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Experimental Design in Plasma Welding of SUS 304 Stainless Steel Thin Plates

Minh Hung Ha [1,2], Duong Vu [3,*], Hai Tinh Do [1]
[1] National Research Institute of Mechanical Engineering, Ha noi, Vietnam
[2] High-Tech Development Institute, Ha noi, Vietnam.
[3] Duy Tan University, Da Nang, Vietnam
*Corresponding Author: duongvuaustralia@gmail.com

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ABSTRACT

Background: This research focuses on the evaluation of the independent influence and the bidirectional interaction of some welding parameters in butt welding for the SUS 304 stainless steel thin plates using the automatic plasma welding system (450 +/- Plasma, SP7Turmatic from Lincoln).
Contribution: The findings will serve as a reliable background to design the mathematical model for the prediction of the tensile strength for the plasma welding of steel SUS 304 thin plates in terms of the nomination of the optimal process for adopting the requirement in industry.
Method: The welding setting is nominated for 04 main changing parameters, such as the peak current of welding (I_h, A); the background current of welding (I_b, A); the welding speed (v_h, cm/min); the feeding rate of the welding wire ($v_{c.d}$, cm/min); the diameter of the wire (d = 1.0 mm); and the flow rate of the shielding gas ($G_{k.p}$, 2.0 l/min). Mathematical statistics software ANOVA using to analyze the influence of the parameters on the tensile strength of the weld as the target function.
Results: The tensile strength of the plasma welding samples is about 650 MPa at the equivalent level of the other publications. This proved the reasonable welding setting for the preliminary investigation.
Conclusion: Authors proved the nomination of the main plasma welding technological parameters, such as the peak current, the background current, the welding speed, and the feeding rate of the wire, is reasonable towards the maximum tensile strength, one of the important criteria in the weld performance.

INTRODUCTION

304 steel is also known as 18/8 stainless steel. This name has been derived from the composition of chromium and nickel elements present in the alloy. There are other trademarks for this steel: AISI 304 and 304L. This steel found the widest application in chemical containers, including those used for transportation, food processing equipment, automotive components, and aerospace components. Plasma and micro-plasma welding are the suitable and applicable manufacturing processes for the production of the buttweld thin plate components. Recent study in Vietnam [1] presented the experiment results of butt-welding stainless steel thin plates SUS 304 using the automatic welding system 450+/Plasma–SP7 Turnmatic TT from company Lincoln C3-MATIC 32–33—the solution in the industry scale.

The quality of the welding was evaluated via the morphology of the surface and the maximum deformation of the connection after cooling in room conditions. In [2], the research team continued to present the results of the tensile strength testing of the weldment in the different conditions. However, the average tensile strength varied in the range of 417,334 – 723,211 MPa. The failure track occurred mostly in the parent metal, and it is still present at the boundary between the parent metal and the heat-affected zone (HAZ). In order to conduct the deeper study, [3] presented the investigation of the microstructure and microhardness of the weld metal in the different zones, such as the central weld, the boundary closing to the HAZ, the HAZ, and the parent metal. The experiment from the studies made a comparison of the mechanical properties of the weld metal according to the different welding settings. Regarding the micro-plasma welding parameters in [4], the butt weld from AISI 304 steel had been evaluated on the hardness and the microstructure.

They change the following welding parameters, such as rotational speed, current intensity, arc voltage, and flow rate of plasma gas (tic welding system 450+/Plasma—SP7 Turnmatic TT from company Lincoln C3-MATIC 32–33—the solution in the industry scale). The quality of the welding was evaluated via the morphology of the surface and the maximum deformation of the connection after cooling in room conditions. In [2], the research team continued to present the results of the tensile strength testing of the weldment in the different conditions. However, the average tensile strength varied in the range of 417,334 – 723,211 MPa. The failure track happened mostly in the parent metal, then remained in the boundary between the parent metal and the heat-affected zone (HAZ). In order to conduct the deeper study, [3] presents the investigation of the microstructure and microhardness of the weld metal in the different zones, such as the central weld, the boundary closing to the HAZ, the HAZ, and the parent metal. The experiment from the studies that made the comparison of the mechanical properties of the weld metal according to the different welding settings is available.

