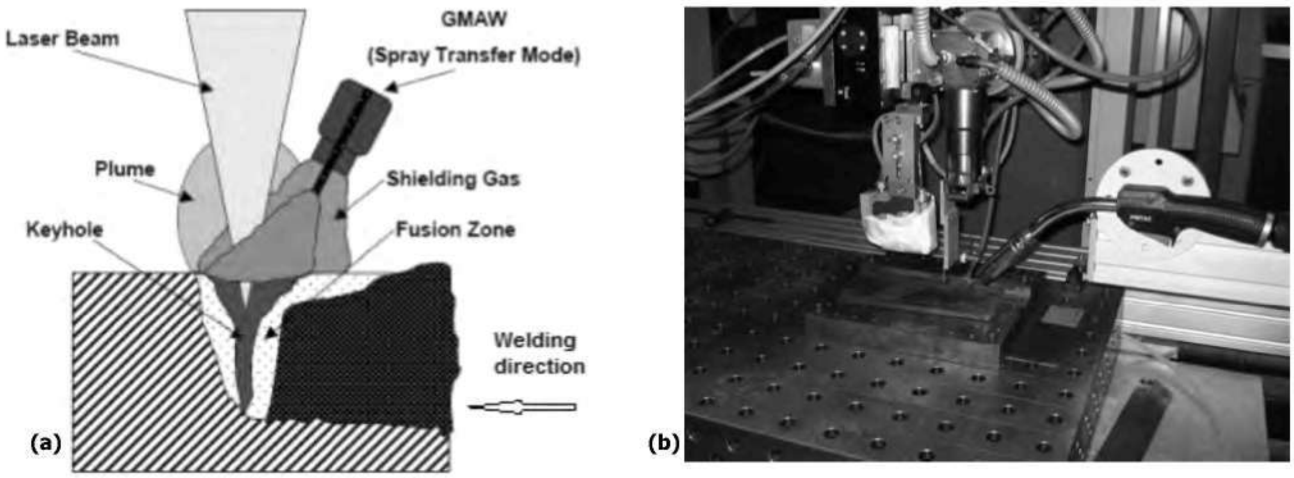


Fig. 1 : (a) Schematic of laser hybrid welding; (b) Laser-MIG welding set up at ARCI

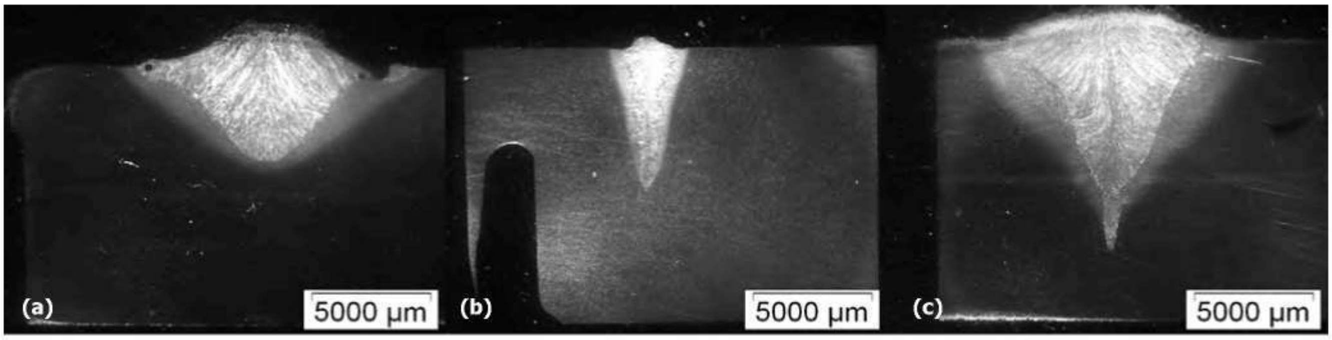


Fig. 2 : Weld cross-section of (a) – MIG, (b) – Laser and (c) – Laser-MIG hybrid welded mild steel specimens

