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Original scientific paper

Multi-Objective Optimization in Friction Welding Process Parameters on EN353 Alloy Steel using Taguchi based GRA

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Abstract: Joining of similar materials by varying the input factors on a continuous drive friction welding process is done in this study. The intention is to find the optimal solution in friction welding input process parameters. Among several types of welding processes, friction welding forms good metal joints. The process factors considered for this material joining practice are Upset Time (*UT*), Heating Time (*HT*), Heating Pressure (*HP*), Upset Pressure (*UP*), chemical composition and measurements of the materials. Frictional joints provide better mechanical properties, hence it is attracted by researchers. Here, EN353 is used as the specimen, for its extensive usage in the automobile and manufacturing sectors. Axial shortening, hardness testing and the temperature during welding are evaluated, compared and optimized using Taguchi Design of Experiments (DoE) scheme using L27 orthogonal array and Grey Relational Analysis (GRA).

Keywords: design of experiments; friction welding parameters; mechanical properties; optimizing method; output responses; welding procedure

1 INTRODUCTION

Friction welding is a type of metal joining method by employing heat and pressure. Numerous scholars have contributed to numerous welding methods used to combine metals. In this investigational study, the input process parameters chosen are normally *UT*, *HT*, *HP* and *UP*.

Peng Li et al. [1] investigated the joining procedure of dissimilar aluminium/steel materials, mechanical performance and its joining face microstructural analysis using refilled friction stir spot welding. Omar S Salih, et al. [2] conducted the control of procedure parameters in microstructural development and characterization of Al-Mg-Si alloy welded friction. Feng Jin et al. [3] examined friction co-efficient form and combined formation in rotating friction welding of SUS304 and A286 stainless steels. In this model, distributions of friction heat were analyzed through MAT Lab analysis. Yu Su et al. [4] analysed the microstructure as well as physical characteristics of high carbon rail steel to bonding factors in linear friction welding. Xinyu Wang et al. [5] assessed the effects of welding process factors on surface distribution, microstructure and mechanical characteristics of a Ti-6.5Al-3.5Mo-1.5Zr-0.3Si titanium alloy joint during linear friction welding. T.J. Ma et al. [6] assessed the hard solution toughened Ni based super alloy using linear friction welding using various process factors. Grain structure and the mechanical performance were analyzed. The linking of molybdenum and TZM parts was found to be more complicated by Stutz et al. [7] owing to the greater difference in thermal and mechanical characteristics. El-oualid Bouarroudji et al. [8] found the optimum friction time to get the needed temperature for better joints. To evaluate the optimal welding conditions, researchers used numerical modeling and thermal analysis. Meisnar et al. [9] analyzed the weld interface and micro structural properties of unrelated materials AA6082 and Ti-6Al-4V rotating frictional joints. Kannan et al. [10] used the friction welding procedure to explore the dissimilar mechanical and metallurgical characteristics of joining EN24 and ETP copper. Rupinder Singh et al. [11] showed the use of metal fine particle corroboration to optimize frictional joints of unrelated plastic/polymer components for production purposes. FurkanSarsilmaz et al. [12] used the friction welding method to test the microstructure and mechanical description of duplex steel joints AISI2205 and Armor 500 steel at various joining factors. Packiaraj Rajendran et al. [13] considered the improved quality of strength and microhardness of friction welded joints of mild steel AISI 1010 and high-carbon high-chromium steel D3 after the post weld heat treatment process. Ramu et al. [14] used ANOVA and GRA techniques to investigate the feed, depth of cut and speed to optimize MRR values and surface irregularity in CNC machines. From GRA, the authors concluded that cut depth plays a vital role in turning parameters followed by speed and feed. Palanisamy Angappan et al. [15] optimized the machining factors, impact on Taguchi's source along with GRA by turning an 800H incoloy. SenthilkumarVagheesan et al. [16] studied the quality characteristics of aluminium alloy in the CO_2 laser cutting process and concluded that ANN-GA method can be effectively applied to the process factors to obtain the best output. The axial shortening properties of AISI 4340 by friction welding were investigated by Ganesan et al. [17]. The authors concluded that 'larger is better' conditions have a stronger bonding condition than other combinations of process parameters, and in the welded friction joints, *HT* plays a vital role.

2 MATERIALS AND METHODS
2.1 Investigational Work

The investigational setup consists of a KUKA continuous drive friction welding machine, Rockwell hardness apparatus, and measuring instruments like digital vernier caliper, weighing machine and IC thermometer.

