Multi response Optimization of Welding Parameters in Dissimilar Plasma Arc Welded Joints Using RSM Based GRA Coupled with PCA

K Palani¹ and S Arunprasad²

¹ Department of Mechanical Engineering, Sri Chandrasekharendra Saraswathi Viswa Mahavidyalaya (Deemed to be University), Kanchipuram, 631561, Tamilnadu, India
² Department of Production Engineering, Sri Sairam Engineering College, Chennai, 600 044, Tamil Nadu, India

E-mail: palani.k@kanchiuniv.ac.in

Abstract. The quality of the joints is essential to achieve customer satisfaction and earning profit in manufacturing industries. This work investigates the multi-response optimization of the plasma arc welded (PAW) process parameters of the dissimilar Ti-3Al-2.5V titanium alloy and AA8011-H24 aluminium alloy joints using RSM based GRA coupled with PCA. The principal component analysis is incorporated into the response surface methodology based grey relational analysis to achieve the optimum responses viz., tensile strength and tensile elongation with the welding parameters, viz., welding current, torch angle, gas flow rate and welding speed of the PAW joints. The response surface and contour plots are used to study the effect of parameters of the joints. The welding speed is the most significant parameter on the composite welding quality index (CWQI) followed by welding current, gas flow rate and torch angle to decide the quality of the joints at the optimal levels.

Keywords: Titanium alloy; Aluminium alloy; Grey relational analysis; Principal component analysis; Composite welding quality index

1. Introduction

In aerospace, aviation and transportation industries, the joining of dissimilar alloys, viz., titanium alloys and aluminium alloys are focused due to its unique properties, viz., improved strength in Ti alloys and also, better corrosion resistance and high strength to weight ratio in aluminium alloys [1, 2]. It is the difficult task in joining of high and low melting materials due to their various thermal properties viz., coefficient of heat transfer coefficient and melting temperature in fabrication industries [3]. The formation of the intermetallic compounds (IMCs) are occurred in the weld interface especially in the heat-affected zone (HAZ) of the dissimilar Al and Ti alloys by the variation in melting and solidification temperatures in the welding process and these brittle IMCs deteriorates the strength properties of the dissimilar joints [4, 5]. The dissimilar alloys such as Ti alloys and Al alloys are conventionally fusion welded using the tungsten inert gas welding [6], spot welding [7], and laser welding [8] in the aviation and automobile industries. The solid-state joining processes such as friction welding [9], diffusion bonding [10], friction stir welding processes [11-14] and friction stir processing [15, 16] are used in joining of dissimilar alloys.

The formation of the weld failures, viz., porosity, improper fusion, hot cracking, and solidification shrinkage are reduced in the fabricated dissimilar welded joints using the high energy fusion welding techniques such as electron beam welding and plasma arc welding processes [17]. Lakshminarayanan et al. [18] examined that the higher tensile strength and the toughness of the FSW joints whereas 24% and 39% higher tensile strength and the toughness of the GTAW process were examined due to the appearance of fine and equiaxed grains in the weld nugget zone of thee interstitial free steels.
Mvola et al. [19] investigated that the dissimilar magnesium and aluminium alloys were successfully welded with cold metal transfer and the appearance of fractures were occurred in the magnesium alloy fusion zone (FZ) due to the formation of Al-Cu IMCs in the welded joints. Esmaily et al. [20] successfully butt welded joints on Ti-6Al-4V alloy using friction stir welding and tungsten inert gas welding processes and reported that the broader fusion zone and heat-affected zone were observed in gas tungsten arc welding compared to friction stir welding process at 650 rpm rotational speed. The multi-response optimization methods are applied to identify the effective responses of the PAW process in the dissimilar alloy materials.

Rajakumar et al. [21] examined that the optimum shear strength of 87 MPa, the microhardness of 163 HV and interface layer thickness of 7 μm for the optimum process settings of bonding temperature of 510 °C, bonding pressure of 17 MPa and holding time of 37 min using the developed mathematical models of diffusion bonded dissimilar Cp-Ti with AA7075 aluminium alloys. The hybrid optimization technique viz., response surface methodology and grey relational analysis coupled with principal component analysis were applied on the Electro discharge machining process on dissimilar alloy materials by Sahu et al. [22]. Palani et al. [23] applied the hybrid fuzzy-based response surface optimization of welding parameters on Vickers microhardness and impact strength of FSWed AA8011-H24 aluminium alloy joints. Also, they suggested that the reduction of the multiple responses into a single effective response with significant contribution of the machining process were effectively used in determining with the grey relational grade.

