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Investigation of Laser Welding Processes for Automotive Structural Applications

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Abstract

The motive behind this study was to investigate the autogenous laser welding (ALW), and Hybrid laser arc welding (HLAW) processes in the aspects of productivity and quality for the application in automotive industries. Presently, Gas metal arc welding (GMAW) process is being used for the manufacturing of two-wheeler frame. Low power density of GMAW process limits the depth of penetration and productivity of the process which are the two key concerns in automotive industries. Therefore, GMAW process was compared with advanced laser welding processes in the aspects of productivity, heat input, weld bead geometries and gap bridgeability. Effects of these welding methods on distortion and mechanical properties were also evaluated. The trade-off between productivity and quality were interpreted in each processes. Low carbon steel (S275) of 2 mm, 4 mm and 8 mm thick materials with square butt joint configuration were used for the evaluation. Better weld quality with complete penetration was achieved in autogenous laser welding and hybrid laser arc welding processes with improved productivity by a factor of 8 times compared to GMAW in 2 mm and 4 mm thick materials and in 8 mm thick material, complete penetration with an improvement of productivity by a factor of 3 times was achieved. High power density of ALW and HLAW processes provided complete penetration even at ~70% to 80% less heat input than GMAW process which eventually reduces the fusion zone area by ~ 50% to 70%. Therefore, these processes control the metallurgical damage to the base material. Moreover, high power density of HLAW and ALW processes results in ~75% and ~85% less distortion than GMAW process respectively. HLAW process improved the productivity with considerably less increase in hardness than ALW process. For instance, in 2 mm thick material, productivity was improved by 8 times than GMAW process with 55% and 17% increase in average fusion zone hardness in ALW and HLAW processes respectively. In mechanical strength standpoint, all three welding processes produced weld region stronger than base material. Negligible increase in strain was observed on weld metal in DIC test. Therefore, fracture occurred in the base material during tensile test. Lack of bead reinforcement and poor gap bridgeability were found to be the critical concerns in autogenous laser welding process. However, hybridization of laser and arc resolved these issues. Overall, HLAW process found to be superior to GMAW and ALW processes in the aspect of productivity and quality.

Keywords: Gas metal arc welding; autogenous laser welding; hybrid laser arc welding; productivity; weld bead geometry; gap bridgeability; distortion; mechanical properties.

1.0 Introduction

Frame is a skeleton of the vehicle [1], and thus the quality of a frame should be superior to provide better vehicle performance. Moreover, all structural and styling parts are mounted on the frame. Therefore, the contribution of frame in vehicle fit and finish are predominant. Depending on the vehicle requirement, a frame is made of different materials such as steel, aluminium alloy, magnesium alloy and even by carbon fibre in special application [2]. Moreover, it is being designed in different structures which are single cradle frame, double cradle frame, monocoque frame, perimeter frame and trellis frame [1].

Gas metal arc welding is one of the key welding processes, which has wider industrial applications, mainly in automotive industries, aerospace industries, ship building industries and heavy structures welding. The critical limitations of GMAW process are low productivity [3], high distortion [4], high fusion zone and HAZ area [5] and more metallurgical damage to the parent material. In GMAW process, the critical problems associated with welding of thin structures are distortion and burn through [6] whereas limitation on weld penetration in thick sections is a key concern. However, GMAW process exhibits good gap bridging capability which is much needed characteristics for series production lines. On the other hand, high power density of laser welding processes can provide deep penetration with narrow fusion zone and HAZ area along with minimal distortion. High welding speed results in increase of cooling rate which in turn produces the hard phases [7]. Higher hardness in the fusion zone increases the brittleness of the weldment. Extremely small spot size requires precise part fit-up to obtain better weld quality [8]. Laser welding with filler wire and hybrid laser arc welding processes are developed to overcome this issue [8]. Microstructure of the fusion zone can be altered by the addition of filler wire which greatly helps to reduce the hardness [7]. Fusion zone and HAZ of laser welded joints exhibits 40% and 15% more hardness than laser-GMA hybrid welding respectively [7]. Qian Sun et al. made a comparative study of Laser beam welding (LBW) and Gas metal arc welding (GMAW) of 800 MPa grade Nb-Ti-Micro alloyed C-Mn steel with thickness of 5 mm. Width of the weld seam and width of the HAZ in GMAW were 3 to 7 times and 4 to 5 times of LBW respectively. LBW provided better depth to width ratio than GMAW. LBW provides 5 to 6.25 times higher than GMAW (0.7 to 1.67) [5]. Moreover, Laser hybrid welding process was reported to produce less fusion width and HAZ width than MAG weld in the range of 45% and 71.1% respectively [9]. Sun et al. compared Laser beam welding and CO_2 gas arc welding process in the response of distortion and residual stress distribution. The maximum deformation was observed in CO_2 gas arc welding which was 8.7 mm whereas the deformation in LBW was only 0.23 mm. Almost 97% of reduction in weld deformation was observed in LBW process [4]. Colegrove et al. investigated the influence of welding processes on distortion and fusion zone area. A comparative study was done [10] among Submerged arc welding (SAW), DC Gas metal arc welding, Pulsed gas metal arc welding, Cold metal transfer, Autogenous laser welding and Hybrid laser arc welding. Among these processes, autogenous laser welding exhibited less distortion and less fusion zone area than the other processes. Next to that, hybrid laser arc welding process produced less distortion and less fusion zone area. Shi and Hilton compared [8] the gap bridging capability of autogenous CO_2 laser welding, CO_2 laser with cold filler wire and hybrid CO_2 laser MAG welding for the butt weld steel plate. Among these processes laser hybrid arc welding process showed superior gap bridging capability than laser welding with filler wire and autogenous laser welding processes.

