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Optimization and Influence of GMAW Parameters for Weld Geometrical and Mechanical Properties Using the Taguchi Method and Variance Analysis

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Abstract:

Gas metal arc welding is a high-efficiency arc fusion method commonly utilised in industry. The precise selection of input parameters directly affects weld quality and may minimise weld material use, enhance weld characteristics, and boost process productivity. This research will optimise a set of weld parameters using the Taguchi Method and assess their effect using a Variance Analysis (ANOVA). The macrography and transversal tensile strength tests supplied the geometrical and mechanical qualities.The ANOVA showed the effect of the input factors on the response parameters. With 63.54 percent reinforcement, 66.36 percent width and 66.94 percent penetration, weld speed was the most important parameter for weld geometry, while weld torch angle was the most important for ultimate transversal tensile strength (41.39 percent). In terms of reinforcement, 22.4 [V], 400 [mm/min], 30 [°] is optimal, as is 22.4 [V], 300 [mm/min], 0 [°], 23.3 [V], 400 [mm/min], 0 [°], and 24.1 [V], 200 [mm/min], 15 [°]. The Taguchi approach provided an effective experiment design and excellent results.

1. Introduction:

Gas Metal Arc Welding (GMAW) is a 20th-century welding technique. This technique was established to increase output because of its high dependability, all-position capability, cheap cost, high deposition rate, the convenience of use, lack of fluxes, cleanliness, and automation [1]. Most manufacturing operations used steel. High-strength steels give a higher weight-to-strength ratio, high productivity, and reduced production costs [2].

Today, steel qualities are widely accepted for various operations, but aluminium and its alloys deliver light weight and strength to increase final product performance.

About 20 years ago, the human weld was becoming less common, and the robot weld is expanding in contemporary manufacturing, where arc welding technology is widely used [3]. For example, the car sector relies heavily on weld robots to keep its production line running.

Welding is an expensive technique that requires time to prepare a joint, remove oil, preheat, position, weld, remove slag and spatter, examine, transport, machine setup, repair, and rework [4]. To cut expenditures, optimization approaches such as the Design of Experiments (DOE) [5], Taguchi method

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[6], and an ANOVA parameter impact analysis [7] are performed, reducing product development cycle time for both design and manufacturing, achieving a high cost-quality ratio and improving profits.

Experiments [8] may be designed to find the optimal response parameter configuration based on welding input parameters. The Taguchi approach optimizes experimental orthogonal array [9] with process control parameters.

Acebo [10] suggested optimizing GMAW parameters to increase weld ultimate tensile strength (UTS) using the Taguchi approach and determining the influence of each input weld parameter (voltage, current, weld duration, and weld speed) on the UTS response parameter. Sarfcar and Das [11] adjusted weld metal hardness, bending stress at a 10° bend angle, weld bead reinforcement shape, and GMAW penetration on stainless steel specimens using Taguchi's orthogonal experiment array design, signal-to-noise ratio, and Grey relational analysis.

Rizvi, Tewari, and Ali [12] used Taguchi to MIG welding on IS2062 steel. Signal-to-noise functions optimized the L16 orthogonal array. ANOVA showed the welding parameters' contribution. Yousefieh, Shamanian, and Saatchi [13] employed Taguchi to improve PCGTAW parameters for super duplex stainless steel (UNS S32760) welds.

Yao, Zhou, Lin, Xu, and Yue [14] used double-pulsed GMAW to investigate the weld bead formation rule and examine the weld parameters' impacts; therefore, a novel method was established. Waqas, Qin, Xiong, Wang, and Zheng [15] optimized the effective area of deposition based on GMAW additive manufacturing process parameters and assessed a multi-layer weld.

Zhang and Xue examined weld bead creation. Each gas metal arc welding test had a distinct current level and weld profile. Yao, Zhou, and Huang [17] optimized welding robot input settings. These parameters were grouped into a 9x3 orthogonal experiment. Mechanical weld characteristics were examined.

