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Hybrid laser arc welding – state of the art in technology

Hibridno lasersko elektrolučno zavarivanje – pregled stanja tehnologije

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Abstract

Hybrid laser arc welding is complex process where two heat sources act simultaneously in a common weld pool. The synergy effect of laser beam and electric arc offers several advantages over other individual technological processes, such as: higher welding speed, increased productivity, deeper penetration, better gap bridging ability, stable process, less heat input to the welding material, etc. However, the combination of two heat sources in a single welding process leads to large number of parameters that need to be synchronized and optimized in order to obtain a perfect weld. This paper presents the current state of hybrid laser arc welding in terms of its development, industrial application and scientific research. The introduction part contains a general overview of the hybrid laser arc welding process, its advantages and operating principles, and chronological development. In the second part, welding parameters that directly influence on the hybrid process have been discussed. The third part presents the performance and weld qualities achieved by hybrid welding process in accordance with previous research. In the final part, examples of industrial application and conclusions for further research and development related to hybrid laser arc welding are given.

Rezime

Hibridno zavarivanje sa laserskim snopom i električnim lukom je kompleksan proces gde dva izvora toplote istovremeno utiču na istom mestu na radnom materijalu. Efekat spajanja laserskog snopa i električnog luka nudi velike prednosti u odnosu na ostale individualne tehnološke procese, kao na primer: veće brzine zavarivanja, povećanu produktivnost i penetraciju, bolju popunu žlebova, stabilan proces, manje termičko opterećenje radnog materijala itd. Međutim, spajanje dva izvora toplote u jednom procesu zavarivanja vodi do povećanog broja parametara koji bi trebalo da se sinhronizuju i optimizuju u cilju dobijanja kvalitetnog zavarenog spoja. U ovom radu predstavljeno je trenutno stanje hibridnog zavarivanja sa laserskim snopom i električnim lukom u odnosu na njegov razvoj, industrijsku primenu i eksperimentalna istraživanja. Uvodni deo sadrži opšti pregled hibridnog procesa zavarivanja, njegove prednosti i principe rada, kao i hronološki razvoj. U sledećem delu detaljno su objašnjeni parametri koji direktno utiču na stabilnost hibridnog procesa. Dalje, predstavljene su performanse i kvalitet zavarenih spojeva dobijenih hibridnim procesom zavarivanja, a u skladu sa prethodnim istraživanja. Na kraju dati su primeri praktične primene hibridnog zavarivanja kao i predlozi za dalja istraživanja i razvoj.

1. Introduction

Today's globalization is characterized by an accelerated process movements of capital, resources, products and services, resulting in a completely new world trade structure, economic and financial flows, internationalization of production and acceleration of technical and technological development. As a part of mechnical engineering, the welding have not been lagging in technological development, new welding techniques and technologies are constantly being introduced, which would result in reduced production costs and improved technical characteristics of the welded joints [1].

The conventional joining process Gas Metal Arc Welding – GMAW is widely used process for welding of strucutural steel in a number of engineering fields such as shipbuilding, civil construction, mining equipment and metallurgy [2]. Consequently, several innovations appear in this welding process, that contributes for its improvement [3]. 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 and Flux-Cored Arc Welding – FCAW represents an excellent substitute for conventional welding processes [4].

Even though GMAW is widely used welding process due to its advantages such as simple handling, relatively low cost for implementation, ability to bridge large root openings, welds with large cross sections and high deposition rate, the welding speed of GMAW is limited by the formation of defects [5]. In addition, during the welding process GMAW applies a high heat input to the welding material, resulting in large heat-affected zones HAZs and occurrence of the undesired microstructure [6]. On the other hand, LBW provides deep and narrow welds at high welding speeds, due to its high energy density, leading to a small HAZ and low distortion [7]. However, the LBW process like any other process has disadvantages, one of them is high cooling rate from the welding zone that leads to high weld metal hardness and low toughness, which sometimes cannot meet the minimum mechanical properties [8].

