Effect of plasma arc welding variables on fusion zone grain size and hardness of AISI 321 austenitic stainless steel

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Abstract. In the present work, pulsed current microplasma arc welding is carried out on AISI 321 austenitic stainless steel of 0.3 mm thickness. Peak current, Base current, Pulse rate and Pulse width are chosen as the input variables, whereas grain size and hardness are considered as output responses. Response surface method is adopted by using Box-Behnken Design, and in total 27 experiments are performed. Empirical relation between input and output response is developed using statistical software and analysis of variance (ANOVA) at 95% confidence level to check the adequacy. The main effect and interaction effect of input variables on output response are also studied.

1. Introduction
Austenitic stainless steel (ASS) is 300 series steels having high toughness and strength at both high and low temperatures. AISI321 is an austenitic stainless steel with excellent strength and good ductility at high temperature. It is widely used in bleed air components of aero-engine and cryogenic components. It can be joined using variety of welding process, both arc and non-arc welding process. Plasma arc welding (PAW) is one of the most important processing which is convenient to use in thin sheet joining. It is available in two forms: continuous current (CC) mode and pulsed current (PC) mode. Pulsed current MPAW is recommended for joining thin sheets because of stable nature of arc [1, 2]. Based on the work published by earlier researchers [3-8], four independent variables that influence the process are peak current, base current, pulse rate and pulse width, which are dominating variables influencing the weld quality.

In the present work, experiments conducted using design of experiments, developed mathematical models to predict the output responses. Most of the works reported by researchers studied the bead geometry, heat-affected zone, bead volume, etc., using mathematical models for various welding processes [9-11]. However, the desired welding input process variables are found based on the experience of the welder or from the data available in the handbook and one cannot relay the results obtained as the results are close to optimal [12]. Many researchers adopted statistical tools and other optimization like genetic algorithm, neural networks, etc. [13,14].

From the literature, it is understood that Kim et al. revealed that regression modeling, neural network, and Taguchi methods are helpful in attaining optimal solution only when the welding process was carried out at near the optimal conditions or at a stable operating range [15], however, near-optimal conditions cannot be easily found through full-factorial experiments when the number of experiments and levels of variables are more. Because of nonlinear characteristics of steepest ascent method, the results obtained can lead to an incorrect direction of the welding process. Modern
optimization techniques like genetic algorithm (GA) and simulated annealing algorithm can overcome the above problems incurred with full-factorial experiments [16].

The work presented in this paper discusses the effect of welding variables such as peak current, base current, pulse rate and pulse width on grain size and hardness at fusion zone (FZ) of PAW AISI 321 sheets.

2. Welding procedure
Weld specimens of 100 x 150 x 0.3 mm size are prepared from AISI 321 sheets and joined using square butt joint. Tables 1 and 2 indicate the chemical composition and tensile properties of AISI 321 stainless steel sheetsArgon is used as a shielding gas and a trailing gas to avoid contamination from outside atmosphere. The welding conditions adopted during welding are presented in table 3. From the works carried out by researchers [3-8], it is revealed that the peak current, back current, pulse rate and pulse width are the important variables which affect the weld quality characteristics in PAW process. The values of process variables considered in the present work are based on trail experiments. Peak current, base current, pulse rate and pulse width are chosen as variables and their levels are presented in table 4. Details about experimental setup are shown in figure 1. Four factors and three levels are considered and 27 experiments are performed as per Box-Benken Design matrix shown in table 5.

| Table 1. Chemical composition of AISI 321 (weight %). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| C  | Si  | Mn  | P  | S  | Cr  | Ni  | N  |
|-----|-----|-----|----|----|-----|-----|----|
| 0.05| 0.52| 1.30| 0.028| 0.021| 17.48| 9.510| 0.04|

| Table 2. Mechanical properties of AISI 321. |
|-----------------|-----------------|-----------------|
| Elongation (%)  | Yield strength (MPa) | Ultimate tensile strength (MPa) |
| 53.20 | 272.15 | 656.30 |

| Table 3. Welding conditions. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Power source    | Secheron microplasma arc machine (Model: PLASMAFIX 50E) |
| Polarity        | DCEN            |
| Mode of operation | Pulse mode     |
| Electrode       | 2% thoriated tungsten electrode |
| Electrode Diameter | 1 mm           |
| Plasma gas      | Argon & hydrogen |
| Plasma gas flow rate | 6 L per minute |
| Shielding gas   | Argon           |
| Shielding gas flow rate | 0.4 L per minute |
| Trailing gas    | Argon           |
| Trailing gas flow rate | 0.4 L per minute |
| Copper nozzle diameter | 1 mm          |
| Nozzle to plate distance | 1 mm           |
| Welding speed   | 260 mm/minute   |
| Torch position  | Vertical        |
| Operation type  | Automatic       |
Table 4. Process variables and their limits.

| Input Factor | Units      | -1 | 0  | +1 |
|--------------|------------|----|----|----|
| Peak Current | Amps       | 6  | 7  | 8  |
| Base Current | Amps       | 3  | 4  | 5  |
| Pulse rate   | Pulses /Second | 20 | 40 | 60 |
| Pulse width  | %          | 30 | 50 | 70 |

Figure 1. Microplasma arc welding setup.