Regarding the micro-plasma welding parameters in [4], the butt weld from AISI 304 steel had been evaluated on the hardness and the microstructure. They change the following welding parameters, such as rotational speed, current intensity, arc voltage, flow rate of plasma gas (Ar), and flow rate of shielding gas (H_2). The microstructure analysis specified a uniform structure throughout the entire volume of the weld. The specific method introduced in [5] focused on the pulse current for welding ANSI 304 L steel with a thickness of 0.25 mm. They investigated the microstructure, the microhardness, and the tensile strength of weldments. It is concluded that the peak current, the background current, the pulse rate, and the pulse width are important welding parameters. Between the different stainless steels (AISI 304L, AISI 316L, AISI 316Ti, and AISI 321), for the same welding condition, the AISI 304L steel had the better performance, considering the weld bead geometry, the hardness, and the tensile strength. For the variation of

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welding parameters, the authors in [6] selected some differently, namely: the welding current, welding speed, and pilot arc length.

The methodology in this work is also modified, including the genetic algorithm and Taguchi technique for the prediction of the welding pool contour. Through a microstructure analysis, they introduced the extrapolation to evaluate quantitatively the weld strength without the quantitative value of the tensile strength. A significant contribution regarding the optimization method for the different welding processes of duplex stainless steel was presented in [7]. However, there was a lack of comparison in the performance of the optimization method. A very valuable survey of the different welding processes of AISI 304L stainless steel had been presented in [8], which proved its application in the manufacturing component without the heat treatment. The welding processes introduced in this paper are: friction welding, gas tungsten arc welding (GTAW/TIG), gas metal arc welding (GMAW), shielded metal arc welding (SMAW), plasma arc welding (PAW), laser welding, and flux-core arc welding (FCAW).

Most of the research focused on the high welding current for thick metal. But the important finding here is that for the welding of the thin plates, GTAW is the most efficient process. According to the information contained in the paper [9], the thin stainless steel had different applications, for example, fabricating the fuselage shell of an airplane, a vehicle body, etc., where good quality and a lower weight are preferred criteria. The only disadvantage of pulse micro-plasma welding is its high production cost at medium scale. In [10], the researcher preferred to consider the influence of the welding parameters, such as the current, the voltage, and the wire feed, in determining the target function of the tensile strength. But they did not describe the welding methodology in detail, and is it necessary to quote all pertinent parameters? The software MINITAB17 was involved in setting up the regression function. The significant conclusion about the tensile strength, according to the optimization, was about 680 MPa. In contrast to all the above investigations, in [11], a new method for optimization was introduced in TIG welding for austenitic stainless steel when they used the Grey Wolf Optimization Method, selecting the current, welding speed, and gas flow rate as the main technological parameters.

They reached the optimal value for the tensile strength of 640 MPa. In the conclusion of the paper, the authors expected to overcome the Taguchi method, but only for TIG welding. To diversify the type of technological parameter for welding, [12] introduced another combination consisting of current, voltage, and wire feed in plasma arc welding. By the nomination of these parameters in the range of 230 A, 28 V, and 740 mm/min, accordingly, the estimated tensile strength was achieved at 687.35 MPa for SS 304 of 6 mm thickness. All researchers considered in their investigation that the stainless steel plates are thin when the thickness is about 2.0 mm. For the ultra-thin plates having a thickness less than 1.0 mm, better apply the micro-plasma welding process [13]. They reached the following optimization parameters: a peak current of 7 A, a background current of 4 A, a pulse rate of 40 pulses per second, and a pulse width of 50% to achieve the minimum grain size of 20.045 μm. In the 5th International Conference on Engineering Research and Application 2022 [14] (ICCERA—December 2022), the authors presented the results of the tensile testing and macrostructure of the plasma weld SUS 304 from 12 samples having a thickness of 2.0 and 1.5 mm. However, it is necessary to study in more detail the influence of the plasma welding parameters on the targeting function, with the tensile strength as the most important criterion in the performance of the welding connection.

Consequently, the aim of this work is to conduct an in-depth investigation using special software to localize the optimum for three main parameters impacting the quality of the weld. The model suggested for 3^3 is applied in the plan design for 27 inputs [15]. The findings will serve as a reliable background to design the mathematical model for the prediction of the tensile strength for the plasma welding of the SUS 304 stainless steel thin plates in terms of the nomination of the optimal process for adopting the requirement in industry.

