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Parametric Optimisation of Gas Tungsten Arc Welding (GTAW) on the Tensile Strength of AISI 316l Austenitic Stainless Steel Using Taguchi Method

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ABSTRACT

The purpose of this present study, was to use the Taguchi robust design of experiments (DOE) technique to find the optimum GTAW parameters on the tensile strength of AISI 316L austenitic stainless steel. Taguchi L9 orthogonal array experiments were performed on 250 mm by 250 mm by 10 *mm dimensions of AISI 316L austenitic stainless plate using ER316 filler material. Three GTA welding parameters; welding current, welding voltage, and shielding gas flow rate, were changed up to three levels; low, medium and high. The results that were obtained were analysed using a bigger-the-better option for signal-to-noise S/N ratio and analysis of variance (ANOVA) with the aid of MINITAB 18 software. It was observed that, for optimisation of each response, welding current was the most influential factor with a 65% contribution. Maximum tensile strength was achieved at the welding process parametric combination of welding current of 100 A, welding voltage of 25 V and gas flow rate of 20 L/min.*

1. Introduction

Austenitic stainless steels with their combination of high strength and good corrosion resistance have led to their widespread use by the oil and gas industry for both seawater and process systems [1],[2]. The austenitic alloys constitute the largest group of stainless steels in use, making up 65 to 70 % of the total [3]. Welding as a fabrication process is one of the widely used production processes for most manufacturing industries [4]. There are a number of welding methods available for welding materials such as shielded metal arc welding, Gas metal arc welding, Flux-cored arc welding, submerged arc welding, electro slag welding, electron beam welding, and gas tungsten arc welding methods [5]. The welding process chosen for specific applications; depends on several factors; primarily among them are the compositional range of the material to be welded, the thickness of the base materials and the type of current [6]. Most metals oxidize rapidly in their molten state, and therefore, the weld area needs to be protected from atmospheric contamination; this is achieved in gas tungsten arc welding (GTAW) by a shielding gas such as argon, helium, nitrogen [4]. GTAW also called tungsten inert gas (TIG) welding is one of the most efficient welding techniques available today, capable of joining most metal or metal alloys [7]. GTAW is preferred because of its better weld properties suited for joining advanced steel plates [6]. This welding procedure is favoured because of its inherent characteristics, which include high-quality welds, restricted HAZ, fewer spatters and little distortion [8]. TIG welding has a wide range of applications which include the automobile industry [9], the aerospace industry, nuclear reactor coolant piping, the food processing industry, maintenance and repair work and the precision manufacturing industry [10]. However, the microstructural changes that occur during welding and at weld joint is still a major challenge today as it affects both the corrosion resistance and the mechanical properties [4].

Primary GTAW process parameters include welding current, welding voltage, welding speed, input energy (arc energy), shielding gas and filler metal [5]. The various selected parameters of any welding operation are very important in establishing the mechanical properties or quality, of the weldment, and might include impact strength, ultimate tensile strength, hardness and bend strength. As a result, selecting the right welding process parameters and levels is critical for achieving the best mechanical properties and weld bead geometry [9].

