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OPTIMIZATION OF QUALITY OF ENERGY CONSUMPTION AND SOME WELD QUALITY RESPONSE PARAMETERS IN GAS TUNGSTEN ARC WELDING

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Abstract- The present research work focuses on the optimization of quality of energy consumption and weld quality response parameters in case of gas tungsten arc welding of stainless steel 304. The quality of energy consumption parameter consists of power factor (PF) and weld quality response parameters consist of tensile strength and hardness. The Taguchi method based L9 orthogonal array has been used for the design of experiments and significance of the welding input parameters has been found by ANOVA at 95% confidence level. Welding current, gas flow rate and travel speed are three selected welding input parameters for the present research work. Results reveal that 95A welding current, 5 lpm gas flow rate and 25 cm/min travel speed welding input parameters are accountable for optimum PF (0.58 Leading). Optimum tensile strength (846.66MPa) has been found to be at welding input parameters of 95A welding current, 7 lpm gas flow rate and 13.84 cm/min travel speed. Optimum value of hardness (277Hv) occurs at welding input parameters of 85A welding current, 5 lpm gas flow rate and 25 cm/min travel speed. Welding current is found to be the most critical welding input parameter for PF and hardness whereas travel speed is the most contributing parameter for the tensile strength. It has been found that there is 5.45% increase in PF from lowest value of PF which is a good improvement to tackle with the penalties in the electricity bills. The effect of welding input parameters on tensile strength and hardness is found to be similar as in the literature. Predicted value and experimental value of hardness are very near to each other.
Keywords: Welding, Quality of Energy Consumption, Power Factor, Weld Quality, Optimization, Taguchi, ANOVA.

1. INTRODUCTION

Gas tungsten arc welding (GTAW) is the welding process in which non consumable tungsten electrode is used for joining the metal surfaces or edges permanently. During welding there is considerable amount of energy losses which increases the energy consumption of the welding process. Manufacturing industries use approximate 37% of the total world's energy consumption [1]. So, in the manufacturing field, there is a strong demand for energy conservation.

Most of the researchers had done their work in case of welding processes to improve or optimize the process parameters for better weld bead quality. Juang et al. [2] used Taguchi method to optimize the welding parameters for the weld quality of stainless steel in case of gas tungsten arc welding. They selected four input parameters for the study i.e. air gap, flow rate, welding current and welding speed, among which, welding speed was found to be most contributing parameter for weld pool geometry. Khatter et al. [3] had done the optimization of welding parameters for gas tungsten arc welding. They found that parameters had different effect on tensile strength, and voltage had great impact on tensile strength. Shen et al. [4] studied the effect of welding current on microstructure and mechanical properties of gas tungsten arc welded AZ31 with and without TiO_2 coatings. They observed that surface appearance of welded seam deteriorated with TiO_2 coating. Karpagaraj et al. [5] investigated the effect of TIG welding input parameters on the properties of titanium alloy of thickness 1.6 mm and 2 mm. They found that the weakest portion was HAZ in both thicknesses for tensile strength. Kumar et al. [6] optimized the welding input parameters viz. welding current, voltage and gas flow rate for tensile strength. They used Taguchi method for the design of experiments and analysis. The welding voltage was found to be the most significant and contributing parameter for tensile strength. Bodude et al. [7] investigated the effect of welding parameters on the mechanical properties of the low carbon steel. They considered two types of welding processes under the study viz. oxy acetylene welding and shielded metal arc welding. Wen et al. [8] studied the effect of high frequency vibrations on the properties of gas tungsten arc welded joints of AZ31 magnesium alloy. They found the refinement of the microstructure of welded joint, and increase in hardness and tensile strength with the application of vibrations. Srirangan et al. [9] had done the optimization of process parameters for gas tungsten arc welding. They found the welding current to be the most contributing and significant input parameter for multi-response characteristics such as ultimate tensile strength, yield strength and toughness.

