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Response Surface Optimization of Interpulse TIG welding for the Optimum Weld bead of Ti-6Al-4V

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Abstract: The Interpulse technique is a narrow bead and an advancement of Tungsten inert gas (TIG) welding process. The benefit of Interpulse technique is the, magnetic constriction of the arc which produces penetration welding of titanium alloys with a low input current. The titanium alloy (Ti-6Al-4V) exhibits unique properties of exceptional strength to weight ratio, low density, high operational thermal conductivity and low modulus of elasticity made these alloy a functional material for the various structural applications in aerospace as well non aerospace industrial applications. In these experimental investigation three factors at five levels response surface rotatable central composite design is used to design the experiment and analyze the individual and simultaneous effects of input variables (main current, Interpulse current, background current and an additional welding speed), on output responses (weld bead width and reinforcement height). The outcome shall be useful in determining suitable parameters of Interpulse TIG welding of titanium alloy (Ti-6Al-4V) to obtain the desirable shape of the weld bead.
Keywords: Interpulse technique, Response surface methodology, TIG welding, (Ti-6Al-4V) titanium alloy, Weld bead geometry

I. INTRODUCTION

Gas tungsten arc welding is well-known as tungsten inert gas welding (TIG), widely used an arc welding process for the joining of different metals and their alloys of thin sections such as most of the steels, Aluminum, Magnesium, nickel based superalloys such as Monel, Inconel and Nimonic and also sensitive materials like Titanium and Zirconium. The welding is carried out using an electric arc which is getting struck between the non consumable tungsten electrode and the workpiece. The welding arc is defined as a sustained electrical discharge in an ionized gas which produces sufficient amount of heat energy for the joining of different metals and their alloys by the fusion. The argon was used as a shielding gas to avoid atmospheric contaminations of the molten weld pool. The problem with TIG welding is distortion of the component caused due to high heat input which can be controlled by the pulsing the current to a higher value and to a lower value. So the average input current value is always to be low. Further development in pulsing of current in TIG welding brought up the superimpose of a high frequency Interpulse current, which creates magnetic constriction of the arc by significantly minimizing the net heat input. The principle of Interpulse technique is the strength of the electric field is directly proportional to the rate of change of the magnetic field (11). Ti-6Al-4V is an alpha-beta titanium light weight alloy exhibits unique properties of high strength, low density. The alloy is used widely as structurally efficient metal for the manufacturing of the critical and high performance jet engine and airframe components. Response surface methodology is a combination of mathematical and statistical techniques which is useful for the building of an empirical model and the objective is to optimize the input variables to identify the effect of change in input variables on output response (10). The objective of this experimentation is to identify the Interpulse TIG welding process parameters and their suitable ranges for the joining of 1.2 mm thick Ti-6Al-4V titanium alloy and to optimize the input process parameters to find out the minimum weld bead width and reinforcement height using response surface methodology.

II. EXPERIMENTAL PROCEDURE

Numbers of trail welding were carried out using 1.2 mm thick rolled sheets of Titanium alloy (Ti-6Al-4V) to find feasible working limits of Interpulse TIG welding process input parameters. Visual inspection of the weld bead width, re-inforcement height and penetration are checked to select the working limits of welding parameters. The observations are made from the visual inspections are, if main current is less than 60 Amps there is lack of penetration and excess penetration like burn through is seen when the main current is increase more than 108 Amps. Constriction of arc is not observed when InterPulse current is less than 2 Amps and more than 6 Amps more constriction leading to difficult to control the arc. Welds were produced at room temperature in a clean environment. Appropriate fixture is provided to hold the two sheets tightly together and then tacked before the complete joining of the two sheets to prevent misalignment, distortion, buckling. Molten weld metals are protected from environmental contamination by a quiescent blanket of inert shielding gas such as argon. The welding was carried out to get penetration weld where main current always greater than the Interpulse current. Two rolled sheets of titanium alloy (Ti-6Al-4V) of size 300×150×1.2 is butt welded by

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the Interpulse TIG welding process. The process parameters are main current (I_m), Interpulse current (I_p), background current (I_b) are chosen. And an additional parameter welding speed (S) is measured and tabulated below in the table 3. The other process parameters like voltage (9 Volt), pulse frequency (20000 Hz), pre and post purging gas flow rate are kept constant throughout the experiment. The chemical compositions of titanium alloy (Ti-6Al-4V) are given below in the table I.