Table 1 Friction Welding Process Factors

S.No.	Input Parameters	Units	Levels		
			1	2	3
1	HP	bar	12	19	25
2	HT	s	3	5	7
3	UP	bar	22	29	35
4	UT	s	3	5	7

The L27 orthogonal array is best focused on Taguchi's method to accomplish the analysis with controllable factors which was proposed by Kus et al. [18]. The dimensions of the test specimen selected are 100 mm in length, 16 mm in diameter and a constant rotational speed of 1500 rpm. Fig. 1 shows samples after joining. The *UT*, *HT*, *HP* and *UP* to expand the fine value of frictional joints are given in Tab. 1.

The specimen composition of chemicals is presented in Tab. 2.

Table 2 Chemical composition of base metal by wt %

Elements	Mn	C	Ni	Si	S	Cr	Mo	P	Fe
Composition	0.57	0.16	1.05	0.25	0.03	0.95	0.12	0.03	Remaining

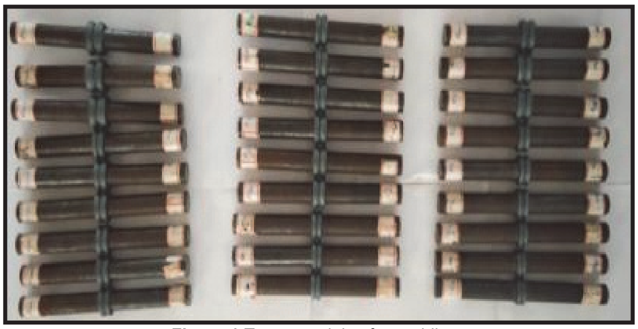

Figure 1 Test materials after welding

3 RESULTS AND DISCUSSION

The findings of different measures, such as axial shortening, hardness tests, and temperature tests, are presented.

3.1 Optimization of Axial Shortening

The axial shortening is the difference between the length of the specimen before welding and after welding. It is done using digital vernier caliper to find the shrink length of the specimen and find the optimal process parameters. A specimen's axial shortening is due to developing a flash. It is measured as a material loss and known as burn off. Optimization of the burn off length must be done to have sufficient strength in the joints. Tab. 3 shows the research findings of this analysis as well as the S/N ratio measured using Minitab tools given in Eq. (1).

The output result is investigated as an outcome of input factors in frictional welding of EN353 alloy. Thus the 'larger is better' method is selected for this investigation. The correlation between input and output responses is displayed in Tab. 4. From the response table, the authors found that HT plays a dominating part in this experimental investigation. Fig. 2 depicts the key influence of input process factors in the axial shortening of EN353steel frictional joining.

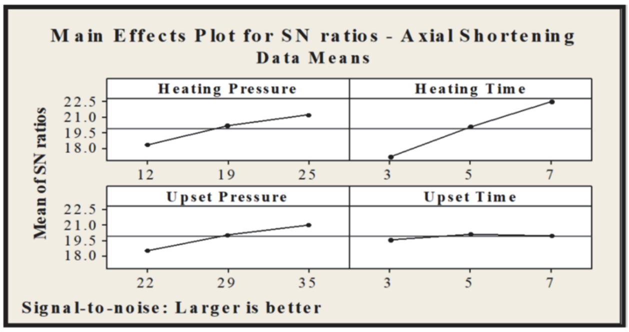

Figure 2 Axial Shortening - Main Effect Plot

Table 3 Investigational Results for Axial Shortening, Hardness and Temperature

Exp No.	Axial Shortening / mm	S/N Ratio	Hardness / RHN	S/N Ratio	Temperature / ºC	S/N Ratio
1	4.88	13.85	103	40.45	276.0	48.77
2	4.92	13.85	106	40.45	277.8	48.77
3	4.98	13.85	107	40.45	270.0	48.77
4	8.88	18.95	100	40.02	345.0	50.78
5	8.80	18.95	99	40.02	350.0	50.78
6	8.90	18.95	102	40.02	344.0	50.78
7	12.90	22.18	98	39.82	340.8	50.76
8	12.80	22.18	97	39.82	345.0	50.76
9	12.85	22.18	99	39.82	350.0	50.76
10	7.70	17.69	101	40.14	314.0	49.88
11	7.66	17.69	100	40.14	302.0	49.88
12	7.64	17.69	104	40.14	321.0	49.88
13	11.45	21.23	97	39.76	383.5	51.62
14	11.52	21.23	96	39.76	381.5	51.62
15	11.58	21.23	99	39.76	379.0	51.62
16	12.13	21.68	97	39.82	351.0	50.84
17	12.12	21.68	99	39.82	347.0	50.84
18	12.14	21.68	98	39.82	348.0	50.84
19	9.80	19.80	99	39.91	357.0	51.36
20	9.78	19.80	101	39.91	378.4	51.36
21	9.76	19.80	97	39.91	376.0	51.36
22	10.14	20.12	96	39.71	413.0	52.58
23	10.12	20.12	97	39.71	438.0	52.58
24	10.16	20.12	97	39.71	428.0	52.58
25	15.35	23.72	98	39.85	481.0	53.59
26	15.40	23.72	99	39.85	480.6	53.59
27	15.30	23.72	98	39.85	473.0	53.59

