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EFFECT OF LASER BEAM AND ARC POWER ON WELD BEAD GEOMETRY IN HYBRID LASER ARC WELDING OF STRUCTURAL STEEL

UTICAJ LASERSKOG SNOPA I SNAGE ELEKTRIČNOG LUKA NA GEOMETRIJU ZAVARA KOD HIBRIDNOG LASERSKOG ELEKTROLUČNOG ZAVARIVANJA KONSTRUKCIONIH ČELIKA

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Abstract

Hybrid Laser Arc Welding – HLAW combines the advantages of Laser Beam Welding - LBW and Gas Metal Arc Welding - GMAW, resulting in a welding process of high welding speed, less heat input, deeper penetration into the welding material, and increased process efficiency compared to conventional welding processes. The merger of the two heat sources, laser beam and arc, in a single welding process leads to a weld joint characterized by two zones, an upper-wide zone or laser-arc zone and a lower narrow zone or laser zone. This study investigates the impact of laser beam and arc currents on the weld bead geometry in the arc-leading hybrid laser arc welding process of 12 (mm) structural steel. Through systematic experimentation, single-pass hybrid laser arc welds were performed in a butt joint configuration with zero-gap at various power settings, laser beam power range 10 - 13 (kW), and arc current range 340 - 400 (A) to determine their influence on weld bead width, height, and depth. The quality level of the hybrid laser arc welds was evaluated according to ISO 12932.

Rezime

Hibridno zavarivanje laserskim snopom i električnim lukom (HLAW) kombinuje prednosti zavarivanja laserskim snopom – LBW i zavarivanja električnim lukom – GMAW, što rezultira procesom zavarivanja velikim brzinama zavarivanja, manje termićko opterećenje, povećanu penetraciju i efikasnost porcesa u poređenju sa konvencionalnim procesima zavarivanja. Efekat spajanja dva izvora toplote, laserskog snopa i električnog luka, u jednom procesu zavarivanja vodi do zavarenog spoja koji karakterišu dve zone, gornju – široku zonu ili zonu laserskog snopa i električnog luka i donju – usku zonu ili zonu lasera. Ova studija istražuje uticaj laserskog snopa i električnog luka na geometriju zavara kod hibridnog laserskog elektrolučnog zavarivanja konstrukcijskog čelika debljine 12 (mm). Kroz sistemski eksperiment, izvedeni su hibridni zavari sa jednim prolazom u konfiguraciji sučeonog spoja bez zazora pri različitim podešavanjima snage: opsegom snage laserskog snopa 10-13 (kW) i opsegom struja električnog luka 340 – 400 (A) da bi se odredio njihov uticaj na geometriju zavara, širinu, visinu i dubinu.

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The results indicate that increasing laser beam power enhances weld bead depth and narrows bead width, while the arc current is directly related to weld bead height and overall smoothness. The findings show that weld bead geometry is a function of laser beam and arc power ratio, an increased ratio leads to a narrow weld bead and vice versa.

Nivo kvaliteta hibridnih laserskih zavarenih spojeva je ocenjen u skladu sa ISO 12932. Rezultati pokazuju da povećanje snage laserskog snopa sužava i povećava dubinu zavara, dok je struja električnog luka direktno povezana sa visinom zavara i opštom glatkoćom. Zaključak je da je geometrija zavara funkcija odnosa snage laserskog snopa i električnog luka, odnosno da povećanje odnosa dovodi do suženje zavara.

1. Introduction

Gas Metal Arc Welding – GMAW is a conventional joining process widely used for welding structural steel in various engineering fields such as shipbuilding, civil construction, and metallurgy [1]. Its flexibility and efficiency allow quality welding of materials with different thicknesses and complex shapes. Consequently, several innovations in this welding process that contribute to its improvemen [2]. One of the improvements is automated hybrid laser arc welding, whereby combining the advantages of two different processes, Laser Beam Welding – LBW and semi-automatic welding processes such as Gas Metal Arc Welding – GMAW or Flux-Cored Arc Welding – FCAW represents an excellent substitute for conventional welding processes [3]. This combination results in a welding process characterized by high welding speeds, low heat input, high penetration depth into the welding material, and precise control over the weld bead's chemical composition.