many advantages, it is more complex compared either laser alone or MIG alone due to increased number of process parameters to be controlled to be able to really get the synergistic effect of combining the two processes. For example, if the arc generates too much plasma, all the laser energy gets entrapped in it and none of it contributes to penetrate the work piece. Similarly, when the distance between the laser source and the MIG arc are not optimized, the synergy of the process cannot be achieved. Several researchers carried out investigations on effect of various process parameters to draw the best benefit from the process. Ming Gao et al [9] studied microstructure characteristics of CO_2 laser-MIG bead on plate welds on 7 mm thick mild steel. They showed that hybrid weld shape has wide upper zone (arc zone) and narrow nether zone (laser zone) and the microstructure, alloy element distribution and microhardness all have evident difference between arc zone and laser zone. Giovanni Tani et al [10] examined the effect of different shielding gas compositions and gas flow rates on CO_2 Laser-MIG hybrid butt welding of 10mm thick AISI 304 stainless steel plates. They observed that minimum 30% helium content in gas mixture is required to limit plasma formation. In India, there are no investigations carried out on this process (to the best knowledge of the authors) until the Centre for Laser Processing of Materials at ARCI, Hyderabad set up the laser hybrid welding system (**Fig. 1b**) by integrating an existing 3.5 kW slab CO_2 laser and a pulsed MIG welding system a couple of years ago. Information from laser hybrid welding practitioners is that an every 1 mm depth of penetration 1 kW of laser power is required. However, as the slab laser at ARCI has high beam quality with capability to weld 7 mm thick steel plates in single pass it was felt that it may be attempted to use the facility for as high thickness as possible. Accordingly, in the present study, laser hybrid welding of low carbon steel plates (mild steel) of 12 mm thickness was chosen, as the experience and data could be useful for a wide variety of applications. It is attempted to maximize the depth of penetration by optimization of welding parameters such as shielding gas, laser beam focal plane, distance between the laser beam spot and MIG arc and MIG wire feed rate to reduce plasma shielding effects, increase laser penetration, maximize synergistic effects of laser and arc welding processes and further enhance weld penetration and filling of the joint to be able to butt weld 12 mm thick plates in single pass, with the available 3.5 kW laser power. Weld geometry and quality of the butt welds were evaluated by metallography, tensile testing and bend testing.

2.0 EXPERIMENTAL DETAILS

2.1 Equipment

The laser hybrid welding system comprised of Rofin DC035 slab CO_2 laser integrated with Kemmpi synergic pulsed MIG system. Laser beam in gaussian mode (TEM_{00}) was focused using 300 mm focal length focusing mirror using a welding head supplied by Precitec, which gives a focused spot size of 180 microns. The MIG system (Kemppi make) was integrated with the laser in such a way that the arc and laser can operate together. MIG power source is attached with a Witt-Gasetechniks gas mixing unit which is capable of supplying different mixtures with gases like Ar, He, N_2, CO_2 and O_2. The flow rate of the gas mixture can be controlled by controlling the pressure at the outlet, which can be varied from 0.5 – 6 bar. The gas mixture is passed through MIG welding torch and no separate plasma/shielding gas was used for the CO_2 laser. MIG welding was used in synergic pulsed mode.

2.2 Materials

The filler wire was 1.2 mm dia. mild steel Cu coated wire of specification AWS ER 70S-6. The chemical composition of mild steel and filler wire is given by weight percent (%) in **Table 1**. Steel specimens of size 220 mm x 110 mm x 12 mm with varying joint designs were used for laser hybrid butt welding experiments.

2.3 Methodology

Initially, bead-on-plate (BOP) welding experiments were carried out on 12 mm thick mild steel plates to optimize the laser hybrid welding parameters such as composition of torch gas (50% Ar + 50% He, 45% Ar + 45% He + 10% CO_2, 40% Ar + 45% He + 15% CO_2 and 40% Ar + 40% He + 20% CO_2), wire feed rate (4 to 14 m/min), distance between sources (2 to 8 mm), focal position of the laser with respect to the surface (2-6 mm below the surface), and the optimal parameters were subsequently applied on butt welding with Y-groove edge preparation with various root face heights and included angles. A laser power of 3.5 kW was used for all the experiments. A gap of 0.2 mm was maintained between the edges of the prepared specimens. Before each weld, the laser beam in conjunction with MIG was aligned with the joint, to ensure an equal and constant amount of melting in both plates.

2.4 Characterization

After visual inspection of the welds, dye penetrant testing was conducted according to ASTM standard (ASTM E 165), to identify surface defects, if any. The weld bead on both face and root side was cleaned properly and penetrant sprayed on the weld area and allowed 15 minutes dwell time. The excess penetrant was removed by applying the cleaner. Then to view the defects, developer was applied and allowed to dry. Metallographic specimens were prepared as per standard procedures. Subsequently, the samples were etched using 2% nital and the macrostructures were taken using a stereo microscope. The bead geometry measurements like depth of penetration, width of the weld, width of HAZ, etc were conducted using image analysis software attached to the microscope. The butt welds were subjected to transverse tensile testing according to ASTM E8. Specimen schematics is shown in **Fig. 3**.

