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

Angela Topić, Branko Bauer, Zoran Kožuh, Nikola Knezović

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Abstract

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. 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, while it is not so significant for the microstructure. 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 effects of the shielding gas on geometrical characteristics and microstructure of welded joint, were obtained.

Keywords: laser; welding; duplex steel; shielding gas; weld geometry; microstructure

1. Introduction

Duplex and super-duplex steels are materials that have been increasingly used and applied in the last years. 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 (Heat Affected Zone), 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. The most used shielding gases for the laser welding of duplex steels are argon, helium and nitrogen. 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 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 certain components into the mixture is to investigate whether such a mixture has a more favourable effect upon the specific properties than a single component. The aim was to describe quantitatively the effect of the mixture composition on the geometrical characteristics and microstructure 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 fulfill the quality requirements according to the standard EN ISO 131919-1. Also, it is important to see 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. 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 and microstructure 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- μ m 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 $\times$ 130) mm and (230 $\times$ 130) mm. Prior to welding, the samples were machined and 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 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 additionally conducted. A complete plan of the experiment is shown in Figure 1.

The constant parameters in all states of the experiment were power ($P=1800$ W), optic focal length ($f = 120$ mm), tip diameter of the coaxial gas nozzle (5 mm) and distance of gas nozzle tip from the workpiece (8 mm).

Fig. 1. Plan of experiment with 28 states

Shielding gas	State of exp.	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	

Table 1. States of experiment (v – welding speed, Q – gas flow rate, z – focus position relative to the workpiece surface)

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 magnification.

With the aim of determining the quality of the laser welded joint according to the standard EN ISO 13919-1, 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.

For microstructure inspecting the same specimens were used, but with 500-times magnification. Specimens were reviewed with optical microscope, connected with software for analysis obtained pictures. After erosion with special tool, it could be seen that austenite and ferrite are different coloured, and that was the basis for analysis. 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 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, N₂ and He appear. In the square model, members of second order, i.e., Ar*N₂, Ar*He and N₂*He appear, and in special cubic model, the member Ar*N₂*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

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. All the laser welds are classified into group B according to standard EN ISO 13919-1 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. Good results also showed up when nitrogen was used as the shielding gas. This is an important finding, because of its favourable effect upon ferritization [2,3].

3.1.1. 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 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.

3.1.2. 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 2. 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 3. shows a graphical representation of the geometric characteristics of the weld for the experimental condition a. The mixture Ar/N₂ 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.

Fig. 2. 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 ($v_{\max}$, $Q_{\min}$)

Fig. 3. 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)

3.1.3. 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 N₂ and Ar to helium cause a width reduction. The smallest width of the welded joint is obtained in the centre applying a (Ar/N₂/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 (quadratic) 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. 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 of the application of pure Ar. Additions of N₂ 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 is negative, 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 can not 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 is reduced with additions of argon and helium. In state ab, the largest surface is obtained for mixtures Ar/N₂ and Ar/He and it is reduced for the center (Ar/N₂/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.

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 2. Mathematical models of weld width b_{zav} , root width b_{kor} , HAZ width b_{zut} , area of the weld cross-section A

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 $b_{zav} =$ $+1.615 * Ar$ $+1.670 * N_2$ $+1.855 * He$ $+0.430 * Ar * N_2$ $-0.300 * Ar * He$ $-0.450 * N_2 * He$ $-4.395 * Ar * N_2 * He$		
2	Quadratic "Prob>F"<0,0001 Adjusted R-squared=0,9920 $b_{kor} =$ $+1.49894 * Ar$ $+1.21394 * N_2$ $+0.94894 * He$ $-0.76879 * Ar * N_2$ $+0.32121 * Ar * He$ $+0.49121 * N_2 * He$		
3	Reduced quadratic "Prob>F"<0,0001 Adjusted R-squared=0,9140 $A =$ $+2.750 * Ar$ $+2.760 * N_2$ $+2.437 * He$ $-0.355 * Ar * He$ $+0.385 * N_2 * He$		

Table 3. Mathematical models and graphical plots for condition a (v_{max} , Q_{min})

3.2. Microstructure of welded joints

Structure of welded joint was made of austenite and ferrite. Ferritization happened in all states of experiment (ferrite portion was from 87% to 93%, what is much more than wanted 65%). In Table 4 portion of ferrite for every state of experiment is shown.

	I				II				III				IV			
State of ex.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
% ferrite	89,3	90,3	91,1	91,3	87,8	91,8	91	89	92,1	89,8	91,6	87,4	90	88,2	91,7	91,4
	V				VI				VII							
State of ex.	17	18	19	20	21	22	23	24	25	26	27	28				
% ferrite	88,3	92,4	89,3	90	88,3	92	90,5	89	88,4	91,4	92,1	87,4				

Table 4. Ferrite portion in microstructure

Obtained models made possible to partially calculate ferrite portion that will be obtained with laser welding of duplex steels, using Ar, N₂, He and their mixtures as shielding gases, for all combinations of upper and lower level of welding parameters (maximum and minimum parameters).