The various hybrid optimization techniques were applied to find the very effective parameters which were helpful to decide the quality of the welded joints. Siddiquee et al. [24] applied the hybrid grey relational analysis with principal component analysis on the centreless cylindrical grinding process. They reported that the reflection of the relative importance of the responses was found by applying grey analysis whilst the weightage of the responses is improved the quality of the grinding process by using PCA. The optimization of multiple responses of submerged arc welding parameters, viz., bead width, bead penetration and bead reinforcement successfully made using response surface methodology based fuzzy logic with trapezoidal and triangular membership functions (MF) by Sharma et al. [25]. Also, they reported that the optimized results using a trapezoidal membership function showed the better-optimized results than the triangular membership functions. In this investigation, the work has been carried out on the multi-response optimization of welding parameters in dissimilar plasma arc welded joints using RSM based GRA coupled with PCA.

2. Experimental work

In this investigation, the Ti3Al2.5V alloys and AA8011 aluminium alloys [26] (Procured from Sri Kataria Steels in Mumbai) were used with the dimensions of 150 mm x 150 mm x 6 mm for butt joint configuration using the plasma arc welding process (Model PWH/2A with the thermal arc 2A plasma welding torch) and are presented in Figure 1. The specifications of the PAW machine setup are listed in Table 1. This setup carries the PAW machine control module, the direct current power source, gas supply (Plasma gas cylinder, Shielding gas cylinders with 80% Argon gas and 20% Hydrogen gas and, Coolant supply. The shielding gas environment is provided for the fabrication of the aluminium alloys and titanium alloy joints due to the oxidation behaviour of the alloy materials.
Table 1. Specifications of the PAW Machine (Model: PWH-2A)

| Sl. No. | Specifications | Details |
|---------|---------------|---------|
| 1       | Operation type| Automatic|
| 2       | Plasma gas    | Argon gas|
| 3       | Shielding gas | 80% Ar and 20% H₂ |
| 4       | Nozzle to Plate distance | 1 mm |
| 5       | Plasma gas flow rate | 15 – 20 Lpm |
| 6       | Torch Angle   | 85° – 95° |
| 7       | Welding Speed | 25 – 50 mm/min |
| 8       | Welding Current| 90 – 120 Amp |
| 9       | Polarity      | DCEN |
| 10      | Filler rod    | ER4043 standard |
| 11      | Electrode     | 3% Thoriated ‘W’ electrode |
| 12      | Electrode Diameter | 1.2 mm |

Figure 1. Schematic arrangement of PAW Machine setup

The chemical composition of the AA8011 aluminium alloy and Ti3Al2.5V alloy are presented in Table 2. The plates for investigation initially washed with an ultrasonic bath sonicator and the butt surfaces were cleaned with acetone.

Table 2. Chemical composition of the AA8011-H24 Aluminium alloy and Ti3Al2.5V alloy

| Chemical composition (Wt.%) of AA8011-H24 Aluminium alloy |
|----------------------------------------------------------|
| Fe – 0.74       | Mn – 0.10          |
| Zn – 0.08       | Si – 0.56          |
|                | Cu – 0.12          |
|                | Mg – 0.10          |

| Chemical composition (Wt.%) of Ti3Al2.5V Ti alloy |
|-------------------------------------------------|
| Fe – 0.33         | Si – 0.15         |
| C – 0.06          | Al – 2.9          |
| H – 0.02          | V – 2.5           |
| N – 0.02          | O – 0.15          |
|                   | Remaining Ti      |

3. Central Composite Design

In this present investigation, the effects of the welding parameters on the mechanical properties of the dissimilar AA8011-H24 Al alloy and Ti3Al2.5V Ti alloy joints were discussed using the four factors, five levels of the central composite rotatable design with the thirty-one different welding experiments for the PAW process. The design of experiments was conducted using the Design Expert® 11.0 software to examine the optimal responses on the superior responses of PAW process.

3.1 Identifying the Important FSW and PAW Process Parameters

The fishbone diagram is applied to find the various parameters, viz., work and tool material properties, dimensions of the workpiece and tools, filler materials and machining parameters involved in dissimilar PAW process to decide the good quality of the welded joints. In this work, the independent welding process parameters, welding current (Iw), torch angle (θ), plasma gas flow rate (Fr) and welding speed (S) are selected based on the previous literature related to the fusion welding process [27], machine capability and preliminary trial experiments which affects the tensile properties of the fabricated joints.
3.2 Finding the working limits of parameters

