The effect of welding direction in CO₂ LASER - MIG hybrid welding of mild steel plates

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Abstract. In this paper, hybrid laser-arc welding process has been studied based on the relative position of the laser and the arc (i.e. laser-leading and arc-leading arrangement) and, the effects of welding parameters, such as the laser power, arc current, arc voltage and the welding speed on the weld bead were investigated. The study indicates that the welding direction has a significant effect on the weld bead and weld pool behaviour. The result shows that laser-leading configuration shows better bead characteristics when compared to arc-leading configuration. This is because in the laser-leading case molten metal flow is inward, while in the arc-leading case the metal flow is outward leading to variation in solidification front resulting in lack of synergic effects of both processes.

1. Introduction

Hybrid laser-arc welding (HLAW), also known as laser hybrid welding or simply hybrid welding, is a metal joining process that combines laser beam welding (LBW) and arc welding in the same weld pool. In HLAW process, heat generated by two sources namely, laser beam and arc is used to join similar or dissimilar materials with or without filler material [1, 2]. The arrangement of the welding direction is shown in the Figure 1. There are two variants of the process, laser-leading and arc-leading configuration[3, 4]. The weld surface geometries, penetration and fusion zone microstructure vary with welding direction[5]. The weld bead appearance of a laser-leading process was found to be of high quality. This is because the abatement gas flow does not perturb the molten pool created by the arc, whereas in the arc-leading frame up the shape of the bead surface is unsettled by the assist gas blow into the molten pool [6]. The bead characteristic of MAG laser hybrid welded high strength steel is found to be similar to that of arc welded high strength steel. This is due to the fact that the key hole was first created by the laser and then the MAG forms the weld bead.

Zhao et al. utilized gassed up video camera and an in-situ X-ray transmission imaging system to investigate the molten metal flow on the pool surface and inside of the samples. The molten metal flow behaviour is outward in case of arc-leading arrangement; and the metal flow is inward for the
laser-leading arrangement [7-9]. The HLAW process has good applications in various engineering fields like ship building industry, automobile industry, tank construction, pipe joining etc. Kim et al. [10] investigate on the residual stress due to the effects of heat input ratio of hybrid laser arc welding. The residual stress was not affected by the heat input ratio of laser to arc. Leo et al. [11] report that the arc and laser powers affect the quality of hybrid welded aluminium alloy. Increasing laser power decreased the magnesium content in the joints while the increasing the porosity affecting the strength and ductility of the joints. Chaki et al. [12] develop three integrated soft computing based models for the joint strength of hybrid laser welding.

Zhang w et al., [13] investigates the metal transfer in Laser GMAW-P hybrid welding by using argon-helium mixtures and the effect of the laser on the metal transfer. Casalino[14] evaluated the effects of laser and arc powers on the weld geometry and properties of hybrid laser MIG welded 3-mm thick AA5754-H111 in butt configuration. Moradi et al., [15] investigates the effect of welding speed (1 to 5 mm/s), TIG current (90 to 130 A) and distance of heat sources (1 to 5 mm) on weld surface width, weld seam area, and weld penetration during laser-tungsten inert gas(TIG) hybrid butt joint welding of stainless steel. Turichin et al., [16] investigates the influence of the gap width and speed of the welding wire on the changes of the geometry in the welded joint in the hybrid laser-arc welding of shipbuilding steel RSE36. Ma et al.,[17] correlates the arc and laser energy ratio to width ratio RW of weld profile, and explores the effect of different energy ratios on the welding deformation and residual stress during hybrid laser arc welding. Telesang et al.[18] investigates optimum laser parameters to achieve clad-substrate bonding. Optimum parameter settings result in maximising the joint strength and other properties [19]. In this work, laser hybrid welding of mild steel has been studied by changing the relative position of the arc and laser. The effect of relative position and welding parameters on the weld bead were also investigated.