Hybrid Laser Arc Welding – HLAW combines the advantages of both welding processes, LBW and GMAW or FCAW, resulting in welding process that is characterized with high welding speed [9], low heat input, high penetration depth into the welding material, and the possibility of controlling the chemical composition of the weld bead [10].

For the first time, the hybrid laser arc welding process was introduced in the late 1970s by Prof. W. M. Steen [11], and the process was defined as “arc-augmented laser welding”. The results of its research showed a clear advantage of combining an electric arc and a laser beam for welding. Despite of the successful demonstration, hybrid welding’s further research and development experienced a slow growth due to lack of reliable laser source with high power, required human skills, and incomplete knowledge of the process [12]. In the late 1980s, the development of reliable and consistent high power industrial lasers, the researchers' attention was focused on improving the HLAW process for its application in everyday production [13]. Several drawbacks of the individual welding processes have been eliminated, such as gap bridging ability and reflectivity of the materials which were issues for successful welding [14]. In the 1990s, hybrid laser arc welding had acquired considerable developments due to availability of high-power CO2 lasers, where a mixture of CO_2:He:N_2 was used as the active medium [15, 16].

The first industrial hybrid laser arc welding system was introduced in 2000 by Fraunhofer ILT, Germany, in an oil tank manufacturing industry [17]. Later, this system has been installed in several industries including shipbuilding, steel tube manufacturing and automotive industries, etc. In 2001, the world-famous welding company Fronius introduced hybrid laser arc welding system with a compact laser hybrid head to a standard industrial robot, which integrated MIG/MAG welding torch and laser optics, figure 1 [16, 95].

Nowadays, plenty of hybrid laser arc welding systems are commercially available in the industry. The quantity of these systems has increased in the last decade not only as a result of commercially available integrated hybrid welding heads development, but also due to more cost-effective powerful lasers with advanced automated control [18].

Besides hybrid welding of laser beam and arc welding, today there is also available hybrid welding with combination of laser beam and plasma arc or submerged arc welding – SAW [16].

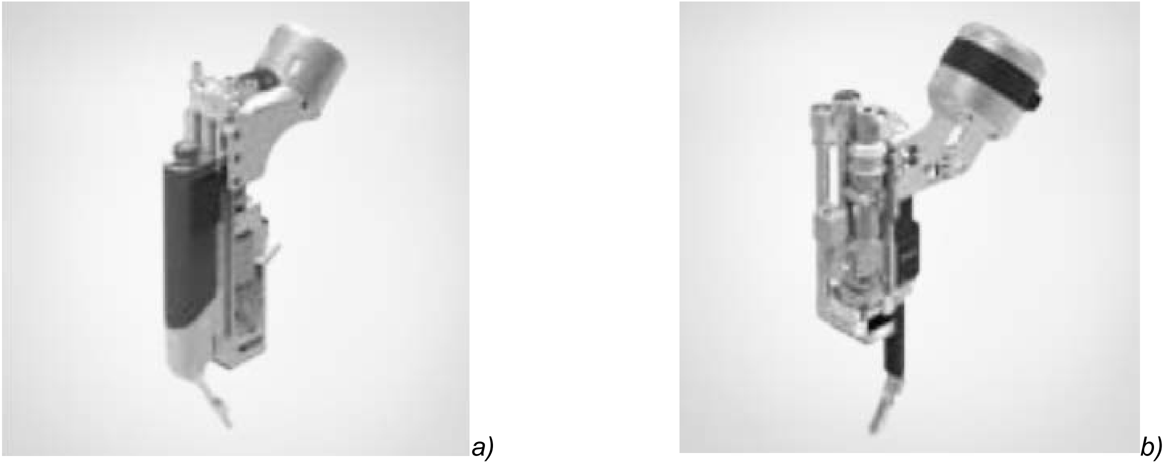


Figure 1. *a) Compact, b) Ultracompact – integrated welding head [16, 95]*

Slika 1. *a) Kompaktna, b) Ultrakompaktna – integrisana zavarivačka glava [16, 95]*

Furthermore, HLAW compensates the limitations of the individual LBW and GMAW processes, reducing the cooling rates from the weld zone and increasing the dimensional tolerances of the joints in comparison to LBW [20]. Additionally, HLAW offers several process advantages, such as: higher welding speed [21], requirement of fewer number of welding passes [22], increased penetration depth [23], narrow weld seam with small heat affected zones HAZs [24] and stable welding process [25].

