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PREDICTING THE FUSION ZONE PROFILES OF INTERPULSE TIG WELDED NICKEL BASE SUPER ALLOYS

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ABSTRACT

Interpulse Tungsten Inert Gas (IPTIG) welding is a new variant of conventional Tungsten Inert Gas (TIG) welding process. This process offers many advantages over conventional TIG welding process such as narrow heat affected zone, deeper penetration. For welding titanium and nickel base alloy the IPTIG process were used by few researchers recently. The results are found to be interesting and comparable to electron beam welding. In this investigation, an attempt has been made to study the effect of IPTIG welding parameters on weld bead geometry of nickel based super alloy (Su-718) sheets. Four factors, five levels central composite design matrix was used to conduct the experiments. Bead geometries such as depth of penetration, width of bead and fusion zone area were recorded. Empirical relationships were developed to predict bead geometries incorporating IPTIG welding parameters. Perturbation plots were constructed to study the effect of IPTIG welding parameters on bead geometries.

***Keywords**: Interpulse TIG Welding, Nickel base alloy, Design of Experiment, and ANOVA.*

1. Introduction

Inconel 718 is one of the most widely used Ni-based superalloys due to its superior mechanical properties and oxidation resistance at high temperature. Inconel 718 is, therefore, utilized as the main construction material for gas turbine engine [1]. This alloy is usually welded with Tungsten Inert Gas (TIG) process, which introduce large heat affected zone (HAZ), deformation and residual stresses, which can affect sizing and production [2]. Electron beam welding (EBW) has been proposed for welding these alloys, since it can be possible to reduce the detrimental thermal effects on the base material adjacent to the fusion zone, but the process needs to be performed in vacuum.

Additionally, when considering Inconel 718, it has been pointed out that two beam passes are needed, the first being fully penetrative and the second for cosmetic reasons with low heat input and large beam size to reduce surface undercuts resulting from the first pass. Furthermore, microfissuring in the heat-affected zone as well as a high amount of brittle intermetallic Nb-rich Laves phases, which are well-recognized as being detrimental to weld mechanical properties, are produced both in arc and electron beam welding of Inconel 718 [3]. The magnetic arc oscillation technique resulted in refined Laves phase with lesser inter connectivity. The full benefits of current pulsing in breaking the dendrites could not be realized due to relatively higher heat input used in the welding process. In the direct aged condition weldments prepared using magnetic arc oscillation technique exhibited higher tensile strength due to the presence of refined and lesser-interconnected Laves particles. [4]

In order to reduce these harmful impacts, new processes derived from TIG, have been developed to reduce the heat input. Usually, the main innovations come from the optimisation of the welding arc. The process chosen for this study is the Interpulse TIG (IPTIG) developed by Vaccum Brazing Company (VBC), UK. The InterPulse operates at 20,000Hz and produces a magnetically constricted columnar profile arc, like that of a plasma arc. This constriction of the arc reduces the weld pool cross sectional area thus reducing the overall heat input. This enables the InterPulse to successfully salvage-weld unweldable and costly superalloy precision gas turbine casting components. The constriction of the arc produces narrow weld beads along with a narrow heat affected zone which in turn reduces dramatically if not eliminating micro-fissuring.[5][6].

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Based on the literature survey, it is observed that there is no research work has published to understand the relation between Interpulse TIG welding process parameters and weld bead profile of Inconel. It is also understood that most of the researchers have considered main current,arc frequency, and welding speed as the input welding parameters but there is no research work has been conducted involving delta current one of the important input welding parameter for weld bead profile study. Hence this research is paying attention on the optimization of important IPTIG welding parameters namely main current,

Table 1 Chemical Composition (wt%) of Base Materials Nickel Super alloy (Su-718)

Ni	Cr	Fe	Co	Mo	Nb	Ti	Al	C	Mn	Si	B	Cu	S
Bal	17.704	21.835	0.041	2.994	4.964	0.932	0.444	0.043	0.017	0.06	0.003	0.001	0.004

2. Experimental Procedure

Nickel base Super alloy Su718 sheets (100mm x 100mm x 1.2mm) in the specified dimension were prepared for conducting bead on plate welding experiments. The chemical composition of the base materials are presented in Table 1. Based on preliminary trails, the independent IPTIG welding process parameters affecting the Fusion zone characteristics were identified they are: main current (P), delta current (D), delta frequency (F), and welding speed (S). The upper limit of the each process parameter was coded as +2 and lower limits as -2. The intermediate coded values were calculated from the following relationship.

$$X_i=2[2X-(X_{max}+X_{min})]/(X_{max}-X_{min})] \text{-------->}(1)$$

Where X_i is the required coded value of variable X; X is any value of the variable from X_{min} to X_{max}; X_{min} is the lower limit of the variable and X_{max} is the upper limit variable. The selected process parameters with limits are presented in Table 2.

