PARAMETRIC STUDY AND INVESTIGATIONS OF SURFACE QUALITY OF GTAW- BASED WIRE ARC ADDITIVE MANUFACTURING

BY

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CERTIFICATE

This is to certify that the thesis titled "PARAMETRIC STUDY AND INVESTIGATIONS OF SURFACE QUALITY OF GTAW- BASED WIRE ARC ADDITIVE MANUFACTURING" being submitted by Mr. Yogesh Narayana Gangisetty (Admission no: 20je1122), Mrs. Ruchita Naga Durga Yerra (Admission no:20je0816), Mrs. Panduga Akhila (Admission no:20je0658), Mr. Rohit Meena (Admission no: 20je0812) the award of the degree of Bachelor of Technology in the Department of Mechanical Engineering of Indian Institute of Technology (Indian School of Mines), Dhanbad is a record of Bonafide research work carried out by him/her under my supervision. In my opinion, the thesis is worthy of consideration for the award of the degree of Bachelor of Technology in accordance with the regulations of the institute. The results presented in the thesis have not been submitted to any other university or institute for the award of any degree.

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DECLARATION

I hereby declare that the work which is being presented in this dissertation entitled “Parametric Study and Investigations of surface quality of GTAW- Based Wire arc Additive Manufacturing of Mild Steel” in partial fulfillment of the requirements for the award of the degree of B.Tech Mechanical Engineering in IIT ISM Dhanbad is an authentic record of my own work carried out during the period from January 01-01-2024 to May 08-05-2024 under the supervision of Prof. Nirmal Kumar Singh, Department of Mechanical Engineering, Indian Institute of Technology (ISM) Dhanbad, Jharkhand, India.

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ABSTRACT

Wire arc additive manufacturing (WAAM) is popularly becoming an important and cost-effective manufacturing process to fabricate medium-large size components. The process provides the ability to build a near- net-shape structure with a high production rate (50–130 gm/min) and high material usage efficiency (80–90%). However, as per other additive manufacturing (AM) processes, process planning and optimization provide a uniform, time-efficient, and defect-free deposition. Therefore, this study focuses on the parametric study and process optimization to fabricate single layer components. The most commonly and widely used SS304 stainless steel metallic wire has been used to fabricate the sample using single-layer bead deposition. Welding current, welding speed and shielding gas flow rate (SGFR) has been selected as the input process parameters and the Surface roughness (Sa) and the surface waviness (Sz) selected as the output parameter. These output parameter values of Sa and Sz are found using the non-contact type profilometer. The nine experiments were performed using the L9 orthogonal array based on the Taguchi method and then implemented the analysis of variance (ANOVA) to describe various properties. The resultant data has been analyzed and studied using Minitab-17 software. The results obtained showed that the optimum condition for the Sa and Sz are 140A welding current, 14 cm/min welding speed, and 20L/min SGFR. The order of process parameters influencing the Sa and Sz are welding current, welding speed and SGFR. These results were validated by conducting confirmation experiments and found satisfactory.

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Notations and Abbreviations

WAAM-Wire Arc Additive Manufacturing

GTAW-Gas Tungsten Arc Welding

SGFR - Shielding Gas Flow Rate

Sa – Arithmetical Mean Height

Sz – Maximum Height (sum of the largest peak height value and the largest peak depth value)

Chapter 1

Introduction

1.1 WAAM

Additive manufacturing (AM) has gained significant attention from both academia and industry in recent years. Since its inception in the 1980s, AM has been under continuous development, with research in this area showing a substantial uptick. This technology is valued for its ability to produce highly customized parts. Unlike traditional manufacturing processes that remove or shape material, AM constructs objects by adding material layer by layer. Among AM techniques, wire-based processes are generally 2 to 50 times less costly than those that use powder. Additionally, wire-based methods can produce larger and closer-to-finished components due to their high deposition rates and efficient material usage.

Wire and arc additive manufacturing (WAAM) is a subset of direct energy deposition processes, using wire as the material source and an electric arc for energy. WAAM can be performed using various types of arc welding, such as gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and plasma arc welding (PAW). Several key factors affect the quality of WAAM components, including the choice of materials, travel speed, voltage, and current.

One of the main advantages of WAAM is its lower equipment cost compared to other metal-based AM techniques, as well as the flexibility to work with different materials. A WAAM setup typically consists of a computer-controlled robotic system, a welding power source, a welding torch, and a wire feed system, all of which can be assembled from commercially available parts. This affordability makes WAAM suitable for both large-scale production and small machine shops focused on manufacturing and repairs.

Moreover, wire-based materials are cheaper, easier to source, and safer to handle than metal powders, contributing to lower initial and operational costs.
Wire-feed AM processes, including WAAM, generally offer higher deposition rates compared to other metallic AM methods, such as those based on powder. However, this high deposition rate comes with a trade-off: reduced detail resolution and a poorer surface finish. Parts created with WAAM often require additional machining to achieve the desired dimensions and surface quality. Despite this extra machining step, WAAM is still more cost-effective than entirely subtractive machining due to less material waste.