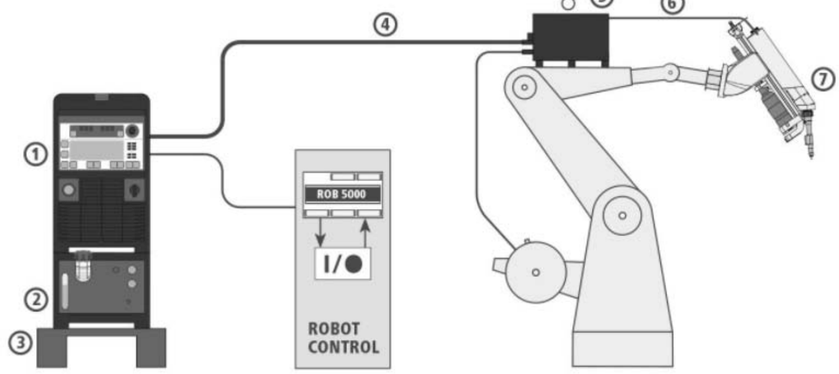
The use of secondary heat source, as electric arc, compensates the requirement of high-power laser, thus directly affecting the cost of the set-up [21]. Hybrid laser arc welding process due to its advantages compared to other welding processes allows wide application in many industries, starting from the automotive to heavy metal industries [26], while welding different steels with thickness range from 1mm to 50mm [27].

Although the hybrid laser arc welding process has numerous process advantages, the process has certain limitations too, such as: controlling large numbers of process welding parameters, requirement of accurate positioning and proper fit-up of the welding material, higher initial investment, and additional safety measures. Consequently, HLAW is a complex welding process due to the combination of two heat sources in a single weld pool [28], resulting in non-acceptance by the industry [29].

2. Hybrid welding with laser beam and electric arc – HLAW

In the last decade, the development of the hybrid laser arc welding has been characterized by improvements of the welding technique where the laser beam and the electric arc act on the welding material at the same time and in the same place.

Several hybrid laser arc welding systems have been developed based on different combinations of laser beam and arc welding systems. The most commonly used lasers are gas CO2 lasers with continuous wave or Nd:YAG lasers with pulsed operation, while the second sources is electric arc MIG/MAG or TIG depending on the type and thickness of the welded material.



1. TransPuls Synergic

2. Cooling unit

3. Upright console

4. Interconnecting hosepack

5. Robot wirefeeder

6. Torch hosepack

7. LaserHybrid welding head

Figure 2. *System components of hybrid laser arc welding [95]*

Slika 2. *Komponente hibridnog sistema lasersko elektrolučnog zavarivanja [95]*

Although HLAW offers significant advantages over the individual LBW and GMAW processes, merger of the two heat sources in a single welding process leads to increased number of parameters that need to be synchronized. Moreover, the values of the parameters that are ideal for each process separately, are likely not to be optimal for successful welding with HLAW due to mutual influence. Consequently, an accurate study [30] of all the parameters used in the hybrid welding process is the basis for the stability and repeatability of the process and obtaining a weld with excellent mechanical and dimensional characteristics.

Usually, the lasers types that are used as a primary heat source in hybrid laser arc welding are gas CO_2 laser or solid state Nd:YAG laser that generate different wavelengths. The laser beam wavelength is the main welding parameter of HLAW, due to the direct influence on the choice of other welding parameters [31]. The type of laser source affects the distance between the both sources, Nd:YAG laser allows closer access to the electric arc compared to CO_2 laser due to a lower interaction with the electric arc [32].

