Optimization of process parameters in friction welding of super duplex stainless steel

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Abstract. Super duplex stainless steel (SDSS) of grade UNS 32750 is a material with high corrosive resistance and strength. Due to these properties SDSS finds application in chemical, and oil industries. Welding plays a crucial role in the above industries for fabricating crucial components. Among the various welding processes, friction welding is least explored in joining SDSS. In this work, Friction welding was used to join SDSS in order to get properties required for oil industries. Welding trials were done based on L9 Taguchi array carried out with friction load (kg), friction time (s), forge load (kg) and forge time (s) as input parameters. The weld quality was assessed by measuring tensile strength and hardness. Grey Relational Analysis was used to identify the optimised parameter combinations. From GRA, it is understood that the optimised parameter combination lies outside L9 welding trials. Confirmation test was done based on the GRA predicted optimised parameters and the experimental results were found to be in good agreement with the predicted values. The metallurgical aspects of the weld are also discussed with the help of microstructures taken through optical microscope.

1. Introduction:
Super duplex stainless steel (SDSS) alloy contains high amount of molybdenum (3 %) and chromium (24 %) and owing to these composition, SDSS possesses high yield strength and pitting resistance [1, 2]. SDSS alloy consists of an equal percentage of austenite and ferrite which helps in getting better strength and ductility. Ease in fabrication and weldability makes SDSS the most suitable material for a variety of applications in chemical industry products such as pipe fittings, tubes, sheets and round bars [3, 4]. Due to its high corrosion resistance, SDSS is used in the piping systems of oil & gas industry, marine application, offshore oil production, chemical process pressure vessels, piping and heat exchangers. In fabrication of the above said components welding plays a crucial role. Joining of SDSS is explored to a large extent by fusion welding processes. As the material is subjected to melting point in fusion welding processes, the properties are hugely affected after welding. It also results in the formation of defects such as cracks, pores and bigger heat affected zone. Saravanan et al. [5] joined SDSS using laser welding process and the authors were able to achieve full penetration for all the welding trails. The authors observed a trend of decrease in weld tensile strength with increase in heat input. The strength of the weld was lower than the base metal owing to the variations in the volume fraction of ferrite and austenite. Devendranath Ramkumar et al. [6] welded SDSS using electron beam welding process and the authors observed austenitic structure formed in the weld is similar to the base metal. But, the authors observed a significant reduction in the strength and hardness owning to the
formation of minute cracks and coarser grains in the weld zone. In order to overcome the reduction of mechanical properties after welding, other options such as solid state welding processes should be explored. Friction welding is one of the important solid state welding processes, where two materials are joined with the applications of heat and pressure [7].

Udayakumar et al joined SDSS using Friction welding process and the authors were able to achieve reasonable strength and hardness owing to the formation of fine grains in the weld zone. The fracture surface from the tensile test specimen revealed dimples signifying the ductile mode of fracture [8]. Successful implementation of any process on a particular material depends on the selection of correct combinations of input parameters. Soft load (kg), rotation speed (rpm), cooling time (s), friction load (kg), friction time (s), forge load (kg) and forge time (s) are the major input parameters associated with friction welding process [9]. One of the easiest way to identify the optimised parameters is the usage of some multi objective optimisation techniques. Grey relation analysis is one of the multi objective optimisation techniques and it is widely used in all the manufacturing processes. GRA has the capability to identify the optimised parameter combinations even with lesser data [10]. GRA convert the multiobjective function into a single objective using number of steps. Ramesh T et al successfully identified the best parameter combination in laser welding of NiTinol using GRA [11]. Similarly, Sahu et al and Srinivasan L et al recommended to use GRA for identifying the optimised parameters as the results obtained in their work were satisfactory [12, 13]. Analysis of variance (ANOVA) is a statistical method that collects data and helps to identify the most influencing parameter on an objective function [14, 15]. ANOVA is widely used in the manufacturing processes to understand the individual parameter effect on the objective function. Sampreet et al successfully used ANOVA to find out the most influencing welding parameter of CO2 laser welded hastelloy C-276 [16].

From the above literatures, it is understood that welding of SDSS plays a key role in the oil and gas industries. It is also understood that most of the work related to joining of SDSS is done using fusion welding process and friction welding process is least explored. Hence in this work, an attempt is made to investigate the joining of SDDS rods using friction welding process. In addition to that, an attempt is made to identify the optimised parameter combination using GRA optimisation technique. ANOVA was also used to identify the significant factors in friction welding of SDSS.

