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Article

Enhancing Metal Active Gas Welding Parameters through Taguchi-Six Sigma Framework for Improved Quality and Performance

Nadia Hamzawy*, **Attia Hussien Gomaa**

Department of Mechanical Engineering, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt

*Corresponding author: Nadia Hamzawy, nadia.mohamed@feng.bu.edu.eg

Abstract

Optimizing Metal active gas (MAG) welding parameters is vital for enhancing weld quality, mechanical performance, and overall manufacturing efficiency. This study introduces an integrated optimization framework that combines Taguchi's design of experiments (DOE) with the statistical rigor of six sigma to identify optimal welding conditions while minimizing process variability. The framework was applied to Steel 37, a widely used structural material, focusing on key process variables: wire diameter, feed rate, welding voltage, and gas flow rate. These parameters and their interactions were systematically analyzed for their influence on critical mechanical properties, including ultimate tensile strength (UTS), weld hardness, and impact resistance. To support optimization, a regression-based predictive model was developed to provide data-driven insights for selecting optimal process settings. The proposed model serves as a practical industrial tool to reduce variability, enhance weld integrity, and improve productivity in real-world manufacturing environments. The findings demonstrate the potential of integrating Taguchi's robust design and six sigma methodologies to develop high-performance, cost-effective, and sustainable welding processes. By leveraging structured experimentation, statistical modeling, and systematic analysis, this framework offers a deeper understanding of parameter interrelationships and supports the advancement of reliable and efficient manufacturing operations.

Keywords

Process optimization, Taguchi-based six sigma, Mechanical properties, Ultimate tensile strength, Impact resistance

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1. Introduction

Metal active gas (MAG) welding, also known as gas metal arc welding (GMAW), is one of the most widely utilized processes in modern manufacturing, particularly in industries where strong, durable joints are essential. Its advantages-speed, versatility, and automation capability–make it indispensable across sectors such as automotive, aerospace, construction, and shipbuilding. MAG welding is particularly favored for its ability to join a broad range of materials, including steel, aluminum, and stainless steel, making it a go-to method in structural applications where joint strength and durability are paramount [1-3]. As the demand for high-quality welded structures grows, optimizing MAG welding parameters becomes crucial for ensuring superior mechanical properties, such as ultimate tensile strength (UTS), weld hardness, and impact resistance [4,5].

The key to achieving optimal weld quality lies in the precise control of various welding parameters, including wire diameter, feed rate, welding speed, voltage, and shielding gas flow rate. These factors are critical in determining the weld's mechanical properties and overall performance [6,7]. Even small variations in parameter settings can result in defects such as porosity, excessive heat input, or cracks, all of which compromise the structural integrity of the welded joint. Thus, a systematic approach to parameter optimization is essential for enhancing weld quality, minimizing variability, and ensuring the reliability of the welded structure [8,9].

To address these challenges, this study adopts an integrated framework combining Taguchi's design of experiments (DOE) methodology and six sigma principles–referred to as the taguchi-based six sigma (TSS) approach. Taguchi's robust design methods, which focus on minimizing variability through structured experimentation, are paired with six sigma's data-driven process improvement techniques. This powerful combination allows for a comprehensive optimization strategy that not only enhances the quality of the weld but also improves the efficiency and consistency of the overall welding process [10-13].

This research applies the TSS methodology to optimize MAG welding parameters for Steel 37, a widely used material known for its excellent balance of strength and durability. MAG welding is well-suited for Steel 37, yet achieving optimal mechanical properties requires precise parameter control. By systematically evaluating the influence of factors such as wire diameter, feed rate, voltage, and shielding gas flow rate, this study identifies the optimal welding conditions for producing high-quality, defect-free welds. Additionally, a regression-based predictive model is developed, offering a practical tool for industry professionals to determine the best welding parameters for specific applications, thereby enhancing production efficiency and weld quality [1,3,4].

In addition to optimizing MAG welding for Steel 37, the findings of this study underscore the broader applicability of the TSS methodology for welding process optimization across various materials and industries. This research contributes to advancing the field of welding technology by demonstrating the effectiveness of a data-driven, systematic approach to process improvement, and providing valuable insights that can be used by both researchers and industry practitioners to refine welding practices.

2. Literature Review

The TSS approach integrates six sigma's systematic defect reduction methodology with the Taguchi method's robust experimental design to optimize process performance, minimize variability, and enhance product quality. While six sigma employs structured problem-solving techniques, such as DMAIC (Define, Measure, Analyze, Improve, Control), to improve process capability and reduce defects [14-18], Taguchi's DOE focuses on optimizing control factors and minimizing the effects of noise variables to achieve consistent and reliable outcomes [19-20]. By combining these methodologies, TSS enables organizations to identify critical process parameters, enhance resource efficiency, and improve operational reliability. This integrated framework not only reduces defects and waste but also supports continuous improvement, data-driven decision-making, and cost-effective manufacturing. By leveraging statistical rigor and process optimization principles, TSS ensures that manufacturing systems consistently deliver high-quality products, meet industry standards, and fulfill customer expectations, ultimately driving sustainable competitive advantage and long-term process excellence [21-23].

2.1 Review of TSS

The integration of lean six sigma (LSS) and the Taguchi method has emerged as a powerful strategy for optimizing process performance and enhancing product quality across diverse industries [24,25]. The Taguchi method, with its emphasis on minimizing variation and improving reliability, complements LSS's structured problem-solving approach, enabling organizations to systematically identify and control key process parameters, reduce defects, and improve operational efficiency [26-29]. By leveraging Taguchi's DOE within the six sigma framework, companies can achieve data-driven decision-making, robust process optimization, and sustainable quality improvements.

As highlighted in Table 1, numerous studies demonstrate the effectiveness of integrating LSS with the Taguchi method. For instance, Gomaa [22] proposed an LSS framework for spare parts manufacturing, utilizing tools such as process mapping, SIPOC, KPI analysis, OEE, sigma levels, DOE, analysis of variance (ANOVA), value stream mapping, and cause-effect diagrams to systematically enhance process efficiency. Similarly, Gomaa [30] applied a DMAIC-based framework incorporating Taguchi's methodology to optimize machining processes in car spare parts manufacturing, improving both product quality and operational performance. Other studies, such as Chen et al. [31] and Muraleedharan et al. [32], successfully implemented Taguchi-based DMAIC approaches in transistor gasket production and galvanized iron manufacturing, respectively, while Duc et al. [11] optimized molybdenum processing, further demonstrating the method's broad applicability.

Table 1. Summary of key studies on TSS methodology in various industries.

Study/Author	Industry/Application	Key Contributions
Gomaa [22]	Spare Parts Manufacturing	Optimized processes, reduced defects, and enhanced overall performance in spare parts manufacturing.
Gomaa [30]	Car Spare Parts Manufacturing	Improved machining efficiency and quality in car spare parts production.
Chen et al. [31]	Transistor Gasket Production	Optimized process parameters, leading to improved gasket production quality.
Muraleedharan et al. [32]	Galvanized Iron Manufacturing	Enhanced production parameters for better quality in galvanized iron manufacturing.
Duc et al. [11]	Molybdenum Processing	Established optimal conditions for oil immersion tanks in molybdenum processing.
Yusof and Lee [33]	Macaron Production	Improved product quality and process performance in macaron production.
Erlangga and Wahyuni [13]	SMEs	Boosted productivity and reduced defects in SMEs through process improvements.
Gerger and Firuzan [34]	Automotive Industry	Improved process performance and reduced customer complaints in the automotive industry.
Omprakas et al. [35]	Sand Casting	Reduced shrinkage defects and improved product quality in sand casting.
Ketabforoush and Abdul Aziz [36]	Green Construction Materials	Reduced variation and improved consistency in green construction material production.
Ibrahim et al. [37]	Telecommunications	Identified critical control factors for business process improvement in telecommunications.
Chou and Chen [38]	CNC Milling	Optimized surface roughness and process efficiency in CNC milling.
Kaushik et al. [39]	Green Sand Casting	Reduced defects, improving product quality in green sand casting.
Lin and Wong [40]	Hand Tool Drilling	Enhanced quality and efficiency in hand tool drilling processes.
Yu et al. [41]	Multi-Characteristic Products Manufacturing	Optimized manufacturing processes, enhancing quality for multi-characteristic products.
Ganganallimath et al. [42]	Green Sand Casting	Minimized defects, enhancing product quality in green sand casting.

