



Research Article

Mitigating Weld Defects in AISI 4145 Medium-Carbon Steel During Shielded Metal Arc Welding

Delelegn Gizaw Toga^{*} , Seyidu Wohabrebi , Misganu Kabeta ,
Samuel Alemu

Mineral Industry Development Institute, Ministry of Mines, Addis Ababa, Ethiopia

Abstract

Welding defects pose significant challenges to product quality and productivity in manufacturing industries. Shielded metal arc welding (SMAW) is the most widely used welding method in developing countries such as Ethiopia. This thesis identifies and addresses the root causes of welding defects in SMAW of medium carbon steel (AISI 4145) at Akaki Basic Metal Industry (ABMI), and optimizes welding parameters to enhance weld quality and reduce defect rates. Pareto analysis identified porosity and undercut as the most critical defects, together accounting for a 6% rejection rate in production over two years. Ishikawa (cause-and-effect) diagrams were used to analyze the root causes of these defects in detail, including incorrect welding parameters, inadequate preheat/post-heat treatment, improper technique, and inconsistent quality checks. A Taguchi L9 orthogonal array was then applied to optimize welding current, voltage, and speed. Welding current had the greatest effect on tensile strength (72.18% contribution), followed by voltage (19.73%) and speed (3.88%). Applying the optimized parameters (140 A, 40 V, 80 mm/s) reduced the defect rate from 6% to 2.7%. The study concludes that systematic optimization of welding parameters can effectively mitigate defects, improve weld quality, and enhance productivity in SMAW processes.

Keywords

Shielded Metal Arc Welding, AISI 4145, Welding Defects, Pareto Analysis, Ishikawa Diagram, Taguchi Experimental Design

1. Introduction

Shielded Metal Arc Welding (SMAW) remains one of the most widely used welding technologies in developing manufacturing sectors and heavy machinery fabrication due to its operational flexibility, field adaptability, and equipment affordability [1]. However, manual arc processes are highly susceptible to parameter fluctuations and operator technique variations, which often induce structural discontinuities such as porosity, slag inclusions, incomplete fusion, and undercutting [2, 3]. Process control becomes exceptionally critical when

welding medium-carbon alloy steels like AISI 4145. The material's elevated carbon content (0.43–0.48 wt. %) and alloy additions (chromium and molybdenum) significantly increase its hardenability and susceptibility to cracking within the heat-affected zone (HAZ) [4, 5].

At Akaki Basic Metal Industry (ABMI) in Ethiopia, SMAW accounts for approximately 90% of fabrication activities, utilized in producing structural components, agricultural tools, disc-plough assemblies, and high-pressure irrigation tubing. Despite its widespread application, recent operational

^{*}Correspondence: Delelegn Gizaw Toga (delelegngizaw@gmail.com)

Received: 27 August 2026; Accepted: 28 September 2026; Published: 26 October 2026



Copyright: © The Author(s), 2026. Published by Science Publishing Group. This is an **Open Access** article, distributed under the terms of the Creative Commons Attribution 4.0 License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

reports (2023–2024) reveal a persistent weld rejection and rework rate exceeding 6% across major product lines. These recurring defects lead to substantial material wastage, increased filler metal consumption, extended production delays, and reduced structural integrity. While shop-floor operators frequently attribute these flaws to manual error, process instability in SMAW stems from complex interactions between current, voltage, and travel speed [6, 7]. Specifically, the persistent defect rate at ABMI is primarily driven by a reliance on arbitrary operator experience rather than systematically optimized processing parameters for the 10 mm thick AISI 4145 steel plates used in production.

Although existing literature validates the effectiveness of Taguchi method for optimizing arc welding parameters, significant gaps remain regarding its industrial application to medium-carbon AISI 4145 steels under local shop-floor conditions and due to differences in experimental designs, material grades, joint geometries, and parameter constraints [8, 9, 13,

16]. Furthermore, conventional statistical experimental designs—such as Taguchi optimization studies—often evaluate process variables in isolation, without incorporating plant-specific root-cause diagnostics [16, 18, 28, 29, 38]. Optimizing SMAW parameters specifically for AISI 4145 under local industrial production conditions remains an unaddressed empirical gap [30]. To bridge this empirical and operational gap and directly mitigate weld defects, this study systematically investigates the principal causes of SMAW discontinuities at ABMI using a data-driven optimization strategy. By combining shop-floor root-cause diagnostics (Pareto and Ishikawa analyses) with a Taguchi L9 orthogonal array, this research evaluates three key control variables: welding current, arc voltage, and travel speed. The ultimate objective is to establish an optimized parameter window that maximizes ultimate tensile strength and minimizes defect formation, thereby providing a scalable quality control framework for fabrication facilities facing similar challenges.



Figure 1. Welded products and their defects at ABMI.

2. Literature Review

2.1. Process Fundamentals and SMAW Metallurgy

Shielded Metal Arc Welding (SMAW) remains a vital joining technology across industrial fabrication sectors due to its operational flexibility, equipment affordability, and field adaptability [1, 6]. The process relies on an electric arc struck between a flux-coated consumable electrode and the metallic work piece. Under intense arc temperatures, the protective flux coating thermal-decomposes to generate a gaseous envelope CO_2 , CO , H_2 and a floating slag cover, which collectively shield the molten weld pool from atmospheric oxygen and ni-

trogen contamination [10-12, 15]. The microstructural evolution, bead geometry, and mechanical integrity of the joint are fundamentally governed by the net thermal heat input. Because SMAW relies on manual electrode manipulation, transient operating conditions significantly impact heat input stability. Excessive heat input increases thermal dissipation times, causing grain coarsening within the heat-affected zone (HAZ) and encouraging joint distortion. Conversely, insufficient heat input induces rapid thermal quenching, forming hard, brittle phase structures and incomplete sidewall fusion [12-14].

2.2. Weld Defect Genesis Mechanisms and Common Weld Discontinuities in SMAW

Shielded Metal Arc Welding (SMAW) is governed by complex thermo-mechanical dynamics where heat input, molten pool fluid flow, and solid-state phase transformations directly

dictate joint integrity [2, 3, 38]. Unlike continuous-wire processes such as Gas Metal Arc Welding (GMAW) or Submerged Arc Welding (SAW), SMAW relies on a flux-coated consumable electrode to generate both a shielding gas envelope and a protective slag layer [6, 15]. Consequently, joint soundness is exceptionally sensitive to transient operating conditions, electrode handling, and parameter settings [1, 14]. Defects in SMAW are broadly categorized into processing-oriented and metallurgical discontinuities, driven by coupled thermal, fluid, and mechanical phenomena [15, 19]. Industry benchmarks established by the American Society of Mechanical Engineers (ASME) indicate that process parameter misconfigurations account for roughly 45% of total weld defects, followed by operator error (32%), improper technique (12%), consumable degradation (10%), and joint preparation errors (5%) [27, 32]. Because discontinuities such as porosity and undercutting act as critical stress risers concentrations that severely degrade fatigue life and structural load capacity [25, 26], strict controlling heat input variables, specifically welding current, arc voltage, and travel speed, is essential mandatory for effective defect mitigation [16, 22]. The predominant defect mechanisms encountered during SMAW include:

Porosity: Formed by entrapment of evolved gases (N_2 , O_2 , or H_2) during solidifying pool dynamics. Key drivers include damp electrode coatings, surface oil or mill scale, excessive arc length, or severe shielding envelope turbulence [8, 16, 18].

