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СВОЈСТВА РУЧНО ЗАВАРЕНИХ ЛАСЕРСКИХ СПОЈЕВА

PROPERTIES OF HAND-WELDED LASER JOINTS

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Abstract: Laser welding technology is a rapidly developing field of material joining. Compared to traditional welding methods, it has been relatively little studied. This article presents the results of tests on welded test joints made of stainless steel, using three types of shielding gases: nitrogen, argon, and a mixture of argon with hydrogen. Strength tests were conducted on hand-held laser welded joints, the chemical composition of welding fumes, and the corrosion resistance of test joints in neutral salt spray (NSS). Strength testing in a static tensile test showed that the welding process of X5CrNi18-10 (AISI 304) steel did not significantly reduce most parameters. None of the tested specimens fractured in the weld or in the HAZ zone, regardless of the type of shielding gas. The tensile strength for all specimens was at a similar level, only slightly lower compared to the steel before welding. The corrosion resistance test using the NSS test revealed a greater susceptibility to corrosion in welded joints made under a pure nitrogen shield. The first corrosion spots appeared after only 8 days of testing. The highest corrosion resistance was demonstrated by plates welded in a shielding gas mixture of argon with added hydrogen. An analysis of welding fumes was conducted for test joints welded. The content of manganese oxides, iron oxides, and nitrogen oxides was analyzed. Analysis of the content of manganese oxides and iron oxides in welding fumes showed a significantly higher concentration of these substances during welding in a nitrogen shield. The concentration of substances harmful to health was approximately 20% higher than during welding in an argon-hydrogen mixture shield. The results of the study indicate that the reducing properties of hydrogen have a beneficial effect on welders' working conditions and on corrosion resistance, without reducing the strength properties of the welded joints.
Key words: Laser welding, shielding gases, stainless steel, durability, quality, fracture.

Rezime: Технологија ласерског заваривања је брзо развијајућа област спајања материјала. У поређењу са традиционалним методама заваривања, она је релативно мало проучавана. Овај чланак представља резултате испитивања заварених испитних спојева од нерђајућег челика, користећи три типа заштитних гасова: азот, аргон и мешавину аргона са водоником. Проведена су испитивања чврстоће на ручно завареним ласерским спојевима, хемијског састава заваривачког дима и отпорности на корозију испитних спојева у неутралном сланом спреју (НСС). Статичко испитивање затезне чврстоће показало је да процес заваривања челика X5CrNi18-10 (AISI 304) није значајно смањио већину параметара. Ниједан од испитиваних узорака није пукао у зони завара или у зони утицаја топлоте (ЗУТ), без обзира на врсту заштитног гаса. Затезна чврстоћа свих узорака била је на сличном нивоу, само нешто нижа у поређењу са челиком пре заваривања. Тест отпорности на корозију помоћу НСС теста открио је већу склоност ка корозији код заварених спојева изведених под заштитом чистог азота. Прве мрље корозије појавиле су се након само 8 дана тестирања. Највећу отпорност на корозију показале су плоче

заварене у заштитном гасу мешавини аргона са додатим водоником. За заварене испитне спојеве спроведена је анализа заваривачког дима. Анализирани су садржај манган оксида, гвожђе оксида азотних оксида. Анализа садржаја манган оксида и гвожђевих оксида у заваривачким испарењима показала је значајно вишу концентрацију ових супстанци током заваривања у заштити азотом. Концентрација супстанци штетних по здравље била је приближно 20% виша него током заваривања у заштити од аргон-водоничне мешавине. Резултати истраживања указују да редукујућа својства водоника имају повољан утицај на радне услове заваривача и на отпорност на корозију, без смањења чврстоће заварених спојева.
Kljčne reči: Ласерско заваривање, заштитни гасови, нерђајући челик, трајност, квалитет, прелом