Kurt, Oduncuoglu, Yilmaz, Ergul, and Asmatulu [18] used arc stud welding to study the impacts of weld parameters using a Taguchi technique and an artificial neural network and then compared the approaches based on experimental data. Schneider, Lisboa, Silva, and Lerman [19] examined TIG weld bead geometry using the Taguchi technique of 27 tests.

This study aims to determine the effects of weld voltage [V], weld speed [mm/min], and weld torch angle [°] on weld reinforcement [mm], breadth [mm], depth penetration [mm], and ultimate transversal tensile weld strength [MPa]. The experiment was developed using the Taguchi technique and the L9 orthogonal array. These welding parameter combinations were macrographed and tensile tested. With test findings, signal-to-noise ratios computation revealed optimal levels, and ANOVA demonstrated the most influential input parameter on output (response) parameters.

2. Material and Methods:

This research employed GMAW to weld plate joints. This welding method has been used to connect materials for over 50 years. 0.8 [mm] steel wire electrodes were utilised to create welding deposits over a plate top joint using an experimental equipment controlled by numerical instructions and a GMAW machine that can modify weld input parameters. The Taguchi technique was used to perform the experiments. The approach combines experiment parameters in optimum combinations to describe the full research in fewer encounters.

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Voltage [V], welding speed [mm/min], and torch angle [°] were studied. Each parameter was allocated three levels (Table 1) and grouped into a L9 orthogonal array (shown in Table 2). This approach uses a L8 array, however it only works with two layers, hence a L9 array is suggested.

TABLE 1: Study parameters and their levels

Levels	Parameters		
	Voltage [V]	Welding Speed [mm/min]	Torch Angle [°]
Level 1	22.4	200	0
Level 2	23.3	300	15
Level 3	24.1	400	30

TABLE 2: Taguchi L9 array with the study parameters

Experiment Number	Voltage [V]	Welding Speed [mm/min]	Torch Angle [°]
1	22.4	200	0
2	22.4	300	15
3	22.4	400	30
4	23.3	200	15
5	23.3	300	30
6	23.3	400	0
7	24.1	200	30
8	24.1	300	0
9	24.1	400	15

With the experiment combinations established, welding deposits may be created on steel plates DIN C20 of 3 [mm] thickness top joints.

TABLE 3: Chemical composition of DIN C20

C	Mn	P max.	S max.
0.18 - 0.23	0.30 - 0.60	0.04	0.05

To create the test specimen, European Standards ISO 4136:2012 [20] and ISO 6892-1:2009 [21] were employed. to determine test specimen size, preparation, and Tension test. Figure 1 shows the final design.

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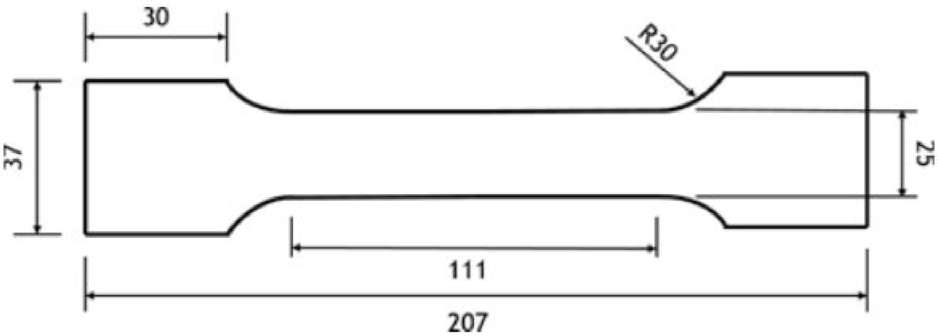

Figure 1: Tensile test specimen [mm}

The final plate dimension was determined by machining circumstances such as a 12-mm milling tool, milling trajectory, and screw size. Each plate comprised 420 x 285 x 3 mm and six test specimens. Taguchi needs nine tests, however there will be at least two for each combination. To test 18 samples, you'll need three plates. The plates were sliced in half across their width, and three welds were used to connect them. Each weld had a distinct combination of parameters established by the technique, and two samples were taken from each. Figure 2 shows welds.