Undercutting: A severe surface geometry defect appearing as an unfilled groove at the weld toe. It is primarily induced by excessive welding current, high arc voltage, or improper electrode work angles that erode the base metal without sufficient filler metal deposition [13, 17, 22].

Incomplete Fusion and Penetration: Occurs when thermal heat input is insufficient to melt the joint root or sidewalls, driven by low welding current, fast travel speeds, or improper joint preparation [12, 18, 21].

Cracking and Slag Inclusions: Driven by high localized thermal stresses, elevated carbon/sulfur contents, hydrogen embrittlement, or incomplete inter-pass slag removal [7, 23].

2.3. Metallurgical Characteristics and Weldability of Medium-Carbon Steel (AISI 4145)

Weldability is intrinsically linked to chemical composition, carbon equivalent, thermal conductivity and dissipation rates, and microstructural phase transformations under rapid thermal cycles [23, 24, 30, 32]. Medium-carbon low-alloy steels, such

as AISI 4145, balance high yield tensile strength, fatigue resistance, and toughness, making them ideal for heavy-duty applications including agricultural machinery, power transmission hubs, tractor yokes, suspension plates, and hydraulic tubing [3, 22]. However, the elevated carbon content and alloy additions (chromium and molybdenum) in AISI 4145 increase hardenability and susceptibility to cold cracking, heat-affected zone (HAZ) embrittlement, and porosity if cooling rates and heat inputs are not strictly controlled. Under rapid cooling rates, the HAZ is highly susceptible to brittle martensitic transformations and hydrogen-induced cold cracking (HICC) [8, 12, 30, 34]. Achieving defect-free welds in AISI 4145 requires controlled thermal management to prevent localized burn-through while guaranteeing complete sidewall fusion. Furthermore, using low-hydrogen basic electrodes (such as AWS E7018) combined with controlled cooling cycles is critical to suppressing micro-cracking and gas entrapment in medium-carbon joint geometries. Maintaining a balanced heat input via precise current-voltage-speed combinations is therefore essential to prevent rapid thermal quenching while ensuring complete sidewall fusion [7, 23, 34, 35].

2.4. Taguchi-Based Parameter Optimization Methods in SMAW

To move beyond empirical trial-and-error, Statistical Design of Experiments (DOE)—specifically Taguchi method orthogonal arrays has been widely applied to optimize process variables in arc welding [17]. Utilizing orthogonal arrays allows researchers to evaluate main effects and Signal-to-Noise (S/N) ratios while drastically minimizing experimental iterations [17, 18]. Previous empirical studies demonstrate the efficacy of Taguchi L9 arrays in suppressing characteristic SMAW flaws. For instance, optimizing current, voltage, travel speed, and electrode angle yielded parameter combinations (I, V, S) that reduced porosity and incomplete fusion [18, 19]. Similarly, Taguchi-based optimization on AISI C1020 mild steel achieved a peak ultimate tensile strength (UTS), travel speed, and a root gap [13, 16]. Evolutionary algorithms and central composite designs have also been deployed; research on mild and stainless-steel joints established that parametric sets current and travel speeds maximize deposition rates and tensile capacity [9, 20]. Across these studies, Analysis of Variance (ANOVA) consistently identifies welding current as the primary determinant of joint penetration depth and ultimate tensile strength, followed by arc voltage and travel speed [16, 17, 21, 37].

Table 1. Summary of Literature Review.

Author(s) & Ref.	Process & Material	Optimization Method	Key Input Parameters	Key Findings & Optimum Settings
Pradeep et al. [18]	SMAW (Mild Steel)	Taguchi L9	Current, Voltage, Speed, Electrode Angle	Reduced porosity by 63.19% and incomplete fusion by 73.72% at 90 A, 24 V, 40 cm/min, and 60 °.
Ramesh et al. [19]	SMAW (Mild Steel)	Taguchi L9	Current, Arc Length, Travel Speed, Angle	Achieved a 30.31% reduction in pinhole defects; identified current and speed as dominant factors.
Siddique et al. [16]	SMAW (AISI C1020)	Taguchi L9	Current, Speed, Root Gap, Angle	Peak tensile strength of 487 MPa (S/N = 53.74dB) achieved at 100 A, 3.6 mm/s, and 3.3 mm root gap.
Kumar et al. [9, 20]	SMAW (Stainless Steel)	Genetic Algorithm	Current, Travel Speed, Angle, Root Gap	Optimal deposition rate and strength obtained at 91.8 A current and 6.7 mm/s travel speed.
Verma et al. [13]	SMAW (Mild Steel)	Response Surface (CCD)	Current, Travel Speed, Angle, Gap	Max tensile strength of 394.5N/mm ² achieved at 101 A current and 7.0 mm/s speed.

3. Research Methodology and Materials

3.1. Research Methodology

This study combines quantitative and qualitative research approaches to triangulate findings. Experimental research comprising nine trials was conducted using an L9 Taguchi orthogonal array. Data on welding defects, parameters, and their interaction with weldability were gathered through direct observation of the welding process, examination of weld samples, and mechanical testing, ensuring accurate and useful information for process optimization. Primary data collection involved real-time observation of current, voltage, and speed; interviews with welders and engineers; and mechanical testing of welded samples. Secondary data collection involved review of quality-control reports, maintenance logs, historical defect records, industry standards, and relevant research publications. Methods included direct observation of the welding process, structured discussions with ABMI welders and engineers, and review of existing quality and maintenance records to supplement observational and interview data.

3.2. Materials Specifications and Preparation

Experimental tests were conducted on selected base metal AISI 4145 medium-carbon steel plates measuring 100 mm x 50 mm x 10 mm thick with a baseline tensile strength of 565 MPa, yield strength 310 MPa, elongation 16%, reduction area 40% hardness 120 HV for the parent material and were welded using AWS E7018 low-hydrogen electrodes 3.2mm and

4.0mm to eliminate moisture absorption and prevent hydrogen-induced cracking risk during Shielded Metal Arc Welding (SMAW). A spectrometer test confirmed its chemical composition is equivalent to standard carbon steel (Table 2). Prior to welding, plate edges were machined to form single-V groove geometry with a 60 °included angle, a 2 mm root spacing, and a 3–4 mm root face with edges cleaned of contaminants.

**Figure 2.** Experimental preparation.**Figure 3.** Specimen after welding.

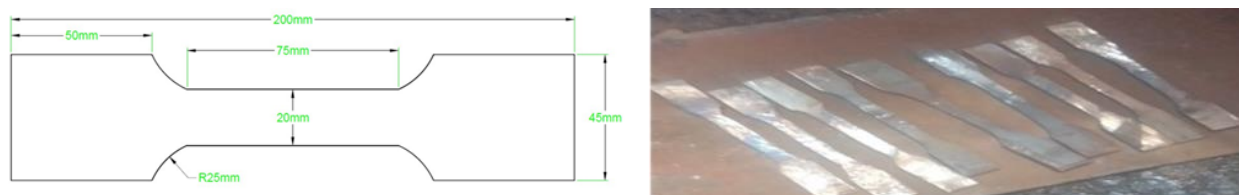


Figure 4. Tensile test specimens.

Table 2. Chemical Composition of the AISI 4145 test samples (wt. %).

Grade	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	W	Fe	CSN
AISI 4145	0.33	0.10	0.45	0.041	0.07	0.006	0.0030	0.028	0.033	0.04	98.8	12040

Welding operations (manual metal arc (MMA)) were performed using an industrial CEMONT YARD heavy-duty rectifier DC power source to ensure arc stability and controlled heat input across varying current, voltage, and travel speed settings as shown in table below.