A lot of research has been carried out on how best to optimally perform the joining of ASS plates. Different types of welding, equipment, tools and input parameters have been tested for the best results when welding austenitic steel [11]. Vikas and Jadoun [12] performed a study on the joining of two dissimilar metals SS304 and low carbon steel by metal inert gas (MIG) welding and optimized the process parameters by using the Taguchi design of experiment (DOE) method and reported that the effect of welding parameters on the ultimate tensile strength of the joint can be ranked in decreasing order as follows: voltage followed by speed, and then followed by the current. Balaji et al. [13] carried out a study on gas tungsten arc welding parameters on the mechanical properties of SS316L welds. Kutelu et al, [4] reported that 316L ASS rods of dimensions of 75 mm in length and 25 mm in diameter were used; in which welding current, bevel angles and gas volumes inputs, were varied whereby Taguchi L-9 orthogonal array approach was used and results acquired confirmed that the current of amperes per, bevel angle of 60˚ and a gas flow of 0.7 L/m provided the maximum tensile strength, while the minimum tensile strength was obtained with a current of 100 amperes, bevel angle of 60˚ and a gas flow of 0.9 L/m; and showing that sample with the lowest tensile strength produced the maximum microhardness, thereby concluding that, as tensile strength decreases, microhardness increases. Vinoth et al. [14] optimised the input parameters for the TIG welding process of stainless steel, using the mechanical properties of the weld bead as output parameters. Glauco et al. [11] carried out experimental research on the parametric optimisation of the GMAW process in thin thickness of austenitic stainless steel by the Taguchi method; and reported that for the best value of weld bead root penetration, the results of the Taguchi method and analysis of variance produced a combination, a travel angle of 36^o, of a robot speed of 150 cm/min, a welding current of 180 A and a welding voltage of 20.8 V. Next, for an optimal bead width the combination of a robot speed of 150 cm/min, a welding voltage of 20.8 V, a movement angle of 53^o, and a welding current of 180 A would be the best; and from ANOVA, it was possible to identify the most impacting parameter, being the welding voltage, with a contribution of 43.5 percent for the welding penetration and 75.26 percent for the bead width. Chandrakant et al. [15] experimentally studied the optimisation and non-destructive test analysis of SS316L welds using GTAW by optimising the welding process parameters of SS 316L stainless steel and observed that gas flow has a major influence and bevel angle has the least influence in affecting the tensile strength. Rekha et al. [16] studied the optimisation of process parameters for gas tungsten arc welding (GTAW) for optimising the weld pool geometry of stainless steel (SS 202 & SS316) using the Taguchi method, while the process parameters like welding current, wire diameter, shielding gas, and groove angle was varied at three different levels to find out the impact of parameters on weld bead geometry, i.e., weld bead width and weld bead height; and from the results, it was observed that bead width for SS 202 and SS 316 tends to increase significantly with the increase in groove angle from 60^o to 90^o;

with welding current and shielding gas found to be the most significant factors leading to changes in weld bead height for SS 202 and SS 316 samples respectively.

There are several methods for optimising input parameters, the main ones being: factorial design; linear regression; response surface methodology; artificial neural networks; finite element methods; and the Taguchi method [17]. However, in this present experimental study, the influence of the various selected parameters of gas flow rate, welding voltage and welding current of the TIG welding process, on the tensile strength of AISI 316L ASS plates using ER316 filler metal of diameter size 3.2 mm was researched upon. The results obtained have been analysed using the optimisation method of Taguchi L9 orthogonal array DOE and ANOVA. The ‘bigger-is-better’ option for the signal-to-noise ratio (S/N) analysis was used to achieve optimum parameters in order to maximise the tensile strength, while ANOVA was applied to determine the statistical influence of the various selected input process parameters on the tensile strength of the steel.

2.0 Materials and Method

2.1 Material preparation

The base material used for carrying out this study was a commercial AISI 316L austenitic stainless-steel plate of dimensions 250 mm × 250 mm × 10 mm as shown in Figure 1, which was acquired from a local vendor. Energy-dispersive X-ray (EDX) analysis was used to obtain the elemental chemical constitution. The physical properties and mechanical properties of the metal are shown in Tables 1, 3 and 4 respectively. The chemical constitution of ER316 filler metal is depicted in Table 2.

Figure 1. GTA welded AISI 316L ASS plate

2.2 Welding procedure

The GTAW equipment used in this study for welding the AISI 316L steel was DC argon arc welding machine (Miller Gold Star 602) as shown in Figure 2. ER 316 filler wire of diameter 3.2 mm was selected for this experiment as shown in Figure 3. The elemental chemical composition of ER 316 filler wire is stated in Table 2. Three parameters were chosen for this study; including gas flow rate, current and voltage for the optimisation of the welding process. Before welding was carried out, the steel samples were thoroughly cleansed with acetone and dried to remove all impurities. Down hand flat position was used during the welding process. Single V-butt joints with an included- bevel-angle of 60^o between AISI 316L steel with a root gap of 2 mm as shown in Figure 6, were welded by GTA welding using ER 316 filler metal wire. Selected input parameters were employed to fabricate V - butt joints. Nine ASTM-standard tensile test samples with their weld bead located at the centre of each sample were prepared. Experimental test samples used for this study are shown in Figure 4. The universal testing machine (UTM), as shown in Figure 5, was used to conduct the tensile tests.

