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Optimization of TIG welding parameters for tensile load testing on dissimilar material joints of galvanized steel (SGCC) and low carbon steel (SPCC-SD)

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Abstract

Tungsten Inert Gas (TIG) welding uses a tungsten electrode and argon or helium gas for shielding. It offers excellent shielding, stable arc, adjustable heat input, minimal spattering, and attractive welds. Widely used in various industries, especially for thin materials like galvanized sheets, TIG welding can be challenging for dissimilar materials like galvanized steel and low-carbon steel due to their different melting points. Studying optimal welding parameters is crucial for success. This research focuses on TIG welding of SPCC-SD (JIS 3141) and SGCC (JIS 3302) materials with thicknesses of 0.6 mm and 0.8 mm. The electric current was varied at 45, 50, and 55 A, whereas the gas flow rate was varied at 12, 15, and 18 LPM. The weld bead diameter was varied as 5, 8, and 10 mm. Subsequently, the welded samples were subjected to tensile testing using a SHIMADZU AGS-X 10Kn STD E200V tensile testing machine. The data from the tensile tests were analysed using S/N ratio analysis and Analysis of Variance (ANOVA) with the assistance of the Minitab software. The results of the S/N ratio analysis indicated that the most optimal parameters were an electric current of 55 A, flow rate of 15 LPM, and weld bead diameter of 10 mm. Conversely, the ANOVA revealed that the weld bead diameter significantly influenced the tensile load in TIG welding of SPCC-SD (JIS 3141) with SGCC (JIS 3302) materials, accounting for up to 44.42% of the variation. Following the weld bead diameter, the flow rate and welding current contributed to 21.93% and 16.41%, respectively.

Keywords:
ANOVA, galvanized, S/N ratio, tensile strength, TIG welding.

1 Introduction

Welding is one of the metal joining techniques involving the melting of a portion of the base metal and filler metal with or without pressure, and with or without additional flux, resulting in a continuous joint [1]. Tungsten Inert Gas (TIG) welding is a welding technique that employs a tungsten electrode and argon or helium gas to shield the welding area [2]. TIG welding results are superior to those of Shielded Metal Arc Welding (SMAW) [3]. TIG welding offers many advantages, including excellent shielding effects, a stable arc, easy adjustment of heat input, minimal material spatter, and a visually appealing weld appearance [4]. However, TIG welding also has some disadvantages, such as relatively shallow penetration and low productivity [4-6], which can increase production costs [7]. TIG welding is widely used in various sectors of the modern industry [8, 9], particularly for welding thin materials such asgalvanised sheets. Galvanisation involves the formation of an alloy metal layer of Fe (Fe-Zn) on the surface of iron and steel products by dipping them in molten Zn [10]. Galvanised steel sheets are widely used in various industries, including automotive, marine, building structures, and infrastructure, owing to their cost-effectiveness and high resistance to atmospheric corrosion compared with ordinary steel [11]. Galvanised steel is gaining popularity in line with the efforts of the automotive industry to reduce vehicle weight and improve fuel efficiency.

The use of a combination of low carbon steel with galvanized steel in automotive and other applications, such as fence/tralis manufacturing, is increasing. Low-carbon steel has a maximum carbon content of 0.3% [12], whereas galvanised steel is steel coated with molten zinc (Zn), providing excellent corrosion resistance [10]. However, this material presents challenges during the welding process. The zinc (Zn) layer on galvanised steel poses difficulties owing to the disparate melting points between the Zn layer and low-carbon steel [13]. When galvanised steel is exposed to high temperatures during welding, the Zn layer on its surface evaporates and diffuses into the surrounding area before the steel reaches its melting point [6]. Some Zn vapor bubbles get trapped in the molten material during the welding process [6]. When these bubbles burst, they create holes that compromise the weld quality [14, 15]. Welding parameters such as electric current, welding time, and standard testing criteria for similar metals cannot be directly applied to dissimilar metal welding [16]. Therefore, studies on optimal welding parameters for welding dissimilar materials are essential.