2. Experimental procedure
Super Duplex Stainless Steel cylindrical rod of 10mm diameter was used throughout the study. The material composition of the specimen is tabulated in Table 1.

| Elements | Cr     | Ni     | Mo     | N     | Cu | C   | Mn   | P   | S   | Si |
|----------|--------|--------|--------|-------|----|-----|------|-----|-----|----|
|          | 24.0-26.0 | 0.24-0.32 | 3.0-5.0 | 0.24-0.32 | 0.5 | 0.030 | 1.20 | 0.035 | 0.02 | 0.8 |
| Composition | Max   | Max   | Max   | Max   | Max | Max |

Friction welding machine with a maximum capacity of 10 Tonne were used in this work and the picture of the same is presented in Figure 1.
Welding trials were done based on the L9 Taguchi array. Four welding parameters namely forge load (kg), forge time (s), friction load (kg) and friction time (s) were considered as input parameters. The input parameters along with the levels are presented in Table 2.

Table 2. Level of Parameters.

| Factors            | Level 1 | Level 2 | Level 3 |
|--------------------|---------|---------|---------|
| Friction load (Kg)| 750     | 800     | 850     |
| Friction time (S)  | 4       | 5       | 6       |
| Forge load (Kg)    | 900     | 1000    | 1100    |
| Forge time (S)     | 5       | 6       | 7       |

The L9 taguchi array with both input and output parameter is presented in Table 3.

Table 3. Design of Experiments.

| Trial Number | Friction load (Kg) | Friction time (S) | Forge load (Kg) | Forge time (S) | Tensile Strength (MPa) | Weld Zone (HRC) | Heat Affected Zone (HRC) |
|--------------|--------------------|-------------------|-----------------|----------------|------------------------|-----------------|--------------------------|
| 1            | 750                | 4                 | 900             | 5              | 743.73                 | 61.6            | 61.16                    |
| 2            | 750                | 5                 | 1000            | 6              | 619.31                 | 58.8            | 57.66                    |
| 3            | 750                | 6                 | 1100            | 7              | 682.80                 | 57.03           | 62.2                     |
| 4            | 800                | 4                 | 1000            | 7              | 511.26                 | 54.40           | 55.34                    |
| 5            | 800                | 5                 | 1100            | 5              | 657.75                 | 53.16           | 55.6                     |
| 6            | 800                | 6                 | 900             | 6              | 661.70                 | 60              | 60.9                     |
| 7            | 850                | 4                 | 1100            | 6              | 651.21                 | 56.7            | 57.2                     |
| 8            | 850                | 5                 | 900             | 7              | 737.67                 | 52.5            | 55.3                     |
| 9            | 850                | 6                 | 1000            | 5              | 779.56                 | 54.1            | 54.6                     |

The rods welded through friction welding machine are presented in Figure 2.
After welding, welded samples were cut along the cross section using a wire cut EDM machine and the samples were mounted using cold mounting powder and liquid. Initially, the samples were polished using an emery sheet followed by cloth polishing. The polished samples were etched using kalling’s reagent for 15 seconds. Microstructure was taken with the help of an optical microscope at 100 X Magnification. Tensile test was carried out using the Universal testing machine (UTM). Tensile Specimens were prepared based on the standard ASTM E8-04. The gauge length was maintained at 45 mm and the strain rate was maintained at 1 mm/min. Hardness was measured using a digital Rockwell hardness testing machine and the test was done based on the standard ASTM E18-03. 150 Kgf load was applied through a diamond cone indenter and the dwell time was around 10 seconds.

3. Results and discussions

3.1. Tensile test

Tensile test was done for all the samples and the ultimate tensile strength values of the same are presented in Figure 3.
All samples broke in the weld zone indicating that weld zone is the weakest. Base metal tensile strength was in the range of 800 MPa. All the welds had tensile strength lower than the base metal. From the above figure, it can be seen that weld obtained through 9th experimental run had highest tensile strength and the weld obtained through 4th experimental run had least tensile strength. Taguchi analysis was used to understand the effect of individual parameters on the Tensile strength. The main effect plot for tensile strength is presented in Figure 4.

From the above figure it is clear that, the tensile strength was found to increase with increase in Friction time, whereas for all the remaining parameters, the tensile strength decreased first and then again showed an increasing trend. Maximum variation in tensile strength was found for forge time variation followed by friction time, forge load and friction load respectively.

