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Influence of the Gap Width on the Geometry of the Welded Joint in Hybrid Laser-Arc Welding

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Abstract

The aim of this research was the experimental investigation of 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 RS E36. The research was divided into three parts. First, in order to understand the influence of the gap width on the welded joint geometry, experimental research was done using continuous wave fiber laser IPG YLS-15000 with arc rectifier VDU-1500DC. The second part involved study of the geometry of the welded joint and hardness test results. Three macrosections from each welded joint were obtained. Influence of the gap width and welding wire speed on the welded joint geometry was researched in the three lines: in the right side of the plates, middle welded joint and in the root welded joint.

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Keywords: Hybrid laser-arc welding, gap influence, welded joint geometry, mathematical model, high strength steel

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1. Introduction

The first mention of laser-arc welding was made in 1978 by W.M. Steen (Eboo et al., 1978). Today, hybrid laser-arc welding (HLAW) is widely used in different branches of industry: pipe industry (Rethmeier et al, 2013), (Turichin et al., 2014), shipbuilding (Dilthey et al., 2006), bridge-building (Sorrentino S. et. al., 2009), carriage engineering (Hansen, 2013), aerospace industry (Verhaeghe, 2007) and many others (Wouters, 2005).

The wide use of HLAW in the industrial world can be explained by advantages of the HLAW in comparison to the traditional types of welding. The most important of them are high productivity, low distortions, the possibility to vary of the mechanical properties of the welded joint and the ability to weld with a gap (El Rayes et al., 2004). The research of the influence of gap width on the weld geometry and mechanical properties using HLAW is important for determining the mechanical pre-processing accuracy and assembly of welding samples for the implementation of longitudinal seams in pipe industry, joining of panels in shipbuilding and other areas of the heavy engineering industry.

Different experimental researches in this field have been carried out. The welded joint had good appearance at the gap width from 0 mm to 0.4 mm at the experimental research of the influence of gap width at the HLAW for commercial pure titanium plates with thickness 1.5 mm (Li et al., 2010). Kong et al. (2013) found that tensile strength decreases and fracture of the tensile tests moved from base metal to HAZ at the HLAW of high-strength AISI A514 steel with thickness 6.63 mm when increasing gap width from 0 mm to 1.25 mm. Also the inner defects at about 1 mm air gap weren't found. I. Tsibulskiy al. (2014) experimentally showed that the highest efficiency and deepest penetration of alloy elements of the welding wire at the HLAW with gap width of 1 mm at the welding shipbuilding steel RS E36 with thickness 20 mm for one pass. In this work, the gap was varied from 0 mm up to 1 mm. Good weld appearance at the HLAW aluminum alloy A5052 with thickness 2 mm was observed with a gap width from 0 mm up to 0.5 mm (Wang et al., 2013). Also comparison of maximal gap width at laser welding and HLAW has been carried out (Ono et al., 2002). Good weld appearance was created at the HLAW of the low alloy high strength steel with thickness 16 mm with a various gap widths from 0 mm up to 0.7 mm (Rethmeier et al., 2009). Also it can be seen that researches of the influence of gap width on the weld geometry at the HLAW are ongoing (Brandizzi et al., 2013).

The article includes experimental research of the influence of the gap width on the welded joint geometry, analysis of experimental results for the future creation of a mathematical model, which will be able to predict the welded joint geometry for an arc welding process with different gap widths. The connection of the model with the engineering analyzation system LaserCAD will allow to predict the welded joint geometry at the HLAW with different gap widths.

2. Experimental methods

2.1. Experimental set up

Plates from low-alloy high strength steel RS E36 with overall dimensions 230 x 70 x 7 mm and welding wire Power bridge 60M (Pb 60M) with diameter 1.6 mm were used as welding materials. Chemical compositions and mechanical properties of the steel and welding wire are given in the Table 1 and the Table 2 respectively.

Table 1 – Chemical compositions (wt%) of the base material (upper) and welding wire (lower).