The feasible working limits of the input parameters are found by conducting a large number of trial experiments for PAW welding process using the dissimilar AA8011-H24 Al alloy and Ti3Al2.5V Ti alloys with 6 mm thick plates. The trial experiments are conducted by keeping one of the parameters as variable and other parameters were kept constant. The range of each welding parameter is selected based on by inspecting the presence of defects, viz., hot cracking, solidification shrinkage, tunnel defect, wormhole, piping defect, and kissing bond through the macrostructure across the weld direction. The upper and lower limits of the four-factor, five levels of the design matrix are coded as +2 and -2 respectively and the intermediate coded values are determined by the equation (1),

\[
X_i = \frac{2 [2X - (X_{\text{max}} + X_{\text{min}})]}{(X_{\text{max}} - X_{\text{min}})}
\]  

(1)

Where,

\[X_i\] is the required coded value of a variable \(X\); \(X\) is any value of the variable lies between \(X_{\text{min}}\) to \(X_{\text{max}}\); \(X_{\text{min}}\) is the lower limit of the variable, and \(X_{\text{max}}\) is the upper limit of the variable.

The selected welding parameters with their limits, units and notations of the PAW process are presented in Table 3.

| Process parameters       | Unit       | Notation | Levels |
|--------------------------|------------|----------|--------|
|                          |            |          | -2     | -1    | 0     | +1    | +2    |
| Welding current          | Amps       | \(I_w\)  | 94     | 98    | 102   | 106   | 110   |
| Torch angle              | deg        | \(\theta\) | 86     | 88    | 90    | 92    | 94    |
| Gas flow rate            | Lpm        | \(F_r\)  | 16     | 17    | 18    | 19    | 20    |
| Welding speed            | mm/min     | \(S\)    | 25     | 30    | 35    | 40    | 45    |

3.3 Development of Design Matrix

The various combinations of each process parameters were formed which carries the different experimental trails in the rows and the levels of each welding parameters in the columns of a design matrix [28]. In this work, the four factors, five levels of CCD matrix were used to conduct the 31 sets of coded conditions for the experiments. The non-linear quadratic models were developed from the design matrix which has 31 experimental conditions due to the welding behaviour on the alloy materials on the tensile properties of PAW butt joints using the response surface methodology.

![Figure 2](image) (a) Standard Tensile Specimen (b) Fabricated Tensile Specimens and (c) Fractured Tensile Specimens
Table 4. Design Matrix for PAW Process (Coded Values)

| Std | Welding Current (Amp) | Torch Angle (Deg) | Gas Flow rate (Lpm) | Welding Speed (mm/min) | Tensile Strength (Mpa) | Tensile Elongation (%) |
|-----|-----------------------|-------------------|---------------------|------------------------|------------------------|------------------------|
| 1   | -1                    | -1                | -1                  | -1                     | 132.4                  | 3.21                   |
| 2   | +1                    | -1                | -1                  | -1                     | 143.1                  | 3.48                   |
| 3   | -1                    | +1                | -1                  | -1                     | 130.1                  | 4.10                   |
| 4   | +1                    | +1                | -1                  | -1                     | 138.9                  | 4.02                   |
| 5   | -1                    | -1                | +1                  | -1                     | 135.0                  | 3.56                   |
| 6   | +1                    | -1                | +1                  | -1                     | 136.6                  | 3.66                   |
| 7   | -1                    | +1                | +1                  | -1                     | 130.2                  | 4.12                   |
| 8   | +1                    | +1                | +1                  | -1                     | 128.4                  | 3.88                   |
| 9   | -1                    | -1                | -1                  | +1                     | 133.8                  | 3.35                   |
| 10  | +1                    | -1                | -1                  | +1                     | 141.2                  | 3.84                   |
| 11  | -1                    | +1                | -1                  | +1                     | 138.0                  | 3.92                   |
| 12  | +1                    | +1                | -1                  | +1                     | 142.3                  | 4.08                   |
| 13  | -1                    | -1                | +1                  | +1                     | 139.6                  | 3.55                   |
| 14  | +1                    | -1                | +1                  | +1                     | 137.2                  | 3.87                   |
| 15  | -1                    | +1                | +1                  | +1                     | 141.2                  | 3.75                   |
| 16  | +1                    | +1                | +1                  | +1                     | 136.2                  | 3.78                   |
| 17  | -2                    | 0                 | 0                   | 0                      | 134.0                  | 3.44                   |
| 18  | +2                    | 0                 | 0                   | 0                      | 138.8                  | 3.72                   |
| 19  | 0                     | -2                | 0                   | 0                      | 140.0                  | 3.16                   |
| 20  | 0                     | +2                | 0                   | 0                      | 136.3                  | 3.91                   |
| 21  | 0                     | 0                 | -2                  | 0                      | 135.4                  | 3.95                   |
| 22  | 0                     | 0                 | +2                  | 0                      | 132.1                  | 4.00                   |
| 23  | 0                     | 0                 | 0                   | -2                     | 136.4                  | 3.95                   |
| 24  | 0                     | 0                 | 0                   | +2                     | 144.2                  | 3.96                   |
| 25  | 0                     | 0                 | 0                   | 0                      | 145.4                  | 4.39                   |
| 26  | 0                     | 0                 | 0                   | 0                      | 146.4                  | 4.42                   |
| 27  | 0                     | 0                 | 0                   | 0                      | 144.4                  | 4.38                   |
| 28  | 0                     | 0                 | 0                   | 0                      | 145.7                  | 4.42                   |
| 29  | 0                     | 0                 | 0                   | 0                      | 143.3                  | 4.41                   |
| 30  | 0                     | 0                 | 0                   | 0                      | 145.1                  | 4.43                   |
| 31  | 0                     | 0                 | 0                   | 0                      | 143.8                  | 4.42                   |