A significant challenge for wire-feed AM processes like WAAM is managing the residual stresses and distortions that arise from high energy inputs, rapid deposition rates, and substantial temperature gradients. This issue can affect the structural integrity and precision of the finished components. WAAM is gaining traction in industries like aerospace, shipbuilding, and high-speed rail due to its advantages in cost and flexibility.

The classification of the WAAM process is based on the type of welding technique used to deposits such as gas metal arc welding (GMAW) based WAAM, gas tungsten arc welding (GTAW) based WAAM, and plasma arc welding (PAW) based WAAM. The WAAM systems can be developed from commercially available components such as a CNC or robotic system, a welding power source, and a welding torch attached to a wire feeder system. Therefore, with the development of the WAAM process, several works have been done and continue to optimize the process parameters with different software and strategy to minimize or eliminate the process limitation. The optimal value for Travel Speed, Welding Current and Shielding Gas Flow Rate has been obtained to optimize the Surface Roughness and Surface Waviness.

From past research, it has been observed that many attempts have been made to develop mathematical models and optimize the process parameters for single-layer weld bead deposition for various mechanical properties of the weld bead. However, there exists a research gap in the optimization of parameters for surface roughness and waviness. Therefore, an attempt has been made in this study to have a parametric study to optimize the process parameters for desired bead quality.

1.2 Problem Statement of the Thesis

Parametric Study and Investigations of surface quality of GTAW- Based Wire arc Additive Manufacturing of ER70S-6 Mild Steel. Finding the optimum conditions for better surface roughness for GTAW component of single layer deposition.

1.3 Objective of the Thesis

The objective of the thesis is Optimizing process parameters of surface quality of GTAW- Based Wire arc Additive Manufacturing. Analysis of Surface Roughness and Surface Waviness for GTAW component of single layer deposition. Optimizing Travel Speed, Welding Current and Shielding Gas Flow Rate using Taguchi method

1.4 Organization of Thesis

Chapter 1: Details about the WAAM, how does it work, different type of WAAM, Components required along with its advantage. Also specifies the various factors which effects the surface quality and desired dimensions.

Chapter 2: It includes the literature review on WAAM-GTAW. It encompasses the previous studies and research that has been done in this field. Researchers have extensively studied on WAAM. It describes how GTAW component gets affected by changing the wire feed rate and travel speed, shielding gas, heat input on surface quality.

Chapter 3: It describes the experimental equipment and its working principle. Provides the reason for selecting the Mild Steel Wire ER70S-6 for fabrication. Procedure we have used for fabrication of GTAW component. It provides the idea of input parameters which we have used and its output parameters. Used Taguchi method for optimizing the process and quality.

Chapter 4: Describes the results of the Taguchi method which we have used for optimizing in the previous section. Covers the how welding speed, welding current and SGFR effects the surface roughness and surface waviness of the component. It provides the results of Sa and Sz which we have got through non-contact profilometer

Chapter 5: Deals with the conclusions of this study and mentions the recommendation for the future work.

Chapter 2

Literature Review

When reviewing previous research and findings on parametric studies and investigations of surface quality in Gas Tungsten Arc Welding (GTAW)-based Wire Arc Additive Manufacturing (WAAM) of mild steel, several key themes and studies are explored. An increase in the wire feed rate typically results in thicker beads, which may increase surface irregularities. Studies have explored the optimal balance between deposition rate and surface quality. Slower travel speed can lead to larger beads with more surface irregularities, while faster speeds can produce smaller, more consistent beads. Different gases (like argon, helium, or a mixture) affect the stability of the arc and the quality of the weld. Studies have examined how these gases impact surface quality by reducing oxidation and spatter. Higher gas flow rates can lead to smoother surfaces by preventing oxidation, but they might also cause turbulence and increased spatter.

Studies have shown that higher heat input can lead to larger weld beads, resulting in increased surface roughness. Conversely, lower heat input can produce finer weld beads but may lead to incomplete fusion or undercuts. Researchers have examined the effects of adjusting current, voltage, and travel speed to optimize heat input for better surface quality. Proper overlap between adjacent beads is crucial for consistent surface quality. Studies have analyzed different overlap strategies to find the optimal balance. Some studies have investigated the use of grinding, machining, or other finishing processes to improve the surface quality of WAAM-produced parts. These studies also consider how post-processing affects the mechanical integrity of the parts. Identified challenges include maintaining consistent surface quality across large parts, minimizing defects, and achieving uniform bead geometry. Research has begun exploring advanced control systems, artificial intelligence, and machine learning to improve surface quality and automate parameter adjustments. e parametric studies focus on identifying the optimal process parameters to ensure high surface quality, and the investigations aim to understand the underlying mechanisms affecting this quality. Further research often aims to refine these parameters, develop more sophisticated control

Chapter 3

Materials and Experimental Techniques/Methodology

3.1 Experimental setup

1 6-axis robotic arm
2 Wire feeder
3 GTAW welding system
4 CNC control system
5 Power Supply
6 Shielding gas setup
7 Monitoring and control system
8 Non-contact type Optical Profilometer

3.2 Selection of materials

The most versatile and widely used Mild Steel Wire ER70S-6 has been used to fabricate the wall using single layer deposition. The detailed chemical composition of the metallic wire and the mild steel base plate has been mentioned in Tables 1 and 2 respectively. The dimension of the base plate was $250mm \times 100mm \times 5mm$ over which a single-layer bead has been deposited. The diameter of the metallic wire used for the deposition was 1.2 mm. The carriage clamps were used to hold the base plate and prevent it from distortion caused due to continuous heating and cooling of the plate during the fabrication of the wall structure.