Research on the optimisation of TIG welding parameters has been conducted in previous studies. L. Natrayan et al. [9] conducted research on optimizing welding parameters using AISI 4140 material. The results showed that welding speed is a more significant parameter than welding current and filler diameter. The Taguchi method is commonly used to determine factors and levels for research parameters in various studies [9, 13]. Budiyanto et al. [17] conducted TIG welding research to evaluate the influence of electric current and filler diameter on microstructure and tensile strength using low carbon steel type St 37. The highest tensile strength of welded joints obtained was 41.74 N/mm². This result was achieved using TIG welding with a filler diameter of 1.6 mm and electric current of 120 A. The lowest tensile strength of 39.71 N/mm² was obtained with a filler diameter of 2.0 mm and an electric current of 120 A. Tensile testing was performed to assess the quality of the welded joints [18]. The tensile test results were analysed using various analytical methods. Analysis of Variance (ANOVA) is often used to determine the significance of input parameters used [9, 13, 19].

Based on various references, this study employed TIG welding on SPCC-SD (JIS 3141) and SGCC (JIS 3302) materials with a thickness of 0.6 mm and 0.8 mm. This is crucial as automobile bodies typically use low carbon steel ranging from 0.6 to 0.98 mm in thickness [20], with a coating thickness of 12.75 microns [13]. In this study, welded joint results underwent tensile load testing and analysis using Minitab software. The aim was to determine the optimum parameters for the TIG welding process using the Taguchi method. The input parameters included welding current (A), argon gas flow rate (LPM), and weld bead diameter (mm).

2 Materials and Methods

2.1 Material

The materials used in this study were SPCC-SD (JIS 3141) and SGCC (JIS 3302) with a thickness of 0.6 mm and 0.8 mm respectively. The chemical properties of these materials are displayed in Table 1, while the mechanical properties are shown in Table 2.

Table 1. Chemical properties of material

Materials	Composition (%)			
	C	Mn	P	S
SPCC-SD [21]	0.15	0.6	0.1	0.05
SGCC [22]	0.15	0.8	0.05	0.05

Table 2. Mechanical properties of material

Materials	Yield point (N/mm^2)	Tensile strength (N/mm^2)
SPCC-SD [21]	0.15	0.6
SGCC [22]	0.15	0.8

The test specimens utilized materials with lengths and widths of 100 and 25.4 mm respectively, with different thicknesses of 0.8 and 0.6 mm welded using a DAIDEN TIGi 200 welding machine as depicted in Fig. 1. For materials with a thickness of 0.6 mm, three variations of Welding Bead (WB) diameters were created: 5, 8, and 10 mm.

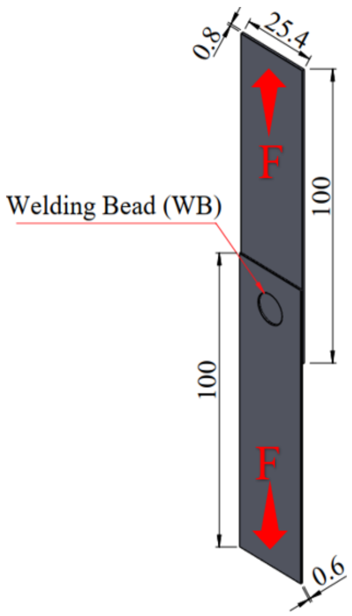

Fig. 1. The welding position scheme of the test specimens.

2.2 Taguchi Experimental Design

Several parameter variations were performed to obtain the optimal parameters for the welding results. Table 3 provides a description of the Taguchi experimental design [23-26], employing a 3-level experiment with 3 factors: welding current, argon gas flow rate, and weld bead diameter.

Table 3. Taguchi experimental design

Code	Parameters	Levels of experiment		
		I	II	III
A	Welding current (A)	45	50	55
B	Argon gas flow rate (LPM)	12	15	18
C	Weld bead diameter (mm)	5	8	10

2.3 Tensile Load Test

Tensile load testing was conducted using a SHIMADZU tensile testing machine, model AGS-X 10Kn STD E200V. For each test, two specimens with the same parameters were used, and the results were averaged for the analysis. The testing process is shown in Fig. 2, and the test specimen matrix is presented in Table 4.