Table 1. Specification of the CEMONT YARD welding machine SMAW Power Source.

Parameter	Specification
Input power	22.8 kVA – 13 kW
Maximum input current	57 A – 30 A
Input voltage	230 V (single) / 400 V (three-phase)
Effective input current	34 A – 19.5 A
Welding current range	50 A – 325 A
Connector size	13 mm

Workshop faces were mechanically wire-brushed and degreased to eliminate surface oxide, mill, rust, and residual contamination. Transverse tensile test specimens, Universal Testing Machine (UTM) in accordance with ASTM E8/E8M standards using a precision power hacksaw were used to evaluate post-weld quality and joint performance for uniaxial tensile testing and a Vickers hardness tester 136 °diamond pyramid indenter to measure microhardness distributions across

the weld metal, heat-affected zone (HAZ), and base metal, using a Vickers hardness tester (HV10) under a 10kg applied load establishing a data-driven framework to mitigate defects and optimize joint integrity in AISI 4145 fabrications. The experimental setup required a combination of base metals, consumables, welding power sources, testing machinery, and secondary tools/safety equipment, as summarized in Table 4.

Table 4. Experimental Materials, Equipment, and Tools.

Category	Item / Description
Machinery	• SMAW machine
	• Universal Testing Machine (UTM)
	• Vickers Hardness Tester/ Rockwell hardness tester

Category	Item / Description
	Tensile strength tester
Consumable Materials	• AISI 4145 Medium-Carbon Steel Plates (100 x 50 x 10 mm) • E7018 Electrodes (Ø 3.2 mm, Ø 4. mm) • Cutting & Grinding Discs
Tools & Equipment	• Tape Measure, Bench Vise, Chipping Hammer, C-Clamp • Wire Brush, screwdriver, file
Safety Equipment	Welding Goggles, Jacket, & Helmet, Hand gloves, Leather Apron

3.3. Experimental Design Approach

Process optimization was conducted using a Taguchi's Design of Experiments (DOE) L9 orthogonal array methodology [19] to evaluate the effects of three primary operating parameters—Welding Current (I), Arc Voltage (V), and Travel Speed (S) across each three levels based on shop-floor baseline parameters and electrode manufacturer specifications (Table 5). Signal-to-Noise (S/N) ratio analysis and Analysis of Variance (ANOVA) were performed in Minitab 19 software to identify parameter contributions to ultimate tensile

strength [21]. The relative impact of each control factor on tensile strength variation was quantified via Analysis of Variance (ANOVA) at a 95% confidence interval ($\alpha = 0.05$). The total sum of squares (SST), factor sum of squares (SSF), mean square (MS), F-ratio, and percentage contribution (%P) were evaluated.

$$N = L^{(P-1)}$$

Where N = number of experiments, P = number of parameters, L = number of levels.

Table 2. SMAW process control parameters and experimental levels (Taguchi L9 experimental matrix).

Factor	Parameter	Symbol	Unit	Level 1	Level 2	Level 3
A	Welding Current	I	A	90*3	120*3	140*3
B	Arc Voltage	V	V	30, 40, 70	30, 40, 70	30, 40, 70
C	Travel Speed	S	mm/min	80, 100, 120	80, 100, 120	80, 100, 120

3.4. Root-Cause Diagnosing and Parametric Optimization Procedures

The experimental procedure provides a structured approach to investigating root causes of weld defects in SMAW joints of AISI 4145 by systematically varying welding parameters, performing thorough inspections, and analyzing the resulting mechanical properties [33, 36]. A combined quantitative and qualitative framework was implemented to identify defect drivers (undercut, porosity, cracks, etc.) and evaluate joint

performance. Root Cause Analysis (RCA) was structured using Pareto distribution principles to isolate defect mechanisms under actual production conditions, primary shop-floor data—including operational parameters, direct visual inspections, operator interviews and welder technical evaluations—were triangulated with secondary quality-assurance records from Akaki Basic Metal Industry for over 80% of total plant rework. [25, 31, 33]. Defect occurrence data collected from historic production at ABMI were classified into discrete defect categories. Subsequently, Ishikawa (cause-and-effect) diagrams were constructed across six major vectors (*Man, Machine, Material, Method, Measurement, and Environment*) to trace root causes.

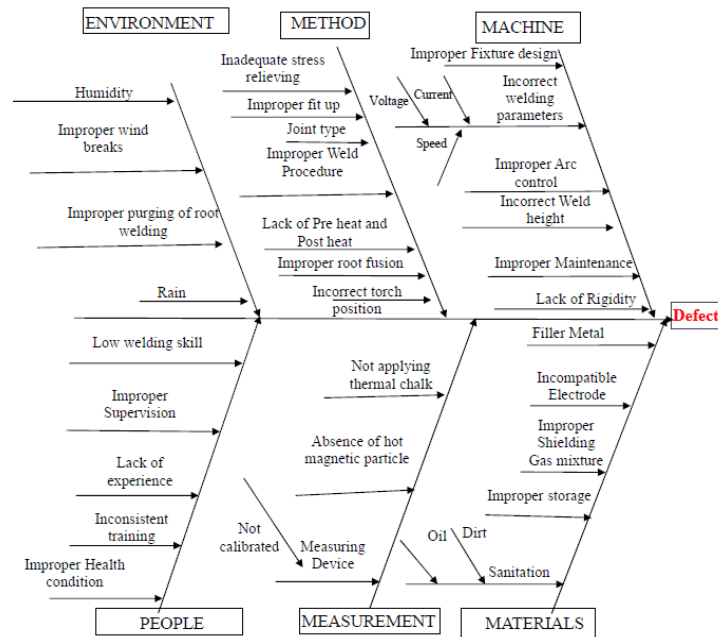


Figure 1. Root-Cause Diagnosing and Parametric Optimization Procedures.

4. Results, Analysis, and Discussion

4.1. Weld Defect Identification, Distribution and Pareto Analysis

This section presents the results of the cause-and-effect analysis investigation conducted on historical production from Akaki Basic Metal Industry (ABMI) to evaluate and establish quality-control priorities using the Pareto optimization principle (2023–2024). The analysis identified an overall weld rejection/rework rate of 6% across SMAW operations on medium-carbon steel (AISI 4145) components. Cumulative defect distribution was evaluated using the Pareto principle (80/20 rule) to prioritize mitigation efforts. Weld quality at ABMI is influenced by base-metal composition, welder skill and technique (electrode angle, speed, arc length), welding parameters (current, voltage, speed), joint design and preparation, environmental conditions (moisture, wind, temperature), and equipment condition, including correct use of shielding. ABMI products commonly exhibit SMAW defects such as overlap, undercut, porosity, distortion, slag inclusion, lack of fusion, incomplete penetration, incomplete fusion, and cracking, which can cause leaks, structural failures, and operational inefficiencies, increase costs and reduce customer satisfaction. Categorizing defects into materials, methods, machines, man, measurement, and environment allows systematic identification of root causes and corrective action.



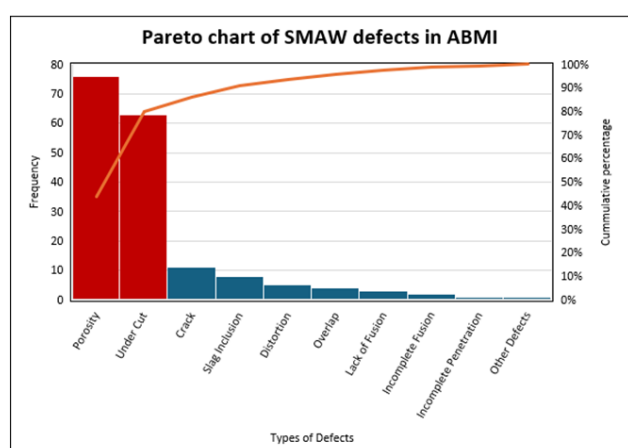
Figure 6. (left) Vickers hardness testing machine.



