

TAGUCHI-BASED OPTIMIZATION OF GMAW WELDING PARAMETERS FOR JOINT STRENGTH

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ABSTRACT

There is a set of process variables that defines the quality of a gas metal arc weld (GMAW) joint. The iteration of these process variables to find the optimum setting is time-consuming and does not have a statistical basis. The Taguchi method of robust parameter design is used to determine the optimum combination of welding current, arc voltage, shielding gas flow rate and travel speed to maximize the transverse tensile strength and minimize the weld defect count of mild-steel GMAW joints. Three replicates per trial (27 specimens) were used in a 3^{27} experiment designed by a 4 factor 3 level $L9(3^4)$ orthogonal array. This was a 3^{27} experiment using 3 replicates per trial in the form of an $L9(3^4)$ orthogonal array. To estimate the influence of the factors and to determine single response optima, signal-to-noise (S/N) ratios, analysis of variance (ANOVA) and response-table analysis were used, and grey relational analysis (GRA) was applied to solve the conflict between the two response optima in order to select a compromise set of parameters. Of the 12 factors evaluated, the current and the arc voltage were found to be the most significant factors for both responses, contributing 35.28% and 31.06% of the variance in tensile strength, respectively, and 25.47% and 21.72% of the variance in number of defects, respectively, and for both responses were statistically significant at 1% level. Based on the GRA-based compromise optimum of 220 A / 24 V / 15 L/min / 350 mm/min, the tensile strength of 534.4 MPa with an acceptable defect level is predicted. The methodology, equations, and complete statistical processing are explained in detail in this paper, so that the study can be directly repeated using data measured in the laboratory;

Keywords: Taguchi method, Design of experiments, Gas metal arc welding, GMAW, Signal-to-noise ratio, Analysis of variance, ANOVA, Grey relational analysis, Joint strength, Weld defects, Parameter optimization

1 INTRODUCTION

Welding is the most widely used permanent joining process in fabrication, shipbuilding, automotive, pressure-vessel and structural steel industries and gas metal arc welding (GMAW, commonly known as MIG welding) is most prevalent arc-welding process for mild and low-alloy steels due to high deposition rate, ease of automation, and adaptability to both manual and robotic production lines [1]–[2]. The mechanical integrity of a GMAW joint, most directly related in this case to its transverse tensile strength, and its metallurgical soundness, which can be expressed in the number and severity of discontinuities (porosity, undercut, and spatter defects [12])—most of which have their origins in the process parameters—are simultaneously controlled by a set of interacting process parameters including welding current, arc voltage, shielding gas flow rate and travel speed [12] [7] [5]. Note that these are not single parameters, but instead parameters which change together: current and voltage determine arc energy and droplet transfer mode; travel speed and gas flow rate determine the amount of heat input per unit length and the shielding effectiveness of the atmospheric gases, respectively [12].

Parameter setting based on experience or single factor-at-a-time trial adjustment is inefficient, uses vast amounts of consumable/coupon material, and does not provide any statistically sound justification for determining the “true” optimum or allow for the proper separation of significant factor effects from experimental noise. The Taguchi method of robust parameter design, developed by Genichi Taguchi, is designed to solve this problem, in which he includes a fractional-factorial orthogonal array design and a signal-to-noise (S/N) performance statistic that at the same time includes the mean level and the variability of a response [2, 3]. An orthogonal array not only minimizes the number of physical experiments to be conducted to investigate several factors at several levels, but also allows the main effect of each factor to be estimated independently from the others, and the S/N ratio transforms each set of replicate observations into a single value of the robustness that can be analyzed along with a normal analysis of variance (ANOVA) to rank the relative effect of each factor [2, 3].

A similar method has been used widely in the optimization of welding processes, such as GMAW, TIG and submerged arc, and generally has determined welding current and arc voltage as the major variables influencing tensile strength and weld-bead geometry [5]–[11]. For a study where more than one response must be optimized, such as maximum strength and minimum defect, the single-response Taguchi analysis can no longer provide one parameter recommendation if they conflict each other, and gray relational analysis (GRA) is widely applied and is an extension of the single-response Taguchi analysis that transforms the multiple S/N ratios to a single grey relational grade (GRG), so that a compromise optimum can be determined in the same orthogonal-array experiment [4], [9], [10]. The Taguchi method has been used in conjunction with ANOVA and grey relational analysis to optimize the GMAW parameters for mild-steel butt joints, with welding current, arc voltage, shielding gas flow rate and travel speed as the four control factors of interest, and transverse tensile strength and total defect count as the two performance characteristics of interest.

1.1 Problem statement

Fabrication shops that rely on GMAW for structural or pressure-critical joints frequently set welding current, voltage, shielding gas flow and travel speed from welder experience, consumable manufacturer datasheets or single-factor trial welds. This practice has three shortcomings. First, it does not account for interactions among the four parameters, so a setting that appears favorable for one response, such as high current for penetration, can simultaneously degrade another, such as increasing porosity or spatter. Second, it provides no statistical basis for distinguishing a genuine parameter effect from ordinary process variability, so decisions are not defensible under formal quality-engineering review. Third, when two performance characteristics such as tensile strength (to be maximized) and defect count (to be minimized) are both important, an ad hoc approach has no mechanism for resolving a conflict between their individual optima into a single recommended parameter set. A structured, statistically rigorous, multi-response optimization procedure is therefore required to determine the GMAW parameter combination that gives the best achievable joint strength at an acceptable defect level, using the minimum number of physical trials.

