

Research Article

Optimization of Tungsten Inert Gas Welding Process on the Tensile Properties of Dissimilar Metal Using Taguchi Method

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Abstract

Tungsten inert gas (TIG) welding also known as Gas Tungsten arc welding (GTAW) is a popular choice of welding process when high level of weld quality is required. In present investigation, TIG welding is observed using Taguchi L9 orthogonal method on the dissimilar Stainless Steel 304 and aluminum 2000. The two metals were butt joined using two filler metals joined simultaneously. The selected input parameters were Current, Voltage and Gas flow rate. Three levels of factors were chosen according to the previous works done on those materials. Further the mechanical testing was performed and ultimate tensile stress was studied as response. The different specimen have the same behavior describe as elastic material. The best stress at break of the joint was 9.525MPa which was very low compare to the ones of the aluminum and stainless steel works. That experimental stress was slightly higher than Predicted stress 8.89 MPa confirming the validity of the optimal setting.

Keywords

Tensile Properties, Tungsten Inert Gas Welding, Dissimilar Metals, Optimization

1. Introduction

Arc welding is the process of fusing two or more parts, using heat, pressure or both. It is mostly done on metals, thermoplastics and even woods. The resulting joint is known as weldment and the other conjoint parts are called the parent material. We have many types of arc welding and amongst them Gas Tungsten Arc Welding (GTAW) also called as Tungsten Inert Gas (TIG) welding is the method often preferred over Metal Inert Gas (MIG) welding nowadays [1-3]. This is due to the fact that TIG welding allow for better results in welding of lighter gauge metals [4]. Under optimized circumstances TIG welding could possibly produce high quality

welds. There are many TIG input process parameters that influence the mechanical properties of the welded joint such as welding current, voltage, welding speed, gas flow rate and dimensions of the welding filler rod [5]. TIG welding is commonly employed in industries that need high-quality welding, such as beverage, nuclear, industrial, and petrochemicals, combined heat and power plants, and the offshore sector. TIG welding is also used on the application of aerospace, art and craft, automobile industry, food manufacturing industry, building and construction [6, 7]. Figure 1 below presents the equipment of TIG process.

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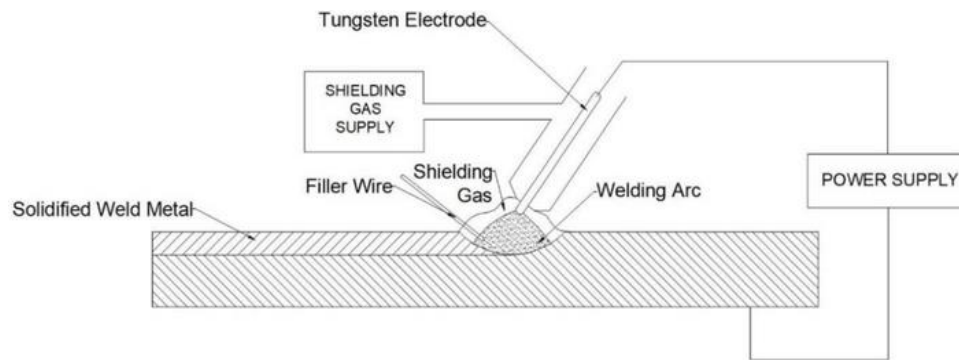


Figure 1. A diagram of a complete gas tungsten arc welding station.

Over the years, welding technology has advanced significantly, driven by its extensive industrial applications. While joining similar materials is relatively straight forward, welding dissimilar materials presents unique difficulties due to differences in metallurgical, chemical, and thermal properties. Despite these complexities, the potential benefits, such as cost savings and weight reduction, make dissimilar welding highly attractive in various industrial sectors, including automotive, aerospace, and ship building, where each metal component offers distinct advantages [8, 9]. Welding dissimilar materials, such as aluminum and stainless steel, is particularly complex and poses unique challenges due to their vastly different physical, chemical, and thermal properties. Aluminum high thermal conductivity leads to rapid heat dissipation, making it difficult to reach the necessary melting temperature and creating a thermal imbalance at the joint interface. This issue is exacerbated when welding materials with contrasting characteristics, resulting in uneven heat distribution. However, welding those kind of dissimilar materials presents challenges due to their differing physical and thermal properties. To address these issues, TIG welding are mostly selected for its precise heat in put control, critical when joining materials with contrasting thermal conductivities, such as aluminum and stainless steel. TIG welding minimizes the risk of overheating, distortion, and defects, resulting in clean, strong welds with excellent fusion and high quality joints, crucial for applications demanding durability and precision [10-12]. Dissimilar welding is where weldments are made from metals of different compositions or thicknesses, or both. It is attracting attention nowadays, due to its many advantages, such as low manufacturing cost and the ability to reduce working operations [13-16]. Besides that, this type of joining offers the potential to utilize the advantages of different materials, which often produces a whole structure with unique mechanical properties. For example, hybrid structures of aluminum alloy and stainless steel are suggested for spacecraft, automotive and steamships to improve their fuel efficiency, increase their range and control air pollution by reducing weight [17, 18].