Table 5. Design matrix with experimental results.

| Experiment No. | Peak Current (Amps) | Base current (Amps) | Pulse Rate (Pulses/second) | Pulse width (%) | Grain size (Microns) | Hardness (VHN) |
|----------------|---------------------|---------------------|-----------------------------|------------------|-----------------------|-----------------|
| 1              | 6                   | 3                   | 40                          | 50               | 23.812                | 207.000         |
| 2              | 8                   | 3                   | 40                          | 50               | 30.226                | 198.000         |
| 3              | 6                   | 5                   | 40                          | 50               | 29.508                | 208.000         |
| 4              | 8                   | 5                   | 40                          | 50               | 30.536                | 202.000         |
| 5              | 7                   | 4                   | 20                          | 30               | 29.323                | 203.000         |
| 6              | 7                   | 4                   | 60                          | 30               | 32.206                | 200.000         |
| 7              | 7                   | 4                   | 20                          | 70               | 28.994                | 201.000         |
| 8              | 7                   | 4                   | 60                          | 70               | 27.491                | 202.000         |
| 9              | 6                   | 4                   | 20                          | 50               | 28.290                | 203.000         |
| 10             | 8                   | 4                   | 60                          | 50               | 31.835                | 200.460         |
| 11             | 6                   | 4                   | 20                          | 50               | 30.764                | 201.000         |
| 12             | 8                   | 4                   | 20                          | 50               | 30.695                | 209.000         |
| 13             | 7                   | 3                   | 60                          | 30               | 30.095                | 201.000         |
| 14             | 7                   | 5                   | 40                          | 30               | 29.109                | 201.500         |
| 15             | 7                   | 3                   | 40                          | 50               | 30.385                | 203.000         |
| 16             | 7                   | 5                   | 40                          | 50               | 28.013                | 203.000         |
| 17             | 6                   | 4                   | 40                          | 30               | 23.788                | 205.000         |
| 18             | 8                   | 4                   | 40                          | 30               | 28.270                | 198.200         |
| 19             | 6                   | 4                   | 40                          | 70               | 32.663                | 205.800         |
| 20             | 8                   | 4                   | 40                          | 70               | 30.263                | 199.200         |
| 21             | 7                   | 3                   | 20                          | 50               | 28.270                | 203.000         |
| 22             | 7                   | 5                   | 20                          | 50               | 32.030                | 200.000         |
| 23             | 7                   | 3                   | 60                          | 50               | 27.626                | 204.000         |
| 24             | 7                   | 5                   | 60                          | 50               | 28.626                | 206.000         |
| 25             | 7                   | 4                   | 40                          | 50               | 26.845                | 204.000         |
| 26             | 7                   | 4                   | 40                          | 50               | 28.845                | 201.000         |
| 27             | 7                   | 4                   | 40                          | 50               | 23.145                | 208.500         |
3. Recording output responses

3.1. Measurement of microstructure & grain size
Specimens for measurement of microstructure and grain size are prepared according to ASTM E3-1 standard. Three samples were prepared from each weld joint, leaving the edges. The samples are mounted on Bakelite and polished using 1/0, 2/0, 3/0 and 4/0 polishing papers. After polishing, disc polishing was done using Aluminum oxide. The polished specimens are etched with oxalic acid to reveal the microstructure. The etching time is increased to reveal the grain size of the welded specimen as per ASTM E407. Macrographs are taken using metallurgical microscope Axiovert 40MAT by Carl Zeiss at x100 magnification. Figures 2 and 3 represent microstructure of heat-affected zone (HAZ) and fusion zone (FZ). Figures 3 and 4 represent grain size at HAZ and FZ.

As the grain size cannot be measured accurately, scanning electron microscope (SEM) is used to measure the exact grain size. The grain size represented in table 5 is average value of the measured grain size in FZ. Sample SEM image is presented in figure 6.
3.2. Measurement of hardness
Vickers hardness test was performed along HAZ and FZ of the welded joint at an interval of 0.3 mm. Using an MMT-X7 testing machine by Metsuzawa Ltd., Japan, Vickers’ microhardness measurements were made by applying a load of 0.5 Kg as per ASTM E384. Figure 7 represents the indentation points. The values presented in table 5 are the average values at FZ.