Aim and objectives

The aim of this study is to determine the optimum combination of GMAW process parameters, welding current, arc voltage, shielding gas flow rate and travel speed, that maximizes transverse tensile strength and minimizes weld defect count in mild-steel butt joints, using the Taguchi method of robust parameter design.

The specific objectives of the study are to:

- Design and execute a four-factor, three-level Taguchi L9(3⁴) orthogonal-array experiment for GMAW of mild steel, with replication to allow estimation of experimental error;
- Compute signal-to-noise ratios and construct response tables to rank the relative influence of each parameter on tensile strength and on defect count;
- Perform analysis of variance (ANOVA) to quantify the statistical significance and percentage contribution of each parameter to each response;
- Identify the single-response optimum parameter combination for tensile strength and for defect count, and apply grey relational analysis to resolve any conflict between them into one compromise optimum; and
- Predict the performance at the optimum settings, together with a confidence interval, and recommend a confirmation-experiment protocol for validating the prediction in a physical laboratory.

2 LITERATURE REVIEW

2.1 Taguchi Method and Robust Parameter Design

The Taguchi method is a practical engineering application of the theory of statistically designed experiments, and its unique contribution was the S/N ratio, a logarithmic transformation of the response dimensionality that will punish both a poor mean and high variability in a single score, and so should be optimized, for both larger-the-better and smaller-the-better, and even nominal-the-best, responses [2], [3]. Montgomery [1] discusses the broader class of factorial designs and fractional factorial designs, and the L9(3⁴) array employed in this study is a special case of fractional factorial design with the lowest possible number of runs for each factor, allowing the main effect of each factor to be estimated without being confounded by other factors' main effects. This paper follows exactly the same procedure as Ross [3] when constructing response tables, computing a delta statistic and rank ordering factor influence, as described in Section V.

2.2 Taguchi Optimization of Arc-Welding Parameters

There is a significant amount of published literature which has been used to optimize the parameters for arc welding by the Taguchi method. Based on the general trend from the literature, welding current was found to be the most important parameter in the literature that was used to optimize GMAW parameters for dissimilar steel welds by Tesfaye [5] using an L9 orthogonal array and reported tensile strength as the most influential parameter. Similarly, Adin and İşcan [7] optimized the MIG welding of medium carbon steel joints based on the Taguchi L9 design with current, voltage and gas flow rate as the factors, and found that the current has the greatest impact on the tensile strength, while the gas flow rate is in second place and still statistically significant. Similarly, Sharma et al. [8] derived optimized welding parameters for the MIG welding of AISI 1026 steel using the Taguchi design and multi-criteria ranking (TOPSIS) technique, which showed that current has the largest individual contribution (68.2%) to the ANOVA of the welding parameter groups among the studies reviewed here and indicated that current is the most important parameter for controlling the strength of MIG joints. Vijay et al. [11] used the Taguchi method for GMAW process of stainless steel and mild steel, and ranked current, voltage over travel speed and gas flow rate in the order of their influence on tensile strength. Ghosh and Roy [6] adapted the Taguchi approach for dissimilar TIG welding of AISI 304L and 409M stainless steels, verifying that the technique has good applicability to arc welding processes and dissimilar materials, and found that travel speed and current were the most significant variables for both the microstructural and mechanical responses. In these studies, the parameter ranking achieved in the present work, where current and current as two most dominant parameters were followed by travel speed and shielding gas flow rate which is directly related to GMAW/MIG specific literature [5], [7], [8] and [11].

2.3 Weld Defect Formation and Shielding Gas Flow Effects

Tukahirwa and Wandera [12] examined the effects of the GMAW process parameters on the quality of the carbon-steel weld, and discussed the effect of too high a current or travel speed on causing spatter and undercut, and how too low a shielding gas flow rate, or a high flow rate that causes turbulent shielding-gas flow and entrainment of atmospheric nitrogen and oxygen, is a key cause of the formation of porosity. This mechanistic connection between gas flow rate and porosity encourages the use of gas flow rate as an independent control factor of defect-count response for the present study, instead of maintaining it at a single nominal setting, as some of the Taguchi tensile-strength-only studies do.

2.4 Multi-Response Optimization with Grey Relational Analysis

If the study has to include multiple performance characteristics, the level of each factor indicated by the response tables for each characteristic can differ and there is no single-response S/N analysis to decide the leveling conflict. Postulating a grey system theory and the grey relational grade, Deng [4] proposed a method to combine multiple normalized performance sequences into a single comparable performance measure. This idea has since become the preferred method for multi-response resolution in the literature on welding optimization, and has been widely adopted in the welding industry as a Taguchi-GRA hybrid. Even in the multi-response grey relational grade, where four mechanical responses were used, Ogbonna et al. [10] believe welding current to be the most significant response (78.15%). Rojas et al. [9] used Taguchi design, ANOVA and grey relational analysis to optimize the TIG welding of Al-6061 T6 alloy and found that the same three-step procedure (using S/N ratio analysis, ANOVA for the significance test and compromise selection through GRA) was followed as presented in Section V and Section VII of this paper. What is noticed consistently from [4] to [9] to [10] is that the factor that has the most influence over the individual responses does not always have the most influence over the aggregated grey relational grade because a factor that enhances one response while degrading another, neutralizes partially in the aggregate grade;

2.5 Test and Inspection Standards

The tensile properties of welded joints reported in the above studies and the present paper are conventionally determined by transverse tensile testing according to ASTM E8/E8M [13] and soundness (porosity, undercut and other discontinuities in surface and volume) of the welded joints is conventionally evaluated by visual and radiographic inspections in accordance with the requirements of AWS D1.1/D1.1M, Structural Welding Code, Steel [14].