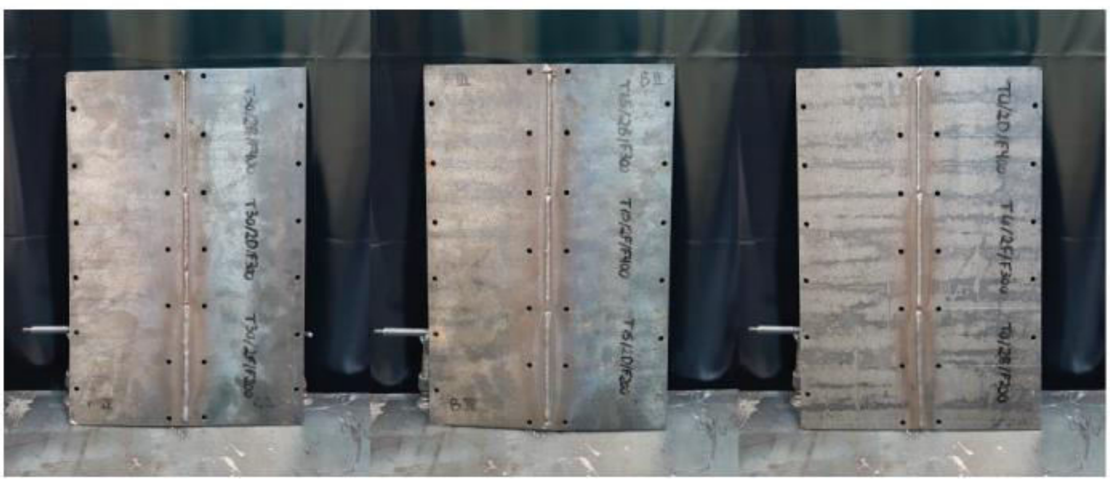

Figure 2: Plates welded with all the Taguchi experiment parameters

After machining, test specimens were ground to eliminate superfluous metal. 3 shows specimens.

To optimize the use of the plates, the spaces between the similar test specimens were also extracted with the purpose to obtain weld samples (Figure 4). Those samples enable the study of the geometry of the weld. The geometry can be measured and checked with the macrography technique.

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Figure 3: Tensile test specimens

Figure 4: Weld samples for macrography inspection

Taguchi needs a signal-to-noise function to improve operations. This function checks which process experienced more disruptions and chooses the one with the greatest signal-to-noise ratio. "Larger is better", "nominal is best", "nominal is best (default)," and "smaller is better" are four optimization scenarios. Weld penetration, width, reinforcement, and transversal tensile strength were optimised. For weld penetration and breadth, "nominal is best" was used to ensure both had the same plate thickness. "Smaller is better" was used for weld reinforcement, while "bigger is better" for ultimate tensile strength. Table 4 lists expressions.

TABLE 4: Signal to noise Taguchi expressions

Signal to Noise Expressions		
Smaller is best	Nominal is best	Larger is best
$S/N_S = -10 * \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$	$S/N_t = -10 * \log\left(s_y^2\right)$	$S/N_L = -10 * \log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right)$

"y" represents the test data, "Sy2" the variance, and "n" the number of measurements. Finding the impact of input welding parameters on output or reaction parameters was another study aim. Analysis of Variance (ANOVA) is a statistical technique used to validate contribution. In this example, ANOVA gives the impact of voltage, welding speed, and torch angle on weld geometrical features and ultimate tensile strength.

2.1. Tensile Strenght Test:

The transverse tensile strength test was based on ISO 4136:2012 and ISO 6892-1:2009. These standards are used to design test specimens, create test parameters, and determine material attributes. This test is performed using a machine that changes the tensile force until the specimen ruptures. ISO 6892-1:2009 advises basing the proper parameter on the material's elastic modulus.

The DIN C20 steel's elastic modulus is 210 GPa, hence the specification requires a stress rate between 6 and 60 MPa/s. The machine system is based on claw displacement, hence the stress rate was translated to 0.0026 [mm/s]. Thus, displacement grew till rupture. Figure 5 shows the tensile test setup.

