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LASERSKO ZAVARIVANJE KONSTRUKCIJSKOG ČELIKA S355

LASER WELDING OF STRUCTURAL STEEL S355

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SAŽETAK

Prilikom odabira načina zavarivanja, potrebno je uračunati različite faktore poput brzine zavarivanja, temperature zavarivanja, potrebe za dodatnim materijalom, potrebe za izvorom energije, veličine, cijene i jednostavnosti održavanja uređaja i aparature. U ovom radu istražuje se primjena laserskog zavarivanja na konstrukcijskom čeliku S355 korištenjem industrijskog uređaja izrađenog za tu svrhu. Nakon temeljite pripreme površina i optimizacije parametara prvog i višestrukih prolaza, provedena su laboratorijska ispitivanja koja uključuju ne-razorne (NDT) i razorne (DT) metode. Rezultati pokazuju da je primijenjena metoda sposobna proizvesti homogen i kvalitetan zavareni spoj s minimalnim oštećenjima uzrokovanim utjecajem razvijene topline. U radu su detaljno analizirani parametri poput brzine skeniranja, širine laserske zrake, snage i frekvencije te su dobivene mehaničke karakteristike uspoređene s relevantnim normama i standardima.

Ključne riječi: *Lasersko zavarivanje, konstrukcijski čelik S355, mehanička svojstva, NDT, DT*

ABSTRACT

When choosing a welding method, it is necessary to consider various factors such as welding speed, welding temperature, the need for additional material, the need for energy source, size, cost, and the ease of maintenance of the equipment and apparatus. In this paper, the application of laser welding on structural steel S355 is investigated using an industrial device designed for this purpose. After thorough surface preparation and optimization of the parameters for both the initial and multiple passes, laboratory tests were conducted, including non-destructive (NDT) and destructive (DT) methods. The results show that the applied method is capable of producing a homogeneous and high-quality welded joint with minimal damage caused by the generated heat. The paper provides a detailed analysis of parameters such as scanning speed, laser beam width, power, and frequency, and the obtained mechanical characteristics are compared with relevant norms and standards.

Keywords: *Laser welding, structural steel S355, mechanical properties, NDT, DT*

1. UVOD

1. INTRODUCTION

Welding is a process of joining materials, most commonly metals or plastics, in which the edges of the material melt and often, with the help of additional material, form a single, strong bond after cooling. This technique has a long history, as its first applications date back to the Bronze Age, when bronze and copper were melted to improve the aesthetic and functional properties of weapons, tools, and armour. Significant progress in welding was recorded at the beginning of the Industrial Revolution (18th and 19th centuries), when manual production was replaced by steam engines, leading to the development of gas welding and electric arc welding methods. In the 20th century, with the emergence of gas and arc welding, the process gained a new dimension in terms of mass production and industrial growth. Today, advanced techniques such as laser welding, TIG (Tungsten Inert Gas), and MAG (Metal Active Gas) welding are used, allowing for more precise and efficient material joining. With continuous technological advancements, including automation, electronics, robotics, and mechatronics, welding has become a key technology in various industries, including shipbuilding, energy, aviation, automotive, and construction. [1]

In this work, the possibilities of applying laser welding to structural steel S355 are explored. The motivation for the research stems from the need for faster, more precise, and energy-efficient methods of joining materials in modern industrial production. Previous research [2] has shown that traditional welding methods often result in greater material damage caused by heat, which negatively affects the mechanical properties of the weld. Therefore, it is reasonable to assume that properly optimized parameters of laser welding can ensure a high-quality welded joint with minimal thermal impact. The paper presents an experimental procedure, analyses the results of laboratory tests, and compares the obtained data with relevant standards.

2. PRINCIP SPAJANJA MATERIJALA POSTUPCIMA ZAVARIVANJA

2. PRINCIPLE OF MATERIAL JOINING BY WELDING PROCESSES

Welding is not necessarily a complex process and requires three basic elements:

1. Welding equipment (depending on the welding method).
2. Base and filler materials for welding.
3. Protective equipment during the welding process.

