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INFLUENCE OF THE GAS COMPOSITION ON THE GEOMETRY OF LASER-WELDED JOINTS IN DUPLEX STAINLESS STEEL

VPLIV VRSTE ZAŠČITNEGA PLINA NA GEOMETRIJO ZVARA PRI LASERSKEM VARJENJU NERJAVNEGA DUPLEKSNEGA JEKLA

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Shielding gases, i.e., argon or an argon-nitrogen mixture, are normally used during the laser-beam welding of duplex stainless steel. Helium is also often added to the argon. The effect of the type of shielding gas – argon, nitrogen, helium and their mixtures – on the geometrical characteristics of laser-welded joints of the duplex steel W.Nr. 1.4462 was studied. The welding was carried out according to the experimental model with mixtures. The effect of the welding speed and the gas flow rate were additionally explored using a factorial experiment. The obtained data were statistically processed and mathematical modeling, applying the method of response surfaces, was carried out. The analysis revealed that the impact of the shielding gas mixtures on the geometrical characteristics of the joint is significant. The effect of the gas flow rate on the geometrical characteristics was registered, while the effect of the heat input is the most significant. Special cubic, quadratic and reduced quadratic models, depicting the effects of the shielding gases on the geometrical characteristics of the welded joint, were obtained.

Key words: laser, welding, duplex steel, shielding gas, weld geometry

Pri laserskem varjenju dupleksnega jekla se kot zaščitna plina večinoma uporabljata čisti argon in mešanica argona z dušikom, pogosto pa se k argonu dodaja tudi helij. Pri laserskem varjenju dupleksnega jekla W.Nr. 1.4462 se je preučeval vpliv vrste zaščitnega plina: argona, dušika, helija in njihovih mešanic, na geometrijske značilnosti zvarov. Varjenje je bilo izvedeno po eksperimentalnem modelu z mešanicami. Na osnovi faktorskega eksperimenta je bil preučen tudi vpliv hitrosti varjenja in pretoka zaščitnega plina. Dobljeni rezultati so bili statistično ovrednoteni in ustvarjen je bil matematični model po metodi odzivnih površin. Rezultati tako dobljene analize razkrivajo, da je vpliv zaščitnega plina na geometrijske značilnosti zvarov signifikanten. Ob opaznem vplivu pretoka zaščitnega plina na geometrijske značilnosti zvara je očitno dejstvo, da je najbolj signifikanten vnos toplote. Dobljeni so bili posebni kubični, kvadratični in reducirani kvadratični modeli geometrijskih značilnosti zvarov.

Ključne besede: laser, varjenje, dupleksno jeklo, zaščitni plin, geometrija zvara

1 INTRODUCTION

Duplex and super-duplex steels are materials that have been increasingly used and applied in the past ten years. The petrochemical, food processing, chemical, paper and cellulose, oil and gas, transport and tanker production industries are just some of the areas where duplex steels have found many applications. In many steel constructions, duplex steels are replacing the standard carbon steels and austenite stainless steels very effectively.

Duplex stainless steels are optimised with respect to mechanical properties and corrosion stability so that their structures contain equal proportions of austenite and ferrite. However, the weldability of duplex steel when the laser-welding process is applied is still under investigation and is particularly related to an increased rate of ferrite formation after welding, induced by the high cooling rates. A large ferrite content tends to produce a deterioration of the mechanical properties and in particular a reduction of the corrosion resistance. The ferrite content may be higher than 90 % in the microstructure of the weld metal and HAZ, while the target is to achieve at least 35 % of austenite. One of approaches to realize such a goal is to apply filler material that may increase the costs and the technical difficulties. Another approach includes heat treatment, applying a defocused laser beam, induction heating or treatment in a furnace. Such methods also involve increased production costs. Heat treatment in a furnace additionally impedes the main advantage of laser welding, i.e., the production rate. Welding without filler material tends to produce a strong formation of ferrite and a large grain growth in the weld metal, but there is an advantage in the case of laser welding, for it much simplifies the actual execution of the welding [1–5].