	C	Si	Mn	P	S	Al	Cr	Ni	Cu	V	Nb	Fe
RS E36	0.18	0.15	0.9	-	-	0.02	-	-	-	0.05	0.02	Bal.
		0.5	1.6	0.02	0.015	0.06	0.3	0.4	0.35	0.10	0.05	
Pb 60M	0.04	0.4	1.3	-	-	-	-	0.4	-	-	-	Bal.
	0.08	0.8	1.6	0.015	0.015			0.6				

Table 2 – Mechanical properties of the base material (GOST 5521-93) and welding wire (GOST 26271)

Mechanical properties	RS E36	Pb 60M
Ultimate tensile strength, MPa	490-620	590-700
Yield strength, MPa	355	> 470
Elongation, %	21	≥ 21
Impact energy, J at temperature -40°	> 24	≥ 50

A 15 kW fiber laser LS–15 and rectifier VDU – 1500 DC were used. Technical characteristics of the laser and the arc sources are given in Table 3.

Table 3 - Technical characteristics of the Nd:YAG laser and semiautomatic welding machine.

Characteristics	Typical value
Fiber laser LS – 15	
Operation mode	Continuous wave (CW) mode
Maximal output power, kW	15
Emission wave length, nm	1070
Beam parameter product, mm/mrad	6.7
Working fiber core diameter, μm	200
Focusing lens focal length, mm	400
Focal point diameter, μm	450
Arc rectifier VDU – 1500 DC	
Arc current, A	200 – 1500
Current and voltage at continuous loading 60%	1250A / 44V
Arc voltage, V	20 – 55
Supply voltage	380V / 50 Hz / 3 phases
Arc type	Continuous

HLAW was carried out in the PA welding position. Arc torch had angle 30° from vertical axis with wire stick out 16 mm, see Figure 1. Arc had a leading position. Distance from axis of electrode to laser beam axis was 3 mm. Laser beam focal plane was 5 mm under the top surface of the plate. Mixture of Ar and CO_2 was used for welding pool shielding in ratio 80%-20% with rate 25 l/min.

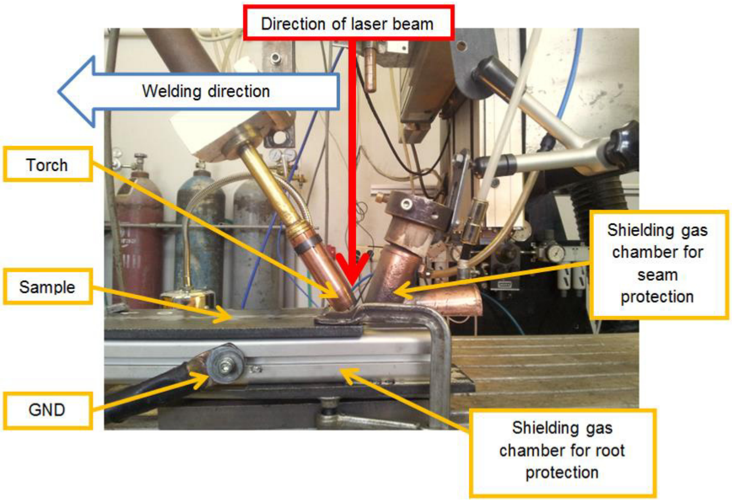


Fig. 1 – Experimental set up.

2.2. *Detection methods of a quality and estimation of the welds*

All welds were inspected visually. Three macrosections were made from every weld using saw band and macrosections preparation system Buhler. All macrosections were etched by 10% nitric acid.

The total estimation of the weld quality was carried out using visual inspection and metallography research using optical microscope Observer (Carl Zeiss).

Weld area and weld metal geometry was measured using digital photos of the macrosections and demo version software “Datinf Measure”. The welded metal geometry was measured in three lines: top surface of the plate, in the middle and on the return surface of the weld, Fig. 2.

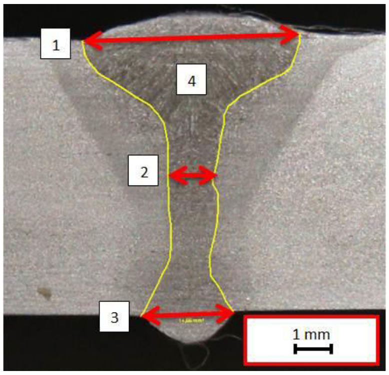


Fig. 2 - Measurements of the weld geometry:
1 – top surface of the plate; 2 – middle of the plate; 3 – return surface of the plate; 4 – weld metal area.

