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ORIGINAL ARTICLE

Application of grey relational analysis for optimizing weld bead geometry parameters of pulsed current micro plasma arc welded inconel 625 sheets

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Abstract Pulsed current micro plasma arc welding (MPAW) is one of the most widely used welding processes in sheet metal manufacturing industry. In any fusion arc welding process, the weld bead geometry plays an important role in determining the mechanical properties of the weld and hence quality of the weld. Moreover, the geometry of weld bead involves several simultaneously multiple quality characteristics such as front width, back width, front height and back height, which must be closely monitored, controlled and optimised. This paper presents the optimization of the pulsed current MPAW process by using the grey relational analysis considering the aforementioned quality characteristics. The specific targets are maximum front width and back width, minimum front height and back height. Experiments were performed under different welding conditions such as peak current, base current, pulse frequency and pulse width using Inconel 625 sheets of 0.25 mm thick. A response surface method (RSM)-based central composite design (CCD) experimental design is used to conduct experiments. Optimal welding parameters were determined by the grey relational grade obtained from the grey relational analysis. Optimal results have been verified through confirmation experiments.

Keywords Pulsed current · Micro plasma arc welding · Inconel 625 · Weld bead geometry · Grey relational analysis

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1 Introduction

The plasma welding process was introduced to the welding industry in 1964 as a method of bringing better control to the arc welding process in lower current ranges [1]. Today, plasma retains the original advantages it brought to the industry by providing an advanced level of control and accuracy to produce high quality welds in both miniature and pre-precision applications and to provide long electrode life for high production requirements at all levels of amperage. Plasma welding is equally suited to manual and automatic applications. It is used in a variety of joining operations ranging from welding of miniature components to seam welding to high volume production welding and many others.

Pulsed current MPAW involves cycling the welding current at selected regular frequency. The peak current is selected to give adequate penetration and bead contour, while the base current is set at a level sufficient to maintain a stable arc [2, 3]. This permits arc energy to be used effectively to fuse a spot of controlled dimensions in a short time producing the weld as a series of overlapping nuggets. In pulsed duty cycle current welding, the heat required to melt the base material is supplied only during the peak current pulses allowing the heat to dissipate into the base material leading to narrower heat-affected zone (HAZ). Advantages include improved bead contours, greater tolerance to heat sink variations, lower heat input requirements, reduced residual stresses and distortion, refinement of fusion zone microstructure and reduced width of HAZ.

In MPAW process, peak current, base current, pulse frequency and pulse width are the most dominant parameters which affect the weld quality characteristics like weld bead geometry, microstructure, grain size, hardness and tensile properties. From the literature on PAW, it is understood that most of the works reported on materials having higher thickness (greater than 1 mm). Very few works are reported on MPAW of thin sheets. The present work is related to welding of metal bellows of wall thickness 0.25 mm. Hence, the present work employed MPAW process, which is more economical when compared to laser beam welding and electron beam welding.

Regarding optimization of weld bead geometry parameters namely front width, back width, front height and back height, one need to use a multi-objective optimization technique, since all the above parameters are related to a specific input parameter combination. Several researchers used various multiobjective techniques like grey relational analysis, principal component analysis, genetic algorithm, simulated annealing algorithm and so on to optimise the parameters. However, the optimization techniques like Genetic Algorithm and Simulated Annealing Algorithm are population-based techniques, which require a proper function and more data, where as grey relational analysis and principal component analysis can be applied to little data without any function.

Saurav Datta et.al [4] used Taguchi approach followed by grey relational analysis to solve multi-response optimization problem. Voltage, traverse speed, stick out, wire feed rate and creed feed were chosen as input parameters, and weld penetration, weld width, weld reinforcement and depth of HAZ are chosen as output parameters. Ugur Esme et.al [5] investigated multi-response optimization of TIG welding process for an optimal parametric combination to yield favourable bead geometry of weld joints using grey relational analysis and Taguchi method. Y.F. Hsiao et.al [6] studied the optimal parameters process of plasma arc welding by the Taguchi method with grey relational analysis. Torch standoff, welding current, welding speed and plasma gas flow rate (Argon) were chosen as input variables, and welding groove root penetration, welding groove width and front-side undercut were measured as output parameters. Hakan Aydin et al. [7] studied optimization of friction stir welding process for an optimal parametric combination to yield favourable tensile strength and elongation using the Taguchi-based grey relational analysis.