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Energy conservation is the today's need in manufacturing field. Because welding uses energy vigorously, so there is the need to determine and optimize the energy consumption in case of welding. Researchers had done the optimization for energy consumption mostly in case of machining processes e.g. turning, milling etc but very few work has been done on the determination and optimization of energy consumption parameters in case of welding. Shrivastava et al. [10] had done the comparison of the energy consumption by the friction stir welding (FSW) and metal inert gas welding (MIG). They found that there was 40% less energy consumed by FSW than MIG welding and also there was less impact of FSW on environment than MIG welding. Bhattacharya et al. [11] analyzed the energy utilization in case of gas tungsten arc welding. They used mathematical expressions to calculate the energy losses due to convection and radiation. Bilga et al. [12] optimized the response parameters viz. power factor (PF), energy efficiency (EE) and active energy consumed by the machine (AECM) in case of turning. They selected L_{27} orthogonal array by Taguchi method for design of experiments and analysis. They found the depth of cut as the most critical parameter for PF and EE, and feed rate as the main affecting factor in lowering down AECM. Athreya et al. [13] optimized the process parameters for surface roughness in case of lathe facing operation. They compared the results of two types of design of experiments viz. Taguchi method and full factorial design technique. They concluded that the Taguchi technique was simple and easiest technique to be adopted for optimization.

Most of the researchers had done the work on optimization of welding parameters for better strength of the joint, but there is very less attention paid on energy consumption during the operation in case of welding. The power factor (PF) is a dimensionless number which shows the quality of the power used during the process. Most of the researchers did not concentrate on the importance of the PF in case of welding process. The PF is the ratio of the active power to the apparent or total power given to the electrical equipment.

PF = Active power/Apparent power

The apparent power is the total power given to the electrical circuit. It is the vector sum of the active power and reactive power. The active power is the actual power which is used to do the productive work [13]. Reactive power does not perform any productive work. It is always desired that electrical system should not use reactive power as it reduces the active power and consequently PF drops. The PF of the equipment should be equal or near to the unity for better utilization of energy provided, otherwise, electricity board can put penalties to the industrialists.

The welded joints should also have enough strength to withstand any deformation or stress during the application. So, it is also desirable to have good weld quality as well as less energy consumption in case of welding process.

The present research work concentrates on the importance of the quality of energy consumption i.e. PF and the weld quality response parameters in case of gas tungsten arc welding. The various welding input parameters which have been selected for the study are welding current, gas flow rate and travel speed. The effect of these parameters has been studied for the PF, tensile strength, and hardness. The design of experiments using L_9 orthogonal array of Taguchi method has been done in Minitab software.

2. METHODS AND MATERIALS

2.1 Work piece material

The AISI Stainless steel (SS) 304 of dimensions 300mm x 150mm x 2mm has been selected for the study. There was no need of v-grooves because thickness of the plates is very small. It is also called 18/8 stainless steel because it contains 18% chromium and 8% nickel. This material is used in food processing units, domestic vessels and dairy units. The nominal composition of AISI SS 304 [14] and actual composition as per the test report from the authorized agency is given in the Table 1. Tensile strength of the base material is 500-600 MPa [15].

Table 1 Composition of Stainless Steel 304.

Elements	C	Cr	Ni	P	Mn	Si	S
Nominal composition as per AISI (%)	0.06	18.4	8.17	0.045	1.38	0.32	0.03
Actual composition (%) (Test report)	0.06	18.730	8.310	0.032	1.02	0.260	0.012

2.2 Selection of Input and Output Parameters

Table 2 and Table 3 report the welding input parameters and response parameters respectively. Trial runs were made to get the welding input parameters range for the experimentation. The welding current range is selected 85-100 amperes and gas flow rate is selected 5-10 liters per minute. Travel speed is selected according to the bead required.

Table 2 Welding Input Parameters for Experimentation.

Parameters (Factors)	Units	Level 1	Level 2	Level 3
Welding Current	Amperes	85	90	95
Gas Flow Rate	Lpm	5	7	10
Travel Speed	cm/min	13.84	21.17	25

Table 3 Response Parameters.

Quality of Energy Consumption Response Parameter	Weld Quality Response Parameters
Power Factor	Tensile Strength
	Hardness

2.3 Design of Experiments

The design of experiments has been done by taguchi method in Minitab software. L_9 orthogonal array has been selected for the study. The Taguchi method is a systematic application of design and analysis of the experiments for the purpose of designing and improving quality. Table 4 shows the array of the design of experiments. The values for welding current, gas flow rate and travel speed have been selected and shown in the Table 4.

Table 4 Design of Experiments Orthogonal Array by Taguchi Method.