The versatility of the TSS approach extends across multiple sectors. In the food industry, Yusof and Lee [33] applied this methodology to optimize macaron production, showcasing its relevance beyond traditional manufacturing. In small and medium-sized enterprises (SMEs), Erlangga and Wahyuni [12] reported significant reductions in product defects and increased productivity by integrating LSS and Taguchi. Within the automotive sector, Gerger and Firuzan [34] leveraged this approach to enhance process performance and reduce customer complaints, while Omprakas et al. [35] employed a TSS DMAIC framework to address shrinkage defects in sand casting.

Beyond manufacturing, this methodology has been successfully implemented in construction and telecommunications. Ketabforoush and Abdul Aziz [36] applied the Taguchi-based approach to reduce variation in green construction material production, supporting sustainability and quality consistency. In telecommunications, Ibrahim et al. [37] used this methodology to identify key factors for business process improvement (BPI), highlighting its effectiveness in service-oriented industries. Additionally, studies such as Chou and Chen [38] on CNC milling, Kaushik et al. [39] on green sand-casting defect reduction, and Lin and Wong [40] on hand tool drilling optimization demonstrated substantial improvements in surface quality, production efficiency, and operational performance.

Overall, the TSS methodology has proven to be a highly effective and adaptable approach for enhancing process performance across various industrial sectors, including automotive, electronics, food production, construction, and telecommunications. This integrated framework enables organizations to minimize process variation, improve product quality, and implement robust process designs to address complex manufacturing challenges. Fostering a culture of continuous improvement, it supports sustained performance enhancement and facilitates the production of high-quality products that meet both industry standards and customer expectations.

2.2 Review of the Optimization of Welding Process Parameters

Achieving high-quality welding while minimizing waste and enhancing manufacturing efficiency requires a systematic approach that ensures reliability, repeatability, and process predictability. The Taguchi method, known for its robust design principles and variability reduction strategies, is particularly effective in welding operations where inconsistencies directly impact product quality. By integrating quality control early in the development process, the Taguchi method enhances welding performance across diverse conditions, leading to more consistent and reliable outcomes [43,44]. Optimizing key parameters such as welding speed, voltage, current, and travel speed is essential for achieving high-quality welds, and the Taguchi method provides a structured framework to refine these parameters while minimizing variability.

As highlighted in Table 2, several studies have demonstrated the effectiveness of the Taguchi method and six sigma in welding process optimization. Antony et al. [43] highlighted its application across industries, including food processing, reinforcing its role in process improvement. Sabry et al. [45] applied six sigma methodologies to enhance welding operations by establishing a framework to set improvement objectives, monitor progress, and control variability. This approach led to significant defect reductions and improved process reliability. Sabry et al. [46] further utilized the DMAIC framework to optimize MIG welding for aluminum pipes, improving both tensile strength and hardness through systematic parameter adjustments. Their findings underscored six sigma's potential to enhance mechanical properties critical for structural integrity. Additionally, Sabry et al. [47] employed response surface methodology (RSM) to optimize friction stir welding (FSW) of aluminum pipes by adjusting rotation speed, wall thickness, and travel speed. Their experimental trials identified optimal conditions for maximizing tensile strength in Al 6061 friction stir welded joints, demonstrating the power of statistical methods in process refinement.

Table 2. Summary of studies on the application of six sigma and Taguchi method in welding process optimization.

Study/Author	Industry/Application	Key Contributions
Mekonone et al [2]	MIG welding (structural applications)	Investigated temperature distribution, cooling rates, and microstructural changes for optimal mechanical properties.
Antony et al. [43]	Various industries, including food processing	Reviewed the effectiveness of the Taguchi method in process optimization.
Shelar et al. [5]	MIG welding (Mild Steel)	Used the Taguchi method to optimize welding parameters, identifying welding current as a critical factor.
Tesfaye et al. [4]	TIG-MIG hybrid welding (EN24 mild steel)	Used L27 orthogonal array to optimize tensile strength and hardness; identified welding current and voltage as key factors.
Tesfaye et al. [3]	GMAW welding (Dissimilar steel joints)	Optimized tensile strength using the L9 Taguchi array, identifying voltage as the most significant factor.
Sabry et al. [46]	MIG welding (Aluminum pipes)	Optimized welding parameters using DMAIC to improve tensile strength and hardness.
Sabry et al. [45]	FSW of Aluminum pipes	Used RSM to optimize process parameters for maximum tensile strength.
Sabry et al. [47]	Welding operations	Applied six sigma to enhance welding reliability, reduce defects, and improve workflow efficiency.
Kumar et al. [1]	GMAW	Applied Taguchi and ANOVA to optimize weld quality, highlighting welding voltage as the key parameter.
Sabry et al. [8]	Various industries	Demonstrated six sigma's impact on defect reduction, productivity, and cost-effectiveness in welding.
Yakkundi et al. [6]	Water tube boiler welding	Implemented six sigma (DMAIC) to reduce defects and enhance weld quality.
Kakaei-Lafdani et al. [48]	Spiral welded pipes for water and gas transmission	Applied six sigma (DMAIC) to reduce defects and improve production efficiency.
Kumar et al. [49]	Underwater UWFSW	Identified key welding parameters affecting weld quality and mechanical properties.
Abebe et al. [50]	Butt-weld joint welding	Used L9 Taguchi array to optimize tensile and bending strength; identified gas flow rate and current as the most influential factors.
Pratiwi et al. [51]	SMAW for SS316 & ASTM A36	Applied grey-based Taguchi method to optimize welding conditions and mechanical properties.

Yakkundi et al. [6] successfully applied six sigma to welding water tube boilers, reducing defects and improving weld quality through the DMAIC framework. Ibrahim et al. [8] also demonstrated six sigma's effectiveness in enhancing welding performance, productivity, and cost efficiency across various industries. Kakaei-Lafdani et al. [48] improved the quality of spiral-welded pipes for water and gas transmission by implementing six sigma's DMAIC approach. They identified key factors affecting weld quality and reduced both defects and production costs, highlighting six sigma's effectiveness in large-scale manufacturing environments. Kumar et al. [49] investigated underwater friction stir welding

(UWFSW), concluding that rotational speed, traverse speed, and pin length significantly influenced weld quality. Optimized parameters improved cooling rates, grain refinement, and mechanical properties such as tensile strength and hardness.

Mekonone et al. [2] explored MIG welding parameter optimization, focusing on temperature distribution, cooling rates, residual stress, and microstructures. Their study found that optimal conditions—100 A current, 21 V voltage, and 3.85 mm/s welding speed—significantly influenced mechanical properties, residual stress, and microstructural integrity. Shelar et al. [5] examined the effects of welding current, voltage, and gas flow rate on the UTS of mild steel in MIG welding. Using the Taguchi approach with an L9 orthogonal array, they determined that welding current contributed 74.85% of the variation in tensile strength. Tesfaye et al. [3] optimized welding parameters for dissimilar steel joints using the L9 Taguchi array and found that voltage was the most significant factor. Their study identified optimal GMAW parameters as 25 V, a wire feed rate of 5.7 m/min, and a welding speed of 55 m/h. Expanding on this, Tesfaye et al. [4] conducted process optimization for EN24 mild steel using an L27 orthogonal array. Their findings revealed that MIG welding current and voltage were the most critical factors, contributing 44.19% and 49.20% to variability, respectively.