3.2.1. Relationship between microstructure of the welded joint and the composition of the shielding gas

In Table 5. there is obtained mathematical model which shown gas mixture affect on ferrite portion in welded joint. An adjusted R-squared close to 1 and model variance analysis show there is significant special cubic model in state b, with all linear and quadratic members as significant, and one significant cubic member. In states 1, a and ab models are not significant, because adjusted R-squared is less than 0,75. In state b there is an „Outlier“, which occurs using Ar/N₂/He mixture.

No	Model	2D plot	3D plot X1=A=Ar; X2=B=N ₂ ; X3=C=He
b	Specijalni kubni "Prob>F"<0,0001 Prilagođeni R- kvadrat=0,9791 F = +88.300 * Ar +87.800 * N ₂ +92.100 * He +8.800 * Ar * N ₂ -7.600 * Ar * He -6.800 * N ₂ * He -14.250*Ar*N ₂ *He		

Table 5. Mathematical model and graphical plot for state b

From graphical plot of state b can be seen that helium and mixture Ar/N₂ give largest ferrite portion in welded joint. The lowest ferrite portion is obtained with nitrogen and argon, and mixing nitrogen and argon with helium, until helium portion is maximum 50%. Adding more than 50% of helium to nitrogen or argon causes ferrite portion starts to grow. Low ferrite portion is also obtained in center with mixture Ar/N₂/He. It can be concluded that type of shielding gas or mixture affects on portion of ferrite in welded joint only at minimum welding speed and maximum gas flow, what can be fine described with model. In other states of experiment mean value of measured ferrite portions better predicts response than the model.

3.2.2. Relationship between the microstructure of welded joint and the welding parameters

Significant models with Ar and N₂/He i Ar/N₂/He mixtures are obtained and they are shown in Table 6.

State	Model	2D plot	3D plot
Ar	Glavni efekti "Prob>F"=0,0066 Prilagođeni R- kvadrat=0,8119 F = +86.820 -0.180 * Q +0.045 * v		
N ₂ /He	Interakcijski "Prob>F"=0,0006 Prilagođeni R- kvadrat=0,9677 F = +106.825 -1.351 * Q -0.145 * v +0.011 * Q * v		
Ar/N ₂ /He	Interakcijski "Prob>F"=0,047 Prilagođeni R- kvadrat=0,9121 F = +123.803 -2.040 * Q -0.241 * v +0.015 * Q * v		

Table 6. Mathematical models depicting the impact of the welding parameters on portion of ferrite in welded joint

3.2.3. *Mathematical models depicting the relationship between the composition of the shielding gases and the geometrical characteristics of the welded joint*

In members of interaction models at N_2 and mixture $Ar/N_2/He$ gas flow is significant as linear member and as member in interaction with welding speed ($Q \cdot v$). For mixture $Ar/N_2/He$ welding speed is not significant as linear member, but only in interaction with gas flow ($Q \cdot v$). "Outliers" did not occur.

From graphical plot for mixture N_2/He it can be seen there is significant affect of welding speed and gas flow, and with decrease of welding speed and gas flow ferrite portion is reduced (for large flow more significant than for the low). Decrease of gas flow also affect reduction of ferrite portion (for high speed more significant than for the low). That is cause of interaction between welding speed and gas flow ($Q \cdot v$). The lowest ferrite portion is obtained using minimum welding speed and minimum gas flow.

From graphical plot for mixture $Ar/N_2/He$ it can be seen that the lowest ferrite portion is obtained using minimum welding speed and maximum gas flow, and for mixture N_2/He only for minimum welding speed. For Ar there is significant linear impact of welding speed and gas flow. From graphical plot it can be seen that decreasing of welding speed and increasing of gas flow reduce ferrite portion. The lowest ferrite portion is obtained using minimum speed and maximum flow. Also, for argon there was an „Outlier“ in state 1 (v_{min} , Q_{min}).

For interaction and for linear models the lowest ferrite portion is obtained using minimum welding speed (that is accordant with literature), but impact of gas flow, so conclusion could be that impact of gas flow depends on type of mixture, but that should be subject for further researches.

4. Conclusion

Metal sheets of duplex steel W. Nr. 1.4462, 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, and not so much impact on microstructure. 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 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.

In all states of experiment microstructure consisted of austenite and ferrite, and ferrite portion was from 87% to 93%. By analysing mathematical models it was noticed that shielding gas type (or mixture) affects ferrite portion only using minimum welding speed and maximum gas flow. The lowest ferrite portion is obtained using nitrogen and argon as shielding gas, and mixing argon and nitrogen with helium, but until helium portion is maximum 50%.

Also, significant models which describe impact of welding speed and gas flow of ferrite portion in welded joint using argon and mixtures N_2/He i $Ar/N_2/He$ are obtained. The lowest ferrite portion is obtained using lower welding speeds, and gas flow impact on ferrite portion varies from model to model. That means that gas flow impact on ferrite portion in welded joint depends on mixture type, and to describe that more precisely further researches have to be done, and that also could be some proposal for anyone interested in that.

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

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