Martin Petreski [1,a], Dobre Runchev [1,b], Gligorche Vrtanoski [1,c], Aleksandra Krstevska [1,d]

EFFECT OF SYNCHRONIZING GMAW AND LBW PROCESSES ON WELD QUALITY AND MECHANICAL CHARACTERISTICS OF STRUCTURAL STEEL

UTICAJ SINHRONIZACIJE GMAW I LBW PROCESA NA KVALITET ZAVARA I MEHANIČKE KARAKTERISTIKE KONSTRUKCIONOG ČELIKA

Original scientific paper / Originalni naučni rad

Paper received / Rad primljen:

June 2026.

Paper accepted / Rad prihvaćen:

September 2026.

Author's address / Adresa autora:

[1] Ss. Cyril and Methodius" University of Skopje, Faculty of Mechanical Engineering, Skopje, Republic of North Macedonia

Email / ORCID ID:

[a] martin.petreski@mf.edu.mk / 0000-0001-6308-3366
/ [b] 0000-0001-7657-1799
/ [c] 0009-0000-1318-015X
/ [d] 0000-0002-5596-6596

Keywords: hybrid welding, welding parameters, tensile strength, hardness, penetration depth

Ključne reči: hibridno zavarivanje, parametri zavarivanja, zatezna čvrstoća, tvrdoća, dubina penetracije

Abstract

The combination of two or more welding processes within the same welding pool offers significant advantages over the limitations of individual processes. This paper presents an experimental investigation of Hybrid Laser Arc Welding (HLAW) achieved by synchronization Gas Metal Arc Welding (GMAW) and Laser Beam Welding (LBW), with the aim of evaluating theirs positive effects on the weld characteristics. The experiments were performed on 12 mm thick S355J2+N structural steel in a zero-gap butt joint configuration. The process parameters were kept constant for the individual GMAW and LBW processes, as well as for the HLAW process: laser beam power 8 kW, welding speed 1,5 m/min, welding current 316 A and arc voltage 33,1 V. The quality of the weld and its mechanical characteristics were determined by non-destructive testing, tensile testing and hardness measurements. The experimental results show that the applied welding parameters enable deeper penetration by HLAW process compared to conventional GMAW process. The synergistic interaction between the electric arc and laser beam improves energy efficiency and reduces stringent edge preparation requirements, resulting in lower overall heat input, improved tensile strength and a hardness reduction of at least 50 HV, particulary in the laser zone. These findings demonstrate the potential of the HLAW process as an efficient and reliable welding process for high-productivity industrial applications.

Rezime

Kombinacija dva ili više procesa zavarivanja unutar istog zavarivačkog kupatila nudi značajne prednosti u odnosu na ograničenja pojedinačnih procesa. Ovaj rad predstavlja eksperimentalno istraživanje hibridnog laserskog zavarivanja (HLAW) postignutog sinhronizacijom elektrolučnog zavarivanja topljivom elektrodom u zaštitnom gasu (GMAW) i zavarivanja laserskim snopom (LBW), sa ciljem procjene njihovih pozitivnih efekata na karakteristike šava. Eksperimenti su izvedeni na konstrukcionom čeliku S355J2+N debljine 12 mm u konfiguraciji sučeonog spoja bez zazora. Parametri procesa održavani su konstantnim za pojedinačne GMAW i LBW procese, kao i za HLAW proces: snaga laserskog snopa 8 kW, brzina zavarivanja 1,5 m/min, struja zavarivanja 316 A i napon luka 33,1 V. Kvalitet šava i njegove mehaničke karakteristike utvrđeni su ispitivanjima bez razaranja, zateznim ispitivanjem i mjerenjem tvrdoće. Eksperimentalni rezultati pokazuju da primijenjeni parametri zavarivanja omogućavaju dublju penetraciju HLAW procesom u poređenju sa konvencionalnim GMAW procesom. Sinergijska interakcija između električnog luka i laserskog snopa poboljšava energetsku efikasnost i smanjuje stroge zahteve za pripremu ivica, što rezultira manjim ukupnim unosom toplote, poboljšanom zateznom čvrstoćom i manjom tvrdoćom za najmanje 50 HV, posebno u zoni delovanja lasera. Ovi nalazi demonstriraju potencijal HLAW procesa kao efikasnog i pouzdanog procesa zavarivanja za industrijske primene visoke produktivnosti.