Fig. 2. Tensile load test process.

Table 4. The test specimen matrix

Code	Welding current (A)	Argon gas flow rate (LPM)	Weld bead diameter (mm)
$A_1B_1C_1$	45	12	5
$A_1B_2C_2$	45	15	8
$A_1B_3C_3$	45	18	10
$A_2B_1C_2$	50	12	8
$A_2B_2C_3$	50	15	10
$A_2B_3C_1$	50	18	5
$A_3B_1C_2$	55	12	8
$A_3B_1C_3$	55	15	10
$A_3B_1C_1$	55	18	5

2.4 Signal to Noise Ratio

In the Taguchi experimental method, the analysis of Signal to Noise (S/N) ratio plays a crucial role. The signal represents the desired value for the output result, while the noise reflects the undesired value. At a certain point, an optimal or highest tensile load parameter exists [27]. Calculation of the S/N ratio depends on the quality of the target data. Taguchi divides the quality characteristic data into three parts, and the calculation can be performed using Eq. 1-Eq. 3 [13, 27-29].

Smaller is better:

$$\frac{S}{N} = -10\ Log \sum_{i=1}^{n_0} \frac{y_i^2}{n_0} \tag{1}$$

Larger is better:

$$\frac{S}{N} = -10\ Log \frac{1}{n_0} \sum_{i=1}^{n_0} \frac{1}{y_i^2} \tag{2}$$

Nominal is the best:

$$\frac{S}{N} = -10\ Log \frac{\bar{y}^2}{s^2} \tag{3}$$

Where n, y, and $\bar{y}$ respectively refer to the number of samples, response factor, average response factor, and variance of the response factor. Due to the fact that in this study the characteristic of tensile load is the stronger or the higher its value, the better, the Taguchi analysis design used is "larger is better" [15], with the settings displayed in Fig. 3.

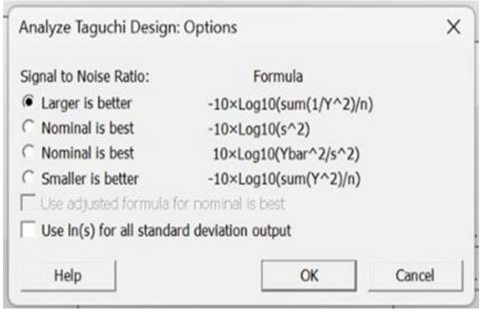

Fig. 3. The analysis setting using Taguchi.

3 Results and Discussion

3.1 Tensile Load Analysis

The tensile load test results are presented in Table 5. Each parameter was tested twice, labeled as sample 1 and sample 2. The tensile load test results are displayed in Fig. 4. From Fig. 4, it can be observed that the lowest tensile load value occurred in sample $A_1B_1C_1$, and the highest in sample $A_1B_3C_3$, at 3232.065 N and 5761.745 N respectively. The average measured tensile load for the combination of galvanized steel (SGCC) with low carbon steel (SPCC-SD) is approximately 4555.73 N with a standard deviation of around 672.46 N. This indicates that the average tensile load value in the welding parameter combination testing tends to approach 4555.73 N, while individual values tend to vary around 672.46 N from this mean. This variability indicates that some welding parameter combinations may result in more extreme tensile loads than others, highlighting the importance of finding parameter combinations that produce the desired tensile load for the material combination.