This paper investigates the effects of different welding methods (ALW, HLAW and GMAW) on weld morphology, productivity, gap bridgeability, distortion and mechanical properties. Through this investigation, an effort was made to compare GMAW, ALW and HLAW processes in different aspects to study its applicability in automotive industries.

2.0 Materials and Methods

2.1 Materials

The chemical composition (%wt) and mechanical properties of both base material and filler wire are shown in **Table 1** and **Table 2** respectively. S275 grade of base material and Supra-MIG Ultra (Lincoln Electric) filler wire of 1 mm diameter were used for GMAW and Hybrid laser arc welding process.

Table 1 : Chemical composition of base material and filler wire

Element	Base Material % wt			Filler wire % wt
	(2 mm)	(4 mm)	(8 mm)	(ER70S6)
C	0.140	0.150	0.163	0.079
Si	0.021	0.030	0.016	0.940
Mn	0.790	0.790	0.940	1.670
P	0.011	0.014	0.018	0.011
S	0.011	0.002	0.003	0.020
Cr	0.040	0.010	0.020	0.039
Mo	0.005	0.000	0.001	0.010
Ni	0.050	0.000	0.008	0.013
Cu	0.060	0.010	0.005	0.011
V	0.003	0.002	0.001	0.006
Al	0.060	0.046	0.048	0.003
Nb	0.002	0.001	0.001	-
N	0.005	0.005	0.005	-
CE	0.289	0.285	0.325	0.370

Table 2 : Mechanical properties of base material and filler wire

Element	Base material			Filler wire
	2 mm	4 mm	6 mm	ER70S6
Yield strength (N/mm^2)	392	329	362	538
Tensile strength (N/mm^2)	490	440	489	595

2.2 Welding Methods

Joint configuration and specimen dimension are shown in **Fig. 1**. Square butt joint configuration was used. Edges of the specimen were machined to ensure the proper butting and zero joint gap. Clamping system used for the experimentation is shown in **Fig. 2**. Plates were tack welded by GTAW process before welding to control distortion while welding. Backing bar was used for GMAW process wherein autogenous laser and hybrid laser arc welding process were carried out without backing bar.

The laser welding experiments were carried out using IPG YLR-8000 continuous wave multimode fibre laser system without filler wire. Fronius Transpuls synergic 5000 CMT R welding machine was used for GMAW experimentation. In hybrid laser arc welding process, both these systems are synchronized. Laser leading configuration was used for all HLAW experiments with 2 to 3 mm of laser to arc distance. Autogenous laser welding process was operated without shielding gas whereas 80% of Ar + 20% of CO_2 with flow rate of 20 lpm was used for GMAW and HLAW processes. Triton electronics limited- AMV 4000 arc monitoring system was used to monitor the arc current and voltage. The sample rate used for the voltage and current accusation was 20 kHz. The critical parameters used for the experimentation are shown in **Table 3**.