Tensile testing was carried out using servo controlled Instron 5584 machine at a cross head speed of 1 mm/min. All the acceptable butt welds were subjected to root bend testing according to ASTM E192 using specimens as shown in **Fig. 4**. The welds were subjected to only root bend test because it is more critical than the face bend tests. The testing was performed on a hydraulic controlled bend testing machine.

Table 1: Chemical composition (wt %)

Grade	C	Mn	S	P	Si	Fe
Mild Steel	0.15	0.47	0.021	0.017	0.2	Bal.
Filler wire AWS ER 70S-6	0.07- 0.15	1.4-1.85	0.035	0.025	0.8-1.15	Bal.

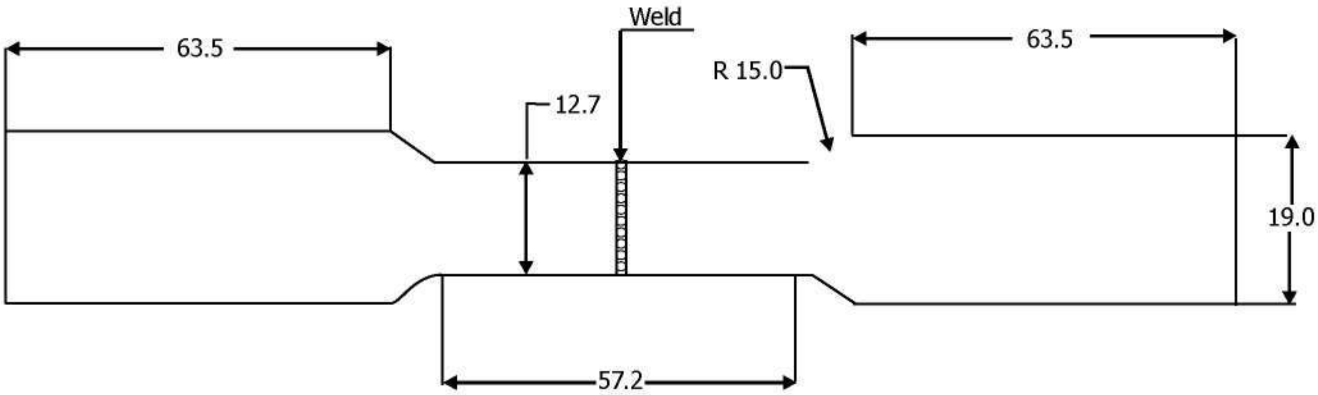


Fig. 3 : Dimensions of the tensile test specimen in mm

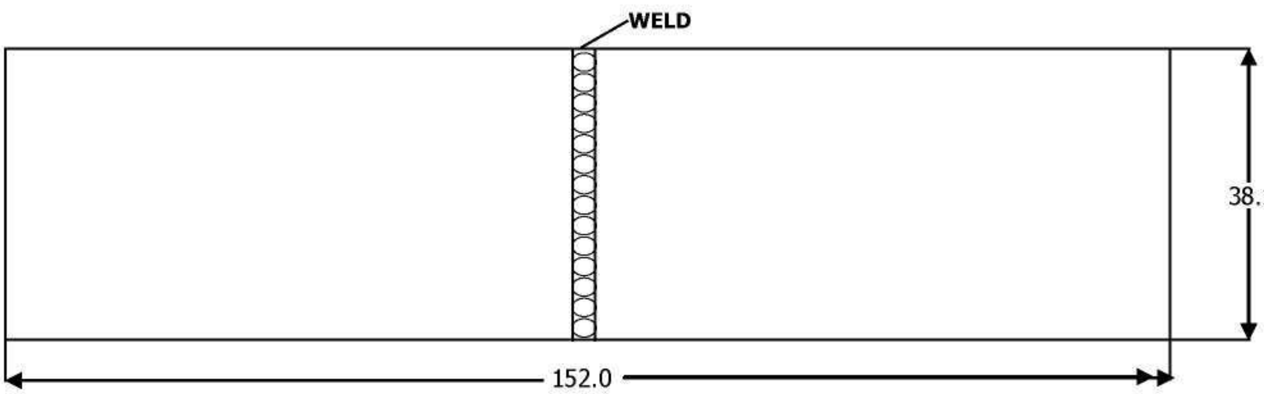


Fig. 4 : Schematic of bend test specimen, dimensions in mm

3.0 RESULTS AND DISCUSSION

3.1 Bead-on-Plate (BOP) Welding

Although some of the results are reported in earlier works [11] of the authors, for the sake of better appreciation of the process and completeness, some of the results are explained here again. Cross sectional macrograph of typical laser hybrid bead-on-plate weld is shown in **Fig. 5**. Nomenclature of various geometrical features is also shown. It shows a typical "wine-cup" shape: wide upper zone (arc zone) and narrow nether zone (laser zone). This is similar to that reported by other workers.

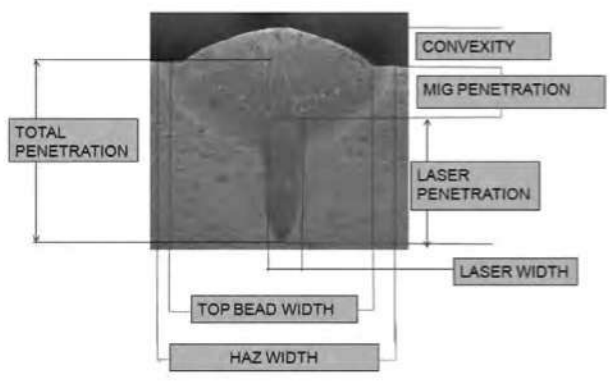


Fig. 5 : Cross sectional macrograph of a typical laser-MIG hybrid bead on plate

Fig. 6 shows the effect of torch / shielding gas combination on weld penetration, due to laser and MIG. MIG penetration decreased with increasing He content and reducing carbon dioxide. This probably may be effect of reducing carbon dioxide, which generally aids in more heat input as it is a reactive gas. Laser penetration increased with increasing He and reducing Ar and CO_2. This may be attributed to reduced plasma formation. It is well known that the plasma plume formed in the weld zone traps the laser energy and causes reduction in the power density and consequently reduction in depth of penetration. Overall penetration is high when a minimum of 50% He is present in the shielding gas.