METHOD

For the experiment, we used 09 buttweld pieces from SUS 304 steel, whose chemical composition is given in [16], with a thickness of 2.0 mm, and 03 pieces with a thickness of 1.5 mm. The remaining sizes of these pieces are: the width x the length, or 150 mm x 300 mm, respectively. The welding setting is nominated for 04 main changing parameters, such as the peak current of welding (I_h, A); the background current of welding (I_b, A); the welding speed (v_h, cm/min); the feeding rate of the welding wire ($v_{c.d}$, cm/min); the diameter of the wire (d = 1.0 mm); and the flow rate of the shielding gas ($G_{k.p}$, 2.0 l/min). In Figures 1a,b , the image is snapped during the experiment in welding the thin plates of stainless steel SUS 304 (JIS SUS 304) using the welding system of the company Lincoln C3-MATIC 32-33. All samples, after welding and cooling in the room condition, are cut off into pieces to be fabricated according to TCVN 97:2002 to prepare for the tensile testing (Figure 1c).

Table 1. The Chemical Composition of SS 304 [16].

Fe	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Nb	V
71.4	0.039	0.294	1.16	0.037	0.007	18.26	0.400	8.48	0.25	0.0338	0.0806

a) b) c)

Figure 1. The experiment in butt welding the stainless - steel thin plates SUS 304: The unit for the automatic setting of the welding mode and the online monitoring the welding seam (a, b); the welding sample after welding (c).

RESULTS AND DISCUSSION

1. The Result of Tensile Testing

Table 2 outlined all data from the tensile testing of the welding samples by the different welding settings.

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Table 2. The result of the tensile testing of the weldment from steel SUS 304

Mark	Examined technological parameters					Diameter of fill wire, d_b, mm	Thickness of weldment, δ, mm	Tensile strength of weldment, σ_k, MPa	Yield strength of weld metal, σ_s, MPa
	I_h, A	I_b, A	v_h, cm/min	$v_{c.d}$, cm/min	$G_{k.p}$, l/min				
1-2	100	60	34	80	2.0	1.0	2.0	655.304	320.092
2-2	80	50	40	90	2.0	1.0	2.0	417.334	314.865
3-4	90	50	30	80	2.0	1.0	2.0	686.925	321.872
4-3	90	50	25	80	2.0	1.0	2.0	665.738	304.414
5-5	90	50	30	90	2.0	1.0	2.0	723.211	344.653
6-2	90	50	28	90	2.0	1.0	2.0	693.656	327.134
7-3	95	50	32	90	2.0	1.0	2.0	665.392	308.785
8-4	95	50	30	90	2.0	1.0	2.0	661.757	312.935
9-6	100	50	30	90	2.0	1.0	2.0	669.687	316.749
11-4	60	30	30	75	2.0	1.0	1.5	658.198	296.290
12-4	50	25	25	65	2.0	1.0	1.5	569.470	306.007
13-4	70	35	30	75	2.0	1.0	1.5	632.675	304.270

2. The Result of Analysis of The Experiment Data

From the processing of the experiment in Table 2 using the mathematical statistics software ANOVA, the findings in Tables 3–5 are as follows: In the scope of this study, the authors only investigated the influence of plasma welding technological parameters on the tensile strength of the weld metal. The evaluation of the independent variable and the binary variable as the plasma technological parameter in the regression equation on the tensile strength as the target function (σ_k) from the welding of thin plates of stainless steel SUS 304 in order to select the most reasonable weld setting based on the reliable scientific background In Table 1, among the four plasma technological parameters selected to conduct the experiment on the step, exploring I_h, I_b, v_h, and vc.d., or the binary factors (I_h*I_b), I_b*$v_{c.d.}$, and v_h*$v_{c.d.}$, does it become necessary to define the degree of impact on the step? Thus, nominate the exploring zone, covering the three main significant technological parameters needed to design the full orthogonal matrix of the experiment N27 on the next step.