The paper was published in its original form in the Proceedings of the 1st Conference with international participation "Technology of Joining Materials" held in Bečići, Montenegro from May 14 to 16, 2026.

1. Introduction

In recent years, traditional manufacturing processes have gradually failed to meet the needs of the manufacturing industry due to the rapid development of the economy. Global trends in manufacturing of welded components are characterized by a growing demand for reduced welding operation costs and welding cycle times on the one hand and consistent or even improved, quality and mechanical integrity of welded components on the other [1]. In this context, welding processes are in urgent need of innovation and improvement, and welding-related industries must keep pace with international advanced standards [2]. One such advancement is automated Hybrid Laser Arc Welding (HLAW), which integrates the benefits of Laser Beam Welding (LBW) and Gas Metal Arc Welding (GMAW), offering a highly efficient alternative to conventional welding processes [3].

The HLAW has gained significant attention in various industrial applications due to its ability to leverage the synergistic benefits of both processes, including high welding speed, low residual stresses, minimal distortion, deep penetration, and the ability to control the chemical composition of the weld seam [4].

Despite its numerous advantages, the process has certain limitations, such as high equipment costs and the need to precisely control multiple welding parameters to prevent defects and avoid solidification cracking, particularly when welding thick-section steel [3]. Moreover, the efficiency of HLAW depends not only on the proper selection and synchronization of welding parameters, but also on the method of edge preparation.

Therefore, the aim of this study is to investigate the effect of synchronizing GMAW and LBW processes on weld seam quality and its mechanical characteristics by welding the 12 mm thick structural steel in a zero-gap butt joint configuration. Several single-pass welds were performed using constant welding parameters for the individual GMAW and LBW processes, as well as for the HLAW process.

2. Materials and methods

For the welding experiments of the present stud, S355J2 structural steel with thickness of 12 mm where employed. The pieces were cut to dimensions 150 x 400 mm before welding preparation. The welds were performed in an I-joint configuration with zero-gap. The welding wire used for HLAW was a solid wire G3Nil according to EN ISO 14341-A: G 42 3 M21 3Sil with a diameter of 1.2 mm. As a shielding gas is used a mixture of argon with 18% CO2 - CORGON 18 according to EN ISO14175: M21 ArC 18 with a flow rate of 25 1 min-1. The base material has a carbon equivalent value of max. 0.39 (CEIw for low alloy steels, CEIIW = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15).

For edge preparation two different industrial methods are used: milling and plasma cutting. The average measured profile of the edges for milling and plasma cutting are following: roughness of profile 1.84/3.64 μm (Ra), height of profile 4.66/12.14 μm (Rp) with waviness included, and mean peak to valley height of primary profile 8.68/ 20.67 μm (Rz). The plasma cutting edges are characterized with higher roughness with visible striations, that lead to no zero-gap between the pieces, at the bottom it is nearly 0 mm and opens slightly towards the top.

A high – power fiber laser IPG YLR-20000 of IPG was used in the experiments with the following parameters: an optical fiber with a 200 μm, beam parameter product of 11 mm×mrad, and 1070-nm wavelength. A laser processing head, BIMO HP, with a focal length of 350 mm providing a spot focus diameter (df) of 0.56 mm was used. A welding machine, Qineo Pulse 600 of Cloos, with a maximum current of 600 A was applied as a power source for the arc. GMAW was performed with direct current of positive polarity (DC+).

The laser optics and GMAW torch were mounted on the robot arm, where the laser beam longitudinal inclination angle was 0° from normal towards the welding surface reflections, while the GMAW torch was tilted 65° to the welding surface, and the position of the robot remains unchanged during all welding process. All the experiments were carried out with an arc leading orientation with the distance of 3 mm between the two heat sources. The focal position of the laser beam was -3 mm relative to the workpiece surface. The wire stick-out was set to 15 mm. The HLAW process configuration is shown in Figure 1.