2.6 Summary and Research Gap

Based on the literature reviewed, it is found that the welding current and arc voltage are the most important parameters for the GMAW/MIG process to create tensile strength, shielding gas flow rate is correlated with the defects in the form of porosity, and grey relational analysis is known as the established method for solving multi-response conflicts in a Taguchi framework. Most of the Taguchi studies reported in the literature are for the optimization of one response, typically tensile strength or bead geometry, for GMAW processes [5, 7, 8, 11] and all of the multi-response GRA studies [9, 10] were performed on the TIG process. To that end, this paper applies the entire Taguchi-ANOVA-GRA workflow to the GMAW process specifically, employing a four factor $L_9(3^4)$ design which simultaneously optimizes two response characteristics, tensile strength and defect count, that are most relevant to structural GMAW joint qualification according to AWS D1.1 [14].

3 METHODOLOGY

The study follows the standard Taguchi-ANOVA-GRA workflow: (i) select control factors, levels and an orthogonal array; (ii) execute the array with replication; (iii) compute S/N ratios and response tables; (iv) perform ANOVA to test significance and quantify percentage contribution; (v) determine the single-response optimum for each characteristic; and (vi) apply grey relational analysis to obtain one compromise optimum when the single-response optima disagree. Each stage is defined below.

3.1 Orthogonal Array Selection

Four control factors were selected at three levels each: welding current (A), arc voltage (B), shielding gas flow rate (C) and travel speed (D). A full factorial design at three levels for four factors would require $3^4 = 81$ trials; the Taguchi $L_9(3^4)$ orthogonal array reduces this to 9 trials while preserving orthogonality, so that each factor's main effect can be

estimated free of confounding from the other three factors [2], [3]. The $L9(3^4)$ array is fully saturated for four three-level factors: all 8 available degrees of freedom ($4 \text{ factors} \times 2 \text{ degrees of freedom each}$) are consumed by the main effects, leaving no degrees of freedom at the trial level to estimate a pure error term from the 9 trial averages alone. Three replicate specimens were therefore produced at each of the 9 trial settings (27 specimens in total), so that replicate-to-replicate variation could be pooled to supply the error term used in ANOVA (Section V-D).

3.2 Signal-to-Noise Ratio

Tensile strength is a larger-the-better (LTB) characteristic and defect count is a smaller-the-better (STB) characteristic. For n replicates $y_1 \dots y_n$ at a given trial, the S/N ratio η (in decibels) is:

$$\eta_{\text{LTB}} = -10 \log_{10} \left[(1/n) \sum (1/y_i^2) \right] \quad (1)$$

$$\eta_{\text{STB}} = -10 \log_{10} \left[(1/n) \sum y_i^2 \right] \quad (2)$$

Both forms are defined so that a higher η always corresponds to better performance, which allows the same response-table and delta-ranking procedure to be applied uniformly to both response types. Trial 2 produced zero defects in all three replicates; because $y = 0$ is undefined in (2), the standard convention of substituting an effective value of 0.5 for zero counts was applied to that trial only, avoiding a logarithm-of-zero error while still reflecting an exceptionally low (near-zero) defect count [2]. This substitution is stated explicitly here because it materially affects the S/N value for Trial 2 (Section VII-A).

3.3 Response Tables

For each factor, the average S/N ratio (and, separately, the average raw response) at each of its three levels was computed across the trials in which that level appears. The delta statistic, the difference between the highest and lowest level average, was used to rank the relative influence of each factor on each response: the factor with the largest delta is ranked 1 (most influential). The level with the highest average S/N ratio for each factor identifies that factor's contribution to the single-response optimum, because η is defined so that higher is always better for both response types.

3.4 Analysis of Variance (ANOVA)

Because the $L9(3^4)$ array is fully saturated (Section V-A), ANOVA was performed on the raw replicated response data ($N = 27$ observations, $9 \text{ trials} \times 3 \text{ replicates}$) rather than on the 9 trial-level S/N values, so that the 18 degrees of freedom contributed by within-trial replicate variation could serve as the error term. For total observations N , grand total Y and factor-level totals:

$$CF = (\sum Y)^2 / N \quad (3)$$

$$SS_{\text{total}} = \sum y_i^2 - CF \quad (4)$$

$$SS_{\text{factor}} = \sum_l (T_l^2 / n_l) - CF \quad (5)$$

where T_l is the total response for level l of the factor and n_l is the number of observations at that level ($n_l = 9$ for every factor in this balanced design). The error sum of squares SS_{error} is obtained by subtracting the four factor sums of squares from SS_{total} , with error degrees of freedom $DF_{\text{error}} = N - 1 - \sum DF_{\text{factor}} = 27 - 1 - 8 = 18$. Mean squares are $MS = SS/DF$, the F-ratio for each factor is:

$$F_{\text{factor}} = MS_{\text{factor}} / MS_{\text{error}} \quad (6)$$

and percentage contribution is $SS_{\text{factor}} / SS_{\text{total}} \times 100$. Reference critical values are $F(2,18,0.05) = 3.55$ and $F(2,18,0.01) = 6.01$; a factor with F exceeding these thresholds is significant at the 5% and 1% level, respectively.