Figure 2. Gas tungsten arc welding machine

Figure 3. ER316 filler metal

Figure 4. Experimental tensile test samples

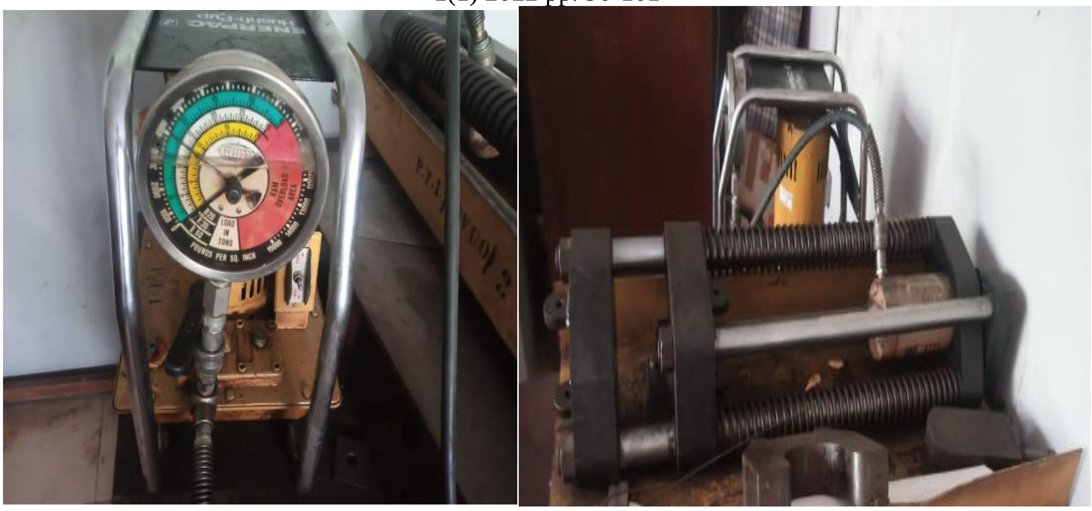

Figure 5. Universal testing machine

Table 1: Elemental composition of AISI 316L steel used in this study

Element	Cr (%wt)	Ni (%wt)	Mn (%wt)	S (%wt)	Mo (%wt)	C (%wt)	Si (%wt)	N (%wt)	P (%wt)	Fe (%wt)
AISI 316L	18.000	4.000	2.000	0.030	2.500	0.030	1.000	0.10	0.045	Bal

Table 2: Elemental composition of filler metal ER316

Filler metal	C (%wt)	Cu (%wt)	Mn (%wt)	P (%wt)	Si (%wt)	S (%wt)
ER316	0.080	0.180	1.530	0.009	0.880	0.010

Table 3: Physical properties of AISI 316L at ambient temperature [18]

Material	Thermal conductivity (W/mK)	Melting point (K)	Specific heat capacity (J/kgK)	Thermal expansion (/K)
AISI 316L	14.6	1678	500	16.5×10^{-6}
	Young Modulus (kN/mm^2)	**Density g/cm^3**	**Shear modulus (kN/mm^2)**	**Electrical resistivity (μΩcm)**
	7.9	196	78	74

Table 4: Mechanical properties of AISI 316L at ambient temperature [18]

Material	Hardness (BHN)	Tensile strength (N/mm^2)	Elongation (%)	0.2% Yield strength (N/mm^2)
AISI 316L	203	538	55	195

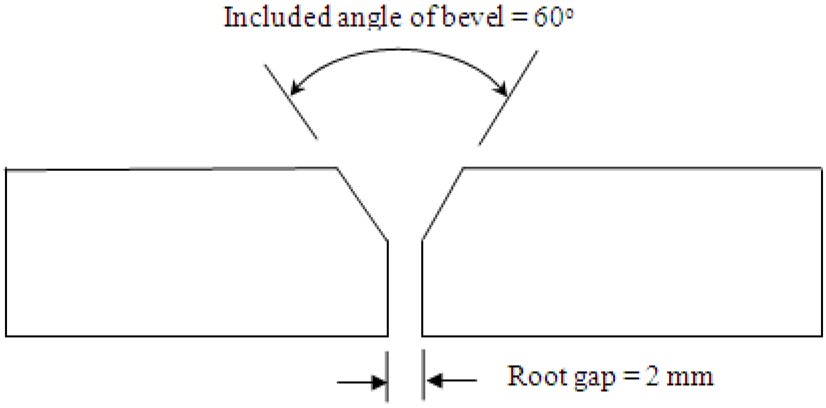

Figure 6. Schematic diagram of the joint geometry

2.3 Taguchi design of experiments

Different approaches for optimising input parameters exist, among the popular optimisation methods include artificial neural networks (ANN); response surface methodology (RSM); factorial design (FD); fuzzy logic; finite element method (FEM); linear regression and the Taguchi method [11], [17].