Although Hybrid Laser Arc Welding (HLAW) offers numerous advantages, it also presents certain limitations [4]. The most significant limitation is controlling a large number of welding parameters in order to acquire welds with acceptable quality. The values of the parameters that are ideal for each process separately are probably not optimal for successful welding with HLAW due to mutual influence. Current research has shown that hybrid laser arc welding parameters are not specified enough to replicate the conditions for a particular operation [5]. Mainly, the weld quality and weld bead geometry in HLAW depend on the ratio between the two heat sources, laser power and arc power, that can be calculated by dividing the laser power by the arc power [14]. The weld quality is evaluated in terms of its mechanical characteristics, microstructure, and weld bead geometry. In practice, maximum weld penetration and minimum weld bead height and width are always required, and hybrid laser arc welding can achieve these requirements [6].

Generally, if the laser-arc power ratio is not appropriate that will have adverse effect on weld quality. Weld humping and lack of penetration are the most significant imperfections affecting the fatigue life of the hybrid weld. The amount of heat input is the main parameter directly related to these two imperfections [7].

Therefore, this paper will investigate the influence of the laser-arc power ratio on the weld bead geometry in the arc-leading hybrid laser arc welding process of 12 (mm) structural steel S355J2. Several single – pass hybrid laser arc welds were performed in a butt joint configuration with zero-gap at various power settings, laser beam power range 10 - 13 (kW), and arc current range 340 - 400 (A) to determine their influence on weld bead width, height, and depth. After the welding, the quality level of the hybrid laser arc welds was evaluated according to ISO 12932.

2. Hybrid laser arc welding parameters

A detailed understanding of the parameters involved in Hybrid Laser Arc Welding (HLAW) is crucial to comprehending their overall impact on the welding process. In HLAW, the laser power is the main heat source that determines the penetration depth, while the arc current influences the weld width and the weld gap fill [2, 3]. Based on the weld cross-section area, hybrid laser arc welding has a higher melting efficiency than the individual LBW and GMAW welding processes.

Laser type and power – is one of the densest energy sources for welding. The output power P_L(W) and wavelength (λ) are the most important parameters for choosing the laser type. The penetration is directly proportional to the laser output power, and therefore, it represents the main parameter in the selection of the type of laser [4].

Positioning of the laser beam and the electric arc – the HLAW can be set up in two directions, laser leading and arc leading, despite the fact that they act on the same point. The distance between the laser source and the arc is an essential parameter for controlling penetration in hybrid laser arc welding. It usually consists of a few millimeters, and the separation distance is in the range of 0 to 5 mm [7].

Focal positioning – Laser heat sources use a focusing system to focus the energy on a single point, thus increasing the heat flux.

Work angle of the electrode – It affects the penetration of the weld and is directly related to the shielding gas flow, thereby influencing the absorption of laser energy [8].

Shielding gas and flow rate – In HLAW the inert shielding gas has a fundamental role of stabilizing the arc and in turn, the stability of the welding process and the weld quality [9]. Shielding gases like Argon (Ar) and Helium (He) are used to protect the weld pool from the atmosphere and stabilize the arc. Helium increases penetration depth, while Argon stabilizes the arc. A small amount of oxygen can also reduce spatter and improve metal transfer. The gas flow rate must be optimized to ensure sufficient plasma suppression and protection of the weld pool without causing turbulence [3, 9, 10].

Welding speed – Welding speed is a critical parameter in HLAW, directly affecting penetration depth and weld quality. The weld penetration and weld with are inversely affected by the welding speed [11].

Wire feed rate – A higher wire feed rate increases the weld's cross-sectional area and can speed up the process, but it also requires a corresponding increase in current to maintain arc stability. The balance between wire feed rate and welding speed is essential for achieving the desired weld shape and penetration [2, 12].

Effects of GMAW current, voltage, and polarity – Due to the high welding speed, the metal transfer mode is crucial to obtaining a stable and repeatable welding process. Therefore, spray transfer or pulsed GMAW are typically used instead of short-circuiting or globular transfer [1]. The type of the current and its polarity is another parameter that affects the process stability.

Joint gap width and edge preparation – HLAW can easily achieve acceptable welds with joint gaps of 1 mm. The main parameter is the laser-arc power ratio that influences joint gap and welding speed [11].

3. Materials and methods

The welding experiments of the present study were conducted on 12 (mm) thick plates of structural steel in quality S355J2. 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 G3Ni1 according to EN ISO 14341-A: G 42 3 M21 3Si1 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 (l min^{-1}).