Figure 7. (right) Tensile testing machine.

Table 6. Frequency, Cumulative frequency and cumulative percentage of SMAW defects at ABMI.

Defect Type	Frequency	Cumulative frequency	Cumulative Contribution (%)	Category
Porosity	76	76	43.68	Vital Few
Undercut	63	139	79.89	Vital Few
Crack	11	150	86.21	Trivial
Slag inclusion	8	158	90.80	Trivial
Distortion	5	163	93.68	Trivial
Overlap	4	167	95.98	Trivial
Lack of fusion	3	170	97.70	Trivial
Incomplete fusion	2	172	98.85	Trivial
Incomplete penetration	1	173	99.43	Trivial Many
Other defects	1	174	100.00	Trivial

**Figure 8.** Pareto chart of SMAW defect frequency in ABMI.**Figure 9.** Various defect types observed at ABMI.

4.2. Root-Cause Diagnostic Analysis and Defect Prioritization & Ishikawa Findings

Porosity and undercut together account for a cumulative total of 79.89% of all recorded fabrication failures. Pareto analysis of historical production records (2023–2024) revealed

that porosity and undercutting constitute overall weld failures at ABMI. In accordance with Pareto's 80/20 rule, these two flaw types represent the "vital few" defects governing overall weld quality, establishing them as the primary focus for root-cause diagnostic analysis and experimental parameter optimization to yield significant improvements in weld quality. Structured technical interviews with welders and experts, shop-floor observations, and cause-and-effect analysis was conducted using Ishikawa (fishbone) diagrams to isolate the key operational drivers of porosity and undercut and systematically categorizing potential causes into six main groups: methods, machines, materials, measurement, environment, and man. Accordingly, the analysis identified the following key root causes of porosity and undercut such as incorrect welding parameters monitoring (current, voltage, speed); inadequate preheat/post-heat treatment; malfunctioning welding equipment, improper welding technique (electrode angle, travel speed, weld-pool control); inadequate shielding gas flow; lack of consistent quality checks; moisture in the electrode or base metal; a contaminated work area; insufficient welder skill or experience; and operator fatigue or negligence (see below diagram). Together, these factors confirm that porosity and undercut at ABMI stem primarily from improper welding parameters, equipment issues, material contamination, and environmental conditions – with current, voltage, and speed emerging as the most critical, directly affecting arc stability, weld pool behavior, and gas shielding. These diagnostic findings confirmed that welding current, arc voltage, and travel speed serve as the critical control variables governing defect formation.

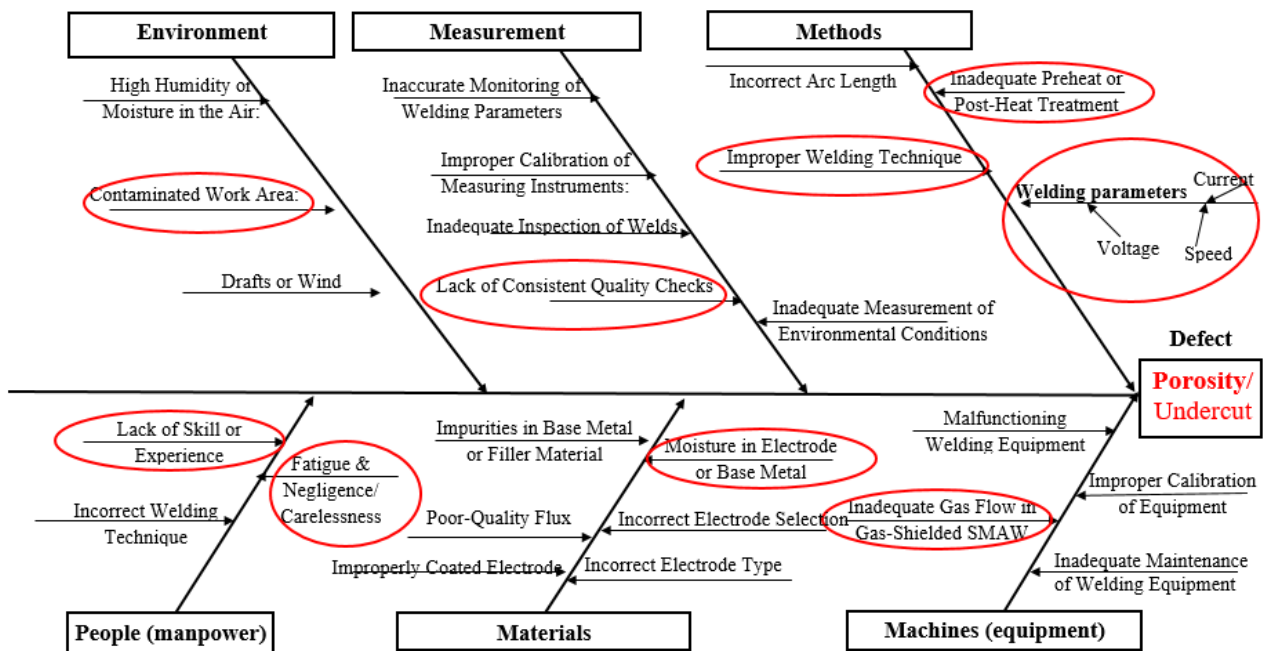


Figure 10. Root Causes-Effects diagram of SMAW Porosity and Undercut.

4.2.1. Porosity Formation Mechanisms (Causes)

Porosity in AISI 4145 SMAW welding is primarily from atmospheric gas entrapment within the solidifying weld pool:

Method: Unstable / Incorrect manual electrode manipulation (excessive/ long arc length, erratic weave speed/ movement) and uncalibrated heat input parameters (I, V, S) disrupt molten pool shield stability, trapping evolving gas bubbles during solidification, wrong electrode type, or improperly set current/voltage/speed causing insufficient heat input and gas entrapment.

Man: Inexperienced, tired, or insufficiently trained welders failing to maintain correct arc length, speed, or electrode angle.

Material & Environment: Surface contaminants (rust, oil, mill scale or paint) on base plates surface, moisture absorption in AWS E7018 basic electrode flux coatings, moisture-absorbed electrodes and high ambient humidity, or shop drafts, or airborne contaminants disrupting the protective gas envelope/ coverage or unsuitable filler material causing gas entrapment.

Machine & Measurement: Power supply output fluctuations and uncalibrated display meters yield transient arc instabilities. Malfunctioning welding machines, damaged electrode holders/cables, or power supply fluctuations causing unstable arc and shielding, Incorrect calibration or inconsistent monitoring of current and voltage leading to deviations from optimal settings.

4.2.2. Mechanisms (Causes) of Undercut Formation

Undercutting which manifest as continuous or intermittent

grooves along the weld toe is fundamentally driven by improper thermal management and base-metal erosion:

Parameters & Method: Excessive /low welding current (deep penetration, edge melting, poor fusion) which causes aggressive base-metal toe melting, high/low arc voltage (broad, fluid pool, poor fusion) which produces an overly fluid weld pool that sags under gravity, Excessive /slow travel speed (quick solidification, heat sagging) that restricts filler metal deposition, leaving unfilled toe grooves and unsuitable electrode characteristics.