2. Materials and Experimental procedure
A CNC controlled 3-axes hybrid welding station with a 3.5 kW carbon dioxide laser and a 40 V synergic-pulsed MIG welding machine was used for hybrid welding. The spot diameter of the laser is 180 μm. The workpiece dimension is 150 mm × 150 mm × 10 mm and the filler material used is ER70S-6 with a diameter of 1.2 mm. The plate surfaces are cleaned by wire brush and acetone is used

| Material      | C  | Mn | Si  | P   | S   | N   | Fe  |
|---------------|----|----|-----|-----|-----|-----|-----|
| Base Material | 0.19 | 0.65 | 0.32 | 0.040 | 0.09 | --- | balance |
| ER70S-6      | 0.1 | 0.7 | 0.5 | 0.045 | 0.03 | 0.1 | balance |
for removing the oxide layers. The chemical composition of the base and filler material is given in Table. The hybrid laser-arc welding parameters adopted are listed in the Table 2 and Table 3.

Table 2. Hybrid laser-arc welding configuration

| Parameters                  | Configuration             |
|-----------------------------|---------------------------|
| Welding position            | Flat                      |
| Welding condition           | Bead on plate, butt joint |
| Laser power (kW)            | 3.5                       |
| Focal length (mm)           | 298                       |
| Shielding gas               | 100% Helium               |
| MIG current (A)             | 170-270                   |
| MIG voltage (V)             | 20-40                     |
| Torch angle (degree)        | 53                        |
| Stick-out distance (mm)     | 15                        |
| Distance between sources (mm)| 2-3                      |
| Flow rate (litres/min)      | 40                        |

Table 3. Welding parameters

| Ex No | Laser power (kW) | Current (A) | Voltage (V) | Welding speed (m/min) | Wire feed rate (m/min) |
|-------|------------------|-------------|-------------|------------------------|------------------------|
| 1     | 3.5              | 171         | 27.9        | 0.8                    | 6                      |
| 2     | 3.5              | 176         | 27.9        | 0.8                    | 6                      |
| 3     | 3.5              | 220         | 33          | 0.8                    | 8                      |
| 4     | 3.5              | 217         | 31.6        | 0.8                    | 8                      |
| 5     | 3.5              | 263         | 34          | 0.8                    | 10                     |
| 6     | 3.5              | 257         | 35          | 0.8                    | 10                     |
| 7     | 3.5              | 180         | 26.9        | 1.0                    | 6                      |
| 8     | 3.5              | 174         | 26.9        | 1.0                    | 6                      |
| 9     | 3.5              | 231         | 32          | 1.0                    | 8                      |
| 10    | 3.5              | 225         | 30          | 1.0                    | 8                      |
| 11    | 3.5              | 265         | 35          | 1.0                    | 10                     |
| 12    | 3.5              | 262         | 33          | 1.0                    | 10                     |

Figure 2. Bead geometry nomenclature for hybrid welding
After welding, the transverse cross-section of the welded sample is polished and then etched with Nital solution (98% ethanol and 2% nitric acid). The bead characteristics are measured with the help of stereomicroscope. The nomenclature of the various weld bead dimensions for the hybrid welding is shown in Figure 2.

3. Results and Discussion

The bead geometry of the laser welded plates were analysed to explore the effect of the mode of welding.

3.1 Laser-leading Mode

The macrostructure and top bead appearance of the laser-leading welded samples is shown in Table 4. From the table, it is evident that the upper portion is acted up by arc and the lower portion is acted up by the laser. This synergic effect of both the processes leads to the wine-cup shaped weld bead.

The weld bead characteristic of the laser-leading configuration is shown in Table 4. Absence of metallurgical defects in the transverse cross sections shown in Table 4 and Table 5 indicate defect free weld. From the Table 4, and Figure 3, we can infer that with increase wire feed rate there is an increase in both penetration and bead width which is due to higher deposition of filler material in to the base material. Further with increase in welding speed there is a decrease in penetration and bead width which must be due to less heat input to the base material.

| Ex. No | Transverse cross-section | Top – bead appearance |
|--------|--------------------------|-----------------------|
| 1      | ![Image](image1.png)     | ![Image](image2.png)  |
| 3      | ![Image](image3.png)     | ![Image](image4.png)  |
| 5      | ![Image](image5.png)     | ![Image](image6.png)  |
| 7      | ![Image](image7.png)     | ![Image](image8.png)  |
Figure 3 Penetration and bead width in Laser-Leading Configuration

