Optimization of Process Parameters for MIG Welding by Taguchi Method

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Abstract

Manufacturer's often face the problem to achieve a good welded joint with the required quality due to control of the input process variables. The main objective of this investigation is to find best process parameters for good quality weld in MIG welding. Taguchi Method with L_9 orthogonal array was used to find best settings of welding current, welding voltage, welding travel speed and number of welding passes. The study of the welding parameter's effect on residual stresses and hardness of weld specimen were carried out by statistical technique i.e. analysis of variance (ANOVA) and Signal to Noise (S/N) ratio. The optimum parametric conditions were found out by Taguchi method. Confirmatory test was performed to achieve the validity of the results. By performing investigation procedure, it was found by the analysis based on S/N ratio and ANOVA that the welding voltage contributes 57.3% towards the total variation observed in residual stresses. The welding current contributes 26.14% of the total variation observed in residual stresses. The welding voltage contributes 61.59% towards the total variation observed in hardness. The variable travel speed contributes 32.28% of the total variation observed in hardness.

Keywords *- MIG welding, Fe_3 410WC Plates, Taguchi Method, L9 array, ANOVA, Signal to noise ratio.*

1. Introduction

In any manufacturing industry welding is widely used to assemble various products. It is well known fact that during welding unequal temperature field produces unwanted residual stresses and deformation in the assembled components. It is observed that irrespective of the application of any service or external loads, the residual stresses always exists in any structural material or component. Mainly residual stresses in any manufactured objects are introduced by all manufacturing and fabrication processes. The in-service repair or modification is also the other common cause of residual stresses. The amount, direction and distribution of the stress with respect to the load induced stresses also define the effects of residual stresses that whether stresses are useful or harmful. It is believed that fatigue strength of the component increases due to the effect of compressive stresses that is found very beneficial in industry. Sometimes in industries, residual stresses are introduced deliberately through some post manufacturing treatment. However in some manufacturing processes in industry such as welding residual stresses have severe effect on structural integrity due to their tensile nature. Similarly out of tolerance in final geometry may also be affected due to welding distortion and this may create major hindrance in assembly of the product. By reworking or by means of external load compensation the rectification can be done in any misalignments during fitting.

The problems of residual stresses and overall deformation in many steel manufacturing industries such as ship building, aero-space industry, marine structures has been and continues to be a major issue. Today still now welding joint is considered as the weak joint in mechanical engineering design. The mismatch of the mechanical properties at the joints and shortcoming of welding technology became the main reason and, last but not least, due to the residual stresses. Due to these the analysis of residual stresses in welding joints becomes an important task in any industry. The main cause of unwanted deformation and residual stresses showed the reduction in the fatigue and creep lifetime of the weldment. Many factors both process related and geometry dependent and due to the inherent complexities of the welding processes also affect the final residual stresses .The residual stresses are measured by many experimental approaches however; most of them are costly and destructive. The residual stresses are affected by various parameters such as the geometry of the parts being jointed, the material properties of the weld and parent material. The composition, microstructure, thermal and mechanical properties, tack-weld design, and root gap etc.also effects the residual stresses. The measurement of residual stresses have been employed by various techniques like stress relaxation techniques, diffraction techniques, cracking techniques and indirect techniques based on stress sensitive properties The complete stress distribution cannot obtained by these techniques because most of them are expensive and time consuming and some of them are destructive. The most important technique which is used to measure residual stresses by strain gauge hole drilling method. With this method on the test object a specially configured electric resistance strain gauge rosette was bonded. A hole was drilled through the centre of the rosette. Due to the hole the local changes in strain were measured and from these measurements the residual stresses are calculated.

Today mostly for the welding of any ferrous and non ferrous materials in an industry are done by means of Metal Inert Gas (MIG) welding. The control of welding variables in manual welding operation, which affect the weld penetration, bead geometry and to achieve the best weld quality are done by the welder. The selection of proper welding variables like welding current, welding voltage, travel speed, wire electrode size, position helps in increasing the quality of weld. MIG Welding process also helps in joining of Fe_3 410WC plates. The parameters like current, voltage, travel speed and number of welding passes are taken for the analysis. Taguchi Design of experiment techniques are applied to get optimization result of welding parameters. The analysis of signal to noise ratio was done by using MINITAB 17 software.