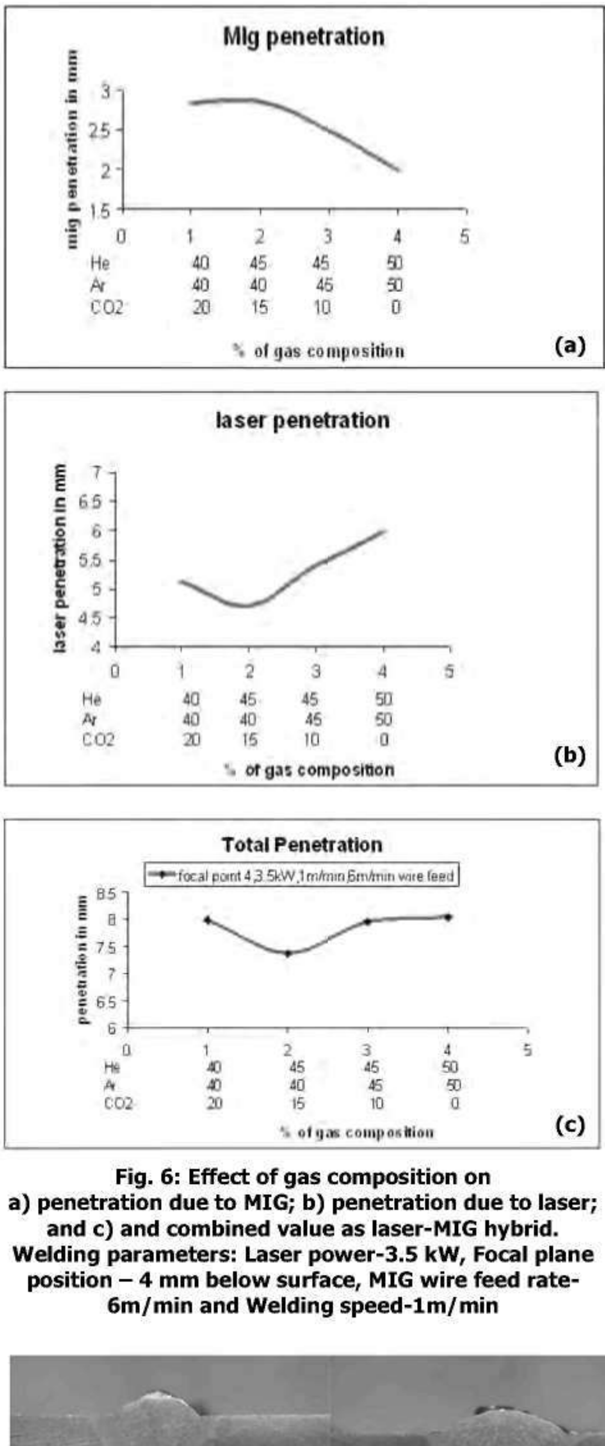


Fig. 6: Effect of gas composition on a) penetration due to MIG; b) penetration due to laser; and c) and combined value as laser-MIG hybrid. Welding parameters: Laser power-3.5 kW, Focal plane position – 4 mm below surface, MIG wire feed rate-6m/min and Welding speed-1m/min

Fig. 7 shows the effect of distance between laser and MIG with laser power of 3.5 kW, wire feed rate of 6 m/min (current of 172A and voltage of 29.3V) on weld bead geometry. As the distance varied from 2 – 8 mm there is no significant change in penetration. But, weld width increased. The experiments were repeated at higher wire feed rate 14 m/min. The bead geometry variations at two wire feed rates are compared in **Fig. 8**. In both the cases increase in the distance between sources resulted in decrease in depth of penetration. But, the decrease is more significant at wire feed rate of 14 m/min than at 6 m/min. At higher wire feed rates, due to increased current, the arc plasma will be more compared to lower wire feed rates which, can attenuate the laser beam resulting in loss of laser energy. Further, beyond 4 mm distance between sources, at low wire feed rates, the combined effect of the heat sources is not seen and the penetration is by autogenous laser welding only. However, at higher wire feed rates the