The Interpulse TIG welding process parameters and their feasible working ranges are given below in the table II. The response surface rotatable central composite design is used to derive the 17 numbers of experimental conditions which is followed for this investigation given below in the table III. The weld bead geometry and its terminologies are presented below in figure 1. Where the weld bead width is defined as the maximum width of the weld metal deposited over the metal surface. The weld bead width increases with increase in arc current, voltage and decreases with increase in welding speed. Penetration height is defined as the distance from the base plate top surface to the maximum extent weld metal projected across the gap between the two metal pieces. The load carrying capacity of the welded structure is depends upon the penetration. The two responses weld bead width and reinforcement height is measured using vernier caliper of least count 0.01 mm and the results are given below in table III. Interpulse TIG welding machine setup was used for the experimentation shown below in figure 2. The JMP statistical software is used to draw the experimental design matrix and analysis of the result. Optimization of the chosen process parameters using response surface methodology is done to locate the optimum and desirable condition for the higher performance.

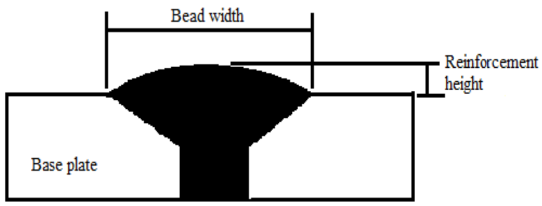

Fig. 1 Weld bead geometry

TABLE I CHEMICAL COMPOSITIONS OF (WT %) OF TITANIUM ALLOY (TI-6AL-4V)

C	Fe	N	O	Al	V	Ti
0.08	0.25	0.05	0.20	5.5-6.75	3.5-4.5	Bal.

Table Ii Interpulse Tig Welding Process Parameters And Their Feasible Working Range

S. No.	Interpulse TIG welding process parameters	-1.682	-1	0	+1	+1.682
1	Main current (I_m)	60	70	84	98	108
2	InterPulse current (I_p)	2	3	4	5	6
3	Background current (I_b)	28	30	32	34	36

Fig. 2 InterPulse TIG welding machine setup

Table Iii 17 Numbers of Experimental Conditions Of Interpulse Tig Welding

Sl. no.	I_m (A)	I_p (A)	I_b (A)	Bead Width (mm)	Predicted weld bead width (mm)	Error in prediction	Reinforcement Height (mm)	Predicted Reinforcement Height (mm)	Error in prediction	Heat Input (J/mm)	"S"(mm/ min)
1	70	5	30	5.26	5.23	0.03	0.28	0.29	0.01	256	58
2	70	5	34	5.15	5.13	0.03	0.35	0.34	0.01	274	56
3	70	3	30	5.19	5.16	0.03	0.29	0.28	0.01	246	58
4	70	3	34	4.98	4.92	0.03	0.49	0.48	0.01	260	57
5	98	5	30	5.45	5.46	0.03	0.51	0.51	0.01	221	84
6	98	5	34	5.41	5.39	0.03	0.42	0.42	0.01	255	75
7	98	3	30	5.56	5.53	0.03	0.26	0.26	0.01	241	75
8	98	3	34	5.33	5.32	0.03	0.34	0.32	0.01	266	70
9	60	4	32	4.95	4.99	0.029	0.37	0.36	0.009	270	50
10	108	4	32	5.54	5.53	0.029	0.42	0.41	0.009	229	87
11	84	6	32	5.49	5.49	0.03	0.44	0.42	0.01	246	70
12	84	2	32	5.32	5.35	0.03	0.31	0.31	0.01	253	64
13	84	4	28	5.44	5.44	0.03	0.34	0.33	0.01	240	72
14	84	4	36	5.11	5.13	0.03	0.44	0.44	0.01	239	70
15	84	4	32	5.02	5.03	0.021	0.28	0.28	0.007	253	66
16	84	4	32	5.00	5.03	0.021	0.3	0.28	0.007	232	72
17	84	4	32	5.05	5.03	0.021	0.29	0.28	0.007	253	66

III.RESULT AND DISCUSSION

In this study, the response function of the joint, weld bead width and reinforcement height (**σ**), are functions of main current (I_m), InterPulse current (I_p), background current (I_b), and it can be expressed as: $\sigma = f\ (I_m, I_p, I_b)$. The second order polynomial (regression) equation that represents the response surface "Y" is:

$$Y = b_0 + \Sigma\ b_i x_i + \Sigma\ b_{ii}\ x_i^2 + \Sigma\ b_{ij}\ x_i\ x_j \qquad (1)$$