Table 5. The tensile load test results

Code	Parameters			Tensile load (N)		
	Welding current (A)	Argon gas flow rate (LPM)	Weld bead diameter (mm)	Sample 1	Sample 2	Average
$A_1B_1C_1$	45	12	5	3421.02	3043.11	3232.065
$A_1B_2C_2$	45	15	8	4098.86	3576.06	3837.46
$A_1B_3C_3$	45	18	10	6132.04	5391.45	5761.745
$A_2B_1C_2$	50	12	8	3887.4	3827.9	3857.65
$A_2B_2C_3$	50	15	10	5421.1	5261.82	5341.46
$A_2B_3C_1$	50	18	5	2670.87	4765.22	3718.045
$A_3B_1C_2$	55	12	8	6035.39	3661.5	4848.445
$A_3B_1C_3$	55	15	10	4697.02	5580.27	5138.645
$A_3B_1C_1$	55	18	5	4938.87	5459.49	5199.18

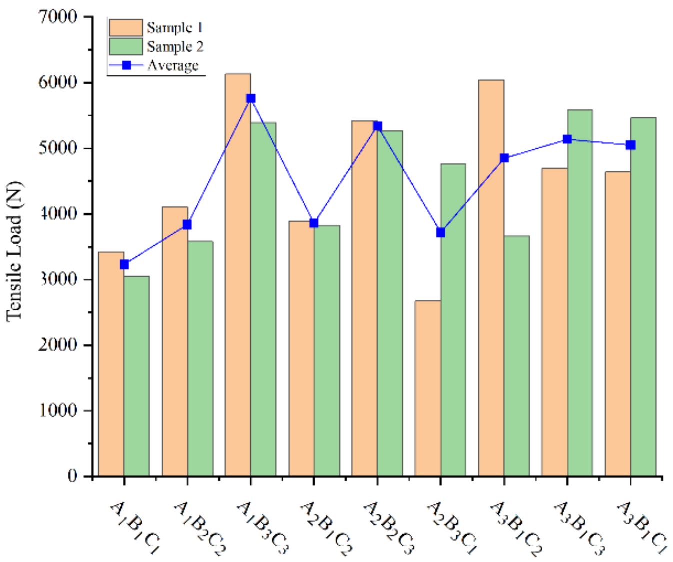

Fig. 4. Tensile load test results.

From the presented data, there appears to be a significant variation in the tensile load values among different welding parameter combinations for the joining of galvanised steel (SGCC) and low-carbon steel (SPCC-SD). Although some cases show an increase in tensile load with higher welding current values, there is no consistent pattern indicating a linear relationship between welding parameters (current, gas flow rate, and tungsten diameter) and tensile load. The interaction between these variables seems complex, with different outcomes between the sample 1 and sample 2 tests with the same parameter combinations. Further analysis using statistical methods and graphical visualization may help uncover more detailed patterns in this data, providing deeper insights into the influence of welding parameters on the tensile load of the material joint.

3.2 S/N Ratio Analysis

The main effect of the S/N ratio graph is displayed in Fig. 5, indicating that the most optimal parameters recommended are a welding current of 55 A, flow rate of 15 L/min, and weld bead diameter of 10 mm. In contrast to the findings reported by [30], the welding current is the most significant parameter affecting the tensile load of the TIG welding results. In welding using another method, namely resistant spot welding, as reported by [31], welding current is identified as the most significant parameter influencing the tensile load of the welding results. This research presents different conditions when adding the variable of welding bead diameter, which has the highest influence on the new tensile load, followed by the welding current and flow rate. This condition is attributed to the larger diameter expanding the welding area, which significantly increases the tensile load. This phenomenon aligns with the basic material strength formula, where tensile load is directly proportional to the tensile strength of the material used and the welding surface area [13, 31, 32].

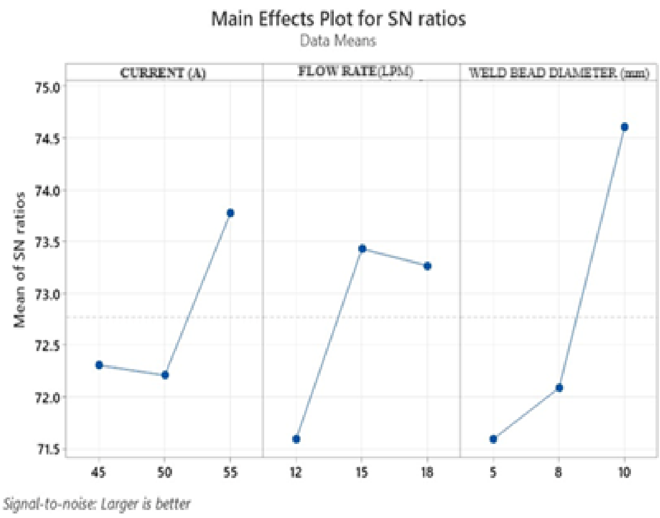

Fig. 5. Main effect of S/N ratio.