In laser beam welding, the increase of laser power leads to deeper weld penetration [34]. In hybrid laser welding this phenomenon is often emphasized because the reflectivity of the workpiece metal is reduced when the metal is heated by the arc [35]. The hybrid laser arc welding process provides two different layouts for the heat sources. First layout is when the laser source is the first source that heats the working material - laser leading hybrid process. The second layout or arc leading hybrid process is when the electric arc is the first heat source that "attack" [36]. The layout depends on several factors, such as the characteristics of the welding material, the power of the laser beam and the electric arc [37].

The distance between the laser source and the arc is an important parameter to control the penetration in hybrid laser arc welding and normally is consisted of few millimeters value, separation distance is in the range of 0 to 5 mm [38]. Increasing the distance between the heat sources might result in loss of hybridization effects, i.e.to reduce the interaction between the laser beam and the electric arc [39]. When heat sources are placed in parallel or at a very short distance might lead to a problem of absorption of the laser energy by the electric arc, which partially blocks the laser beam resulting in less penetration [38, 40].

Another parameter in HLAW that directly affects the depth of the weld, but also the stability of the arc [41], and thus on the quality of the welded joint [28] is the shielding gas. In general, the shielding gas used in HLAW contains a high percentage of inert gas such as argon (Ar) and helium (He). During hybrid laser arc welding with CO_2 laser, absorption of the laser energy by the laser induced plasma and reduction of the laser intensity that reaching the weld pool is often occurred, due to longer wavelength [40]. The use of high ionization potential shielding gas like helium reduces the effect of plasma absorption, therefore during hybrid laser arc welding with CO_2 laser, a mixture of argon, helium and CO_2 is used [35, 38, 40]. The use of helium ensures deeper penetration, the argon improves the arc stability, while a small percentage of oxygen less than 5% reduces the spatter formation and improves metal transfer during the welding process [42, 43]. The mode of metal transfer is an influential parameter for stable and repeatable welding process, for hybrid laser arc welding pulsed/spray-arc is recommended in relation to short/globular-arc [34, 43].

The angle of electrode is a parameter that affects the penetration of the weld provided by HLAW, this angle is related with the shielding gas flow and thus directly affecting the laser energy absorption [44]. The angle of electrode is typically set around 45^o – 65^o from the welding material surface, which reduces the arc length, and the laser beam is focused on the welding pool [36]. Generally, the laser beam is directed normal to the welding material surface to obtain better penetration. However, during the welding of highly reflective materials the laser beam is tilted at an angle in order to avoid any damages of the laser head due to the reflected beam, that must be different from the electrode's angle [45].

The main advantage of hybrid laser arc welding is the high welding speed and it's strictly related to the weld penetration. However, weld width and weld penetration are inversely affected by the welding speed [7, 9, 46]. The weld penetration increases when the welding speed decreases as a result of the higher heat input per unit length of weld [46]. The gap filling capability is improved at lower welding speeds, at constant filler wire feed rate [47]. The welding speed to filler wire feeding ration is an important factor for the stability of the keyhole and thus for the stability of the process itself [13, 17]. On the other hand, a too high welding speed leads to a fast heating and cooling cycle in the workpiece, which may result in metallurgical defects in weld fusion zone. Too low welding speed may create a larger weld pool with deep penetration until the limit of burn through the welding material [48,49].

In HLAW, the laser power is the main heat source for the welding efficiency improvement, which produces the keyhole and ensures the deep penetration [21, 50]. Therefore, the ratio of the power of the two heat sources should be considered and obtained by dividing the laser power with the arc power [48, 49]. The geometry and metallurgical properties of the weld strictly depend on the balance between the influences of the laser source and arc source [50]. In HLAW increasing of the power ratio leads to a narrow weld width, reducing the tendency of grain growth and modifies the microstructure of fusion zone [16, 45, 51, 52]. In conditions of constant filler wire feed rate and laser power, a higher power arc causes an increase of the width of the bead until it reaches a maximum value [53]. This effect mainly is caused by the arc power, by increasing the voltage at constant filler wire feed speed, the arc length and its diameter grow up and consequently the area of molten pool grows up [16, 51, 53]. Under appropriate welding parameters, hybrid laser arc welding with high power ratio can ensure higher welding speed with better shape and microstructure of the weld, and thus directly affecting its mechanical properties [33, 54].