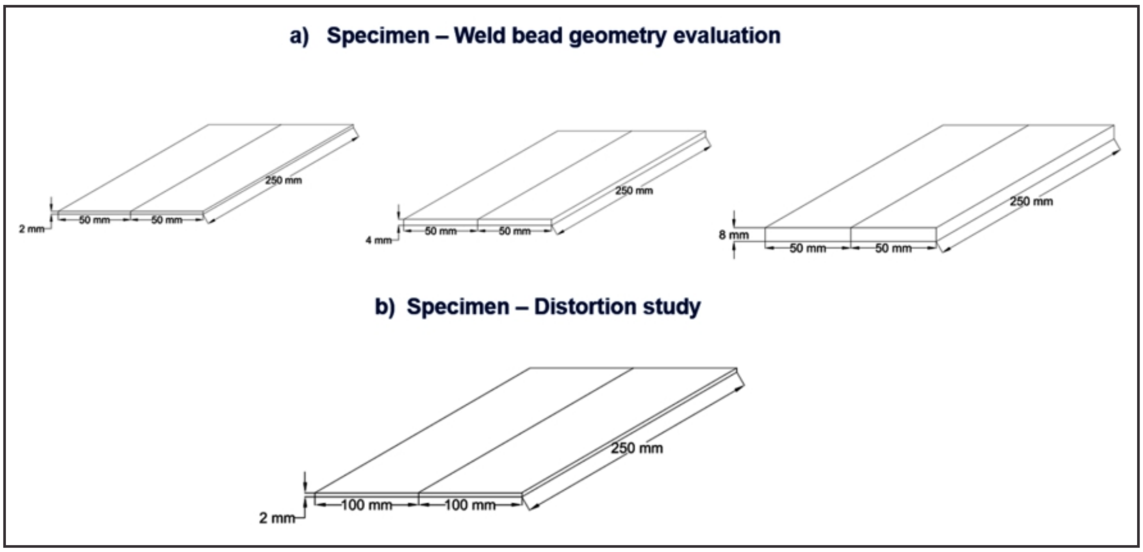


Fig. 1 : Joint configuration and Specimen dimension

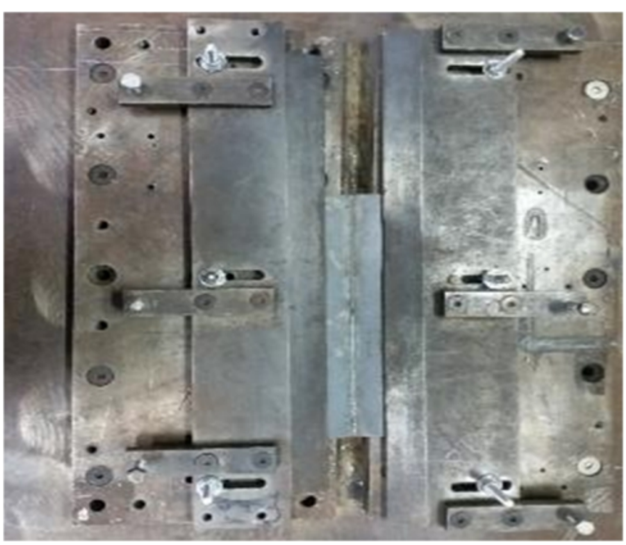


Fig. 2 : Clamping system

2.3 Gap Bridgeability Study

Gap bridgeability of ALW and HLAW processes with respect to weld bead geometry and aesthetic appearance of weld beads were evaluated. Results of ALW and HLAW processes were compared with the GMAW process. At the same set of parameters, samples were welded with different root gaps such as 0 mm, 0.5 mm and 1 mm. Root gaps were pre-set by feeler gauge after that samples were tack welded to maintain uniform root gap while welding.

2.4 Distortion Measurement

Distortion study was carried out in 2 mm thick specimen. Distortion measurement locations i.e. grid points were marked in the tack welded samples. Layout for the distortion measurement points are shown in **Fig. 3**. Experimental methodology was adopted from [11]. Out of plane distortion was studied by measuring the surface height in each grid point.

Measurements were taken before and after welding. Only static distortion measurements were carried out [11]. In all the trials, welded components were allowed to cool down for 10 minutes before unclamping. Based on the observations the following interpretations were made.

- Distortion index (Average of distortion in each grid point)
- Peak distortion (Maximum distortion)
- Surface deflection (Profile of deformation)

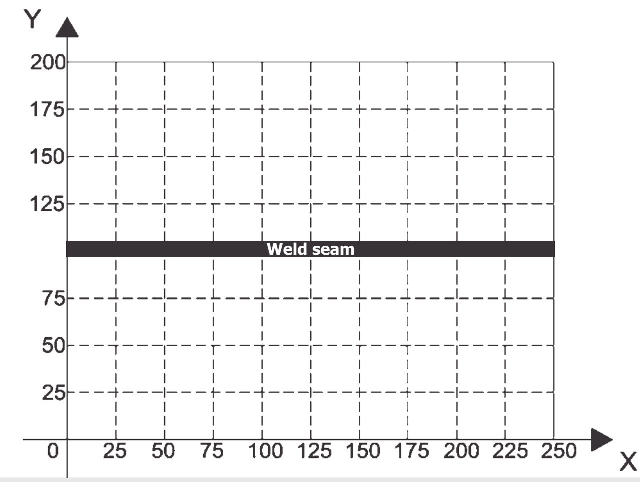


Fig. 3 : Layout for distortion measurement

2.5 Preparation of Samples

Samples were cleaned by acetone prior to welding for the removal surface contaminants. Specimen surfaces were free from oxide layers.

After welding, samples were cut perpendicular to the weld seam using abrasive cutting machine. The cut was made exactly middle in all the weld samples. Then cut samples were ground and polished at different stages followed by etching with 2% nital solution for 10 sec. The macrostructure of the specimen was captured by stereo microscope of LEICA E23. Carl Zeiss Axio vision 4.6 image analysis software was used to measure the fusion zone area.

Samples welded for distortion study in 2 mm thick sheets were prepared for microhardness and tensile strength test.

2.6 Microhardness Test

Microhardness test was carried out with respect to ASTM E384-17 standard by using Zwick/Roell ZHV equipment. 0.3 kg load was applied for dwell time of 15s and test was carried out at room temperature.

2.7 Tensile Strength Test

Tensile strength of the weldment was investigated as per ASTM E8/E8M-16a standard by using an electro-mechanical equipment Instron 5500R with a load cell of 30 kN. Dantec 3D-Digital Image Correlation (DIC) system was used to measure the distribution of strain on the specimen. The whole deformation process was recorded by the stereoscopic cameras which were mounted perpendicular to the testing surface. All the deformations were captured at the rate of 1 frame/s. The tensile specimen dimensions are shown in **Fig. 4**.

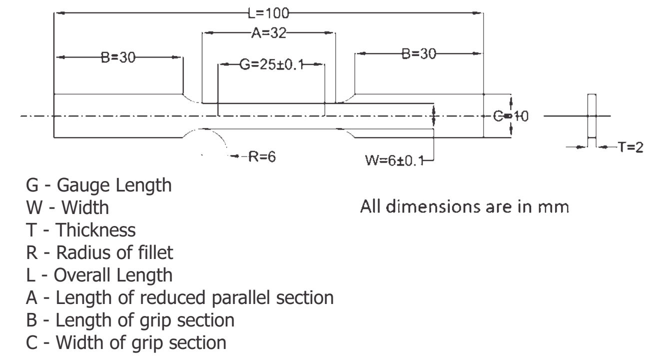


Fig. 4. : Tensile Specimen dimensions - 2 mm thick specimen

3.0 Results and Discussion

3.1 Effects of Welding Methods on Weld Morphology

GMAW process produced welds with better bead reinforcement and no visual defects were noticed. In all 2 mm, 4 mm and 8 mm thick samples, uniform bead reinforcement was observed and weld non-conformities were not observed as shown in Fig. 5. However, penetration depth was limited in 4 mm and 8 mm thick materials in GMAW process. Moreover, in GMAW process, penetration depth cannot be controlled independently with bead geometry. On the other hand, autogenous laser welding process produced welds with complete penetration in all the three thickness of materials without any spatters. No porosity was observed in the macroscopic evaluation. High power density and narrow heat source of laser produced complete penetration with less fusion zone and heat affected zone area. However, lack of reinforcement was found to be the limitation of ALW process. On the other hand, laser and arc with addition of filler wire in hybrid laser arc welding process, produced complete penetration with better bead reinforcement and high weld aspect ratio as shown in **Fig. 5**. Therefore, HLAW process provided more control over penetration depth and bead geometry. However, underfill was observed in 8 mm thick material. Wire feed speed and travel speed need be optimized for better bead profile in HLAW process [8].