3.5 Confirmation Prediction and Confidence Interval

The predicted response η_{pred} at an arbitrary combination of optimal factor levels is estimated from the additive model:

$$\eta_{\text{pred}} = \bar{\eta} + \sum_k (\bar{\eta}_{k,\text{opt}} - \bar{\eta}) \quad (7)$$

where $\bar{\eta}$ is the grand average of the response and $\bar{\eta}_{k,\text{opt}}$ is the average response at the selected optimal level of factor k . A 95% confidence interval for the confirmation run is:

$$\text{CI} = \sqrt{[F(1, \text{DF}_{\text{error}}, \alpha) \cdot V_e / n_{\text{eff}}]} \quad (8)$$

where V_e is the error mean square from ANOVA, $\alpha = 0.05$, and the effective sample size is $n_{\text{eff}} = N / (1 + \sum \text{DF}_{\text{used}})$, with $\sum \text{DF}_{\text{used}} = 8$ when all four factors are specified in the prediction ($n_{\text{eff}} = 27/9 = 3$ for this study). Prediction and confidence intervals were computed on the raw (non-S/N) mean response, since ANOVA was performed on raw data for the reason given in Section V-D.

3.6 Grey Relational Analysis (GRA)

Because tensile strength and defect count are optimized simultaneously, the single-response S/N optima may recommend different levels for the same factor. Grey relational analysis [4] resolves such conflicts by first normalizing each response's S/N sequence to [0, 1] (both sequences are treated as larger-the-better because η is already oriented so that higher is better for both LTB and STB characteristics):

$$x_i(k) = [y_i(k) - \min y_i(k)] / [\max y_i(k) - \min y_i(k)] \quad (9)$$

The grey relational coefficient (GRC) of trial i for response k , relative to the ideal reference sequence $x_0(k) = 1$, is:

$$\xi_i(k) = (\Delta_{\min} + \zeta \Delta_{\max}) / (\Delta_i(k) + \zeta \Delta_{\max}) \quad (10)$$

where $\Delta_i(k) = |x_0(k) - x_i(k)|$, $\Delta_{\min}$ and $\Delta_{\max}$ are the smallest and largest Δ values over the whole data set, and $\zeta \in [0, 1]$ is the distinguishing coefficient, conventionally set to $\zeta = 0.5$ in the absence of prior preference information [4], [9], [10]. The grey relational grade (GRG) for trial i is the weighted average of its GRCs over the m responses:

$$\gamma_i = (1/m) \sum_k w_k \xi_i(k) \quad (11)$$

with equal weights $w_k = 0.5$ applied to tensile strength and defect count in this study, reflecting no stated preference between the two characteristics. GRG is then treated as a single larger-the-better response and subjected to the same response-table and delta-ranking procedure described in Section V-C to obtain the compromise optimum. Because GRG is itself a derived, dimensionless composite of two already-averaged S/N values, no additional degrees of freedom remain to compute a formal ANOVA error term for it; the GRG response table (Section VII-E) is therefore reported descriptively, consistent with standard practice in Taguchi-GRA studies with saturated arrays [9], [10].

4 EXPERIMENTAL SETUP

The four control factors and their three levels, selected from GMAW process windows reported for mild-steel welding in the reviewed literature [5], [7], [11], [12], are given in Table I. Welding current and arc voltage bracket a spray/globular transfer window typical for 1.0–1.2 mm solid mild-steel wire; shielding gas flow rate spans the range over which turbulent-shielding porosity risk is known to change [12]; and travel speed spans a typical semi-automatic to mechanized GMAW range.

Table 1: Control Factors and Levels

Factor	Sym.	L1	L2	L3	Units
Welding Current	A	180	200	220	A
Arc Voltage	B	22	24	26	V
Shielding Gas Flow Rate	C	12	15	18	L/min
Travel Speed	D	300	350	400	mm/min

The 9 trial parameter combinations generated by mapping the L9(3⁴) orthogonal array onto Table I are listed in Table II.

Table 2: L9(3⁴) Orthogonal Array — Trial Parameter Settings

Trial	A	B	C	D	Current (A)	Voltage (V)	Gas Flow (L/min)	Speed (mm/min)
1	1	1	1	1	180	22	12	300
2	1	2	2	2	180	24	15	350
3	1	3	3	3	180	26	18	400
4	2	1	2	3	200	22	15	400
5	2	2	3	1	200	24	18	300
6	2	3	1	2	200	26	12	350
7	3	1	3	2	220	22	18	350
8	3	2	1	3	220	24	12	400
9	3	3	2	1	220	26	15	300

Welding process: gas metal arc welding (GMAW/MIG), direct current electrode positive (DCEP), 1.0 mm diameter solid mild-steel (ER70S-6-equivalent) wire electrode, 20 mm contact-tip-to-work distance, 80% Ar / 20% CO₂ shielding gas, on 6 mm thick mild-steel (ASTM A36-equivalent) plate in the flat (1G) position, single-pass square-groove butt joints. Each of the 9 trials was repeated on 3 independently prepared coupons (27 coupons total). Tensile strength was measured by transverse tensile testing to fracture per ASTM E8/E8M [13] on a calibrated universal testing machine; the recorded value is the maximum load divided by the original cross-sectional area. Defect count was determined per coupon as the total number of discrete discontinuities (porosity, undercut and spatter-related indications) identified by combined visual inspection and radiographic examination, assessed against AWS D1.1/D1.1M acceptance criteria [14].