Table 1 Chemical composition of Inconel 625 sheets (weight %)

C	Mn	P	S	Si	Cr	Ni	Al
0.0300	0.0800	0.0050	0.0004	0.1200	20.8900	61.6000	0.1700
Mo	Cb	Ta	Ti	N	Co	Fe	
8.4900	3.4400	0.0050	0.1800	0.0100	0.1300	4.6700	

Table 2 Important factors and their levels

Levels			1	2	3	4	5
Reference number	Input factor	Units	−2	−1	0	+1	+2
A	Peak current	A	6	6.5	7	7.5	8
B	Base current	A	3	3.5	4	4.5	5
C	Pulse frequency	Hz	20	30	40	50	60
D	Pulse width	%	30	40	50	60	70

In the present study, it is intended to determine the optimal process condition in pulsed current MPAW process to yield desired weld quality in terms of weld bead geometry. Grey relational analysis approach for process optimization has been carried out to solve this multi-response optimization problem.

2 Experimental setup

2.1 Materials and methodology

Inconel 625 sheets of 100×150×0.25 mm are welded autogenously with square butt joint without edge preparation. The chemical composition of Inconel 625 sheet is given in Table 1. High purity argon gas (99.99 %) is used as a shielding gas and a trailing gas right after welding to prevent absorption of oxygen and nitrogen from the atmosphere. From the literature, four important factors of pulsed current MPAW as presented in Table 2 are chosen. The welding has been carried out under the welding conditions presented in Table 3. A large number of trail experiments are carried out using 0.25-mm-thick

Table 3 Welding conditions

Power source	Secheron micro plasma arc machine
Model number	PLASMAFIX 50E
Polarity	DCEN
Mode of operation	Pulse mode
Electrode	2 % thoriated tungsten electrode
Electrode diameter	1 mm
Plasma gas	Argon and Hydrogen
Plasma gas flow rate	6L/m
Shielding gas	Argon
Shielding gas flow rate	0.4 L/m
Purging gas	Argon
Purging gas flow rate	0.4 L/m
Copper nozzle diameter	1 mm
Nozzle to plate distance	1 mm
Welding speed	260 mm/min
Torch position	Vertical
Operation type	Automatic

Inconel 625 sheets to find out the feasible working limits of pulsed current MPAW process parameters. The following observations are made while conducting trail experiments.

a. For peak current below 6 A incomplete fusion was noticed and for peak current above 8 A undercut and spatter are observed.
b. For back current below 3.5 A shorter arc length was noticed and for back current above 5 A unstable arc wandering was observed.
c. For pulse frequency below 20 H_z thinner weld bead width was noticed and for pulse frequency above 60 arc spatter was observed.
d. For Pulse width below 30 % weld nugget formation was noticed and for pulse width above 70 % over melting of base metal and overheating of tungsten electrode was observed.

Experiments are conduced response surface method (RSM) based on four factors, five levels and rotatable central composite design (CCD) matrix. Table 4 indicates the 31 sets of coded conditions used to form the design matrix. Central composite designs (CCDs), also known as Box-Wilson designs, are appropriate for calibrating the full quadratic models described in Response Surface Models. There are three types of CCDs, namely, circumscribed, inscribed and faced. The geometry of CCDs is shown in Fig. 1. Each design consists of a factorial design (the corners of a cube) together with centre and star points that allow the estimation of second-order