Various optimization techniques such as Analysis of Variance, Taguchi, Response Surface Methodology (RSM), Genetic Algorithm (GA), Artificial Neural Network (ANN) etc.,

can be used for optimization of welding processes. Taguchi technic is used for its inherent efficiency in solving problems of single objective nature. The Taguchi method is a powerful tool that uses a special design to study the parameter space with small number of experiments through orthogonal arrays. In the factorial design, the number of factors and levels increases exponentially. This technique provides an efficient, simple and systematic approach to optimize design for quality, performance and cost [19]. Some authors have worked on the optimization TIG welding of dissimilar metals using many techniques.

Sreekumar & Sivakumar (2021) focused on optimizing TIG welding parameters for dissimilar welding of AA7075-T6 and AA6061-T6 aluminum alloys using response surface methodology. It likely explores the effects of welding parameters on weld quality and mechanical properties to determine optimal settings [20].

Mishra et al. (2020), employed response surface methodology (RSM) to optimize TIG welding parameters for dissimilar metal joints. They investigated the relationship between welding parameters and mechanical properties to identify optimal parameter settings [21].

Zhang & Zhang (2020), analyzed the microstructure and mechanical properties of TIG welded dissimilar joints between stainless steel and aluminum alloy. It likely provides insights into the weld microstructure and its correlation with mechanical properties [22].

Cao & Cong (2020), studied an orthogonal experimental method to optimize TIG welding parameters for dissimilar metals. They focused on enhancing weld quality and mechanical properties through systematic variation and analysis of welding parameters [23].

Zhu & Zeng (2019), focused on dissimilar TIG welding between titanium alloy Ti6Al4V and stainless steel 304. They likely explored the challenges and solutions in welding those dissimilar materials and evaluated the mechanical properties of the resulting joints [24].

Yang & Li (2019), examined the laser-TIG hybrid welding of dissimilar metals, specifically aluminum alloy to stainless steel. It likely investigates the feasibility and effectiveness of

this hybrid welding process in achieving high-quality dissimilar metal joints [25].

Keshavarz & Mousavizadeh (2019), focused on studying the mechanical properties of dissimilar joints between AA7075-T6 and AA5083-H111 aluminum alloys welded using TIG. They likely evaluated the influence of welding parameters on the strength and integrity of these dissimilar welds [26].

Hou & Wang (2019), explored the TIG welding process and properties of dissimilar joints between stainless steel and aluminum alloy. It likely delves into the challenges and solutions specific to welding these two dissimilar materials [27].

Xu & Du (2018), investigated the dissimilar joining of aluminum alloy to stainless steel using hybrid TIG-MIG welding. It likely explores the advantages and challenges of this hybrid welding process and evaluates the mechanical properties of the resulting joints [28].

Jafarian & Kermanpur (2018), examined the effects of welding parameters on the mechanical properties and microstructure of dissimilar joints between stainless steel and AISI 4130 steel, fabricated using TIG welding. It likely provides insights into optimizing parameters for desired weld quality [29].

Vidit et al. (2024) focuses on optimizing Tungsten Inert Gas (TIG) welding parameters, namely Welding Speed, Feed, and Distance of Welding Flux, for dissimilar metals Aluminium 6061 and Stainless Steel 304, using the Taguchi Method. The optimal combination of welding parameters was determined based on the Taguchi Method, providing valuable insights for achieving superior weld quality and mechanical performance in dissimilar metal TIG welding applications [30].

Researches on TIG welding of aluminum and stainless steel is still limited because of the difficulty to associate these two type of materials. Shah et al. (2013) lap-welded Aluminum AA6061 and stainless steel SUS304 by using but MIG welding with aluminum filler ER5356 (Group 1) and stainless steel filler ER308LSi (Group 2). Based on the investigation throughout this study, it can be concluded that the welding voltage of 18 V and aluminum filler ER5356 is the optimum filler in joining the dissimilar metals aluminum AA6061 and stainless steel SUS 304. [31].

Mallieswaran et al. (2024) developed an empirical relationship between Friction Stir Welding (FSW) parameters and tensile strength of the friction stir welded AA1100 with AA6061 aluminum alloys. To obtain the desired strength, it is essential to have a complete control over the relevant process parameters to maximize the tensile strength for forming of TWB on which the quality of a weldment is based. Therefore, it is very important to select and control the welding process parameter for obtaining maximum strength. To achieve this statistical tool such as response surface method (RSM), analysis of variance (ANOVA), Students t-test, coefficient of determination, etc., can be applied to define the desired response through developing mathematical models to specify the relationship between the output response and input variables. Four

factors, five levels central composite design have been used to minimize number of experimental conditions. The developed mathematical relationship can be effectively used to predict the tensile strength of friction stir welding (FSW) joint s of AA1100/ AA6061 aluminum alloy at 95% confidence level [32]. Others studies have been donne on dissimilar aluminium and steel and the tensile strength were around hundred MPa. Many other studies were carryout like Ali et al. (2023) on Aluminum 2024 and Stainless steel 304 and GTAW joints gave tensile strength of 138 MPa [33]. Compendium investigated on Aluminum-Stainless steel dissimilar weld quality using different filler metals and obtained 20–104 MPa and 47.8–104.4 MPa [34]. Jawad et al. (2024) worked on evaluation of 70–30 Cu–Ni filler metal for Aluminum 2024 Stainless Steel 304 Hybrid Joints and obtained low hundreds of MPa tensile strength [35]. Yang et al. (2024) workrd on Dissimilar welding of aluminium to steel and reach tens–hundreds MPa [36]. Liu et al. (2024) investigated on Al–steel hybrid joints and obtained 150 MPa of tensile strength [37].