Figure 5: Tensile strength test setup

Macrophotography was used to measure weld geometry. Using this technique, the weld profile can be seen. Figure 4 samples were cut so that two more samples could be obtained from each. These samples were implanted in thermosetting Bakelite resin for metallography processing. This preparation involves sanding the implanted steel from finer to coarser grits. The item is then polished, and a 7 percent solution of Nital ($HNO3$) exposes the weld. Figure 6 shows an embedded sample (a).

Weld bead profiles were captured using Newtec IRIS software and a macroscope. These photos (Figure 6(b)) were processed with "ImageJ," which converts pixel length into millimetres to determine weld bead geometry.

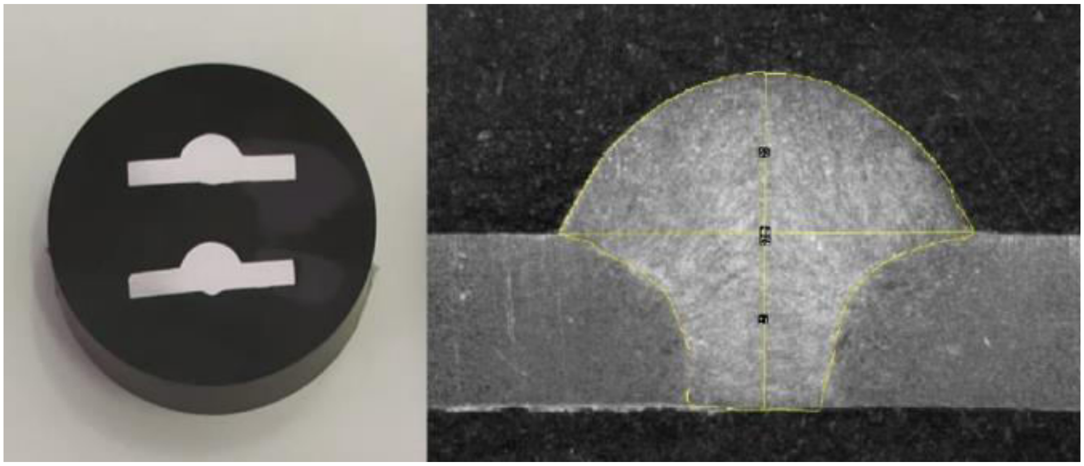

Figure 6: Macrography (a) embedded samples and (b) treated image of weld bead.

3. Results and Discussion:

After all operations, the transversal tensile test and macrography findings were utilised to optimise and verify the welding parameters' contribution using ANOVA.

3.1. Transverse Tensile Strength Test:

During the tensile strength test, the machine computer saved the experiment's data. After the specimen ruptured, the same computer reassembled the data into a Force [kN] x Displacement [mm] graph. Each L9 parameter combination supplied two transversal tensile strength test specimens, so all nine tests could be repeated. All 18 Stress [MPa] x Displacement [mm] graphs were plotted using MS Excel and MathWorks MATLAB. In Figure 7, first-group test results are linked to second-group tests. Table 5 shows the average ultimate tensile strength (UTS) of the two groups.

3.2. Macrography Measurements:

The macrography weld sample samples allowed for two more samples each piece. Like the tensile test, two test samples are generated from each parameter combination to compute the weld dimensions. Table 6 displays the average measurements.