Table 3. General analysis of the regression function of the tensile strength of plasma weld steel SUS 304

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	62059.6	10343.3	11.97	0.079
Ih	1	3038.9	3038.9	3.52	0.202
Ib	1	1574.7	1574.7	1.82	0.310
Vh	1	150.1	150.1	0.17	0.717
Vc	1	1292.0	1292.0	1.50	0.346
Ih*Vc	1	3165.4	3165.4	3.66	0.196
Vh*Vc	1	1167.0	1167.0	1.35	0.365
Error	2	1728.1	864.1		
Total	8	63787.7			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
29.3948	97.29%	89.16%	

Table 4. Evaluation of the variation of the plasma weld technological parameters on the tensile strength of wel metal SUS 304

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	3663	5383	0.68	0.566	
Ih	-66.3	35.3	-1.88	0.202	441.181
Ib	-9.95	7.37	-1.35	0.310	5.59
Vh	-74	177	-0.42	0.717	5097.91
Vc	42.0	34.4	1.22	0.346	273.16
Ih*Vh	2.10	1.10	1.91	0.196	1389.03
Vh*Vc	-1.38	1.19	-1.16	0.365	2390.39

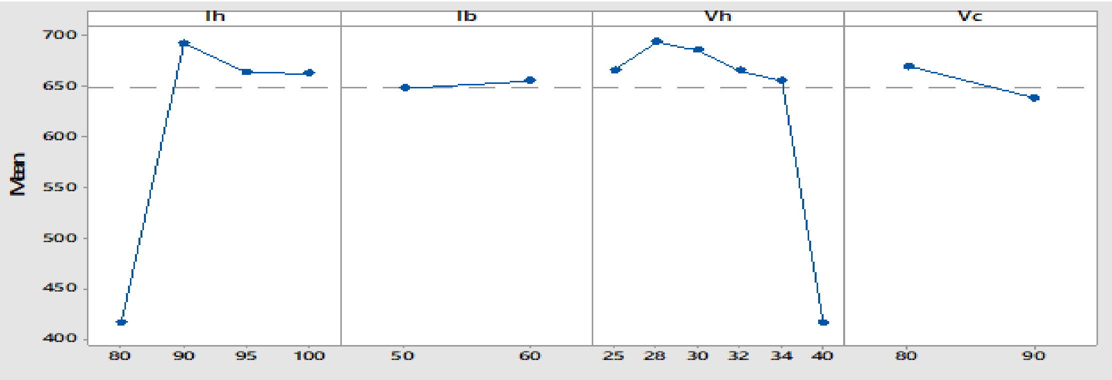
Table 5 . The forcast of the unnormal obsrevation in testing weld metal SUS 304

Fits and Diagnostics for Unusual Observations

Obs	Sigma K	Fit	Std Resid	*	X
1	655.3	655.3	-0.0	-1.04	X
2	417.3	418.5	-1.1	*	X
3	686.9	686.9	-0.0	*	X
4	665.7	665.7	-0.0	*	X

In Figure 2, the independent interactions of four plasma technological parameters are presented: the upper welding current (I_h), the welding opposite current (I_b), the welding speed (V_h), and the feeding rate of wire (V_c). How they impact the tensile strength (σ_k = Sigma K) in the plasma weld from thin plates of SUS 304 stainless steel having the thickness of 1.5 mm and 2.0 mm. Figure 3 illustrates simultaneously the interaction of four examined parameters at the moment of plasma welding. The mathematical model derived from the analysis is:

$$\sigma_k = f(I_h; I_b; v_h) = \text{Sigma K} = 3663 - 66.3\, I_h - 9.95\, I_b - 74\, v_h + 42.0\, v_{c}.d + 2.10\, I_h.V_h - 1.38\, v_h.v_{c.d} \quad (1)$$



a) b) c) d)

Figure 2. The dependence of the tensile strength of plasma weld metal (σ_k) from the independent parameters I_h (a); I_b (b); v_h (c) and $v_{c.d}$ (d) accordingly.