Although the optimization of TIG welding parameters for dissimilar metal joints has been widely investigated, the present research distinguishes itself by focusing on the Aluminium 2000–Stainless Steel 304 combination, a pairing that remains one of the most challenging due to its severe differences in physical and chemical properties. Aluminium and stainless steel possess markedly distinct melting temperatures, thermal expansion coefficients, and electrical conductivities, which often result in uneven heat distribution, poor wettability, and the formation of brittle intermetallic compounds such as FeAl_3 and Fe_2Al_5 at the interface. These challenges have historically limited the successful application of TIG welding to such dissimilar pairs. To overcome these barriers, the present study introduces a novel dual-filler approach employing ER4043 (Al–Si-based) and ER45 (Fe–Cr–Ni-based) filler wires. This dual-filler strategy is designed to improve metallurgical compatibility by facilitating a graded compositional transition between the aluminum and steel sides, thus minimizing the formation of brittle phases and improving the integrity of the fusion zone. The study further utilizes the Taguchi optimization method to systematically identify and rank the most influential process parameters such as welding current, voltage and gas flow rate on the tensile strength. This comprehensive experimental design enables a precise understanding of parameter interactions and leads to a statistically optimized welding configuration.

Unlike previous investigations that primarily concentrate on similar alloys or employ a single filler metal, this research provides a methodologically innovative pathway for joining highly incompatible materials. The proposed approach not only enhances joint strength and ductility but also demonstrates superior microstructural homogeneity across the weld interface, validating the effectiveness of the dual-filler strategy. From an industrial standpoint, the outcomes of this research are highly relevant to automotive, aerospace, marine, and energy applications, where lightweight and high-strength

hybrid structures are increasingly required. The optimized TIG process developed in this study provides a cost-effective, easily implementable, and scalable joining solution for integrating aluminium and stainless steel components. It thus contributes to the advancement of multi-material design, supporting goals of weight reduction, improved fuel efficiency, and enhanced structural performance in modern manufacturing. The selection of the Aluminium 2000 series (Al–Cu alloys) paired with Stainless Steel 304 (SS304) is deliberate and driven by both mechanical performance targets and industrial relevance. Aluminium 2000 alloys are heat-treatable, age-hardenable aluminium–copper alloys that provide higher yield and ultimate tensile strengths than common structural alloys such as 6061 and 5083. This higher strength-to-weight ratio makes Al-2000 attractive for structural and aerospace applications where minimizing mass while maintaining strength is critical. SS304 is chosen as the counterpart because it offers excellent general corrosion resistance, good ductility, and widespread industrial availability, making it a practical choice for components that require both strength and corrosion resistance.

Scientifically, the Al2000–SS304 pairing emphasizes two research-relevant contrasts that justify focused investigation: (1) mechanical property contrast Al2000's higher strength and

lower stiffness compared with SS304 requires careful control of joint geometry and residual stresses to obtain acceptable tensile behavior; (2) electrochemical and metallurgical contrast the presence of copper in Al2000 alters its electrochemical behavior (and corrosion susceptibility) compared with Mg- or Si-rich aluminums, and it increases the risk of forming brittle Fe–Al intermetallics when fused with steel. Many authors' works on the observation of the microstructure of heat affected zone (HAZ) of welded material and the influence on the chemical composition of the different metals [38–40].

2. Material and Methods

2.1. Material

Materials used are aluminum 2000 (AA2000) and stainless steel (SUS304). Both materials are commonly used in industry due to their high corrosion resistance and versatility. The filler metals used are stainless steel based ER45 and aluminum based ER 4043 with diameter of 2.5 mm. Table 1 represents the chemical composition of AA 2000 and aluminum filler ER 4043 while Table 2 presents mechanical properties of AA 2000.

Table 1. Chemical composition of AA 2000 and aluminum filler metal ER 4043 (wt%).

Metals	Si	Fe	Mn	Cu	Mg	Zn	Ti	Be	Al
AA2000	/	/	0.6	2.75	0.6	1	0.05	/	Bal
ER 4043	5.25	0.80	0.05	0.30	0.05	0.10	0.20	0.0003	Bal

Table 2. Mechanical properties of AA 2000.

Properties	Density (kg/m ³)	Tensile strength (MPa)	Yield Strength (MPa)	Elongation (%)	Elastic modulus (GPa)
Values	2.80	485	415	50	72.4

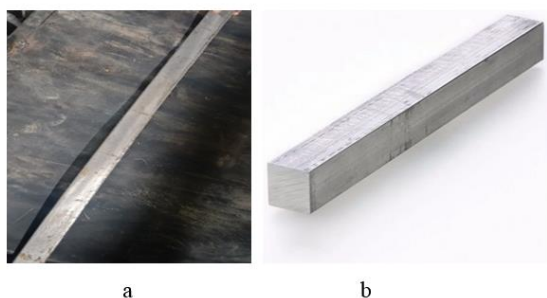
The chemical composition of SUS 304 and stainless steel filler metal ER 45 are shown in Table 3 and mechanical properties of SUS 304 on Table 4. Figure 2 below presents the different materials.