Low heat input of ALW and HLAW processes results in 50% to 70% less fusion zone area than GMAW process. **Fig. 6** shows fusion zone area obtained against heat input.

Table 3 : Critical process parameters used for the experimentation

Study description	Thickness (mm)	Process	Sample No.	WFS (m/min)	TS (m/min)	P_L (W)	CTWD (mm)	Arc mode	Heat input (J/mm)
Weld bead geometry evaluation	2	GMAW	G - 1	5.6	0.5	-	11	CMT	298
		ALW	A - 1	-	4	2300	-	-	35
		HLAW	H - 1	8	4	2300	13.5	CMT	86
	4	GMAW	G - 2	8.2	0.5	-	11	CMT	583
		ALW	A - 2	-	4	5200	-	-	78
		HLAW	H - 2	8	4	5200	13.5	CMT	130
	8	GMAW	G - 3	10.2	0.5	-	11	CMT	716
		ALW	A - 3	-	1.5	7600	-	-	304
		HLAW	H - 3	3	1.5	7600	13.5	CMT	355
Gap bridgeability study	2	GMAW	G - 4	5.6	0.3	-	11	CMT	480
		ALW	A - 4	-	1	1200	-	-	72
		HLAW	H - 4	2	1	1200	13.5	CMT	130
Distortion study	2	GMAW	G - 5	5.6	0.5	-	11	CMT	355
		ALW	A - 5	-	4	2300	-	-	38
		HLAW	H - 5	8	4	2300	13.5	CMT	96
Filler wire diameter = 1 mm, Laser beam diameter = 0.6 mm									

3.2 Effect of Welding Methods on Productivity

In automotive welding applications, travel speed is the primary measuring stick for productivity. Thus, travel speed and weld penetration were taken as the determining factor for productivity with respect to quality. In GMAW process, complete penetration can be achieved in 2 mm thick sheet with acceptable weld quality at limited travel speed of 0.5 m/min. Further increase in travel speed resulted in lack of penetration whereas increase in both wire feed speed and travel speed resulted in burnthrough. However, achieving complete penetration in 4 mm and 8 mm thick materials without groove preparation were difficult as shown in **Fig. 5** (G-2 and G-3). On the other hand, high power density of laser welding processes produced complete penetration in all the three thicknesses of materials even at high welding speed of 4 m/min. Thus, the productivity of the process is significantly improved than GMAW process. Addition of arc energy in hybrid laser arc welding process even simplified the achievement of penetration and enhances the application of higher welding speed. Complete penetration with better weld bead profile was obtained in HLAW process. In ALW and HLAW process on 8 mm thick material, travel speed was limited to 1.5 m/min due to limitation on maximum power capacity of the laser system.

Therefore, both ALW and HLAW processes were improved productivity by a factor of 8 times in both 2 mm and 4 mm thick plates whereas 3 times improved productivity was obtained in 8 mm thick plates. **Fig. 7** shows the maximum travel speed at which optimal weld bead quality was obtained in different welding processes.

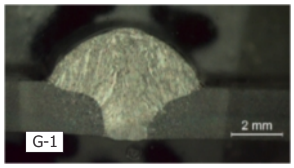
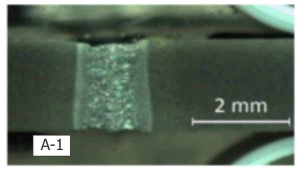
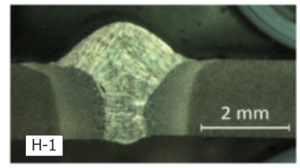
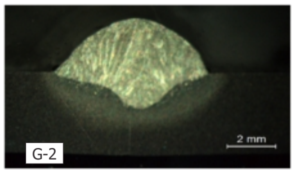
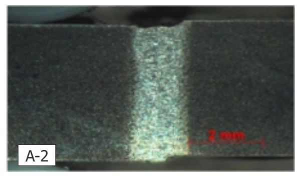
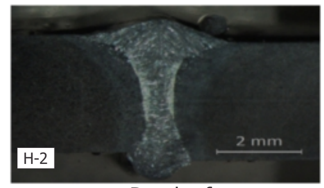
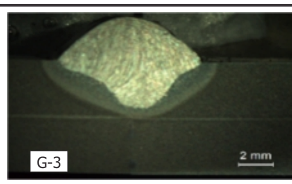
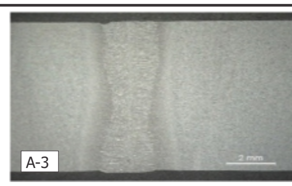
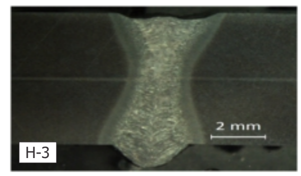
Thickness	GMAW	ALW	HLAW
2 mm	 Depth of penetration = 100%	 Depth of penetration = 100%	 Depth of penetration = 100%
4 mm	 Depth of penetration = 69%	 Depth of penetration = 100%	 Depth of penetration = 100%
8 mm	 Depth of penetration = 41%	 Depth of penetration = 100%	 Depth of penetration = 100%