Material Susceptibility: The elevated alloy elements content of AISI 4145 (Cr, Mo, C) increases fluid flow sensitivity if not welded correctly, rendering toe boundaries vulnerable to severe undercutting under uncalibrated thermal inputs, low-quality electrodes; surface contamination.

Machine & Operator Control (Man): Equipment degradation (Worn machines, damaged holders/cables, unstable rectifiers or power supply) combined with welder fatigue directly accelerates edge erosion and causing inconsistent current/voltage delivery. Inexperienced or fatigued welders struggling to control arc/electrode angle consistently.

Environment and Measurement: Incorrect calibration or inaccurate monitoring of parameters, cold environments causing rapid cooling; wind/drafts disturbing shielding; high humidity causing hydrogen-induced cracking.

This diagnostic triangulation confirms that welding current, arc voltage, and travel speed are the primary controllable root-cause variables governing arc stability, pool fluid dynamics, and joint soundliness at ABMI and set the stage for optimizing via the Taguchi experimental design with the goal of improving tensile strength and hardness while minimizing the heat-affected zone (HAZ).

4.3. Parametric Optimization Using Taguchi Methods and Experimental Results

The Taguchi method optimizes quality characteristics using an orthogonal array to minimize the number of experimental

runs. In this study, an L9 array was used to vary current, voltage, and speed across three levels to identify settings that enhance ultimate tensile strength (UTS), hardness, and minimize HAZ.

4.3.1. Experimental Results of Tensile Strength, Hardness and Heat-Affected Zone (HAZ)

Table 7. Taguchi L9 experimental layout, measured UTS data, and calculated S/N ratios.

Trial Run	Current I (A)	Voltage V (V)	Travel Speed S (mm/min)	Tensile strength /UTS (MPa)	S/N ratio
1	90	30	80	520	54.32007
2	90	40	100	522	54.35341
3	90	70	120	444	52.94766
4	120	30	100	447	53.00615
5	120	40	120	386	51.73175
6	120	70	80	392	51.86572
7	140	30	120	583	55.31337
8	140	40	80	589	55.40231
9	140	70	100	479	53.60671

Table 8. Taguchi L9 experimental runs, data, measured hardness, and calculated S/N ratios.

Trial Run	Current (A)	Voltage (V)	Speed (mm/min)	Hardness	S/N	Rank
1	90	30	80	93.1	19.8878	3
2	90	40	100	96.8	15.0441	4
3	90	70	120	96.90	12.5486	8
4	120	30	80	89.7	21.0377	7
5	120	30	100	97.3	9.0291	6
6	120	40	100	101.5	3.0099	9
7	140	30	80	88.2	22.0502	5
8	140	40	100	93.60	18.5555	2
9	140	70	120	94.64	16.9776	1

Table 9. Taguchi L9 experimental runs, HAZ readings, and calculated S/N ratios.

Trial Run	Current (A)	Voltage (V)	Speed (mm/s)	HAZ	S/N ratio
1	90	30	80	90.5	39.1330
2	90	40	100	95.6	39.6092
3	90	70	120	100.0	40.0000

Trial Run	Current (A)	Voltage (V)	Speed (mm/s)	HAZ	S/N ratio
4	120	30	100	93.5	39.4162
5	120	40	120	99.5	39.9565
6	120	70	80	97.09	39.7435
7	140	30	120	90.7	39.1521
8	140	40	80	88.1	38.8995
9	140	70	100	94.3	39.4902

4.3.2. Analysis of Tensile Strength, Hardness and Heat-Affected Zone (HAZ) Testing Results

Tensile strength results for each parameter combination were analyzed and hardness of welds at ABMI was evaluated using Vickers and Rockwell methods from recorded results across each experimental run while HAZ hardness was recorded after testing each sample, and their S/N ratios were computed using Minitab 19 software (smaller-is-better criterion). Because heat input at the weld zone exceeds that of the HAZ during welding, the hardness of the HAZ is generally greater than that of the weld zone when optimal parameters are not applied; the fusion zone reflects weld defects, whereas the HAZ reflects only metallurgical change. The HAZ is the portion of base metal that undergoes microstructural and mechanical property changes due to welding heat, with temperature decreasing with distance from the weld pool, causing varying degrees of metallurgical transformation.

Experimental trial runs across the Taguchi L9 array specimens yielded ultimate tensile strength (UTS) values ranging from 386 MPa to 589 MPa, alongside corresponding Vickers microhardness values distributions across the weld zone ranging from 88.2 to 101.5 HV10. Response data were converted into logarithmic Signal-to-Noise (S/N) ratios using the "larger-is-better" quality characteristic formulation to maximize joint performance and minimize process variance. The mean S/N response analysis isolates the main effects of each parameter across the three defined levels. Higher mean S/N ratios values correspond directly to minimized process variance and maximized tensile strength. Welding current demonstrated the strongest influence on tensile strength, exhibiting a continuous monotonical increase in tensile strength performance from Level 1 (90A) to Level 3 (140A) due to higher/improved current ensures full root fusion /penetration in AISI 4145. Arc voltage ranked second peaking (40V) while higher/Excessive voltage (70V) induced/ causes arc turbulence and

severe undercutting, while insufficient voltage (30V) results in incomplete sidewall fusion. Travel speed exhibited a minor overall influence with optimal bead profile morphology reaching/ achieving (120mm/min). Consequently, the optimal parameter combination was determined /identified as A3B2C3 (140A Welding Current, 40V Arc Voltage, 120 mm/min travel speed).

(i). Effect of Input Parameters on Tensile Strength, Hardness and HAZ

Welding current affects heat input and weld-pool size; higher currents typically improve fusion and tensile strength, but excessive current can cause overheating, porosity, or cracking. Welding voltage controls arc length and heat intensity; higher voltage increases penetration but can cause spatter, HAZ widening, or distortion if excessive. Welding speed affects heat input and cooling rate; slower speeds increase heat input and can improve fusion and tensile strength. The S/N ratio and mean were greatest at a welding voltage of 70 V, current of 120 A, and speed of 80 mm/s, indicating these as proper/optimum welding variables for maximum tensile strength.

The highest hardness (94.64) was recorded at 140 A, 70 V, and 120 mm/s. Medium current supports a stable weld pool and balanced microstructure; higher current increases the overall weld pool size; higher voltage supports consistent penetration and uniform hardness; and medium travel speed provides a balanced cooling rate favoring a fine-grained, higher-hardness microstructure. Higher welding current increases heat input, potentially enlarging the HAZ and causing microstructural coarsening. Higher voltage increases heat intensity and can enlarge the HAZ; excessive voltage can cause overheating and HAZ softening. Slower travel speed increases heat input and cooling time, extending the HAZ; excessively slow speeds can cause grain growth and softening.

Table 10. Response table for S/N ratios (larger is better) – tensile strength.