3. HLAW performance and characteristics

Welding performance of HLAW is measured in terms of weld penetration, increase of welding speed, and gap bridging ability while reducing the operative costs. The weld quality achieved by HLAW can be assessed in terms of improving the microstructure of the weld and its mechanical properties by reduction of the welding defects [57].

The laser beam welding provides high welding speed and high weld quality, but on the other hand requires precise preparation of the welding groove and set-up of the welded elements, which is not the case for HLAW [16]. For comparison, the HLAW process is 50% faster than the laser beam welding [49].

For hybrid welding of thin sheets and elements with different thickness, a combination Nd:YAG laser and MIG/MAG welding with thinner wire is used. On the other hand, for welding of thicker elements, a combination of gas CO2 laser with continuous wave with MIG electric arc is used [16, 58]. The HLAW enables welding of thin sheets at high welding speed in the range of 4m/min – 14m/min [59, 60]. The researchers Kutsuna and Chen compared the hybrid CO2 laser MIG/MAG welding of a low carbon steel with laser welding and found 30% faster welding speed during the hybrid welding. Additionally, the Nielsen’s results showed that the welding speed can be increased in the range of 30%-100% during hybrid CO2 laser MIG/MAG welding of C/Mn steel compared to laser welding using cold filler wire. According to Frostevarg and Kaplan, the speed can be further increased up to 200% when a joint gap of 0.6mm is constant between the welding elements [63]. The results obtained through numerical simulation, showed that the HLAW enables double welding speed compared to laser welding for identical laser beam parameters [64]. Moreover, the hybrid laser arc welding produced weld joints with higher strength and ductility than classic laser beam welding, due to the use of filler wire [65].

Based on the previous research, cross-sections of the weld joint provided by hybrid welding was divided in two zones: the upper-wide zone or laser-arc region and lower-narrow zone or laser region [66]. In both zones, the difference is terms of microstructure and distribution of alloying elements, due to the temperature difference and crystallization process [53, 67, 68, 69].

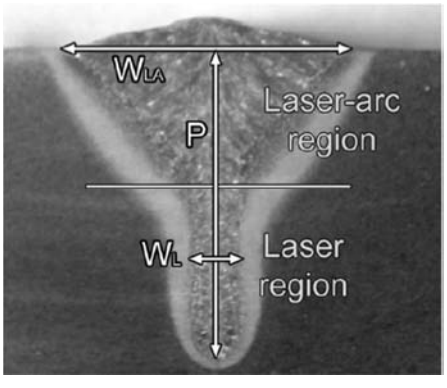


Figure 3. *Geometric characteristics of the HLAW weld cross-sections [4]*

Slika 3. *Geometrijske karakteristike poprečnog preseka HLAW zavarenog spoja [4]*

Except for thin sheets, the HLAW is used for thick sheets welding and usually is applied for thickness that can be welded in a single pass [56]. The steel plates with thickness up to 15mm are successfully welded in a single pass with a welding speed of 1 m/min by using a hybrid 20 kW laser MAG welding system [71]. Also, the constructive steel plates with thickness of 30mm can be welded, in dual passes using Hybrid welding with Double Rapid Arc – HyDRA, where two MAG torches are placed in two different sides of the plates [26]. In addition, steel plates with higher thickness can be welded by hybrid laser arc welding with multiple weld passes and optimum joint gap between the welding elements [72, 73]. The HLAW is capable to bridge a joint gap up to few millimeters depending on the laser power, welding speed, filler wire feed rate as well as the material thickness [74, 76]. However, by increasing the thickness of the welding elements, the possibility of pores and hot cracks in the weld increases as well [78, 79]. The second type of weld imperfections are more critical due to their sharpness [80, 81].