Table 2 Interpulse TIG welding parameters and their Levels

No.	Parameter	Notations	Unit	-2	-1	0	+1	+2
1.	Main Current	P	Amp	10	15	20	25	30
2.	Delta Current	D	Amp	5	10	15	20	25
3.	Delta Frequency	F	kHz	5	10	15	20	25
4.	Welding Speed	S	mm/min	50	55	60	65	70

2.1 Finding the working limits of the parameters

A large number of trial runs were carried out using 1.2mm of Nickel Superalloy Su718 to find out the feasible working limits of IPTIG welding parameters. Different combinations of IPTIG welding parameters were used to carry-out the trial runs. The weld penetration, bead appearance and weld quality were inspected to identify the working limits of the welding parameters, leading to the following observations:

1. When the main current was less than 10 A, incomplete penetration and lack of fusion were observed. At the same time, when the main current was greater than 30 A, undercut was observed on the weld bead surface.
2. When the delta current was less than 5 A, less constriction of arc was observed. At the same time, when the delta current was greater than 25 A, over melting of base metal was noticed.
3. When the delta frequency was 0 kHz, bead appearance and bead contours appear to be similar to that of constant current weld beads. Further,

when the delta frequency was greater than 25 kHz, more arc glare had experienced.

The selected design matrix is shown in Table 3. It is a four-factor, five-level central composite rotatable design matrix (CCD) consisting of 30 sets of coded conditions and composed of 16 factorial points, 8 star points and 6 center points, thus 30 experimental runs allowed the estimation of the linear, quadratic and two way interactive effects of the process parameters on bead geometries. All the experiments were conducted as per the conditions dictated by the design matrix with the IE 175i Interpulse TIG welding machine.

Table 3 Design Matrix and Experimental Result

Expt. No.	P	D	F	S	P	D	F	S	DEPTH OF PENETRATION (mm)	WIDTH OF BEAD (mm)	FUSION ZONE AREA (mm^2)
1	-1	-1	-1	-1	15	10	10	55	0.051	0.0625	0.075
2	+1	-1	-1	-1	25	10	10	55	0.789	0.955	1.146
3	-1	+1	-1	-1	15	20	10	55	0.457	0.72	0.864
4	+1	+1	-1	-1	25	20	10	55	1.2	1.975	2.37
5	-1	-1	+1	-1	15	10	20	55	0.599	0.906	1.088
6	+1	-1	+1	-1	25	10	20	55	0.669	0.733	0.88
7	-1	+1	+1	-1	15	20	20	55	0.855	1.1603	1.393
8	+1	+1	+1	-1	25	20	20	55	0.909	1.262	1.515
9	-1	-1	-1	+1	15	10	10	65	0.26	0.0725	0.087
10	+1	-1	-1	+1	25	10	10	65	0.673	0.719	0.863
11	-1	+1	-1	+1	15	20	10	65	0.753	0.838	1.006
12	+1	+1	-1	+1	25	20	10	65	1.2	1.776	2.132
13	-1	-1	+1	+1	15	10	20	65	0.538	0.53	0.637
14	+1	-1	+1	+1	25	10	20	65	0.276	0.0858	0.103
15	-1	+1	+1	+1	15	20	20	65	0.868	0.822	0.987
16	+1	+1	+1	+1	25	20	20	65	0.599	0.63	0.757
17	-2	0	0	0	10	15	15	60	0.334	0.189	0.227
18	+2	0	0	0	30	15	15	60	0.818	0.975	1.17
19	0	-2	0	0	20	5	15	60	0.479	0.558	0.67
20	0	+2	0	0	20	25	15	60	1.2	1.797	2.157
21	0	0	-2	0	20	15	5	60	0.45	0.81	0.973
22	0	0	+2	0	20	15	25	60	0.445	0.622	0.747
23	0	0	0	0	20	15	15	50	0.846	1.182	1.423
24	0	0	0	-2	20	15	15	70	0.746	0.533	0.64
25	0	0	0	+2	20	15	15	60	0.455	0.505	0.607
26	0	0	0	+2	20	15	15	60	0.441	0.471	0.566
27	0	0	0	+2	20	15	15	60	0.443	0.471	0.566
28	0	0	0	+2	20	15	15	60	0.441	0.476	0.572
29	0	0	0	+2	20	15	15	60	0.439	0.465	0.558
30	0	0	0	+2	20	15	15	60	0.441	0.471	0.566