Fig. 5 : Macrographs of welds

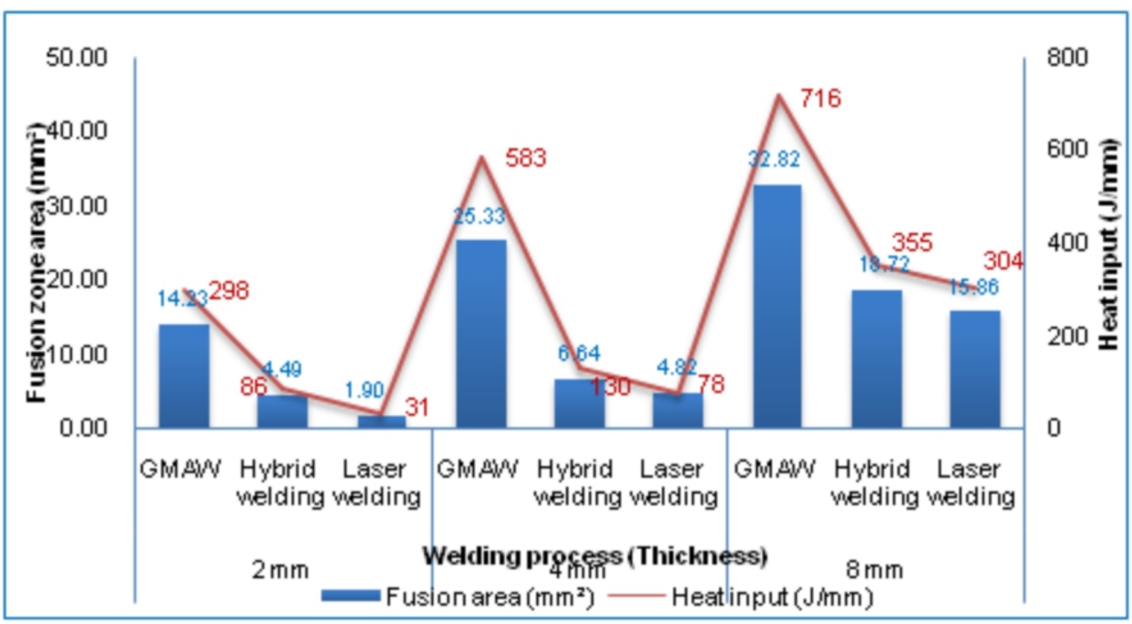


Fig. 6 : Comparison of fusion zone area obtained in different welding processes at different heat input

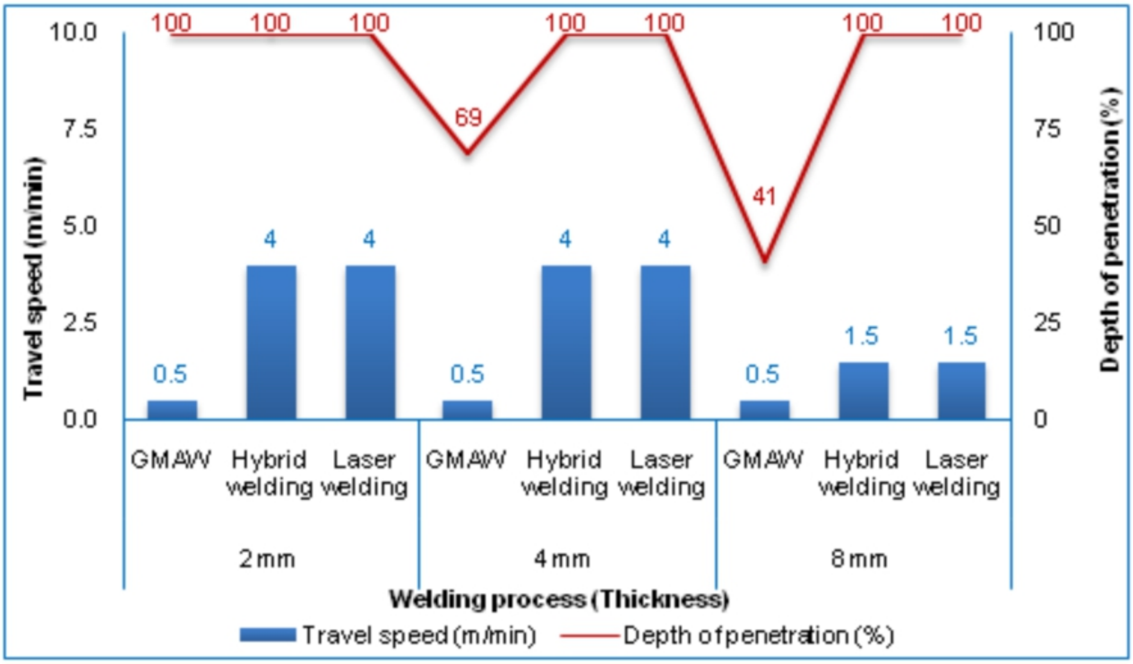


Fig. 7 : Comparison of penetration achievement in different welding processes at different travel speed