The shielding gas has an important role in laser welding, fulfilling the following tasks: protection of molten pool and heat-affected zone from the effect of the surrounding atmosphere, affecting the shape of the weld and protection of the optics of the device against metal vapors and spatter droplets. According to the reference data, argon as a shielding gas is the best selection in Nd:YAG laser welding. An acceptable shape of welded joint may be achieved with all shielding gases [6,7]. Argon and helium are inert gases, having no effects on the metallurgical processes during welding. Nitrogen is a reactive gas, affecting the metallurgical processes occurring in the welded joint [6]. When nitrogen shielding is used, a significant amount of nitrogen is absorbed into the welded joint. Doping the welded joint with nitrogen is particularly important in the welding of duplex steel, since nitrogen stimulates the formation of austenite [6,8]. The most frequently used shielding gases for the laser welding of duplex steels are pure argon and argon/nitrogen mixtures. Also, there is a widespread use of argon/helium mixtures.

The application of argon-based gas mixtures with the addition of nitrogen and/or helium for the Nd:YAG laser welding may reduce the ferritization rate. Current investigations indicated that the application of the mentioned mixtures ensures an acceptable appearance and quality of the welded joints [2,3]. In such investigations, testing with specific gas mixtures has been made without detecting the interaction between the components of gas mixtures and mathematical modeling. An experimental model for the mixtures appears to be suitable for the investigation and mathematical modeling of the effects of shielding-gas mixtures on the welding [9–13]. The mixture contains two or more constituents. The target of mixing certains components into the mixture is to investigate whether such a mixture has a more favorable effect upon the specific properties than a single component. The application of the planned experiment is of utmost importance in such investigation, since this approach provides rational determination of the response functions. The next aim was to describe quantitatively the effect of the mixture composition on the geometrical characteristics of the welded joint, applying a mathematical model, developed on the basis of the experimental data measured for a three-component mixture.

It is important to achieve the optimum weld shape and geometry to fullfil the quality requierments according to the standard EN ISO 131919-1. It is important to optimize the root width, which could compensate for the inaccuracy of the positioning and the clamping of the sheets, and also the inaccuracy of the laser-beam guidance, to eliminate the lack of fusion defects. In this way, the costs of the equipment for positioning and clamping in th eindustrial production of laser-beam welded structures could be reduced.

These concepts indicate that investigations of the effects of input energy, type and flow rate of the shielding gas on achieving a two-phase microstructure with approximately equal portions of austenite and ferrite are justified. Welding with maximum speed, without the use of filler material and with the use of the appropriate gas mixture that contains nitrogen would considerably increase the economy and productivity of laser welding.

The final objective of this research was to determine the influence of the shielding gas – argon, nitrogen, helium and their mixtures – on the geometrical characteristics of the welded joint on a 2-mm-sheet of duplex stainless steel W.Nr. 1.4462 and additionally explore the influence of the welding speed and the gas flow rate for every shielding-gas and mixture.

2 EXPERIMENTAL WORK

2.1 Equipment

The welding was performed using a Nd:YAG laser "ROFIN CW 020" with a continuous power of 2 kW. An optical fiber with a 600-μm core diameter was used for the beam transfer. Focusing optics of 120/120 mm were used. The beam diameter in the focus was equal to 0.6 mm. The focusing optics were attached to the robot arm, and the robot "IGM Limat RT 280" features 6 degrees of movement freedom.

2.2 Experimental

The welding was performed on 2-mm-thick sheets of duplex steel W.Nr. 1.4462. The sample dimensions were (250 × 130) mm and (230 × 130) mm. The longer welded sides were machined. Prior to welding, the samples were cleaned by applying emery paper and ethanol. The samples were fixed in the jigging tool and argon was used for the root shielding.

The tests were conducted according to a "simplex grid" planned experiment [9]. The simplex grid for a three-component mixture is represented by a triangle, within which the states of the experiments are distributed uniformly in a "grid" pattern. A uniform distribution of