Table 4 Design matrix and experimental results

Serial no	Peak current (A)	Base current (A)	Pulse frequency (H_Z)	Pulse width (%)	Front width (mm)	Back width (mm)	Front height (mm)	Back height (mm)
1	6.5	3.5	30	40	1.218	1.144	0.0489	0.0488
2	7.5	3.5	30	40	1.363	1.292	0.0468	0.0368
3	6.5	4.5	30	40	1.153	1.093	0.0510	0.0400
4	7.5	4.5	30	40	1.273	1.214	0.0449	0.0349
5	6.5	3.5	50	40	1.223	1.170	0.0461	0.0363
6	7.5	3.5	50	40	1.253	1.188	0.0475	0.0376
7	6.5	4.5	50	40	1.238	1.147	0.0479	0.0378
8	7.5	4.5	50	40	1.231	1.171	0.0458	0.0358
9	6.5	3.5	30	60	1.298	1.220	0.0479	0.0380
10	7.5	3.5	30	60	1.360	1.277	0.0451	0.0351
11	6.5	4.5	30	60	1.291	1.216	0.0452	0.0351
12	7.5	4.5	30	60	1.331	1.275	0.0432	0.0333
13	6.5	3.5	50	60	1.214	1.141	0.0485	0.0374
14	7.5	3.5	50	60	1.153	1.075	0.0470	0.0366
15	6.5	4.5	50	60	1.275	1.202	0.0480	0.0380
16	7.5	4.5	50	60	1.192	1.125	0.0464	0.0374
17	6	4	40	50	1.290	1.220	0.0478	0.0378
18	8	4	40	50	1.351	1.283	0.0449	0.0349
19	7	3	40	50	1.221	1.151	0.0455	0.0355
20	7	5	40	50	1.196	1.127	0.0444	0.0344
21	7	4	20	50	1.365	1.296	0.0462	0.0363
22	7	4	60	50	1.235	1.166	0.0444	0.0344
23	7	4	40	30	1.169	1.106	0.0516	0.0426
24	7	4	40	70	1.230	1.153	0.0482	0.0382
25	7	4	40	50	1.300	1.231	0.0486	0.0386
26	7	4	40	50	1.350	1.281	0.0477	0.0377
27	7	4	40	50	1.292	1.221	0.0487	0.0387
28	7	4	40	50	1.288	1.219	0.0486	0.0386
29	7	4	40	50	1.273	1.201	0.0487	0.0387
30	7	4	40	50	1.270	1.202	0.0456	0.0356
31	7	4	40	50	1.170	1.101	0.0476	0.0375

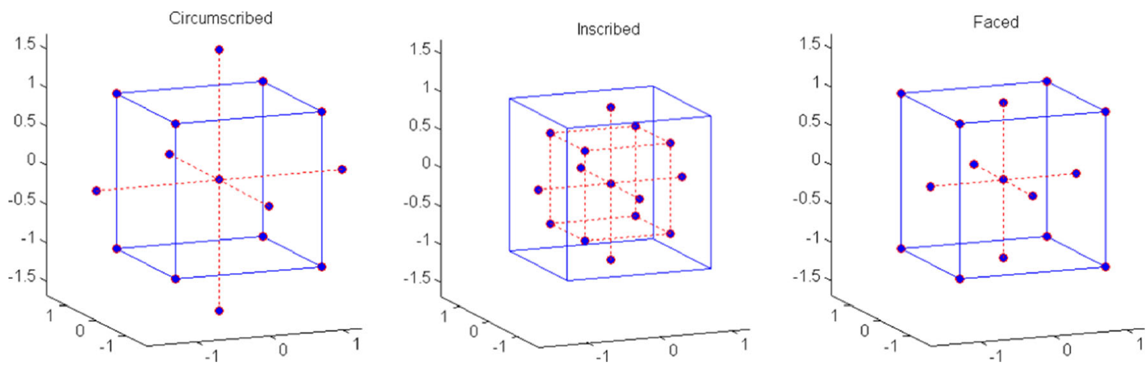

Fig. 1 Circumscribed, inscribed and faced designs

effects. For a full quadratic model with n factors, CCDs have enough design points to estimate the $(n+2)$ $(n+1)/2$ coefficients in a full quadratic model with n factors. The type of CCD used (the position of the factorial and star points) is determined by the number of factors and by the desired properties of the design. A design is rotatable if the prediction variance depends only on the distance of the design point from the centre of the design [8, 9].