The tensile specimens were sliced perpendicular to the weld direction using a power hacksaw and machined as per ASTM-E08 standards and were tested in the Omega Inspection and Analytical Laboratory, Chennai [29]. The fabricated plasma arc welded tensile specimens and fractured specimens are presented in Figure 2. The recorded experimental tensile test responses, namely Tensile Strength and Tensile Elongation for PAW processes are presented in Table 4 in the design matrix using response surface methodology.

4. Result and Discussions

This work was carried the optimisation of multi responses of the PAW process variables, namely welding current ($I_w$) in Amp, torch angle ($\theta$) in deg, gas flow rate ($Fr$) in LPM and welding speed ($S$) in mm/min. The range of the above independent variables should be considered as $102 \leq I_w \leq 110$; $86 \leq \theta \leq 94$; $16 \leq Fr \leq 20$; and $25 \leq S \leq 45$. Furthermore, the grey relational analysis was applied to convert the multi-response optimisation problem into the single response optimisation problem using the calculated grey relational grade [30].
4.1 Normalised sequence of PAW responses

The normalisation of the measured responses of the PAW process is the primary step for grey relational analysis based on the Larger the better concept using Eqn. (2) and this step prevents the large variation in the measured responses, viz., tensile strength and tensile elongation. Usually, the normalised responses are considered in the range 0 to 1 [31]. Table 5 shows the normalised values of the responses of the dissimilar plasma arc welded Ti-3Al-2.5V Ti alloy and AA8011-H24 aluminium alloy joints.

For higher-the-better

\[ x_i^*(k) = \frac{x_i(k) - x_i^-(k)}{x_i^+(k) - x_i^-(k)} \quad \text{For} \quad (i = 1, 2 \ldots m \text{ and } k = 1, 2 \ldots n) \]  

(2)

Where \( x_i^-(k) \) is the normalised response, \( x_0(k) \) is the desired responses, \( x_i^+(k) \) is the maximum of \( x_i(k) \), and \( x_i^-(k) \) is the minimum of \( x_i(k) \).

Table 5 Normalised responses, Grey relational coefficient and Grey relational grade of the Responses
4.2 Calculation of the grey relational coefficient and grey relational grade

The calculation of grey relational coefficient (GRC) is to express the relationship between the predicted and the actual experimental responses of the experiments in Table 5. The grey relational coefficient \( \zeta_i(k) \) can be calculated based on Eqn. (3),

\[
\zeta_i(k) = \frac{\Delta_{\text{min}} + \psi \Delta_{\text{max}}}{\Delta_{oi}(k) + \psi \Delta_{\text{max}}}
\]

(3)

In this, the distinguishing coefficient, \( \psi \) of 0.5 is considered for the determination of the grey relational coefficient [32].

4.3 Determination of the eigenvalues, eigenvectors and principal component scores

The eigenvalues and eigenvectors are determined from the correlation coefficient and the Variance-Covariance matrix array is represented in Eqn. (4) as follows:

\[
(N_{kl} - \lambda_k I) V_{ik} = 0
\]

(4)

Where \( N \) is the correlation coefficient matrix form of \( N_{kl} \) and \( \lambda_k \) is the \( k^{th} \) eigenvalue and \( \sum_{k=1}^{n} \lambda_k = n, \ k = 1, 2 \ldots n \) and \( V_{ik} = [a_{k1} a_{k2} \ldots a_{kn}]^T \) is the eigenvector corresponding to the eigenvalue \( \lambda_k \).

The principal component score, \( \psi_j \) corresponding to each experiment is formulated based on Eqn. (5) as follows:

\[
\Psi_n = \sum_{j=1}^{n} X_{ij} \cdot V_{jk}
\]

(5)

Where \( \psi_1, \psi_2, \psi_3 \ldots \) represents the first principal component, second principal component, third principal component and so on. \( X_{ij} \) is the corresponding normalised measured response matrix, and \( V_{jk} \) is the eigenvector corresponding to the eigenvalues \( \lambda_k \).