The effective stage of input parameters in this investigation is dealt by utmost rate throughout the main effect chart. Starting with this chart, it is shown clearly the influence of each input process parameter increases as the number of variables increases. Analysis of variance is an arithmetical approach employed to estimate the difference between data sets. With the hold up of ANOVA table in Tab. 5, the influence of different friction welding factors is established. It has been discovered that *HT* has a major effect on the axial shortening of the friction welded joint.

$$Equation\ for\ calculating\ S/N\ ratio = -10\cdot\log\left(\Sigma\left(1/Y^2\right)/n\right) \quad (1)$$

Table 4 S/N Ratio - Response Table

Level	*HP* / bar	*HT* / s	*UP* / bar	*UT* / s
1	18.33	17.12	18.55	19.60
2	20.20	20.10	20.12	20.14
3	21.22	22.53	21.07	20.00
Delta	2.89	5.41	2.52	0.54
Rank	2	1	3	4

Table 5 Axial Shortening - Analysis of Variance Table

Source	d*F*	*Seq SS*	*Adj SS*	*Adj MS*	*F*-value	*P*- value	% of Contribution
HP / bar	2	37.354	37.354	18.677	10249.47	0.000	16.6036
HT / s	2	161.686	161.686	80.843	44364.99	0.000	71.8684
UP / bar	2	25.119	25.119	12.560	6892.48	0.000	11.1652
UT / s	2	0.784	0.784	0.392	215.13	0.000	0.3485
Error	18	0.033	0.033	0.002	--	--	0.0147
Total	26	224.975	--	--	--	--	100
S = 0.0426875 *R-Sq* = 99.99% *R-Sq*(*adj*) = 99.98%							

The regression equation:

$$Axial\ Shortening = -5.93 + 0.221\cdot HP + 1.50\cdot HT + 0.179\cdot UP - 0.0947\cdot UT$$

$$S = 0.235601,\ R-Sq = 99.5\%,\ R-Sq(adj) = 99.4\%$$

3.2 Optimization of Hardness

The Rockwell hardness machine is used to evaluate the hardness of the weld by a number of input factors. Tab. 3 displays the experimental results of this analysis as well as the S/N ratio measured using software and Eq. (1). The friction welding of EN353 is chosen as a result of input process variables. The collected results will be investigated, and the state of 'larger is better' will be used for this inquiry.

Table 6 S/N Ratio - Response Table

Level	*HP* / bar	*HT* / s	*UP* / bar	*UT* / s
1	40.10	40.17	39.99	40.02
2	39.91	39.83	40.01	39.92
3	39.82	39.83	39.83	39.89
Delta	0.28	0.33	0.17	0.13
Rank	2	1	3	4

Correlation between input and output responses is offered in Tab. 6. Based on the response table, the authors found that *HT* plays a major dominating role in this experimental investigation followed by *HP*, *UT* and *UP*. The friction welding process in joining related materials EN353 alloy, selected for this examination, the associations involving the input factors with their output responses are presented in the main effect plot as revealed in Fig. 3.

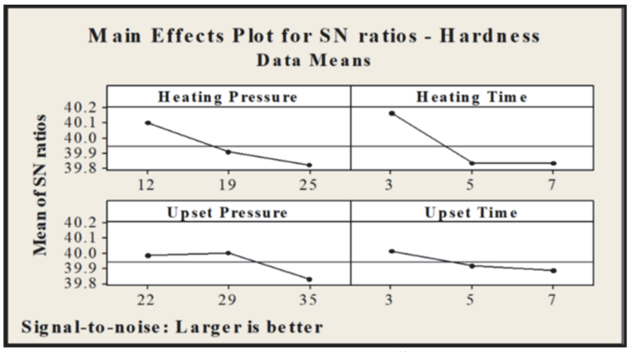

Figure 3 Hardness - Main effect plot

Analysis of variance is a statistical method for evaluating the sum of differences in a series of variables. The control of various friction welding factors is identified with the help of ANOVA Tab. 7. It has been discovered that *HT* is the most significant factor influencing the hardness of EN353 joints.