1. INTRODUCTION

Welding processes have long been one of the basic and most developed technologies for joining metal components, finding widespread use in both heavy industry and the production of thin-walled products. Their importance stems not only from the ability to permanently join materials but also from the direct impact of welding technology on the functional properties, durability, and quality of the entire structure. During welding, the material is exposed to a variable temperature field, which leads to changes in its structure and physical and mechanical properties. Therefore, the proper selection of process parameters and the assessment of the resulting joint, encompassing not only its strength but also its workmanship, durability, and surface appearance, are particularly important [1]. One technology that has gained increasing importance in recent years is laser welding. Compared to traditional welding methods, this process is characterized by very high energy density focused on a small area of the material. This allows for a limited width of the heat-affected zone (HAZ), reduced thermal impact on the structure, and limited deformation. At the same time, it allows for narrow and deep welds, high-speed welding, and precise control of the energy input. Another important advantage is the possibility of automating the process and monitoring its parameters, which creates conditions for obtaining repeatable, high-quality joints [2].

Despite these advantages, laser welding has long remained a more specialized solution than conventional welding technologies. Its use requires proper preparation of the joined components, high precision, and the correct selection of process parameters. Factors such as laser power, beam focus position, welding speed, and gas shielding conditions are particularly important. In the case of thin-walled components, even minor inaccuracies in edge preparation can lead to joint defects, such as lack of fusion. However, the development of laser technologies and their application in mass production demonstrate that these limitations can be compensated for by high precision, speed, and process repeatability. This technology is already used in vehicle manufacturing, mechanical engineering, energy production, electronics, medical technology, and the production of household appliances, among others [3, 4].

Therefore, research on laser-made joints is important not only for the development of welding technology itself, but also for the design and operation of steel structures. Determining the relationship between process parameters and the quality of the resulting joint allows for better utilization of laser technology, reducing the risk of inconsistencies, and increasing production repeatability. Therefore, it's worth considering a laser joint not only as a result of the technological process, but as an integral element of the design, the quality of which can determine its safety, durability, and functionality. Combining the assessment of appearance and workmanship with the analysis of mechanical properties allows for a more comprehensive characterization of this technology's capabilities. Determining process parameters that allow for a compromise between high joint quality, strength, durability, aesthetics, and method efficiency is particularly important.

It should be emphasized that one of the most important parameters of laser welding is the type of shielding gas used [5, 6]. It plays several key roles. First, it protects the molten metal from environmental influences, prevents the laser beam from dispersing, and protects the laser welder's optics from damage. The gas is responsible for isolating atmospheric air from the molten metal, reducing the formation of oxides [7, 8]. Additionally, a properly selected shielding gas minimizes laser beam dispersion, which translates into improved weld quality and increased welding efficiency. In manual laser welding, the most common shielding gases used are argon, helium, nitrogen, and carbon dioxide (CO_2), and less frequently, gas mixtures.

Argon is more commonly used than helium. It is cheaper and provides equally stable arc properties. It does not react with the materials being welded, so the area around the weld remains free of contaminants. This is especially important when welding metals such as aluminum or stainless steel, which are highly sensitive to oxidation [9].

Nitrogen is also a good solution for laser welding. It is often used for welding stainless steels. Nitrogen increases weld penetration and facilitates the formation of stronger bonds in the base material. Furthermore, nitrogen can prevent excessive oxidation and reduce slag formation.

Carbon dioxide is used less frequently because it can cause more spatter compared to argon. In some welding applications, it is used because it is more affordable than other gases. This makes it an attractive option in applications where cost-effectiveness is a priority. For economic reasons, pure argon or nitrogen is standard in commonly used handheld laser welders.

Sometimes, a specialized argon mixture with a small amount of hydrogen (e.g., 98% Ar + 2% H_2) is used for laser welding. Unfortunately, the use of hydrogen in welding is usually limited, primarily due to the protective attitude of standards authors. It's worth mentioning that the reducing properties of hydrogen help remove oxides from the metal surface, ensuring a cleaner weld and reduced porosity. Furthermore, adding hydrogen to the argon mixture increases the temperature and thermal efficiency of the arc or plasma, allowing for faster welding.

The properties of the argon-hydrogen mixture described above justify further research into joints made by laser welding, which may contribute to the wider and more informed use of this technology in the construction of steel structures.

The aim of this study was to examine handheld laser welds made in three types of gas shielding, in terms of:

- tensile strength,
- corrosion resistance of test joints in the NSS test,
- composition of welding fumes affecting welders' health.