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 a direct current of positive polarity (DC+). 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 (mm), 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.

The laser optics and GMAW torch were mounted on the robot arm with the angle between them of 25^{o}, and the position of the robot remains unchanged during the welding process. The edge walls were cleaned with acetone to remove grease prior to welding, and tack welds at the beginning and end of the plates were applied to ensure zero-gap of an I-joint configuration. All the experiments were carried out with an arc-leading orientation and a 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 experiment was conducted to analyze the influence of laser beam and arc current on the weld bead geometry in hybrid laser arc welding. Therefore, the laser beam power was changed to 10 – 13 (kW), and the arc current was changed to 340 - 400 (A), while the other process parameters were kept constant or slightly adjusted to simplify the study. The HLAW welding parameters can be found in Table 1.

***Table 1.** Single – pass hybrid laser arc welding parameters*

***Tabela 1.** Parametri jednoprolaznog hibridnog laserskog elektrolučnog zavarivanja*

Weld no.	Methods of edge preparation	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	13	Pulse	390	38.2	14	1.8	-3*	25	15	3
2	Milling	0	11.5	Pulse	390	38.1	14	1.8	-3*	25	15	3
3	Milling	0	10	Pulse	389	38.2	14	1.8	-3*	25	15	3
4	Milling	0	13	Pulse	359	36.7	12	1.8	-3*	25	15	3
5	Milling	0	11.5	Pulse	352	36.9	12	2.2	-3*	25	15	3
6	Milling	0	12.4	Pulse	362	37.8	13	1.8	-3*	25	15	3
7	Milling	0	12.4	Pulse	399	38	14	2	-3*	25	15	3
8	Milling	0	10	Pulse	355	36.8	12	1.8	-3*	25	15	3

After the welding, the test specimens of appropriate length were removed from the middle of the welded plates and polished using standard metallographic procedures, and subsequently etched with 2% nital reagent. The macro morphology of the welds was then examined by using a stereo microscope and evaluated the weld bead geometries according to ISO 12932. The weld bead geometries that were measured and evaluated are shown in Figure 1.

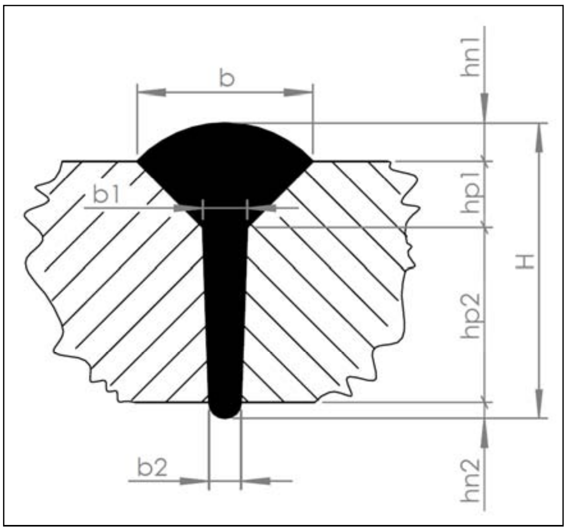

***Figure 1.** Schematic illustration of HLAW welded butt joint and weld bead geometries*

***Slika 1.** Šematska ilustracija HLAW zavarenog sučeonog spoja i geometrije šava*

4. Results and discussion

The experiment was conducted to achieve a weld without imperfections that will meet the standards EN ISO 12932 requirements with maximum possible productivity. The visual inspection of HLAW found that seven of eight welded plates can be evaluated with acceptable quality according to ISO 12932. In Table 2, all measured dimensions of the preformed welds can be found.

The micrographs of the welds are shown in Figure 2, and in the Weld No. 8 can be noted incomplete root penetration that is imperfection no.4021 according to ISO 6520-1. According to ISO 12932 the size of imperfection exceeds even the lowest quality level D: h ≤ 0.15h, but maximum 1 (mm) [13]. This type of imperfection results from lower heat input due to the laser beam power of 10 (kW). On the other hand, the top bead profile is bigger due to the high arc current and a disturbed ratio between the heat sources that leads to inappropriate melt flow dynamics [5]. In relation to the height and width of the other weld beads it can be observed that there are within the highest required quality level B: h ≤ 1 (mm) + 0.1b, but maximum 5(mm).