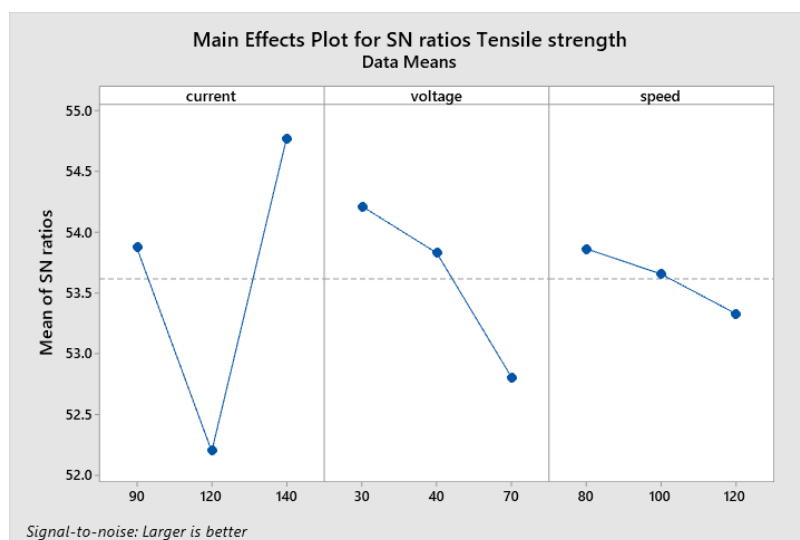
Level	Welding current	Welding voltage	Welding speed
1	53.87	54.21	53.86
2	52.20	53.83	53.66
3	54.77	52.81	53.33
Delta	2.57	1.41	0.53
Rank	1	2	3

Table 11. Response table for S/N ratio (medium is better) – hardness.

Level	Welding current	Welding voltage	Welding speed
1	95.37	91.57	92.03
2	96.83	94.40	94.47
3	91.03	97.27	96.73
Delta	5.80	5.70	4.70
Rank	1	2	3

Table 12. Response table for S/N ratios (medium is better) – HAZ.

Level	Current	Voltage	Speed
1	95.60	90.33	96.07
2	92.83	92.57	93.71
3	92.15	97.68	90.80
Delta	3.45	7.35	5.27
Rank	1	3	2

**Figure 11.** Main effects plot for S/N of tensile strength.

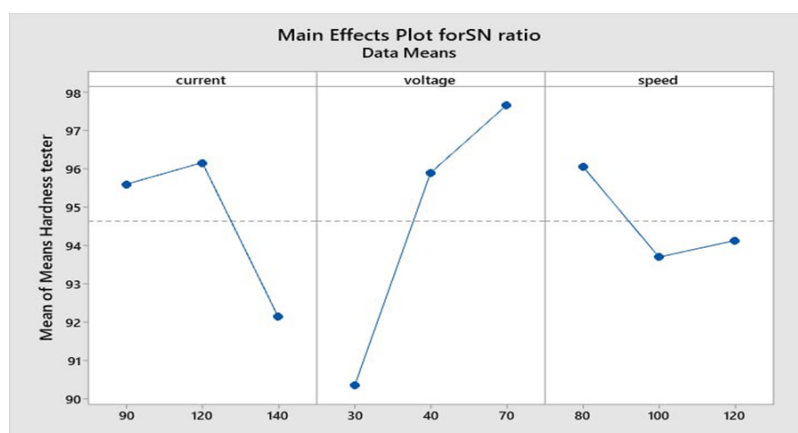


Figure 12. Main effects plot for S/N of hardness.

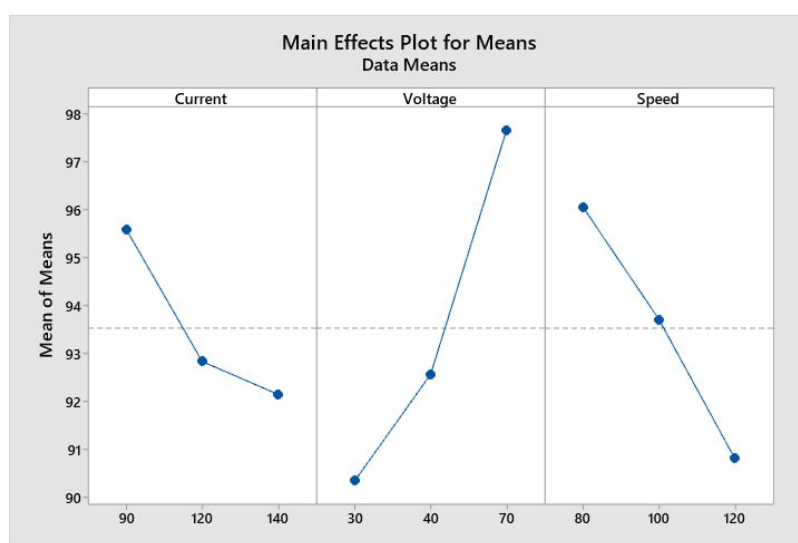


Figure 13. Main effects plot for S/N of HAZ.

(ii). Analysis of Variance (ANOVA) for Tensile Testing, Hardness and HAZ

ANOVA was performed at a 95% confidence level ($\alpha = 0.05$); sources with $p < 0.05$ are considered statistically significant contributors to tensile strength, Hardness and HAZ (table). With $F_{cr}(0.05, 2, 8) = 4.46$, all three parameters proved statistically significant ($p < 0.05$). By percentage contribution to tensile strength, welding current is the dominant factor (72.18%), followed by voltage (19.73%) and speed (3.88%), with total error of 4.21% (0.816% relative to total variation) and while to the hardness contribution of current is dominant (39.82%), followed by voltage (33.46%) and speed (25.91%) with total error relative to total variation was 0.816% (table).

Current and voltage have p -values below 0.05, confirming significant influence on HAZ hardness; welding speed is comparatively less significant. By percentage contribution, current (42.23%) ranks first, followed by voltage (36.68%) and speed (16.80%), with total error of 0.816% (table). Analysis of Variance, ANOVA was executed at a 95% confidence level ($\alpha = 0.05$) to evaluate and quantify statistical significance and percentage contributions (%P) of each process parameter toward ultimate tensile strength. Analysis of Variance, ANOVA at a 95% confidence interval ($\alpha = 0.05$) results confirms that welding current is the statistically significant parameter, contributing to total strength variance in tensile strength. Arc voltage and travel speed contribute 6.06% and 1.88%, respectively, with residual error remaining below 1% validating the experimental accuracy of the model.

Table 13. ANOVA for tensile strength.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Current	2	53.962	72.18%	53.962	26.9809	17.16	0.008
Voltage	2	45.334	19.73%	45.334	22.6672	4.69	0.008
Speed	2	35.104	3.88%	35.104	17.5522	0.92	0.011
Error	2	1.106	4.21%	1.106	0.5532		
Total	8	135.507	100.00%				

Table 14. ANOVA for hardness.

Source	DOF	SS	Contribution	SS	MS	F-value	P-value	Remark
Current	2	53.962	20.76%	53.962	26.9809	48.77	0.020	Significant
Voltage	2	45.334	67.99%	45.334	22.6672	40.97	0.024	Significant
Speed	2	35.104	6.77%	35.104	17.5522	31.73	0.031	Significant
Error	2	1.106	4.48%	1.106	0.5532			
Total	8	135.507	100.0%					

Table 15. ANOVA for HAZ.

Source	DOF	SS	Contribution	SS	MS	F-value	P-value
Current	2	53.962	42.23%	53.962	26.9809	48.77	0.008
Voltage	2	45.334	36.68%	45.334	22.6672	40.97	0.008
Speed	2	35.104	16.80%	35.104	17.5522	31.73	0.011
Error	2	1.106	4.30%	1.106	0.5532		
Total	8	135.507	100.00%				

Table 16. Experimental validation of optimal parameters.