Table 3. Chemical composition of SUS 304 and stainless steel filler ER 45 (wt%).

Metals	Cr	Ni	Mo	Cu	C	Si	Mn	P	Fe
SUS 304	18.36	9.23	0.07	0.08	0.051	0.76	0.97	0.027	Bal
ER 45	0.30	0.30	0.20	0.30	0.08	0.10	0.05	0.035	Bal

Table 4. Mechanical properties of SUS 304.

Properties	Density (kg/m ³)	Tensile strength (MPa)	Yield Strength (MPa)	Elongation (%)	Elastic modulus (GPa)
Values	8000	515	205	50	192

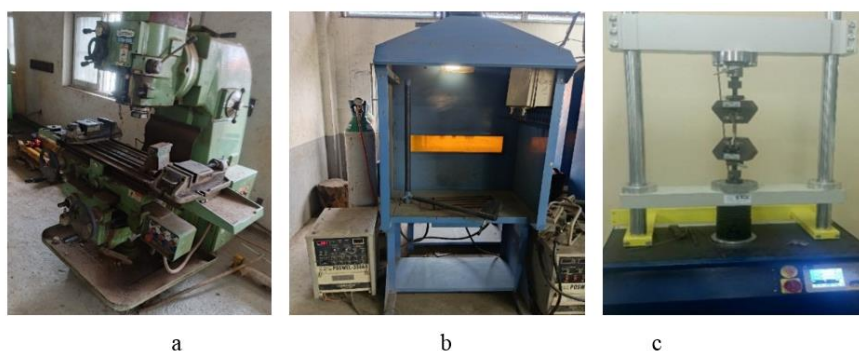
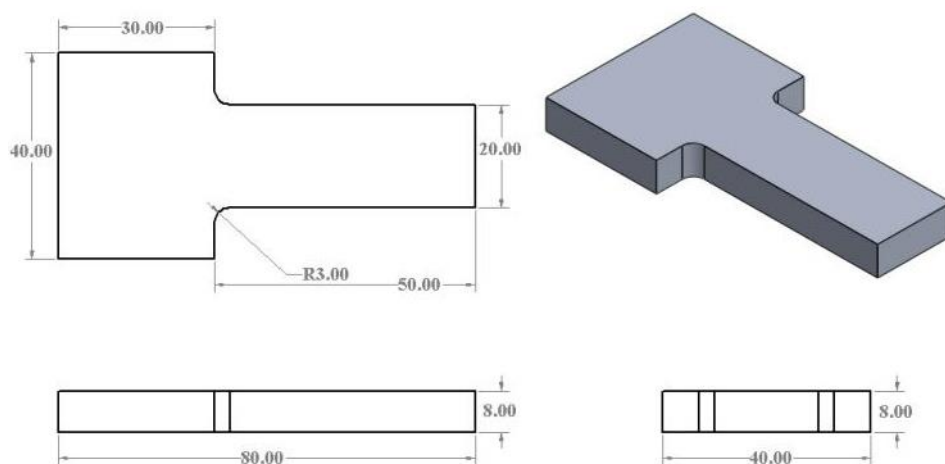
**Figure 2.** Materials used a- Stainless steel SUS 304 and b-Aluminum AA 2000.

The equipments used to realize the dissimilar pieces were

milling machine of KIHEUNG mark to cut and give the standard shape to different pieces. The TIG welding machine of SUNJINWELD CO. LTD mark were used for the assembly of different pieces. We also used the universal testing machine for the realization of tensile testing. Figure 3 below presents the different machines. We also used Taguchi method for the design of experiments.

2.2. Method

The preparation of samples was carryout in Centre de formation d'excellence workshops of Douala in Cameroon. We first realized the different pieces according to the ASTM E8 standard with the sizes of 50 mm × 20 × 8 mm as indicated on Figure 3 below using milling and cutting machine.

**Figure 3.** Equipments used a-Milling machine b-TIG welding machine c-Universal testing machine.**Figure 4.** Dimmensions of differents pieces.

Aluminum and stainless steel were butt joint welded using TIG welding machine to fabricate dissimilar materials samples. Before welding the V-groove was realized on the both sizes of the metals with the grinding machine as indicated on Figure 5 bellow. The two wire metals used were joined together during the welding process. The gas used was the argon

and the electrode was the thorium tungsten. Current, AC Voltage and Gas flow rate of TIG welding process were the 3 factors selected as indicated in the Table 5 bellow with the different arbitrary attributed symbols. We also choose three levels of factors for the design of experiment based on previous studies [38].