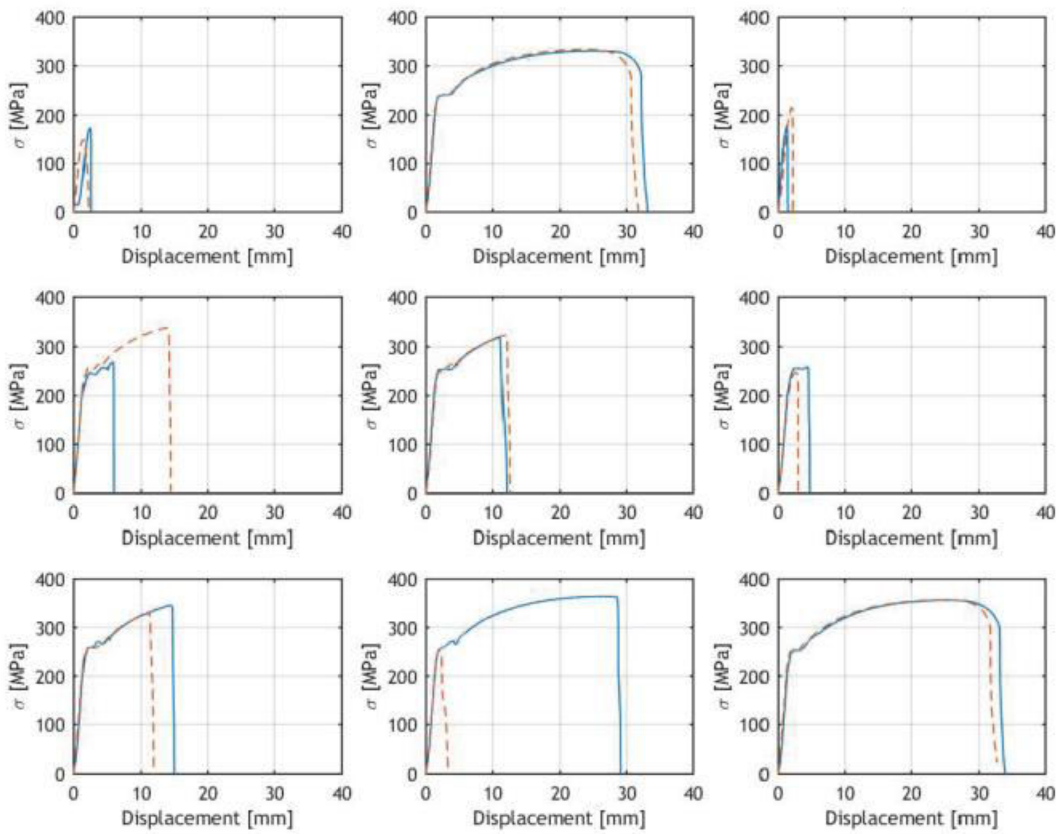

Figure 7: Ultimate tensile strength from both test groups

TABLE 5: The ultimate tensile strength results

Experiment Number	Ultimate Tensile Strength [MPa]
1	309.79
2	321.51
3	161.73
4	356.73
5	197.53
6	252.82
7	331.97
8	337.60
9	304.21

TABLE 6: Average values from the weld geometry parameters

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Experiment Number	Reinforcement [mm]	Width [mm]	Penetration [mm]
1	2.389	6.240	1.878
2	2.759	5.729	1.690
3	1.711	4.284	1.430
4	2.904	7.450	3.012
5	2.387	5.261	1.254
6	2.024	5.164	1.441
7	2.584	7.072	3.013
8	2.216	6.174	1.946
9	2.170	5.930	1.651

3.3. Analisys of Variance (ANOVA):

The ANOVA determines the impact of welding voltage [V], welding speed [mm/min], and welding torch angle [°] on geometrical parameters (reinforcement, width, and penetration) and ultimate tensile strength. This approach used Minitab 17. Table 7 shows the ANOVA findings for each response parameter.

TABLE 7: Level of contribution of the input welding parameters

Parameter	Reinforcement [mm]	Width [mm]	Penetration [mm]	Ultimate Tensile Strength [MPa]
Voltage	3.45 %	18.94 %	12.69 %	18.56 %
Speed	63.54 %	66.36 %	66.94 %	35.93 %
Angle	28.17 %	13.94 %	5.84 %	41.39 %

3.4. Signal to Noise Ratio:

In order to optimise each response parameter, the signal-to-noise ratio must be computed for each experimental input welding parameter combination. "Small is best" was the motto for weld reinforcement. For penetration and breadth, the goal was to manage it such that both achieved 3 [mm] plate thickness, hence the "nominal is better" formula was needed. "Larger is better" for transversal tensile strength offered the optimum ratio for weld strength. Each response parameter's signal-to-noise ratio is paired with an input parameter combination, and an average value is determined for each level to optimise. Figure 8 displays the average signal-to-noise ratio for each weld setting.