Saluja and Moeed [1] adopted the factorial design approach to examine the Metal Inert Gas welding variables (viz. current of welding, welding speed, and welding arc voltage and stick-out distance of electrode) on aluminum by measuring geometry of weld bead and penetration of weld. For sound quality bead width, bead penetration and weld reinforcement on butt joint was investigated by the development of a mathematical model. The welding current was found to be the most influencing parameter on the weld geometry. Patel and Gandhi [2] recorded tensile strength for parameters of MIG welding such as current, arc voltage, welding speed and shielding gas flow. It was noted that the tensile strength increased with increasing the welding current. Palani and Saju [3] examined the TIG welding process parameters (viz. travel speed of welding, current and flow rate of gas) on welding of aluminium and also used the methodology of response surface to perform the experiments for measuring the strength of weld joints. It was noted that welding current was highly influencing parameter on the tensile strength and percent elongation. Haragopal and Ravindra Reddy [4] studied the effect of pressure of gas, current, angle of groove and preheat on MIG welding of Al- 65032 by Taguchi method. The current of welding was found to influence the ultimate tensile strength. The significant variables for proof stress, elongation and impact energy is found to be the pressure of gas. Padmanaban and Balasubramanian [5] investigated tensile strength in AZ31B magnesium alloy by the effect of pulsed current gas tungsten arc welding. The tensile strength has greatly influenced by pulse frequency followed by peak current, pulse on-time and base current.

Joshi et al. [6] adopted the full factorial method in their design of experiment to generate the tensile strength values for all combination levels of the different variables of welding (viz., current of welding, flow rate of gas and wire feed rate of MIG welding, whereas welding current and gas flow for TIG welding). The grey relational analysis (GRA) technique has been used to perform parametric optimization. The method of approach followed by Joshi et al. [6] required more number of experiments. It is preferable to have less number of experiments by adopting the Taguchi's approach, which uses the orthogonal array to study large number of design variables by conducting minimum number of experiments. Saxena et al. [7] examined the influence of MIG welding parameters on tensile strength of AM-40 (EN AW5083) aluminum alloy using Taguchi technique. Welding current and welding voltage are influencing the tensile strength of welded joint. The signal-to-noise (S/N) ratio transformation in the Taguchi's design of experiments considered by Saxena et al. [7] was on a single value of each test run output response. In fact, Taguchi has created the S/N ratio transformation to consolidate several repetitions into one value to reflect the amount of variation present. Hence, the unwanted S/N ratio transformation adopted by them has no added advantage other than additional computational work. Process was recommended. To improve penetration capability of TIG process for joining of aluminum alloys, mainly the process recommended was the Flux bounded tungsten inert gas welding [8-10]. Several optimization methods have been adopted for modeling, control and optimizing the different weld process to achieve a good quality of weld joints [11-18]. There are very less comparative study was done to study the performance of those methods.

The adequacy for the selection of optimum process parameters of the MIG welding of low carbon steel was investigated by Taguchi method. The optimum welding process variables (viz. current of welding, Voltage, travel speed and number of passes) were identified by the utilization of these results. This study clearly demonstrates the simplicity of the Taguchi method to obtain optimum weld process parameters to achieve maximum hardness and minimum longitudinal residual stresses through less number of experiments.

2. Taguchi Method

Taguchi design of experiment is one of the best techniques which are used widely. The variation in a process is minimized through robust design of experiments by this method. To provide best product quality at low cost to manufacture is the main objective of this study. The variations are maintained by this method which was developed by Dr. Genichi Taguchi of Japan. The orthogonal arrays which are used to optimize the parameters affecting and the levels at which they should be varies are done by Taguchi design of experiment. A set of well defined experiment provided by orthogonal arrays. Signal–to-Noise ratios(S/N),developed by Dr. Taguchi serve as main objective functions for optimization, helps in analysis of data and prediction of optimal results which are log functions of desired output.