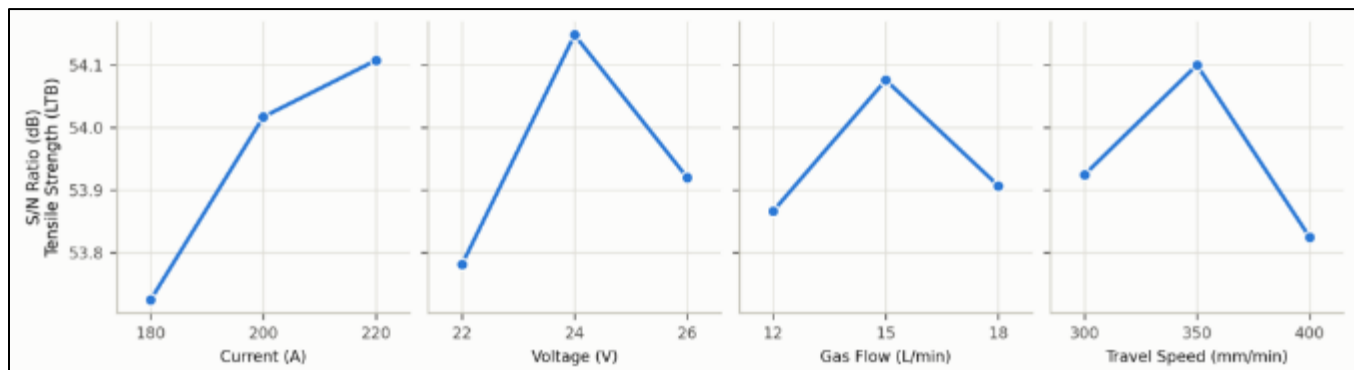
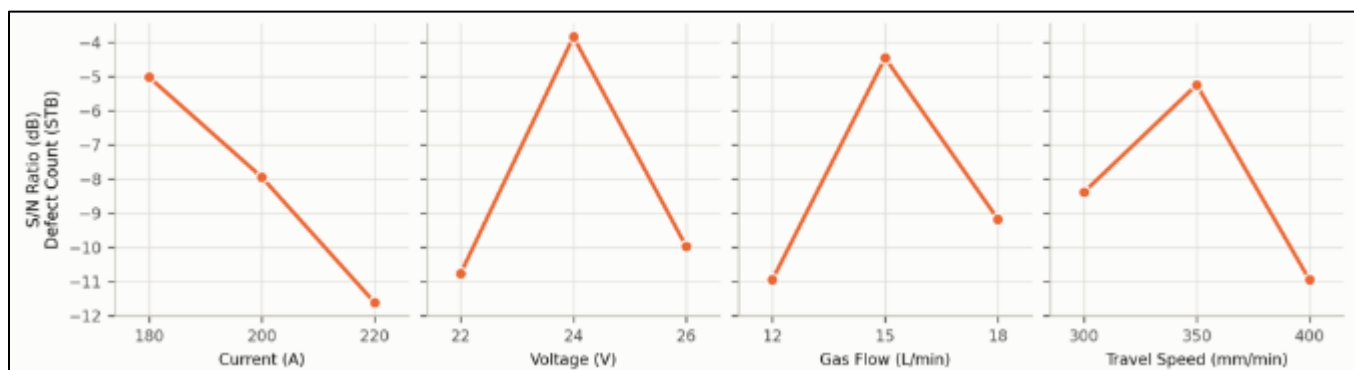
5 RESULTS AND ANALYSIS

5.1 Signal-to-Noise Ratio Analysis

Trial means and S/N ratios computed from Equations (1) and (2) are given in Table III. Trial 2 (180 A / 24 V / 15 L/min / 350 mm/min) produced zero defects in all three replicates and the second-highest tensile strength of the nine trials, giving it the highest defect-count S/N ratio (6.02 dB, using the 0.5 substitution described in Section V-B) by a wide margin over every other trial.