3.3 Fabrication of Single layer deposited samples

The GMAW based WAAM technique due to its semi-automatic features and non-requirement of wire feeder attachment has been used to deposit the single layer wall for parametric study and process optimization. The systematic diagram of the experimental setup has been shown in Fig. 1. The semi-inert Argon Gas (Ar) has been used to shield the deposition environment to prevent surface oxidation and arc generation. The selected input parameters are Welding Current, Travel Speed, and SGFR. The Surface Roughness (S.R) and Surface Waviness (S.W) has been selected as the output parameter to study the parametric setting and its optimization for single-layer deposition. Taguchi as the experimental design developed by Genichi Taguchi has been considered as quite a simple, efficient, and well-structured method for optimization of the process, quality, and cost. Therefore, is widely used by researchers and engineers to conduct their experiments with the minimum number of trials. So, Taguchi L9 orthogonal array has been adopted to study parametric behavior and to optimize the deposition process. Also, the most widely used statistical tool ANOVA has been further used to analyze the experiment data in Minitab Software.

3.4 Determining the welding parameters and their levels

The suitable range for selected input parameters has opted from the number of the trial experiment performed. The detailed parametric setting for the single layer wall deposition has been mentioned in Table 3. After the trial experiment, three-level values for input parameters Welding Current, Travel Speed, and SGFR have been selected to design the experiment using Taguchi L9 orthogonal array technique in the Minitab software. Accordingly, the nine experiments as per DOE have been performed to study the effect of input process parameters on the bead geometry. The three selected factors and their values have been mentioned in Table 4 while the complete DOE using the Taguchi L9 method has been tabulated in Table 5. The Surface Roughness (S.R) and Surface Waviness (S.W) has been measured by non-contact type optical Profilometer for different-different beads.

Table1: Chemical Composition of Substrate plate used for Deposition.

Element	C	Mn	Si	P	S	Cu
wt.%	C<0.2%	1.40-1.85%	0.8-1.15%	P<0.025%	S<0.035%	0.5%

Table2: Chemical composition of feed wire (ER70S-6)

Element	C	Cr	Ni	Mo	Cu	Mn	Si
wt.%	0.06-0.15%	0.15%	0.15%	0.15%	0.50%	1.40-1.85%	0.80-1.15%

Table3: Process parameters for WAAM and their values.

Process Parameters	Values/Ranges
Wire diameter(d)	1.2mm
Standoff distance(l)	5mm
Torch angle	90^o
Wire Feed rate(f)	1m/min
Shielding gas	Argon (Ar)

Table4: Factors and their respective values.

S/No.	Factors	Type	Level1	Level2	Level3
01	Welding Current	Fixed	140	150	160
02	Travel Speed	Fixed	10	12	14
03	SGFR	Fixed	10	15	20

Table 5: Orthogonal arrays L9 DOE based on Taguchi.

S.No.	C1	C2	C3	C4	C5
	Travel Speed UNITS	Welding Current	SGFR	**Sa**	**Sz**
1	10	140	10	43.471	307.487
2	10	150	15	63.375	356.164
3	10	160	20	71.891	408.153
4	12	140	10	34.114	305.694
5	12	150	15	53.097	306.918
6	12	160	20	73.861	396.642
7	14	140	10	30.443	278.990
8	14	150	15	46.285	328.072
9	14	160	20	52.388	338.264