Where b_0 the average of all responses and b_i, b_{ii}, b_{ij} are the coefficients that depends on the respective main and interaction effects of the parameters. The developed second order regression expression for the response weld bead width and reinforcement height are given below in the equation 2 and 3 respectively. The adequacy of the developed second order regression expression is analyzed using the analysis of variance technique (ANOVA). ANOVA suggests if the calculated 'F' ratio of the developed model is less than the standard 'F' ratio (from F-table) at a desired level of confidence (95%), the model is considered adequate within the confidence limit. The ANOVA results for the responses weld bead width and reinforcement height is given below; the terms taken are degrees of freedom, sum of squares, mean square, and 'F' ratio. The 'F' ratio is defined as the ratio of the between group variation divided by the within group variation. It is understood that the developed relationship is adequate at 95% confidence level.

The terms which has values of 'probability > F' is less than 0.05, the relationship term will be considered as significant term. The values are greater than 0.05 indicates that the relationship terms are not significant. Therefore the significant terms are main current, interpulse current, background current and it has individual as well as interaction effects of main current and interpulse current, background current and interpulse current on the weld bead width. The summary of fit, where Root-Square also called coefficient of multiple determination is calculated by taking the ratio of sum of squares (model) and sum of squares (C. total). An R-Square closer to 1 indicates better fit the data than does when the Root-Square closer to 0. If the lack of fit is insignificant then it suggests the model fits the data well. The summary of fit, analysis of variance, lack of fit, effects test for the response models weld bead width and reinforcement height are tabulated below in the tables from IV to VIII. Correlation graphs between actual and predicted response values of the response weld bead width and reinforcement height is presented below in figure 3. Contour plots figure 4 and 5 and response surface plots figure 6 and 7 are plotted below to indicate the predicted response values and optimum values in both the way of representations of 2 dimensional and 3 dimensional views respectively. Contour plot report shows the normalized transformation of obtained weld bead width values with respect to the InterPulse TIG welding process parameters such as main current, InterPulse current and background current. The outcome of response on surface is whether minimum or maximum or minimax or maximin both are equal. So in the case of weld bead width the solution is minimum whereas in the case of reinforcement height is at saddle point i.e. origin at (0, 0) that is whether minimax or maximum. The desirability function used for the multiple response optimizations, given below in figure 8 is a representation of the response variables in 0 to 1 scale, where 0 suggests that the response is completely undesirable and 1 indicates the response value is the most desirable.

$$\text{Weld bead width} = 5.03 + 0.15 * \left(\frac{(I_m - 84)}{14}\right) + 0.034 * (I_p - 4) - 0.078 * \left(\frac{(I_b - 32)}{2}\right) + \left(\frac{(I_m - 84)}{14}\right) * ((I_p - 4) * -0.033) + \left(\frac{(I_m - 84)}{14}\right) * \left(\left(\frac{(I_b - 32)}{2}\right) * 0.0062\right) + (I_p - 4) * \left(\left(\frac{(I_b - 32)}{2}\right) * 0.036\right) + \left(\frac{(I_m - 84)}{14}\right) * \left(\left(\frac{(I_m - 84)}{14}\right) * 0.08\right) + (I_p - 4) * ((I_p - 4) * 0.097) + \left(\frac{(I_b - 32)}{2}\right) * \left(\left(\frac{(I_b - 32)}{2}\right) * 0.065\right) \quad (2)$$

$$\text{Reinforcement height} = 0.29 + 0.015 * \left(\frac{(I_m - 84)}{14}\right) + 0.027 * (I_p - 4) + 0.029 * \left(\frac{(I_b - 32)}{2}\right) + \left(\frac{(I_m - 84)}{14}\right) * ((I_p - 4) * 0.06) + \left(\frac{(I_m - 84)}{14}\right) * \left(\left(\frac{(I_b - 32)}{2}\right) * -0.035\right) + (I_p - 4) * \left(\left(\frac{(I_b - 32)}{2}\right) * -0.037\right) + \left(\frac{(I_m - 84)}{14}\right) * \left(\left(\frac{(I_m - 84)}{14}\right) * 0.035\right) + (I_p - 4) * ((I_p - 4) * 0.02) + \left(\frac{(I_b - 32)}{2}\right) * \left(\left(\frac{(I_b - 32)}{2}\right) * 0.024\right) \quad (3)$$

