Parametric optimization of TIG welding of duplex stainless steel without filler rod by PCA method

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Abstract. The weld quality is mostly depended on the welding input factors. Welding quality is controlled by appropriately controlling the using process factors with sound knowledge base. The major influencing Tungsten Inert Gas (TIG) welding parameters are welding current, gas flow rate and speed of the welding. Controlling these parameters, the quality of the Duplex Stainless Steel (DSS) welding joints are improved. These welding process parameters are optimized to achieve the better quality of DSS welding joints. Here, the Principal Component Analysis (PCA) method and concept of Taguchi’s signal to noise ratio (S/N) are used to optimize the above TIG welding process parameters of UNS 2205 DSS. The quality of the TIG welding of DSS has been evaluated in term of tensile test. Statistical tool like Analysis of Variance (ANOVA) is applied to evaluate the significance of the individual factors on the desired responses like ultimate tensile strength, yield strength etc. The optimal result is verified by the additional experiment. This result shows the application possibility of the PCA method for incessant development of welding quality of DSS in many fields, like chemical industries, oil & gas refineries, manufacturing industries etc.

1. Introduction
Duplex stainless steel ancestors have been enhanced through initiating nitrogen accompaniments for the period of last fifty decades. The exceptional blend of double phase configuration of ferrite with austenite has been seen in DSS. Austenite structure provides a unique arrangement of strength. Ferrite phase provides local corrosion resistance. DSS is being extremely used in oil and chemical industry. Several works has been reported for studying the mechanical behaviour of TIG welded DSS. The proper knowledgebase regarding TIG welding of duplex stainless steel is not sufficiently rich. More research is required to develop a sound knowledgebase of the various aspects related to duplex stainless steel welding.

Palani and Murugan [1] investigated the cladding effect on the weld bead geometry using different welding factors. Diaz et al. [2] showed the significant role of material characteristics of dissimilar stainless steels using finite element technique with the birth and death procedure. Zou et al. [3] investigated the effect of oxygen on crystallographic orientation in DSS weld. Magudeeswaran et al. [4] observed the phase structure of duplex stainless steel. They showed the equal amounts of bcc ferrite and fcc austenite phase structure of DSS material. They also observed that DSS had higher strength compare to single-phase austenitic stainless Steel. Lakshminarayanan et al. [5] researched on the mechanical and microstructural properties of AISI 409M ferritic stainless joints. Badjia et al. [6] observed the mixture of recrystallization texture and deformation in the material of single phase BCC and FCC structure. The crystallographic orientation of HAZ (heat affected zone) area was affected by the welding process, when the material was annealed at 1050°C. Juang and Tarng [7] determined the best TIG weld bead structure. They used Taguchi technique to analysis the weld pool structure using different welding process factors like gas flow rate, arc gap, speed and welding current. Tarng and Yang [8] optimized the weld bead geometry of GTAW process by Taguchi method. Tarng et al. [9] investigated on weld bead geometry of TIG welding of stainless steel. They used Taguchi method to determine the optimum welding process parameters. Tarng et al. [10] researched related to grey-based Taguchi technique to decide optimal process factors of submerged arc welding, concern of various
weld properties. Yilmaz and Uzun [11] performed the destructive tests of welding joints created by GMAW and GTAW process on austenitic stainless steel. Rawlands et al. [12] showed that Taguchi technique was the most accepted method to solve the optimization difficulties within the area of manufacturing technology.

In the present work, some experiments and analyses have been completed regarding TIG welding of duplex stainless steel. Work material, considered in the present work is duplex stainless steel UNS 2205 (UNS means unified numbering system of North America). Nine butt-welded samples are made. Dimension of each sheet is 75mm x 50mm x 3mm. TIG welding is performed using varied input parameters. The parameters are current, gas flow rate and speed of welding. Taguchi’s orthogonal array design is used to design the experiments by these controllable parameters. The levels of the parameters have been fixed based on trial runs and available literature. The effects of TIG welding process factors on ultimate tensile strength of these butt welding joints of UNS 2205 DSS have been experimented and optimized the above parameters of TIG welding using PCA method. Then, ANOVA test has been carried out to identify the significance of the individual factors on the desired responses like ultimate tensile strength, yield strength by Minitab 16.2.1.