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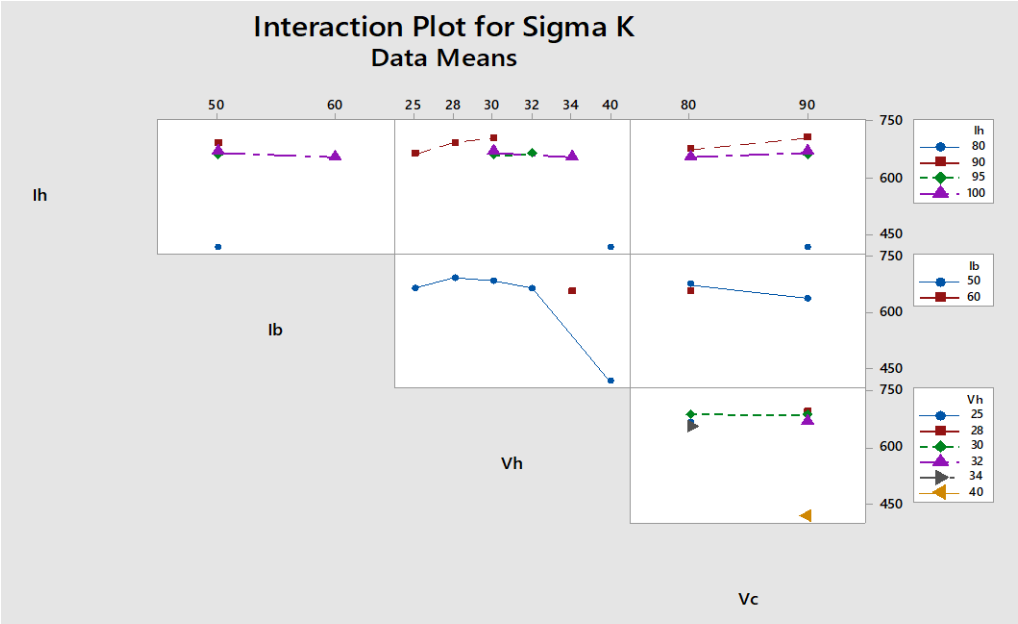
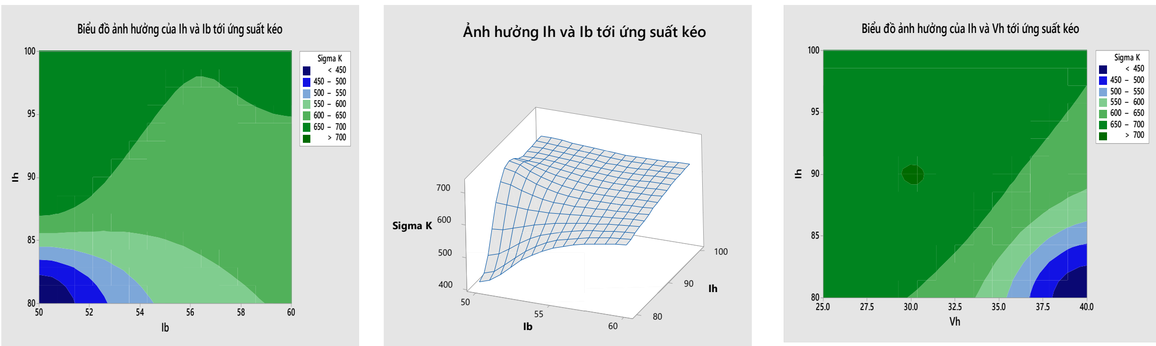


Figure 3. The dependence of the tensile strength of the plasma weld metal (σ_k) from the simultaneous influence of the independent binary variables: I_h*I_b; I_h*v_h; and I_h*$v_{c.d.}$

3. The Illustration of The Interaction of The Welding Modes on The Quality of The Plasma Weld Metal from Stainless Steel SUS 304

The interpretation in 2D and 3D in Figure 4 illustrated the degree of influence of the major technological parameters of the plasma welding of the thin plates of SUS 304 steel on the tensile strength (σ_k). Thus, it can be an analysis of the simultaneous interaction of the binary plasma technological parameters in plasma welding of the steel SUS 304 having a thickness of 2.0 mm in the series of targeted technological exploration discussed in the above-mentioned sections. The findings helped to derive the following comments in the next paragraph.