The principal component analysis is incorporated into the response surface methodology based grey relational analysis for optimising the welding process parameters, namely tensile strength, yield strength, tensile elongation and joint efficiency to achieve the quality of the fabricated joints effectively and the weights of each response are determined. The correlation coefficient array was applied to determine the eigenvalues and eigenvectors and these are used to find the principal components of the responses of the PAW welded joints is represented in the Eqn. (4).

The Principal components and Eigenvalues of the responses for dissimilar plasma arc welded AA8011-H24 aluminium alloys and Ti-3Al-2.5V titanium alloy joints are given in Table 6. The weights of the responses are found by squaring of the eigenvalues of the principal components assigned for the experiments. The cumulative contribution of each response of the friction stir welded joints are calculated based on the weights determined for the responses using principal component analysis is listed in Table 7.
Table 6. Principal component and Eigen Values of the responses

| Items                   | Principal Components |          |          |
|------------------------|----------------------|----------|----------|
|                        | PC(1)                | PC(2)    |          |
| Eigenvalues            | 1.6944               | 0.3056   |          |
| Proportion             | 0.8472               | 0.1528   |          |
| Accumulated Proportion | 0.8472               | 1.0000   |          |
| Responses              |                      |          |          |
| Tensile Strength, (MPa)| 0.707                | 0.707    |          |
| Tensile Elongation,(%) | -0.707               | -0.707   |          |

Table 7. Contribution of the responses

| PAW Responses          | Contribution | Cumulative Contribution (%) |
|------------------------|--------------|----------------------------|
| Tensile Strength, (MPa)| 0.7323       | 73.23                      |
| Tensile Elongation,(%) | 0.2677       | 100                        |

The quality of the joints is decided with above 85% of the contribution of the parameters on the responses. This work has the combined first two principal components, PC (1) and PC (2) has 100% of the variation of the responses [33]. The composite welding quality index (CWQI) is determined from the first two principal component scores which are used to optimise the responses of the PAW joints. This CWQI is calculated by the sum of the products of the first two principal component scores multiplied by their corresponding eigenvalues is represented in Eqn. (6).

\[ CWQI = \sum_{k=1}^{2} (\lambda_{k} \times PCS(k)) \]  

(6)

The higher CWQI value of 4.7613 was examined on the 26th experimental runs which provide the optimum responses of the PAW process. This optimum CWQI value shows the higher tensile properties, viz., tensile strength and tensile elongation of the dissimilar plasma arc welded AA8011-H24 aluminium alloy and Ti-3Al-2.5V titanium alloy joints.

The mathematical model is developed for the composite welding quality index from the coefficients of the PAW responses based on the second-order polynomial model using the Design Expert 8.0® software at 95% of confidence intervals [34, 35]. The backward elimination procedure is applied to eliminate the insignificant parameters for the CWQI values to adjust the fitted quadratic model. The final quadratic model of composite welding quality index in terms of coded and actual PAW parameters are presented in Eqn. (7) as follows:

\[ CWQI \text{ (Coded)} = +21.77 + (1.81 \times Iw) - (0.31 \times \theta) - (0.85 \times Fr) + (2.15 \times Sw) - (1.01 \times Iw \times \theta) - (2.42 \times Iw \times Fr) - (0.58 \times Iw \times S) - (1.17 \times \theta \times Fr) + (1.26 \times \theta \times S) + (0.69 \times Fr \times S) - (3.30 \times Iw^2) - (2.89 \times \theta^2) - (3.46 \times Fr^2) - (1.97 \times S^2) \]  

(7)
Table 8. Four principal component scores and the composite welding quality index