The main steps for the parameter design phase of the Taguchi method are:
1. First of all identify the main objective of the experiment.
2. Identify the output response and its system of measurement.
3. Find out the different factors that may affect the output response, level and main interactions.
4. Choose the suitable orthogonal array.
5. Perform the experiments given by the trials in the OA.
6. The data can be analyzed by using the statistical techniques signal to noise ratio, the analysis of variance and factor effects to find the significance of process parameters.
7. Find out the optimal levels of variables.
8. Confirmatory experiments done for the verification of the optimal design parameters.

2.1. Quality Characteristics selection criteria

The experimental outputs which were measured by the selection of quality characteristics greatly influenced by the experiments done by means of statistical methods. The selection of quality characteristics to influence the welding parameters of Fe_3 410WC Plates are minimum residual stresses and maximum hardness.

2.2 Selection criteria for welding variables

This is the most important experimentation phase. The information obtained from the experiments will not be in a sense of positivity if unknowingly main variables are left out of the experiments. The performance of MIG welding on residual stresses and hardness are influenced by means of these following parameters which are listed below are:

1. Welding current
2. Welding Voltage
3. Travel speed
4. Number of welding passes

Table 2.1: Main parameters and their values at different levels

Main welding Parameters	Level 1	Level 2	Level 3
Current(Amp)	150	175	200
Voltage(Volts)	19	22	25
Travel Speed(cm/min)	12.24	15.36	19.32
Welding passes	2	3	4

During the welding a manufacturer can control the various main welding parameters. It was observed that the main parameters levels chosen were in the operational range of the MIG Welding. Different experimental runs were done by varying one of the welding parameters and keeping the others at constant values. The selection of levels for the main control parameters are given in Table 1. The three different levels were selected for the study of four main control parameters.

2.3 Assignments of main welding variables

To design the plan of experiments Taguchi uses a special set of orthogonal arrays ($OA_{s)}$ which are always predefined. The full information of those factors that affect the process performance was found out by use of these standard arrays.

Table 2.2 Orthogonal Array (L_9) and Control Parameters

Exp. Trial No.	Current (A)	Voltage(V)	Travel speed (cm/min.)	Welding passes
1	150	19	12.24	2
2	150	22	15.36	3
3	150	25	19.32	4
4	175	19	15.36	4
5	175	22	19.32	2
6	175	25	12.24	3
7	200	19	19.32	3
8	200	22	12.24	4
9	200	25	15.36	2

3. Experimental Method and Materials

For the measurement of residual stresses the hole drilling strain gauge method is the most practical technique described in ASTM Standard E837.This technique uses a specially configured electric resistance strain gauge rosette that was adhered to the surface of the test workpiece and a small deep hole was drilled through the centre of the rosette. The size of drilled hole both in diameter and depth is typically 2.0 mm. Due to introduction of hole the local changes in strain were measured and from these measurements the relaxed residual stresses were computed.

3.1 Work piece material

The work piece material used for present study is low carbon steel i.e. Fe_3 410WC Plates. The dimension of the work piece material are length 100mm, width 100 mm and thickness 10mm. The chemical composition of the work piece material are shown in Table 3 and the physical and mechanical properties are shown in Table 4.The specifications of strain gauges used in hole drilling process are shown in Table 5.

Table 3.1 Chemical composition of Low carbon steel plates [Fe_3 410WC]

Element Wt %	C	Mn	Si	P	Cr	Ni	Fe
Low carbon steel	0.17	1.46	0.34	0.015	0.30	-	Balance

Table 3.2 Physical and Mechanical properties of Low carbon steel plates [Fe_3 410WC]

S. No.	Properties	Units
1	Elastic modulus	1.9 e $^{+011}$ N/m^2
2	Poisson ratio	0.29
3	Shear modulus	7.5 e^{+010} N/m^2
4	Mass density	8000 kg/m^3
5	Tensile strength	517017000 N/m^2
7	Yield strength	206807000 N/m^2
8	Thermal expansion coefficient	1.8e^{-005} / Kelvin
9	Thermal conductivity	16 w/m. K
10	Specific heat	500 J/ Kg. K