Table Iv Summary Of Fit For The Response Models: Weld Bead Width And Reinforcement Height

Models	Weld bead width	Reinforcement height
RSquare	0.98	0.99
RSquare Adjust	0.96	0.97
Root mean square error	0.03	0.01
Mean of response	5.25	0.36
Observations	17	17

Table V Anova And Lack Of Fit For The Response Model Weld Bead Width

Source (ANOVA)	Degrees of freedom	Sum of squares	Mean square	F ratio	Whether significant or not
Model	9	0.69	0.076	51.26	
Error	7	0.01	0.0015	Prob > F	
Corrected total	16	0.702		<.0001	Yes
Source	Degrees of freedom	Sum of squares	Mean square	F ratio	
Lack of fit	5	0.0092	0.0018	2.915	
Pure error	2	0.0012	0.0006	Prob > F	
Total error	7	0.01		0.2749* (Insignificant) Maximum root square 0.9982	

Table Vi Effect Tests For The Response Model Weld Bead Width

Source	Degrees of Freedom	Sum of Squares	F Ratio	Prob > F	Whether significant or not
I_m (70, 98)	1	0.34	228.65	<.0001*	Yes
I_p (3, 5)	1	0.018	12.607	0.0093	Yes
I_b (30, 34)	1	0.097	65.11	<.0001*	Yes
$I_m \times I_p$	1	0.009	6.07	0.0431	Yes
$I_m \times I_b$	1	0.0003	0.208	0.6619*	No
$I_p \times I_b$	1	0.01	7.01	0.0331*	Yes
I_m^2	1	0.07	48.208	0.0002*	Yes
I_p^2	1	0.18	125.59	<.0001*	Yes
I_b^2	1	0.08	56.006	0.0001*	Yes

Table Vii Anova And Lack Of Fit For The Response Model Reinforcement Height

Source (ANOVA)	Degrees of freedom	Sum of squares	Mean square	F ratio	Whether significant or not
Model	9	0.097	0.01	68.99	
Error	7	0.001	0.000158	Prob > F	
Corrected total	16	0.099		<.0001*	Yes
Source	Degrees of freedom	Sum of squares	Mean square	F ratio	
Lack of fit	5	0.0009	0.00018	1.8092	
Pure error	2	0.0002	0.0001	Prob > F	
Total error	7	0.001		0.3931* (Insignificant) Maximum root square 0.998	

Table Viii Effect Tests For The Response Model Reinforcement Height

Source	Degrees of Freedom	Sum of Squares	F Ratio	Prob > F	Whether significant or not
I_m (70, 98)	1	0.003	19.32	0.0032*	Yes
I_p (3, 5)	1	0.012	76.67	<.0001*	Yes
I_b (30, 34)	1	0.013	83.808	<.0001*	Yes
$I_m \times I_p$	1	0.028	182.508	<.0001*	Yes
$I_m \times I_b$	1	0.009	62.103	0.0001*	Yes
$I_p \times I_b$	1	0.011	71.29	<.0001*	Yes
I_m^2	1	0.013	86.14	<.0001*	Yes
I_p^2	1	0.008	54.64	0.0002*	Yes
I_b^2	1	0.011	75.98	<.0001*	Yes

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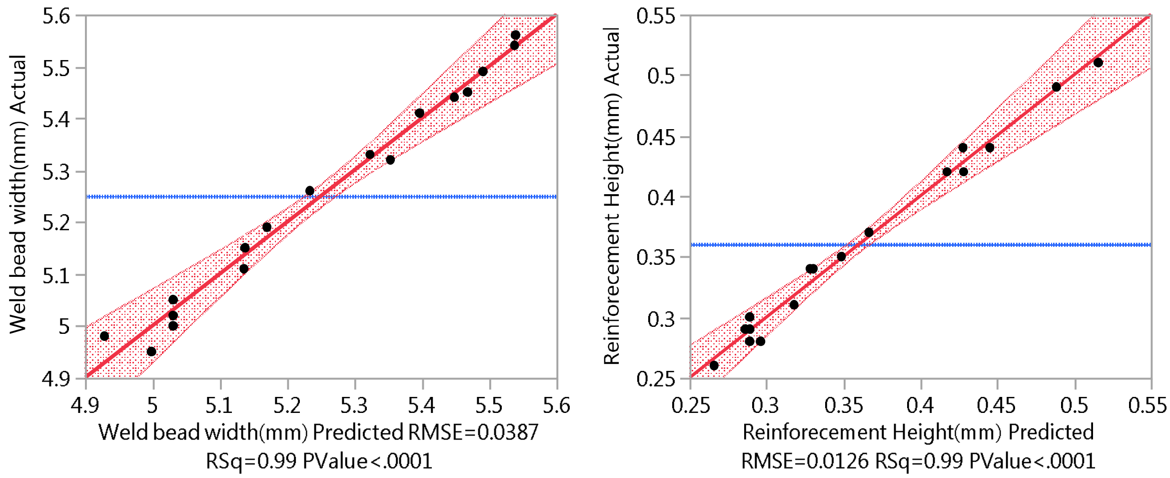