2.3. Testing Equipment

Estimation of the welds hardness (HV_1) was carried out according to DIN EN ISO 14577 using macrosections. Hardness tests were performed across the weld metal, fusion zone, HAZ and the base metal. The tests were done at room temperature in three lines: 2 mm above the root, in the middle of the weld and at 2 mm from the top of the weld using micro hardness equipment MicroMet 5103 with measurement error about ±10 HV.

2.4. Design-of-experiment method

HLAW stability was checked by welding the sample no. 4 with varied gap (from 0.6 mm to 1.5 mm) for creation of design-of-experiment plan with variable gap size. The indicator of the HLAW stability was a welded joint with good formation. Therefore the HLAW with stable good welded joint formation was defined on the distance 178 mm from the start. The end point of the HLAW stability had a critical gap size about 1.3 mm. The root of the sample is shown in Fig. 3.

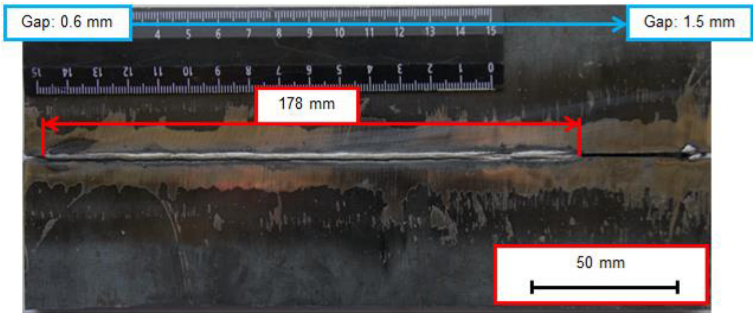


Fig. 3 - View of the root side of weld no. 4 with variable gap width.

Single-factor experiment was created by varying the gap width from 0 mm to 1.2 mm with step of 0.3 mm while other HLAW parameters were kept constant. Arc current and voltage depended from welding wire feed rate and therefore they were varied too, see Table 4.

3. Experimental results

HLAW of the welds was carried out at the welding speed (V) of 25 mm/sec with laser power (P_L) of 7000 Watt. Welding wire (V_w) rate was 4.3 m/min. Arc current (I_A) and arc voltage (U_A) were 290 A and 25 V accordingly. The gap width and appearance of the welds produced are presented in the Table 4.

Table 4 – Variable HLAW parameters and welded joints appearance.

No.	Gap width, mm	Top weld appearance	Root weld appearance
1	0		
2	0,3		
3	0,6		
4	0,9		
5	1,2		

All welds had a stable full penetration. Welds with 0 mm and 0.3 mm gaps had good top bead. Other welds had top beads with undercut or didn't have it. Welds with gap 0 mm and 1 mm with welding wire feed rate 9.1 m/min had root bead with drops. All other welds had good root beads. It was noticed the height of the top bead was decreased with increasing gap widths. Welds geometry was changed from "cup-shaped" form to "vase-shaped" form. One from three macrosections of the overall welds is shown on the Fig. 4.

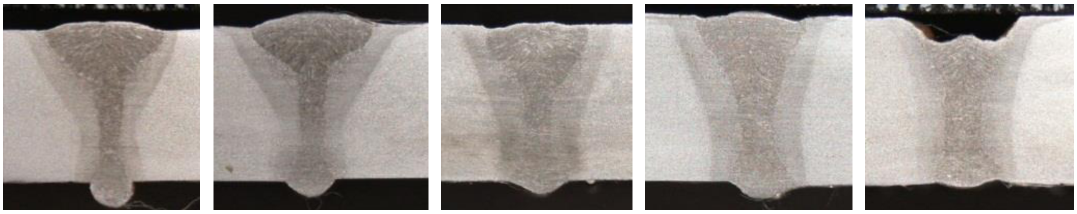


Fig. 4 – Weld macrosections with different gap width: a – 0 mm; b – 0.3 mm; c – 0.6 mm; d – 0.9 mm; e – 1.2 mm.

3.1. Influence of the gap width on the welded joint geometry at the HLAW

The measurement of the weld metal geometry in the three lines and weld metal area shows their dependence from the gap width. Thus weld metal width on top of the plates decreased at the increasing gap width from 0 mm up to 0.3 mm. The next increasing gap width didn't have a strong influence on the weld metal width on the top plate. Weld metal width in the root and in the half depth increased when the gap width was increasing; therefore the weld metal area increased too. And therefore the welding wire alloy element penetration increased too. Influence of the gap width on the average values of the weld metal width from the three macrosections is visualized in Fig. 5.