The principle of welding is based on creating heat that brings the material to a liquid or plastic state and, with the possible addition of filler material, enables the creation of a solid joint without mechanical defects. During the process, the joint cools and solidifies, and the final properties of the welded joint depend on the technology used, welding parameters, and the type of filler material. The main welding methods are divided into pressure welding and fusion welding, as shown in (table 1). [3]

***Tablica 1** Postupci zavarivanja pritiskom i zavarivanja taljenjem*

***Table 1** Welding procedures by pressure and welding by melting*

Pressure welding	Fusion welding
Ultrasonic welding	Arc welding
Forge welding	Gas welding
Resistance welding	Electron beam welding
Friction welding	Laser beam welding

Each of the mentioned methods has its advantages and disadvantages, and when selecting the appropriate procedure, factors to be considered include the thickness of the base material being processed, the need for using filler material, the need for using shielding gas, the material's resistance to thermal deformation, and the cost-effectiveness and efficiency of the chosen process. The butt joint is classified as one of the simplest types of welded joints, and it is obtained by joining two materials along their edges, which can be prepared in "I", "V", or "U" shapes. In this work, a butt-welded joint was achieved using a laser beam with edges previously prepared in a "V" shape.

3. LASERSKO ZAVARIVANJE

3. LASER WELDING

The first laser was developed and built in 1960 by the American T. Maiman. The word laser is an acronym in English and stands for "Light Amplification by Stimulated Emission of Radiation". When comparing the light source of a laser with other light sources, it can be concluded that laser light is coherent and directional, which means it has the same wavelength, amplitude, and phase shift. A laser is always the same colour because its wavelength does not change.

The laser welding process uses a laser beam to melt material in order to create a bond between two materials being processed. The advantage of this type of welding is the high precision of energy (laser beam) direction, which reduces and almost eliminates energy loss. It is possible to create homogeneous, reliable, and strong welded joints. [4] Before using the laser welder, the workpiece needs to be cleaned and fixed in a position ready for welding. The work was carried out by an experimental procedure under industrial conditions. The surfaces of steel plates made of S355 material were prepared by grinding to remove rust and impurities. Structural steel S355 is used in almost all parts of structures and structural fabrication and is present in almost all industries, and the filler material used is a VAC 60 electrode suitable for welding steels with strengths up to 530 N/mm2. Using the laser welder model HGLW 3000EW shown in (Figure 1), the plates were joined. The parameters for the first pass were: scanning speed 300 mm/s, laser beam width 4.0 mm, maximum power 1900 W, frequency 5000 Hz, inert gas nitrogen 5.0. Also, on the feeder control panel, the speed for the first tool pass (weld) was set to 12 cm/min to ensure slower welding and thus greater passage of filler material to the other side of the butt joint.

Slika 1 *Uređaj za lasersko zavarivanje HGLW 3000EW*

Figure 1 *Laser welding device HGLW 3000EW*

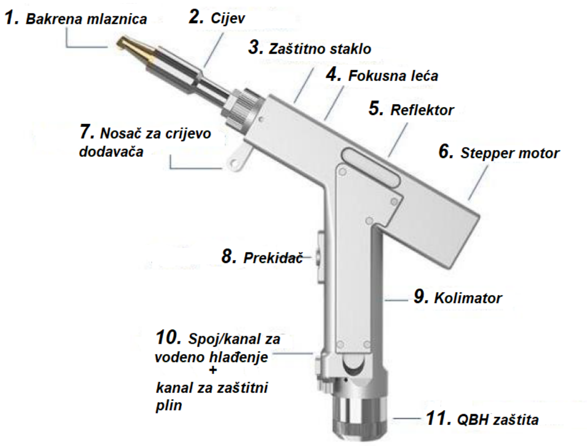
Laser welding technology has certain limitations depending on the thickness of the material being welded. Given that a single pass allows welding of 3 mm thick sheet metal, in this work, welding thicker sheets required multiple passes to achieve a homogeneous butt welded joint. Multiple passes were performed with adjustments to the filler material feed rate to ensure even joint filling. The laser welding device used for the purposes of this work has, in addition to the welding option, cutting and material cleaning options as needed. Furthermore, the advantages of this apparatus include ease of use, high welding speed, and automatic addition of filler material using an electric motor that guarantees consistency and precision. Some of the materials for which this apparatus is intended are stainless steel, carbon steel, and aluminium alloys. The technical specifications of the laser welding device are shown in (table 2).