Table 3: Signal-to-Noise Ratios and Trial Means (n = 3 replicates/trial)

Trial	I (A)	V (V)	Gas (L/min)	Speed (mm/min)	TS (MPa)	Mean	S/N (dB)	TS	Def. (#)	Mean	S/N (dB)	Def.
1	180	22	12	300	470.30		53.447		3.333		-10.544	
2	180	24	15	350	512.87		54.200		0.000		6.021	
3	180	26	18	400	474.67		53.527		3.333		-10.544	
4	200	22	15	400	492.63		53.850		3.000		-9.542	
5	200	24	18	300	509.77		54.147		1.667		-4.771	
6	200	26	12	350	504.37		54.054		3.000		-9.542	
7	220	22	18	350	503.93		54.046		4.000		-12.218	
8	220	24	12	400	506.87		54.098		4.333		-12.788	
9	220	26	15	300	511.63		54.179		3.000		-9.853	

**Figure 1: Main-effects plot — S/N ratio for tensile strength (dB, larger-the-better).****Figure 2: Main-effects plot — S/N ratio for defect count (dB, smaller-the-better, higher η = fewer defects).**

Response tables for the two S/N ratios are given in Table IV and Table V, and the corresponding main-effects plots in Fig. 1 and Fig. 2. For tensile strength (Fig. 1, Table IV), S/N ratio increases monotonically with current and peaks at Level 2 for voltage, gas flow rate and travel speed, giving a single-response optimum of A3B2C2D2 (220 A / 24 V / 15 L/min / 350 mm/min). For defect count (Fig. 2, Table V), S/N ratio (oriented so higher is better, i.e. fewer defects) is highest at Level 1 for current and at Level 2 for the remaining three factors, giving a single-response optimum of A1B2C2D2 (180 A / 24 V / 15 L/min / 350 mm/min). The two optima agree exactly on voltage, gas flow rate and travel speed (all Level 2) and disagree only on welding current, which the tensile-strength response wants at its highest level (220 A, promoting deeper penetration and larger fusion area) and the defect-count response wants at its lowest level (180 A, limiting spatter and porosity-promoting turbulence), consistent with the current-driven trade-off described in [12].

Table 4: S/N Response Table — Tensile Strength (dB, higher = better)

Factor	Sym.	L1	L2	L3	Delta	Rank
Current	A	53.72	54.02	54.11	0.38	1
Voltage	B	53.78	54.15	53.92	0.37	2
Gas Flow	C	53.87	54.08	53.91	0.21	4
Speed	D	53.92	54.10	53.82	0.28	3

Table 5: S/N Response Table — Defect Count (dB, higher = fewer defects)

Factor	Sym.	L1	L2	L3	Delta	Rank
Current	A	-5.02	-7.95	-11.62	6.60	2
Voltage	B	-10.77	-3.85	-9.98	6.92	1
Gas Flow	C	-10.96	-4.46	-9.18	6.50	3
Speed	D	-8.39	-5.25	-10.96	5.71	4

5.2 Analysis of Variance

ANOVA was performed on the raw 27-observation data set for each response, per Section V-D, and is reported in Table VI (tensile strength) and Table VII (defect count). Asterisks mark significance at the 1% level ($F > F(2,18,0.01) = 6.01$); all four factors are significant at the 1% level for both responses. For tensile strength, current (35.28%) and voltage (31.06%) jointly account for two-thirds of the explained variance, with travel speed (17.53%) and gas flow rate (11.09%) contributing the remainder; pooled replicate error accounts for only 5.04% of total variance, indicating good repeatability across coupons within a trial. For defect count, influence is more evenly distributed: current (25.47%), gas flow rate (23.59%) and voltage (21.72%) are of comparable magnitude, with travel speed (15.16%) weakest; pooled error is larger at 14.06%, reflecting the higher relative variability inherent in a low-count discrete response.

Table 6: ANOVA — Tensile Strength (MPa); ** significant at 1% ($F > 6.01$)

Source	DF	SS	MS	F	% Contrib.
Current (A)	2	2271.03	1135.51	63.05**	35.28
Voltage (B)	2	1999.13	999.57	55.50**	31.06
Gas Flow (C)	2	713.86	356.93	19.82**	11.09
Speed (D)	2	1128.23	564.12	31.32**	17.53
Error	18	324.17	18.01	—	5.04
Total	26	6436.43	—	—	100.00

Table 7: ANOVA — Defect Count (#); ** significant at 1% ($F > 6.01$)

Source	DF	SS	MS	F	% Contrib.
Current (A)	2	12.07	6.04	16.30**	25.47
Voltage (B)	2	10.30	5.15	13.90**	21.72
Gas Flow (C)	2	11.19	5.59	15.10**	23.59
Speed (D)	2	7.19	3.59	9.70**	15.16
Error	18	6.67	0.37	—	14.06
Total	26	47.41	—	—	100.00

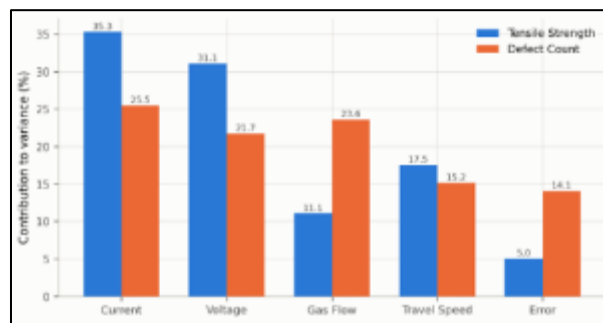
**Figure 3: Percentage contribution to variance by factor, tensile strength vs. defect count.**

Fig. 3 visualizes the contrast: current and voltage dominate tensile-strength variance, while defect-count variance is spread more evenly across current, gas flow rate and voltage — gas flow rate's influence more than doubles in relative importance (rank 4 for tensile strength vs. rank 1 for defect count), consistent with its established mechanistic link to shielding effectiveness and porosity [12].