2.2 Measurement of weld bead geometry

Three metallurgical samples were cut from each joint, with the first sample being located at 25 mm behind the trailing edge of the crater at the end of the weld and mounted using Bakelite. Sample preparation and mounting were done as per ASTM E 3–1 standard. The transverse face of the samples was surface grounded using 120 grit size belt with the help of belt grinder, polished using grade 1/0 (245 mesh size), grade 2/0 (425 mesh size) and grade 3/0 (515 mesh size) sand paper. The specimens were further polished by using aluminium oxide initially and the by utilising diamond paste and velvet cloth in a polishing machine. The polished specimens were macro-etched by using Aqua regia solution to reveal the geometry of the weld bead (Fig. 2) [10] . Several critical parameters, such as front width, back width, front height and back height of the weld bead geometry (Fig. 3), are measured. The weld bead geometry was measured using Metallurgical Microscope (Make: Dewinter Technologie, Model No. DMI-CROWN-II) at ×100 magnification.

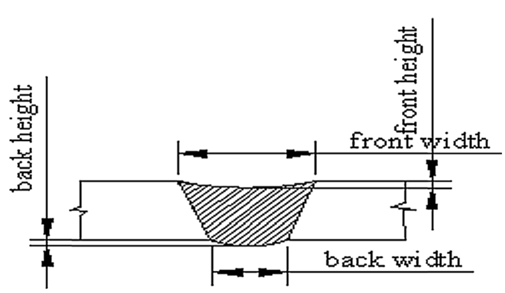

Fig. 2 Typical weld bead geometry

3 Grey relational analysis

The grey system theory was proposed by Deng [11]. The grey means the primitive data with poor, incomplete and uncertain information in the grey systematic theory. The incomplete relation of information among these data is called the grey relation. Grey relational analysis can effectively be recommended as a method for optimising the complicated interrelationships among multiple performance characteristics [12]. Through the grey relational analysis, a grey relational grade is obtained to evaluate the multiple performance characteristics. As a result, optimization of the complicated multiple performance characteristics can be converted into the optimization of a single grey relational grade.

In grey relational analysis, experimental data, i.e., measured features of quality characteristics are first normalised ranging from zero to one. The process is known as grey relational generation. Next, based on normalised experimental data, grey relational coefficient is calculated to represent the correlation between the desired and actual experimental data. Then, overall grey relational grade is determined by averaging the grey relational coefficient corresponding to selected responses. The overall performance characteristic of the multiple response process depends on the calculated grey relational grade. This approach converts a multiple response process optimization problem into a single response optimization

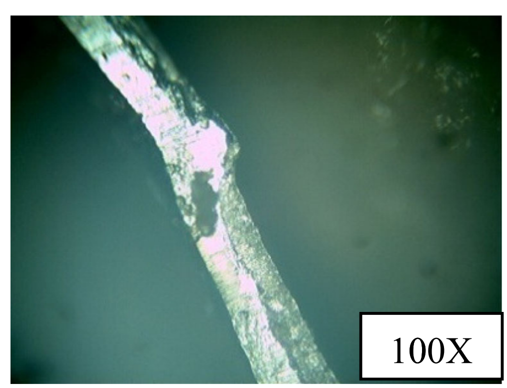

Fig. 3 Macrographs of weld

situation with the objective function is overall grey relational grade. The optimal parametric combination is then evaluated which would result into highest grey relational grade.

The steps followed in the optimization process are:

i. Normalising the experimental responses for all the trials.

The normalised expression (1) corresponding to smaller-the-better criteria is:

$$y_i(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (1)$$

where k=1 to n; i=1 to 31, n is the performance characteristic and i is the trial number.

The normalised expression corresponding to larger-the-better criteria is:

$$y_i(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)}$$
$$y_i(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (2)$$

where $y_i(k)$ is the value after grey relational generation, min $x_i(k)$ is the smallest value of $x_i(k)$ for k^{th} response and max $x_i(k)$ is the largest value of $x_i(k)$ for the k^{th} response

ii. Performing the grey relational generating and to calculate the grey relational coefficient (γ).