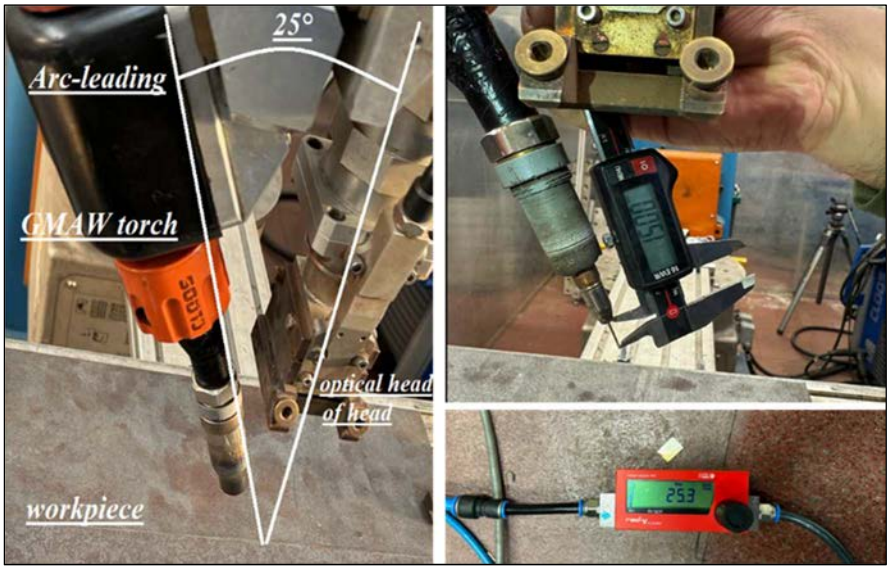


Figure 1. *HLAW system; a) experimental setup; b) stick-out; c) gas flow rate.*

Slika 1. *HLAW sistem: a) eksperimentalna postavka; b) slobodna dužina elektrode; c) protok zaštitnog gasa.*

The experiment was conducted to analyze the effect of synchronizing the GMAW and LBW processes on weld quality and to achieve welds free of imperfections, meeting the requirements of the EN ISO 12932 standard while maximizing productivity. The welding parameters are given in Table 1.

After the welding, a visual inspection is performed to detect surface defects, such as overlap, undercutting, surface craters, humping and misalignment.

Table 1. *Single-pass welding process parameters.*

Tabela 1. *Parametri procesa zavarivanja u jednom prolazu.*

Weld no.	Methods of edge prepartion	Gap (mm)	Laser power (kW)	Arc mode	Arc current (A)	Arc voltage (V)	Wire feed (m/min)	Wedling speed (m/min)	Focal position (mm)	Gas low rate (l/min)	Wire stickout (mm)	Arc - laser distance (mm)
1	Milling	0	10	Pulse	325	34	10	1.4	0	25	15	5
2	Milling	0	10	Pulse	389	38.2	14	1.8	-3*	25	15	3
3	Milling	0	10	Pulse	355	36.7	12	1.8	-3*	25	15	3
4	Milling	0	11.5	Pulse	359	36.8	12	1.8	-3*	25	15	3
5	Plasma cut	0	10	Pulse	355	36.8	12	1.8	-3*	25	15	3
6	Milling	0	8	/	/	/	/	1.5	-3*	25	/	/
7	Milling	0	8	Pulse	371	37.3	13	1.5	-3*	25	15	3
8	Milling	0	/	Pulse	378	37.6	13	1.5	/	25	15	/