| Exp No | Principal Components Scores | \((\lambda_1^{*}\text{PCS}(1))\) | \((\lambda_2^{*}\text{PCS}(2))\) | CWQI | Rank |
|--------|-----------------------------|-------------------------------|-------------------------------|-------|------|
| 1      | 1.0718                      | 0.0020                        | 0.78488                       | 0.00054 | 0.78541 | 30   |
| 2      | 4.3206                      | 0.0037                        | 3.16398                       | 0.00099 | 3.16497 | 10   |
| 3      | 1.4082                      | 0.0046                        | 1.03122                       | 0.00123 | 1.03246 | 28   |
| 4      | 3.6735                      | 0.0063                        | 2.69010                       | 0.00169 | 2.69179 | 13   |
| 5      | 2.1903                      | 0.0029                        | 1.60396                       | 0.00078 | 1.60473 | 24   |
| 6      | 2.8500                      | 0.0015                        | 2.08706                       | 0.00040 | 2.08746 | 20   |
| 7      | 1.3618                      | 0.0063                        | 0.99725                       | 0.00169 | 0.99893 | 29   |
| 8      | 0.6841                      | 0.0040                        | 0.50097                       | 0.00107 | 0.50204 | 31   |
| 9      | 1.5184                      | 0.0041                        | 1.11192                       | 0.00110 | 1.11302 | 27   |
| 10     | 4.2239                      | 0.0004                        | 3.09316                       | 0.00107 | 3.09423 | 11   |
| 11     | 3.3621                      | 0.0052                        | 2.46207                       | 0.00139 | 2.46346 | 17   |
| 12     | 4.7775                      | 0.0051                        | 3.49856                       | 0.00137 | 3.49993 | 9    |
| 13     | 3.4661                      | 0.0031                        | 2.53823                       | 0.00083 | 2.53905 | 14   |
| 14     | 3.3870                      | -0.0001                       | 2.48030                       | -0.00003 | 2.48027 | 16   |
| 15     | 3.8546                      | 0.0083                        | 2.82272                       | 0.00222 | 2.82495 | 12   |
| 16     | 2.8122                      | 0.0029                        | 2.05937                       | 0.00078 | 2.06015 | 21   |
| 17     | 1.5652                      | 0.0062                        | 1.14620                       | 0.00166 | 1.14786 | 26   |
| 18     | 3.4053                      | 0.0040                        | 2.49370                       | 0.00107 | 2.49477 | 15   |
| 19     | 3.1164                      | 0.0024                        | 2.28214                       | 0.00064 | 2.28278 | 18   |
| 20     | 2.7660                      | 0.0069                        | 2.02554                       | 0.00185 | 2.02739 | 23   |
| 21     | 2.8060                      | 0.0029                        | 2.05483                       | 0.00078 | 2.05561 | 22   |
| 22     | 1.8611                      | 0.0043                        | 1.36288                       | 0.00115 | 1.36403 | 25   |
| 23     | 2.8587                      | 0.0068                        | 2.09343                       | 0.00182 | 2.09525 | 19   |
| 24     | 5.1131                      | 0.0059                        | 3.74432                       | 0.00158 | 3.74590 | 8    |
| 25     | 6.1687                      | 0.0030                        | 4.51734                       | 0.00080 | 4.51814 | 3    |
| 26     | 6.5009                      | 0.0027                        | 4.76061                       | 0.00072 | 4.76133 | 1    |
| 27     | 6.0520                      | 0.0000                        | 4.43188                       | 0.00000 | 4.43188 | 5    |
| 28     | 6.2459                      | 0.0038                        | 4.57387                       | 0.00102 | 4.57489 | 2    |
| 29     | 5.8095                      | -0.0005                       | 4.25430                       | -0.00013 | 4.25416 | 7    |
| 30     | 6.0926                      | 0.0037                        | 4.46161                       | 0.00099 | 4.46260 | 4    |
| 31     | 5.9272                      | 0.0001                        | 4.34049                       | 0.00003 | 4.34052 | 6    |

The analysis of variance test is conducted for composite welding quality index which is applied to predict the model at the 95% confidence level [36]. From Table 9, the composite welding quality index has the \(R^2\) value of 0.9948 and the model for CWQI shows a reasonable agreement with 99.48% of the variability. The Adjacent \(R^2\) value of 0.9902 is confirmed the model which is highly significant. The Predicted \(R^2\) value of 0.9848 is in reasonable agreement with the corresponding Adjacent \(R^2\) value. The lack of fit F-value of 94.41% is examined for CWQI which measures the failure of a model not considered in the regression. The most significant parameters are identified from the quadratic model for composite welding quality index [37]. The main effects of the process parameters of the PAW process on CWQI are examined in Table 10 and Figure 3 respectively.
Table 9. Analysis of Variance on Composite Welding Quality Index