Table 5 Grey relational generation and Δ_{0i} of each performance characteristics

Serial no	Normalised				Deviation sequence (Δ_{0i})			
	Front width	Back width	Front height	Back height	Front width	Back width	Front height	Back height
1	0.306604	0.312217	0.321429	0	0.693396	0.687783	0.678571	1
2	0.990566	0.9819	0.571429	0.774194	0.009434	0.0181	0.428571	0.225806
3	0	0.081448	0.071429	0.567742	1	0.918552	0.928571	0.432258
4	0.566038	0.628959	0.797619	0.896774	0.433962	0.371041	0.202381	0.103226
5	0.330189	0.429864	0.654762	0.806452	0.669811	0.570136	0.345238	0.193548
6	0.471698	0.511312	0.488095	0.722581	0.528302	0.488688	0.511905	0.277419
7	0.400943	0.325792	0.440476	0.709677	0.599057	0.674208	0.559524	0.290323
8	0.367925	0.434389	0.690476	0.83871	0.632075	0.565611	0.309524	0.16129
9	0.683962	0.656109	0.440476	0.696774	0.316038	0.343891	0.559524	0.303226
10	0.976415	0.914027	0.77381	0.883871	0.023585	0.085973	0.22619	0.116129
11	0.650943	0.638009	0.761905	0.883871	0.349057	0.361991	0.238095	0.116129
12	0.839623	0.904977	1	1	0.160377	0.095023	0	0
13	0.287736	0.298643	0.369048	0.735484	0.712264	0.701357	0.630952	0.264516
14	0	0	0.547619	0.787097	1	1	0.452381	0.212903
15	0.575472	0.574661	0.428571	0.696774	0.424528	0.425339	0.571429	0.303226
16	0.183962	0.226244	0.619048	0.735484	0.816038	0.773756	0.380952	0.264516
17	0.646226	0.656109	0.452381	0.709677	0.353774	0.343891	0.547619	0.290323
18	0.933962	0.941176	0.797619	0.896774	0.066038	0.058824	0.202381	0.103226
19	0.320755	0.343891	0.72619	0.858065	0.679245	0.656109	0.27381	0.141935
20	0.20283	0.235294	0.857143	0.929032	0.79717	0.764706	0.142857	0.070968
21	1	1	0.642857	0.806452	0	0	0.357143	0.193548
22	0.386792	0.411765	0.857143	0.929032	0.613208	0.588235	0.142857	0.070968
23	0.075472	0.140271	0	0.4	0.924528	0.859729	1	0.6
24	0.363208	0.352941	0.404762	0.683871	0.636792	0.647059	0.595238	0.316129
25	0.693396	0.705882	0.357143	0.658065	0.306604	0.294118	0.642857	0.341935
26	0.929245	0.932127	0.464286	0.716129	0.070755	0.067873	0.535714	0.283871
27	0.65566	0.660633	0.345238	0.651613	0.34434	0.339367	0.654762	0.348387
28	0.636792	0.651584	0.357143	0.658065	0.363208	0.348416	0.642857	0.341935
29	0.566038	0.570136	0.345238	0.651613	0.433962	0.429864	0.654762	0.348387
30	0.551887	0.574661	0.714286	0.851613	0.448113	0.425339	0.285714	0.148387
31	0.080189	0.117647	0.47619	0.729032	0.919811	0.882353	0.52381	0.270968

Table 6 Grey relational coefficient and grey relational grade of each performance characteristics (ζ=0.5)