Expt. No.	Welding Current (A)	Gas Flow Rate (lpm)	Travel Speed (cm/min)
1	85	5	13.84
2	85	7	21.17
3	85	10	25.00
4	90	5	21.17
5	90	7	25.00
6	90	10	13.84
7	95	5	25.00
8	95	7	13.84
9	95	10	21.17

2.4 Equipment and Instrument

The gas tungsten arc welding equipment has been used for the study whose specifications are as follows:

Model	SAVER-300
Output current range	10-300 amp
Open circuit voltage	75-85 V
Input supply	415 V, 3 PH, 50Hz

HIOKI made compact 3-Phase 4-Wire energy loggers (PW3360) monitor power demand and other power parameters to aid in energy audits and validate energy saving measures. This power logger is used to note down the readings of PF. Two types of the clamps are used to install the logger on the machine. Readings have been made after every one second and averages of the readings have been used for the study. Table 5 shows the technical specifications of the power logger:

Table 5 Technical Specifications of Power Logger.

Voltage	5 V to 1000 V
Current	50 mA to 500 A
Power	300 W to 9 MW

The tensile strength has been tested on the ultimate tensile testing machine and hardness has been tested on Micro Vickers Hardness Tester.

2.5 Experimental Procedure

The work pieces of stainless steel 304 of selected dimension are cut from the sheet and clamped on the trolley. This trolley is derived by an electric motor. Wiring of the power logger is done according to the instruction manual of power logger [16]. The welding input parameters are set according to the design of experiments. Then welding has been done and observations of PF are recorded directly from the power logger. Three runs have been made for the same experimental conditions for all nine set of experiments and averages of these three runs are used for the analysis. After the welding process, destructive testing which includes tensile testing and hardness have been done. IS 1608-2005 standard **[**17] has been used for the tensile test and ASTM E384 [18] standard has been used to check the micro hardness of the test specimens. The results of the output parameters are then used for the optimization in Minitab software.

2.6 Observations and Calculations

Table 6 shows the observations of PF, tensile test and hardness. Three runs are made for same experimental conditions for PF and they are reported as PF1, PF2 and PF3. One specimen has been cut from each welded specimen for tensile test and observations for their tensile strengths are named as tensile strength1* (TS1*) and tensile strength 2* (TS2*). Only one specimen has been cut for same experimental conditions for hardness, so, total nine specimens have been cut and prepared for hardness.

3. RESULTS AND DISCUSSION

The values for means and signal to noise ratios (S/N ratios) of all response parameters are reported in Table 7 and Table 8 respectively. There are three types of the quality characteristics for signal to noise (S/N) ratios i.e. smaller-the-better, larger-the-better and nominal-the-better. In the present work, all the response parameters should be maximum, so, larger-the-better characteristic has been selected. Equation (1) shows the formula for the larger-the-better characteristic:-

$S/N = -10 \times \log [\Sigma(1/Y^2)/n]$ (1)

Where, Y = responses for the given factor level combination and n is the number of responses in the factor level combination. Analysis of variance (ANOVA) has been performed at 95% confidence level for all the response parameters for optimization. ANOVA is a statistical tool which is a decision making tool for the desired quality of the output parameters. It helps in determining the significance of the various input parameters in any type of the process. It helps in determining the percentage contribution of input parameters on output parameters. Percentage contribution is defined as the ratio of the sum of the squared deviations to the total sum of the squared deviations [13].

3.1 Analysis of Power Factor (PF)

Average values of means and S/N ratios are plotted as shown in the Fig.1. As shown in the Fig.1a for means, PF increases with increase in welding current. Maximum value of PF occurs at welding current of 95A. PF decreases as gas flow rate is increased and maximum PF occurs at the gas flow rate of 5 lpm. PF decreases with increase in travel speed from 13.84 cm/min to 21.17 cm/min and then again increases from 21.17 cm/min to 25 cm/min. Maximum PF occurred at travel speed of 25 cm/min. Ranks of welding input parameters for means values of PF are reported in Table 9a in which welding current is at rank 1 with percentage contribution of 79.48% followed by gas flow rate with 8.87% and then travel speed with 5.05%.