3.2. Rockwell Hardness Test
Base metal had a hardness value of 57.1 HRC. Hardness was measured in different zones of the weld along the transverse direction. Five values were taken and the average value is plotted in the Figure 5. The hardness variation between the different zones of the weld was very less. The Weld region found to have slightly lesser hardness than the heat affected zone. Weld obtained through the first welding parameter combination had a maximum hardness value (61.6 HRC). Graph representing Hardness values at weld zone, left interface and right interface has been presented in Figure 5.
Taguchi analysis was implemented to study the effect of individual parameters on the hardness value. The mean effect plot for hardness is presented in Figure 6.

![Main Effects Plot for Hardness at Weld Zone](image)

**Figure 6.** Mean Effect Plot for Hardness.

From the mean effect plot for hardness, it is inferred that with increase in friction load, forge load, the hardness value was found to decrease continuously. Whereas, the hardness first decreased with increase in friction time but on reaching third level, again hardness increased.

### 3.3. Grey Relation Analysis

GRA is a multiobjective optimization technique which is broadly used in the manufacturing processes for identifying the optimised parameter combinations. The steps in GRA as follows,

I. Normalization of output responses
II. Identifying sequential Normalized values
III. Computing Grey relational coefficient
IV. Calculation of GRG
V. Ranking based on the GRG value.

Normalization for maximisation criteria is calculated using the Equation 1,

\[
G_i^* (V) = \frac{g_i(V) - \min g_i(V)}{\max g_i(V) - \min g_i(V)} \quad \text{.....(1)}
\]

Where, 
\(i = 1 \ldots w\)
\(V = 1, 2, 3 \ldots q\)
\(w=\) number of trails
\(q=\) number of responses
\(g_i=\) original order
\(G_i^*=\) value after GRG

Min \(g_i (V)\) and max \(g_i (V)\) are the minimum value of \(g_i (V)\) and maximum value of \(g_i (V)\) respectively. For the smaller criterion, Normalization is done using the equation 2,

\[
G_i^* (V) = \frac{\max g_i(V) - g_i(V)}{\max g_i(V) - \min g_i(V)} \quad \text{.....(2)}
\]

Normalized values of tensile strength and hardness were calculated and presented in Table 4.
## Table 4. Normalized value table

| Specimen number | Tensile strength | Hardness | Heat affected zone |
|-----------------|-----------------|---------|-------------------|
| 1               | 0.866           | 1       | 0.8631            |
| 2               | 0.4027          | 0.6923  | 0.4026            |
| 3               | 0.6393          | 0.4978  | 1                 |
| 4               | 0               | 0.2087  | 0.0973            |
| 5               | 0.5459          | 0.0725  | 0.1315            |
| 6               | 0.5607          | 0.8241  | 0.8289            |
| 7               | 0.5178          | 0.4615  | 0.3421            |
| 8               | 0.8438          | 0       | 0.0921            |
| 9               | 1               | 0.1758  | 0                 |

### 3.3.1. Grey Relational Coefficient (GRC)

Grey relation analysis is used to assess two systems relationship. The GRC is calculated by equation 3,

\[ \mu_i(V) = \frac{\Delta p + \tau \Delta \text{max}}{\Delta o_i(K) + \tau \Delta \text{max}} \]  

\[ \Delta o_i(K) \] is the difference between \( G_o*(k) \) and \( G_i*(k) \). 

\( G_o*(k) \) = reference progression. 

\( \Delta \text{max} \) = largest value of \( \Delta o_i(V) \). 

\( \Delta \text{min} \) = smallest value of \( \Delta o_i(V) \), the coefficient (\( \tau \)) is taken as 0.5.

### 3.3.2. Grey Relation Grade

The grey relational grade (GRG) is attained by taking average of the grey relation coefficient. The GRC and grey relation grade was calculated and presented in Table 5.