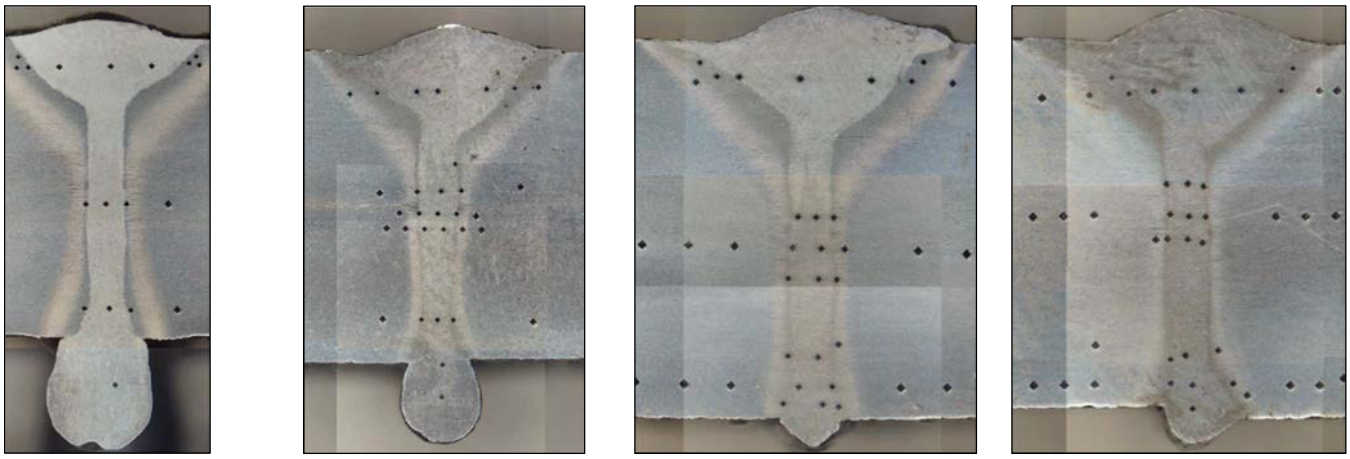
For the macrostructure analysis of the welds, test specimens of appropriate length were extracted from the middle of the welded plates, polished using standard metallographic procedures, and subsequently etched with a 2% Nital solution before being examined under a stereo microscope.

All welds were subjected to mechanical testing – tensile and hardness testing. Cross-weld tensile test was performed based on EN ISO 4136 using the standard dimension and geometry of the tensile test specimen.

Vickers hardness test (HV10) was performed in accordance with two standards, ISO 9015-1 and ISO 22826, the first one was applied in the upper zone, the arc–laser zone, and the second one in the laser zone. The measurements were performed in three rows of material thickness: one below the weld face and one from the root side at depth of <2mm, and one in the middle of material thickness [5].

3. Results and discussion

The visual inspection found that two of five hybrid welds can not meet the lowest requirements according to EN 12932. The macrographs of the weld shown in Figure 2, represent that the main imperfection of milling sidewalls is root humping which is not acceptable.