| Source            | Sum of Squares | df | Mean Square | F Value | p-value Prob > F | Remarks |
|-------------------|----------------|----|-------------|---------|-----------------|---------|
| Model             | 1153.81        | 14 | 82.42       | 217.47  | < 0.0001        | Significant |
| $I_w$-Welding Current | 78.91          | 1  | 78.91       | 208.22  | < 0.0001        | Significant |
| $\theta$-Torch Angle | 2.30           | 1  | 2.30        | 6.08    | 0.0254          | Significant |
| $F_r$ – Gas Flow rate | 17.33          | 1  | 17.33       | 45.73   | < 0.0001        | Significant |
| $S$ -Welding Speed | 111.37         | 1  | 111.37      | 293.8   | < 0.0001        | Significant |
| $I_w \times \theta$ | 16.42          | 1  | 16.42       | 43.32   | < 0.0001        | Significant |
| $I_w \times F_r$  | 93.73          | 1  | 93.73       | 247.32  | < 0.0001        | Significant |
| $I_w \times S$    | 5.31           | 1  | 5.31        | 14.02   | 0.0018          | Significant |
| $\theta \times F_r$ | 21.81          | 1  | 21.81       | 57.56   | < 0.0001        | Significant |
| $\theta \times S$ | 25.41          | 1  | 25.41       | 67.06   | < 0.0001        | Significant |
| $F_r \times S$    | 7.03           | 1  | 7.03        | 20.12   | 0.0004          | Significant |
| $I_w^2$           | 311.32         | 1  | 311.32      | 821.49  | < 0.0001        | Significant |
| $\theta^2$       | 238.23         | 1  | 238.23      | 628.63  | < 0.0001        | Significant |
| $F_r^2$           | 342.01         | 1  | 342.01      | 902.49  | < 0.0001        | Significant |
| $S^2$            | 110.66         | 1  | 110.66      | 292.00  | < 0.0001        | Significant |
| Residual          | 6.06           | 16 | 0.38        |         |                 |          |
| Lack of Fit       | 2.13           | 10 | 0.21        | 0.32    | 0.9441          | Not Significant |
| Pure Error        | 3.94           | 6  | 0.66        |         |                 |          |
| Cor Total         | 1159.88        | 30 |             |         |                 |          |

Table 10. Main Effects of PAW Process Parameters on CWQI

| Process Parameters | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 | (Max-min) | Rank |
|--------------------|---------|---------|---------|---------|---------|-----------|------|
| Welding Current    | 22.5904 | 16.1059 | 41.7938 | 20.9034 | 30.1589 | 25.6879   | 2    |
| Torch Angle        | 30.2374 | 17.7918 | 41.2378 | 19.2175 | 29.8175 | 23.44     | 4    |
| Gas Flow rate      | 30.9467 | 17.3524 | 41.2762 | 19.6569 | 28.5319 | 23.9238   | 3    |
| Welding Speed      | 33.1426 | 12.2888 | 40.0508 | 24.7205 | 42.2656 | 29.9768   | 1    |

Figure 3. Main Effects Plot for CWQI
4.4 Confirmation experiments for dissimilar PAW joints

The optimum welding parameters are found through the determination of the composite welding quality index using the hybrid approach of RSM based GRA coupled PCA analysis. Besides, the five different confirmation tests are conducted at the optimal process settings, such as welding current of 102 Amp, torch angle of 90°, gas flow rate of 18 mm and welding speed of 35 mm/min on the responses of the dissimilar PAW joints. The average values of the tensile properties are listed in Table 11. It is used to determine the maximum value of the CWQI which relates the better quality performance of the fabricated joints. Finally, it is concluded that the hybrid optimisation enhances the tensile properties of the dissimilar plasma arc welded AA8011-H24 aluminium alloys and Ti-3Al-2.5V titanium alloy joints compared to the optimisation of the parameters using the RSM approach.

Table 11. Confirmation Experiment for Dissimilar PAW Joints

| Welding Current (Amp) | Torch Angle (Deg) | Gas Flow Rate (LPM) | Welding Speed (mm/min) | Tensile Strength (MPa) | Tensile Elongation (%) |
|-----------------------|------------------|---------------------|------------------------|------------------------|------------------------|
| 102                   | 90               | 18                  | 35                     | 144.87                 | 4.41                   |

5. Conclusions

- The hybrid approach of RSM based GRA coupled PCA analysis was applied to optimise the tensile properties, viz., tensile strength and tensile elongation of the dissimilar plasma arc welded AA8011-H24 aluminium alloys and Ti-3Al-2.5V titanium alloy joints.

- The developed mathematical models are analysed to correlate the most significant welding process parameters, viz., 102 of Amp welding current, 90° of torch angle, 18 LPM of gas flow rate and 35 mm/min of welding speed on the responses of the dissimilar plasma arc welded joints and these optimum parameters are helpful to optimise the responses in deciding the quality of the welded joints.

- The analysis of variance was applied on the main effects of PAW process parameters on the responses, it was showed that welding speed is the dominant factor to decide the good quality of the welded joints followed welding current, gas flow rate and torch angle based on the CWQI.

- The confirmation tests showed that the experimental results were much closer to the predicted optimum results with minimum variations on the measured responses of the dissimilar PAW joints.