The Taguchi approach is an easy and cost-effective method of obtaining process optimisation with strong quality and performance which greatly reduces the range of experiments needed and offers a relevant correlation between input and output parameters [11]. Taguchi's design of experiments is one of these optimisation techniques which are widely used whereby this approach entails decreasing the variation in a process through the robust design of experiments [5]. The overall objective of the method is to produce: high-quality products at a low cost to the manufacturer [11]. The Taguchi method was developed by Genichi Taguchi of Japan, who developed a technique for designing experiments to find out how different parameters affect the mean and variance of a process's overall performance characteristic that defines how well the process is functioning and the experimental format proposed by Taguchi includes the use of orthogonal arrays to arrange the parameters affecting the process and the levels at which they should be varied [19]. An orthogonal array is a technique of designing an experiment that usually requires only a fraction of the full factorial combinations and during optimisation, it determines the best parameters and uses them at different levels [19]. The Taguchi design of experiments was used for carrying out all the experiments by which the Taguchi L9 orthogonal array with 3 levels of 3 factors was used for designing the experiments, as shown in Table 6, where L9 means only nine experiments are required to complete all variations and the three levels of parameters were designated as low, medium and high [9].

Table 5: Experimental layout using the Taguchi L9 orthogonal array [19]

S. No.	X	Y	Z
1	X_1	Y_1	Z_1
2	X_1	Y_2	Z_2
3	X_1	Y_3	Z_3
4	X_2	Y_1	Z_2
5	X_2	Y_2	Z_3

6	X_2	Y_3	Z_1
7	X_3	Y_1	Z_3
8	X_3	Y_2	Z_1
9	X_3	Y_3	Z_2

Table 6: Design of experiments using Taguchi L9 orthogonal array

Experiment No.	Current (A)	Voltage (V)	Gas flow rate (L/m)
1	95	23	10
2	95	25	15
3	95	27	20
4	100	23	15
5	100	25	20
6	100	27	10
7	105	23	20
8	105	25	10
9	105	27	15

The Taguchi experimental design is an effective statistical technique. Using this statistical approach, quality characteristics are examined by running a minimum number of experiments [5]. Then, these experimental results are converted into signal-to-noise (S/N) ratios and thus, the performance characteristics are found [20]. There are three signal-to-noise (S/N) ratios of common interest for optimisation

Smaller-is-Better: $S/N = -10\ \log\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right)$ (1)

Bigger-is-Better: $S/N = -10\ \log\frac{1}{n}\left(\sum_{i=1}^{n} \frac{1}{y_i^2}\right)$ (2)

Nominal-is-Best: $S/N = -10\ \log\frac{1}{n}\left(\sum_{i=1}^{n} (y_i - \bar{y})^2\right)$ (3)

Where y is the observed data, n is the number of observations and $\bar{y}$ is the average value of the observed experimental data [21].

It is required that the gas tungsten arc welded joint of AISI 316L should have high tensile strength. Therefore, for this reason, in this study, "The bigger- is-better" formula (equation 2) was used to calculate S/N ratios.

2.4 Tensile strength

The Universal tensile testing machine was used to evaluate the ultimate tensile strength of steel samples with fracture occurring at the weld centre. Table 9 and Figure 7 shows experimental results for ultimate tensile strength. The computer software MINITAB 18, was deployed in analysing the quality characteristics, which were thereafter converted into signal-to-noise ratio (S/N).
The response table for the selected welding process parameters (shielding gas flow rate, voltage and current as recorded in Table 10, depicts the mean of each response output (S/N ratios) for each level of each factor, and is ranked using the Delta statistics by comparing the relative sizes of response outputs. The Delta statistic is the value obtained when the smallest mean is subtracted from the largest mean for each factor, whereby MINITAB 18 assigns rank one to the highest Delta value, rank two to the second highest accordingly, and in which the level means in the response table is used evaluate which level of each factor produces the best (or optimal) result [19].