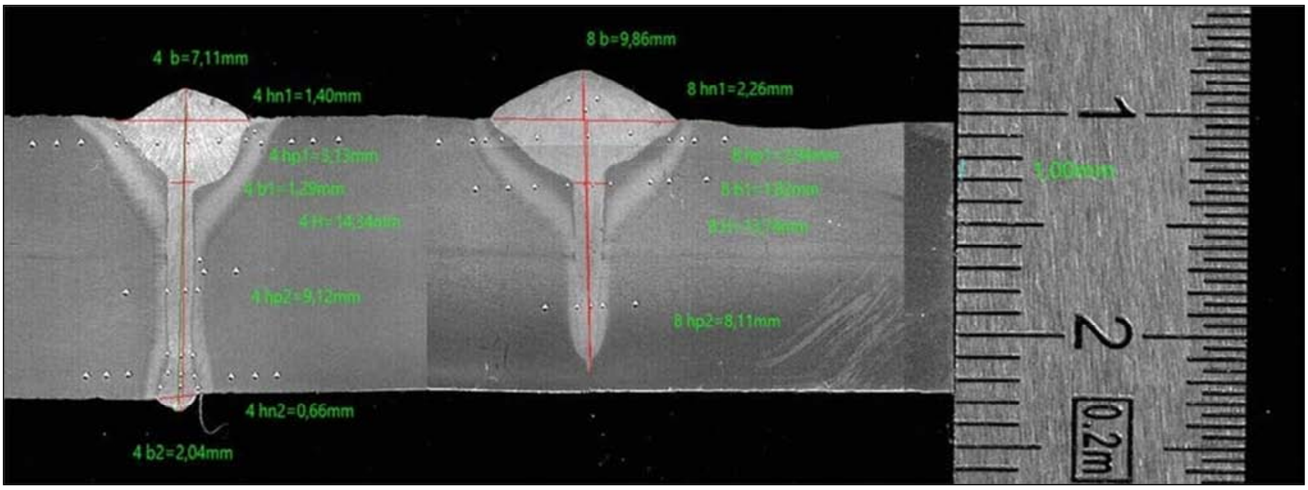

Figure 2. *Cross-sections of HLAW: a) Weld no. 4; b) Weld no.8*

Slika 2. *Poprečni preseci HLAW: a) zavar br. 4; b) zavar br.8*

Table 2. *Measured dimensions of weld bead geometries*

Tabela 2. *Izmerene dimenzije geometrije metala šava*

Sample/Measurement [mm]		1	2	3	4	5	6	7	8
Electric Arc + Laser zone	b	8.4	7.39	7.62	7.11	6.96	7.79	6.18	9.86
	hn1	1.61	1.59	1.4	1.4	1.31	1.5	1.91	2.26
	hp1	3.3	3.37	3.34	3.13	2.88	3.11	2.98	2.94
	b1	1.5	1.34	1.38	1.29	1.42	1.44	1.31	1.82
Laser zone	b2	2.1	2.17	2.23	2.04	1.12	1.99	1.69	/
	hn2	0.72	0.78	1.33	0.66	0.57	0.83	0.8	/
	hp2	8.56	8.7	9.02	9.12	8.98	9.04	9.06	8.11
Weld	H	14.77	14.52	15.22	14.34	13.84	14.46	14.86	13.74

Laser beam power is the main factor influencing the weld penetration and the narrow weld bead. According to Bunaziv et al. [5], the power of the laser beam should be equal to the material thickness in order to achieve full penetration in a single-pass hybrid laser-arc weld, or in this case, the power of the laser beam should be above 12 (kW) for full penetration. The effect of laser beam power on the weld bead geometry and penetration are shown in Figure 3 and 4. The depth of the weld penetration is primarily dependent on the laser power, by increasing the laser power the narrow melt area is produced (b2), and the height of the root is decreasing (hn2). The penetration in not related with the arc current as long as there was sufficient laser power available.