Table 3.3 Specification of Strain gauge

Technical Data		
1	Trade Name	TML PRS-3.17
2	Company Name	Tokyo sokki kenkyuju co.ltd
3	Gauge length	3mm
4	Gauge resistance	$120 \pm 0.5\ \Omega$
5	Gauge factor	$2.08 \pm 1\%$
6	Transverse Sensitivity	1.0%
7	Temp. Compensation	$0.7 \times 10^{-6}/°C$
8	Test condition	23°C, 50% RH

Figure 3.1 shows the attachment of strain gauge to the work piece. Figure 3.2 shows the hole drilling method. Figure 3.3 shows the MIG welding done on the work piece. Figure 3.4 shows the measurement of strain with the help of strain gauge data logger. Figure 3.5 shows the hardness testing machine which was used to measure the hardness of the specimen.

Figure 3.1. Attachment of strain gauges to welded work piece

Figure 3.2. Hole drill Method

Figure 3.3. MIG Welding of work piece

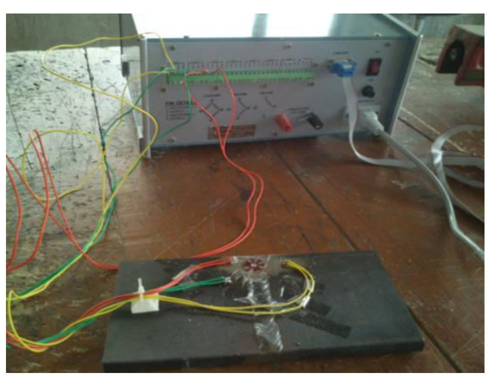

Figure 3.4. Measurement of strain in welded work piece through strain gauge data logger

Figure 3.5. Hardness testing

4.1 Analysis of Signal to Noise Ratio

In the Taguchi method the desirable value (mean) for the output characteristics is represented by the term Signal and the undesirable value (standard deviation) for the output characteristics is represented by the term noise. The minimum residual stresses and maximum hardness are chosen as the two main quality objectives of welded materials specimens' .The Signal to Noise ratio were used to transform the experimental results. The deviation of quality characteristics from the desired value were measured b the use of the S/N ratio which was proposed by Taguchi. The quality characteristics in the analysis of S/N ratio are categorized into three different categories like Larger the better, nominal the best and smaller the better. The S/N analysis was used for calculation of S/N ratio for each level of process parameters. It was observed that better quality characteristics related with the highest S/N ratio of the process parameters. Therefore the level of highest S/N ratio with minimum variance was selected the optimal level.

Table 4.1. Experimental results for Hardness and Residual stresses

Exp. Trial No.	Current (A)	Voltage(V)	Travel speed (cm/min.)	Welding passes	Hardness	Residual Stresses (MPa)
1	150	19	12.24	2	37.4	276.95
2	150	22	15.36	3	49.75	427
3	150	25	19.32	4	33.5	448
4	175	19	15.36	4	16.05	139
5	175	22	19.32	2	48.15	451
6	175	25	12.24	3	50.5	279.23
7	200	19	19.32	3	31.15	366.32
8	200	22	12.24	4	60.5	493
9	200	25	15.36	2	29.85	395.4

Table 4.2. S/N response table for Hardness

Level	Current (A)	Voltage(V)	Travel speed (cm/min.)	Welding passes
1	31.96	28.48	33.72	31.54
2	30.61	34.41	29.18	32.62
3	31.67	31.36	31.34	30.08
Delta	1.36	5.93	4.54	2.54
Rank	4	1	2	3

Table 4.3. S/N response table for Residual stresses

Level	Current (A)	Voltage(V)	Travel speed (cm/min.)	Welding passes
1	-51.49	-47.66	-50.54	-51.29
2	-48.29	-53.18	-49.14	-50.94
3	-52.36	-51.30	-52.46	-49.91
Delta	4.07	5.52	3.33	1.38
Rank	2	1	3	4