Serial no	Grey relation coefficient				Grey relation grade
	Front width	Back width	Front height	Back height	
1	0.418972	0.420952	0.424242	0.333333	0.399375
2	0.981481	0.965066	0.538462	0.688889	0.793474
3	0.333333	0.352472	0.35	0.536332	0.393034
4	0.535354	0.574026	0.711864	0.828877	0.66253
5	0.427419	0.46723	0.591549	0.72093	0.551782
6	0.486239	0.505721	0.494118	0.643154	0.532308
7	0.454936	0.425819	0.47191	0.632653	0.496329
8	0.441667	0.469214	0.617647	0.756098	0.571156
9	0.612717	0.592493	0.47191	0.62249	0.574903
10	0.954955	0.853282	0.688525	0.811518	0.82707
11	0.588889	0.580052	0.677419	0.811518	0.66447
12	0.757143	0.840304	1	1	0.899362
13	0.412451	0.416196	0.442105	0.654008	0.48119
14	0.333333	0.333333	0.525	0.701357	0.473256
15	0.540816	0.540342	0.466667	0.62249	0.542579
16	0.379928	0.39254	0.567568	0.654008	0.498511
17	0.585635	0.592493	0.477273	0.632653	0.572014
18	0.883333	0.894737	0.711864	0.828877	0.829703
19	0.424	0.432485	0.646154	0.778894	0.570383
20	0.385455	0.395349	0.777778	0.875706	0.608572
21	1	1	0.583333	0.72093	0.826066
22	0.449153	0.459459	0.777778	0.875706	0.640524
23	0.350993	0.36772	0.333333	0.454545	0.376648
24	0.439834	0.435897	0.456522	0.612648	0.486225
25	0.619883	0.62963	0.4375	0.59387	0.570221
26	0.876033	0.880478	0.482759	0.63786	0.719282
27	0.592179	0.595687	0.43299	0.589354	0.552552
28	0.579235	0.589333	0.4375	0.59387	0.549985
29	0.535354	0.537713	0.43299	0.589354	0.523852
30	0.527363	0.540342	0.636364	0.771144	0.618803
31	0.352159	0.361702	0.488372	0.648536	0.462692

$$\gamma(y_0(k), y_i(k)) = \frac{\Delta_{\min} + \zeta.\Delta_{\max}}{\Delta_{oi}(k) + \zeta.\Delta_{\max}} \quad (3)$$

where

a. Δ (k)=Py (k)-y (k) P is the absolute value of the difference between y (k) and y (k)
b. Δ=min min Δ (k)
c. Δ=max max Δ (k)
d. ζ (∈0,1)=distinguishing coefficient

iii. Calculating the grey relational grade by averaging the grey relational coefficient.

$$\xi_i = \frac{1}{n}\sum_{k=1}^{n} \gamma_i(k) \quad (4)$$

iv. Performing statistical analysis of variance (ANOVA) for the input parameters with the grey relational grade and to find which parameter significantly affects the process.
v. Selecting the optimal levels of process parameters.
vi. Conduct confirmation experiment and verify the optimal process parameters setting.

4 Analysis of weld data

The specific targets in the present paper are maximum front width and back width, minimum front height and back height. Therefore, for data preprocessing in the grey relational analysis process, front height and back height were taken as the

Table 7 Response table (mean) for overall grey relational grade

Level/ Factor	A (Peak current)	B (Base current)	C (Pulse frequency)	D (Pulse width)
1	0.5720	0.5704	*0.8261*	0.3766
2	0.5130	0.5792	0.6518	0.5500
3	0.5828	*0.6146*	0.5735	*0.6598*
4	0.6572	0.5910	0.5184	0.6202
5	*0.8297*	0.6086	0.6405	0.4862
Delta	0.3167	0.0442	0.3077	0.2831
Rank	1	4	2	3

Table 8 Results of confirmation tests

	Initial	Optimal testing parameters	
		Predicted	Experimental
Combination	A-1,B-1, C-1,D-1	A2,B0, C-2,D0	A2,B0, C-2,D0
Front width	1.218		1.49543
Back width	1.144		1.42798
Front height	0.0489		0.043543
Back height	0.0488		0.031258
Grey relational grade	0.399375	1.1623	0.981121

"lower is better" and front width and back width were taken as "higher is better", respectively. Initially, using Eqs. (1) and (2), experimental data have been normalised to obtain grey relational generation. The normalised data and $\Delta 0_i$ for each of the responses of bead geometry have been furnished in Table 5. The distinguishing coefficient ζ is substituted into Eq. 3 to produce the grey relational coefficient. If all the process parameters are of equal weighting, then ζ becomes 0.5. The grey relational coefficients and grade values for each experiment of the design matrix were calculated by applying the Eqs. 3 and 4 (Table 6).