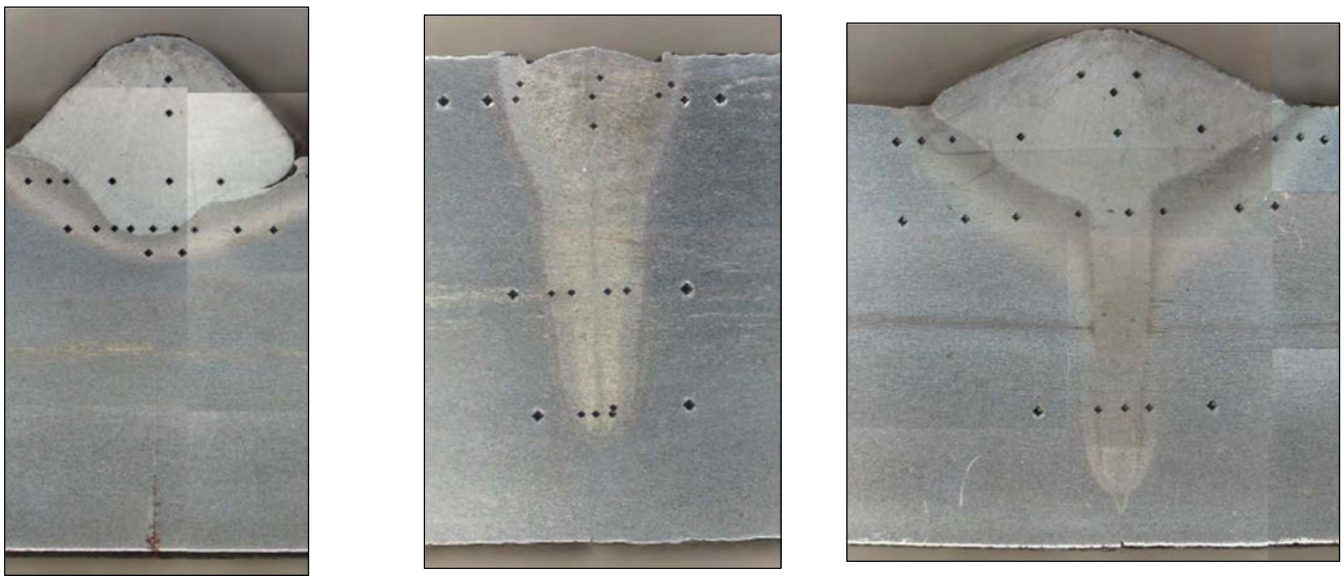
a) b) c) d)

Figure 2. *HLAW weld of 12 mm thick plates; a) no.1, b) no.3, c) no.4, d) no.5.*

Slika 2. *HLAW zavareni spojevi ploča debljine 12 mm: a) br. 1; b) br. 3; c) br. 4; d) br. 5.*

It is evident that arc affects the melt flow by increasing the mass momentum towards the root which is corralled with the amount of molten metal in the weld pool. To suppress humping on pieces with milled edges, the welding speed and laser power were increased. On the other hand, the weld with plasma cutting edges is humping free for the same welding parameters. According to Bunaziv et al. [6] a slight air gap in the I-joint preparation can be beneficial to prevent humping by reducing the pressure at the bottom of the keyhole. Therefore, using the same HLAW process parameters, zero-gap plasma-cut edges performed better because they can reduce the keyhole pressure due to the natural gaps formed by the peaks and valleys of the surface roughness. The striations of the plasma-cut can increase the laser absorption and, at the same time, improve the flow of molten filler material flow further inside the joint. However, an air gap larger than 1 mm can lead to melt humping, as the surface tension is insufficient to prevent molten metal dropout [7, 8]. Furthermore, welding with an air gap introduces additional complexity and reduces reliability due to difficulties in maintaining a consistent gap during production.

The visual inspection of welds produced by the individual LBW and GMAW processes, compared with HLAW using the same welding parameters, shows a positive improvement in weld bead geometry, heat-affected zone, and especially in weld penetration, Figure 3. Deeper penetration in HLAW is achieved due to the synergistic interaction between the laser and arc. The arc preheats the material and enhances laser energy absorption, stabilizes the laser-induced keyhole, and constricts and intensifies the arc through metal vapor interaction. It also improves molten pool dynamics, resulting in more efficient heat utilization and consequently greater weld penetration [9]. According to Ruifeng [1], the melting energy in hybrid laser–arc welding HLAW is higher because the arc preheats the workpiece before laser irradiation, forming a shallow molten layer that reduces reflectivity and improves laser energy absorption.



a) b) c)

Figure 3. *Weld cross-section; a) GMAW, b) LBW, c) HLAW.*

Slika 3. *Poprečni presek zavarenog spoja: a) GMAW; b) LBW; c) HLAW.*

In terms of tensile strength, all weld pieces showed satisfactory results, even those with root hump that are not acceptable from a visual point of view. All standard tensile test specimens exceeded the strength of the base material, reaching at least 385MPa yield strength and 560MPa ultimate tensile strength, resulting in BM failure. Welds with insufficient penetration, resulting from lower welding parameters, tend to fracture within the weld zone. Figure 4 presents the tensile strength curve for weld no. 7 calculated based on the weld area, showing a yield strength of 650 MPa, an ultimate tensile strength of 739 MPa and a total elongation of 5.81%.