4. Statistical analysis
Grain size and hardness values at FZ for all 7 samples were recorded and presented in table 5. In this study, the grain size and hardness measurements were made only for FZ.

4.1. Empirical mathematical modeling
In RSM design, mathematical models are developed using polynomial equations. The type of polynomial equation depends on the problem. A second order polynomial equation is adopted

\[ Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum \sum b_{ij} x_i x_j + \epsilon \]  

Empirical mathematical models are developed using MINITAB Ver.14 statistical software. The model is developed considering only significant coefficients at 95% confidence level.

Grain size = 69.9549 - 4.4302X_1 - 3.9241X_2 - 0.5701X_3 - 0.0126X_4 + 0.0866X_2X_3

Hardness = 243.566 - 43.377 X_1 + 32.806X_2 - 1.046X_3 + 2.434X_4 + 2.877X_1^2 - 0.008X_3^2

-0.005X_2^2 + 0.171 X_1X_3 - 0.058X,X_4 - 0.199X_2X_3 - 0.370X_2X_4

The coded values of peak current, base current, pulse rate and pulse width are represented by $X_1$, $X_2$, $X_3$ and $X_4$ respectively.

4.2. ANOVA analysis of output responses
Analysis of variance (ANOVA) was performed at 95% confidence and presented in tables 6 and 7. From tables 6 and 7, it is revealed that the developed empirical mathematical models are found to be adequate at 95% confidence level and the coefficient of determination ‘$R^2$’ is 0.92, which shows a good agreement to existence between the experimental and predicted values. The variation in experimental and predicted values are shown in in figures 8 and 9 as scatter plots.
of longer time gap between the peak current. According to short on and off time of t subsequently finer grain size in fusion zone. As pulse rate increases decrease in peak current leads to the decrease in the heat input, which leads to faster cooling rate and low during solidification and long the welded joint, wh As peak current and base current 5.1. Results

Individual effect of welding variables on output responses can be studied using main plots as shown in figures 10 and 11.

5. Results and discussion

Individual effect of welding variables on output responses can be studied using main plots as shown in figures 10 and 11.

5.1. Main effect plots for grain size and hardness

As peak current and base current increases, gain size increases. Because of change in cooling rate of the welded joint, when peak current is increased from 6 A, the grain size increases. The cooling rate is low during solidification and long-time interval available for grain coarsening. In contrast, the decrease in peak current leads to the decrease in the heat input, which leads to faster cooling rate and subsequently finer grain size in fusion zone. As pulse rate increases, the grain size increases, because of short on and off time of the welding current. As pulse width increases, grain size decreases, because of longer time gap between the peak current. According to the Hall-Petch equation, hardness and

| Source     | DF | Seq SS  | Adj SS  | Adj MS  | F     | P     |
|------------|----|---------|---------|---------|-------|-------|
| Regression | 12 | 159.779 | 159.779 | 13.3149 | 9.62  | 0.000 |
| Linear     | 4  | 92.160  | 3.586   | 0.8964  | 0.65  | 0.638 |
| Square     | 4  | 27.776  | 2.139   | 0.5347  | 0.39  | 0.815 |
| Interaction| 4  | 39.843  | 39.843  | 9.9608  | 7.20  | 0.002 |
| Residual Error | 14 | 19.378  | 19.378  | 1.3842  |       |       |
| Lack-of-Fit| 1  | 2.801   | 2.801   | 2.8010  | 2.20  | 0.162 |
| Pure Error | 13 | 16.577  | 16.577  | 1.2752  |       |       |
| Total      | 26 | 179.157 |         |         |       |       |

Table 6. ANOVA for grain size.

| Source     | DF | Seq SS  | Adj SS  | Adj MS  | F     | P     |
|------------|----|---------|---------|---------|-------|-------|
| Regression | 12 | 252.513 | 252.513 | 21.043  | 15.31 | 0.000 |
| Linear     | 4  | 106.073 | 81.911  | 20.478  | 14.90 | 0.000 |
| Square     | 4  | 7.434   | 31.958  | 7.990   | 5.81  | 0.006 |
| Interaction| 4  | 139.006 | 139.006 | 34.752  | 25.29 | 0.000 |
| Residual Error | 14 | 19.241  | 19.241  | 1.374   |       |       |
| Lack-of-Fit| 1  | 2.716   | 2.716   | 2.716   | 2.14  | 0.168 |
| Pure Error | 13 | 16.525  | 16.525  | 1.271   |       |       |
| Total      | 26 | 271.753 |         |         |       |       |

Table 7. ANOVA test results for hardness.