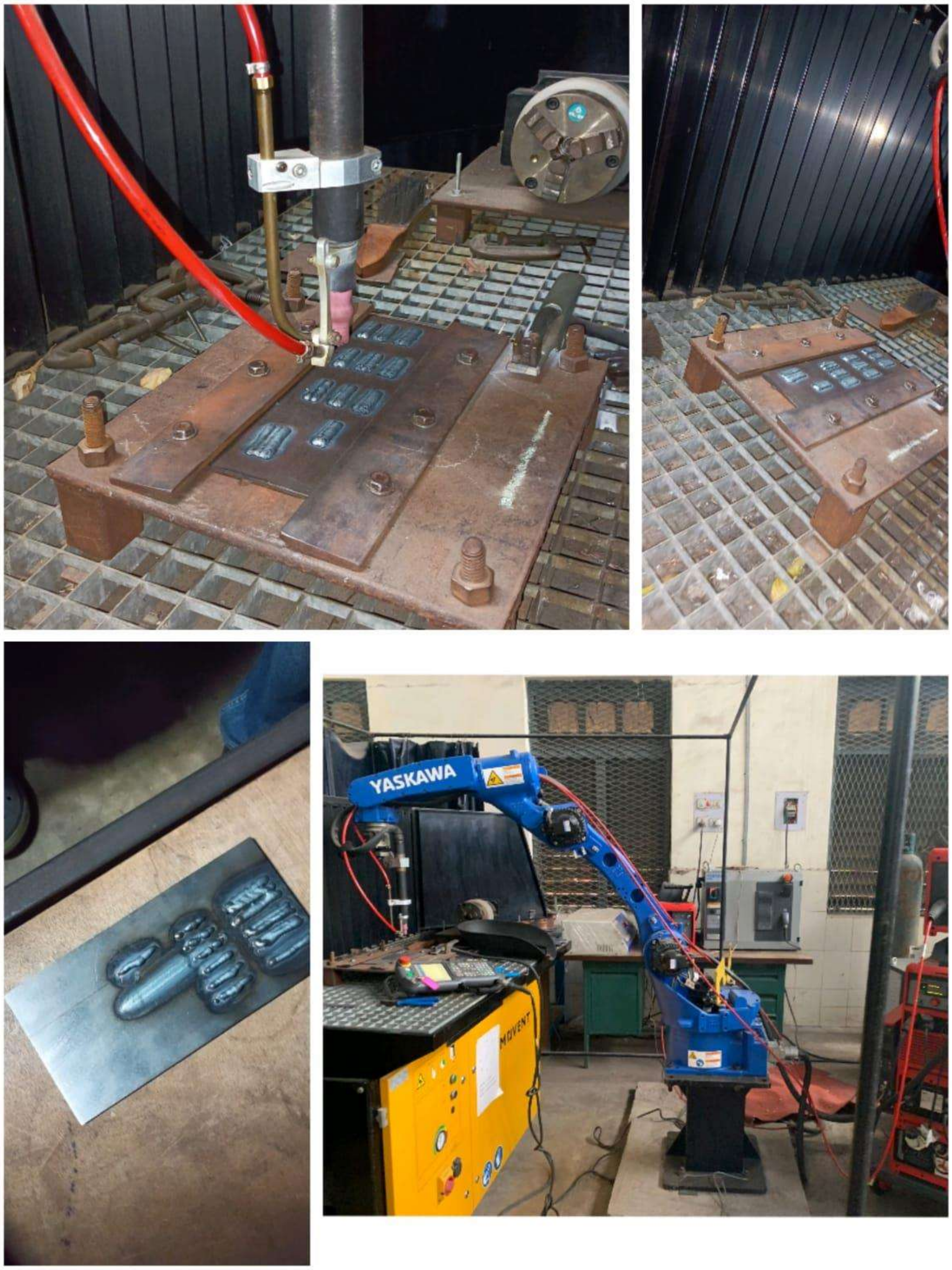

Fig 1. Experimental Setup

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Surface analysis of single layer surface quality using Non-Contact Optical Profilometer

A Non-Contact Profilometer is used to determine surface topography or profile of the nine experimental samples of single layer depositions. The Surface roughness values, and their 3D profile images are recorded for all the samples. The minimum surface roughness value 3D profile image is as shown in figure (-).

Sa corresponds to Surface roughness value. Sa is the extension of Ra (arithmetical mean height of a line) to a surface. It expresses, as an absolute value, the difference in height of each point compared to the arithmetical mean of the surface. This parameter is used generally to evaluate surface roughness.

Sz corresponds to the Surface waviness value. Sz is defined as the sum of the largest peak height value and the largest pit depth value within the defined area.