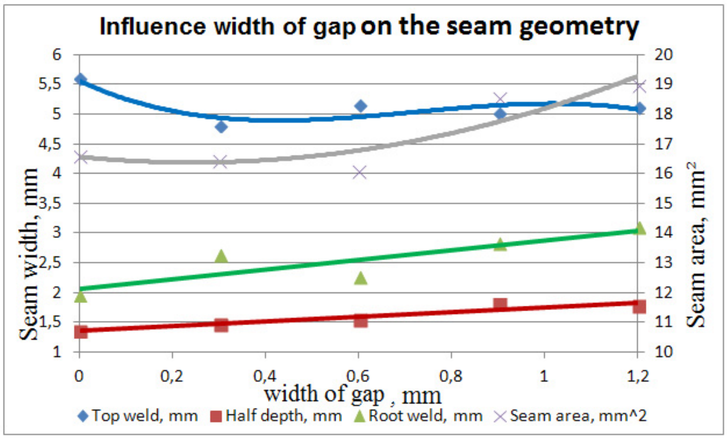


Fig. 5 – Influence of the gap width on the weld metal geometry.

3.2. Influence of the gap width on the top bead area

Welded joints with a gap of 0 mm and 0.3 mm had well defined bead shape on the top plate, see Fig. 4. Other welds had undercuts or lack of the weld metal. For estimation of the bead area or the lack of weld metal area in the top part of the weld all calculations were carried out in relation to weld no.1 bead. For example, the average bead area of the weld no.1 is 1.74 mm^2, and weld no.5 with 1.2 mm gap had a lack of weld metal area of 3.91 mm^2. Therefore total lack weld metal area of the weld no.5 is 5.62 mm^2, as shown in Fig 6. The calculated results are presented graphically in Fig. 7.

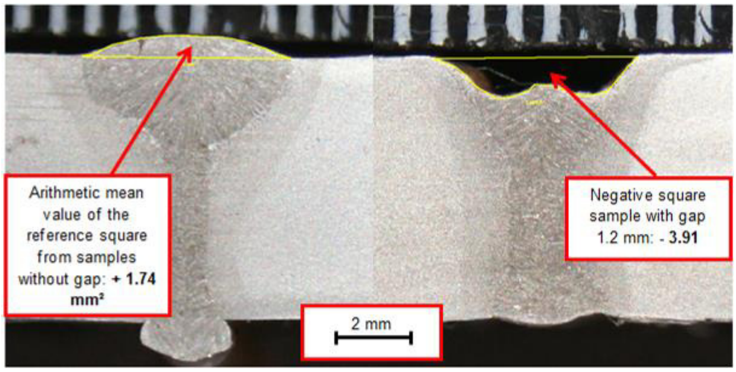


Fig. 6 – Visualization of the material loss in relation to gap size.

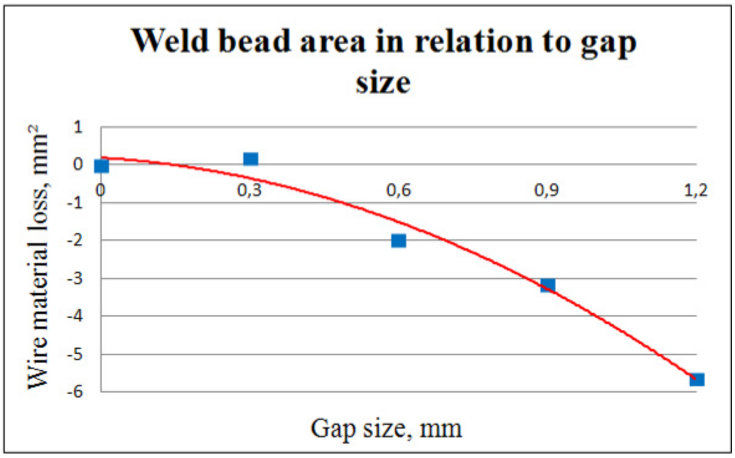


Fig. 7 – Weld bead or weld metal lack area.