2. PROPERTIES OF HAND-HELD LASER WELDED JOINTS DEPENDING ON THE SHIELDING GAS USED

Defining the quality requirements for welding processes is extremely important, but also difficult. This is primarily due to the inability to verify the completed joint without damaging it. Various testing methods are used to reveal defects and nonconformities in welded joints. These are selected depending on the responsibility and class of the structure, ranging from single methods to combinations of several independent testing methods conducted simultaneously. Testing is divided into non-destructive testing (NDT) and destructive testing (DT). The main purpose of NDT is to monitor welding processes in the workshop environment where these structures are manufactured. Technical inspection services inspect joints using visual testing (VT), penetrant testing (PT), ultrasonic testing (UT), or radiographic testing (RT), depending on the recommendations of the designers and technologists [10].

A second method for verifying the quality of welded joints is destructive testing (DT). This involves properly preparing standardized samples and then subjecting them to constant or

variable loads until failure. Destructive testing is also conducted at various (sometimes extreme) temperatures. The behavior of materials under these loads is assessed. In this type of testing, it is crucial to create samples that faithfully replicate actual joints and apply loads as closely as possible to the operating conditions of the tested structures. Destructive testing is used to assess the qualification of welded joints, verify the correctness of welding procedures, and verify welders' qualifications. The basic destructive tests used to evaluate welded joints include: static tensile testing, bend testing, impact testing, hardness measurement, and macroscopic and microscopic examinations.

STATIC TENSILE TEST

To verify the effectiveness of the welded joints created with the handheld laser, a static tensile test was performed. The test plates were welded using a BDP PROLINE Mini Weld 1500 handheld laser in a shielding atmosphere of nitrogen, argon, and an argon-based gas mixture with 2% hydrogen.

The test joints were created with the following parameters:

- Laser power: 1000 [W],
- Welding speed: 600 [mm/min],
- Shielding gas flow: 10 [l/min],

The strength properties of the joints were determined by axial tensile testing of the samples on a SHIMADZU AGS-X testing machine. As previously mentioned, samples with a cross-sectional area of 10 mm² were prepared from each test plate.

Figure 1 shows the relationship between elongation and load for the tested steel in its untreated state. Samples made of the base material (BM), similar to the welded samples, were cut from the sheet metal in the rolling direction. The test confirmed the high mechanical properties of the X5CrNi18-10 steel, and the obtained results exceeded those guaranteed by the manufacturer.