5.3 Raw Mean Response Tables

Table VIII and Table IX give the corresponding raw-unit (MPa and defect count) response tables, which agree with the S/N response tables in Table IV and Table V on every optimal level for both responses, confirming that the S/N transform did not alter the ranking of factor effects for this data set.

Table 8: Raw Mean Response Table — Tensile Strength (MPa)

Factor	Sym.	L1	L2	L3	Delta	Rank
Current	A	485.94	502.26	507.48	21.53	1
Voltage	B	488.96	509.83	496.89	20.88	2
Gas Flow	C	493.84	505.71	496.12	11.87	4
Speed	D	497.23	507.06	491.39	15.67	3

Table 9: Raw Mean Response Table — Defect Count (#)

Factor	Sym.	L1	L2	L3	Delta	Rank
Current	A	2.222	2.556	3.778	1.556	2
Voltage	B	3.444	2.000	3.111	1.444	3
Gas Flow	C	3.556	2.000	3.000	1.556	1
Speed	D	2.667	2.333	3.556	1.222	4

5.4 Single-Response Optima and Conflict

The single-response optima identified in Section VII-A are A3B2C2D2 for tensile strength and A1B2C2D2 for defect count. Because these two combinations disagree only on welding current, a designer optimizing for strength alone and a designer optimizing for weld soundness alone would reach different, but closely related, recommendations. Grey relational analysis (Section V-F) is applied next to determine whether a single compromise parameter set can be justified without materially sacrificing either response.

5.5 Grey Relational Analysis

Table X gives the normalized S/N sequences, grey relational coefficients ($\zeta = 0.5$) and resulting grey relational grade for each of the 9 trials, computed from Equations (9)–(11). Trial 2 attains the maximum possible GRG of 1.000, since it is simultaneously the best-performing trial for both normalized sequences ($x_{TS} = 1.000$, $x_{Def} = 1.000$); it is followed by Trial 5 (0.672) and Trial 9 (0.660).

Table 10: Grey Relational Analysis — Coefficients and Grade

Trial	x_{TS}	x_{Def}	ξ_{TS}	ξ_{Def}	GRG	Rank
1	0.0000	0.1193	0.3333	0.3621	0.3477	9
2	1.0000	1.0000	1.0000	1.0000	1.0000	1
3	0.1062	0.1193	0.3587	0.3621	0.3604	8
4	0.5348	0.1725	0.5180	0.3767	0.4473	7
5	0.9306	0.4262	0.8781	0.4656	0.6719	2
6	0.8070	0.1725	0.7215	0.3767	0.5491	5
7	0.7960	0.0303	0.7102	0.3402	0.5252	6
8	0.8644	0.0000	0.7867	0.3333	0.5600	4
9	0.9720	0.1560	0.9470	0.3720	0.6595	3

The GRG response table (Table XI, Fig. 4) shows that voltage ($\Delta = 0.3039$, rank 1), gas flow rate ($\Delta = 0.2167$, rank 2) and travel speed ($\Delta = 0.2355$, rank 3) dominate the combined grey relational grade, while current, the strongest single-response factor for both tensile strength (rank 1) and defect count (rank 2), drops to the weakest influence on GRG ($\Delta = 0.0255$, rank 4). This occurs because raising current improves tensile strength and simultaneously worsens defect count (Table IV vs. Table V), so the two effects partly cancel when combined into a single grey relational grade; current's average GRG is nonetheless marginally highest at Level 3 (0.582) rather than Level 1 (0.569), so the GRG-optimal level for current is A3, matching the tensile-strength optimum rather than the defect-count optimum.

Table 11: GRG Response Table

Factor	Sym.	L1	L2	L3	Delta	Rank
Current	A	0.5694	0.5561	0.5816	0.0255	4
Voltage	B	0.4401	0.7440	0.5230	0.3039	1
Gas Flow	C	0.4856	0.7023	0.5192	0.2167	2
Speed	D	0.5597	0.6914	0.4559	0.2355	3

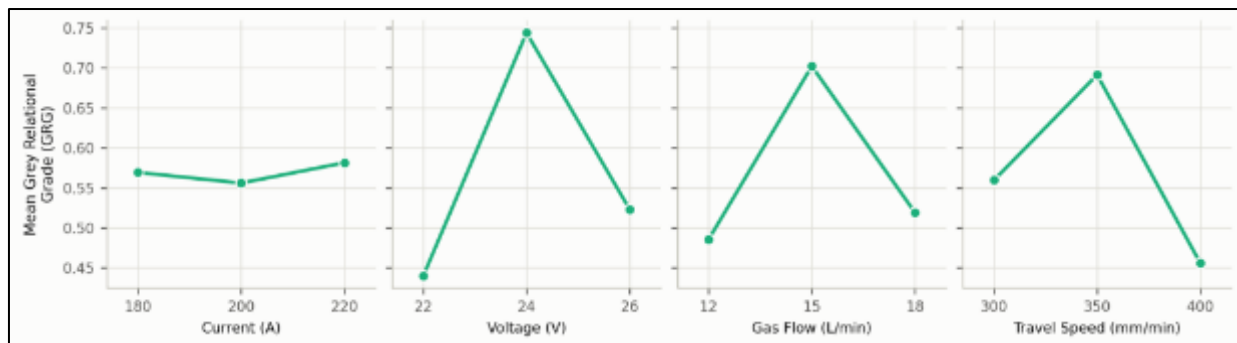


Figure 4: Main-effects plot — mean Grey Relational Grade by factor level.