a) *b)* *c)*

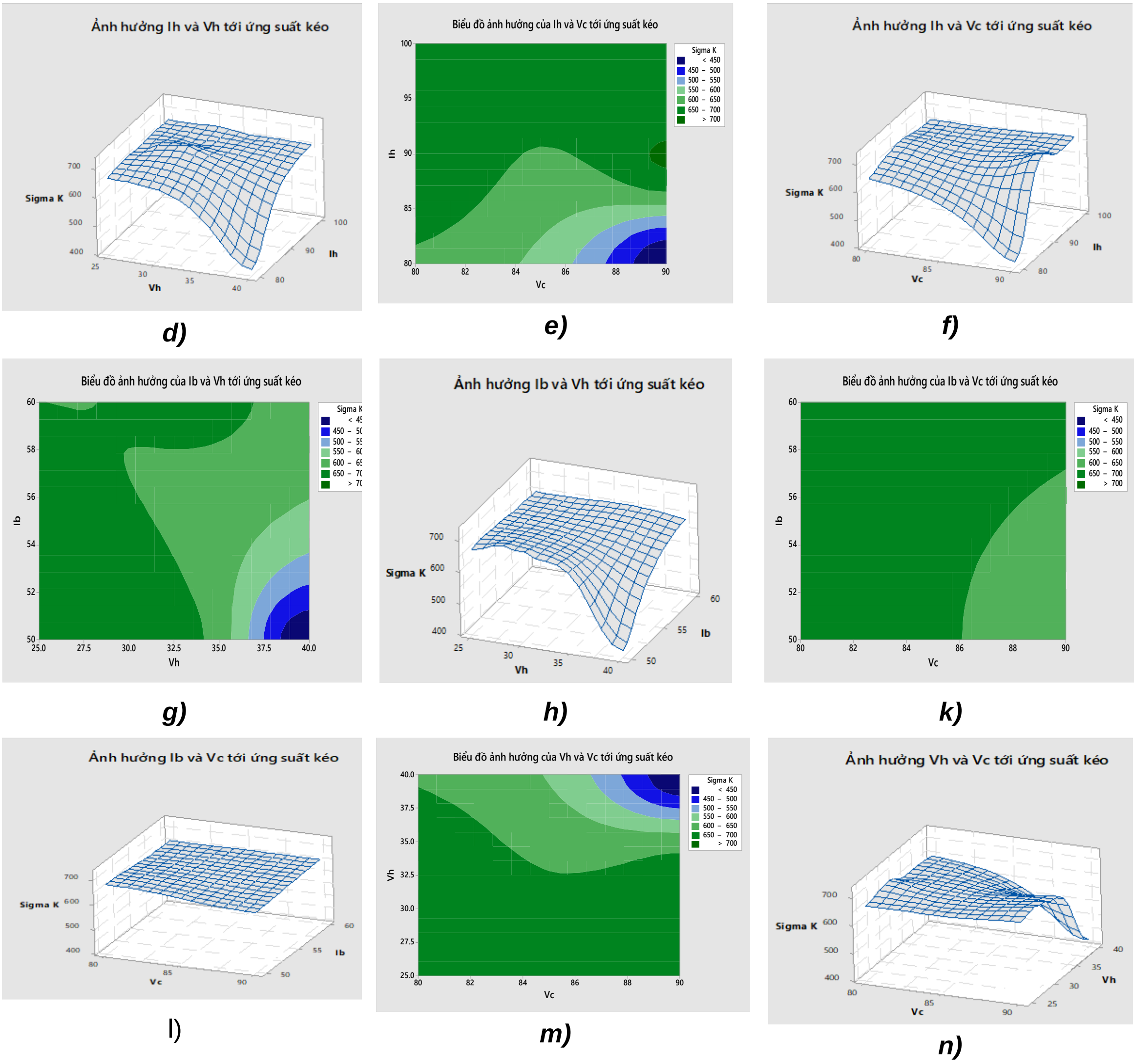


Figure 4. The graphical illustration of the binary influence of the welding mode parameters on the tensile strength of the plasma-welded SU 304 having a thickness of 2.0 mm: *a, b)* $I_h.I_b$; *b, c)* $I_h.v_h$; *e, f)* $I_h.v_{c.d}$; *g, h)* $I_b.v_h$; *k, l)* $I_b.v_{c.d}$; *m,n)* $v_h.v_{c.d}$