Table 7: Welding Parameters and their Levels

Parameters	**Unit**	**Level 1 (Low)**	**Level 2 (Medium)**	**Level 3 (High)**
Current	Ampere (A)	95	100	105
Voltage	Volt (V)	23	25	27
Gas flow rate	Litre per minute (L/m)	10	15	20

Table 8: Constant welding parameters

S/N	Shielding gas	100% argon
1	Bevel angle	30^o
2	Included angle of bevel	60^o
3	Direction of weld	down hand (flat)
4	Electrical characteristic	DCEN (straight polarity)
5	Joint design	Single V-butt
6	Plate dimensions	$250 \times 250 \times 10$ mm
7	Electrode	2% Thoriated tungsten
8	Filler rod diameter	3.2 mm

3. Results and Discussion

Table 9: Experimental results for ultimate tensile strength (UTS)

Experiment No.	**Current (A)**	**Voltage (V)**	**Gas flow rate (L/m)**	**Tensile strength (N/mm^2)**	**S/N ratio (Db)**
1	95	23	10	432.8	52.7257
2	95	25	15	450.3	53.0700
3	95	27	20	559.0	54.9482
4	100	23	15	586.5	55.3654
5	100	25	20	609.5	55.6995
6	100	27	10	598.0	55.5340

7	105	23	20	502.8	54.0279
8	105	25	10	542.2	54.6832
9	105	27	15	515.6	54.2463

Table 10: Response table for signal-to-noise ratios (Tensile strength, bigger is better)

Level	Current	Voltage	Gas flow rate
1	53.58	54.04	54.31
2	55.32	54.48	54.23
3	54.32	54.91	54.89
Delta	1.74	0.87	0.66
Rank	1	2	3

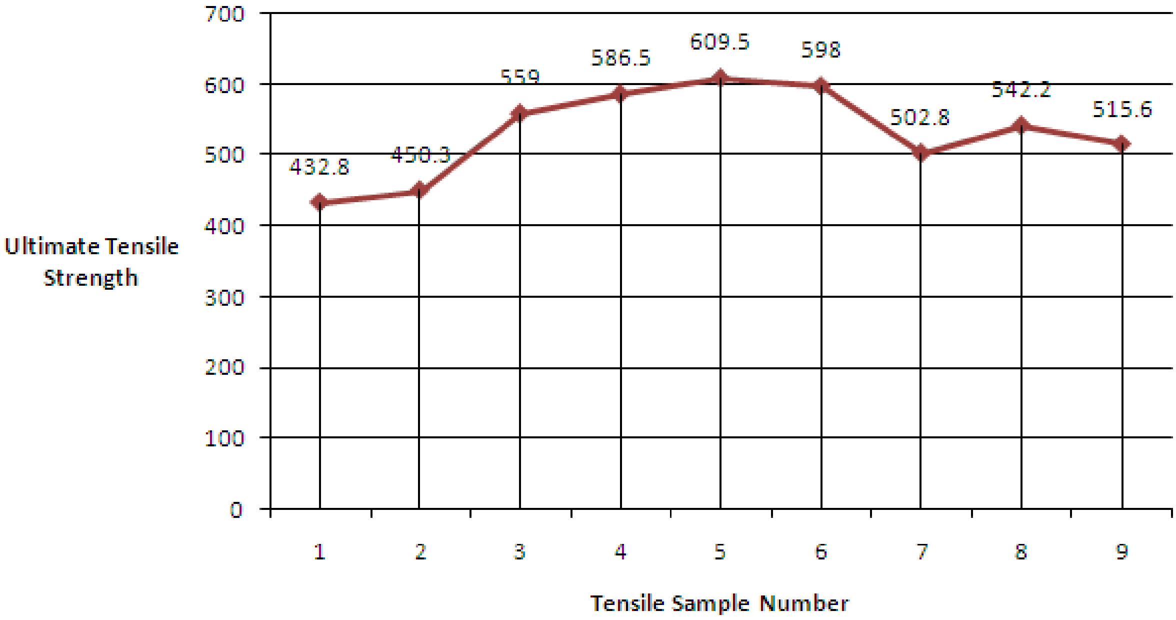

Figure 7. Ultimate tensile strength of GTAW 316L steel tensile samples

Tables 9 and 10 show the experimental analyses for tensile strength. From the experimental analysis, using delta statistics, welding current ranked 1, has the biggest impact on the signal-to-noise ratio as well as the mean; welding voltage was ranked 2 and subsequently gas flow rate ranking 3, with the least influence on both the signal-to-noise ratio as well as the mean. It is obvious that variations of welding parameters affect the tensile strength of GTA weldments of AISI 316L steel, as shown in Figure 7 and Table 9 respectively. The highest magnitude of ultimate tensile strength of 609.5 N/mm^2 was obtained from sample number five, with a current of 100 amps, a voltage of 25 volts and a gas flow rate of 20 litre/minute (which represents the optimum welding parameters); and the lowest ultimate tensile strength of 432.8 N/mm^2 was obtained from sample number one with a current of 95 amps, a voltage of 23 volts and gas flow rate 10 litre/minute.