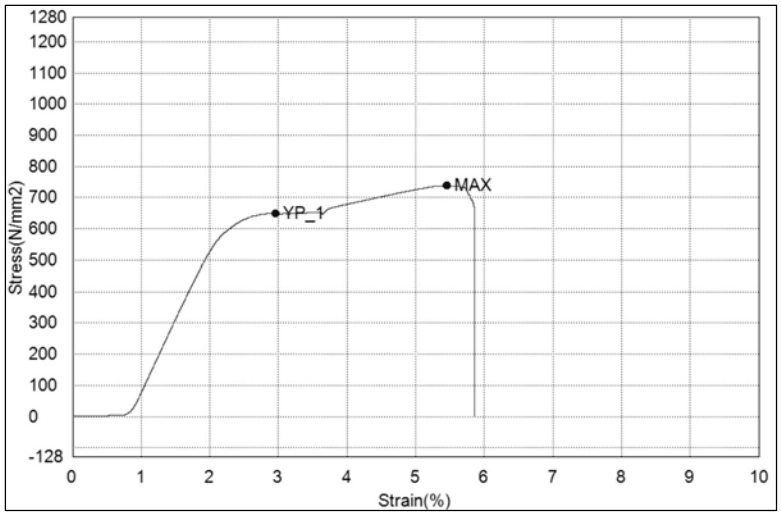


Figure 4. *Tensile strength of hybrid weld no. 7.*

Slika 4. *Zatezna čvrstoća hibridnog zavarenog spoja br. 7.*

The Vickers hardness HV10 distribution across the cross-section of welds no. 6, 7 and 8 are presented in Figure 5.