To find out the optimum process parameters and their effects on selected output parameters, the mean of the grey relational grade for each level of the welding parameter is needed. Table 7 indicates mean for overall grey relational grade. The larger the value of the grey relational grade, the better is the multi-response characteristics. Therefore, the optimal level of the welding parameters is the level with the greatest grey relational grade value. The optimal welding performance for higher front width, back width and lower front height, back height was obtained for the following combination: peak current 8 A, back current 4 A, pulse frequency 20 Hz and pulse width 50 %.

Figure 4 indicates the effect of welding parameters on the multi-performance characteristics and the response graph of each level of the welding parameters for the performance. The higher values in Fig. 4 give the desired quality characteristic. Also, the maximum and minimum values of the grey relational grade show the importance of individual parameter in PCPAW process. Hence, the order of importance of the welding parameters is peak current, pulse frequency, pulse width and base current.

5 Confirmation experiments

After evaluating the optimal parameter settings, the next step is to predict and verify the enhancement of quality characteristics using the optimal parametric combination. Table 8 shows the comparison of the predicted bead geometry parameters with that of actual using the optimal MPAW welding conditions. There is a good agreement between the actual and

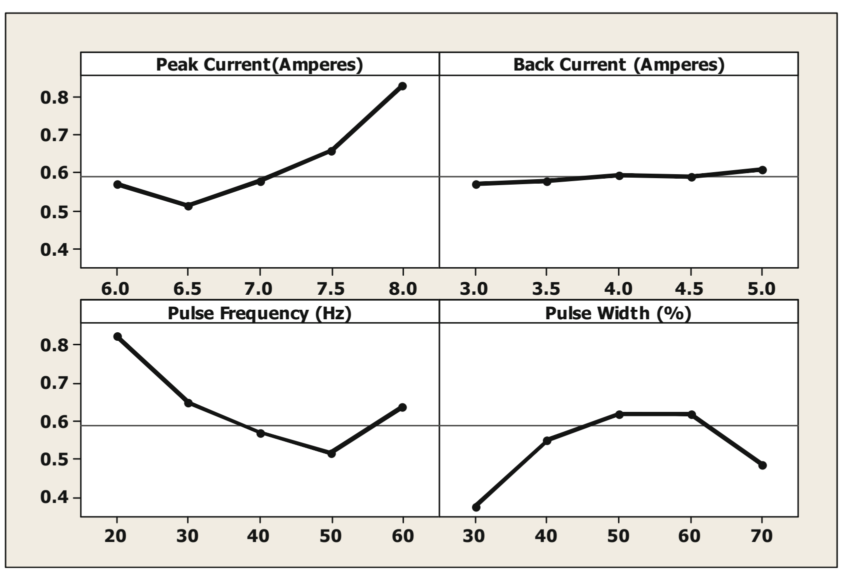

Fig. 4 Effect of welding parameters on grey relational grade

predicted results have been observed (improvement in the overall grey relational grade).

It is found that utilization of the optimal welding parameter combination enhances the grey relational grade from 0.399375 to 0.981121, i.e., grey relational grade has improved by 59.29 %.

6 Conclusions

Inconel 625 sheets of thickness 0.25 mm are successfully welded using pulsed current MPAW process without defects and weld bead geometry is measured using Metallurgical Microscope. The optimization of multi-performance characteristics of pulsed current MPAW process using grey relational analysis based on RSM-based CCD design has been investigated in the present paper. From grey relational analysis, it is observed that the optimal weld bead geometry, the welding parameters of peak current 8 A, base current 4 A, pulse frequency 20 Hz and pulse width 50 %. From grey relational analysis, it is observed that the order of importance of the welding parameters is peak current, pulse frequency, pulse width and base current. The optimum result helps the operator in obtaining desired performance measure which saves the operator's time, cost and helps in increasing the productivity.

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