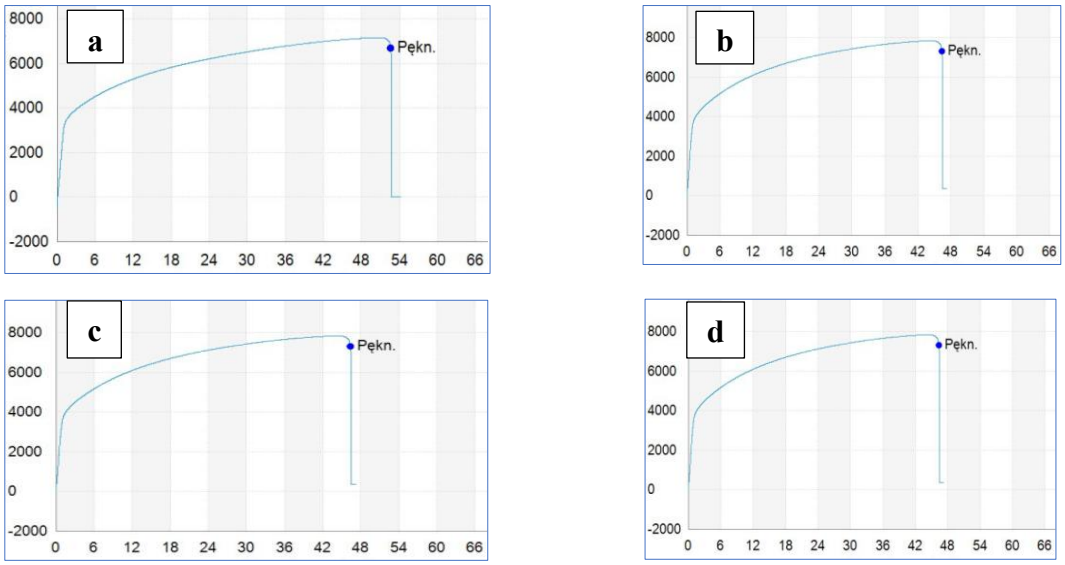


Fig. 1. Tensile test diagram. a) base material, b) sample welded in an Ar-H_2 gas shield, c) sample welded in a Ar gas shield, d) sample welded in a N_2 gas shield.

Strength tests of AISI 304 steel samples welded in nitrogen, argon, and argon-hydrogen gas did not significantly reduce the mechanical properties of the steel. The ultimate tensile strength (UTS) was 712–724 [MPa], which was 1–2% higher than the UTS of the base material. Welding slightly reduced the joint's ductility. The relative elongation of the welded samples (A_5) was 11–13% lower than that of the sheet before welding (**Table 1**). It should be noted that

welding in an argon-hydrogen gas shield requires slightly higher welding power than welding in a pure nitrogen shield.

Table 1. Test results in static tensile test

No.	Studied parameter	Base material	Shielding gas:		
		(BM)	N_2	Ar	98%Ar + 2%H_2
1	Tensile strength [MPa]	706	724	713	712
2	Elongation of welded specimens [mm]	52	47	46	46

Joints made in a pure argon shield, and especially in an argon-hydrogen mixture shield, were characterized by a much smoother transition from the weld material to the weld material itself, both on the face and root sides. This significantly improved the appearance of the joint itself and reduced stress concentration [11].

CORROSION RESISTANCE TESTING USING THE NSS METHOD

Testing the corrosion resistance of a material involves the controlled exposure of samples to destructive factors, such as salt spray. The test is conducted to quickly assess their durability. Samples are placed in a special chamber maintained at a constant temperature (usually 35°C). The chamber's interior is filled with a 5% sodium chloride (NaCl) solution.

Due to its nature, welding is a process that promotes corrosion. Testing the corrosion resistance of welded joints is a crucial element in assessing the quality of a structure, as the welding process drastically changes the material's structure [12]. High temperatures create a heat-affected zone (HAZ), which is often most susceptible to corrosion. This also applies to welding stainless steels, including the melted area and the heat-affected zone (HAZ). This not only leads to a reduction in the mechanical properties of the joined structural components but also promotes severe electrochemical corrosion, particularly in solutions containing chloride ions [12, 13].

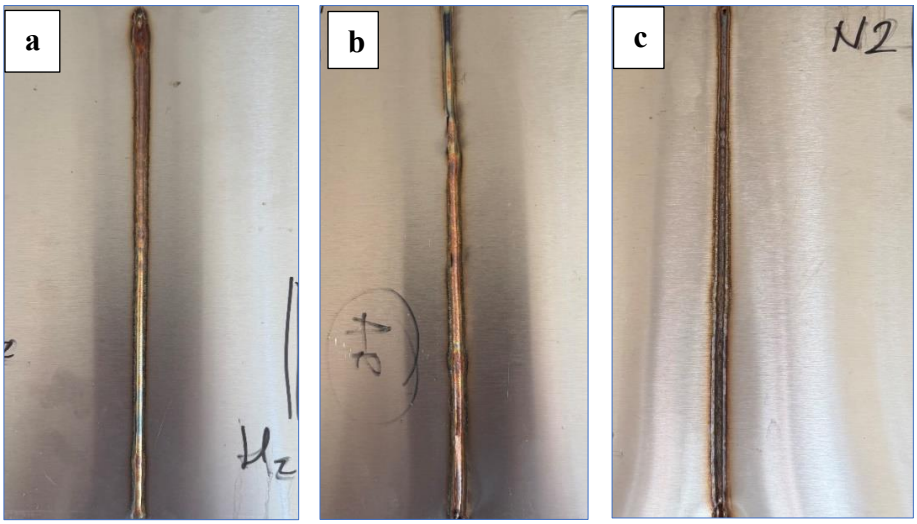


Fig. 2. Samples after 1440 hours of NSS testing. View from the weld face. a) sample welded in an Ar-H_2 gas shield, b) sample welded in a Ar gas shield, c) sample welded in a N_2 gas shield.