Table 7 Hardness - Analysis of Variance Table

Source	d*F*	*Seq SS*	*Adj SS*	*Adj MS*	*F*-value	*P*- value	% of Contribution
HP / bar	2	48.963	48.963	24.481	11.02	0.001	22.8246
HT / s	2	90.741	90.741	45.370	20.42	0.000	42.2997
UP / bar	2	22.741	22.741	11.370	5.12	0.017	10.6009
UT (s)	2	12.074	12.074	6.037	2.72	0.093	5.6284
Error	18	40.000	40.000	2.222	--	--	18.6464
Total	26	214.519	--	--	--	--	100
S = 1.49071 R-Sq = 81.35% R-Sq(adj) = 73.07%							

The regression equation:

$$Hardness = 115 - 0.250 \cdot HP - 0.972 \cdot HT -$$
$$-0.141 \cdot UP - 0.389 \cdot UT$$
$$S = 1.82051,\ R - Sq = 66.0\%,\ R - Sq(adj) = 59.8\%$$

The hardness of the base metal before friction welding process is 72 RHN and the target value is calculated using regression equation as 104 RHN.

3.3 Optimization of Temperature

The temperature produced at the interfaces during the friction welding process is high. For this survey, the machining parameters used are *UP*, *HP*, *UT* and *HT*. The orthogonal Taguchi L27 array is used for experimentation. Tab. 3 shows the experimental parameters, its temperature along with its corresponding signal to noise ratio using the Eq. (1). The result of input process factors in friction welding material EN353 alloy is selected and the output response, temperature is investigated and 'larger is better' position is preferred for this study. The connection between inputs to output responses is offered in Tab. 8. According to this table, the authors found that *HP* acts as a major dominating character in this experimental investigation, followed by *HT*, *UP* and *UT*. The link between the input factors and the output responses is presented in main effect plot as exposed in Fig. 4.

Table 8 S/N Ratio - Response Table

Level	*HP* / bar	*HT* / s	*UP* / bar	*UT* / s
1	50.11	50.01	50.74	51.33
2	50.79	51.67	51.42	51.00
3	52.51	51.73	51.25	51.08
Delta	2.41	1.73	0.69	0.33
Rank	1	2	3	4

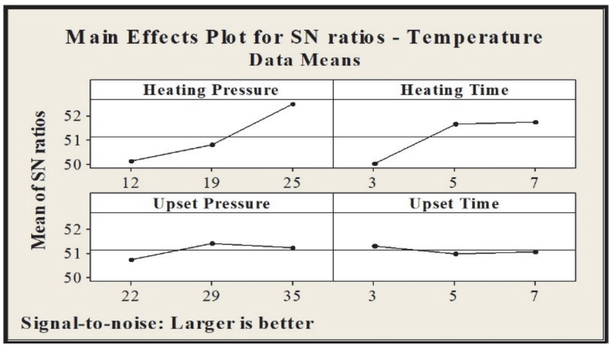

Figure 4 Temperature - Main Effect Plot

This figure confirms the best possible input process factors for experimentation. The arithmetical technique analysis of variance is employed to calculate various values of input variables. Tab. 9 represents the results of input factors that control the temperature. *HT* is found to be the most significant element in deciding the temperature of the EN353 welded joint.

Table 9 Temperatures - Analysis of Variance Table

Source	d*F*	*Seq SS*	*Adj SS*	*Adj MS*	*F*-value	*P*- value	% of Contribution
HP / bar	2	51763	51763	25881	499.76	0.000	59.2247
HT / s	2	28364	28364	14182	273.85	0.000	32.4527
UP / bar	2	3818	3818	1909	36.86	0.000	4.3684
UT (s)	2	2525	2525	1263	24.38	0.000	2.8889
Error	18	932	932	52	--	--	1.0663
Total	26	87401	--	--	--	--	100
S = 7.19632, R-Sq = 98.93%, R-$Sq(adj)$ = 98.46%							