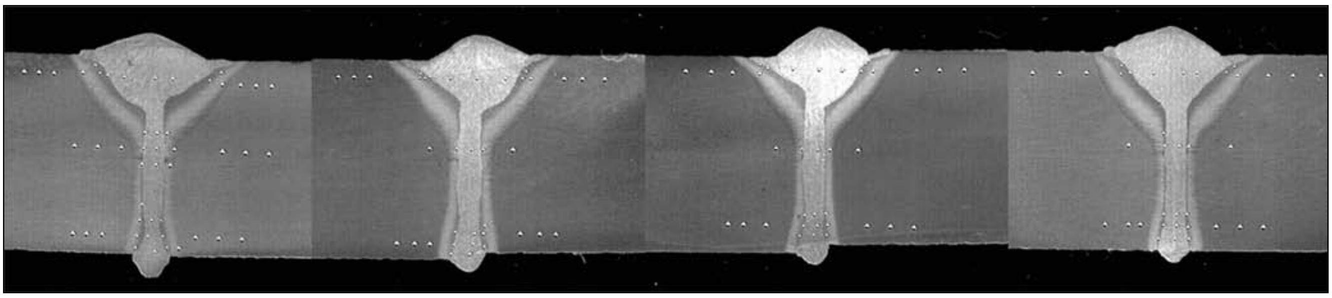

Figure 3. *The effect laser beam on weld bead geometry: a) 10 kW, b) 11.5kW, c)12.4 kW, d)13 kW*

Slika 3. *Efekat laserskog snopa na geometriju metala šava: a) 10 kW, b) 11,5 kW, c) 12,4 kW, d) 13 kW*

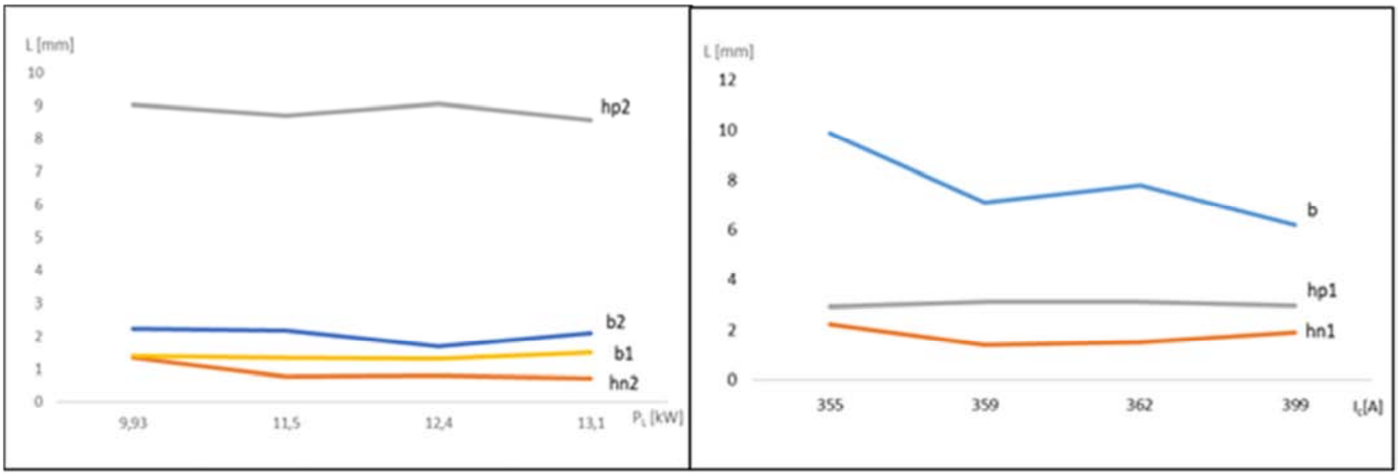

Figure 4. *The effect of the heat sources on weld bead geometry: a) Laser beam power; b) Arc current*

Slika 4. *Uticaj izvora toplote na geometriju šava: a) snaga laserskog zraka; b) struja električnog luka*

From Figure 5 it can be noted that arc current can only influence an upper-wide zone or laser-arc zone. By increasing the arc current the weld bead width (b) decrease while the height (hn1) increases but with different intensity. High arc current results in the undercuts that are acceptable according to ISO 12932.