In tables 6 and 7, SS is sum of squares, MS is mean square, DF is degree of freedom, F is Fisher’s ratio, and P is probability ratio.

**Figure 8.** Scatter plot for grain size.

**Figure 9.** Scatter plot for hardness.
strength of the weld joint are inversely proportional to grain size.

\[ \text{Mean of Grain Size (Microns)} \]

\[ \begin{array}{c|c|c|c|c|c}
\text{Peak current (Amps)} & \text{Base current (Amps)} & \text{Mean of Grain Size (Microns)} \\
\hline
6 & 7 & 28.0 \\
8 & 7 & 26.0 \\
8 & 6 & 24.0 \\
7 & 6 & 22.0 \\
6 & 5 & 20.0 \\
\end{array} \]

\[ \text{Mean of Hardness (VHN)} \]

\[ \begin{array}{c|c|c|c|c|c}
\text{Peak current (Amps)} & \text{Base current (Amps)} & \text{Mean of Hardness (VHN)} \\
\hline
6 & 7 & 205.0 \\
8 & 7 & 203.0 \\
8 & 6 & 201.0 \\
7 & 6 & 199.0 \\
6 & 5 & 197.0 \\
\end{array} \]

5.2. Contour plots for grain size and hardness
Figures 12(a) to 12(f) represent the contour plots for fusion zone grain size. From these plots, the interaction effect between the input process variables and output response can be observed as:

- Fusion zone grain size is more susceptible to change in peak current than base current (figure 12(a)), since the contour lines are more diverted towards peak current.
- Fusion zone grain size is susceptible to peak current than pulse rate (figure 12(b)), since the contour lines are more diverted towards peak current.
- Fusion zone grain size is more susceptible to peak current than pulse width (figure 12(c)), since the contour lines are more diverted towards peak current.
- Fusion zone grain size is more susceptible to base current than pulse rate (figure 12(d)), since the contour lines are more diverted towards base current.
- Fusion zone grain size is more susceptible to base current than pulse width (figure 12(e)), since the contour lines are more diverted towards base current.
- Fusion zone grain size is more susceptible to pulse rate than pulse width (figure 12(f)), since the contour lines are more diverted towards pulse rate.

Among the welding variables considered, it is clear that peak current is the most influencing variables which affect the grain size in the fusion zone of the welded joints, followed by base current, pulse rate and pulse width.
Figures 12(a) to 12(f) represent the contour plots for fusion zone hardness. The effect between the input process variables and output response can be observed from contour plots as:

- Fusion zone hardness is more susceptible to change in peak current than base current (figure 13(a)), since the contour lines are more diverted towards peak current.
- Fusion zone hardness is susceptible to peak current than pulse rate (figure 13(b)), since the contour lines are more diverted towards peak current.
- Fusion zone hardness is more susceptible to peak current than pulse width (figure 13(c)), since the contour lines are more diverted towards peak current.
- Fusion zone hardness is more susceptible to base current than pulse rate (figure 13(d)), since the contour lines are more diverted towards base current.
- Fusion zone hardness is more susceptible to base current than pulse width (figure 13(e)), since the contour lines are more diverted towards base current.
- Fusion zone hardness is more susceptible to pulse rate than pulse width (figure 13(f)), since the contour lines are more diverted towards pulse rate.

Among the welding variables considered, it is understood that peak current is the most influencing variable, which affects the hardness in the fusion zone of the welded joints, followed by base current, pulse rate, and pulse width.
When the pulse rate decreases to 20 pulse/second, observed that at a peak current of 8A, the grain size is lower.

Because of change in cooling rate, when peak current is increased from 6A, the grain size increases.

The minimum grain size is indicated by the nadir of the response surface, as shown in figure 14(a) to 14(f).

From the response figure 14(a), it is seen that at a peak current of 8A, the grain size is lower. Because of change in cooling rate, when peak current is increased from 6A, the grain size increases. Grain coarsening time has been improved because of slower cooling rates. From the surface plot, it is observed that at a peak current of 8A and base current of 4 A, the grain size is minimum.

From figure 14(b), it can be concluded that at a pulse rate of 60 pulse/second, grain size is lower. When the pulse rate decreases to 20 pulse/second, the grain size is increased. Because of finer grains
in fusion zone in strength of the welded joint is improved. Because of violent agitation of weld molten metal, at high pulse rate values, grain refinement in the weld region takes place. From the surface plot, it is observed that at a peak current of 8A and pulse rate of 60 pulse/second, grain size is minimum.