3. Development of Empirical Relationship

The bead geometry (depth of penetration, width of bead and fusion zone area) is a function of IPTIG welding parameters such as main current (P), delta current (D), delta frequency (F) and welding speed (S) and hence, it can be expressed as

$$Y=f(P, D, F, S) \quad (2)$$

For the four selected factors and their interaction factors, the selected polynomial could be expressed as

$$Y=b_0+b_1P+b_2D+b_3F+b_4S+b_{11}P^2+b_{22}D^2+b_{33}F^2+b_{44}S^2+b_{12}PD+b_{13}PF+b_{14}PS+b_{23}DS+b_{23}DS+b_{24}FS \quad (3)$$

Where b_0 is the average of response and $b_{1,}$ $b_2 \ldots$ $b_{4,}$ $b_{11,}$ $b_{13 \ldots}$ b_{34} are the coefficients that depend on the respective main and interaction effects of parameters. DESIGN EXPERT 9.1 software was used to calculate the values of these coefficients and presented in table 4.

Table 4 Co-efficient and its Estimated Factors

Coefficient	Depth of Penetration	Width of Bead	Fusion Zone Area
Intercept	0.44	0.48	0.57
P	0.12	0.19	0.22
D	0.18	0.32	0.37
F	-0.003	-0.057	-0.068
S	-0.023	-0.15	-0.180
PD	0.001	0.074	0.088
PF	-0.17	-0.28	-0.333
PS	-0.079	-0.070	-0.084
DF	-0.043	0.12	-0.141
DS	0.0225	-0.012	0.014
FS	-0.071	-0.11	-0.126
P^2	0.033	0.025	0.030
D^2	0.099	0.17	0.209
F^2	0.0016	0.059	0.070
S^2	0.088	0.094	0.113

After determining the coefficients, the empirical relationship to predict Fusion Zone characteristics was developed. The developed empirical relationship in the coded form, is given below

Depth of Penetration= (5.916+0.23P) - (0.111D) + (0.331F) - (0.337S) + (0.00004PD) - (0.0068PF) - (0.0031PS) - (0.0017DF) + (0.0009DS) - (0.0028FS) + (0.0013P2) + (0.0039D2) + (0.00006F2) + (0.0035S2) mm

Width of Bead= (6.59+0.28P) - (0.16D) + (0.46F) - (0.37S) + (0.002PD) - (0.001PF) - (0.002PS) - (0.004DF) + (0.0004DS) - (0.004FS) + (0.001P2) + (0.006D2) + (0.002F2) + (0.0037S2) mm

Fusion Zone Area = 7.96 + (0.346P) - (0.197D) + (0.556F) - (0.446S) + (0.003PD) - (0.013PF) -(0.003PS) - (0.005DF) + (0.0005DS) - (0.005FS) + (0.0012P2) + (0.008D2) + (0.0028F2) + (0.004S2) mm2

The adequacy of the developed empirical relationship was tested using the analysis of variance (ANOVA) technique with the help of DESIGN EXPERT 9.1 software. The result of the ANOVA are given in Table 5.

The Model F-value of 963.60 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case P, D, F, S, PD, PF, PS, DF, DS, FS, P2, D2, F2, S2 are significant model terms. Values greater than 0.10 indicate the model terms are not significant. the lack of fit F-value 2.72 implies that the lack of fit is not significant relative to the pure error. Non-significant lack of fit is good. The co-efficient of determination R2 values gives the goodness of fitness of the model. For a good model, R2 value is 0.99. this implies that 99% of the experimental data confirms the compatibility with the data predicted by the developed model. The value of the adjusted R2 0.9979 is also high and indicates the high significance of the model. The predicted R2 value is 0.9943, which shows reasonable agreement with the adjusted R2 of 0.98. adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. This model can be used to navigate the design space. The observed values and predicted values of the response are close to each other, which indicate an almost perfect fit of the developed empirical relationship (Table 6) .