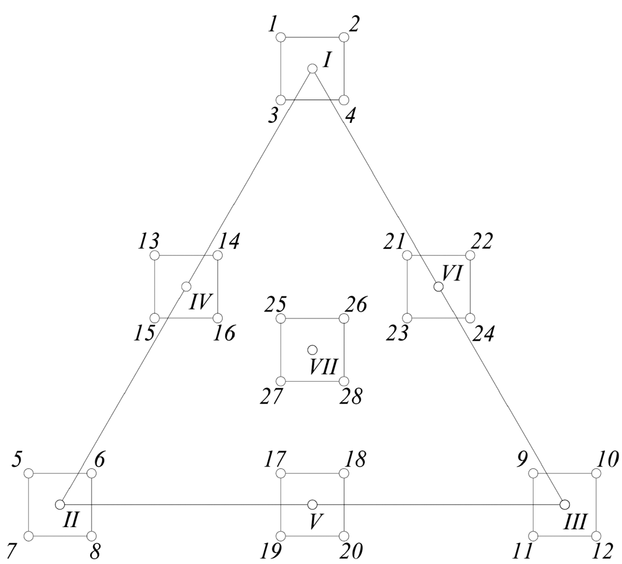


Figure 1: Plan of experiment with 28 states
Slika 1: Načrt eksperimenta z 28 stanji

the states of the experiment in equal intervals of all the component portions in mixture is required to attain an acceptable definition of the response surface. Each response function can be associated with a polynomial and the appropriate coefficients for the equation can be calculated. Seven types for three-component mixtures for the simplex-grid model were selected. For every shielding gas – argon, nitrogen, helium and their mixtures – in the simplex grid, a factorial plan on two levels 2^n, with two factors for the welding speed and gas flow rate were additionaly conducted. A complete plan of the experiment is shown in **Figure 1**.

In **Table 1**, the percentage of components for all 7 points of the experiment and their combinations with the welding parameters are listed. The intervals of the welding parameters providing quality weldments with full penetration were determined through preliminary testing.

Constant welding parameters

The constant parameters in all states of the experiment:

Power: P = 1800 W

Optic focal length: f = 120 mm

Tip diameter of the coaxial gas nozzle: 5 mm

Distance of gas nozzle tip from the workpiece: 8 mm

2.3 Inspection and testing

The welded specimens were inspected visually and with radiographic control, followed by destructive testing methods. In order to determine the weld geometry, macro-etches of the joint cross-sections were prepared. The weld geometry measurement on the macro-etches was performed under 50-times magnificaction.

With the aim of determining the quality of the laser welded joint according to the standard EN ISO 13 919-1, the weld and root reinforcement/underfill, linear misalignment of the sheets and the size of the undercut were measured. Measurements were also performed on the width of the weld b_zav, the width of the HAZ b_zut, the width of the weld root b_kor and the area of the weld cross-section A, in order to determine the influence of the parameters on the geometrical characteristics of the welded joint.

The results of the measurements of local mechanical properties of the welded joint were processed by applying the software package "Design Expert 6.0.6". A statistical analysis of measured data for all 7 states of the experiment revealed the appropriate model. The model

Table 1: States of experiment. (v – welding speed, Q – gas flow rate, z – focus position relative to the workpiece surface)
Tabela 1: Stanja eksperimenta (v – hitrost varjenja, Q – pretok plina, z – položaj žarišča glede na površino varjenca)

Shielding gas/mixture	State of experiment	Mixture components (%)			Process parameters		
		Ar	N_2	He	v (cm/min)	Q (l/min)	z (mm)
I	1	100	0	0	110	18	–1,0
	2				140	18	
	3				110	9	
	4				140	9	
II	5	0	100	0	110	18	–0,8
	6				140	18	
	7				110	9	
	8				140	9	
III	9	0	0	100	110	33	–1,2
	10				140	33	
	11				110	21	
	12				140	21	
IV	13	50	50	0	110	18	–0,9
	14				140	18	
	15				110	9	
	16				140	9	
V	17	0	50	50	110	25	–1,0
	18				140	25	
	19				110	15	
	20				140	15	
VI	21	50	0	50	110	25	–1,1
	22				140	25	
	23				110	15	
	24				140	15	
VII	25	33,33	33,33	33,33	110	23	–1,0
	26				140	23	
	27				110	13	
	28				140	13	

could be linear, quadratic, special cubic, interactional or mean value if there are no significant effects of the tested factors. Subsequently, the significance of the model and the members of the response polynomial was tested by applying the variance analysis. For the linear model, only the members Ar, N_2 and He appear. In the square model, members of second order, i.e., Ar*N_2, Ar*He and N_2*He appear, and in special cubic model, the member Ar*N_2*He.