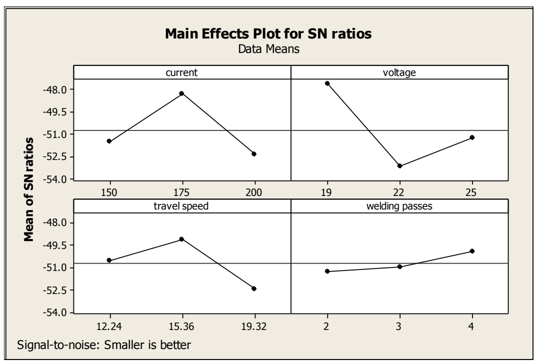

Figure 4.1. Main effect plots for S/N ratio for residual stresses

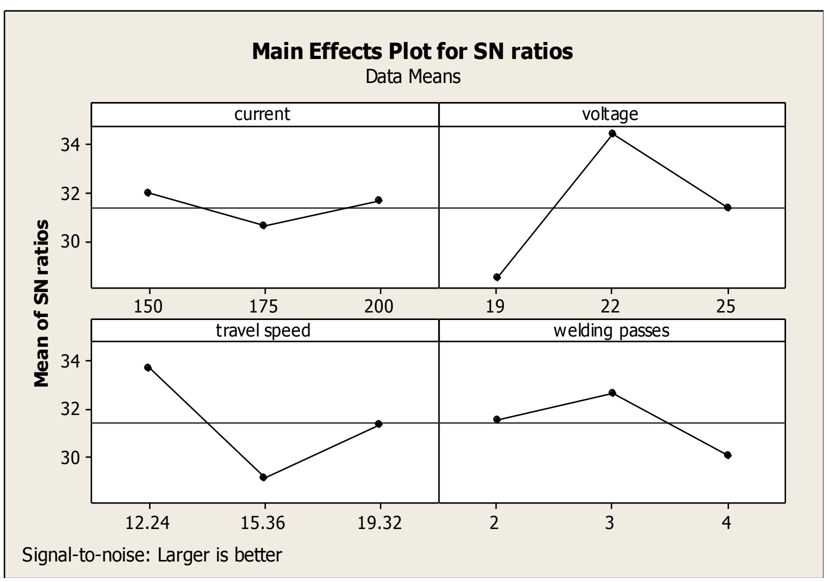

Figure 4.2. Main effect plots for S/N ratio for hardness

4.2 ANOVA

The most significant controlled factor for the manufacturing operations was obtained by applying the technique of Statistical analysis of variance. The optimum combination of process parameters can be predicted which was based on the S/N ratio and ANOVA analysis. The verification of the optimal process parameters obtained from the designed parameters done by the confirmatory run.

Table 4.4. ANOVA Summary of Residual stresses

SOURCE	DF	Seq SS	Adj. SS	Adj.MS	F	P
Current	2	26566	26566	13283	52.95	0.019
Voltage	2	58237	58237	29119	116.08	0.009
Travel speed	2	16310	16310	8155	32.51	0.030
Error	2	502	502	251		
Total	8	101615				

S = 15.8384 R-Sq = 99.51% R-Sq(adj) = 98.03%

Total error would be a: - Error/Total =502/101615 *100 =0.494%

Where, DF – Degree of Freedom, Seq SS – Sum of Square of Variance, Adj SS – Sum of Square of Variance, Adj MS- Mean of Square of Variance, F - Fisher value, it depends on the probability and P - Probability of Variance.

Table 4.5. ANOVA summary of Hardness

SOURCE	DF	Seq SS	Adj. SS	Adj.MS	F	P
Current	2	9.15	9.15	4.58	0.11	0.900
Voltage	2	920.74	920.74	460.37	11.19	0.082
Travel speed	2	482.67	482.67	241.34	5.87	0.146
Error	2	82.67	82.67	41.14		
Total	8	1494.84				

S=6.41372 R-Sq=94.50% R-Sq (adj) =77.99%

Total error would be a: - Error/Total =82.67/1494.84*100 =5.53%

Table 4.6.Modified ANOVA Table for the summary of Residual stresses

SOURCE	DF	Seq SS	Adj. SS	Adj.MS	F	P	%Contribution	Significant
Current	2	26566	26566	13283	52.95	0.019	26.14%	Less significant
Voltage	2	58237	58237	29119	116.08	0.009	57.3%	Significant
Travel speed	2	16310	16310	8155	32.51	0.030	16.05%	Least significant
Error	2	502	502	251			0.5%	
Total	8	101615						