2. Experimental work

2.1. Base metal

In the present work, duplex stainless steel (ASTM/UNS: 2205) is selected as the base material. The austenite and ferrite, both phase structures are observed in the microstructure of duplex stainless steel. After purchasing, the materials have been tested by Met-Lab Laboratory Services, recognised by Government, Public & Privet sector industries, at Mumbai-400004 to confirm about the composition of these materials. The testing results have been confirmed satisfactorily that the materials are UNS 2205 DSS. These materials are supplied by Aich Enterprise, Calcutta- 700141. The chemical composition of this base material is given in Table 1.

| Composition of UNS 2205 DSS | Composition of elements in % |
|---------------------------|-----------------------------|
| C | 0.0210 |
| Si | 0.2800 |
| Mn | 1.7200 |
| P | 0.0220 |
| S | 0.0140 |
| Cr | 22.6500 |
| Mo | 3.1800 |
| Ni | 4.7300 |
| Al | 0.0100 |
| Co | 0.0780 |
| Cu | 0.0090 |
| Nb | 0.0400 |
| Ti | 0.0080 |
| V | 0.0110 |
| Pb | 0.0030 |
| Fe | 67.123 |
| N | 0.1010 |

2.2. Experimental plan

The TIG welding process factors for DSS joints are current, gas flow rate, and speed of welding. The range of these process factors are chosen based on the experimental trials. Three levels are taken for every parameter. Welding process factors and their levels are listed in Table 2. In this work, Taguchi orthogonal array design is most appropriate for process optimization, because it uses comparatively less number of observations to get optimum result. ANOVA will be carried out to identify the significance of the individual factors with the help of PCA method on the desired responses like ultimate tensile strength, percentage elongation etc. Taguchi Orthogonal Array (3rd level design) is given in Table 3 below.
Table 2 Welding process factors with levels

| Factor            | Unit | Notation | Level |
|-------------------|------|----------|-------|
| Welding current   | Amp  | C        | 1 2   3 |
|                   |      |          | 80   85 90 |
| Gas flow rate     | l/min| F        | 7 7.5 8 |
| Speed of welding  | mm/s | S        | 2.3 2.8 3.5 |

Table 3 Taguchi’s 3rd level orthogonal array design

| Run | Welding current (C) | Gas Flow rate (F) | Welding Speed (S) |
|-----|---------------------|-------------------|-------------------|
| 1   | 1                   | 1                 | 1                 |
| 2   | 1                   | 2                 | 2                 |
| 3   | 1                   | 3                 | 3                 |
| 4   | 2                   | 1                 | 2                 |
| 5   | 2                   | 2                 | 3                 |
| 6   | 2                   | 3                 | 1                 |
| 7   | 3                   | 1                 | 3                 |
| 8   | 3                   | 2                 | 1                 |
| 9   | 3                   | 3                 | 2                 |

3. Experimental procedure
The Butt welding joints of UNS 2205 duplex stainless steel sheets have been completed by the IGBT digital welding inverter (400a, iii phase) of Electra engineering (India) Pvt. Limited. The photographic view of welding equipment is shown in Fig.1. In this welding joint, filler rod is not used. Edge preparation has not been done. Welding is performed by 2.5 mm diameter of non consumable electrode. Cup size is 3621. Tungsten shielding gas is argon used. Photographic view of welding sample no. 6 is shown in Fig. no.2.

Fig.1 The photographic view of welding equipment

Fig.2 Photographic view of welding sample no. 6
3.1. Testing of welds
After visual inspection of nine TIG welding specimens, the X-ray radiography tests are completed to determine the internal soundness of welds. Now, tensile test specimens of TIG welding samples have been prepared as per ASTM E8 standard [13] by WEDM machine to calculate yield strength, ultimate tensile strength etc.