R-squared is a determination coefficient that represents the estimation of the total variation of the data described by the model. The adjusted "R-Squared" is R-squared adjusted to the number of members in the model in relation to the number of experiment states. The predicted "R-Squared" is a measure for the variation of the values within a new set of data described by the model. The values of both R-squares should be close to 1, and if they are equal to 1, then 100 % of the variations of the tested values are explained by the model. If the adjusted R-squared is higher than 75 %, the model can be considered as significant.

A mathematical model established through such an approach provides very a distinctive graphic interpretation and the optimization of tested parameters [10,11].

3 RESULTS AND DISCUSSION

3.1 Geometrical characteristics of welded joints

Good welding results were achieved. The welds feature a slight reinforcement of the face and the root without undercuts. Cracks, open pores and other surface defects did not occur and welds without porosity were obtained. According to the standard EN ISO 13919-1 for 2-mm-thick sheets, for high-quality B, the reinforcement of the weld root and the face have to be less than 0.5 mm, whereas the incompletely filled groove, linear misalignment of sheets and root undercuts have to be less than 0.2 mm. All the laser welds are classified into group B, i.e., they are of high quality.

The appearance of the weld face is acceptable for all the experimental conditions, while increased spattering occurred on the root side on certain samples. Increased spattering is noted in all the samples welded in an argon shield. Increased spattering while applying a nitrogen shield is registered in the experimental conditions No. 5 and 7, where a lower welding speed was used. In samples No. 6 and 8, which were welded applying the same shielding gas, but a higher speed, spattering was not registered.

A uniform root shape along the full weld length and full penetration were obtained for all the experimental conditions. All the applied shield gasses and mixtures produced faultless welds without defects and of acceptable geometric shape, this being the first target of the testing. **Figure 2** shows good results when nitrogen was used as the shielding gas. This is an important finding, because of its favorable effect upon ferritization [2,3].

Relationship between the geometric characteristics of welded joint and the welding parameters

For all shielding gasses and mixtures, samples welded with a lower speed have larger geometric characteristics, due to the higher energy input. With a lower welding speed the weld root is wider and therefore this compensates for the beam-guidance accuracy. A higher welding speed is economical but requires better

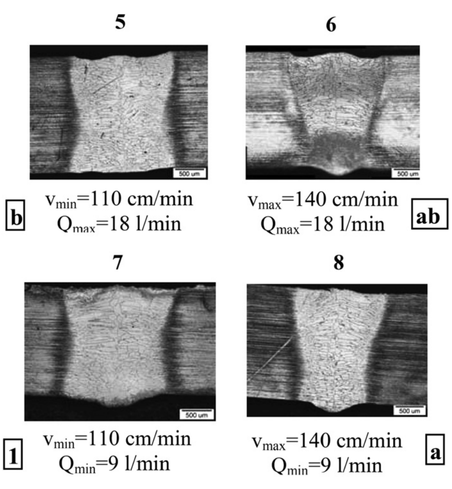


Figure 2: Cross-sections of welded joints in a N_2 shield according to the factorial plan of the experiment – condition 1 (v_{min}, Q_{min}), a (v_{max}, Q_{min}), b (v_{min}, Q_{max}) and ab (v_{max}, Q_{max})

Slika 2: Prečni prerezi zvarov v zaščiti N_2 v skladu s faktorskim načrtom eksperimenta pri pogojih 1: (v_{min}, Q_{min}), a (v_{max}, Q_{min}), b (v_{min}, Q_{max}) in (v_{max}, Q_{max})

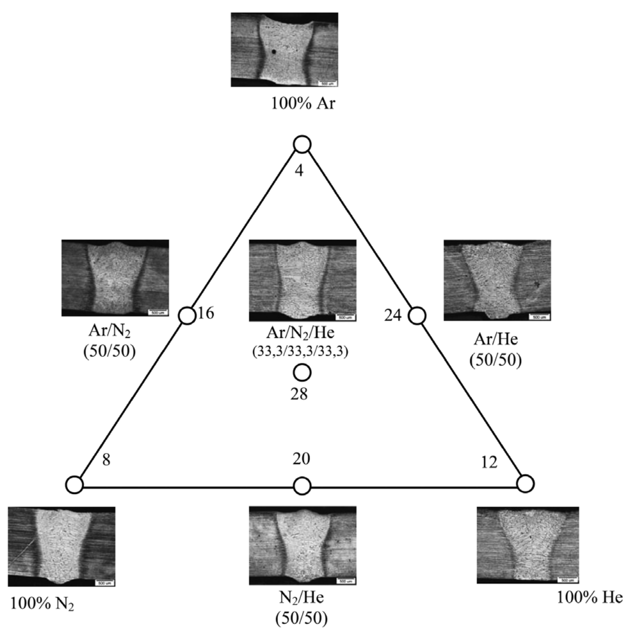


Figure 3: Cross-sections of welded joints for all shielding gases and mixtures at maximum welding speed and minimum flow rate of the shielding gas – experimental condition a (v_{max}, Q_{min})