Tablica 2 *Tehničke specifikacije uređaja za lasersko zavarivanje HGLW 3000EW*

Table 2 *Technical specifications of the laser welding device HGLW 3000EW*

Masa	250 kg
Dimensions	1140x730x930 mm
Maximum Power	3000 W
Voltage	3P AC 380 V
Frequency	50 Hz
Current	50 A

The parts of the welding head are shown in (Figure 2). The copper nozzle is a part of the laser head and assists in guiding the laser beam and allowing the shielding gas to pass through. The tube enables adjustment of the laser's focal length. The protective glass shields the optics from various impurities such as dust or other particles that could cause interference during welding. Focusing lens focuses the laser beam towards the focal point, i.e., the desired welding point. The reflector is an element that redirects the laser beam. The micro stepper motor controls the position of the reflector (reflector lens). The wire holder is used for adding material and serves to fix and hold the tube through which the filler material is supplied. The switch allows the user to turn the laser head on and off. The collimator is an optical device for aligning or "collimating" the laser beam into a straight path before focusing on the material being processed. Water channels supply and circulate water that cools the head during the welding process and maintains a stable temperature. Gas channels supply and circulate the shielding gas, which serves to prevent oxidation during the welding process. QBH (Quick Beam Handling) is a protective cover for the QBH connector that protects the system from stress.



Slika 2 *Dijelovi glave za zavarivanje*

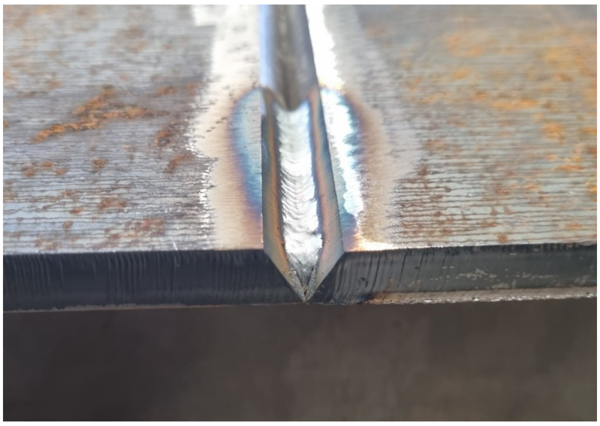
Figure 2 *Parts of the welding head*

The next important part of the laser welder is an auxiliary box, separate from the laser welder itself, which contains two electric motors and stands for spools of filler material (Figure 3) that the device adds as needed during the welding process. In the example shown in the figure, you can see a wire feeder with the ability to add two wires simultaneously or one as needed. The laser source uses semiconductor elements to create a laser beam that is directed towards the welding head via an optical cable. The entire system is cooled by water cooling.

Slika 3 *Dodavač*

Figure 3 *Feeder*

The results of laser welding after the first pass and the creation of the root weld of the butt joint are shown in the following figures. In (Figure 4), the beginning of the root weld after the first pass is visible from the top side.



Slika 4 *Korijeni zavar (gornja strana)*

Figure 4 *Weld root (upper side)*

Figure 5 shows the same beginning of the root weld photographed from the bottom side.