## Table 5. GRC, GRG, Rank table.

| Tensile strength | Hardness | Grey Relation Grade | Rank |
|------------------|----------|---------------------|------|
|                  | Weld zone| Heat affected zone  |      |
| 0.3659           | 0.3333   | 0.3667              | 0.3553 | 9 |
| 0.5538           | 0.4193   | 0.5539              | 0.5090 | 6 |
| 0.4388           | 0.5011   | 0.3333              | 0.4244 | 7 |
| 1                | 0.7054   | 0.8370              | 0.8474 | 1 |
| 0.4780           | 0.8733   | 0.7916              | 0.7143 | 3 |
| 0.4713           | 0.3775   | 0.3762              | 0.4084 | 8 |
| 0.4894           | 0.52     | 0.5937              | 0.5343 | 5 |
| 0.3720           | 1        | 0.8444              | 0.7388 | 2 |
| 0.3333           | 0.7398   | 1                   | 0.6910 | 4 |
3.3.3. Response matrix

Using GRG values of all experimental run, response table was calculated and the same is presented in Table 6.

| Level | Friction load (Kg) | Friction time (S) | Forge load (Kg) | Forge time (S) |
|-------|--------------------|------------------|----------------|---------------|
| 1     | 0.4296             | 0.579            | 0.5008         | 0.5869        |
| 2     | **0.6567**         | **0.654**        | **0.6825**     | 0.4839        |
| 3     | 0.6547             | 0.5079           | 0.5577         | **0.6702**    |
| Delta | 0.2271             | 0.1461           | 0.1816         | 0.1862        |
| Rank  | 1                  | 4                | 3              | 2             |

From response table it is clear that the A2B2C2D3 is the optimised parameter combination. The optimised parameter combination is outside the L9 taguchi array and hence the confirmation test was carried out.

3.3.4. Confirmation Test

The Predicted GRG value for the optimised parameter combination is calculated using Equation 4,

\[ e = \bar{a} + \sum (\alpha - \bar{a}_m) \quad \ldots \ldots \quad (4) \]

Where \( \bar{a}_m \) is average of GRG values, \( \alpha \) is the mean of GRG at the optimum level. The optimized parameters are presented in Table 7.

| Setting level          | Initial Values | Prediction | Experiment |
|------------------------|----------------|------------|------------|
| Tensile strength       | 743.73         | -          | 773.3      |
| Weld zone-Hardness     | 61.6           | -          | 61.02      |
| HAZ-Hardness           | 61.16          | -          | 61.40      |
| GRG                    | 0.3553         | 0.92229    | 0.9364     |

From Table 7, it is understood that the confirmation test results are in good agreement with the predicted GRA values. The percentage deviation from the predicted GRG value is 1.4%.

3.3.5. Analysis of variance

Analysis of variance (ANOVA) was used to compute the contribution of each input parameters on the multi performance characteristics and it is tabulated in Table 8.
Table 8. Analysis of Variance.

| Source            | S    | J      | M      | L      | Contribution (%) |
|-------------------|------|--------|--------|--------|------------------|
| Friction Load (Kg)| 2    | 0.10228| 0.05114| 0.8581 | 42.91            |
| Friction Time (S) | 2    | 0.03203| 0.01601| 0.2686 | 13.43            |
| Forge Load (Kg)   | 2    | 0.05181| 0.02590| 0.4346 | 21.73            |
| Forge Time (S)    | 2    | 0.05225| 0.02612| 0.4383 | 21.91            |
| Error             | 0    |        |        |        |                  |
| Total             | 8    | 0.24489|        | 1.9996 |                  |
| Pooled Error      | 4    | 0.08384| 0.05959|        |                  |

In the above table, S, J, M denotes degree of freedom, adjusted sum of squares, adjusted mean sum of square respectively.

From the ANOVA table and pie chart (Figure 7.) it is clear that friction load is the most prominent parameter followed by forge time, forge load and friction time respectively.

![Figure 7. Pie chart for ANOVA results.](image)

3.4. Microstructural Analysis

The microstructure of the optimised weld is shown in Figure 8. The microstructure of all the specimens are taken at 100X magnification. The grains in the optimised weld was coarser. The grain size was measured based on average grain size method and the grain size was around 8 µm. Austenite and ferrite phases were clearly visible in the weld and the same is marked in the microstructure.
4. Conclusions
The super duplex stainless steel UNS32750 was successfully welded using friction welding machine. The microstructure and mechanical properties of the weldments were analysed and the following results were inferred,

1. Friction load had significant control on the welded specimens tensile strength and hardness, whereas the forge load has minimal influence on the weld mechanical property.
2. Based GRA results, the optimised parameter combination in order to achieve better tensile strength and hardness is A2B2C2D3.
3. The GRA Predicted results are in good agreement with the confirmation test.

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