3.2. X-ray radiography test
The X-ray radiography tests are completed for all the welding specimens. The X-ray radiography test of TIG welded DSS samples are performed at Inspection Survey & Surveillance (India) Pvt. Ltd. The results of X-ray radiography test are shown in Table 4. The X-ray radiography images of welding specimen no. 1 & 2 are shown in Fig. 3.

| Identification No. | Segment | Film Size | Technique              | Thickness (mm) | Type of joint | Observation | Remarks   |
|--------------------|---------|-----------|------------------------|----------------|---------------|-------------|-----------|
| SMP-01             | A       | 3”x6”    | Single Wall            | 3.5            | Butt          | Little undercut | Acceptable |
| SMP-02             | A       | 3”x6”    | Single Wall            | 3.5            | Butt          | No significant defects | Acceptable |
| SMP-03             | A       | 3”x6”    | Single Wall            | 3.5            | Butt          | No significant defects | Acceptable |
| SMP-04             | A       | 3”x6”    | Single Wall            | 3.5            | Butt          | No significant defects | Acceptable |
| SMP-05             | A       | 3”x6”    | Single Wall            | 3.5            | Butt          | Capping undercut   | Acceptable |
| SMP-06             | A       | 3”x6”    | Single Wall            | 3.5            | Butt          | No significant defects | Acceptable |
| SMP-07             | A       | 3”x6”    | Single Wall            | 3.5            | Butt          | No significant defects | Acceptable |
| SMP-08             | A       | 3”x6”    | Single Wall            | 3.5            | Butt          | No significant defects | Acceptable |
| SMP-09             | A       | 3”x6”    | Single Wall            | 3.5            | Butt          | No significant defects | Acceptable |
3.3. Tensile test and results
The tensile test samples have been made by Electronica Sprintcut-734 WEDM (Connected load 15 KVA, Input power supply 3 Phase, AC 415 V, 50 Hz) wire cutting machining. Photographic view of WEDM and tensile specimen preparation by WEDM are shown in Fig.4 (a) and 4(b).

As per requirement, the tensile properties i.e. ultimate tensile strength (UTS) and yield strength (YS) of the welding joints are determined. The photographic view of tensile test specimens is shown in Fig 5.

The tensile test is performed by tensile testing machine INSTRON made by Blue Star Engineering & Electronics Ltd., model no. : BSUT-60-JD-SERVO, serial no. : 2016/048. The maximum capacity of
this machine is 600 KN. Photographic view of tensile testing machine is shown in Fig.7. Photographic view of tensile sample no.6 before test and after test is also shown in Fig. 6 (a) and (b).

Data related to tensile strength are tabulated in Table 5. All these data are analysed by PCA method. The optimal parameter combination is also determined to achieve the desire quality of weld within experimental domain.

| Sample No. | Yield Strength (MPa) | Ultimate Tensile Strength (MPa) |
|------------|----------------------|---------------------------------|
| 1          | 183.3                | 460                             |
| 2          | 236.7                | 595                             |
| 3          | 253.3                | 635                             |
| 4          | 243.3                | 610                             |
| 5          | 260                  | 645                             |
| 6          | 253.3                | 630                             |
| 7          | 256.7                | 640                             |
| 8          | 243.3                | 610                             |
| 9          | 260                  | 650                             |

4. Optimization by using principal component analyses (PCA)

At first, the experimental data of yield strength and ultimate tensile strength are converted into S/N ratio for analysis using PCA method. S/N ratio of yield strength and ultimate tensile strength are shown in table no.6. According to this technique, two types of S/N ratios are categorised. One is lower the better (LB) and another is higher the better (HB). The S/N ratios of LB and HB are calculated with the help of equation 1 and 2 respectively. Then, investigational results (Table 5) are normalized. The main purpose is to maximize the experimental results. Here, Higher-the-Better (HB) criteria are considered. Results are normalized by the following equations:

(a) LB (lower the better)
\[
\gamma_{ij} = -10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} y_i^{-2} \right]
\]  

(b) HB (higher the better)
\[
\gamma_{ij} = -10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right]
\]

Where, \( y_{ij} \) denotes the S/N ratios \( i^{th} \) experiment and \( j^{th} \) response calculated from observed values, \( y_i \) represents the experimentally observed value of the \( i^{th} \) experiment and \( n=1 \) is the repeated number of every experiment of L9 orthogonal array. After normalization of results, verification is completed whether responses are correlated or not, by Minitab.