Slika 5 *Korijeni zavar (donja strana)*

Figure 5 *Weld root (bottom side)*

After completing the first weld pass, the parameters for the second and third passes remained the same, except the filler material feed rate was set to 50 cm/min. For the fourth and fifth passes, the laser beam width was increased from 5.00 mm to 6.00 mm to cover the larger surface area during the welding process. Additionally, the power was increased to 1300 W, and the feeder speed was raised from 50 cm/min to 60 cm/min. After the fourth and fifth passes, a temperature check was performed, measuring 60°C. It's important to note that before each tool pass, the weld area was cleaned to prevent interference during the continuation of welding. Up to the eleventh pass, the parameters remained the same as for the fourth and fifth passes, with the temperature reaching 95°C. For the twelfth pass, the power was increased from 1300 W to 1400 W, and the laser beam width was expanded from 6.00 mm to 7.00 mm. The feeder speed remained constant at 60 cm/min. It was determined that due to the plate thickness, three more passes were needed to ensure complete joint filling.

4. ISPITIVANJA MEHANIČKIH SVOJSTAVA ZAVARENOG SPOJA

4. MECHANICAL PROPERTIES TESTING OF THE WELDED JOINT

For the purposes of this work, structural steel S355 was used, designated according to the EN 10025-2004 standard, with a plate thickness of 10 mm. This type of steel is a medium-strength manganese steel that also contains a low carbon content, is easily weldable, and has good impact resistance.

The specified chemical composition of the used material, expressed as percentage content by mass of individual elements and its grades, is shown in (Table 3). The chemical composition of the electrode used as filler material, VAC 60 with a diameter of 1.6 mm, is shown in (Table 4).

Tablica 3 *Kemijski sastav S355 čelika*

Table 3 *Chemical composition of S355 steel*

	S355 Chemical Compositiion sastav %(≤)						
Razred	**C**	**Si**	**Mn**	**P**	**S**	**Cu**	**N**
S355JR	0.24	0.55	1.60	0.035	0.035	0.55	0.012
S355J0	0.20	0.55	1.60	0.030	0.030	0.55	0.012
S355J2	0.20	0.55	1.60	0.025	0.025	0.55	-
S355K2	0.20	0.55	1.60	0.025	0.025	0.55	-

Tablica 4 *Kemijski sastav elektrode VAC 60*

Table 4 *Chemical composition of the VAC 60 electrode*

C	Si	Mn	P	S
0.08	0.90	1.50	<0.025	<0.025

Test specimens for mechanical testing were prepared according to welding joint testing standards. The tensile test was conducted according to ISO 6892-1 standard on a Messphysik BETA 250 universal static testing machine. The impact toughness test was performed using a ZWICK ROELL RKP450 Charpy impact tester according to ISO 148-1 standard. Macro and micro examinations, as well as the inspection of the "V" notch on impact test specimens, were carried out using an OLYMPUS SZX10 optical stereo microscope and an OLYMPUS BX51 metallographic microscope. The macro and micro examinations of the welded joint were conducted according to the rules of ISO 17639 standard. For macro and micro examinations, samples of the laser-welded joint on S355 steel plate were, after cutting (LECO saw), ground, polished (STRUERS LABOPOL), and etched with a 3% Nital solution for 10 seconds

The average value of tensile strength results for the welded joint of S355 material was Rm=486.24 MPa, while the average elongation of the specimens was A=19.28%. All specimens fractured in the base material zone outside the welded joint area and the heat-affected zone (HAZ). In (Figure 6), the specimens can be seen after static tensile testing, showing visible elongation compared to the initial state, which is also reflected in the tensile test results. The results of the Charpy impact toughness test are, on average, three times higher than those found in the characteristic tables for S355 material.

Slika 6 *Ispitne epruvete nakon statičkog vlačnog ispitivanja*

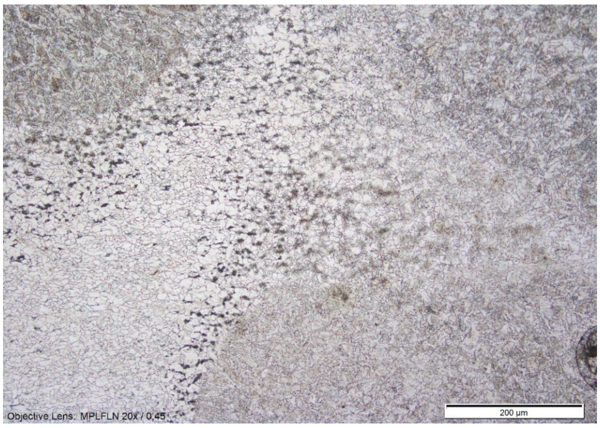
Figure 6 *Test specimens after static tensile testing*

In (Figure 7), a defect can be seen which, due to its regular shape, most likely indicates a zone where the base material did not melt through. Additionally, defects in the form of bubbles and other irregular shapes are observed, which were formed by spatter of the molten material during the welding process.