The aim of the study was to determine the corrosion resistance of sample plates welded with a handheld laser in a nitrogen, argon, and argon-hydrogen gas shield. A 1440-hour cycle

was assumed, with surface inspections every 240 hours. Visual inspection of the surface condition was performed on the weld face (**Fig. 2**) and root side (**Fig. 3**).

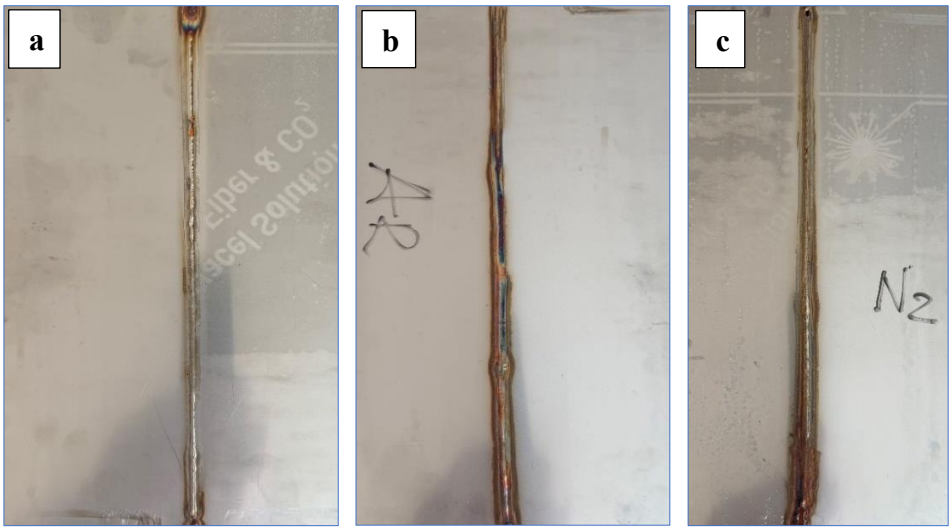


Fig. 3. Samples after 1440 hours of NSS testing. View from the root of weld. a) sample welded in a Ar-H_2 gas shield, b) sample welded in a Ar gas shield, c) sample welded in a N_2 gas shield.

The first corrosion spots appeared after just eight days of testing on samples welded in a pure nitrogen shield. After 1440 hours of testing, significant corrosion damage was already visible. The highest corrosion resistance was demonstrated by sheets welded in an argon-hydrogen gas mixture. In this case, only flash corrosion was visible, and the weld root side was virtually free of any corrosion.

WELDER'S WORKING ENVIRONMENT TEST RESULTS

The results of occupational exposure studies to health-hazardous factors in welders' work environments are presented below. Measurements were conducted on April 16, 2026. The welding facility is centrally heated, with a temperature of 20°C and humidity of 56% on the day of measurement. Measurements of iron oxides (Fe_2O_3), manganese, and its inorganic compounds (Mn and MnO_2) were conducted using individual dosimetry. Measurements of nitrogen oxide (NO) and nitrogen dioxide (NO_2) were conducted using the stationary method over a 60-minute period.

Table 2. Welding fume test results

Occupational exposure to health-damaging factors in the work environment.			**Measurement of concentration at the welding station [mg/m³]**	
No.	**Description of the substance**		**No. 1** shielding gas: **N_2**	**No. 1** shielding gas: **Ar+H_2**
1	Manganese and its inorganic compounds	inhalable fraction	**1,22**	**1,02**
		respirable fraction	**1,09**	**0,89**
2	Iron oxide	respirable fraction	**3,67**	**2,10**
3	Nitric oxide	STEL[1)] in air	**< 0,68**	**< 0,68**
4	Nitrogen dioxide	STEL in air	**< 0,43**	**< 0,43**

[1)]**STEL** - Short-Term Exposure Limit

Two test stations were set up in the laboratory to conduct the tests. The laboratory stations were constructed to filter out as much welding fume and the harmful substances contained within it as possible. Compared to the experimental conditions, the concentration of harmful substances in the workshop is lower because during normal operation, the concentrations of harmful substances are significantly lower and can sometimes be neglected.