combined effect of the heat sources was not seen at a distance beyond 6mm. So, optimum distance between laser and MIG seems to be 2-4 mm. **Fig. 8** also shows the effect of distance between sources on bead width. There is an increase in bead width with increase in distance but not as significant as on depth of penetration.

In laser keyhole welding, for thick section welding the laser is focused below the surface of the material to obtain increased depth of penetration. This effect in case of laser hybrid welding is investigated. **Fig. 9** shows the effect of focal plane position on depth of penetration at different wire feed rates and distance between sources. Increase in defocus of laser has increased the penetration at higher wire feed rates and the effect is more pronounced at distance between sources of 2 mm. However, in case of lower feed rates of 4 m/min, the total penetration has decreased at a distance between sources of 4 mm and has shown very marginal increase at a distance between sources of 2 mm. At lower wire feed rates, the MIG penetration will be less compared to high wire feed rates. However, the increase in total penetration is only upto a

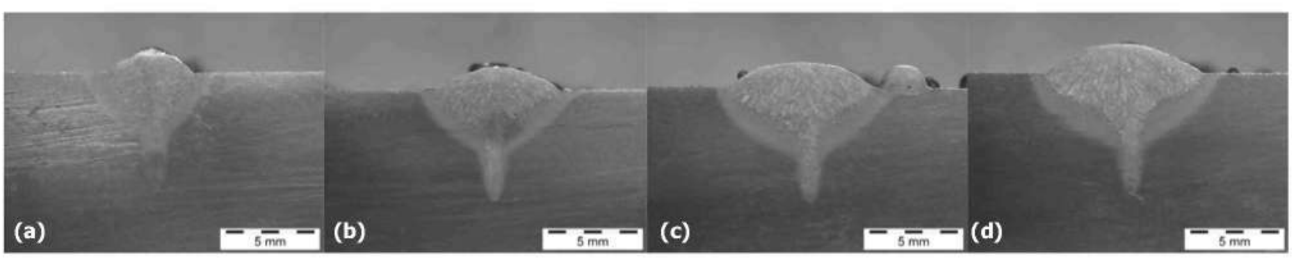


Fig. 7 : Laser hybrid weld cross-sections with varying distance between laser and MIG a) 2mm, b) 4mm, c) 6mm and d) 8mm