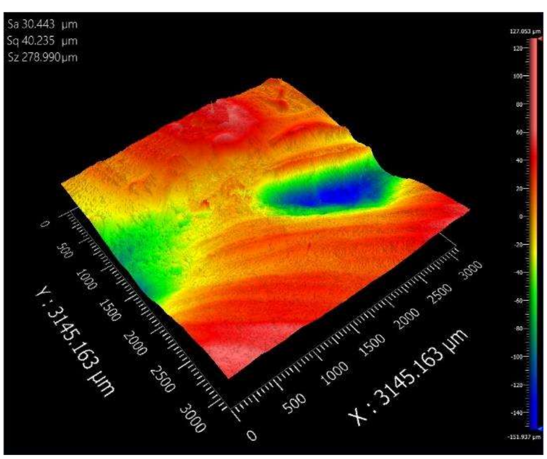

Fig 2. 3D view of Sa and Sz

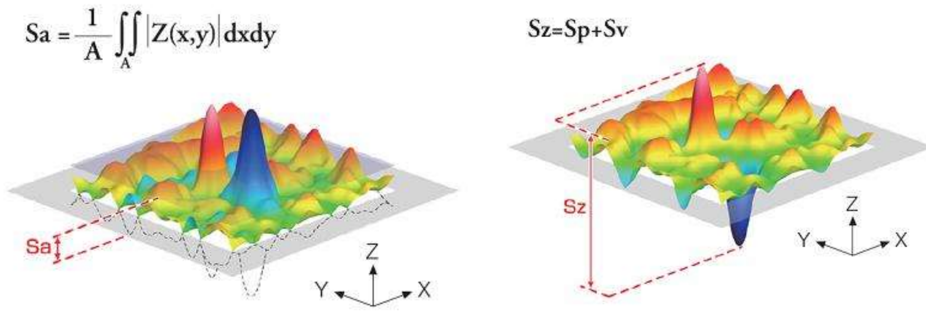

Fig 3. Sa and Sz

4.2. Data analysis of single-layer surface quality using Taguchi

The effect of the welding parameters on the deposited layer surface quality has been investigated in this study. Surface roughness (Sa) and surface waviness (Sz) were considered as responses while variables input process parameters are welding speed, welding current and shielding gas flow rate (SGFR). Taguchi method is used to develop empirical models that correlate the process variables and their interactions with the surface roughness and surface waviness. The response table for the signal to noise (S/ N) ratio and the means has been tabulated in Tables - and – respectively.

The results clearly show process parameter such as welding speed is the most impactful parameter for the surface roughness (Sa) and waviness (Sz) that largely affects the surface quality. Thereafter welding speed follows the secondary importance and is least influenced by the SGFR. The S/N ratio plot and Mean of means plot have been presented in Figs. - and - considering the condition as smaller the better. The condition smaller is better for the surface roughness (Sa) and waviness (Sz) has been taken as for the single layer deposition. For lower welding currents and higher welding speeds, the Sa and Sz values are lower. The results from the S/N plots show that the optimal Sa and Sz values is obtained at welding speed (14 cm/min), welding current (140 A), and SGFR (20 L/min). A similar result has been obtained from the contour plot to support the above results. The contour plot in Figs. - and - an alternative to the 3D surface plot has been obtained for the model that shows the inter-relation and dependency of process parameters on the Sa and

Sz.