Kumar et al. [1] employed the Taguchi technique and ANOVA to optimize GMAW, identifying welding voltage as the primary determinant of tensile strength and hardness. Similarly, Abebe et al. [50] used the L9 orthogonal array to optimize butt-weld joints, determining that gas flow rate and current were the most significant factors, contributing 47.63% and 34.34% to process variation, respectively. Pratiwi et al. [51] applied a grey-based Taguchi method to optimize shielded metal arc welding (SMAW) for SS316 and ASTM A36 joints. Their findings indicated that optimal welding conditions included an E309 electrode, 100 A current, 14 V arc voltage, and 4 cm/min welding speed.

Despite these promising results, limited research has explored the combined application of the Taguchi method and six sigma in MIG/MAG welding processes. This presents a valuable research opportunity, particularly in industries such as automotive and construction, where MIG/MAG welding plays a critical role. Integrating the Taguchi method's robust design principles with Six Sigma's data-driven approach could further enhance welding quality, consistency, and efficiency. By focusing on defect reduction, quality improvement, and variability minimization, this combined approach offers a powerful framework for optimizing welding performance. Future research should explore this integration in greater depth, particularly in MIG/MAG welding, to drive significant advancements in welding process optimization. Such developments could ultimately improve product quality and manufacturing efficiency across multiple sectors.

3. Research Gap Analysis

A thorough review of the literature on six sigma and the Taguchi method in welding reveals several critical research gaps that require further investigation, as summarized in Table 3.

Table 3. Research gap analysis.

Research Gap	Description	Future Research Directions
Limited Integration of TSS in MAG Welding	While six sigma is applied, Taguchi's structured optimization is underutilized in MAG welding.	Develop a TSS framework to enhance weld quality and process efficiency.
Independent Parameter Optimization	Studies optimize tensile strength, hardness, and other parameters separately, ignoring their interactions.	Implement multi-objective models for simultaneous optimization of weld quality and process stability.
Restricted Use of TSS in High-Precision Industries	TSS is mainly applied in automotive and general manufacturing, with limited exploration in aerospace, marine, and energy sectors.	Expand TSS research to industries requiring high-precision welding and stringent quality control.
Short-Term Focus on Weld Performance	Research prioritizes immediate improvements, overlooking long-term durability, fatigue, and corrosion resistance.	Conduct lifecycle studies to assess the long-term reliability and sustainability of optimized welds.
Fragmented Process Improvement Approaches	Lean, six sigma, and Taguchi methods are rarely integrated into a unified welding optimization framework.	Develop a comprehensive Lean-six sigma-Taguchi approach for enhanced efficiency and cost-effectiveness.

(1) Limited application of TSS in MAG Welding: six sigma and Taguchi ideas are broadly incorporated in industry practice, the research literature compares their integrated application with regard to MAG welding, still very limited in study. Where TSS has been integrated, previously published studies [6,46] often simply have applied Six Sigma reflective upon it being grounded upon individualists approaches, with no robustness achievable through integrated approaches relying upon a TSS strategy.

(2) Optimization of multiple welding parameters simultaneously: Most studies focus their research solely on the optimizing of single-factor variables (i.e. tensile strength), without evaluating the variates of multivariate formulations (i.e. wire diameter, feed rate, welding speed, shielding gas flow). A much more comprehensive, interdependent view on the subject would allow for much more effective welding processes to achieve enhanced weld quality and mechanical performance.

(3) Expansion of TSS into specialized industries: There is a limited TSS application in niche industries (e.g. aerospace, marine and energy), where welding needs to occur with high-relieving requirements and could have large implications if welding is not performed adequately and quality control accepted.

(4) Long-term performance evaluation of welded joints: Many research studies show emphasis upon short-term results of a process, with limited performance or durability measurements related to welded joints and long-term performance with respect to fatigue resistance, corrosion behaviour etc., Research that examines the lifecycle performance of welded joints would provide deeper insights into quality improvements and cost efficiency over time.

(5) Comprehensive integration of process improvement methodologies: Limited research has explored the integration of multiple process improvement methodologies—such as lean, six sigma, and the Taguchi method—into a unified framework for MAG welding. A holistic approach that combines parameter optimization with waste reduction, energy efficiency, and cost control would provide a more sustainable and effective solution for modern welding challenges.

In conclusion, addressing these research gaps will significantly enhance the adoption and effectiveness of TSS in MAG welding. Future research should prioritize the simultaneous optimization of multiple parameters, the integration of predictive technologies, and the expansion of TSS into specialized industries. Additionally, evaluating long-term weld performance, integrating multiple improvement methodologies, and conducting real-world validation studies will contribute to improved welding quality, cost-effectiveness, and sustainability in manufacturing.

4. Research Methodology

This study aims to optimize MAG welding parameters using a TSS methodology to enhance weld quality, consistency, and process efficiency. The methodology integrates experimental design, statistical analysis, and process optimization, as outlined in Table 4.

Table 4. Summary of research methodology for MAG welding optimization.

#	Step	Objective	Key Activities	Expected Outcomes
1	Problem Identification	Define welding challenges and goals	Establish key objectives (e.g., tensile strength, defect reduction), identify critical parameters and KPIs	Clear problem scope with measurable improvement targets
2	Literature Review & Benchmarking	Analyze existing research and industry practices	Review Taguchi-six sigma applications, benchmark industry standards, identify gaps and limitations	Comprehensive understanding of methodologies and research gaps
3	Experimental Design	Develop a structured approach for parameter optimization	Select an appropriate Taguchi orthogonal array, define control and noise factors	Well-structured experimental framework for optimization
4	Six sigma DMAIC Implementation	Apply a structured methodology for process improvement	Execute DMAIC phases to optimize welding performance	Data-driven process improvements with defect reduction
5	Parameter Optimization	Determine optimal welding parameters	Conduct signal-to-noise (S/N) ratio analysis, evaluate parameter interactions	Optimized settings for improved weld quality and efficiency
6	Statistical Validation & Analysis	Ensure reliability of optimized parameters	Perform ANOVA, regression analysis, and compare results with baseline	Statistically validated improvements in weld consistency
7	Industrial Application & Case Study	Validate optimized parameters in real-world settings	Implement improvements in production, monitor performance, collect industrial feedback	Practical verification with insights for further refinement
8	Conclusion & Future Research	Summarize findings and outline future directions	Analyze results, propose research on AI-driven monitoring, automation, and multi-objective optimization	Strategic insights for further advancements and industrial adoption

The research begins with problem definition, identifying challenges and setting clear objectives for optimizing MAG welding. The primary goals include enhancing weld quality, minimizing defects, and improving process consistency. A detailed review of existing MAG welding processes identifies limitations, while key performance indicators such as tensile strength, hardness, appearance, and defect rates are established. Critical welding parameters, including heat input, wire feed rate, voltage, current, and shielding gas, are examined for their impact on weld quality.

The next phase involves literature review and benchmarking, analyzing existing research on the Taguchi method and six sigma in welding process optimization. Current MAG welding practices are benchmarked against industry standards, and common welding defects—porosity, cracks, and incomplete fusion—are studied to evaluate their correlation with process parameters.

To optimize welding parameters, the study employs the Taguchi method for experimental design. Key process parameters, including welding speed, current, voltage, shielding gas composition, and wire feed rate, are selected for evaluation. A suitable Taguchi orthogonal array is chosen to ensure efficient testing of parameter interactions. Preliminary tests define parameter ranges and help identify control and noise factors such as environmental conditions and material properties. A structured experiment matrix is developed to balance parameter evaluation and optimize process performance.