Figure 4. Penetration and bead width in Arc-leading configuration
3.2. Arc-leading Mode
Table 5 shows the Top bead appearance and transverse cross-section of arc-leading configuration. From the Table 5, and Figure 4 it can be seen that the arc-leading and laser-leading trials produce similar welds. The bead characteristic of the arc-leading configuration is shown in the Figure 2. When compared to the arc-leading configuration laser-leading configuration provides better bead characteristics. This is because when there is a change in the direction of travel, the distances between the power sources plays an important role and this may lead to different melt pool behaviour. This can be observed from the Table 4 and Table 5. Moreover, when laser is leading the molten metal flow is inward which leads to homogenous distribution of materials where as in arc-leading the molten metal flow is outward which leads non-homogenous distribution of material.

Table 5. Macrostructure and top bead of the Arc-leading welded sample

| Ex. No | Transverse cross-section | Top – bead appearance |
|--------|--------------------------|-----------------------|
| 2      | ![Image](image1.png)     | ![Image](image2.png)  |
| 4      | ![Image](image3.png)     | ![Image](image4.png)  |
| 6      | ![Image](image5.png)     | ![Image](image6.png)  |
| 8      | ![Image](image7.png)     | ![Image](image8.png)  |
| 10     | ![Image](image9.png)     | ![Image](image10.png) |
3.3. Butt-Joint Design
Based on the bead on plate (BOP) experiments, it is evident that the change of welding direction, wire feed rate and welding speed affect the bead geometry. From BOP studies, weld bead characteristics, specifically penetration and fusion area helped in finalizing joint configuration for butt welding experiments. The butt joint configurations selected and the process parameters are listed below in the Table 6. The butt-joint geometry considerations used are shown in Figure 5.

![Figure 5. Geometry of butt-joint](image)

**Table 6. Different butt-joint configuration**

| S. No | Process Parameters | Geometry | Top Bead Appearance | Remarks |
|-------|--------------------|----------|---------------------|---------|
| 1     | Wire feed rate-10m/min, Power-3.5 kW, Welding speed-0.8 m/min, Position-Arc-leading | Y-groove Root face-2.5 mm Included angle-16 degree | ![Image](image) | No penetration |
| 2     | Wire feed rate-10m/min, Power-3.5 kW, Welding speed-0.8 m/min, Position-laser-leading | Y-groove Root face-1.5 mm Included angle-16 degree | ![Image](image) | Full penetration |
The butt-welding experiments were carried out for optimizing root face height and joint configuration. ‘V’ groove configuration with included angle of 16 deg found not feasible since burn through occurs due to excess penetration resulting in under fill i.e., concave weld bead. Subsequently, experiments were carried out with ‘Y’ groove with included angle 16 degree and with root face height of 1.5mm both in pull and push mode and 2.5mm in pull mode configuration only. Full penetration was not attained with root face height of 2.5mm in pull mode while full penetration of 10 mm was attained with 1.5mm root face height in push mode, while in pull mode only 7.8 mm penetration was attained.

4. Conclusion
Mild steel plates of 10 mm nominal thickness were joined using hybrid laser-arc welding by varying the process parameters. The resulting joints were characterized for macrostructure (bead geometry). Based on the results obtained the following conclusions are made:

- Using hybrid laser-arc welding it is possible to weld 10 mm thick mild steel plate in a single pass.
- The weld bead characteristics differ when the welding direction (laser-leading/arc-leading) is changed.
- The weld pool behaviour was different for the arc-leading and laser-leading conditions. An inward flow of the metal was noted when the laser-leading configuration was used and an outward flow was observed for the arc-leading case.
- Laser-leading showed better weld bead characteristics as compared to arc-leading configuration.
- In the laser-leading mode, root face height of 1.5 mm and an included angle of 16 degree provided full penetration.

The scope of this study is to determine the effect of welding direction on the weld bead characteristics of hybrid laser welded mild steel. The study can be further extended to study the effect of the welding direction on mechanical properties and microstructure of laser welded joints.

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