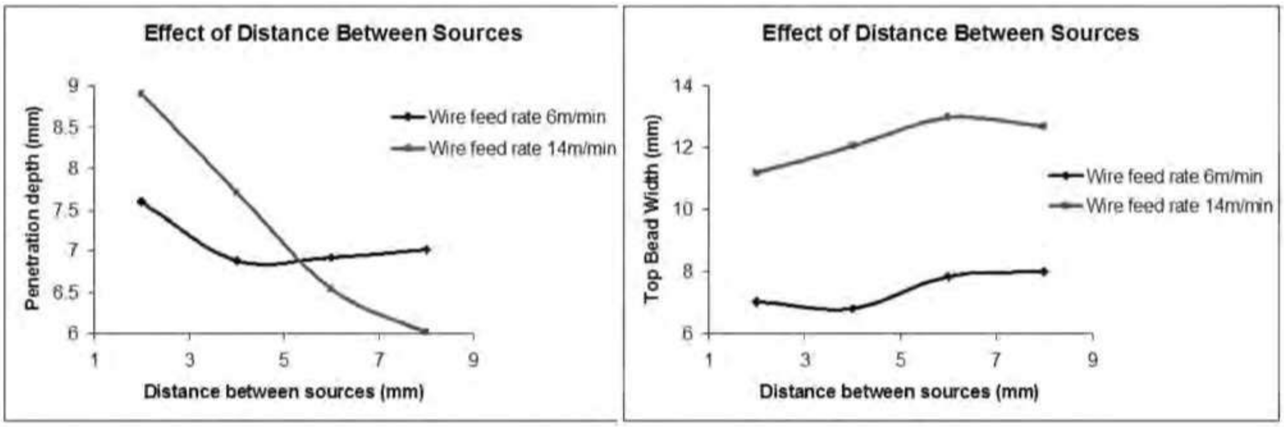


Fig. 8 : Effect of distance between sources on a) Penetration depth and b) Top bead width

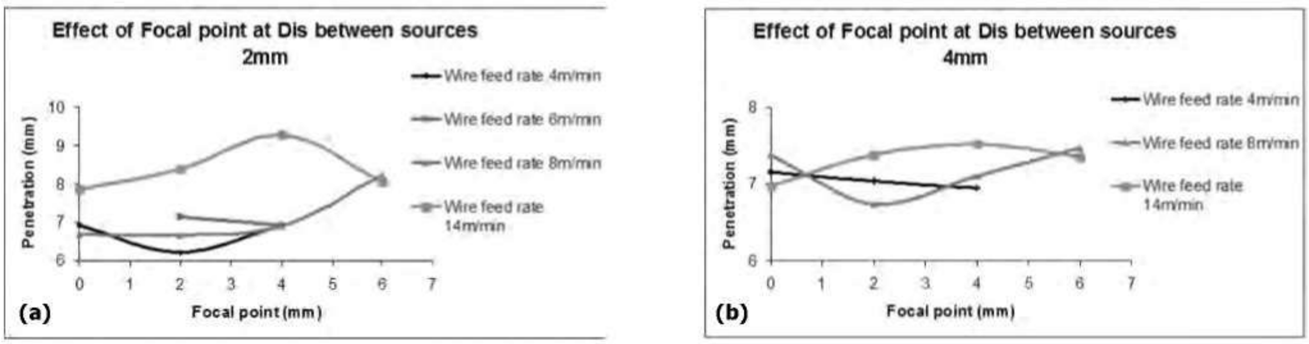


Fig. 9 : Effect of focal plane position on depth of penetration with different wire feed rates and distance between sources a) 2mm and b) 4mm

defocus distance of 5 mm and beyond which again the penetration decreases as the laser power density with respect to the actual un-melted surface reduces.

Based on the bead-on-plate studies, following parameters are identified as most suitable to obtain single pass butt weld specifically for high depth of penetration:

Laser Parameters: Power : 3.5 kW; Spot size : 180 microns; Focal plane position : 5 mm below surface; and

MIG Parameters: Wire feed rate : 14 m/min; Shielding gas : 50%Ar+50%He; Nozzle standoff : 15 mm.

3.2 Butt welding

Having identified the welding process parameters, the next requirement is to get a good butt weld with optimal joint design which can take advantage of laser penetration as well as edge bridging and gap filling by MIG. Experiments were conducted with 'Y' groove configuration (**Fig. 10**) by varying root face heights and included angles.