At station 1, welding was conducted using a pure nitrogen mixture, while at station 2, welding was conducted using a 98% Ar and 2% H_2 mixture.

The experiment was conducted in laboratory conditions, during the production of a large number of short joints. To filter out as many harmful components of welding dust and fumes as possible, both general and workstation mechanical ventilation was turned off in the welder's work environment. The welders produced joints approximately 200 mm long each, using 1 mm thick sheet metal. The obtained test results (**Tab. 2**) indicate that the permissible concentrations of nitrogen oxide and dioxide were not exceeded at any workstation. However, significantly higher concentrations of manganese oxides and iron oxides were recorded at the workstation where welding was performed under a pure nitrogen shield (station 1). Manganese and its inorganic compounds, expressed as Mn, the respirable fraction were 20% higher, and the inhalable fraction was over 22% higher than those recorded at workstation 2, where welding was performed under an argon-hydrogen shield. Significantly higher concentrations of iron oxide (Fe_2O_3) were also recorded. Here, the content of harmful substances in welding fumes was over 74% higher during nitrogen welding (**Tab. 2**). The results of the experiment confirm that adding even a small amount of hydrogen to the shielding mixture can improve not only the quality of welded products but also the quality of working conditions for welders. It should be emphasized that this process is more environmentally friendly.

The reduction of the most harmful elements to human health is carried out according to the formula:

$$MnO_2 + 2H_2 \rightarrow Mn + 2H_2O \quad (2.1)$$

and:

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \quad (2.2)$$

This means that significant amounts of harmful oxides are reduced during the welding process itself, shielded by a hydrogen-containing mixture, where they are generated. If they do not escape from the weld area, they cannot pose a hazard to workers. This is particularly important because research conducted in recent years has confirmed the extremely harmful effects of manganese and its inorganic compounds on human health [14]. Pure metallic manganese is considered harmless, but its compounds with oxygen are toxic – the higher the oxidation state, the more severe it is. For example, manganese oxides are significantly less harmful than manganese peroxides [15].

Studies of human exposure to manganese dust in the workplace have shown a link to neurological problems. Long-term exposure to manganese from welding fumes, in addition to neurological disorders, causes slowness of movement and difficulty speaking, symptoms similar to Parkinson's disease.

3. DISCUSSION

In parallel with the development of welding processes, research is also underway on the influence of shielding gas composition on the metallurgical process and the properties of welded joints. The literature indicates that adding hydrogen to argon increases arc energy, improves wettability, and process stability. However, most available studies do not address this issue for fear of harmful effects of hydrogen on steel during welding. There are few studies on

handheld laser welding using argon-hydrogen mixtures, especially with increased hydrogen content in relation to the strength properties of the finished joints.

The research gap primarily concerns the possibility of safely expanding the scope of hydrogen use while maintaining the required high quality of welded joints. Solving this problem is crucial for the development of welding technologies.

This is crucial for manufacturers producing welded products, as it will improve working conditions for welders.

4. CONCLUSIONS

Testing of welded samples of X5CrNi18-10 steel welded in the shielding gases discussed above showed that the controlled addition of hydrogen does not alter the strength properties of the steel more significantly than welding in pure nitrogen or argon. The reducing properties of hydrogen affect the chemical reactions occurring at high temperatures during the welding process.

Provided that technological recommendations are followed, particularly during steel preparation before welding, the controlled addition of hydrogen from the shielding mixture has a positive impact on the overall quality of welded joints.

The weld test results showed, in particular:

• Handheld laser welding in pure nitrogen allows for high-quality welded joints while maintaining optimal welding costs.

• The tests confirmed the beneficial effect of adding hydrogen to the argon shield on improving the corrosion resistance of welded joints compared to joints protected with pure nitrogen.

• The conducted research confirmed the beneficial effect of adding hydrogen to the argon shield on the chemical composition of welding fumes and the reduction of harmful substances produced during welding.

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