Fig. 3 Co-relation graph, actual and predicted; weld bead width, reinforcement height

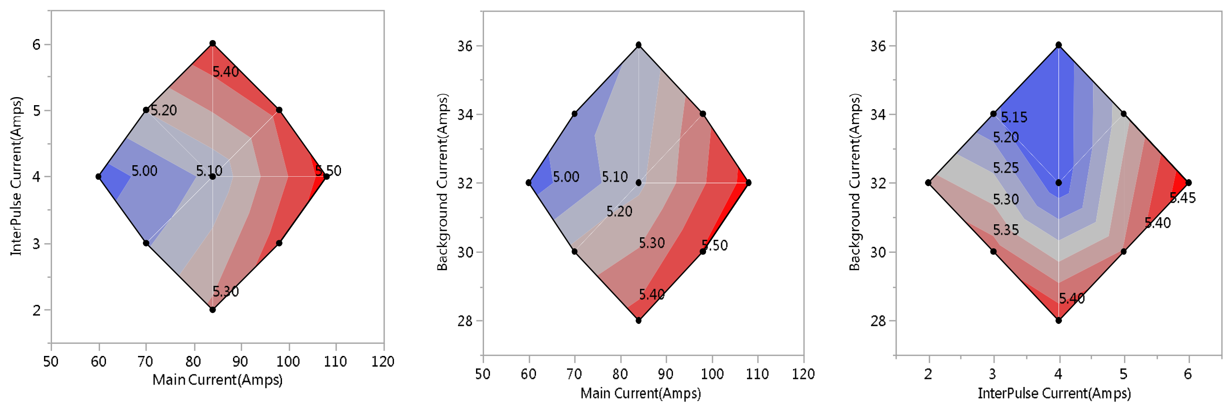

Fig. 4 Contour plots of the response weld bead width

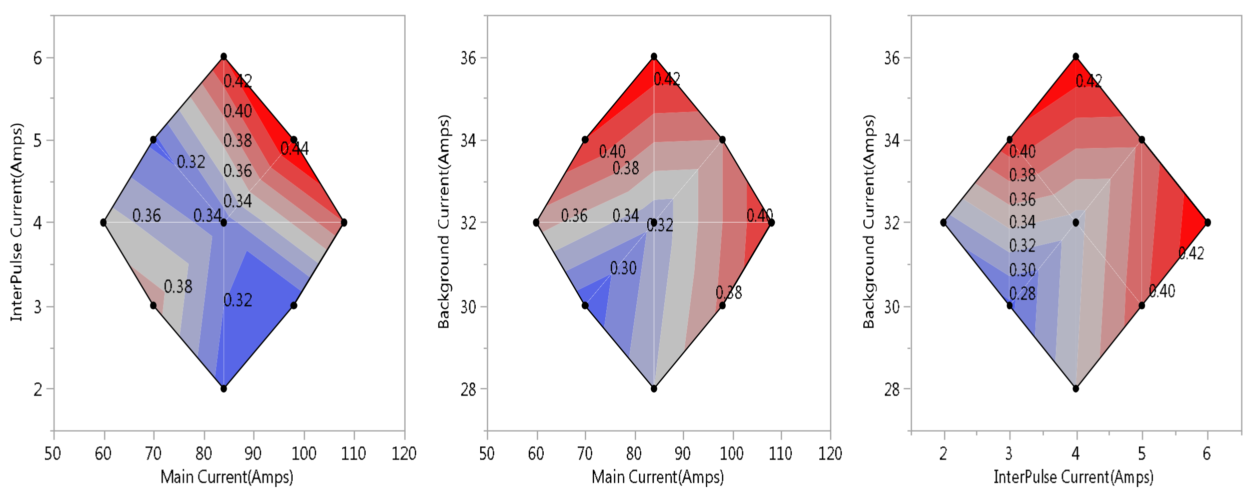

Fig. 5 Contour plots of the response reinforcement height

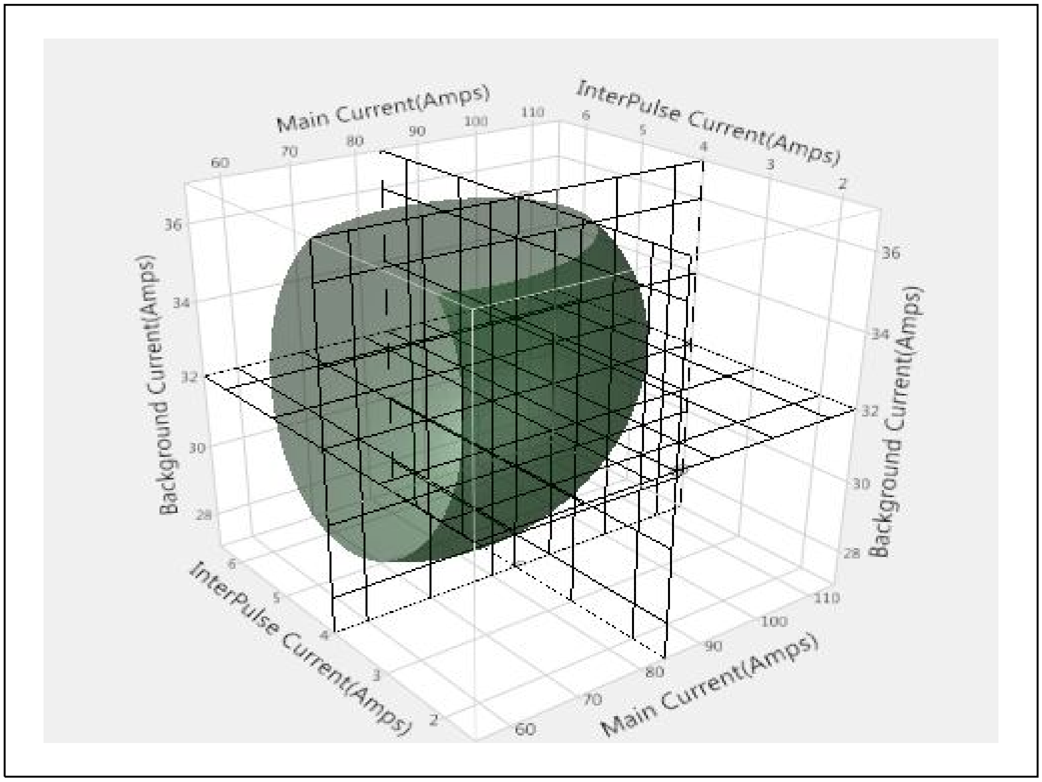

Fig. 6 Isometric response surface plot for the response weld bead width

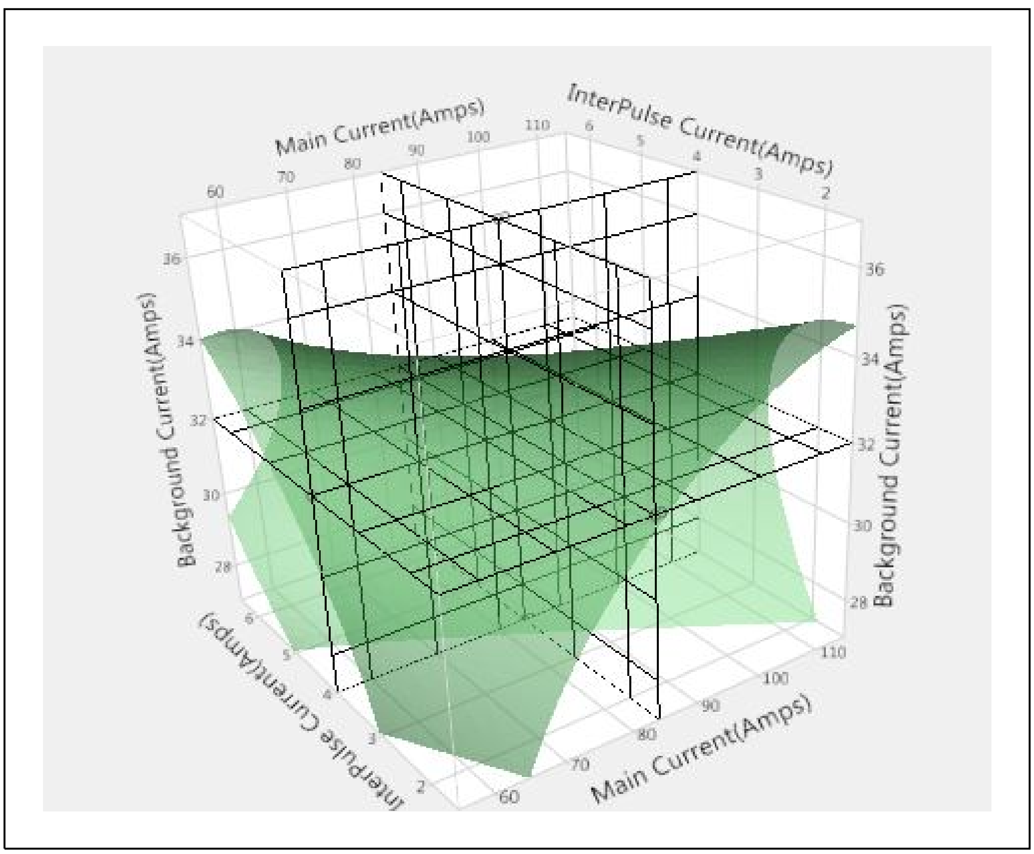

Fig. 7 Isometric response surface plot for the rsponse reinforcement height

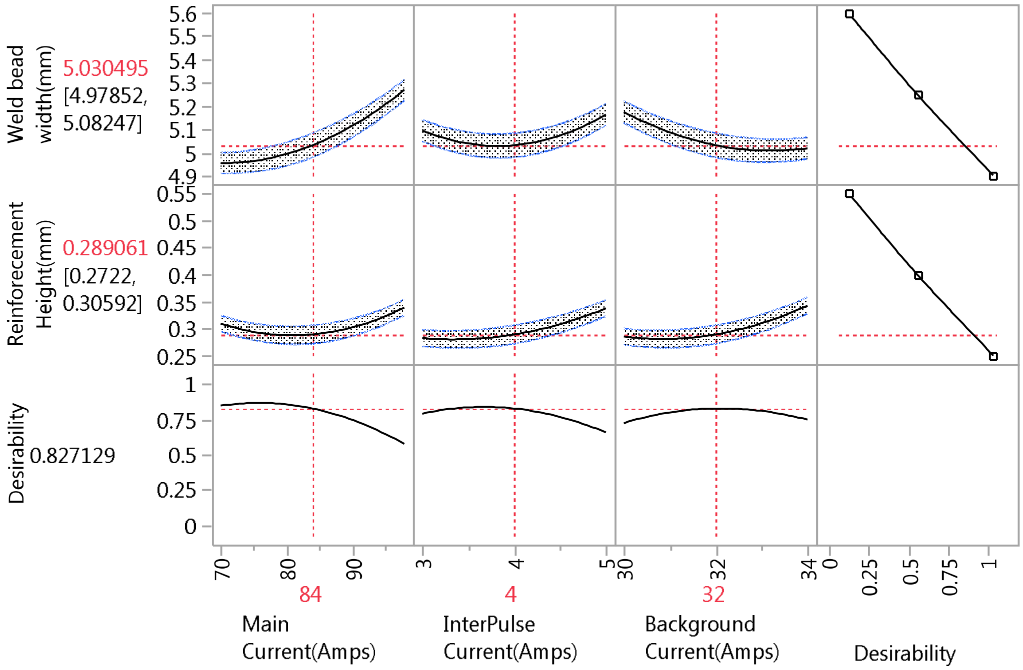

Fig. 8 Desirability profile for multiple response optimization

IV. CONCLUSIONS

An empirical relationship was developed between input parameters and output responses which can be effectively used for the prediction of weld bead width and reinforcement height of InterPulse TIG welding of titanium alloy (Ti-6Al-4V) at 95% confidence level. The lowest error in prediction is considered to choose the optimized parameters and that is, main current 84 Amps, InterPulse current 4 Amps and background current 32 Amps with at welding speed 72 mm/min, which has desirability of 82%. Considering welding conditions the optimized values obtained is, weld bead width 5.03 mm and reinforcement height 0.28 mm. For the validation of obtained relationship and optimized parameters, two more Ti-6Al-4V Titanium alloy sheets of thickness 1.2 mm are welded using the above mentioned optimized parameters values. The weld bead width is obtained 4.9 mm and the response solution minimum. The reinforcement height is obtained 0.29 mm and the response solution is at saddle point i.e. minimax or maximin both are equal.