Fig 4. Main effect plot for Means of Sa values: Smaller is better

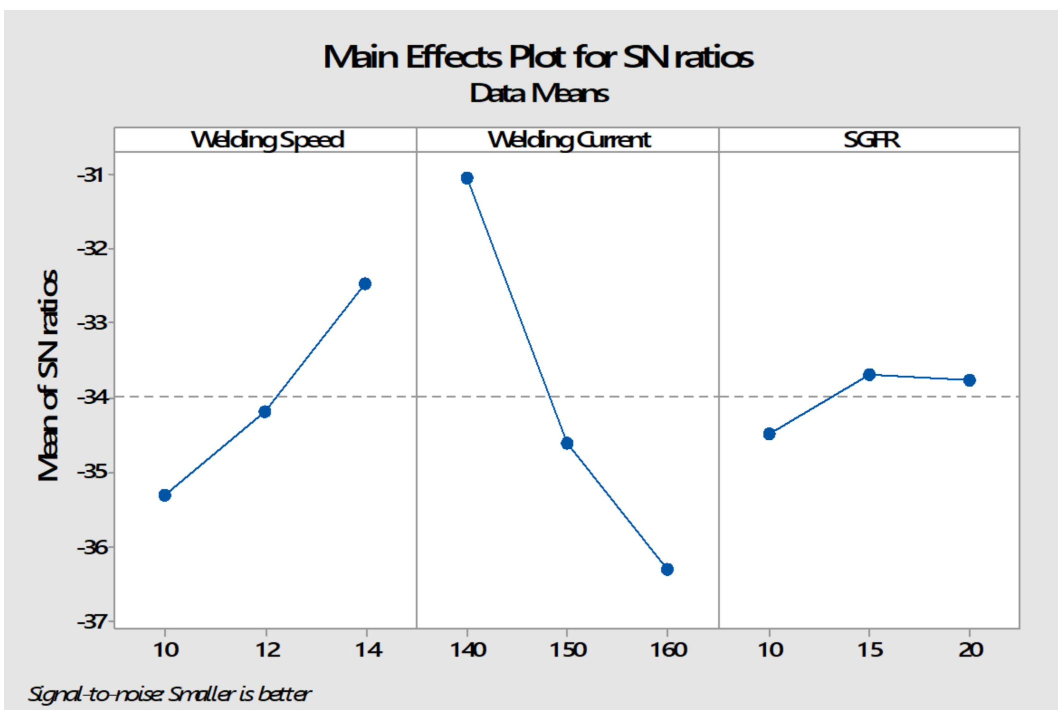

Fig 5. Signal-to-Noise Ratios S/N ratio plot for Sa values: Smaller is better

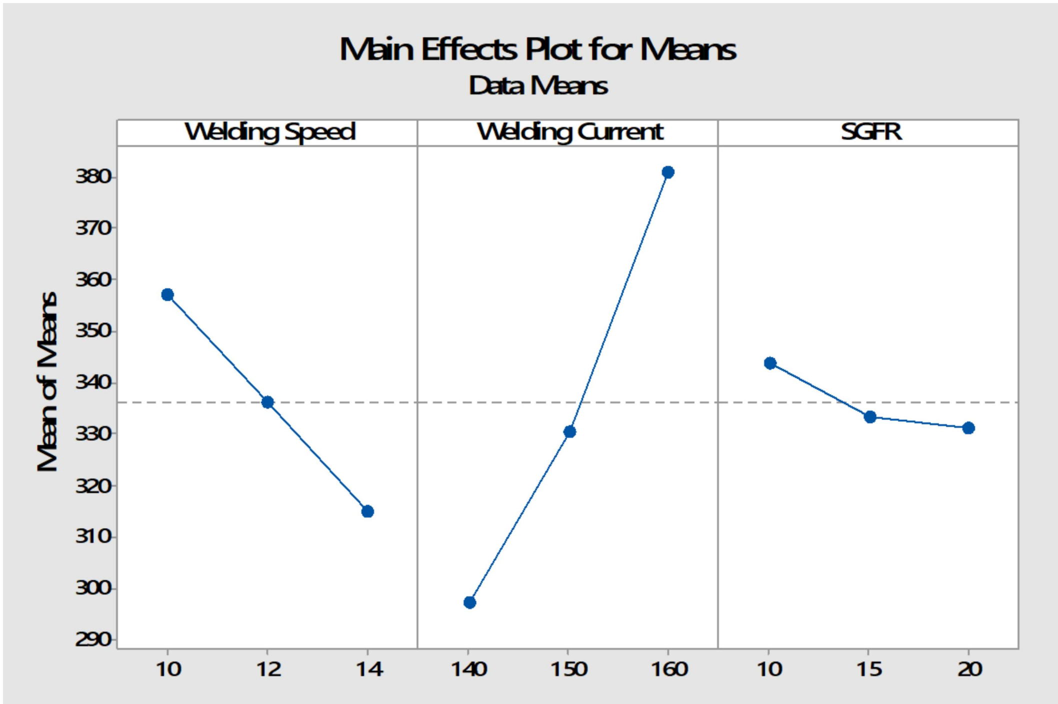

Fig 6. Main effect plot for Means for Sz values: Smaller is better

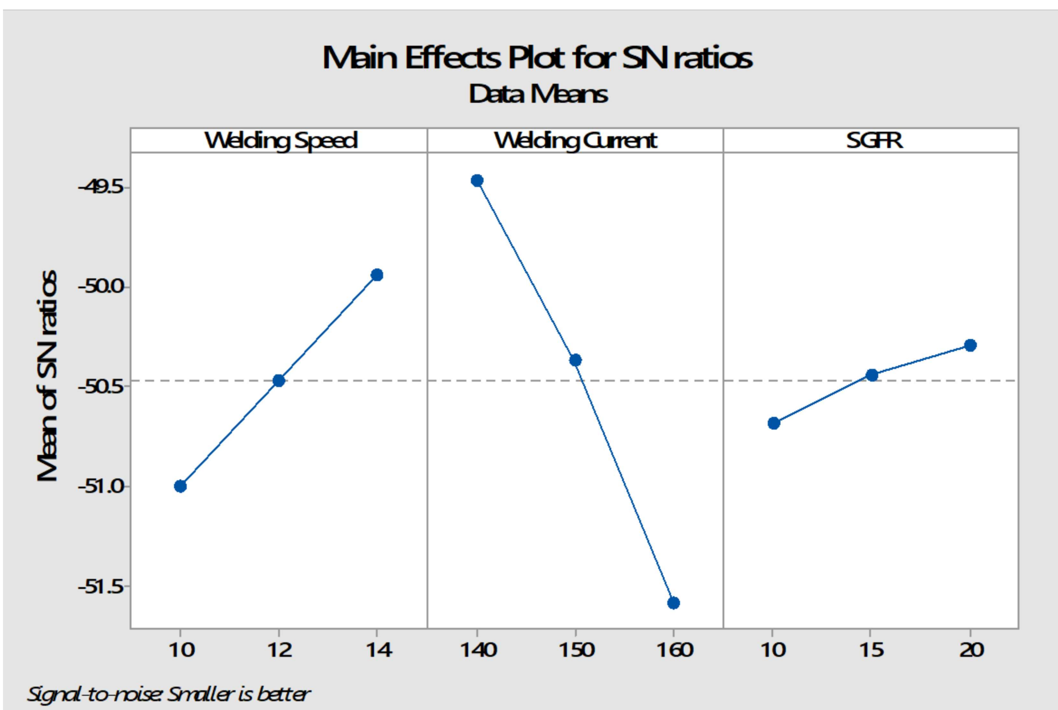

Fig 7. Signal-to-Noise Ratios S/N ratio plot for Sz values: Smaller is better

Taguchi Analysis: Sa versus Welding Speed, Welding Current, SGFR

Table 6: Response Table of Signal to Noise Ratios.