The graph shows that there exists a proportional relation between the gap size growth and the loss of material on the top of the weld. Also it seems that a welding process with just small gaps <0.3 mm is not vulnerable for this phenomenon. But after the gap increases above 0.6 mm, the top of the seam starts decreasing quite fast. At a gap size of 1.2 mm, an average amount of the lost weld metal area 5.34 mm² was detected. Assuming that up to a 0.3 mm gap no material loss occurs, there exists quite a linear relation from the gap size of 0.3 mm till 1.2 mm. Within this interval the increase of material loss per 0.1 mm gap size can be calculated to be 0.61 mm².

3.3. Influence gap size on the HLAW efficiency

Thermodynamic efficiency was accepted as efficiency of the HLAW. Sum of the energy from two heat sources was calculated using input HLAW parameters in one side and energy used for heating and melting weld metal in other side for defining HLAW efficiency. Results of the weld metal measuring for welded joints no. 1 and no. 5 are shown in Fig. 8. Influence of the gap width on the HLAW efficiency is shown in Fig. 9.

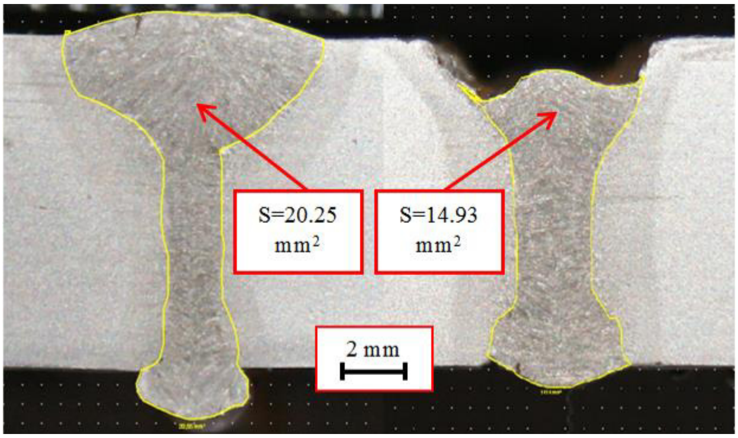


Fig. 8 – Defining the weld area.

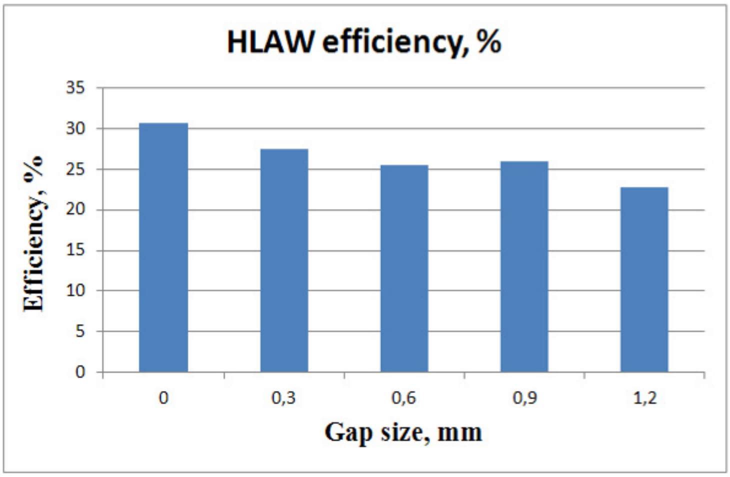
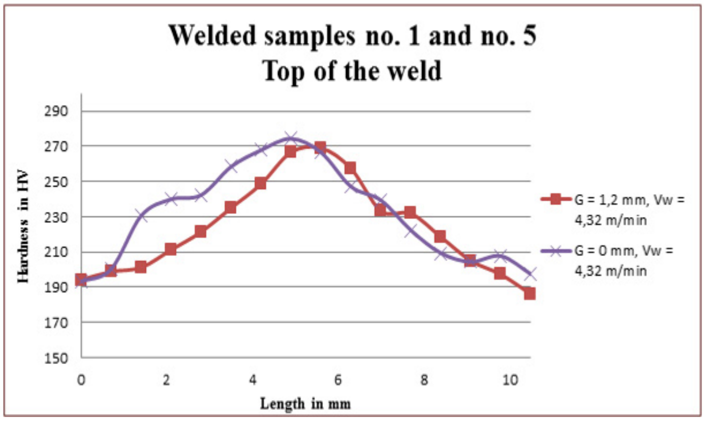


Fig. 9 - Influence of width of the gap on the HLAW efficiency.