Response	Predicted	Experimental	Error %
UTS (MPa)	525 MPa	589 MPa	0.089%
Average hardness (HV)	120 HV	94.63 HV	2.19%

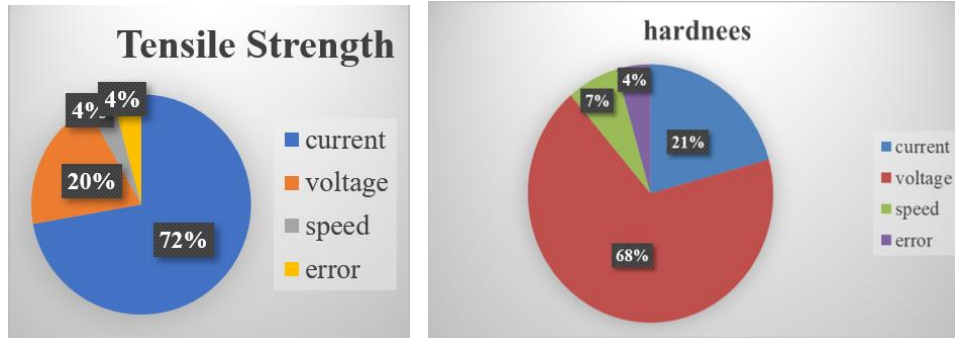


Figure 14. tensile strength and Hardness Pie chart.

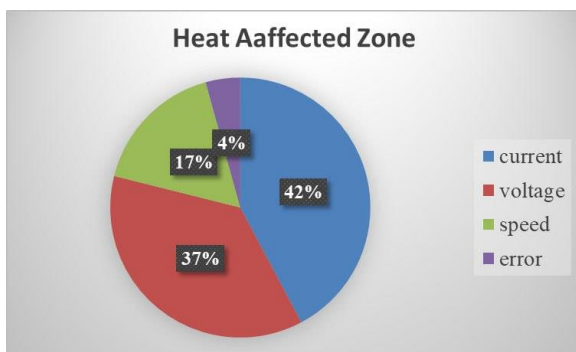


Figure 15. welding parameter contribution to HAZ Pie chart.

5. Conclusions, Recommendations, and Future Research Work

5.1. Conclusions

This thesis systematically investigated the root causes of defects in SMAW of AISI 4145 steel at ABMI and optimized welding parameters to enhance mechanical properties. Using Pareto analysis, Ishikawa diagrams, and Taguchi experimental design, the study identified porosity and undercut as the “vital few” defects most affecting weld quality, arising primarily from incorrect welding parameters, inadequate preheat/post-heat treatment, improper technique, and inconsistent quality checks. Using Taguchi's L9 orthogonal array, the optimal settings identified were 40 V, 140 A, and 80 mm/s. ANOVA confirmed welding current as the most significant factor for tensile strength (72.18% contribution), followed by voltage (19.73%) and speed (3.88%). Applying these optimized parameters reduced ABMI's defect rate from 6% to 2.7%, demonstrating the practical value of the methodology for improving weld quality, production efficiency, and cost-effectiveness in medium carbon steel welding.

5.2. Recommendation

Expand the scope of defect analysis to include distortion, overlap, slag inclusion, and incomplete fusion for a more holistic quality improvement approach.

Explore additional parameters such as electrode type, joint configuration, and environmental conditions (humidity, temperature).

Investigate other welding techniques (e.g., GMAW, TIG) alongside SMAW for comparison.

Implement continuous, real-time monitoring of welding parameters to reduce human error and improve stability.

Provide regular training and certification programs for welders.

Conduct long-term performance testing (fatigue, corrosion resistance, durability) of welded products.

Investigate preheat and post-heat treatments further, particularly for complex joints.

Adopt digital welding-simulation tools to reduce physical trial costs.

Implement environmental control measures (humidity, air drafts) to improve process consistency.

5.3. Future Research Work

This research opens avenues for further work on SMAW of medium carbon steel across additional joint types – flat butt, corner, and T-fillet joints – and welding positions. Suggested directions include:

Extended parameter optimization: exploring pulse-current variation, alternate electrode compositions, and electrode diameters for further mechanical-property gains.

Process modeling and simulation: using computational tools to predict mechanical properties and reduce reliance on extensive physical trials.

Comparative studies of other welding techniques (GMAW, TIG) for medium carbon steel butt joints to determine suitability for specific applications.

Implementing these recommendations at ABMI can further enhance the quality and reliability of its SMAW processes, reduce defect incidence, and improve overall productivity and customer satisfaction.

Abbreviations

SMAW	Shielded Metal Arc Welding
AISI	American Iron and Steel Institute
ABMI	Akaki Basic Metal Industry
METEC	Metals and Engineering Corporation
mm	Millimeter
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
SAW	Submerged Arc Welding
HAZ	Heat-Affected Zone
PWHT	Post-Weld Heat Treatment
DOE	Design of Experiment
ASME	American Society of Mechanical Engineers
mm/s ²	Millimeters per Second Squared
N/mm ²	Newtons per Square Millimeter
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
S/N	Signal-to-Noise (ratio)
HRB	Rockwell Hardness B (Scale)
OA	Orthogonal Array
HV	Vickers Hardness Number
UTMs	Universal Testing Machines
3D	three-dimensional
MMAW	Manual Metal Arc Welding
RCA	Root Cause Analysis

Author Contributions

Deleegn Gizaw Toga: Conceptualization, Methodology, Visualization, Writing – original draft

Seyidu Wohabrebi: Conceptualization, Data curation, Investigation, Project administration, Supervision, Validation, Visualization

Misganu Kabeta: Formal Analysis, Methodology, Software, Visualization, Writing – review & editing

Samuel Alemu: Data curation, Formal Analysis, Investigation, Supervision, Validation, Visualization, Writing – original draft

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] '24, ROOT CAUSE ANALYSIS OF MANUAL METAL ARC WELDING (3) EDITED ppt.'
- [2] L. Resource, *BASIC MANUAL METAL ARC WELDING (MMAW) Learning Resource Metals and Engineering ENG722*. 2016. [Online]. Available: www.dtwd.wa.gov.au
- [3] D. Ary, N. Muhayat, Triyono. Research Gap Finding in Shielded Metal Arc Welding of Steel. E3S Web of Conferences. 2023, 465, 1–7. <https://doi.org/10.1051/e3sconf/202346501012>
- [4] S. H. Crusher, D. C. Birawidha, M. Amin. Analysis of Shielded Metal Arc Welding (SMAW) on High Manganese. [Journal not stated in source]. 2019, 16(2), 93–107.
- [5] C. L. Jenney and A. O'Brien, 'Welding Handbook_Volume 1_WELDING SCIENCE AND TECHNOLOGY,' *Am. Weld. Soc.*; vol. 1, p. 982, 1991.
- [6] D. Hadzihafizovic, 'Welding Defects, Causes & Remedy,' no. January, 2023, <https://doi.org/10.13140/RG.2.2.24115.91689>
- [7] 'Welding defects 16/06/2015 1,' 2015.
- [8] B. O. Fekadu, 'Investigation of Microstructure and Mechanical Properties of Heat Affected Zone in Manual Arc Welded Mild Steel A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering,' 2018.
- [9] L. Maglić, D. Marić, T. Šolić, I. Samardžić. Optimization of Synchropulsed MIG Welding Process Parameters for Welding of AW 5083 Sheets. Materials. 2022, 15(9), Article 3078. <https://doi.org/10.3390/ma15093078>
- [10] S. F. Haider, M. M. Quazi, J. Bhatti, M. Nasir Bashir, I. Ali. Effect of Shielded Metal Arc Welding (SMAW) Parameters on Mechanical Properties of Low-Carbon, Mild and Stainless-Steel Welded Joints: A Review. Journal of Advanced Technology and Engineering Research. 2019, 5(5), 1–9. <https://doi.org/10.20474/jater-5.5.1>
- [11] P. V. I. I. Joining, A. Processes, and F. O. F. Welding, 'Fall 2004 PART VII JOINING & ASSEMBLY PROCESSES Two Types of Welding 2. The Weld Joint 3. Physics of Welding Kwon Fall 2004 Physics of Welding II Approximate Power Densities and Efficiency 4 . Features of Fusion Welded Joint 1. Arc Welding (AW) AW wi,' pp. 1–7, 2004.
- [12] P. K. Baghel. Effect of SMAW Process Parameters on Similar and Dissimilar Metal Welds: An Overview. Heliyon. 2022, 8(12), e12161. <https://doi.org/10.1016/j.heliyon.2022.e12161>
- [13] A. O. Osayi, E. A. P. Egbe, S. A. Lawal. Optimization of Process Parameters of Manual Arc Welding of Mild Steel Using Taguchi Method. American Journal of Mechanical Engineering. 2015, 3(3), 93–97. <https://doi.org/10.12691/ajme-3-3-4>
- [14] P. G. Ahire, U. S. Patil, M. S. Kadam. Genetic Algorithm Based Optimization of the Process Parameters for Manual Metal Arc Welding of Dissimilar Metal Joint. Procedia Manufacturing. 2018, 20, 106–112. <https://doi.org/10.1016/j.promfg.2018.02.015>
- [15] A. Bhatia, 'of Arc Welding Fundamentals Overview,' vol. 272, p. 76, 2012, [Online]. Available: <https://pdhonline.com/courses/g272/g272content.pdf>
- [16] U. S. Patil, M. S. Kadam. Multiobjective Optimization of MMAW Process Parameters for Joining Stainless Steel 304 with Mild Steel by Using Response Surface Methodology. Materials Today: Proceedings. 2019, 305–310. <https://doi.org/10.1016/j.matpr.2019.11.277>