The six sigma DMAIC framework is implemented to systematically refine the welding process. The Define phase establishes the problem scope and desired process improvements. The Measure phase collects baseline data on weld quality, including defect rates and material properties. The Analyze phase employs statistical tools such as ANOVA to determine the significance of welding parameters on performance. The Improve phase applies Taguchi-based optimization to identify the best parameter combinations for enhancing weld quality. Finally, the Control phase develops strategies to ensure long-term process stability and maintain consistent quality.

For parameter optimization, experiments are conducted using the Taguchi orthogonal array, and key weld quality indicators are monitored. A S/N ratio analysis is applied to determine optimal parameter settings, followed by validation through additional experiments. The effectiveness of the optimized parameters is confirmed by improvements in tensile strength, hardness, and appearance, ensuring process consistency.

The statistical analysis and results validation phase further strengthens the reliability of the optimized welding process. ANOVA and regression analysis assess the impact of the selected parameters, while comparisons with baseline data confirm improvements. Additional tests under varying conditions validate the robustness of the optimized process. Control charts and statistical process control (SPC) techniques are implemented for continuous process monitoring and stability assurance.

To assess real-world applicability, the optimized MAG welding parameters are tested in an industrial case study. The optimized parameters are implemented in automotive, aerospace, or pipe manufacturing environments, where their effectiveness is evaluated based on welding consistency and defect reduction. Operator and quality control feedback is gathered to ensure the practical feasibility of the optimized parameters, and adjustments are made for further improvements.

The research concludes by summarizing key findings and emphasizing the contributions of the TSS approach to MAG welding optimization. The study highlights the identification of optimal welding parameters, leading to improved weld quality, reduced defects, and enhanced process efficiency. Broader implications for industrial welding applications are discussed, and future research avenues, such as real-time monitoring, predictive modeling for weld quality, and multi-objective optimization, are suggested to further refine MAG welding processes.

The research is expected to yield optimized MAG welding parameters that significantly enhance weld quality, process stability, and defect minimization. The TSS methodology will provide a structured approach to welding optimization, leading to higher tensile strength, reduced defects, and improved production consistency. The developed framework will be scalable across multiple industries, including automotive, aerospace, and construction, ensuring practical implementation.

The study leverages several advanced tools and methodologies. The Taguchi Method is used for experimental design and robust parameter optimization, while the six sigma DMAIC framework systematically guides process improvement. Statistical analysis tools, including ANOVA, regression analysis, and S/N ratio calculations, are applied to evaluate parameter significance. Additionally, control charts and SPC techniques are implemented to maintain long-term process stability.

In conclusion, this research integrates TSS methodology to optimize MAG welding processes by focusing on critical parameters that reduce defects, improve weld quality, and enhance process efficiency. Through the combined use of the DMAIC framework and the Taguchi method, optimal welding conditions are identified, leading to higher productivity, lower costs, and more consistent quality. The study's findings will benefit industries such as automotive, aerospace, and construction, providing a structured approach to welding optimization. Future research will further refine these methods, exploring real-time monitoring, AI-driven predictive modeling, and multi-objective optimization to enhance the adaptability and effectiveness of MAG welding across industries.

5. Case Study: Optimization of MAG Welding for St37-2 Steel

This study focuses on optimizing MAG welding processes in the Egyptian structural manufacturing industry to enhance efficiency and weld quality. St37-2 steel, a widely used low-carbon structural steel, was selected due to its excellent weldability, favorable mechanical properties, and cost-effectiveness. Its moderate strength and high ductility facilitate the fabrication of complex structures, while its compatibility with various welding techniques ensures its suitability for industrial applications. To systematically improve welding performance, the DMAIC framework was integrated with DOE for a structured, data-driven process optimization approach.

The Define phase focused on identifying key welding challenges, including weld defects, inconsistent penetration, and variations in mechanical properties. Critical process parameters–such as voltage, current, wire feed rate, and welding speed–were established as primary factors influencing weld quality. These parameters provided the foundation for an optimized experimental design, ensuring a structured approach to process improvement.

In the Measure phase, baseline data were collected to assess current process performance, evaluating key output responses such as weld bead geometry, tensile strength, hardness, and defect rates. SPC tools were applied to quantify process variability, pinpoint inefficiencies, and identify key areas for enhancement.

During the Analyze phase, DOE was employed to systematically examine the influence of welding parameters on output responses. The Taguchi method was used to construct an optimized experimental matrix, reducing the number of trials while maximizing insights. ANOVA was performed to determine the statistical significance of each factor, and a predictive model was developed to simulate process behavior under varying conditions. This approach enabled the identification of optimal parameter combinations, ensuring improved weld quality and process stability.

In the Improve phase, the optimized welding settings derived from the analysis were implemented and tested through controlled experiments. S/N ratio analysis was applied to ensure process robustness and minimize variability. Pilot runs validated the improvements, focusing on better weld penetration, enhanced mechanical properties, and reduced defect rates. Additionally, control limits and real-time monitoring mechanisms were introduced to sustain improvements and ensure consistent process performance.

The Control phase ensured the long-term stability of the optimized welding process through the deployment of SPC tools, control charts, and real-time monitoring systems. A proactive feedback loop was established to detect process deviations and enable quick corrective actions. If variations were observed, DOE methodologies were revisited to refine parameter settings further. Standard operating procedures were documented to facilitate knowledge transfer, continuous improvement, and scalability of the optimized process.

By integrating DMAIC with DOE-based parameter optimization, this study successfully enhanced MAG welding performance for St37-2 steel, resulting in higher weld quality, reduced defect rates, improved process stability, and increased manufacturing efficiency.

5.1. Products Defect Analysis

This phase focuses on identifying the root causes of welding defects and addressing process inefficiencies to enhance product quality. As illustrated in Figure 1, the Pareto chart highlights porosity as the most prevalent defect, making it a critical issue requiring immediate attention. Since porosity significantly compromises weld integrity, a structured brainstorming session was conducted to analyze contributing factors, including welding parameters, material properties, environmental conditions, and operator techniques [6,9].

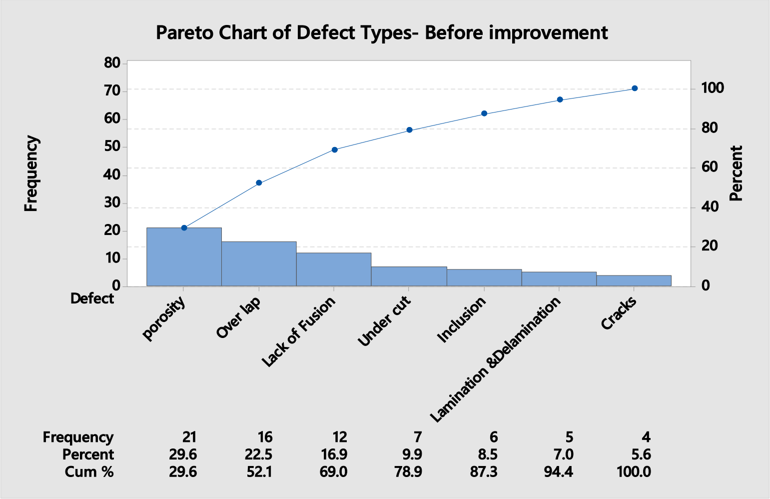

Figure 1. Pareto chart of defect types (before improvement).

To systematically assess the factors influencing the mechanical properties of welded joints, an Ishikawa cause-and-effect diagram was developed, as shown in Figure 2. This diagram categorizes key influencing factors into process variables, operator expertise, equipment condition, and external elements such as shielding gas purity and humidity levels. Understanding these factors is essential for optimizing process parameters and achieving defect-free welding.