Table 10 GRG Ranks and Confirmation Results

Exp No.	*HP* / bar	*HT* / s	*UP* / bar	*UT* / s	*Grey Grade*	*Rank*	*Predicted Value*
1	12	3	22	3	0.5555	2	0.5117
2	12	3	22	3	0.5555	2	0.5117
3	12	3	22	3	0.5555	2	0.5117
4	12	5	29	5	0.4797	8	0.5003
5	12	5	29	5	0.4797	8	0.5003
6	12	5	29	5	0.4797	8	0.5003
7	12	7	35	7	0.5315	4	0.4903
8	12	7	35	7	0.5315	4	0.4903
9	12	7	35	7	0.5315	4	0.4903
10	19	3	29	7	0.4636	9	0.4345
11	19	3	29	7	0.4636	9	0.4345
12	19	3	29	7	0.4636	9	0.4345
13	19	5	35	3	0.5222	5	0.5937
14	19	5	35	3	0.5222	5	0.5937
15	19	5	35	3	0.5222	5	0.5937
16	19	7	22	5	0.5159	6	0.6097
17	19	7	22	5	0.5159	6	0.6097
18	19	7	22	5	0.5159	6	0.6097
19	25	3	35	5	0.4952	7	0.5215
20	25	3	35	5	0.4952	7	0.5215
21	25	3	35	5	0.4952	7	0.5215
22	25	5	22	7	0.5391	3	0.5375
23	25	5	22	7	0.5391	3	0.5375
24	25	5	22	7	0.5391	3	0.5375
25	25	7	29	3	0.7949	1	0.6953
26	25	7	29	3	0.7949	1	0.6953
27	25	7	29	3	0.7949	1	0.6953

The regression equation:

$$Temperature = 113 + 7.80 \cdot HP + 17.9 \cdot HT +$$
$$+1.30 \cdot UP - 4.18\ UT$$
$$S = 26.4971,\ R-Sq = 82.3\%,\ R-Sq(adj) = 79.1\%$$

3.4 GRA Method for Multi Function Analysis

Design of Experiments using Taguchi method is successful in determining the most desirable value of process variables for only one response attribute. Other than one attribute, if we need to try for more than one response with various characters, multi-functional technique is done with the practice of GRA. Thus, GRA method of calculating the multi-functional technique for this frictional welding factor is executed.

3.4.1 Grey Relational Normalized and Coefficient Values

The normalized values for the output responses like axial shortening, hardness and temperature are calculated in GRA from the values obtained in the S/N ratio. All the responses should be taken as 'larger is better' characteristics to calculate the normalized values. Grey relation coefficient values are computed based on deviation sequences, which are obtained from normalized values.

3.4.2 Grey Relational Grades and Ranking

Axial shortening, hardness and the temperature coefficients are considered to calculate GRG values and ranks are presented in Tab. 10. This table demonstrates the GRG of the combination of the output factors. It shows the best possible grouping of factors for the best possible grouping of the reactions like axial shortening, hardness and the temperature.

Table 11 S/N Ratio - Response Table

Level	*HP* / bar	*HT* / s	*UP* / bar	*UT* / s
1	−5.659	−5.963	−5.407	−4.248
2	−6.023	−5.797	−5.017	−6.078
3	−4.488	−4.411	−5.746	−5.845
Delta	1.535	1.552	0.729	1.830
Rank	3	2	4	1

The S/N ratio in the main impact plot for GRG values, which is seen in Fig. 5, supports the grouping of the different parameters.

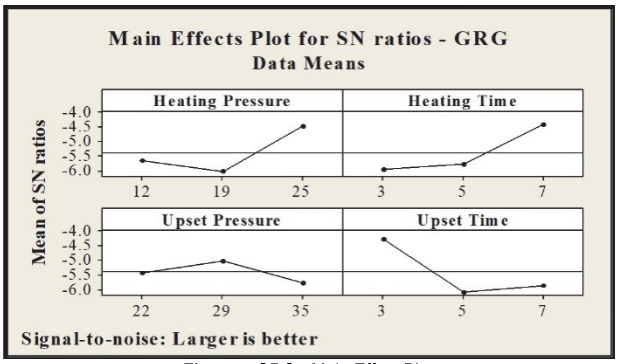

Figure 5 GRG - Main Effect Plot

It clearly shows that the optimal level of the process factors for this research is mainly based on the 'larger is better' condition.

This plot for GRG shows the interaction between the various levels of combination of process factors based on the output response and is presented in Fig. 6.