3.3 Analysis of Variance (ANOVA)

ANOVA is mathematically based on linear regression and the general linear model, which measures the relationship between the dependent variable and independent variables [33]. ANOVA was used to determine the significance of the input parameters. By using ANOVA, the significance of each parameter towards the research target can be identified. The ANOVA results are presented in Table 6. From Table 6, it can be seen that the weld bead diameter significantly influences the tensile load in TIG welding of SPCC-SD (JIS 3141) with SGCC (JIS 3302) materials. The contribution of each parameter is displayed in the Fig. 6 showing the contribution values of weld bead diameter, flow rate, and welding current, with values of 44.42%, 21.93%, and 16.41%, respectively.

Table 6. ANOVA of tensile load in TIG welding

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Welding current	2	4.617	16.41%	4.617	2.309	0.95	0.512
Flow rate	2	6.171	21.93%	2.997	1.498	0.62	0.618
Weld bead diameter	2	12.499	44.42%	12.499	6.25	2.58	0.28
Residual error	2	4.852	17.24%	4.852	2.426		
Total	8	28.139	100.00%				

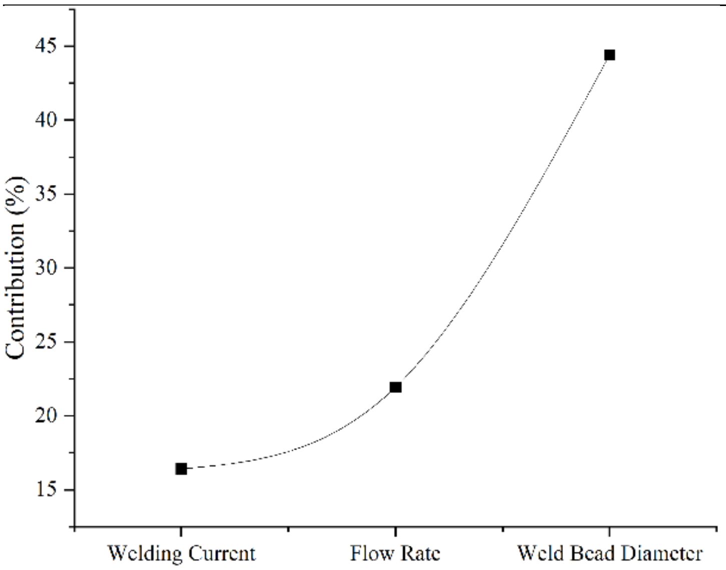

Fig. 6. The contribution of each parameter to the tensile load.

4 Conclusion

This study utilized SPCC-SD (JIS 3141) and SGCC (JIS 3302) materials with a thickness of 0.8 mm. Welding was conducted using the DAIDEN TIGi 200 welding machine, and tensile load testing was performed using the SHIMADZU AGS-X 10Kn STD E200V. The tensile load test data were analyzed using S/N ratio analysis and ANOVA with the assistance of Minitab software. Based on the research results, the conclusions were drawn.

1. SN ratio analysis: The optimal TS load results were achieved by setting the welding current, flow rate, and weld bead diameter at levels III, II, and III, respectively.
2. Influence of weld bead diameter: The SN ratio analysis indicated that the weld bead diameter at level III significantly influenced the TS load, with an S/N ratio exceeding 75.5. This finding aligns with the ANOVA results, which show that the weld bead diameter contributes approximately 45% to the TS load.
3. Impact of weld bead diameter: The weld bead diameter has the most significant impact because a larger diameter requires a higher TS load to achieve the optimum load.

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