Slika 3: Prečni prerezi zvarov za vse zaščitne pline in mešanice pri največji hitrosti varjenja in minimalnem pretoku zaščitnega plina pri pogoju eksperimenta a (v_{max}, Q_{min})

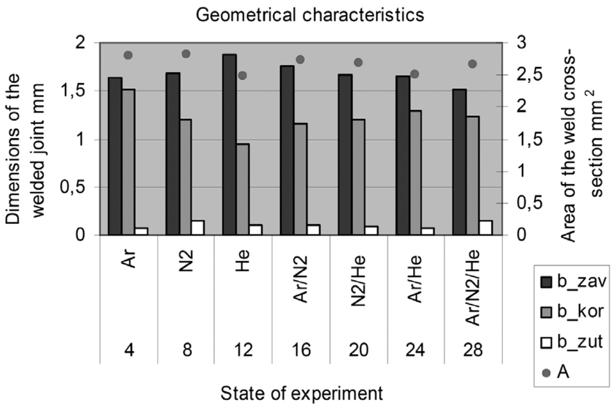


Figure 4: Geometrical characteristics of the welded joint – conditions a(v_{max}, Q_{min}), (b_zav – weld width, b_kor – root width, b_zut – HAZ width, A – area of the weld cross-section)

Slika 4: Geometrijske značilnosti zvara pri pogojih a(v_{max}, Q_{min}), (b_zav – širina temena zvara, b_kor – širina korena, b_zut – širina toplotno vplivanega področja, *A* – ploščina prečnega prereza zvara)

edge preparation, while without any beam-guidance sensor a risk of a lack of fusion defects is higher. For welded samples, by applying a higher welding speed the root is significantly narrower than the joint face, except for the samples made in an argon shield. Thus, with respect to the root width, an argon shield is the best choice. The geometrical characteristics of the welds made applying the same welding speed and different shield flows do not differ significantly.

Relationship between geometric characteristics of the welded joint and the composition of the shielding gas

From the economic point of view, i.e., a reduction of costs, the best solution is to apply the highest welding speed and the lowest flow rate of the shielding gas, thus v_{max}, Q_{min}. **Figure 3**. shows cross-sections of the welded joint for experimental conditions applying all the shielding gases and mixtures at maximum welding speed and minimum flow rate of the shielding gas, i.e., condition a. **Figure 4**. shows a graphical representation of the geometric characteristics of the weld for the experimental condition a. The mixture Ar/N_2 and pure nitrogen, no matter which welding parameters were used, produced welded joints with the largest cross-section and root width within the experiment. This fact may provide a higher content of austenite in the microstructure of the welded joint, thus improving the mechanical properties and the corrosion resistance of the joint.

The use of helium contributes to a reduction of the geometric characteristics of the welded joint. Since the price of helium is significantly higher than that of argon, and particularly nitrogen, its application is not justified.

3.2 Mathematical models depicting the relationship between the composition of the shielding gases and the geometrical characteristics of the welded joint

Mathematical models obtained for mixtures in states 1 (v_{min}, Q_{min}), a (v_{max}, Q_{min}), b (v_{min}, Q_{max}) and ab (v_{max}, Q_{max}) are listed in **Table 2**. "Outliers" did not occur in any model, indicating that none of the measured data has a significant deviation.

An adjusted R-squared value for the weld joint width b_zav, **Table 2**, close to the value of one, and variance analysis of the model indicate that special cubic models are significant for all four combinations of parameters. From the graphic plot for state a (v_{max}, Q_{min}), **Table 3**, it could be noted that the widest face of the weld is obtained for pure He and that additions of N_2 and Ar to helium cause a width reduction. The smallest width of the welded joint is obtained in the centre applying a ($Ar/N_2/He$) mixture. It can be concluded that the type of shielding gas/mixture affects the weld width that can be easily predicted by applying a special cubic mathematic model.