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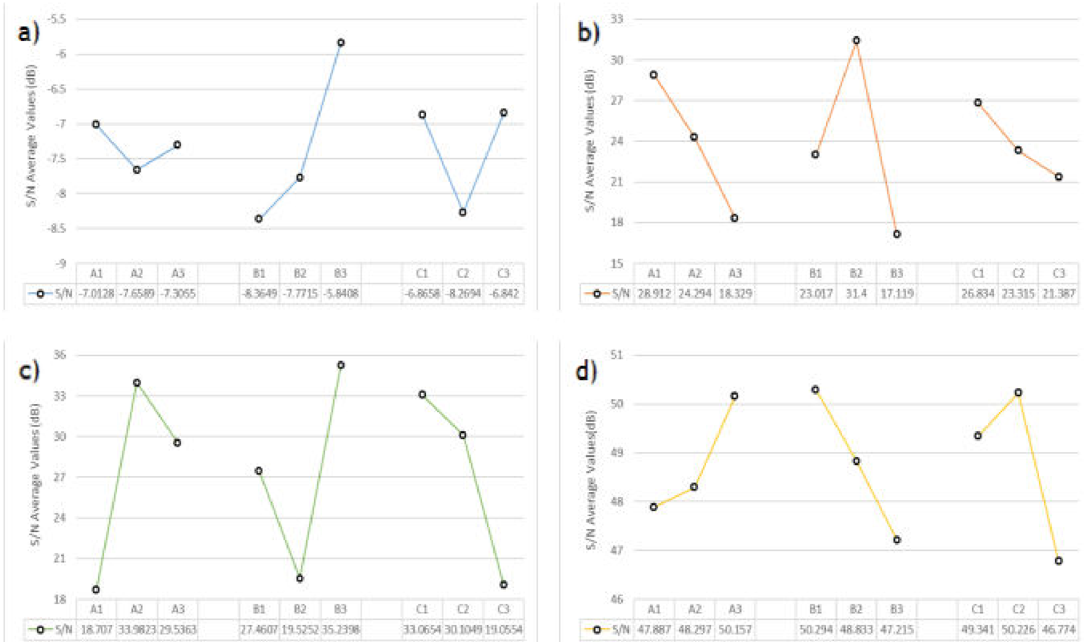

Figure 8: Signal to noise average values for (a) reinforcement, (b) width, (c) penetration and (d) ultimate tensile strength

Based on the graphical signal-to-noise averages, the ideal welding parameter combination for the reinforcement is A1B3C3, for width it's A1B2C1, for penetration it's A2B2C1, and for ultimate transversal tensile strength it's A3B1C2. The lowest reinforcement height is obtained with 22.4 [V], 400 [mm/min], and 30 [°], the width closer to 3 [mm] with 22.4 [V], 300 [mm/min], 0 [°], the penetration with dimension closer to the plate thickness with 23.3 [V], 400 [mm/min], 0 [°], and the ultimate transversal tensile strength with 24.1 [V], 200 [mm/min], 15 [°].

4. Conclusion:

This study uses the Taguchi technique to improve GMAW welding depending on weld parameters. Three levels were employed to explore the interactions between weld input parameters (voltage [V], weld speed [mm/min], and weld torch angle [°]) and response parameters (ultimate transversal tensile strength [MPa] and geometrical parameters) (reinforcement [mm], width [mm] and penetration [mm]). The experiment findings lead to the following conclusions:

1. The robust orthogonal Taguchi technique can describe and analyse the suggested issue.

2. Taguchi presents an effective and straightforward experiment design for GMAW parameter improvement.

3. For the ultimate transversal tensile strength, the torch angle is more important than welding speed.

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