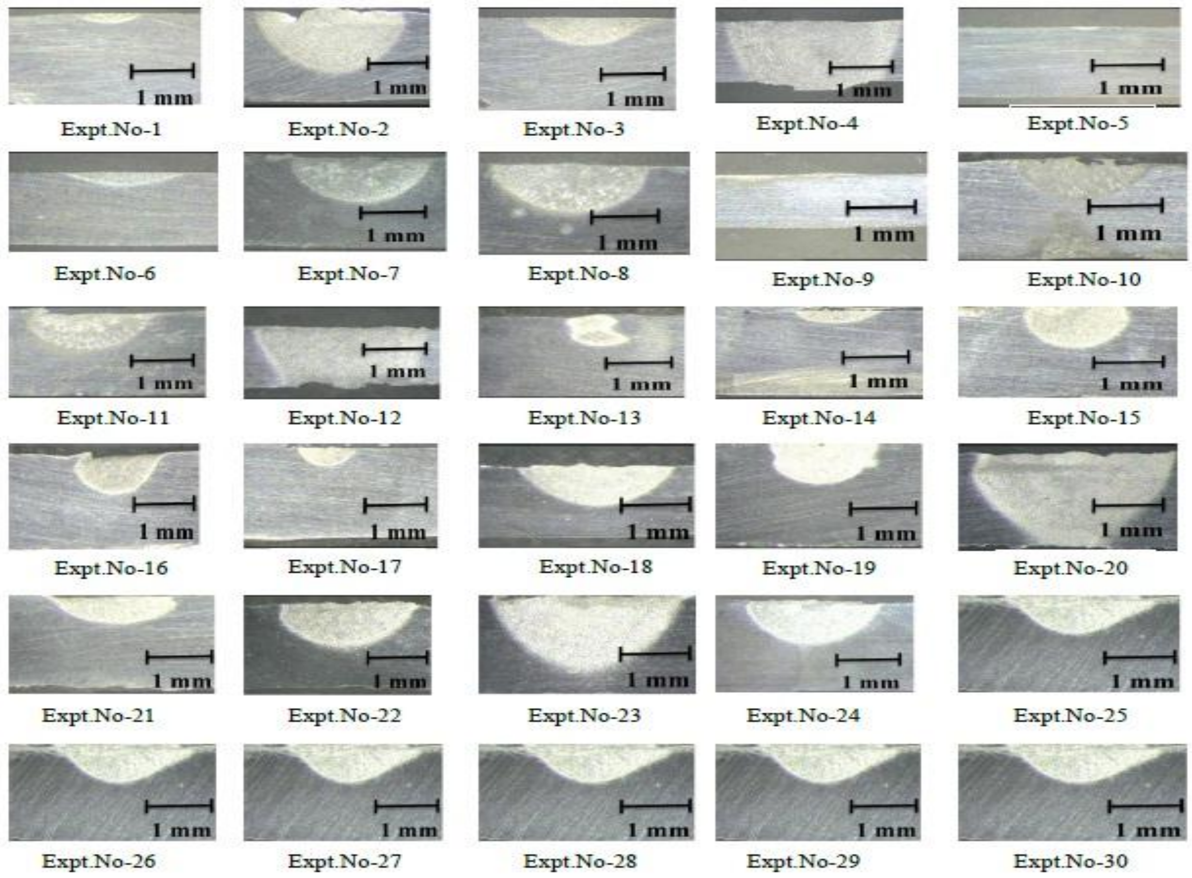

Figure. 1Cross sectional macrographs of IPTIG welded nickel base super alloy

Table 5 ANOVA Test Results for Bead geometries

Source	F Value (DOP)	F Value (WOB)	F Value (FZA))	
Model	2249.12	987.506	963.601	Significant
P	4761.91	1818.38	1772.9	
D	11086.7	4967.88	4847.17	
F	3.61882	160.336	155.822	
S	178.591	1114.48	1090.35	
PD	0.21713	180.031	176.056	
PF	6404.89	2544.42	2483	
PS	1380.95	164.234	160.059	
DF	401.472	456.528	445.398	
DS	109.922	5.05607	4.99438	
FS	1102.27	367.192	358.538	
P^2	425.031	36.8133	35.3303	
D^2	3697.44	1722.53	1677.61	
F^2	1.03395	197.156	191.901	
S^2	2934.58	504.512	495.128	
Lack of Fit	2.72568	3.00647	3.00974	not significant

ANOVA test results clearly shows that Delta current is the most significant factor compared to other factor. Delta current plays major role in fusion zone area because the weld arc is constricted by the magnetic field around the arc only by delta current. This delta current generates high frequency pulse, to alter the magnetic field of the arc, thus enabling the control of the constriction of the arc leads to deeper penetration as well as minimum fusion area for thin sheet welding.