4. Industrial application of HLAW

Today, the hybrid laser arc welding represents an attractive alternative welding process for the different industries, due to several process advantages, such as: better weld quality and higher productivity compared to laser welding or arc welding [17, 82]. The initial costs for procurement of the entire hybrid process equipment can be compensated by providing higher welding speed and deeper penetration in order to reduce the cost per unit length of weld [41, 46]. With HLAW a wide range of materials, from ferrous metals like structural steels, stainless steels to non-ferrous metals like aluminum (Al), magnesium (Mg), Nickel (Ni) and their alloys can be welded [7, 16, 22, 31, 33, 83]. Moreover, HLAW allows the welding of thin sheet metals as well as thick metal plates in one or more weld passes, however compared to conventional welding processes the number of passes are less which results in reduction of weld distortion [30, 73, 79, 94].

The main application of HLAW process is found in automotive and shipbuilding industries, where producing light or heavy vehicles and ships a large number of metal components should be welded [85, 86].

In the automotive industries, companies like Audi AG and Volkswagen have already implemented hybrid laser arc welding in their production lines [87]. Total 48 hybrid fillet and butt welds are made in each of the Volkswagen Phaeton main frame, while the roof frame and its different parts of Audi A8 vehicle are welded by hybrid laser arc welding [88]. The HLAW process is also installed in Daimler AG and has resulted in increased productivity by increasing welding speed and wire efficiency, while maintaining good penetration and improved metallurgical characteristics of the welded joint [59].

The German shipyard company, Mayer-Werft GmbH in its own production line has implemented HLAW process for welding of steel panels and stiffeners that are installed in ships. By using a combination of 12 kW CO2 laser with a 450A GMAW, 12mm thick fillet joints with 12m long weld seams are performed successfully with reduced deformation and thus eliminates the reworking required for flattening of the welded parts. Pieces of tensile, hardness, impact, bending, and fatigue tests were performed from these joints and satisfactory results were obtained [89]. The Italian shipyard company, Fincantieri SpA by using hybrid laser arc welding system with combination of Nd:YAG laser and MAG welding technique, enabled them to overcome the problems with weld distortion and effective bridging of the joint gap [90]. For the shipbuilding industry the HLAW process with fiber laser has been developed and it integrates several software solutions for process control and weld quality monitor [91, 92].

The HLAW is used in power industry to weld tight wall panels and ribbed pipes of boilers, the company Energoinstal SA has applied hybrid laser arc welding due to its advantages, such as process stability, higher joint gap tolerance, higher efficiency and deep penetration [94].

5. Conclusion

The synergy effect of laser beam and electric arc offers several advantages over other individual technological processes, such as: increased productivity, deeper penetration, higher welding speed, better gap bridging ability, better process stability, less heat input to the welding material, etc. Nevertheless, the combination of two heat sources

5. Zaključak

Sinergijski efekat laserskog snopa i električnog luka dovodi do niza prednosti u odnosu na pojedinačne tehnološke procese zavarivanja, kao što su: povećana produktivnost i penetracija, veće brzina zavarivanja,bolja ispuna žlebova, bolja stabilnost procesa, manji unos toplote u radni materijal itd. Međutim, spajanje dva izvora toplote u in a single welding process is challenging due to the increased number of welding parameters that should be synchronized, thus increasing the physical complexity of the process. The values of the parameters that are optimal for each process separately, are not suitable for hybrid laser arc welding, therefore the desired benefits can be obtained by appropriate combination of both heat sources and optimization of the welding parameters. In HLAW the laser power is the primary source of heat on which overall process and the welding penetration depth efficiency depends, while the power of the electric arc and its distance to the laser beam directly affects the process stability, droplet transfer mood and weld bead geometry. The ratio between the welding speed and filler wire feeding is another parameter that affects the entire process stability as well as on the weld shape. Similarly to other welding processes, in HLAW the shielding gas influences the arc characteristics, formation of weld shape, and mode of metal transfer. With hybrid laser arc a few millimeters joint gap welding successfully can be welded, but this distance also depends on the thickness of the materials, layout and ratio between both heat sources, welding speed and wire feed rate.