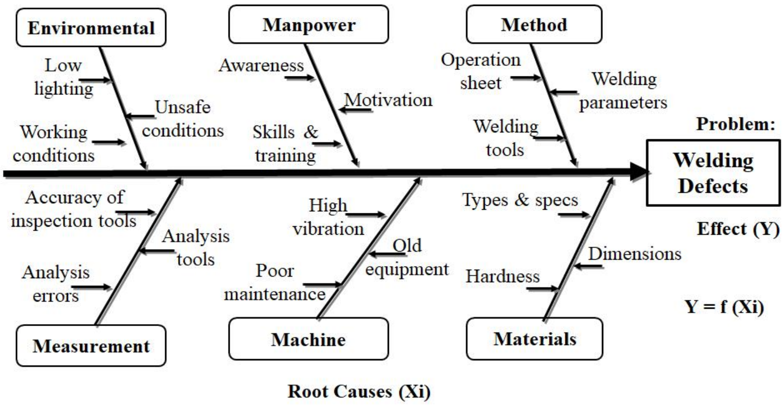

Figure 2. C&E diagram for porosity in welding joint.

To improve weld quality and mechanical performance, an experimental study was conducted using the Taguchi method, facilitating the systematic optimization of critical welding parameters such as voltage, wire diameter, wire feed rate, and shielding gas composition. The primary objective was to enhance UTS, hardness, and impact resistance. By implementing the Taguchi approach, the study established a structured framework for process optimization, ensuring consistent weld quality, minimizing defects, and improving overall manufacturing efficiency [1-2].

Porosity, characterized by voids or gas pockets within the weld, weakens mechanical properties and structural integrity. These voids reduce the effective cross-sectional area of the weld, creating localized stress concentrations that can initiate cracks and lower strength, fatigue resistance, and impact toughness. Additionally, porosity increases the risk of failure under operational loads, making its reduction essential to ensuring the durability and reliability of welded structures.

5.2 Optimization of Welding Process Parameters

This section focuses on optimizing MAG welding parameters using the Taguchi method to enhance key mechanical properties, including UTS, hardness, and impact energy of welded joints. The quality and performance of welded structures are highly dependent on precise control of process parameters, as improper settings can lead to defects, reduced mechanical strength, and inconsistencies in weld integrity. Therefore, optimizing these parameters is essential to achieving superior weld performance and ensuring manufacturing efficiency.

To systematically determine the optimal welding conditions, a DOE approach was employed, integrating S/N ratio analysis using Minitab 18 software. DOE provides a structured methodology for evaluating multiple factors simultaneously, minimizing experimental effort while maximizing data insights. Additionally, an ANOVA was performed to identify the most statistically significant factors affecting weld quality. This statistical evaluation quantified each parameter’s influence on the welding process, ensuring the identification of robust and repeatable settings for optimal mechanical performance.

As illustrated in Figure 3, MAG welding is widely used in industrial applications due to its high deposition rate, automation potential, and adaptability to various materials. In this study, the welding experiments were conducted on St37 steel workpieces with dimensions of 150 mm in length, 100 mm in width, and 10 mm in thickness using the MAG welding process. St37 steel, a widely used low-carbon structural steel, was selected for its excellent weldability, moderate strength, and cost-effectiveness. The chemical composition of St.37 base metal is given in Table 5. Optimizing the welding parameters for this material is crucial for enhancing mechanical properties and ensuring the reliability of welded components in industrial applications.

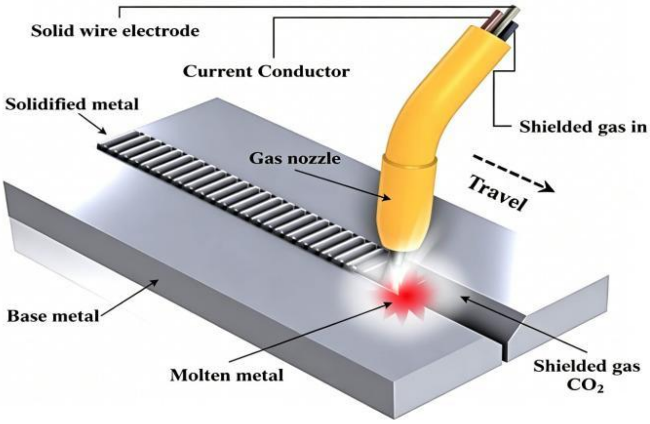

Figure 3. Welding process geometry.

Table 5. Chemical composition of St. 37 base metal (wt.-%).

Element	C	Si	Mn	P	S	Cr	Ni	Fe
Average range weight %	0.11	0.03	0.56	0.007	0.009	0.07	0.03	Bal

To comprehensively evaluate the welding process, influencing factors were classified into control and noise factors, as summarized in Table 6. Control factors included adjustable welding parameters such as voltage, wire feed rate, wire diameter, and gas flow rate, while noise factors represented external variables like environmental humidity, shielding gas purity, and slight variations in material properties. Identifying and addressing these factors is critical for minimizing process variability and enhancing the reproducibility of weld quality. The values of current and welding speed are regarded as constant for the duration of the experiment.

Table 6. Main factors affecting the welding process.

Control Factors	Noise Factors
Machine Type	Machine vibration
Workpiece material	Machine conditions
Workpiece dimension	Workpiece variation
Welding speed (m/min)	Workpiece temperature
Feed rate (mm/rev)	Tool vibration
Gas flow rate (L/min)	Manpower skill
Voltage (v)	Environmental conditions
Wire diameter (WD) (mm)	
Angle butt joint (groove angle) 60°	
Shielded gas type (CO_2)	

As shown in Table 7, four key control factors—voltage, wire feed rate, wire diameter, and gas flow rate—were selected for experimental analysis due to their significant impact on weld bead geometry, heat input, penetration depth, and defect formation. An L9 orthogonal array was employed to systematically investigate the influence of these parameters, assigning three levels to each factor. This experimental design allows for an efficient exploration of parameter interactions while minimizing the number of experimental trials. Figure 4 provides a schematic representation of the experimental setup, illustrating the relationships between input parameters and desired mechanical properties.

Table 7. MAG welding factors and their levels.

Control Factors	Levels
Machine Type	MIG/ MAG welding
Workpiece material	Steel 37
Welding voltage (v)	20, 25, 30
Wire feed rate (m/min)	2, 4, 6
Wire diameter (mm)	0.8, 1.2, 1.6
Gas flow rate (L/min)	10, 15, 20
Gab between work piece (mm)	0.3
Gap between two welded pieces	1.5 mm

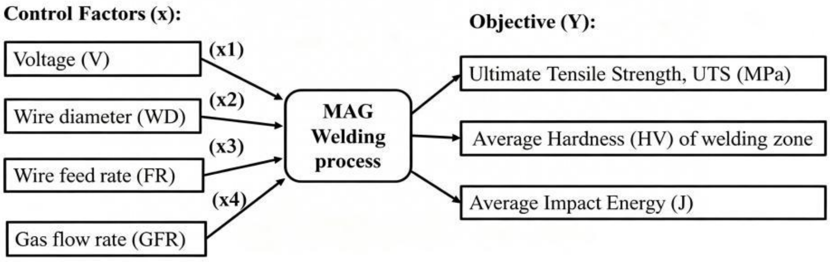

Figure 4. Process parameter diagram.