4. Discussion on the experiment findings

The following is an analysis of the experiment results from Tables 1- 5 and the graphics in Figures 2 – 4.The influence of the thickness of the welding stainless steel thin plates SUS 304 influence of the thickness of the welding stainless steel thin plates SUS 304: Almost all of the welding samples from butt-weld steel SUS 304 with thicknesses of 1.5 mm and 2.0 mm passed the set of criteria for evaluating plasma weld quality: accepted;

The tendency of the influence of the plasma welding upper current (I_h): initially, when Ih increased, the tensile strength (σ_k) increased monotonously in the range of I_h = 80–90 A, then the tensile strength tends to slightly decrease in the range of I_h = 90–100 A. The reason can be the deposited layers in the bottom that caused the elevation or reduction according to the examined ranges of I_h in Figure 2 a;

The tendency of the influence of the opposite plasma welding current (I_b): the increased I_b leading to the slight decreasing of the tensile strength (σ_k) due to the decreased deposited layers in the bottom (Figure 2 b);

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The tendency of the influence of the welding speed (v_h): when the welding speed increased in the range of v_h = 25–28 cm/min, the tensile strength (σ_k) tended to slightly increase, but in the range of v_h = 28–40 cm/min, it decreased inversely according to the increasing of v_h with the significant amplitude, especially when v_h = 40 cm/min (Figure. 2 c). However, through the experiment, it is recommended to nominate tensile strength at the medium level, which will be better.

The tendency of the influence of the feeding rate ($v_{c.d}$): when the feeding rate of the wire increased, the tensile strength of the welding metal tended to slightly decrease (Figure 2 d). This happened probably due to the improper feeding rate of wire upon the welding setting at the proportion I_h / I_b = 1.667–2.0, which in turn caused the welding speed v_h = 25–40 cm/min, leading to the formation of the plasma weld with the unattractive changing appearance on the upper and lower sides. Besides, the contoured forming of the weld seam in the cross section of the weld showing the ununiform deposition of the metal due to the different formation of the filling melted drops on both sides caused the morphology of the weld to be not smooth and fine;

The input examined parameters, such as I_h and vh, significantly influenced the mechanical strength characteristics of the weld metal over the parameters I_b and $v_{c.d}$. The factor v_h is one of the parameters used to evaluate the productivity and quality of the plasma welding process, but at this stage of the technological targeting, it has not been sufficiently investigated due to the limited number of experiments. The linear model (4.1) is not acceptable.

The independence of the tensile strength of the plasma-welded metal (σ_k) from the simultaneous impact of the independent binary factors I_h*I_b, I_h*v_h, and I_h*v_c in the different welding settings described in Figure. 4 provided a more overviewed view in terms of the above discussions. The analysis of the contour graphics and the 3D images in Figure. 4 quoted:

Figure. 4 illustrates the tendency of the influence of the binary factors I_h and I_b on the σ_k: when I_b increased from 50 A to 60 A while I_h increased from I_h = 80 A to I_h = 87 A, the tensile strength of the plasma welding steel SUS 304 tends to decrease. But when the I_h increased from I_h = 87 A to I_h = 98 A, the σ_k initially increased, then it decreased in the range of I_h = 98 A to I_h = 100 A. The unilevel values in the examined zone of the σ_k can be reached from σ_k < 450 MPa up to σ_k > 700 MPa. The 3D graph that motivated the independence of the σ_k from the binary factors (I_h*I_h) in Figure. 4 b helped to observe more deeply the changing characterization of the σ_k at the different crossing levels in the selected examined zone. They are not reasonably nominated; it is necessary to regulate them in the next series of the experiment.