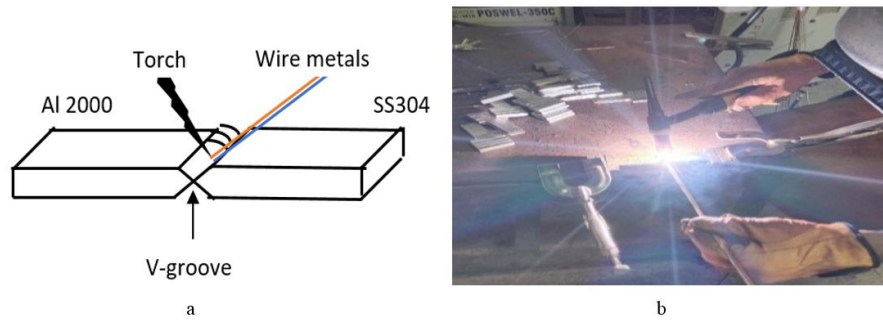


Figure 5. Welding: a- schematic diagram, b- process.

Table 5. Factors and levels for experiment.

Factors	Symbols	Level 1	Level 2	Level 3
Current (A)	C	140	145	150
Voltage (V)	V	90	100	110
Gaz flow rate (L/min)	G	8	10	12

For the design of experiments we choose the Taguchi method to set the experiment according to his efficiency and the low cost in term of the number of tests. Based on the

Taguchi table of L9 orthogonal array suitable for 3 factors x 3 levels. We realized nine specimen and for each specimen we replicate two times in order to minimize errors. At the end we had eighteen experimental units of dissimilar metal by joining together aluminum and stainless steel. The tensile testing was carryout on universal testing machine in the laboratory of civil engineering of the University Institute of Technology of Douala Cameroon. For the tensile testing the specimen were mounted on two grips of the machine, one which is fix and another which is movable. The tensile testing was loaded at 6MPa/s until break. Figure 6 bellow presents the tensile testing experimentation. The data acquisition was recorded automatically in terms of force (N) as function of elongation $\Delta L(mm)$. The response or the quality objective concerning the stress is "higher is better" which consist of maximizing the stress of the material.

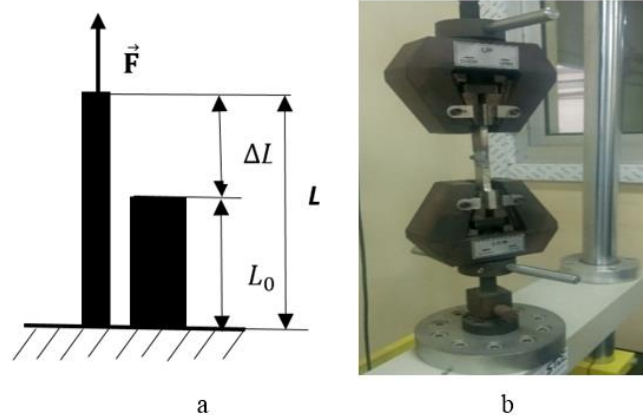


Figure 6. Tensile testing: a- Setup and b- Experimentation.

The stress $\sigma(MPa)$ is calculated according to equation (1) and the strain ΔL is calculated according to equation (2).

$$\sigma = \frac{F}{S} \quad F = \text{force (N) and } S = \text{section (mm}^2\text{)} \quad (1)$$

$$\Delta L = \frac{L - L_0}{L_0} \quad L = \text{final length and } L_0 = \text{initial length (mm)} \quad (2)$$

The curve of stress in function of extension is drawn and the behavior were studied for each material. The response parameter study was the stress at break in function of the three parameters: current, voltage and gas flow rate. The Signal-to-Noise ratio (S/N) is calculated according to the "higher is better" from equation (3). For different factors we also evaluate the average S/N ratio of each level.

$$S/N = -10 \log_{10}(1/y^2) \quad (3)$$

Where y is the value parameter.

We also calculated the range of each factor with the equation (4).

$$\text{Range} = \text{Max S/N} - \text{Min S/N} \quad (4)$$

The relative importance was also evaluated and best factors which gave the highest stress were identified.

Prediction and validation of the experiments

The predicted S/N ratio at the optimal factors levels was evaluated by using the equation (5) and the diagram of effects was also drawn.

$$\hat{\eta}_{opt} = \bar{\eta} + \sum_{i=1}^k (\bar{\eta}_{i,opt} - \bar{\eta}) \quad (5)$$

$\hat{\eta}_{opt}$ = predicted S/N at the optimal factor levels

$\bar{\eta}$ = overall mean S/N across all experiments

$\bar{\eta}_{i,opt}$ = mean S/N at the optimal level of factor i

k = number of factors

At the end, the Analysis of Variance was also used to validate the taguchi method and to observe the contribution of each factor on the experiment.

3. Results and Discussion

The Table 6 bellow presents the Taguchi table L9 with the factors and different responses as force and stress at break. The table also contain the signal-to-noise ratio stress at break.

Table 6. Taguchi table with the factors, responses and signal-to-noise ratio.