The experiment aimed to assess the effect of welding parameters on the mechanical properties of St37 steel, specifically UTS, hardness, and impact energy. After conducting the welding trials, mechanical testing was performed to measure these properties, ensuring that the optimized parameters resulted in enhanced weld performance. Table 8 shows L9 orthogonal array for experimental conditions according to Taguchi method. Figure 5 displays a photograph and schematic images depicting the tensile test specimen and its significant dimensions according to the ASTM standard E8-19. Furthermore, Figure 6 is a schematic image of the Charpy impact test specimen and a photograph of the actual tested specimen. To assess hardness using Vickers hardness across the weld zone, the Vickers hardness profile was determined on a cross-sectional plane perpendicular to the welding direction. In this case, the measurements were made with a Vickers indenter with a 10 kg load, applied for a dwell time of 15 seconds. Hardness was measured in the welded zone at three points, with a spacing of 0.5 mm between each point. The experimental results for UTS, hardness of welding zone and impact energy presented in Table 9. To further support the optimization process, Table 10 summarizes the average UTS, hardness, impact energy, and corresponding S/N ratios, providing a comprehensive assessment of the best-performing parameter combinations. The results demonstrate that optimized welding conditions significantly improve weld strength, durability, and mechanical performance, contributing to greater process stability and reduced defect rates.

Table 8. Taguchi L9 orthogonal array for experimental conditions.

#	**Welding Parameters**			
	Voltage (V)	**Wire diameter (mm)**	**Wire feed rate (m/min)**	**Gas flow rate (L/min)**
1	20	0.8	2	10
2	20	1.2	4	15
3	20	1.6	6	20
4	25	0.8	4	20
5	25	1.2	6	10
6	25	1.6	2	15
7	30	0.8	6	15
8	30	1.2	2	20
9	30	1.6	4	10

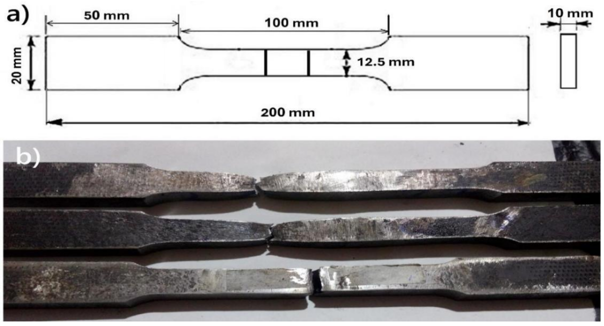

Figure 5. Dimensions of the tensile specimen. (a) A schematic illustration showing the dimensions of the tensile specimen; (b) A photograph of the tensile specimen.

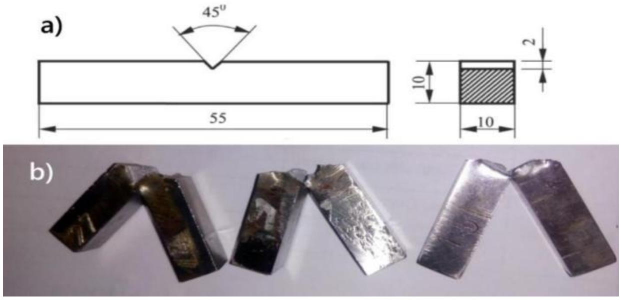

Figure 6. Standard charpy impact test specimen. (a) A schematic illustration showing the dimensions of the impact specimen; (b) A photograph of the impact specimen.

Table 9. Experimental results of UTS, hardness of welding zone and impact energy.

#	**UTS (MPa)**			**Hardness of welding zone (HV)**			**Impact energy (J)**		
	Sample A	**Sample B**	**Sample C**	**Sampl A**	**Sample B**	**Sample C**	**Sample A**	**Sample B**	**Sample C**
1	400.2	390.15	399.62	195	177	180	117	152	130
2	550	420	460	164	176	170	148	130	106
3	340.80	390.6	399.8	138	162	150	157	120	149
4	470.56	380.18	400.27	158	182	170	110	154	147
5	546.32	347.11	420.03	155	190	168	140	150	112
6	389.62	323.00	410.18	153	169	182	97	131	102
7	430.52	399.70	400.71	152	165	199	160	150	128
8	560.20	399.40	424.88	161	197	182	122	96	118
9	480.00	450.00	445.36	189	138	165	127	124	94

Table 10. Average UTS, (MPa), average, and signal to noise %.

#	V	WD	FR	GFR	Average UTS	Average Hardness	Average Impact energy	Signal to Noise % (UTS)	Signal to Noise % Hardness (HV)	Signal to Noise % Impact energy
1	20	0.8	2	10	340	184	133	50.6296	45.2964	42.4770
2	20	1.2	4	15	420	170	128	52.4650	44.6090	42.1442
3	20	1.6	6	20	450	150	142	53.0643	43.5218	43.0458
4	25	0.8	4	20	387	170	137	51.7394	44.6090	42.7344
5	25	1.2	6	10	451.6	171	134	53.0835	44.6599	42.5421
6	25	1.6	2	15	460.1	168	110	53.2570	44.5062	40.8279
7	30	0.8	6	15	444.6	172	146	52.9477	44.7106	43.2871
8	30	1.2	2	20	474	180	112	53.5156	45.1055	40.9844
9	30	1.6	4	10	490	164	115	53.8039	44.2969	41.2140

By integrating the Taguchi method with statistical analysis, this study successfully identified an optimal set of welding parameters for St37 steel, ensuring enhanced mechanical properties, improved manufacturing efficiency, and superior weld quality. These findings provide a valuable reference for industrial applications, paving the way for further advancements in welding technology and process optimization.

5.3 Influence of MAG Welding Parameters on Mechanical Properties

Figure 7 illustrates the effect of MAG welding parameters on the UTS of welded joints, emphasizing their critical role in determining weld quality and mechanical performance. The analysis confirms that voltage, wire diameter, wire feed rate, and gas flow rate significantly influence these properties, making their optimization essential for achieving superior weld strength, durability, and overall efficiency [5]. As shown in Figure 7(a, b), UTS increases with increasing in voltage, Similarly, a larger wire diameter contributes to an enhancement in UTS, a trend that is further amplified by a greater wire feed rate. The Ultimate Tensile Strength (UTS) exhibits a proportional increase with rising gas flow rate from 10 to 15 L/min, however rising gas flow rate from 15 to 20 L/min leads to decreased in UTS. This improvement is attributed to enhanced arc stability, better heat transfer, and improved fusion between the welded materials, leading to stronger joints with minimal defects. Based on the S/N ratio analysis using the "larger-is-better" criterion, the optimal welding parameters for maximizing UTS were identified as a voltage of 30 V, a wire diameter of 1.6 mm, a wire feed rate of 6 m/min, and a gas flow rate of 15 L/min.

For weld hardness (HV), Figure 8(a) indicates that the highest of hardness values are achieved with a voltage of 30 V, a wire diameter of 0.8 mm, a wire feed rate of 2 m/min, and a gas flow rate of 10 L/min. These conditions promote refined grain structures and controlled heat input, enhancing the hardness of the weld zone while preventing excessive brittleness. Achieving an optimal balance between heat input and cooling rate is crucial in obtaining a hardened yet durable weld structure. According to the data presented in Figures 8b, it is evident that increasing the voltage leads to a corresponding rise in hardness HV. However, rising in wire diameter contributes to reduction in hardness HV. Similarly, a slightly smallest wire feed rat contributes to an enhancement in hardness HV, a trend that is further amplified by a lowest gas flow rate.

Regarding impact energy, Figure 9(a) demonstrates that the optimal combination for improving toughness is a voltage of 20 V, a wire diameter of 0.8 mm, a wire feed rate of 6 m/min, and a gas flow rate of 20 L/min. These conditions enhance ductility and impact resistance, making the weld more resilient to dynamic loading and sudden stress variations. Improved toughness is particularly vital in applications where welded joints are exposed to impact forces or cyclic loading conditions. As illustrated in Figures 9 (b), the impact energy exhibits a proportional increase with decreasing voltage. Similarly, lowest wire diameter contributes to height value of impact energy. Conversely, increasing in wire feed rate leads to rising in impact energy. But when gas flow rate increasing results in a slight increase in impact energy.