The influence of the binary factors I_h and V_h on the σ_k is illustrated in Figure. 4 c. In general, when the I_h increased from the value I_h = 80 A to the value I_h = 100 A, the v_h increased from the value v_h = 25 cm/min to the v_h = 40 cm/min, and simultaneously impacted by the I_h, the σ_k tended to decrease according to the increasing of the v_h. The value of the σ_k gained in the range from σ_k< 450 MPa to σ_k > 700 MPa depends on the crossing level in the examined zone of the binary factor (I_h*v_h). However, there is a small subzone in the graphic (Figure. 4 b) where the significant increasing of the σ_k is seen in cases of I_h = 90 A and v_h = 30 cm/min and surrounding. This argument is also implied in the 3D graphic, Figure. 4d. Consequently, it is required to regulate the planning zone for the next stage around the point I_h = 90 A to set the reasonable level and, at the same time, select the level v_h tending to smaller quantities to eliminate the reverse negative impact of the welding speed on the tensile strength of the plasma-welded metal;

The tendency of the simultaneous impact from the binary technological factors (I_h*$v_{c.d}$) illustrated in the contour sketch and the graphic 3D in Figure. 4e, f, is announced: In the examined zone, I_h = 80 - 100 A and $v_{c.d}$ = 80 - 85 cm/min, and the tensile strength of the plasma-welded steel SUS 304 increased proportionally with the increasing of I_h and $v_{c.d}$ in the range from $\sigma_k < 450$ MPa to $\sigma_k > 700$ MPa. However, it is observed that the contour value σ_k tends to reversibly decrease according to the increasing of the $v_{c.d.}$ in the range of $v_{c.d}$ = 85 - 90 cm/min. This finding reminds us of the selection of the level for the feeding rate of the wire at the value $v_{c.d}$ = 85 cm/min in the next stage of the complete planning design N27.

The contour sketches in Figure. 4g and the graphic 3D in Figure. 4h interpret: the influence of the simultaneous-technological binary ($I_b.v_h$) on the σ_k in general tends to be decreased significantly according to the increasing of I_b and v_h, the highest and most stable value of the σ_k having been achieved in the examined range of v_h = 25 - 32 cm/min and I_b = 50 - 55 A;

The contour sketches in Figure. 4k and the graphic 3D in Figure 4l interpret: the influence of the simultaneous technological binary (I_b*$v_{c.d}$) on the σ_k in general tends to be decreased significantly according to the increasing of I_b and $v_{c.d}$, the highest and most stable value of the SK having been achieved in the examined range of $v_{c.d}$ = 80 - 86 cm/min and I_b = 50- 60 A.

The contour sketch in Figure. 4m and the graphic 3D in Figure. 4n interpret: the influence of the simultaneous-technological binary (v_h*$v_{c.d}$) on the σ_k in general tends to be decreased proportionally according to the increasing of v_h and to be increased proportionally according to the increasing of $v_{c.d}$ in the range of $v_{c.d}$ = 80–85 cm/min, then s_k continued tends to be slightly decreased in the range of $v_{c.d}$ = 85–90 cm/min. Thus, the highest and most stable value of the s_k had been achieved in the examined range of $v_{c.d}$ = 80–85 cm/min and v_h = 25–32 cm/min.

The tensile strength of the plasma welding samples is about 650 MPa at the equivalent level of the other publications [17]. For the improvement of the model in the case of micro-plasma welding, is it useful to additionally include other parameters such as the peak current, the background current, and the pulse width [19, 20,21].

CONCLUSION

The tensile strength of the plasma welding samples is about 650 MPa at the equivalent level of the other publications, proving the reasonable welding setting for the preliminary investigation, and the combination of the technological parameters is the right selection. In the planning design of the orthogonal matrix for the experiment model type N27, according to the methodology presented in [5,] to conduct the complete plan of the experiment at 27 nodes aiming to create the mathematical model predicted the tensile strength of the plasma welding thin plated stainless steel SUS 304, it is required to focus on the investigation at 03 selected main technological variables (I_h, I_b, and v_h) affecting on the target function (σ_k), and it is enough to apply this procedure to the thickness of the welding pieces = 2.0 mm. It is required to regulate the localized zone for the better regression planning experiment [18] in comparison with the above-examined stage at the levels: I_h = 80, 90, and 100 A; I_b = 50, 55, and 60 A; v_h = 24, 28, and 32 cm/min; $v_{c.d}$ = 80 cm/min; at the same time, the other remaining boundary conditions have to be maintained properly according to the recommendations from the plasma welding suppliers. For the improvement of the model in the case of micro-plasma welding, is it useful to additionally include other parameters such as the peak current, the background current, and the pulse width and compare with the different processes?

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