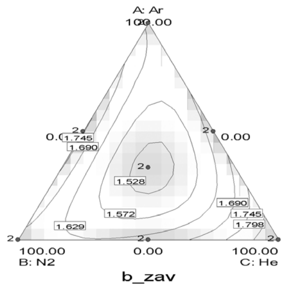
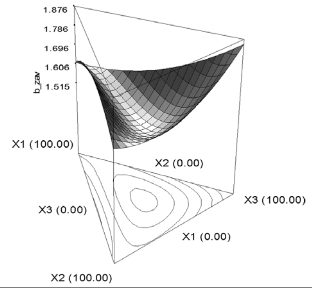
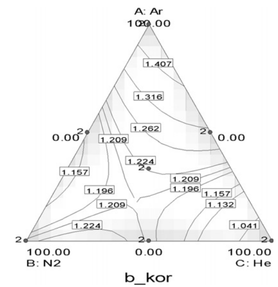
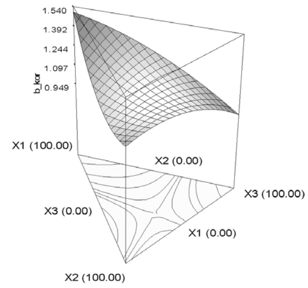
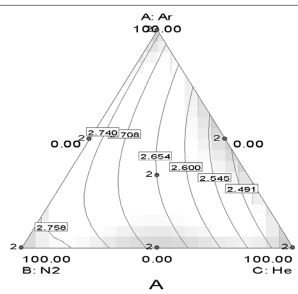
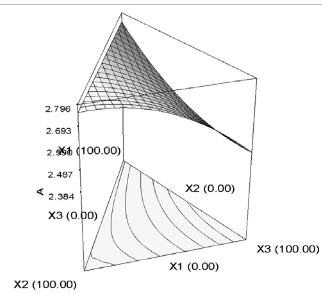
The square model in state a and the special cubic model in state ab have been yielded for the root width b_kor, **Table 2**. For states 1 and b a negative Predicted R-squared was obtained, meaning that the mean value predicts the response better than the special cubic model. For low welding speeds, no significant model was obtained, while for high welding speeds different significant models are revealed. Different models may be explained by the effects of some other factors, unaccounted effects combined with the effects of mixtures. Such factors may be, for example, no uniform gap between the plates clamped in the jig or plates' misalignment. It can be concluded that the selection of the gas mixture has a significant effect on the root width in the case of high welding speeds, while in the case of low welding speeds it is not important which mixture is used. From the graphic plot for state a (v_{max}, Q_{min}, **Table 3**) it can be seen that the root width is the widest in the case

Table 2: Mathematical models of weld width b_zav, root width b_kor, HAZ width b_zut, area of the weld cross-section A

Tabela 2: Matematični modeli širine temena zvara b_zav, širine korena b_kor, širine toplotno vplivanega področja b_zut, ploščine prečnega prereza zvara A

Measured value	State			
	1 – v_{min}, Q_{min}	a – v_{max}, Q_{min}	b – v_{min}, Q_{max}	ab – v_{max}, Q_{max}
b_zav mm	Special cubic	Special cubic	Special cubic	Special cubic
b_kor mm	–	Quadratic	–	Special cubic
b_zut mm	–	–	–	–
A mm^2	Reduced quadratic	Reduced quadratic	Reduced quadratic	Special cubic

Table 3: Mathematical models and graphical plots for condition a (v_{max}, Q_{min})
Tabela 3: Matematični modeli in grafični prikaz za pogoje a (v_{max}, Q_{min})

No	Model	2D plot	3D plot X1=A=Ar; X2=B=N_2; X3=C=He
1	Special cubic "Prob>F"<0,0001 Adjusted R-squared=0,94 b_zav = +1.615 * Ar +1.670 * N2 +1.855 * He +0.430 * Ar * N2 -0.300 * Ar * He -0.450 * N2 * He -4.395*Ar*N2*He		
2	Quadratic "Prob>F"<0,0001 Adjusted R-squared=0,9920 b_kor = +1.49894 * Ar +1.21394 * N2 +0.94894 * He -0.76879 * Ar * N2 +0.32121 * Ar * He +0.49121 * N2 * He		
3	Reduced quadratic "Prob>F"<0,0001 Adjusted R-squared=0,9140 A = +2.750 * Ar +2.760 * N2 +2.437 * He -0.355 * Ar * He +0.385 * N2 * He		

of the application of pure Ar. Additions of N_2 and He to argon reduce the root width.