4. Evaluating the Interaction Effect of Factors on Response

The perturbation plot helps to compare the effect of all the factors at a particular point in the design space. The steep slope or curvature in a factor shows that the response is sensitive to that factor. A relatively flat lines shows insensitivity to change in that particular factor. The fig.2 shows the perturbation graph for minimum fusion zone area and its interaction effect with process factors. The perturbation plots of the responses are presented with the purpose of understanding the main and interaction effects of each factor, considering the full quadratic model. The minimum fusion zone area has been plotted as a function of the normalized independent variables.

It has been demonstrated that the delta current has the most significant effect on the fusion zone area. However, the effects of the main current, welding speed and delta frequency were also found to be significant

Table-6 Validation Test Results

Expt No	Main Current (A)	Delta Current (A)	Delta Frequency (kHz)	Welding Speed (mm/min)	Depth of Penetration (mm)		Error (%)	Width of Bead (mm)		Error (%)	Fusion Zone Area (mm^2)		Error (%)
					Actual	Predicted		Actual	Predicted		Actual	Predicted	
1	24	20	10	60	1.05	1.03	1.94	2.2	2.125	3.52	1.97	1.981	-0.55
2	26	21	11	60	1.2	1.214	-1.15	2.25	2.299	-2.13	2.355	2.331	1.02
3	28	18	10	60	1.2	1.199	0.083	2.32	2.362	-1.77	2.333	2.306	1.17

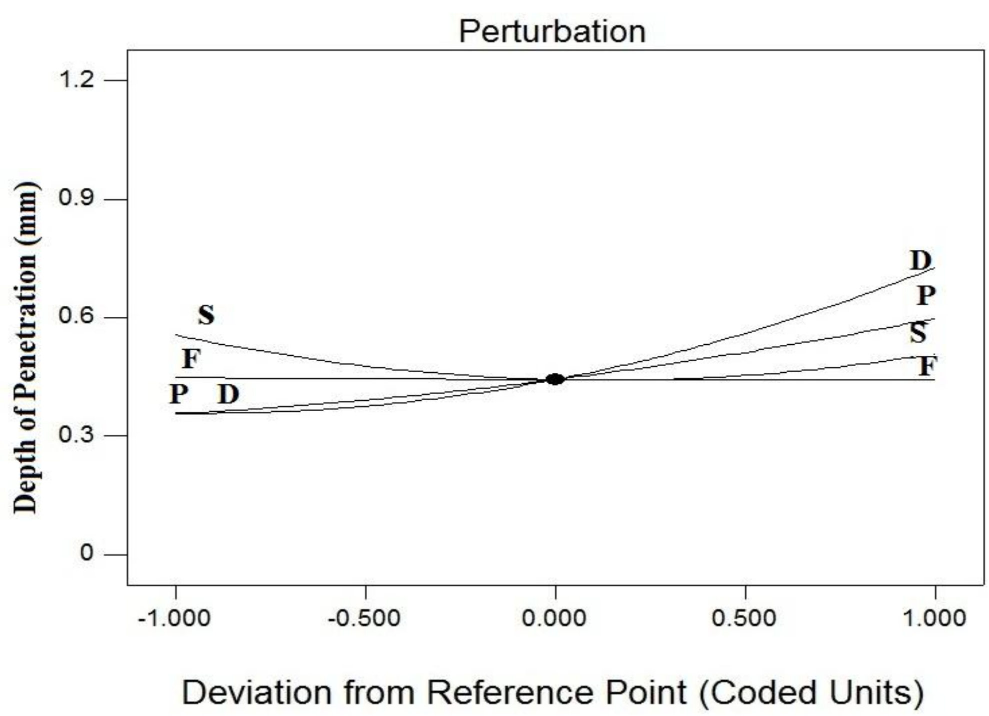

Fig.2 Perturbation Graph of IPTIG welded nickel base super alloy

5. Conclusions

- Empirical relationships were developed to estimate the bead geometries such as depth of penetration, width of weld bead and fusion zone area in nickel base super alloys incorporating important IPTIG welding parameters. These relationships can be effectively used to estimate bead geometries at 95% confidence level.

- Full penetration (1.2 mm) was achieved under three different combinations of IPTIG welding parameters. However, full penetration with minimum weld width and fusion zone area was achieved while using a main current 25A, delta current of 20A, delta frequency of 10kHz and welding speed of 55 mm/min.
- Of the four process parameters investigated, the delta current was found to have the greatest influence on Fusion zone area, followed by main current, welding speed and delta frequency (as per the F ratio).

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