SN	Current (A)	Voltage (V)	Flow rate (L/min)	Force at break (KN)	Stress at break (MPa)			S/N (dB)
					S1	S2	Mean	
1	140	90	8	0.401	2.480	2.282	2.381	7.54
2	140	100	10	0.444	2.943	3.871	3.407	10.65
3	140	110	12	0.401	2.065	2.949	2.507	7.98
4	145	90	10	0.426	1.998	3.326	2.662	8.50
5	145	100	12	0.381	2.789	1.973	2.381	7.54
6	145	110	8	0.492	2.671	3.477	3.074	9.75
7	150	90	12	0.442	2.94	2.584	2.762	8.82
8	150	100	8	0.715	5.47	2.748	4.109	12.27
9	150	110	10	1.524	10.112	8.938	9.525	19.58

Figure 7 bellow presents the different pieces of aluminum-stainless steel and the assembly welded dissimilar metals. The Figure 8 presents the behavior of the different specimen.



Figure 7. Specimen: a-Different metals and b-Welded dissimilar metals.

We realize from the **Figure 8** bellow that the different specimen have the same behavior which are brittle material. From No 1 to No 8 specimen have the stress at break are around 3 MPa and in experiment No 9 we have 9.525MPa. The mechanical properties of the joints are very low compare to different materials taken sparsely 515 MPa and 485 MPa respectively for stainless steel and aluminum. The stress of each material are 55 times higher than dissimilar metal of experiment No 9. This show the difficulty that exist to join the 2 types of material. They are different in term of chemical, thermal, mechanical and physical properties. The tensile strength values in the experiment are much lower due to insufficient solubility between the aluminum-stainless steel which resulted in the de-

crease of tensile strength [31]. It is also due to the wide difference between the melting temperatures of aluminum and stainless steel. The aluminum melts and flows away well before the stainless steel has melted. This situation explains why the aluminum is just barely intact with the stainless steel surface and they are not soluble with each other. We also observed that from experiments No 1 to No 8 the strain is around 0.55%. and their elastic modulus are around 6.5MPa. Experiment No 9 has the strain of 1% and elastic modulus of 9.16MPa. The low strains presented by those materials is the proof that the joints are very brittle and need to be ameliorated. For the quantitative analysis the mean stress at break value is 3.6453 MPa and the standard deviation is 2.28 MPa.

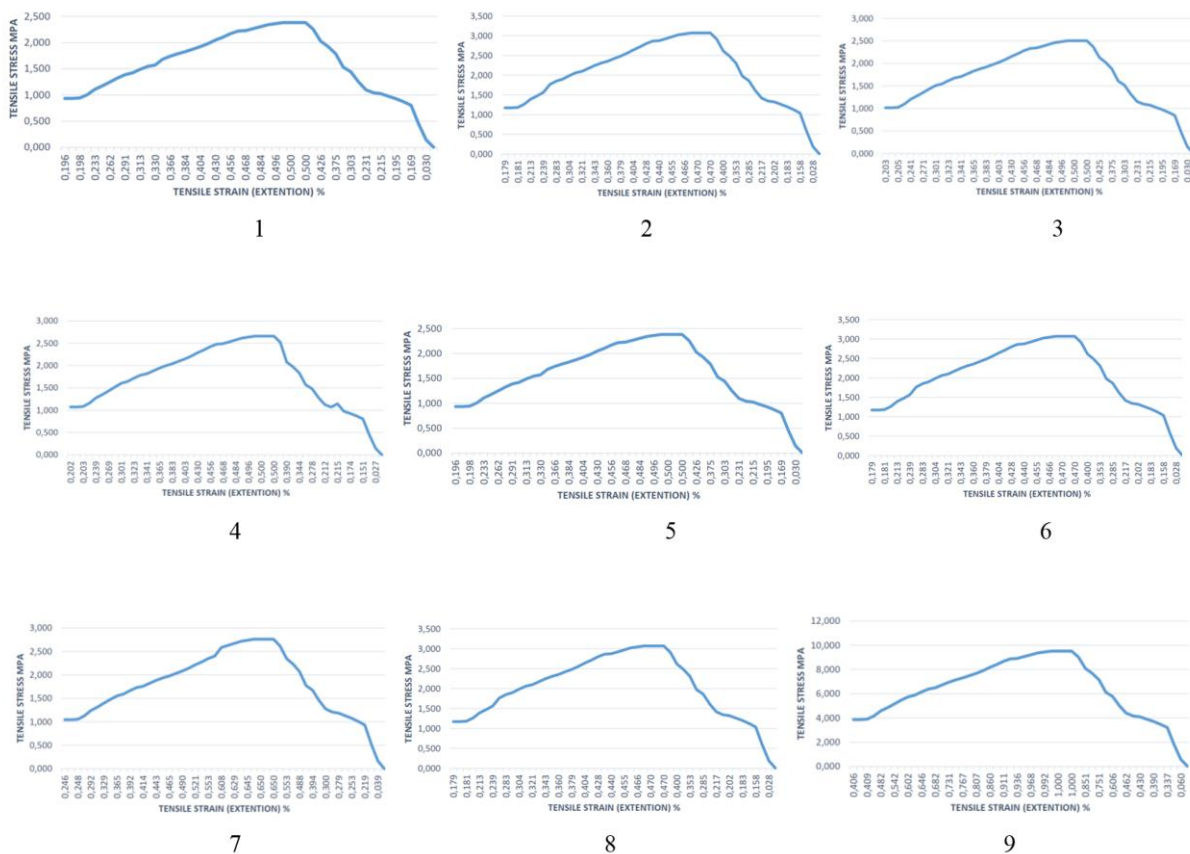


Figure 8. Curve behavior stress-strain of different specimen.