% Contribution= Seq SS / Total*100

Table 4.7.Modified ANOVA Table for the summary of Hardness

SOURCE	DF	Seq SS	Adj. SS	Adj.MS	F	P	%Contribution	Significant
Current	2	9.15	9.15	4.58	0.11	0.900	0.6121%	Least significant
Voltage	2	920.74	920.74	460.37	11.19	0.082	61.594%	Significant
Travel speed	2	482.67	482.67	241.34	5.87	0.146	32.28%	Less significant
Error	2	82.67	82.67	41.14			5.53%	
Total	8	1494.84						

% Contribution= Seq SS / Total*100

5. Experimental Results and Discussion

Experimentation has been completed and minimum residual stress by hole drilling strain gauge method and maximum hardness by Rockwell hardness testing machine was found out. Output response are shown in Table 4.1, this data is used to further analysis i.e. to determine the optimum welding condition to maximize the hardness and minimise the welding residual stresses.

5.1 Effect of welding parameters:

The statistical techniques analysis of variance and signal to noise ratio have been applied on observed data to identify the significant input parameters which expected to influence output response .Result of analysis of variance (ANOVA) test is shown in Table 10 and Table 11. In the ANOVA test, F-tests value of the parameters are comparing with the standard F table value (at 5% significance level) 95% confidence level. If P-value in the table is less than 0.05 then the corresponding variables considered as statistically significant. It is found from Table 10 that P value for current, voltage and travel speed are less than 0.05 .This means that all these parameters have significant effect on the residual stresses.

On the other hand it is found that in Table 11 that P value for current, voltage and travel speed are greater than 0.05 . This means that none of those parameters do have significant effect on the hardness at 95% confidence level.

The percent contribution indicates that the variable welding voltage all by itself (57.3%) contribute the most towards the variation observed in residual stresses. The variable welding current contributes over 26.14%of the total variation observed. The variable travel speed has less contribution towards the total variation in residual stresses.

Similarly the welding voltage and travel speed have main effect on the variation of hardness. The percent contribution showed that the variable welding voltage all by itself (61.594%) contribute the most towards the variation observed in hardness. The variable travel speed contributes over 32.28% of the total variation observed. The variable welding current has less contribution towards the total variation in hardness.

S/N ratio of hardness and residual stresses is calculated for each parametric combination using Taguchi method and shown in Table 6 and Table 7. On examination of S/N ratio of hardness it was found from Delta values, voltage is found to be most significant factor, next is travel speed, next is welding passes and followed by welding current.

On examination of S/N ratio of residual stresses it was found from Delta values, welding voltage is found to be most significant factor, next is current, next is travel speed and followed by number of welding passes.

By using these S/N ratio values given in Table 6 and Table 7, the main effect plots have been made using MINITAB 16 software and shown in figure 1 and figure 2 .While calculating S/N ratio values, larger the better criteria have been applied for hardness, because hardness needs to be maximize. But smaller the better criteria have been applied for residual stresses, because residual stresses needs to be minimized. Optimal parametric setting can be found from the main effect plots at highest S/N ratio values to each corresponding factors. From figure 1 and figure 2 it is observed that the optimum condition for maximum hardness is A1B2C1D2 (i.e. current =150 ampere, voltage=22 volts, travel speed =12.24 cm/min and welding passes 3.) and for minimum residual stresses are A3B2C3D1(i.e. current 200 amperes, voltage 22 volts, travel speed 19.32 cm/min and welding passes 2).

For parameter optimization following formula based upon Taguchi design has been used for hardness :

$$\eta_{opt} = m + (mA1 - m) + (mB2 - m) + (mC1 - m) + (mD_2 - m)$$

Where 'm' is the overall mean of S/N data, mA1 is the mean of S/N data for welding current at level 1 and mB2 is the mean of S/N data for welding voltage at level 2 and mC1 is the mean of S/N data for travel speed at level 1and mD_2 is the mean of S/N data for number of welding passes at level 2.