Level	Welding speed	Welding current	SGFR
1	-35.31	-31.03	-34.48
2	-34.18	-34.62	-33.69
3	-32.45	-36.30	-33.77
Delta	2.86	5.26	0.79
Rank	2	1	3

Table 7: Response Table for Means

Level	Welding speed	Welding current	SGFR
1	59.58	36.01	54.54
2	53.69	54.25	49.96
3	43.04	66.05	51.81
Delta	16.54	30.04	4.58
Rank	2	1	3

Taguchi Analysis: Sz versus Welding Speed, Welding Current, SGFR

Table 8: Response Table of Signal to Noise Ratios.

Level	Welding speed	Welding current	SGFR
1	-51.00	-49.46	-50.68
2	-50.47	-50.36	-50.44
3	-49.94	-51.59	-50.29
Delta	1.06	2.13	0.39
Rank	2	1	3

Table 9: Response Table for Means

Level	Welding speed	Welding current	SGFR
1	357.3	297.4	344.1
2	336.4	330.4	333.4
3	315.1	381.0	331.4
Delta	42.2	83.6	12.7
Rank	2	1	3

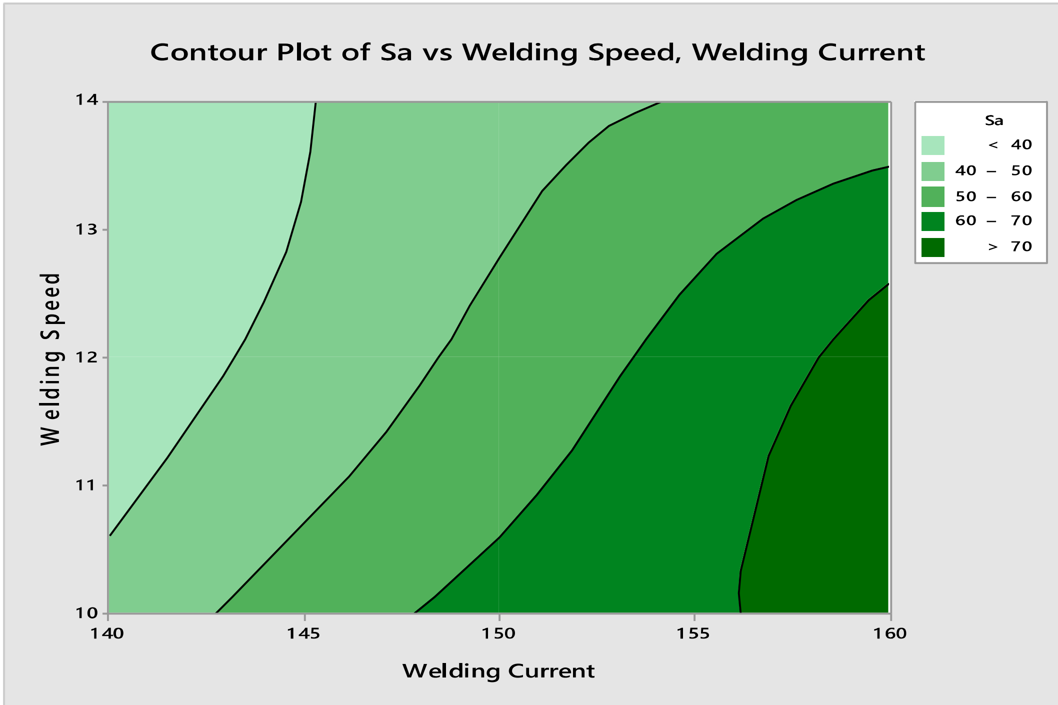

Fig 8. Contour plot of Sa vs welding speed, Welding current

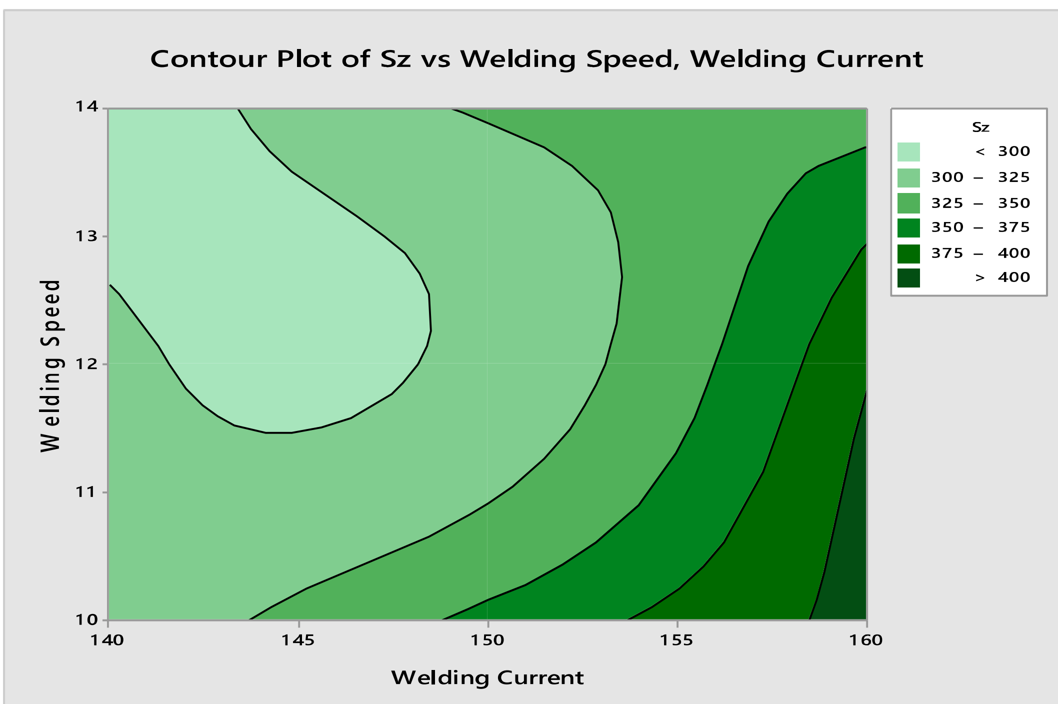

Fig 9. Contour plot of Sz vs welding speed, Welding current

4.3. Data analysis of single layer surface quality using ANOVA

To test the acceptability of the established model, ANOVA has been used. The results obtained from the ANOVA analysis have been presented in Table -. Considering a five percent confidence level, welding speed and welding current are found to be significant parameters for the surface quality. However, the percentage contribution of the welding current was obtained to be largest among all three selected parameters and hence greatly influences the surface quality on fabrication, and the SGFR has the minimum contribution i.e. least influence on the surface profile among the three selected parameter. The p-value for welding current, welding speed and SGFR was observed to be 0.001, 0.009, and 0.524 respectively, and hence satisfy $p < 0.05$ for the significant parameters. The proportion of total variability given by the R^2 value in the model is also close to one, which is also desirable. Equation (-) and (-) represents the regression equation developed from the model that describes the interaction between all the three-parameter to optimize the Sa and Sz values.

Regression equation for S_a:

Sa = -119.5 - 4.135(welding speed) + 1.502(welding current) - 0.273(SGFR)

Regression equation for S_z:

Sz = -145 –10.54 (welding speed) + 4.181 (welding current) - 1.27 (SGFR)

FOR REGRESSION EQUATION:

Regression Analysis: Sa versus Welding Speed, Welding Current, SGFR

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	1774.90	591.63	24.79	0.002
Welding Speed	1	410.37	410.37	17.20	0.009
Welding Current	1	1353.36	1353.36	56.71	0.001