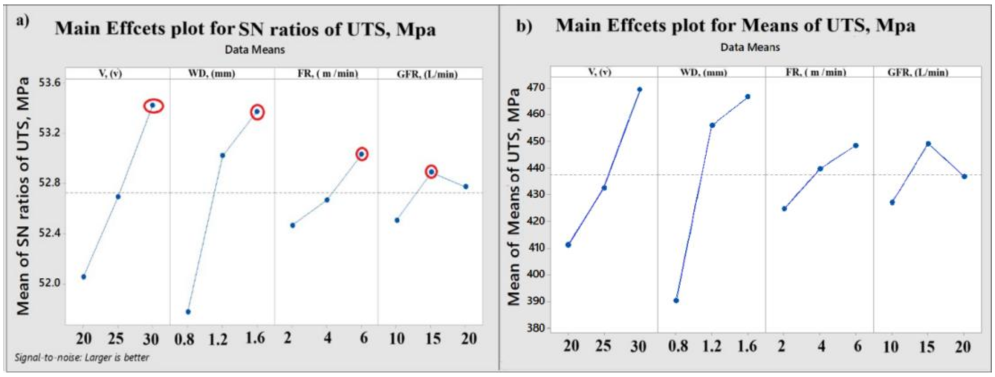

Figure 7. Influence of the welding parameters on UTS. (a) S/N ratios of UTS; (b) Main effect plot of UTS.

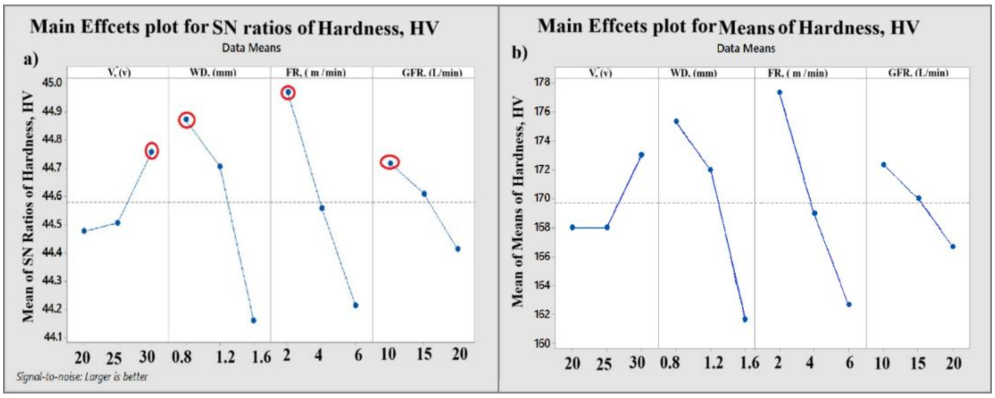

Figure 8. Influence of the welding parameters on average of HV for welding zone. (a) S/N ratios HV; (b) Main effect plot of HV.

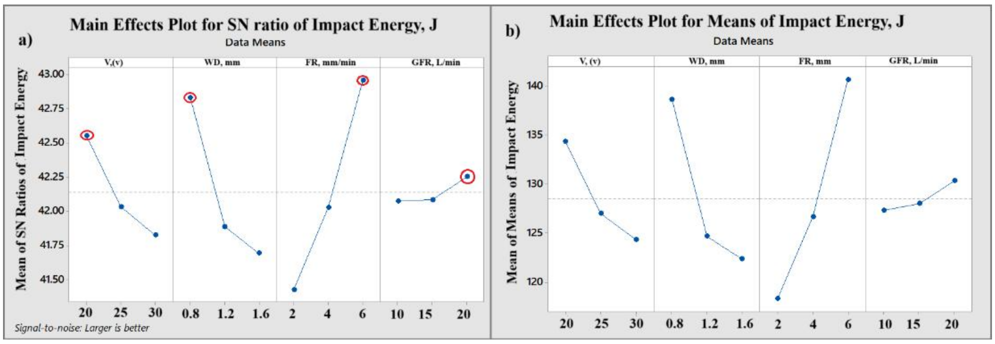

Figure 9. Influence of the welding parameters on average impact energy. (a) S/N ratios; (b) Main effect plot.

These findings highlight the necessity of precise parameter control in optimizing mechanical properties. By systematically adjusting process variables, substantial improvements in tensile strength, hardness, and impact energy can be achieved, leading to superior weld quality and enhanced structural reliability. The insights gained from this study contribute to the development of standardized welding guidelines, reducing defects and enhancing manufacturing efficiency in industrial applications.

To evaluate the reliability and accuracy of the developed model, an analysis of variance (ANOVA) was conducted. ANOVA, in conjunction with the F-test, was used to assess the statistical significance of the welding parameters and their contributions to key mechanical properties in MAG welding. As shown in Tables 11 to 13, the 'Prob. > F' value for the model is less than 0.05, confirming statistical significance. This indicates that the selected welding parameters have a substantial effect on weld quality and mechanical performance.

Table 11. Analysis of variance for UTS.

Source of	DF	Seq SS	Adj SS	Adj MS	Pc%	Rank
V	2	6563.7	6563.70	3281.85	37.9 %	2
WD	2	9592.4	9592.42	4796.21	55.3 %	1
FR	2	876.6	876.58	438.29	5.05%	3
GFR	2	323.1	323.09	161.54	1.86%	4
Error	0	0.0000002	0.000002	0.000001	0.00%	
Total	8	17355.8			100.00%	

Table 12. Analysis of variance for average HV of welding zone.

Source of	DF	Seq SS	Adj SS	Adj MS	Pc%	Rank
V	2	16.889	16.889	8.444	2.53 %	4
WD	2	340.222	340.222	170.111	50.92 %	1
FR	2	256.222	256.222	128.111	38.34%	2
GFR	2	54.889	54.889	27.444	8.21%	3
Error	0	0.000000	0.00000	0.00000	0.00%	
Total	8	668.222			100.00%	

Table 13. Analysis of variance for average impact energy.

Source of	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**Pc%**	**Rank**
V	2	160.89	160.889	80.444	11.42 %	3
WD	2	468.22	468.222	234.111	33.25 %	2
FR	2	764.22	764.222	382.111	54.27%	1
GFR	2	14.89	14.889	7.444	1.06%	4
Error	0	0.000000	0.00000	0.00000	0.00%	
Total	8	1408.22			100.00%	

The contribution analysis shows that wire diameter is the most influential factor affecting UTS, followed by voltage. These parameters are crucial in determining weld strength: wire diameter impacts the volume of filler material deposited, while voltage regulates heat input, affecting fusion depth and joint integrity. In comparison, feed rate and gas flow rate have relatively smaller contributions to UTS, suggesting their influence on tensile strength optimization is less significant.

For the average hardness (HV) of the welded zone, as shown in Table 12, wire diameter remains the dominant factor, followed by feed rate. Voltage has a smaller effect, suggesting that optimizing wire diameter and feed rate is essential for achieving the desired hardness properties. This finding aligns with the understanding that these parameters control material deposition rates and cooling behavior, both of which are vital for hardness.

Regarding impact energy, as shown in Table 13, which measures the weld's ability to absorb energy before failure, feed rate is identified as the most significant factor, followed by wire diameter. A higher feed rate increases heat input, leading to microstructural changes that enhance impact toughness. In contrast, gas flow rate shows the least influence on impact energy, implying that while shielding gas prevents oxidation and contamination, its effect on the weld's energy absorption capacity is less significant compared to other process parameters.

These findings provide valuable insights for optimizing MAG welding parameters to enhance mechanical performance. By prioritizing wire diameter and voltage for UTS, wire diameter and feed rate for hardness, and feed rate for impact energy, manufacturers can systematically refine process conditions based on specific application requirements. The use of ANOVA ensures a data-driven approach to process optimization, facilitating defect reduction, improved structural integrity, and enhanced overall welding efficiency.