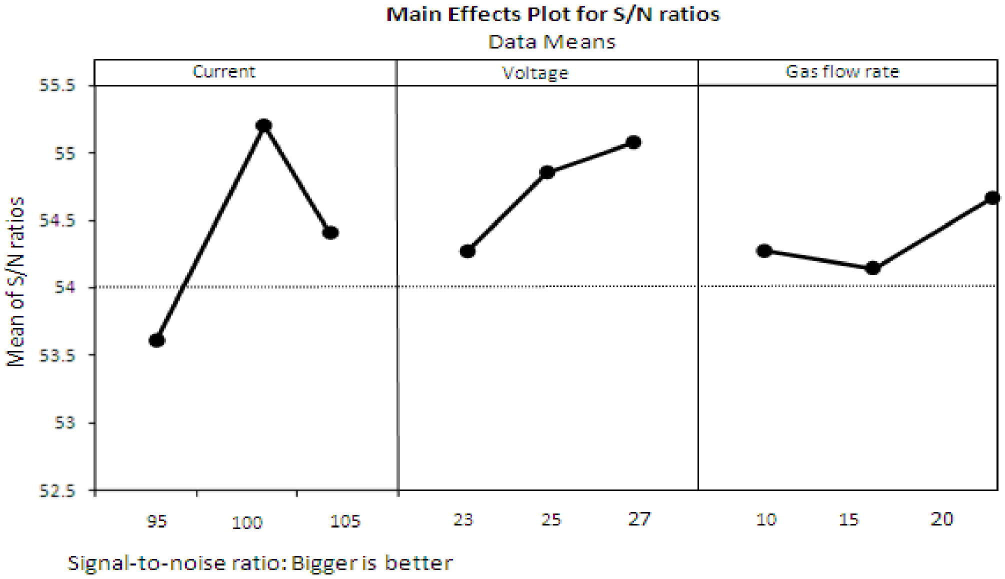

Figure 8. Main effects plot for S/N ratios for tensile strength

Table 11: Analysis of Variance (ANOVA) for S/N ratios

Source	**Degree of freedom**	**Sequential sum of squares**	**Adjusted sum of squares**	**Adjusted mean squares**	**F - factor**	**P – factor**	**% Contribution**
Current	2	5.870	5.870	2.935	4.97	0.168	65.46
Voltage	2	1.135	1.135	0.568	0.96	0.510	12.66
Gas flow rate	2	0.783	0.783	0.392	0.66	0.602	8.73
Residual error	2	1.179	1.179	0.590			13.15
Total	8	8.967					

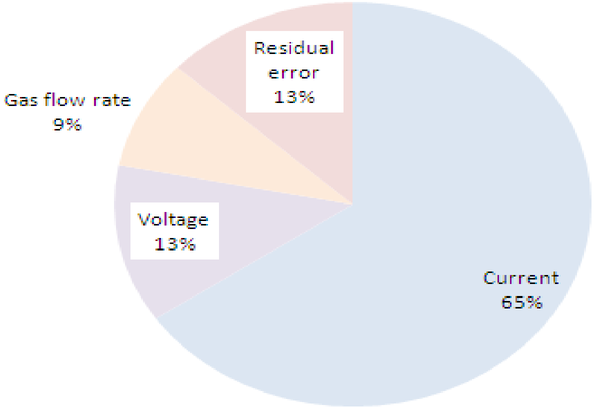

Figure 9: Pie chart for percentage contributions of welding parameters

Table 11 shows the result of the analysis of variance (ANOVA) for tensile strength. The analysis of variance was carried out at a 95% confidence level. It can be seen from ANOVA table 11 and figure 10 respectively, that welding current with an impact factor of 65.46%, has the highest impact factor seconded by welding voltage with an impact factor of 12.66% and gas flow rate with an impact factor of 8.73% has the least impact factor

4. Conclusion

From the experimental analyses conducted on the gas tungsten arc welded AISI 316L tensile test samples using the Taguchi DOE method and ANOVA, the following conclusions were reached: The optimum ultimate tensile strength of 609.5 N/mm^2 was achieved by utilising a combination of a welding current of 100 amps, a voltage of 25 volts and a shielding gas flow rate of 20 litre/minute. Welding current has the maximum impact for tensile strength with 65% significance, followed by voltage with 13% significance and then gas flow rate with 9% significance. Using the Taguchi method, welding process parameter optimisation, improves the tensile strength of GTA weldment of AISI 316L.

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