6. References

[1] Yakabu DY, Macedo BD, Resende HB and Batalha M H F 2018 Int J Adv Manuf Technol 95 1339–1355
[2] Aonuma M and Nakata K 2011 Mater. Trans 52 (5) 948-52
[3] Malikov AG, Orishich AM, Vitoshkin IE 2020 J Appl Mech Tech Phy 61 307–317
[4] Palani K, Elanchezhian C, Ramnath BV, Bhaskar GB Jagadeesh JS and Kumar GM 2017 Int. J. Res. App. Sci. Eng. Tech 5 437–442
[5] Rostami H, Nourouzi S and Jamshidi Aval H 2018 J Mech Sci Technol 32 3371–3377
[6] Ramkumar T, Selvakumar M, Narayanasamy P, Ayisha Begam A, Mathavan P and Arun Raj A 2018 J Manuf Proc 30 290-298
[7] Mousavi Anijdan S H, Sabzi M, Ghobeiti-Hasab M and Roshan-Ghiyas A 2018 Mater. Sci. and Eng. A 726 120-125
[8] Prabakaran MP and Kannan GR 2019 Opt Las Technol 112 314-322
[9] Paventhan R, Lakshminarayanan PR and Balasubramanian V 2012 Int J Iron & Steel Res 19 (1) 66-71
[10] Fernandus MJ, Senthilkumar T, Balasubramanian V and Rajakumar S 2012 Mater and Des 33 31–41
[11] Wei Y, Aiping W, Guisheng Z and Jialie R 2008 Mater. Let 62 2836-39
[12] Palani K, Elanchezhian C, Vijaya Ramnath B, Bhaskar GB and Naveen E 2018 Mater Today: Proc 5 24515–24524
[13] Ilangovan M, Boopathy SR and Balasubramanian V 2015 Def. Tech 11 (2) 174–184
[14] Vijayan S, Raju R and Rao SRK Mater. Manuf. Proc 25 1206-12
[15] Palani K, Elanchezhian C, Sai Prakash K H V, Deepak Kumar, Dayanand, Keshav Kumar and Sreekanth K 2018 IOP Conf. Series: Mater Sci Engg 390 012072
[16] Palani K, Elanchezhian C, Avinash K, Karthik C, Chaitanya K, Yugandar K and Karthik S 2018 IOP Conf. Series: Mater Sci Engg 390 012108
[17] Vaidya WV, Horstmann M, Ventzke V, Petrovski B, Koc M, Kocik R and Tempus G 2010 J. Mater. Sci 45 6242-54
[18] Lakshminarayanan AK and Balasubramanian V 2011 J. Mater. Eng. Perf 20 82-89
[19] Mvola B, Kah P and Martikainen J 2014 Int J Mech Mater Eng 9 21
[20] Esmaily M, Mortazavic SN, Todehfalah P and Rashidi M 2013 Mater. & Des 47 143-150
[21] Rajakumar S and Balasubramanian V 2015 Int. J. Adv. Manuf. Tech 86 (1-4) 1095-1112
[22] Sahu PK, Kumari K and Pal S 2016 Adv. Manuf. 4 237–247
[23] Palani K, Elanchezhian C, Vijaya Ramnath B and Ramadoss R 2020 Mater Today: Proc 23 (2) 573-582
[24] Siddiquee AN, Khan ZA and Mallick Z 2010 Int J Adv Manuf Technol 46 983–992
[25] Sharma A, Chaudhary AK, Arora N and Mishra BK 2009 Int J Adv Manuf Technol 45 1096–1103
[26] Palani K and Elanchezhian C 2015 Appl. Mech. Mater 813 451-55
[27] Şefika Kasman 2013 Int. J. Adv. Manuf. Tech 68 795–804
[28] Datta S, Bandyopadhyay A and Pal PK 2008 Int. J. Adv. Manuf. Technol. 39 (11-12) 1136-43
[29] Palanikumar K, Karunamoorthy L and Karthikeyan R 2006 Mat. Manuf. Proc 21 (8) 846-52
[30] Rajyalakshmi G and Venkata Ramaiah G 2013 Int. J. Adv. Manuf. Technol. 69 (5-8) 1249-62
[31] Palani K and Elanchezhian C 2015 Appl. Mech. Mater 766 921-27
[32] Kimura M, Nakamura S, Kusaka M, Seo K and Fuji A 2005 Sci. Tech. Weld. Join 10 (6) 666-73
[33] Sundaram NS and Murugan N 2010 Mater. Des 31 (9), 4184-93
[34] Palani K and Elanchezhian C 2015 Appl. Mech. Mater 813 446-450
[35] Ranganathan S and Senthilvelan T 2011 Int. J. Adv. Manuf. Technol. (2011) 56 455-62
[36] Gagliardi F, Ciancio C and Ambrogio G 2017 Int. J. Adv. Manuf. Technol. 94 (1-4) 719-28