Calculation, overall mean of SN ratio (m) was taken from Minitab software. m= 31.41

Therefore, $\eta_{opt} = 31.41 + (31.96-31.41)+ (34.41-31.41)+(33.72-31.41)+(32.62-31.41)=38.48$

Y^2 opt = (10) ^ηopt / 10 for properties, greater is better

Y^2 opt = $(10)^{38.48}/10 = 7046.93$

Yopt = 83.94

Therefore, yopt = 83.94

So, Optimum value of hardness = 83.94

From this we conclude that optimum value of hardness at the parameters of welding current 150 ampere, welding voltage 22Volts and travel speed 12.24 cm/min and number of welding passes required 3.

Similarly

For parameter optimization following formula based upon Taguchi design has been used for Residual stresses.

$$\eta_{opt} = m + (mA3 - m) + (mB2 - m) + (mC3 - m) + (mD_1 - m)$$

Where 'm' is the overall mean of S/N data, mA3 is the mean of S/N data for welding current at level 3, mB2 is the mean of S/N data for welding voltage at level 2, mC3 is the mean of S/N data for travel speed at level 3 and mD_1 is the mean of S/N data for number of welding passes at level 1.

Calculation, overall mean of SN ratio (m) was taken from Minitab software. m= -56.96

Therefore, $\eta_{opt} = -56.96+ (-52.36+56.96) + (-53.18+56.96) + (-52.46+56.96) + (-50.94+56.96) =- -38.06$

Y^2 opt = (1/10)^ηopt / 10 for properties, smaller is better

Y^2 opt =$(1/10)^{-38.06/10} = (1/10)^{-3.806} = 6397$

$Y_{opt} = 79.98$ N/m^2

Therefore, y_{opt} = **79.98**

So, Optimum value of residual stress =79.98 N/m^2

From this we conclude that optimum value of residual stresses at the parameters of welding current 200 ampere, welding voltage 22Volts and travel speed 19.32 cm/min and number of welding passes required 2.

6. Confirmatory test

Confirmatory test was conducted at optimum combination of process parameters to check the validity of optimal parameters of welding. From the results of confirmatory test, it was found that optimum condition of welding produces maximum hardness and minimum residual stresses. The validation of the proposed optimization methodology is also confirmed by the output of confirmatory test.

Table 6.1 Confirmatory Test Results

Optimum parametric condition obtained by Taguchi method		**Minimum residual stress obtained by confirmatory test**
Current	200 amperes	92.7 MPa
Voltage	22 volts	
Travel speed	19.32 cm/min	
Number of passes	2	
Optimum parametric condition obtained by Taguchi method		**Maximum hardness obtained by confirmatory test**
Current	**150 amperes**	73
Voltage	22 volts	
Travel speed	12.24 cm/min	
Number of passes	3	

7. Conclusions

The present research work describes the use of Taguchi method and statistical techniques for analyzing and optimizing the minimum residual stresses and maximum hardness in MIG welding of low carbon steel. From the study, the following conclusions are drawn:-

1. From the ANOVA results, it is found that welding voltage contributes 57.3% towards the variation observed in residual stresses. The welding current contributes over 26.14% of the total variation observed on minimum residual stresses. Also, welding voltage contributes 61.59% towards the variation observed in hardness. The variable travel speed contributes over 32.28% of the total variation observed in hardness.
2. Main effect plots reveal that voltage and travel speed has significant influence on hardness whereas welding voltage and welding current has considerable effect on residual stresses.
3. The optimum welding condition obtained by Taguchi method for maximum hardness is A1B2C1D2 (i.e. current = 150 ampere, voltage = 22 volts, travel speed = 12.24 cm/min and welding passes = 3) and for minimum residual stresses are A3B2C3D1 (i.e. current = 200 amperes, voltage = 22 volts, travel speed = 19.32 cm/min and welding passes = 2).
4. Confirmation test confirms the improvement of hardness and residual stresses which also indicate the validity of the present optimization procedure by using Taguchi method.

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