![Surface plot for grain size: (a) peak current vs. base current, (b) peak current vs. pulse rate, (c) Peak current vs. pulse width, (d) Base current vs. pulse rate, (e) Base current vs. pulse width, (f) Pulse rate vs. pulse width.](image)

Figure 14. Surface plot for grain size: (a) peak current vs. base current, (b) peak current vs. pulse rate, (c) Peak current vs. pulse width, (d) Base current vs. pulse rate, (e) Base current vs. pulse width, (f) Pulse rate vs. pulse width.

From figure 14(c), it is seen that at a pulse width of 30%, the grain size is lower. Pulse width promotes the grain growth in the weld region. The time period of the pulse is improved, because of increase in pulse on time. From the surface plot, it is observed that at a peak current of 8A and pulse width of 30%, the grain size is minimum. From figure 14(d), it follows that when the base current is 4A and pulse rate of 60 pulse/second, grain size is minimum. From figure 14(e), it is observed that
when the base current is 4A and pulse width is 30%, the grain size is minimum. From figure 14(f), it is observed that with the pulse rate of 60 pulse/second and pulse width of 30%, grain size is minimum. The above observations reveal that for minimum grain size following is required: peak current of 8A, base current of 4A, pulse rate of 60 pulse/second and pulse width of 30%.

The maximum hardness is indicated by the apex of the response surface, as shown in figures 15(a) to 15(f).

From the response figure 15(a), it can be concluded that at the peak current of 7A, the hardness is lower. The hardness of the weld joint is improved because of fine equiaxed grains in fusion zone. Higher amperage and higher peak current lead to more heat and longer cooling time resulting in coarse grains, which is responsible for lower hardness. This is in line with the variation of fusion zone grain size. From the surface plot, it can be concluded that at a peak current of 7A and base current of 3A, the hardness is maximum.

From the response figure 15(b), it can be concluded that when the pulse rate is 20 pulse/second, the hardness is lower. Because of presence of fine grains in fusion zone, the hardness of the weld joint is improved. At very low pulse rates, the effect of pulsing on the weld bead is less compared to that at high frequency pulsing. At high pulse rate values, the molten bead is agitated violently, resulting in grain refinement in the weld region. From the surface plot, it can be concluded that at a peak current of 7A and pulse rate of 20 pulse/second, the hardness is maximum.

From the response figure 15(c), it can be concluded that at the pulse width of 30%, the hardness is lower. The grain growth in weld region is influenced by pulse width. With the increase in pulse on time, there is an increase in the time period from the start of a pulse to the end of the base time. When pulse width is increased, the welding heat has more time to conduct into the fusion zone promoting grain coarsening. From the surface plot, it can be concluded that at a peak current of 7A and pulse width of 30%, the hardness is maximum.

From figure 15(d), it can be concluded that at a base current of 3A and pulse rate of 20 pulse/second, the hardness is maximum.

From figure 15(e), it can be concluded that at a base current of 3A and pulse width of 30%, the hardness is maximum.

From figure 15(f), it can be concluded that at a pulse rate of 60 pulse/second and pulse width of 30%, the hardness is maximum.

From the above observations, it may be inferred that to achieve maximum hardness the required values of welding variables are: peak current 7A, base current 3A, pulse rate 60 pulse/second and pulse width 30%.
The empirical mathematical models for grain size and hardness of the MPAW welded AISI 321 austenitic stainless sheets of 0.3 mm thickness were developed using the response surface method.

Scatter plots are draw to understand the variation between experimental and predicted values and fond to be close to each other. The correlation coefficient $R^2$ is about 0.92.

From the main effect plots, it is revealed that with the increase in peak current, base current and pulse width grain size decreases and hardness value increases. Whereas grain size increase and hardness decrease with an increase in the pulse rate.

From the contour plots of grain size and hardness, it is revealed that peak current is the most influencing variables which affect the grain size and hardness in the fusion zone of the welded joints, followed by base current, pulse rate, and pulse width.

From the surface plot, it is revealed that for minimum grain size the following is required: peak current of 8A, base current of 4A, pulse rate of 60 pulse/second, and pulse width of 30%.

From the surface plot, it may be inferred that to achieve maximum hardness the required values of welding variables are: peak current of 7A, base current of 3A,
pulse rate of 60 pulse/second, and pulse width of 30%.

- The developed model is valid within the specified range of the selected welding variables; however, one can improve the accuracy of the models by considering more variables and their wider range.

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