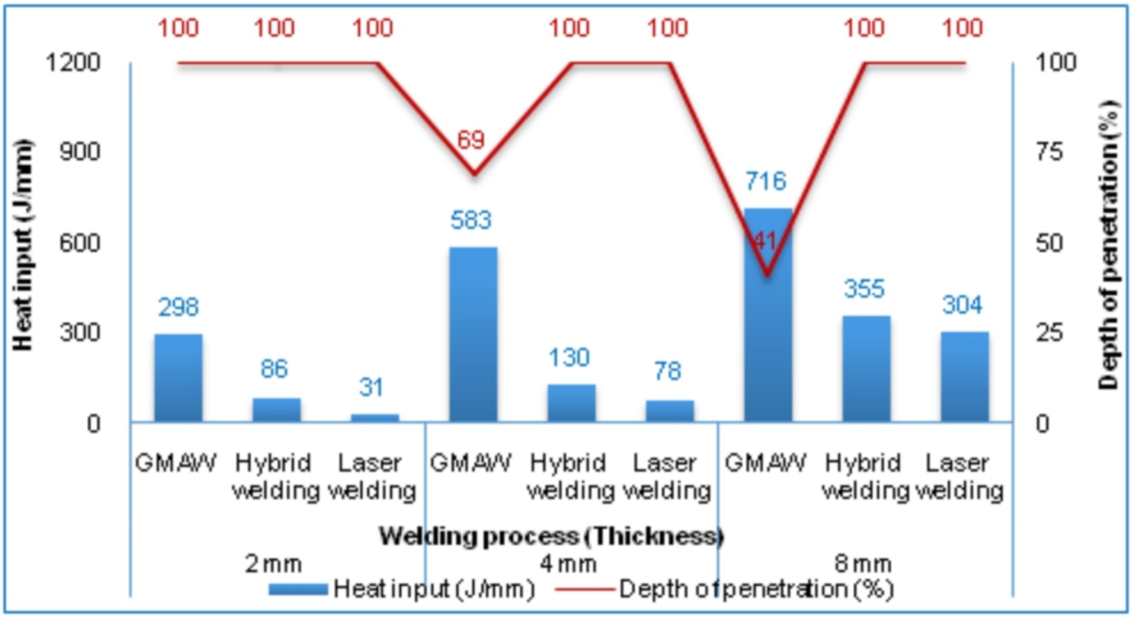


Fig. 8 : Comparison of penetration achievement in different welding processes at different heat input

3.3 Effect of Welding Methods on Heat Input

High power density of ALW and HLAW processes produced deep penetration at very low heat input than GMAW process.

Fig. 8 shows heat input against penetration achievement. It indicates that complete weld penetration can be achieved in ALW and HLAW processes even at lower heat input. GMAW process provided aesthetically acceptable welds with maximum penetration of 69% and 41% in 4 mm and 8 mm thick plates respectively whereas both ALW and HLAW processes produced 100% penetration even at 70% to 80% less heat input than GMAW.

Increase in heat input results in increase of fusion zone area as shown in **Fig. 6**. Heat input shows a near-linear relation with fusion zone area (2 mm thick samples) which can be referred in **Fig. 9**. 68% and 87% of reduced fusion zone area were observed in HLAW and ALW processes respectively than GMAW process. Moreover, low heat input resulted in less metallurgical damage to the material.

3.4 Effect of Welding Methods on Gap Bridgeability

GMAW and HLAW processes are superior to autogenous laser welding process in the aspect of gap bridgeability. At root gap conditions, ALW process produced welds with critical defects such as underfill, incomplete weld and root concavity. The depth of underfill increases with root gap. The decrease in amount of material available for melting and increase in joint area as root gap increases causes the formation of underfill. Addition of filler metal in GMAW and HLAW processes enhances the gap bridging capability of these processes. Hybridization of laser and arc in HLAW process provide better gap bridgeability with complete penetration in all the three thickness of materials even at both 0.5 mm and 1 mm root gap conditions as shown in **Fig. 10**. Better gap bridgeability with complete penetration was found to be advantageous in HLAW process.

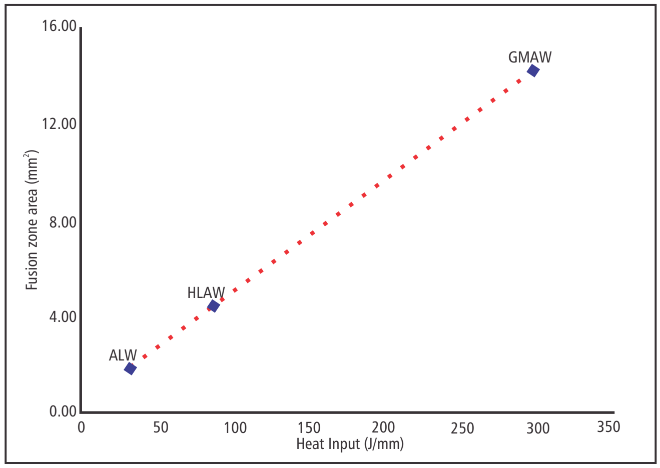


Fig. 9 : Variation of fusion zone area with heat input - 2 mm thickness

Underfill was the main issue in welding of higher thickness material by HLAW process. Therefore, wire feed speed and travel speed would be the key factors which need be optimized according to the range of root gaps in order to obtain better weld quality in HLAW process [8].

Gap bridgeability of all three welding processes can be ordered as below (Higher the better).