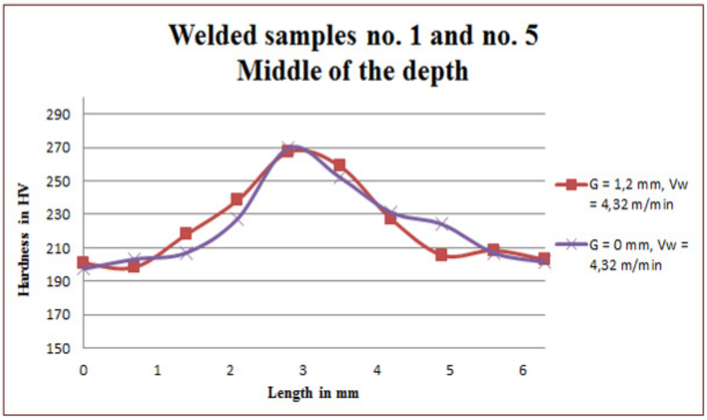
As it can be seen from the Fig. 9, the maximal efficiency of the HLAW is at the gap width 0 mm. The minimal efficiency occurrs at the gap width 1.2 mm. It can be explained that with increasing gap the welding pool width increases too, and, therefore the volume of the dropping melting metal is higher. The reason for this is gravity. Thus Tsibulskiy et al., (2014) found that at the HLAW in PC welding position the maximal efficiency at a gap width of 1 mm. The PC welding position excludes the influence of gravity on the dropping melting metal.

3.4. Hardness test results

The influence of the gap width on the weld metal hardness HV_1 using macrosections of the welded joints no.1, 5 was not noticed. The differences between the chosen samples that represent the welding process without gap and the highest gap just vary in an interval of the hardness testing machine inaccuracy ±10%, as shown in Fig. 10. It is possible that influence was not detected because of base material and welding wire had similar mechanical properties.



a



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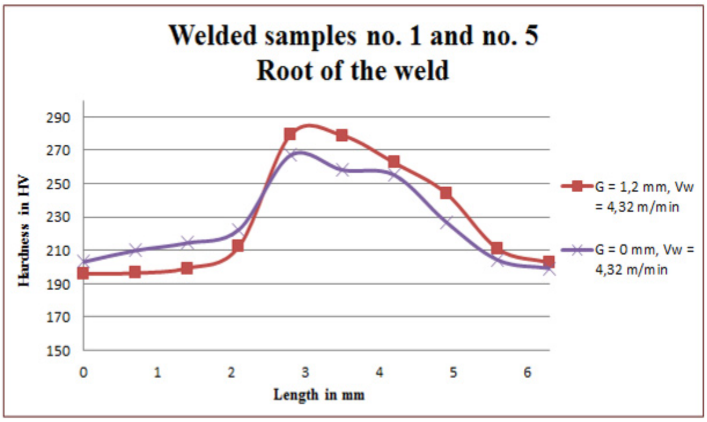

c

Fig. 10 – Influence of the gap width on the weld metal hardness: a – Top of the weld; b – Middle of the weld; c – Root of the weld.

4. Conclusions

The influence of the gap width on the weld metal geometry and mechanical properties using HLAW with 7 mm thick shipbuilding steel RS E36 was studied. The best formation of the welded joint without outside defects was noticed at the gap width from 0 mm up to 0.3 mm. A good formation of the welded joint, but with undercuts, was observed at the gap widths from 0.6 mm up to 0.9 mm. At the gap width 1.2 mm the welded joint had a lack of weld metal. The volume of the welding wire in the root and half depth of the weld increased simultaneously with increasing gap width. Weld metal width on the top did not change between gaps from 0.3 mm up to 1.2 mm and decreased a little with gaps from 0 mm up to 0.3 mm. Also it was found that increasing the gap width from 0 mm up to 1.2 mm decrease HLAW efficiency from 30.6% to 22.7%. The results of the experimental research will be further used for the creation of a mathematical model for the prediction of the welded joint geometry at arc welding and HLAW with gap.

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