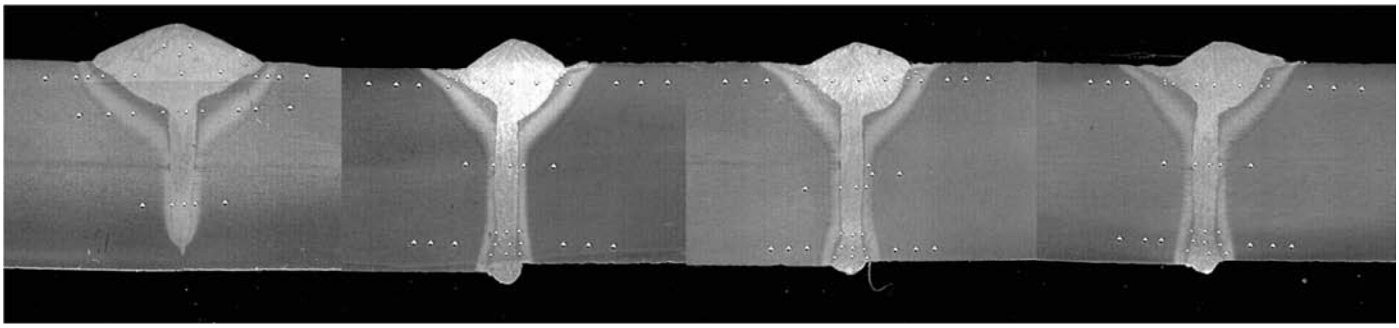

Figure 5. *The effect arc current on weld bead geometry: a) 355A, b) 399A, c) 359A, d) 362A*

Slika 5. *Uticaj jačine struje električnog luka na geometriju metala šava:*

a) 355A, b) 399A, c) 359A, d) 362A

5. Conclusions

In this study, the effects of laser beam power and arc current on the weld bead geometry of butt welds produced by HLAW were examined. The following conclusions were drawn from the above experiment and analysis:

1. The laser-arc power ratio is directly related to the amount of heat input, so it should be set up very precisely to acquire perfect weld bead geometry. Seven of the total welded plates can be evaluated as acceptable quality according to ISO 12932, and six of them can be classified in the highest evolution B.

5. Zaključci

U ovom radu ispitivani su efekti snage laserskog zraka i struje električnog luka kod postupka hibridnog zavarivanja laserskim snopom i električnim lukom (HLAW), na geometriju metala šava sučeonih zavarenih spojeva konstukcionog čelika. Iz izvšenih eksperimenta i analize rezultata izvedeni su sledeći zaključci:

1. Odnos snage lasera i električnog luka je direktno povezan sa količinom unešene toplote, tako da bi trebalo da bude podešen veoma precizno da bi se postigla savršena geometrija metala šava. Za sedam zavarenih ploča, kvalitet se može oceniti kao prihvatljiv, prema standardu ISO 12932, a šest se može svrstati u najvišu klasu B.

2. The laser – arc power should be in the range of 0.7 – 1 for a hump-free root and full penetration of 12 (mm) thickness structural steel. In position 8, this ratio is below 0.6, resulting in no penetration and a wide weld surface.
3. Increasing the laser beam power leads to a narrow weld width (b2) and a decrease in the root height (hn2), while weld penetration is strictly related to laser power instead of the overall heat input process.
4. There is a direct correlation between the laser beam power and weld penetration. To achieve full weld penetration, the laser power expressed in (kW) should be the same intensity or bigger than the material thickness expressed in (mm).
5. Increasing the arc current leads to a decrease of weld bead width (b), but a slight increase of weld bead height (hn1) and arc penetration (hp1).

2. Odnos snaga lasera i električnog luka treba da bude u opsegu od 0,7 – 1 za koreni prolaz i punu penetraciju za konstrukcioni čelik debljine 12 (mm). Za uzorak 8, ovaj odnos je ispod 0.6, što rezultira nedovoljnom penetracijom i širokom površinom zavarenog spoja.
3. Povećanje snage laserskog snopa dovodi do nedovoljne širine vara (b2) i smanjenja visine korena (hn2), dok je penetracija šava striktno povezana sa snagom lasera umesto sa ukupnim procesom unosa toplote.
4. Postoji direktna korelacija između snage laserskog zraka i dubine prodora u zavarenom spoju. Da bi se postigla puna penetracija zavarenog spoja, snaga lasera izražena u (kW) treba da bude istog intenziteta ili veća od debljine materijala izražene u (mm).
5. Povećanje struje električnog luka dovodi do smanjenja širine šava (b), ali do blagog povećanja visine šava (hn1) i prodora luka (hp1).

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