GMAW > HLAW > ALW

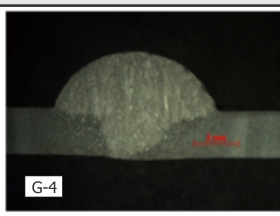
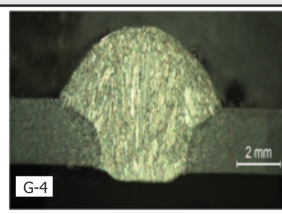
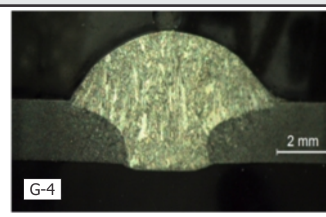
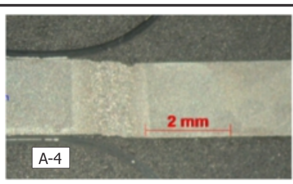
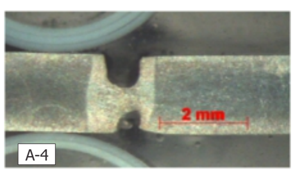
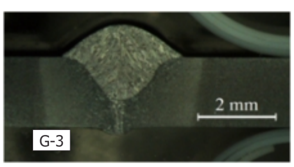
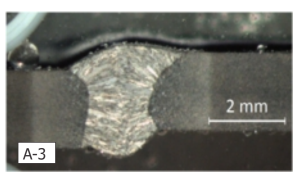
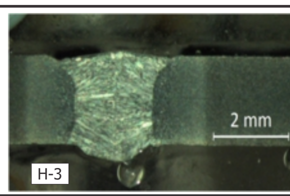
Process/ Root gap	0 mm gap	0.5 mm gap	1 mm gap
Gas metal arc welding			
Autogenous laser welding			
Hybrid laser arc welding			

Fig. 10 : Weld cross-sections of different welding processes at different root gap conditions- 2 mm thickness

3.5 Effects of Welding Methods on Distortion

High power density of laser welding processes was produced complete penetration with low distortion than GMAW process. This is due to much higher energy is needed for penetration in GMAW process than laser processes which consequently increases the distortion index as it is proportional to heat input. Low heat input of ALW and HLAW processes results in less distortion than GMAW process. Heat input exhibits a near-linear relation with distortion as shown in **Fig. 11**. In 2 mm thick samples, 75% and 84% of less distortion index and 72% and 83% of less peak distortion are observed in HLAW and ALW processes respectively than GMAW process as shown in **Fig. 12** and **Fig. 13**. Moreover GMAW process produced more surface deflection than the ALW and HLAW processes as shown in **Fig. 14**.

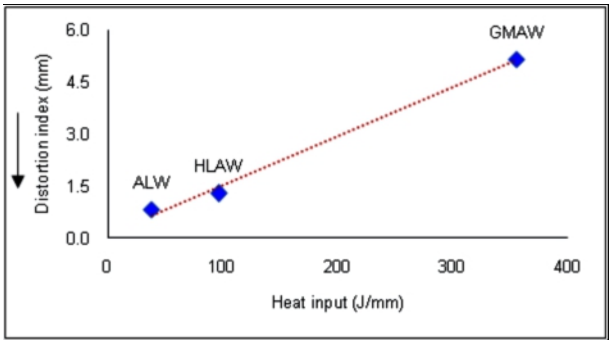


Fig. 11 : Variation of distortion index with heat input – 2 mm thickness

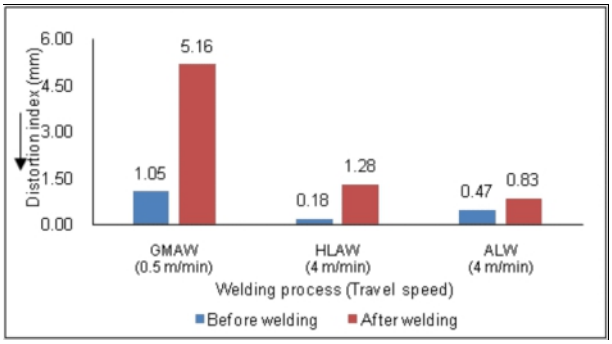


Fig. 12 : Comparison of distortion indices of different welding process conditions– 2 mm thickness

Fig. 11 shows a near-linear trend which proves that distortion is process independent but only depends on the ratio of heat input per depth. GMAW needs to melt more metal to penetrate the same thickness than laser and hence, higher ratio of the melt area to depth and greater the distortion.

Distortion propensity of all three welding processes can be ordered as below (Lower the better).

ALW < HLAW < GMAW

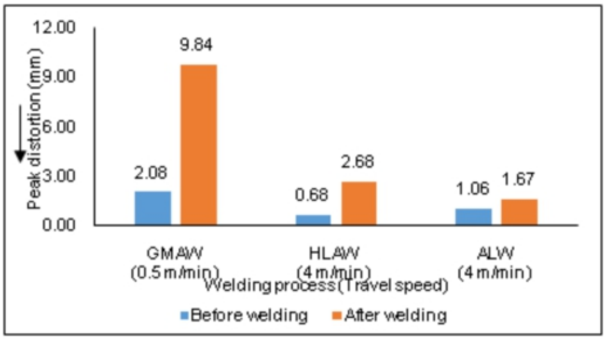


Fig. 13 : Comparison of peak distortion of different welding process conditions– 2 mm thickness