Despite the fact that the hybrid laser arc welding has been accepted by large number of industries and a good number of research have been published related to the advantages of its implementation, its percentage presence in the production lines is far from satisfactory, partly due to higher initial cost, partly due to the large number of process parameters and their mutual influences that have not been sufficiently explored, leading to entire hybrid arc welding process to be insufficiently developed.

For a better understanding of the HLAW process, besides the previous research and implementations, additional simulations and theoretical modeling are necessary to be performed as well as experimental research regarding efficiency and effectiveness of the entire process for welding of structural steel using different types of wires, solid and flux-cored welding wires. Moreover, due to the lack of information about the effects of different shielding gases and different welding wires as well as the influence of the welding groove shape on the quality and mechanical properties of the welded joints, additional experimental research should be performed.

jedan proces zavarivanja predstavlja izazov zbog povećanog broja parametara zavarivanja koje treba sinhronizovati, čime se povećava fizička složenost procesa. Vrednosti parametara koji su optimalni za svaki proces pojedinačno, nisu pogodni za hibridno zavarivanje sa laserskim snopom i električnim lukom, zbog toga jedini način za dobar kvalitet se može postići sa odgovarajućom kombinacijom oba izvora toplote i optimizacijom parametara zavarivanja. Kod hibridnog zavarivanja sa laserskim snopom i električnim lukom, snaga lasera je osnovni izvor toplote od kog zavisi efikasnost celog procesa i veličina prodiranja zavara, dok snaga i položaj elekričnog luka direktno utiču na stabilnost procesa, način prenošenja rastopljenog materijala i oblika zavara u gornjoj zoni. Na stabilnost celog procesa, kao i na oblik zavara utiče odnos između brzine zavarivanja i brzine prenošenja dodatnog materijala. Kao i kod drugih procesa zavarivanja, kod hibridnog zavarivanja zaštini gas utiče na karakteristike luka, formiranje oblika zavara i način prenošenja dodatnog materijala. Hibridno zavarivanje sa laserskim snopom i električnim lukom omogućavaju uspešno punjenje zazora do nekoliko milimetara, ali ovo rastojanje takođe zavisi od debeljine materijala, odnosa između dva izvora toplote i njihovog rasporeda, kao i od brzine zavarivanja i brzine prenosa dodatnog materijala.

Uprkos činjenici da je hibridno zavarivanje sa laserskim snopom i električnim lukom uveliko prihvaćeno od industrije i da je sprovođen neznatan broj istraživanja u vezi prednosti njegove implementacije, njegov udeo u proizvodnim linija daleko je od zadovoljavajućeg, delimično zbog početnih visokih troškova implementacije, delom i zbog velikog broja parametara samog procesa i njihovih međusobnih uticaja koji nisu dovoljno istraženi, što dovodi do toga da je ceo proces hibridnog zavarivanja sa laserskim snopom i električnim lukom nedovoljno razvijen.

Za bolje razumevanje procesa, pored dosadašnjih istraživanja i implementacije, neophodne su dodatne simulacije i teorijsko modeliranje, kako i sprovođenje dodatnih eksperimentalnih istraživanja i efektivnosti procesa pri zavarivanju konstrukcionog čelika korišćenjem različitih vrsta dodatnih materijala, pune i punjene žice. Dodatno, zbog nedostatka informacija trebalo bi ispitati kako debeljina radnog materijala, različiti zaštitni gasovi i žice za zavarianje, kao i uticaj oblika žljeba za zavarivanje utiču na kvalitet i mehanička svojstva zavarenih spojeva.

At the end, economic analysis for hybrid laser arc welding of structural steel should be performed in order to check the economic viability to achieve higher quality at lower costs compared to the individual welding processes.

Na kraju, treba sproveti ekonomsku analizu zavarivanja konstrukcionih čelika hibridnim zavarivanjem sa laserskim snopom i električnim lukom, kako bi se proverila ekonomska opravdanost za postizanje većeg kvaliteta uz niže troškove u odnosu na pojedinačne procese zavarivanja.

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<u>Podsećamo vas da je sada vreme da obnovite vaše članstvo u DUZS i pretplatu za naš časopis.</u>