SGFR	1	11.17	11.17	0.47	0.524
Error	5	119.32	23.86		
Total	8	1894.22			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4.88505	93.70%	89.92%	76.94%

Regression Equation

Sa = -119.5 - 4.135 (Welding Speed) + 1.502 (Welding Current) - 0.273 (SGFR)

Regression Analysis: Sz versus Welding Speed, Welding Current, SGFR

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	13399.4	4466.5	12.51	0.009
Welding Speed	1	2666.1	2666.1	7.47	0.041
Welding Current	1	10490.8	10490.8	29.38	0.003
SGFR	1	242.4	242.4	0.68	0.447
Error	5	1785.4	357.1		
Total	8	15184.8			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
18.8967	88.24%	81.19%	54.60%

Regression Equation:

Sz = -145 - 10.54 (Welding Speed) + 4.181 (Welding Current) - 1.27 (SGFR)

CHAPTER 5
CONCLUSIONS AND FUTURE SCOPE

5.1. Conclusions

In this study, an extensive experimental investigation has been done using L-9 orthogonal array based on Taguchi design, and ANOVA is used to analyze the effect of input process parameters on the surface roughness and waviness of deposited weld bead.

1) Considering the S/N ratio plot, the Sa and Sz values obtained to be largest at level 3 value of welding speed, level 3 value of SGFR, and level 1 value of welding current. So, the optimum conditions for having the smallest value of surface roughness and waviness in all three parameters are 14 cm/min, 20L/min, and 140A.

2) From the ANOVA analysis, the result shows that welding speed, welding current and SGFR are the significant parameters for the surface roughness however, welding current is the most influencing process parameter with 84.95% contribution among the selected input parameter for single layer bead deposition and SGFR is the least impactful parameter with 5.25 % contribution among the three parameters.

5.2 Future Scope

Expanding the investigation to optimize parameters for multi-layer deposition represents a logical progression. This entails delving into how the parameters fine-tuned for single-layer deposition translate to multi-layer configurations and considering additional factors like inter-layer adhesion and distortion management.

Moreover, delving into various materials beyond mild steel, including different steel alloys or non-ferrous metals, could yield valuable insights into how process parameters influence diverse material properties. This research could encompass assessments of material compatibility, detailed microstructural analyses, and evaluations of mechanical properties

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