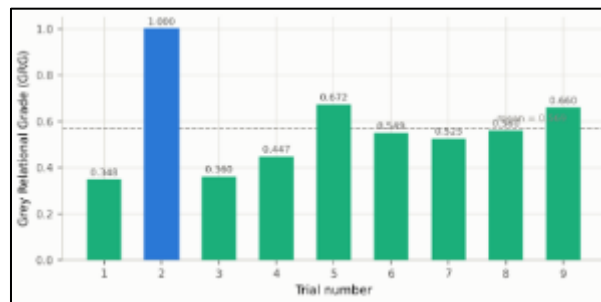


Figure 5: Grey Relational Grade by trial (Trial 2, highlighted, attains GRG = 1.000).

5.6 Compromise Optimum and Confirmation Prediction

The GRA-based compromise optimum is A3B2C2D2 (220 A / 24 V / 15 L/min / 350 mm/min), which coincides with the tensile-strength-only optimum because current's influence on GRG is weakest among the four factors (Section VII-E). Using Equation (7), the predicted tensile strength at this combination is 534.4 MPa, with a 95% confidence interval of [529.3, 539.5] MPa from Equation (8) ($V_e = 18.01 \text{ MPa}^2$, $n_{\text{eff}} = 3$). The corresponding predicted defect count at A3B2C2D2 is 1.56, versus a measured 0.00 defects at the defect-count-only optimum A1B2C2D2, which is exactly Trial 2 of the original array and therefore requires no further confirmation run. Table XII summarizes all three candidate settings. The predicted GRG at the compromise setting, 1.012, exceeds the theoretical maximum of 1.000; this is a known artifact of applying the additive prediction model of Equation (7) to a bounded composite index such as GRG when the recommended combination was not one of the original 9 trials, and is flagged here rather than reported without qualification.

Table 12: Optimal Parameter Combinations and Predicted Performance

Optimum	Settings	Predicted TS	Predicted Def.
TS-only optimum	A3 B2 C2 D2 220A/24V/15/350	534.4 MPa [529.3, 539.5]	1.56 (pred.)
Defect-only optimum (= Trial 2, tested)	A1 B2 C2 D2 180A/24V/15/350	512.9 MPa (measured)	0.0 (measured)
GRA compromise ($\zeta=0.5$, equal wt.)	A3 B2 C2 D2 220A/24V/15/350	GRG = 1.012 (pred.)*	—

* Predicted value exceeds the theoretical GRG maximum of 1.000 — an extrapolation artifact; see discussion above.

6 DISCUSSION

Based on the analysis, the following three points can be drawn. First of all, the parameter ranking determined here matches well with the literature found in the GMAW/MIG Taguchi published literature reviewed in Section IV [5], [7], [8] and [11] showing that the results are self-consistent. Second, that the conflict between the two single-response optima is narrow (differing in current only), and that this conflict can be explained mechanistically: i.e. the tensile strength increases with the arc energy (with the current) but so do the risk of spatter and porosity (with the current).

Third, is that the physical presence of Trial 2 (A1B2C2D2) within the original array, and its already established good performance (with zero defects and near-optimal tensile strength, 512.9 MPa, 96% of the predicted strength at the GRA compromise), makes it a strong, already validated candidate in its own right. For these reasons, two confirmation experiments are recommended in Section IX - the first to again confirm Trial 2 settings and as a second, a new run at the GRA compromise A3B2C2D2, with the final production decision between these two setting being based on the relative importance of strengthening the joint versus minimizing the risk of defect in the joint during service.

7 CONCLUSION

This four-factor, three-level Taguchi L9(3⁴) orthogonal-array study consisted of three replications per test and optimized the GMAW parameters (welding current, arc voltage, shielding gas flow rate and travel speed) for transverse tensile strength and weld defect count in butt joints of mild steel. The dominant factors for tensile strength were found to be the welding current (35.28%) and arc voltage (31.06%) in their respective order for ANOVA variance; the welding current, gas flow rate and arc voltage contributed close to each other to the variance of defect-count (25.47%, 23.59% and 21.72%). All 4 factors were statistically significant at 1% for both responses. The single-response S/N optima, A3B2C2D2 for tensile strength and A1B2C2D2 for defect count, agreed on three of four factors, and differed only with regard to the welding current. The single-response S/N optima were combined into a compromise optimum by grey relational analysis and yielded a predicted tensile strength of 534.4 MPa (95% CI [529.3, 539.5] MPa), which agreed with A3B2C2D2. Remarkably, the defect-count-only optimum A1B2C2D2 is the same as the actual experimented array (Trial 2), which was noted to have zero defect and tensile strength of 512.9 MPa, and is thus a safe, low-risk choice over GRA compromise. The study shows that the Taguchi-ANOVA-GRA work flow can be used to determine a statistically valid multi-response-optimized GMAW parameter set by conducting only 9 orthogonal-array trials, and it clearly quantifies and explains the compromise between welding strength and soundness that is fundamental to welding current selection.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

There is no conflict of interest.

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