- [17] A. A. Sheikh, P. D. Kamble. Optimization of Welding Process Parameter to Minimize Defect in Welding of Sheet. *International Research Journal of Engineering and Technology*. 2008, 9001(56), 4310.
- [18] F. Yusof, M. F. Jamaluddin, K. Lumpur. Welding Defects and Implications on Welded Assemblies. [Journal not stated in source]. 2014, 6, 125–134.
- [19] H. Li, S. Liu, Q. Ma, P. Wang, D. Liu, Q. Zhu. Investigation of Process Stability and Weld Quality of Underwater Wet Flux-Cored Arc Welding of Low-Alloy High-Strength Steel with Oxy-Rutile Wire. *Polish Maritime Research*. 2021, 28(3), 100–109. <https://doi.org/10.2478/pomr-2021-0037>
- [20] M. K. Prasad Reddy, R. Prashanth Naik, M. Samatham, C. Harish Kumar. Review on Different Welding Techniques of Titanium and its Alloys. [Journal not stated in source]. 2020, 286–294. <https://doi.org/10.32628/ijrsrset207150>
- [21] A. F. Hobbacher. The New IIW Recommendations for Fatigue Assessment of Welded Joints and Components: A Comprehensive Code Recently Updated. *International Journal of Fatigue*. 2009, 31(1), 50–58. <https://doi.org/10.1016/j.ijfatigue.2008.04.002>
- [22] M. Afzal, A. Wakeel, M. D. Nasir. Optimization of Process Parameters for Shielded Metal Arc Welding for ASTM A572 Grade 50. *Journal of Engineering Research*. 2024. <https://doi.org/10.1016/j.jer.2024.01.005>
- [23] P. Sathiya, S. Aravindan, P. M. Ajith, B. Arivazhagan, A. N. Haq. Microstructural Characteristics on Bead on Plate Welding of AISI 904L Super Austenitic Stainless Steel Using Gas Metal Arc Welding Process. [Journal not stated in source]. 2010, 2(6), 189–199.
- [24] S. A. Rizvi, W. Alib. Welding Defects, Causes and their Remedies: A Review. *Teknomekanik*. 2019, 2(2), 39–47. <https://doi.org/10.24036/tm.v2i2.3272>
- [25] M. Singh, L. K. Bhagi, H. Arora. Effects of Shielded Metal Arc Welding Process Parameters on Dilution in Hardfacing of Mild Steel Using Factorial Design. *Lecture Notes in Mechanical Engineering*. 2020, 207–220. https://doi.org/10.1007/978-981-15-4748-5_21
- [26] G. Campus, J. Post, K. State. Optimization of Shielded Metal Arc Welding Parameters for Welding of Pipes by Using Taguchi Approach. *International Journal of Engineering Science and Technology*. 2012, 4(5), 2083–2088.
- [27] A. V. Dagmar, Z. J. Husada Tarigan. The Application of the Six Sigma Method in Reducing the Defects of Welding on the Steel Material. *IOP Conference Series: Materials Science and Engineering*. 2021, 1010(1), Article 012044. <https://doi.org/10.1088/1757-899X/1010/1/012044>
- [28] S. Singh. Analysis of Various Defects Involved in Welding Metallurgy. [Journal not stated in source]. 2018, 120(6), 6267–6280.
- [29] K. B. S, S. Vinodh, S. Devarapu, G. Siddhamshetty. Application of Lean Approach for Reducing Weld Defects in a Valve Component: A Case Study. *International Journal of Lean Six Sigma*. 2017, 8(2). <https://doi.org/10.1108/ijlss-01-2016-0001>
- [30] S. Das Lala, D. Saha, E. Barua, P. Deb. Investigating the Geometry of the Weld Bead Formed by Both Metal Inert Gas (MIG) Welding and Submerged Arc Welding (SAW). *Academic Journal of Manufacturing Engineering*. 2022, 20(3), 55–60.
- [31] ESAB University, 'Handbook on Welding Techniques,' *ESAB Weld. Cut. Prod.*, pp. 1–70, 2020.
- [32] S. Development, 'COMPUTERIZED VICKERS HARDNESS TESTING MACHINE VM-50,' 1968.
- [33] M. R. Noorshan, K. Rashid, C. M. Rumaisa, P. K. Sanmishal. Defect Reduction in an Arc Welding Process Using Cause and Effect Diagram. *International Journal of Engineering Innovation & Technology*. 2016, 5(11), 28–34. <https://doi.org/10.17605/OSF.IO/EU69N>
- [34] A. Haftimer, 'ASSESSMENT OF SHIELDED METAL ARC WELDING DEFECTS IN FIVE SELECTED SMALL AND MEDIUM SCALE ENTERPRISE IN THE CASE OF ADDIS ABABA CITY,' 2021.
- [35] K.-H. Grote and H. Hefazi, *Springer Handbook of Mechanical Engineering (2nd ed.)*. 2021. [Online]. Available: <https://doi.org/10.1007/978-3-030-47035-7>
- [36] S. Deepali. Effect of Welding Speed on Depth of Penetration, Hardness of HAZ. *International Journal of Engineering Science and Research Technology*. 2016. <https://doi.org/10.5281/zenodo.49759>
- [37] A. Dadi, P. Bhupesh Goyal, M. H. Patel. A Review Paper on Optimization of Shielded Metal Arc Welding Parameters for Welding of (MS) SA-516 Gr.70 Plate by Using Taguchi Approach. *International Journal of Scientific Research in Science and Technology*. 2018, 4(5), 1536–1543.
- [38] S. Elfallah. Effect of GTAW on the Tensile Strength and Hardness of Mild Steel. *Annals of "Dunărea de Jos" University of Galați, Fascicle XII, Welding Equipment and Technology*. 2022, 33(9), 95–100. <https://doi.org/10.35219/awet.2022.08>