Fig.1b shows the main effects plots for S/N ratio and Table 10b presents the analysis of variance for S/N ratios of PF. As shown from the Fig. 1b, combination values of welding input parameters for optimum PF are third level of welding current (95A), first level of gas flow rate (5 lpm) and third level of travel speed (25 cm/min) which are the conditions for experiment number seven. So, experiment number seven has the optimum PF. Analysis of variance for S/N ratios of PF is reported in Table 9b which shows the percentage contribution and ranks of all the welding input parameters for PF. Welding current has rank 1 with percentage contribution of 79.56 % followed by gas flow rate with 8.90 % and travel speed with 5.08%.

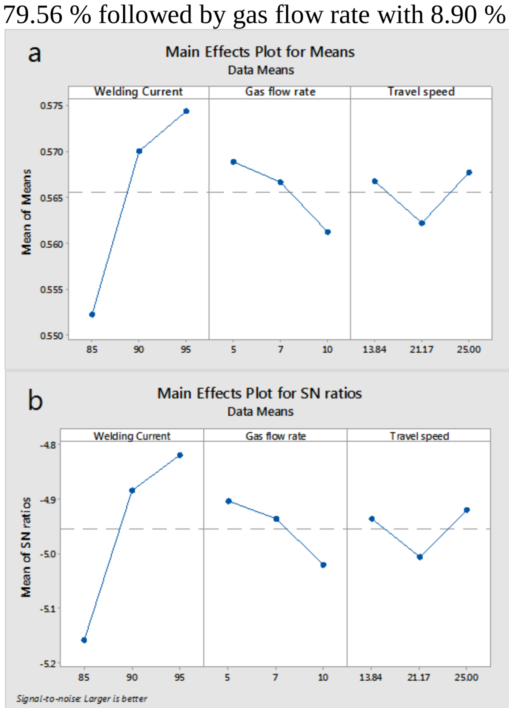

Fig. 1 a Main Effects Plot for Means of Power Factor. b Main Effects Plot for S/N Ratios of Power Factor.

Table 6 Observations of All Response Parameters.

Expt. No.	PF1	PF2	PF3	TS1* (MPa)	TS2* (MPa)	TS3* (MPa)	TS avg (MPa)	VHN (Hv)		
								WB	HAZ	BM
1	(-)0.56	(-)0.55	(-)0.55	760	780	720	753.33	250.70	240.90	193.50
2	(-)0.56	(-)0.55	(-)0.55	660	660	820	713.33	302.00	262.00	223.20
3	(-)0.55	(-)0.55	(-)0.55	320	280	260	286.66	218.00	189.30	152.30
4	(-)0.57	(-)0.58	(-)0.56	760	620	560	646.66	213.00	185.00	150.00
5	(-)0.57	(-)0.57	(-)0.57	760	740	700	733.33	222.00	201.00	174.00
6	(-)0.58	(-)0.57	(-)0.56	680	880	800	786.66	214.00	223.00	196.00
7	(-)0.58	(-)0.59	(-)0.58	720	660	680	686.66	310.50	246.90	205.80
8	(-)0.58	(-)0.57	(-)0.58	860	860	820	846.66	236.31	177.90	140.00
9	(-)0.55	(-)0.57	(-)0.57	780	720	760	753.33	222.20	203.30	168.30

(-) Leading PF

*Three runs have been done for same experimental condition and one specimen is made from each welded specimen for the tensile testing.
VHN- Vickers Hardness Number
WB- Weld Bead
HAZ- Heat Affected Zone
BM- Base Metal

Table 7 Means for Quality of Energy Consumption and Weld Quality Response Parameters.

Expt. No.	**PF**	**Tensile Strength (MPa)**	**Hardness on Bead (Hv)**
1	(-)0.55	753.33	250.70
2	(-)0.55	713.33	302.00
3	(-)0.55	286.66	218.00
4	(-)0.57	646.66	213.00
5	(-)0.57	733.33	222.00
6	(-)0.57	786.66	214.00
7	(-)0.58	686.66	310.50
8	(-)0.58	846.66	236.31
9	(-)0.56	753.33	222.20

(-) Leading PF

Table 8 S/N Ratios of Quality of Energy Consumption and Weld Quality Response Parameters.

Expt. No.	PF	Tensile Strength	Hardness on Bead
1	-5.1412	57.5252	47.9831
2	-5.1412	56.9332	49.6001
3	-5.1928	49.0525	46.7691
4	-4.8852	56.0081	46.5676
5	-4.8825	57.2907	46.9271
6	-4.8795	57.7672	46.6083
7	-4.6825	56.7180	49.8412
8	-4.7824	58.5476	47.4696
9	-4.9884	57.5252	46.9349

Table 9a Analysis of Variance for Means of Power Factor.