The vital process factor which affects the performance characteristics of the friction welding is identified using ANOVA. Thus, ANOVA is computed for the obtained GRG values and presented in Tab. 12.

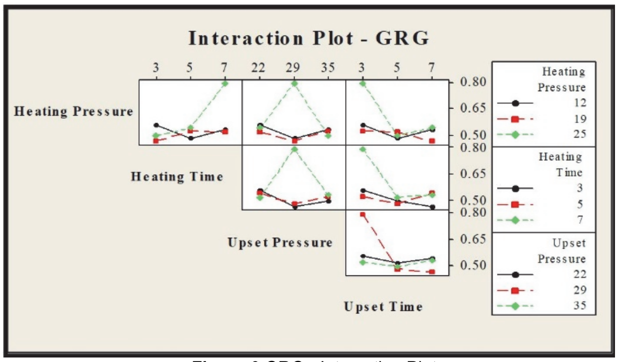

Figure 6 GRG - Interaction Plot

From the GRG table, it is understood that the maximum GRG value will be the most favorable mixture of factors. The response table presented in Tab. 11 is based on GRG values obtained, gives the most dominating input process factors in this work of joining EN353 materials. From the table, the author predicts that *UT* plays a vital role followed by *HT*, *HP* and *UP*.

Table 12 GRG – Analysis of Variance Table

Source	d*F*	*Seq SS*	*Adj SS*	*Adj MS*	% of Contribution
HP / bar	2	0.060129	0.060129	0.030065	25.86
HT / s	2	0.066360	0.066360	0.033180	28.54
UP / bar	2	0.018645	0.018645	0.009323	8.02
UT (s)	2	0.087390	0.087390	0.043695	37.58
Error	18	0.000000	0.000000	0.000000	0
Total	26	0.232524	--	--	100
S = 2.901536E-17, *R-Sq* = 100.00%, *R-Sq(adj)* = 100.00%					

The regression equation:

$$Grey\ Relational\ Grade = 0.467 + 0.00646\ HP +$$
$$+\ 0.0273 \cdot HT - 0.00137 \cdot UP - 0.0282\ UT$$
$$S = 0.0633348,\ R-Sq = 62.0\%,\ R-Sq(adj) = 55.1\%$$

3.4.3 Confirmation Tests

The most favorable grouping of process factors is identified by GRG values and verified using the S/N ratio in the main effect plot of GRG values. The predicted GRG value was computed by means of the regression equation obtained using ANOVA for GRG and is presented in Tab. 10. Furthermore, the results of the validation table show that the expected values are in strong alignment with the grey grades. Thus, to authenticate the obtained results of the analysis, confirmation checks were performed and the optimum values were found from *HP* = 25 bar, *UT* = 3 seconds, *HT* =7 seconds, and *UP* = 29 bar, for axial shortening is 15mm; hardness is 96.69 RHN and temperature is 458.5 ºC.

4 CONCLUSION

In this study, Taguchi and GRA were used to test the optimization of various input variables such as *UT*, *HT*, *HP* and *UP* for EN353 material, and the following points are reported.

In friction welded joints, input process parameters play a crucial role in ensuring good bonding between EN353 alloy steel.

- *HP* 25 bar, *HT* 7 seconds, *UP* 35 bar and *UT* 5 seconds were indeed the perfect stage of axial shortening in this study.
- The investigation's optimum level of hardness was 12 bar *HP*, 3 seconds *HT*, 29 bar *UP* and 3 seconds *UT*.
- In the experimental investigation of temperature, the effective optimal parameter was 25 bar *HP*, 7 seconds *HT*, 29 bar *UP* and 3 seconds *UT*.

The most favorable grouping factors for better grouping of the output responses are *HP* = 25 bar, *UT* = 3 seconds, *HT* =7 seconds, and *UP* = 29 bar due to its highest ranking in GRG values. The grouping of the obtained input process factors was also confirmed by the S/N ratio plots of the GRG values and was validated using the confirmation test from the regression equation of GRG. From the response S/N ratio table of grey relational grade, *UT* play a crucial role in dominating the output responses like axial shortening, hardness and temperature followed by *HT*, *HP* and *UP*. The research findings can be practically employed in the production of components like engine valves, pump shafts and piston rods.

In the future, this research work could be extended to conduct various other analyses like SEM, fatigue tests, bending tests and fracture tests. This work can also be extended to include dissimilar material welding.

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