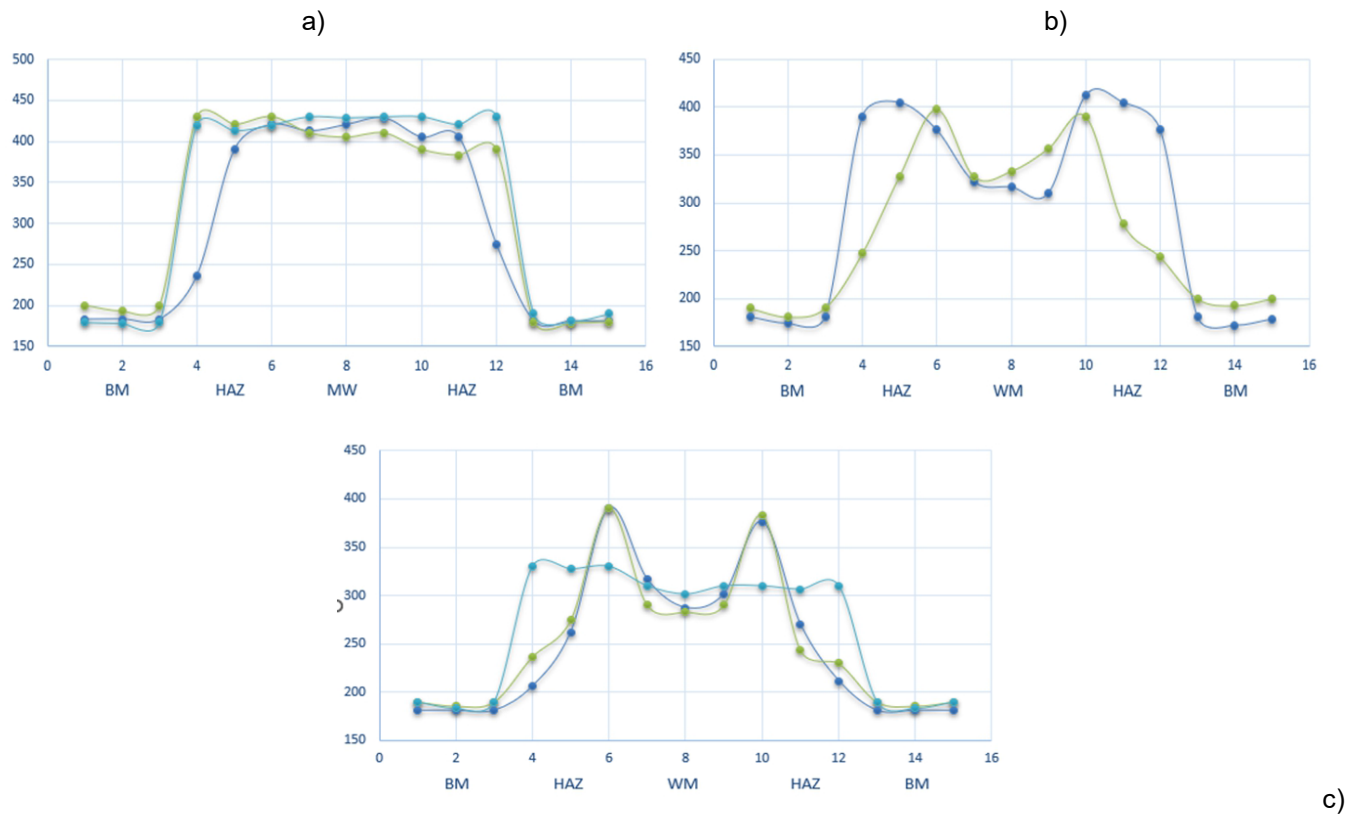


Figure 5. *Results of Vickers hardness HV10; a) LBW, b) GMAW, c) HLAW.*

Slika 5. *Rezultati ispitivanja tvrdoće po Vikersu (HV10): a) LBW; b) GMAW; c) HLAW.*

It can be observed that the hardness profiles of HLAW and GMAW welds exhibit a similar M-shaped distribution, with the highest hardness located in the HAZ due to the coarse-grained microstructure and higher cooling rate. The hardness of the weld metal is slightly lower, primarily due to the use of filler material and the larger molten pool. In contrast, LBW produces a relatively uniform hardness distribution throughout both the weld metal and the HAZ.

A comparison of the average hardness values indicates that the WM and HAZ in HLAW exhibit hardness values of approximately 300 HV and 380 HV, respectively, whereas LBW shows higher hardness values of around 430 HV. The differences of approximately 130 HV in the weld metal and 50 HV in the HAZ can be attributed to the higher energy input per unit length. According to Kawahito et al. [10] hardness values exceeding 400 HV are typical for laser welding of thick steel at welding speeds above 1.00 m/min. According to ISO 15614-1, the maximum allowed hardness level is 350HV. However, HLAW is not covered by this standard. The formation of brittle areas in HLAW which can result in hardness values exceeding 300 HV may be mitigated by reducing the cooling rate or by selecting an appropriate filler material [11].

4. Conclusions

In this study, the effects of synchronizing GMAW and LBW processes on weld quality and mechanical characteristics of structural steel were examined. The most important conclusions drawn from the present experimental results are as follows:

1. The combination of the individual GMAW and LBW processes in HLAW process has proven to be reliable and efficient technology for single-pass welding of the 12 mm thick structural steel in a zero-gap butt joint configuration.
2. Humping in welds with milled edges can be suppressed by increasing the welding speed and laser power, or by improving melt flow dynamics and reducing keyhole pressure through the introduction of a slight air gap.
3. Larger air gaps >1 mm should be avoided due to melt instability and metal dropout, which reduce process reliability because of the difficulty in maintaining a consistent gap during production.
4. HLAW welds are characterized by satisfactory tensile strength, exceeding that of the base material when root hump imperfections are present.
5. The hardness values of HLAW welds are directly correlated with the energy input per unit length and can be improved by controlling the cooling rate.