Source	Seq SS	F	P	PC	Rank
Welding current	0.000833	12.01	0.077	79.48	1
Gas flow rate	0.000093	1.34	0.428	8.87	2
Travel speed	0.000053	0.76	0.568	5.05	3
Residual error	000069				
Total	0.001048				

Table 9b Analysis of Variance for S/N Ratios of Power Factor.

Source	Seq SS	F	P	PC	Rank
Welding current	0.19638	12.34	0.075	79.56	1
Gas flow rate	0.02199	1.38	0.420	8.90	2
Travel speed	0.01255	0.79	0.559	5.08	3
Residual error	0.01591				
Total	0.24683				

3.4 Analysis of Tensile Strength

Fig. 2a and Table 10a show the main effects plot for means and analysis of variance for means of the tensile strength respectively. The tensile strength increases with increase in welding current. Maximum tensile strength is at welding current of 95A. The tensile strength increases from 5 lpm to 7 lpm gas flow then decreases to 10 lpm. The maximum tensile strength is at 7 lpm gas flow rate. The tensile strength decreases with increase in travel speed. The maximum tensile strength is found at the travel speed of 13.84 cm/min. Main reason for this result is, at high welding current and lowest speed, the proper diffusion of the plates occurs due to which tensile strength of the joint is maximum at these welding input parameters. Table 10a shows the analysis of variance for means of tensile strength which shows that travel speed is at rank 1 with 37.36 % contribution followed by welding current with 24.98% and gas flow rate with 17.45%.

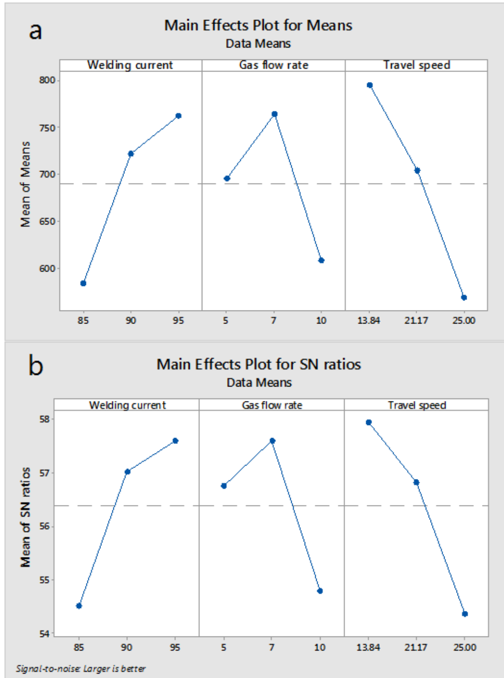

Fig. 2 a Main Effects Plot for Means of Tensile Strength. b Main Effects Plot for S/N Ratios of Tensile Strength.

Table 10a Analysis of Variance for Means of Tensile Strength.

Source	Seq SS	F	P	PC	Rank
Welding current	52188	1.24	0.447	24.98	2
Gas flow rate	36454	0.86	0.537	17.45	3
Travel speed	78054	1.85	0.351	37.36	1
Residual error	42202				
Total	208899				

Table 10b Analysis of Variance for S/N Ratios of Tensile Strength.

Source	Seq SS	F	P	PC	Rank
Welding current	16.24	1.06	0.486	25.24	2
Gas flow rate	12.47	0.81	0.552	19.38	3
Travel speed	20.27	1.32	0.431	31.50	1
Residual error	15.35				
Total	64.33				

Fig. 2b shows the main effects plot for S/N ratio of the tensile strength which shows the conditions for the optimum tensile strength which are found to be the third level of the welding current (95 A), second level of the gas flow rate (7 lpm) and first level of the travel speed (13.84 cm/min). This factor-level combination of welding input parameters lies in the experiment number eight of design of experiments orthogonal array. Table 10b shows the analysis of variance of S/N ratios of tensile strength. The travel speed is on rank 1 with percentage contribution of 31.50%, welding current is on rank 2 with of 25.24% , and gas flow rate of 19.38 % at rank 3. The effect of welding input parameters on the tensile strength is found similar as reported by Khatter et al. [3].