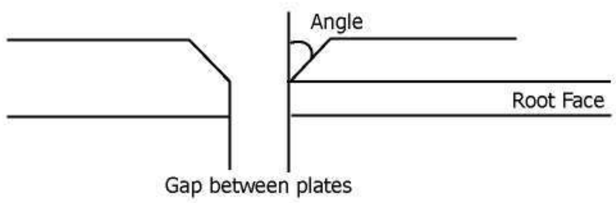
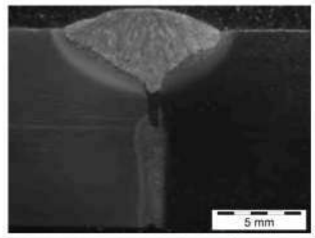
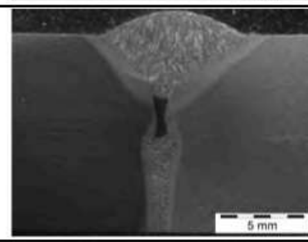
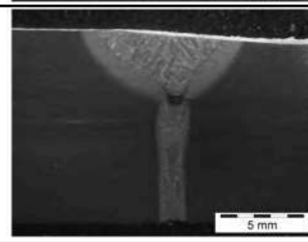
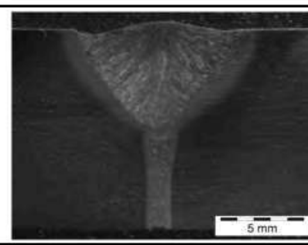
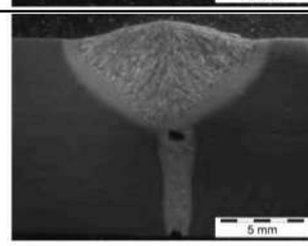


Fig. 10 : Schematic view of various geometrical considerations during butt welding

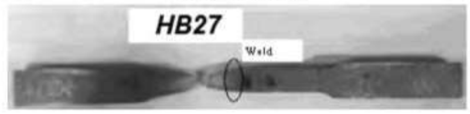
Root gap was maintained at 0.2mm. As 6 mm laser penetration could be consistently obtained, Y-Grooves with 5 mm root face (RF) were started with and groove angles of 8° and 16° were chosen based on volume of the molten material. The macrographs of single pass welds made at different groove designs with almost similar parameters are shown in **Table 2**. At 8° groove angle, while the laser penetration is sufficient to fuse the root, the filling by MIG process was not adequate leaving a gap between the MIG part and the laser part. When the groove angle is increased to 16°, with root face as 5 mm similar gap was observed. Both the situations improved a little

Table 2 : Laser hybrid butt welds with different joints designs

Sample No.	Joint Design	Focal Plane position from top surface (mm)	Welding Parameters			Cross sectional macrograph of the laser hybrid welds
			Welding Speed (m/min)	Laser Power (kW)	WFR (m/min)	
24	5 mm RF 16° angle	-9.0	1	3.5	14	
25	5 mm RF 8° angle	-9.0	1	3.5	14	
26	2.5 mm RF 8° angle	-9.5	1	3.5	14	
27	2.5 mm RF 16° angle	-9.5	1	3.5	14	
28	2.5 mm RF 16° angle	-9.5	0.9	3.5	14	

bit when focal plane was further lowered. The amount of molten metal deposited by the MIG also seems to affect the laser penetration. Acceptable weld without defects could be obtained at a combination of 2.5 mm root face height and 16° groove angle as seen in cross section of sample 27 in **Table 2**. The tensile testing results are given in **Table 3**. All the specimens failed away from the weld in the base metal. The ductility of the welds as can be seen from the **Table 3** was lower than the base material. The low ductility observed in the welds could be due to overmatching weld metal causing strain concentration on one side of the weld which started deforming first. Specimens subjected to bend tests are shown in **Fig. 11**. All the welds showed good bend ductility.

Table 3 : Tensile properties of base materials and laser hybrid welds

Specimen	UTS (MPa)	Elongation (%)	Location of fracture
Base Material	483.88	55.17	--
Single pass butt weld	486.62	43.21	Base metal 