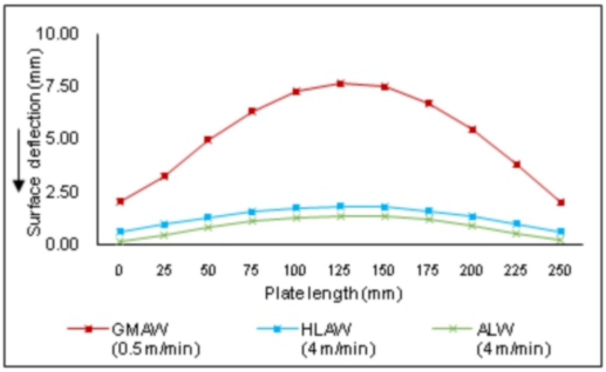


Fig. 14 : Comparison of surface deflection produced by different welding processes – 2 mm thickness

3.6 Effect of Welding Methods on Micro-hardness

The hardness distribution of GMAW, HLAW and ALW welded joints are compared in **Fig. 15**. The average hardness in fusion zone of GMAW, HLAW and ALW processes are 192 HV0.3, 224 HV0.3 and 298 HV0.3 respectively. The average hardness achieved in HAZ of joints welded by all three processes is higher than the hardness of base material. Comparatively, ALW process produced joints with higher hardness than HLAW an GMAW joints. High cooling rate of laser welding processes, increases the hardness in fusion zone.

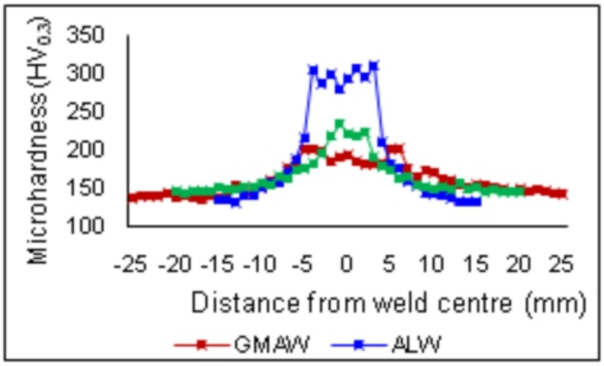


Fig. 15 : Microhardness profiles achieved with different welding processes at welding speed of 0.5 m/min-GMAW (355 J/mm), 4 m/min-HLAW (96 J/mm), 4 m/min-ALW (38 J/mm) – 2 mm thick joints

Average hardness in the fusion zone of all three processes follows the below mentioned sequence.

ALW > HLAW > GMAW

3.7 Effects of welding methods on tensile strength

As from the hardness measurement results of all three processes, higher hardness in weld region than base materials indicates that weld regions are stronger than base material. Consequently, fracture occurred in base material of all the samples during tensile test. Weld zone and HAZ were not experienced to have any fracture. Digital image correlation (DIC) system supports for visualization of relative displacement in sample and thereby enabling the identification of fracture zone [12]. At increasing load condition, DIC test results showed that increase in strain on the weld metal is negligible in samples of all three welding processes. For instance, comparison of strain distribution in sample welded by HLAW process is shown in **Fig. 16**. It can be inferred that as load increases strain on the base material increases and finally fracture occurred on the base material.

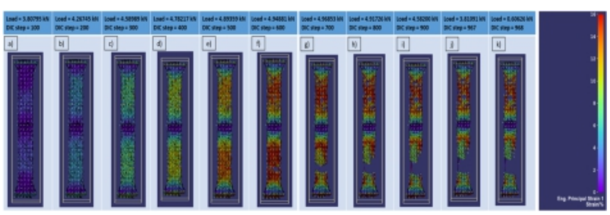


Fig. 16 : Comparison of strain distribution at different load conditions in 2 mm thick sample welded by HLAW process at welding speed of 4 m/min

3.8 Subjective Comparison of Welding Processes

From the above investigation, subjective comparison of all three welding processes has been done as shown in **Fig. 17**; it can be inferred that hybrid laser arc welding process can be recommended for automotive structural application. The key benefits are significant improvement in productivity with enhancement of quality improvements including deep penetration, low distortion, better mechanical properties and good gap bridgeability.

Process	Productivity	Heat input	Bead geometry	Gap bridging	Distortion	Mechanical properties
GMAW	Low	High	Good	Good	High	Good
ALW	High	Low	Poor	Poor	Low	Good
HLAW	High	Low	Good	Good	Low	Good

Good Fair Poor

Fig. 16 : Subjective comparison of welding processes

4.0 Conclusion

Through this investigation, different welding processes such as GMAW, ALW, and HLAW processes were compared in different aspects. Based on the experimental results the following are the conclusions arrived.

- ALW and HLAW processes improved the productivity by a factor of 8 times compared to GMAW process in 2 mm and 4 mm thick plates. In 8 mm thick plates, an improvement of productivity by a factor of 3 times was achieved.
- Both ALW and HLAW processes produced welds with considerably less fusion zone area than GMAW process.
- Lack of reinforcement was found to be a critical limitation of ALW process whereas addition of filler wire in HLAW process was produced welds with uniform reinforcement even at comparable welding speed with ALW process.
- HLAW process produced acceptable welds even with a root gap of 1 mm whereas ALW process could not produce acceptable welds in the experimented conditions.
- ALW process produced least distortion whereas GMAW exhibited larger distortion. ~75% and ~85% less distortion was observed in HLAW and ALW processes respectively than GMAW process.
- Heat input exhibited a near-linear relation with distortion index and fusion zone area.
- The microhardness in ALW joint was found to be higher than GMAW and HLAW joints. In ALW and HLAW joints, average fusion zone hardness was increased by 55% and 17% than GMAW joints respectively.
- HLAW and ALW processes produced stronger weld region with higher hardness than base material hence fracture occurred in the base material and increase in strain on the weld bead was negligible. Moreover, larger the bead area lower the strain on the weld.

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