3.6 Analysis of Hardness Test

Fig. 3a and Table 11a show the main effect plots for means and analysis of variance for hardness on weld bead respectively. As shown in the Fig. 3a, hardness firstly decreases with increase in welding current from 85 to 90A then again increases to 95A. Maximum hardness is at welding current of 85 amps. With increase in gas flow rate, hardness decreases. At 5 lpm of gas flow rate, maximum hardness is found. With increase in travel speed, hardness increases due to rapid heating and cooling. Maximum hardness is found to be at 25 cm/min. Table 11a reports the analysis of variance for means of hardness. Welding current has rank 1 with 28.52 % contribution followed by gas flow rate with 25.24 % and travel speed with 3.84%.
Fig. 3b and Table 11b show the main effects plot for S/N ratio and analysis of variance for S/N ratio of the hardness respectively. The optimum hardness occurs at the first level of the welding current (85A), first level of the gas flow rate (5 lpm) and third level of the travel speed (25 cm/min). This combination of welding input parameters does not lie in the design of experiments orthogonal array, so, predicted value for optimum hardness has been calculated in taguchi analysis which is

found to be 278.75Hv. Table 11b shows the analysis of variance for S/N ratios of the hardness in which welding current is at rank 1 with 30.55% contribution followed by gas flow rate at rank 2 with 26.34 % and travel speed at rank 3 with 2.99% contribution. Table 11c shows the validated experimental values of hardness. The average experimental value is 0.63% lower than the optimum predicted value. The effect of welding input parameters on the hardness is found similar as reported by Talabi et al. [19].

Table 11a Analysis of Variance for Means of Hardness on Weld Bead.

Source	Seq SS	F	P	PC	Rank
Welding current	3246.2	0.67	0.598	28.52	1
Gas flow rate	2872.5	0.60	0.627	25.24	2
Travel speed	437.3	0.09	0.917	3.84	3
Residual error	4824.6				
Total	11380.6				

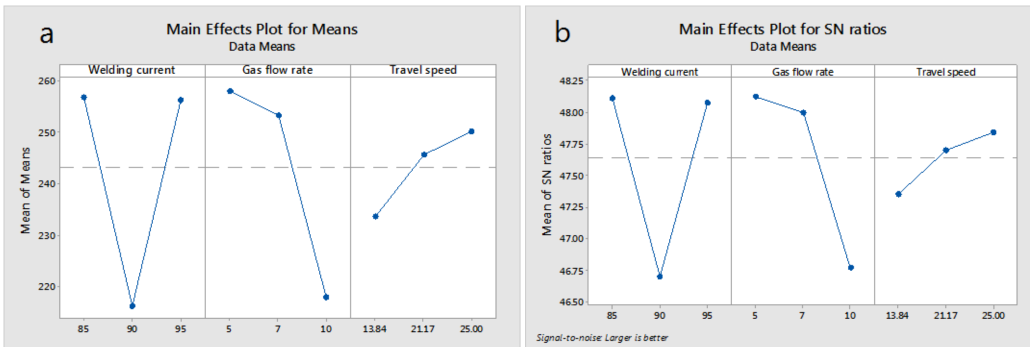

Fig. 3 a Main Effects Plot for Means of Hardness on Weld Bead. b Main Effects Plot for S/N Ratios of Hardness on Weld Bead.

Table 11b Analysis of Variance for S/N Ratios of Hardness on Weld Bead.

Source	Seq SS	F	P	PC	Rank
Welding current	3.9147	0.76	0.568	30.55	1
Gas flow rate	3.3750	0.66	0.604	26.34	2
Travel speed	0.3838	0.07	0.931	2.99	3
Residual error	5.1389				
Total	12.8123				

Table 11c Validation Table for Hardness.

Predicted Value of Hardness on Bead (HV)	Experimental Values of Hardness on Bead (Hv)		Average Experimental Value of Hardness on Bead (Hv)	Percentage Error (%)
	Run 1	Run 2		
278.75	272.00	282.00	277.00	-*0.63

*-: Lower than predicted value

4. CONCLUSIONS

The welding current is found to be the most critical parameter which has maximum contribution in case of the PF and hardness response parameters, and travel speed is the most affecting parameter for tensile strength. The optimization of the response parameters has been done for single objective, so, multi objective optimization can be done for even more response parameters with more factor-level combinations of the welding input parameters.

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