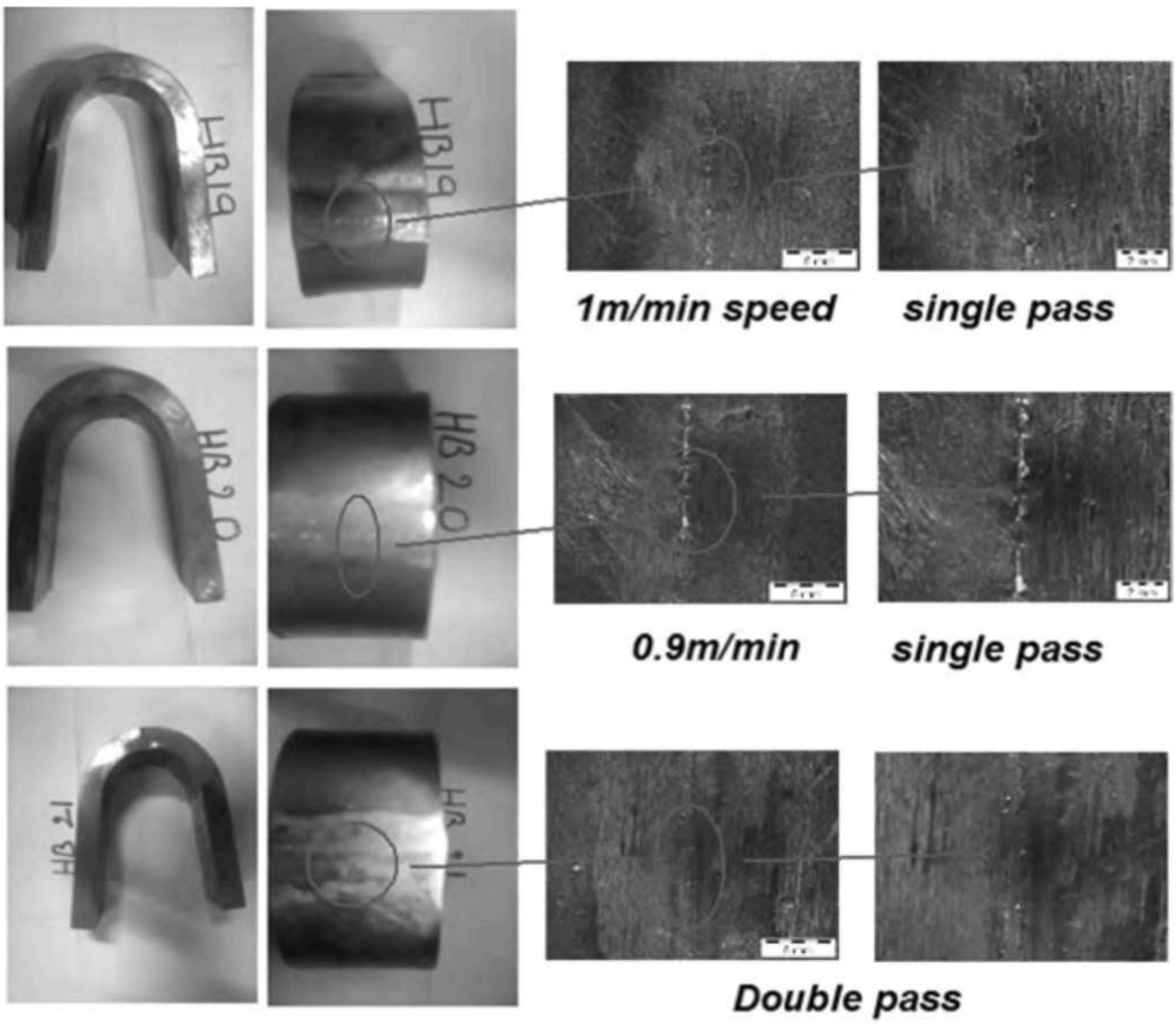


Fig. 11 : Bend tested laser hybrid welds

On the basis of parameter optimization to achieve maximum depth of penetration in bead-on-plate studies and selection of joint design based on volume of metal to be deposited to fill the joint, sound butt welds could be obtained with repeatability. This result could be of great industrial significance as many structures use sections in this thickness range and with this process it is possible to weld at higher welding speeds than conventional processes and with one side access. However, more studies need to be undertaken to establish the welding procedures.

4.0 CONCLUSIONS

1. Butt welding of 12mm thick mild steel plates could be achieved in single pass by laser-MIG hybrid welding at a laser power of 3.5 kW and a MIG wire feed rate of 14 m/min and welding speed of 1 m/min.
2. Not only the welding parameters but the joint design is important in achieving sound joints.
3. The laser hybrid joints showed 100% Joint efficiency and 180° bend ductility.
4. The above result could be of great significance in practical applications and more studies in that direction can be taken up.

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