***Slika** 7 Makro analiza pri uvećanju P=12,5X (nakon nagrizanja)*

***Figure** 7 Macro testing at 12,5X magnification (after etching)*

The change in the microstructure of the welded joint is not of poor quality, except for the occurrence of pitting defects caused by molten material spatter. In (Figure 8), a change in microstructure can be observed, specifically how pearlite concentrates and penetrates into the base material (HAZ zone).



***Slika 8** Mikro analiza pri uvećanju P=200X (osnovni materijal, ZUT i zavar)*

***Figure 8** Micro testing at 200X magnification (Base material, HAZ, and weld Face)*

5. DISKUSIJA
5. DISCUSSION

This paper presents laser welding technology and laboratory material testing, which include material strength testing, impact toughness testing, and micro and macro examinations of the achieved welded joint. The obtained results show that laser welding is a suitable technique for joining S355 structural steel. However, it is necessary to consider the micro and macro analyses, which indicated the presence of defects in the welded joint that occurred as a result of molten material spatter during the welding process and insufficient penetration. To achieve better quality of the welded joint and avoid these defects, it is proposed to adjust welding parameters, ensure and perform additional control of the cleanliness of the welded joint before welding, possibly reduce welding speed, and carry out overall additional preparation before starting the welding process.

The test results, when compared to standard requirements, show that laser welding enables the creation of a homogeneous welded joint with very few defects. Temperature measurements during multiple passes confirmed that the critical value was not exceeded, thereby minimizing the risk of overheating. The static tensile test confirmed the high strength of the joint, while impact toughness tests indicated adequate resistance to dynamic loads. Microscopic analysis revealed an orderly structure of the welded joint, further confirming the quality of the applied technology.

Based on the obtained results, it can be confirmed that laser welding is a more efficient joining method compared to traditional techniques and allows for high precision in energy direction with minimal thermal impact on the surrounding material, higher welding speeds, and less need for additional processing. Disadvantages include the initial investment and the need for highly qualified operators. Experimental tests confirm that the technology is suitable for industrial application and opens up space for further research in process optimization. The achieved results contribute to new insights in the field of modern material joining methods.

6. REFERENCE

6. REFERENCES

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• **Ivan Simetić** - Magistar inženjer strojarstva koji je tijekom studija sudjelovao u brojnim istraživanjima vezanim uz lasersko zavarivanje, čime je nastao ovaj izvorni znanstveni rad. Fokus istraživanja mu je na optimizaciji tehnoloških parametara kako bi se osigurala maksimalna kvaliteta zavara i povećala učinkovitost proizvodnje. Zaposlen je kao suradnik istraživač na IRI projektu u Centru za istraživanje METRIS Istarskog veleučilišta gdje surađuje s brojnim partnerima iz industrije i rješava njihove probleme s materijalima za brojne primjene.

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• **Neven Munjas** - Doktor tehničkih znanosti u području strojarstva. Predavač je na Istarskom veleučilištu, a vanjski je suradnik na Odjelu za inženjerstvo i arhitekturu Sveučilišta u Trstu te na Zavodu za tehničku mehaniku na Tehničkom fakultetu Sveučilišta u Rijeci. Ima 15 godina radnog iskustva u visokom obrazovanju te godinu dana iskustva u privredi, na projektiranju zaštite od buke. Područje znanstvenog interesa je tehnička mehanika (mehanika krutih i deformabilnih tijela), posebno primjena metode konačnih elemenata na probleme elastičnosti, plastičnosti, termomehanike, puzanja i slično. Educiran je za ispitivanje meahničkih svojstava materijala.

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