Then, the Eigen vector, Eigen value, accountability proportion (AP) and cumulative accountability proportion (CAP) are calculated. Eigen analysis of the correlation matrix is given in Table no.7.
Table 6: S/N ratio of Yield strength (YS) and ultimate tensile strength (UTS)

| Sl. No. | SN-YS   | SN-UTS   |
|---------|---------|----------|
| 1       | -45.2632| -53.2552 |
| 2       | -47.484 | -55.4903 |
| 3       | -48.0727| -56.0555 |
| 4       | -47.7228| -55.7066 |
| 5       | -48.2995| -56.1912 |
| 6       | -48.0727| -55.9868 |
| 7       | -48.1885| -56.1236 |
| 8       | -47.7228| -55.7066 |
| 9       | -48.2995| -56.2583 |

Table 7: Eigen analysis of the correlation matrix

| Variable | Eigen vectors |
|----------|---------------|
|          | PC1         | PC2        |
| SN-YS    | 0.707       | 0.707      |
| SN-UTS   | 0.707       | -0.707     |

Eigen value

| Eigen value | \(\xi_1\) | \(\xi_2\) |
|-------------|------------|------------|
|             | 1.9991     | 0.0009     |

The equation MPI = \(\xi_1 \times 1.000 + \xi_2 \times 0.000\) is used to calculate the Multi-response Performance Index (MPI). The MPI results are considered as the single objective function. These are optimised to get the optimum result. The factorial combination that maximized MPI is the optimal parametric arrangement. This parametric arrangement of process parameters is ensured the high tensile strength of the TIG weld joint of DSS. The principal components and calculated MPI are tabulated in Table 8. Optimal setting is determined by the plot (Fig. 7). The optimum arrangement becomes C1F1S1 that means welding current is 80 Amp, gas flow rate is 7 l/min and speed of welding is 2.3 mm/sec. The confirmatory test verifies this optimum result. The result of S/N ratio for MPI is 33.1149. In confirmatory experiment, this result becomes 34.0920. Therefore, this optimum welding process parameter setting has improved the welding quality.
Table 8 Principal components and calculated MPI

| Sample no. | SN-Yield Strength (MPa) | SN-Ultimate Tensile Strength (MPa) | Calculated MPI |
|------------|-------------------------|-------------------------------|----------------|
| 1          | -45.2632                | -53.2552                      | -45.2632       |
| 2          | -47.484                 | -55.4903                      | -47.484        |
| 3          | -48.0727                | -56.0555                      | -48.0727       |
| 4          | -47.7228                | -55.7066                      | -47.7228       |
| 5          | -48.2995                | -56.1912                      | -48.2995       |
| 6          | -48.0727                | -55.9868                      | -48.0727       |
| 7          | -48.1885                | -56.1236                      | -48.1885       |
| 8          | -47.7228                | -55.7066                      | -47.7228       |
| 9          | -48.2995                | -56.2583                      | -48.2995       |

Fig.7 Main Effect plots of the MPI (S/N ratio)

5. Conclusions
Based on the result of present investigation and analysis of the experimental data of TIG welding of duplex stainless steel, the following conclusions come out:

i. In optimum weld process parametric combination, TIG welding of duple stainless steel provides satisfactory butt welding joints.

ii. X-ray radiography results show some welding defects under some parametric conditions (in correspondence with welded specimen nos. 1 and 5). But, most of welding samples are defect free.

iii. The welding joints which are made by proper process parameters combination provide good ultimate tensile strength.

iv. Optimum parametric combination is successfully evaluated by the mean main effect plot. The optimum weld process parametric setting becomes C1F1S1 that means welding current is 80 Amp, gas flow rate is 7 l/min and speed of welding is 2.3 mm/sec.

v. Principal component analyses (PCA) and Taguchi method are mostly capable for satisfactory analysis and optimization of welding process parameters on the desired responses like ultimate tensile strength, yield strength.

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