An adjusted R-squared for the HAZ width for states 1 and ab has a value less than 0.75, while the predicted R-squared has a negative sign, indicating that no one model is significant. Thus, it can be concluded that the mean value predicts the response of model more adequately. Also, it may be concluded that the type of gas mixture has no significant effect on the width of the joint HAZ.

Significant reduced square models for states 1, a and b for the cross-section area of welded joint A were obtained, **Table 2**. A significant special cubic model for state ab has been developed. From graphic plots, relationships between the models produced for different conditions cannot be detected. For state 1 the largest area is for pure argon and it is reduced with additions of nitrogen and helium. In state a (v_{max}, Q_{min}, **Table 3**), argon and nitrogen produce the largest area, which is reduced with additions of helium, attaining its minimum for pure helium. In state b, the largest area is obtained for pure nitrogen and it is reduced with additions of argon and helium. In state ab, the largest surface is obtained for mixtures Ar/N_2 and Ar/He and it is reduced for the center (Ar/N_2/He) and pure gases. It can be concluded that the type of shielding gas/mixture affects the cross-section area of welded joint and it can be well predicted by the model. Also, it can be concluded that the model depends on a combination of welding speed and gas flow rate.

Mixtures have a significant effect on the geometric characteristics of the welded joint. Special cubic, quadratic and reduced quadratic models were obtained. In state a (v_{max}, Q_{min}) the helium content increases the weld width and reduces the root width and the area of the cross-section. Nitrogen content reduces the root width.

4 CONCLUSION

Metal sheets of duplex steel W. Nr. 1.4462, some 2-mm thick, were welded with a Nd:YAG laser. The shielding gases – argon, nitrogen, helium and their mixtures – were used and for root shielding argon was used. A coaxial shielding-gas nozzle was used. The welding was carried out according to the experimental model with mixtures.

For the tested shielding gases and mixtures, high-quality welds were produced, meeting the requirements of the group B in EN ISO 13919-1 standard. No cracks occurred.

Statistical processing of the results and the developed mathematical models indicate that there is a significant effect of welding speed on the geometrical characteristics of the welded joint for the tested range of parameters. An increase of the welding speed reduces the geometrical characteristics, while the effect of the shielding-gas flow rate is not significant.

Special cubic, quadratic and reduced quadratic mathematical models were obtained, which can accurately predict the effects of the shielding gases (argon, nitrogen, helium) and their mixtures on the weld width, root width and the area of cross-section. The shielding gas/mixture has an effect on the geometric characteristics, while the model type depends on a combination of the welding speed and the flow rate of the shielding gas. No model is significant for the width of the HAZ, i.e., the mean value can better predict the response than the model. The type of mixture has no significant effect upon width of the HAZ. Using the obtained mathematical models it is possible to optimize the composition of the gas mixture with regard to the geometrical characteristics of the laser-beam welded joints.

As the application of helium shielding for Nd:YAG welding of duplex steels does not offer advantages over the argon shielding, it may be concluded that the application of much more expensive helium is not justified, particularly because of the higher shielding-gas flow rates. An analysis of the weld appearance quality and the geometrical characteristics of the welded joint, points towards the mixture (Ar/N_2) as being optimal. Considering the root width, the best choice is argon. The best choice to prevent ferritization would be pure nitrogen, provided that an acceptable microstructure and mechanical properties are attained. The Ar/N_2 mixture produces a wider root width and is a better choice if geometric characteristics are considered. Nitrogen is also cheaper than argon and helium, which means that its use contributes to making welding more economical. Additions of nitrogen to argon have no effect on the area of the weld cross-section, while additions of helium cause a reduction.

Duplex stainless steel W.Nr.1.4462 can be successfully welded by applying a laser using the shielding gases argon, nitrogen, helium and their mixtures.

The choice of shielding gas can affect the microstructure of the welded joint. An evaluation of the effects of the tested gas mixtures on the microstructure, mechanical properties and corrosion resistance of duplex grade steels will be the topic of future research.

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