The highest tensile strength of the optimized Al2000–SS304 TIG join in this work was 9.525 MPa. This value is significantly lower than the typical tensile strengths reported for various Al–SS304 dissimilar joins in the literature [32–37], which generally fall in the tens to hundreds of MPa depending on joining method, interlayer/filler selection and nature of aluminum. Several factors can explain this discrepancy: (i) potential incomplete fusion or inadequate heat-input control leading to reduced effective cross-section; (ii) formation of a thick brittle Fe–Al intermetallic layer at the fusion interface

due to excessive dilution; (iii) elevated porosity or shielding failure; or (iv) issues with specimen geometry or testing (units, gripping, or sample type).

The best results was observed for the current of 150A, the voltage of 110V and the gas flow rate of 10 L/min. The perspectives should be to increase the current, the voltage and to reduce the gas flow rate. Table 7 below shows for different factors the average signal-to-noise ratio S/N for each level and Table 8 the presents the Relative importance.

Table 7. Average S/N ratio of different factors for each level.

Factors	Current			Voltage			Flow rate		
Level	140	145	150	90	100	110	8	10	12
S/N (dB)	8.72	8.60	13.56	8.29	10.15	12.44	9.85	12.91	8.11

Table 8. Relative importance (range of influence in dB).

Factors	Current (C)	flow rate (G)	Voltage (V)
Range (dB)	4.96	4.80	4.15

From this table we can have the following ranking $C > G > V$. The first factor that impact the experiment is the current 150A, following by the Gas flow rate 10L/min and at the end we have the voltage of 110V [1].

4. Main Effects (Response Means and Mean S/N)

The mean tensile stress and mean S/N at each level were computed by averaging the trials that include that level. Table 9 and Figure 9 below present the effects which represents the means of response in function of levels of different factors.

Table 9. Main effects — mean tensile stress and mean S/N by factor level.

Factor	Level	Mean tensile stress (MPa)	Mean S/N (dB)
A (Current)	140	2.765	8.722
	145	2.706	8.598
	150	5.465	13.559
V (Voltage)	90	2.602	8.288
	100	3.299	10.152
	110	5.035	12.438
G (Gas flow)	8	3.188	9.855
	10	5.198	12.910
	12	2.550	8.114