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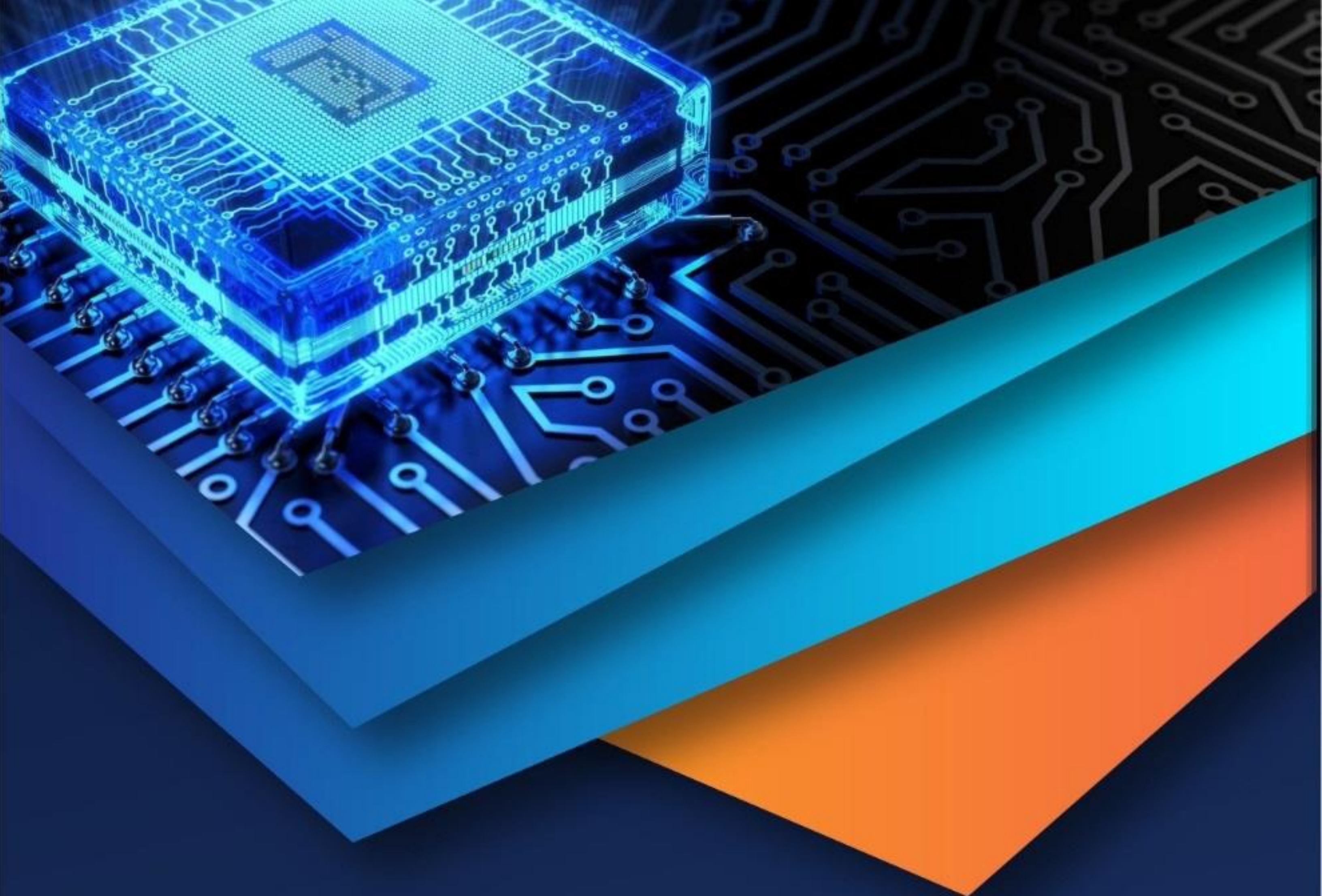

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