4. Zaključci

U ovoj studiji ispitan je uticaj sinhronizacije procesa GMAW i LBW na kvalitet zavarenog spoja i mehanička svojstva konstrukcionog čelika. Najvažniji zaključci izvedeni na osnovu dobijenih eksperimentalnih rezultata su sledeći:

1. Kombinovanje pojedinačnih procesa GMAW i LBW u okviru HLAW procesa pokazalo se kao pouzdana i efikasna tehnologija za jednoprolazno zavarivanje konstrukcionog čelika debljine 12 mm u konfiguraciji sučeonog spoja bez zazora.
2. Pojava ispupčenja zavara kod ploča sa obrađenim ivicama može se suzbiti povećanjem brzine zavarivanja i snage lasera ili poboljšanjem dinamike strujanja rastopa i smanjenjem pritiska u parnom kanalu uvođenjem malog zazora između ploča.
3. Veće zazore, iznad 1 mm, treba izbegavati zbog nestabilnosti tečnog kupatila i ispadanja rastopljenog metala, čime se smanjuje pouzdanost procesa usled otežanog održavanja ujednačenog zazora u proizvodnim uslovima.
4. HLAW zavareni spojevi odlikuju se zadovoljavajućom zateznom čvrstoćom, koja premašuje zateznu čvrstoću osnovnog materijala čak i kada su prisutne nepravilnosti u vidu ispupčenja korena zavara.
5. Vrednosti tvrdoće HLAW zavarenih spojeva neposredno su povezane sa unosom energije po jedinici dužine i mogu se poboljšati kontrolisanjem brzine hlađenja.

References / Literatura

[1] Ruifeng, L., Taotao, L.: Advanced Welding Methods and Equipment, Springer Singapore, 2024.

[2] Pan, Q., Mizutani, M., Kawahito, Y., Katayama, S.: Effect of shielding gas on laser–MAG arc hybrid welding results of thick high-tensile-strength steel plates. Weld World 6, (2020), pp.653–664.

[3] Petreski, M., Runchev, D., and Vrtanoski, G.: Hybrid laser arc welding – State of the art in technology. Welding and welded structures, 66(3), (2021), pp 115-124.

[4] Gook S., Biegler, M., Gumenyuk, A., and Rethmeier M.: Integration of hybrid Laser-Arc and narrow gap submerged arc welding for cost-effective joining of 80 mm thick S355ML steel plates, Optics and Laser Technology 197, (2026), 114796.

[5] Petreski, M., Krstevska, A., Bogatinoski Z.: Mechanical testing od HLAW welded joints in accordance with European standards – Theoretical approach. Mechanical Engineering –Scientific Journal, 40 (1), (2023), p.5-13

[6] Bunaziv, I., Dørum, C., Nielsen, S.E., Suikkanen, P., Ren, X., Nyhus, B., Eriksson, M., and Akselsen, O.M.: Laser-arc hybrid welding of 12-and 15-mm thick structural steel. International Journal of Advanced Manufacturing Technology, 107, (2020), pp. 2649-2669.

[7] Farrokhi, F., and Kristiansen, M.: A practical approach for increasing penetration in hybrid laser-arc welding of steel. Physics Procedia 83, (2016), pp. 576-586.

[8] Petreski, M., Runchev, D., Vrtanoski, G., Krstevska, A: Influence of edge surface quality on hybrid laser arc welding of structural steel S355J2, IIW 2024 International Conference on Welding and Joining, Rhodos, Greece, 2024.

[9] Üstündağ Ö., Gook S., Gumenyuk A., and Rethmeier M.: Hybrid laser arc welding of thick high-strength pipeline steels of grade X120 with adapted heat input. Journal Material Process Technology, 275 (2020), 116358.

[10] Kawahito, Y., Wang, H.Z., Katayama, S. et al., Ultra high power 100kW fiber laser welding of steel, Opt. Lett, 43(19), (2018), pp.4667-4670.

[11] Wallerstein, D., Vaamonde, E., Prada, A., Torres, E.A., Urtiga Filho, S.L., and Santos, T.F.A: Influence of welding gases and filler metals on hybrid laser - GMAW and Laser-FCAW welds. Mechanical Engineering Science, (2020), pp.3-14.