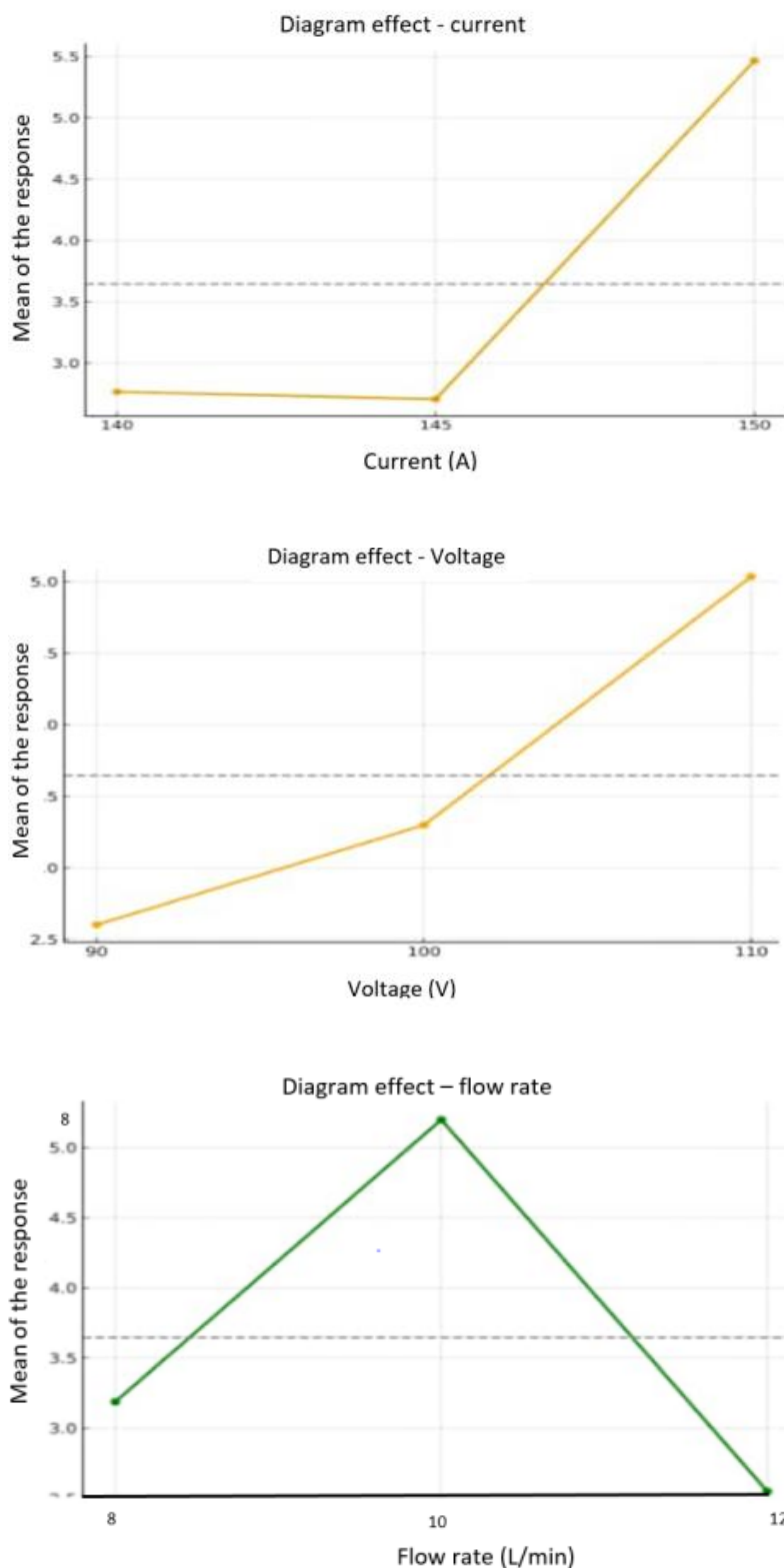


Figure 9. Means of response in function of levels of different factors.

5. Prediction and Validation of Experimental Results

Predicted stress = 8.89 MPa

Expected S/N $\hat{\eta}_{opt}$ = 19.6 dB

Experimental stress 9.525 MPa is slightly higher than Predicted stress with 6.66% as relative error confirming the validity of the optimal setting.

6. Analysis of Variance (ANOVA)

We use a fixed-effects additive model:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \varepsilon_{ijk}$$

where Y_{ijk} is tensile stress μ the grand mean, $\alpha_i, \beta_j, \gamma_k$ the effect of current, voltage, and gas flow respectively, and ε_{ijk} the random error.

ANOVA decomposes the total variability (total sum of squares) into contributions from each factor and the residual/error.

$$\bar{Y} = \frac{1}{9} \sum_{t=1}^9 Y_t = 3.645 \text{ MPa}$$

Sum of squares for factor

$$SS_{factor} = \sum_{l=1}^L n_l (\bar{Y}_l - \bar{Y})^2$$

Where n_l is the number of runs at that level (for L9 with orthogonality, $n_l = 3n$ per level). Using the values of level means reported above, the computed ANOVA Table 10 below is:

ANOVA on mean stress

Table 10. ANOVA summary.

Source	DOF	SS	MS	F	Contribution (%)
Current	2	14.91	7.46	2.66	36.01%
Voltage	2	9.42	4.71	1.68	22.76%
Flow rate	2	11.46	5.73	2.04	27.67%
Error	2	5.61	2.81	—	13.56%
Total	8	41.41	—	—	100%

Welding current (36.0%) is the most influential factor on tensile strength in this design
Followed by gas flow rate (27.7%)
Voltage has a moderate influence (22.8%)
Low experimental error confirms good experimental consistency

7. Conclusion

The Taguchi method combined with ANOVA was effectively used to optimize welding parameters for maximizing the stress at break of welded joints. The results revealed that welding current is the most influential factor, contributing 36.01% to the variation in joint strength, followed by gas flow rate (27.67%) and welding voltage (22.76%). Signal-to-noise ratio analysis using the larger-is-better criterion identified the optimal welding condition as 150 A current, 110 V voltage, and 10 L/min gas flow rate, which produced the highest mean stress at break of 9.525 MPa. The close agreement between the predicted optimal parameters and experimental results confirms the reliability of the Taguchi–ANOVA approach as an efficient and robust tool for welding process optimization. However, it is important to note that the evaluation of joint performance in this study was based solely on tensile testing results. No microstructural characterization was performed due to the unavailability of Scanning Electron Microscopy (SEM). Consequently, detailed analysis of the weld metal, fusion zone, and heat-affected zone (HAZ), as well as the morphology of microstructural joins and fracture surfaces, could not be conducted. The absence of SEM analysis limits

the ability to correlate the mechanical performance with microstructural features such as grain size, phase transformations, porosity, or defects within the welded region. Therefore, while the tensile results clearly demonstrate the effectiveness of the optimized parameters, future work should include comprehensive microstructural investigations using SEM and complementary techniques. Such analyses would provide deeper insight into the metallurgical characteristics of the weld joint and HAZ, enabling a more complete understanding of the relationship between welding parameters, microstructure evolution, and mechanical behavior.

Abbreviations

TIG	Tungsten Inert Gas
GTAW	Gas Tungsten Arc Welding
MIG	Over Metal Inert Gas
MPa	Mega Pascal
ANOVA	Analysis of Variance
RSM	Response Surface Methodology
GA	Genetic Algorithm
ANN	Artificial Neutral Network
FSW	Friction Stir Welding
HAZ	Heat Affected Zone

AC	Alternative Current
S/N	Signal to Noise
dB	Decibel
SEM	Scanning Electron Microscopy
DOF	Degree of Freedom
SS	Sum of Square
MS	Mean of Square
F	Fisher

Author Contributions

Noutegomo Boris: Conceptualization, Data curation, Methodology, Resources, Software, Supervision, Writing – review & editing

Conflicts of Interest

The author declares no conflicts of interest.

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