Using regression analysis with MINITAB 18 statistical software, the influence of welding parameters on key mechanical properties was modeled and expressed through Equations (1-3). These mathematical models were developed to predict the relationships between welding parameters and response variables, including UTS, HV, and impact energy.

$$\text{UTS, MPa} = 259.0 + 33.00 * \text{V} + 38.29 * \text{WD} + 11.8 * \text{FR} + 4.89\ \text{GFR} \tag{1}$$

$$\text{Average hardness}\ (\text{HV}) = 199.89 + 2.00 * \text{V} - 7.33 * \text{WD} - 6.5 * \text{FR} - 3.17\ \text{GFR} \tag{2}$$

$$\text{Average impact energy}\ (\text{J}) = 129.56 - 5.00 * \text{V} - 8.17 * \text{WD} + 11.7 * \text{FR} + 1.50\ \text{GFR} \tag{3}$$

The accuracy and reliability of these models were evaluated using the coefficient of determination (R^2), which indicates how well the independent variables explain the variance in the dependent variables. The analysis yielded R^2 values of 0.99 for UTS, 1.0 for average HV, and 1.0 for impact energy. Generally, an R^2 value above 0.8 signifies a strong correlation and a well-fitted model. The high R^2 value of 99% for UTS, 100% for hardness and impact energy indicate an excellent fit, demonstrating that the selected welding parameters significantly influence tensile strength, hardness and impact energy.

As shown in Table 14, the predicted values exhibit a strong correlation with the measured data, demonstrating the accuracy and reliability of the developed model. For statistical analysis of critical processes to be considered valid, error values should remain below 5%. The minimal deviation between predicted and actual results confirms the robustness of the model in capturing the complex relationships between welding parameters and mechanical properties. This strong agreement validates the model's capability for precise performance prediction, enabling data-driven process optimization. Moreover, the consistency between experimental and predicted outcomes enhances confidence in the model's applicability across different welding conditions, ultimately contributing to improved weld quality, mechanical strength, and overall manufacturing efficiency.

Table 14. Comparison between actual UTS and expected UTS.

#	V	WD	FR	GFR	Actual UTS	Predicted UTS	Actual HV	Predicted HV	Actual IE	Predicted IE
1	20	0.8	2	10	340	347.0	184	184.89	133	129.06
2	20	1.2	4	15	420	402.0	170	167.89	128	133.56
3	20	1.6	6	20	450	457.0	150	150.89	142	138.06
4	25	0.8	4	20	387	401.6	170	174.06	137	138.22
5	25	1.2	6	10	451.6	442.0	171	166.56	134	138.22
6	25	1.6	2	15	460.1	461.5	168	169.06	110	109.22
7	30	0.8	6	15	444.6	441.6	172	172.72	146	142.89
8	30	1.2	2	20	474	461.1	180	175.22	112	113.89
9	30	1.6	4	10	490	501.5	164	167.72	115	113.89

The normality of the data was assessed using a normal probability plot, while the residuals were analyzed for normality, equal variance, and randomness through the (4-in-1) residual plot evaluation. Figures (10-12) illustrate the residual plots for UTS, HV, and impact energy, which are critical indicators of weld quality. In the normal probability plot, most data points align closely along the straight mean line, with minor clustering observed. This suggests that the data distribution is approximately normal, with only slight deviations. These minor deviations may result from experimental variations but remain within an acceptable range, ensuring the reliability of the statistical analysis.

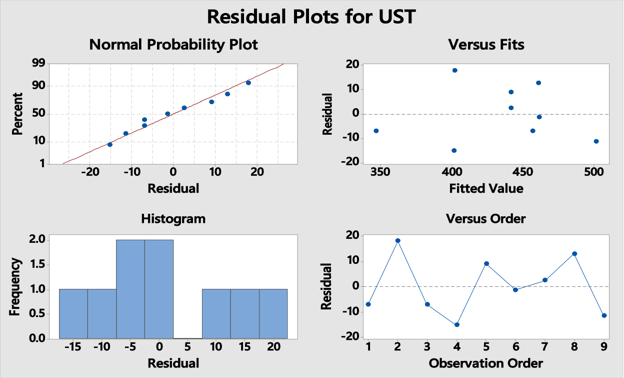

Figure 10. Residual plots for the UTS equation.

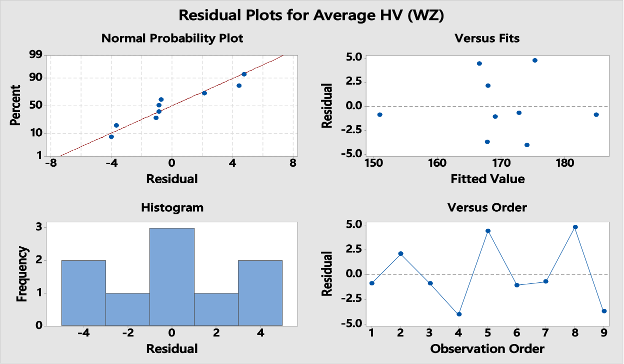

Figure 11. Residual plots for average weld hardness (HV) equation.

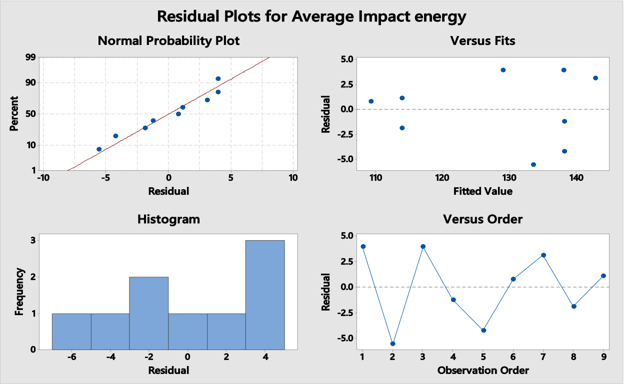

Figure 12. Residual plots for impact energy equation.

The histogram of residuals further supports the assumption of normality, showing a symmetrical distribution centered around the mean. This pattern aligns with the normal distribution law, confirming that the residuals exhibit neither significant skewness nor bias. The versus fit graph, which represents the relationship between residuals and their corresponding fitted values, displays a random scatter of points around the zero line. This randomness indicates that no systematic variation exists in the residuals, confirming that the UTS data is influenced solely by the defined input variables and not by any unidentified external factors. The absence of structured patterns in this plot is a crucial indicator of model adequacy.

Furthermore, the versus order graph was used to examine the randomness of residuals across the sequence of observations. The plot demonstrates that residuals are randomly distributed around the zero line, indicating no correlation between residuals and the order in which data points were recorded. This confirms that the residuals are independent and unaffected by time-dependent factors or external trends that could introduce bias into the model.

Based on these statistical evaluations, the regression model is considered robust, with no violations of key assumptions such as normality, independence, or homoscedasticity. The random distribution of residuals confirms that the model effectively captures the relationship between welding parameters and the mechanical properties of welded joints. These findings validate the model’s accuracy and reliability in optimizing welding parameters and predicting weld performance with a high level of confidence.

The interaction effects of welding parameters on UTS, HV, and impact energy are illustrated in Figures 13-15. These figures confirm the presence of interactions among all four welding parameters—voltage, wire diameter, feed rate, and gas flow rate—as indicated by the non-parallel lines. The more the lines deviate from parallelism, the stronger the interaction between the parameters. The analysis reveals that wire diameter has the most significant influence on UTS and HV compared to voltage, feed rate, and gas flow rate. Meanwhile, feed rate is the most critical factor affecting impact energy, surpassing the influence of wire diameter, voltage, and gas flow rate.

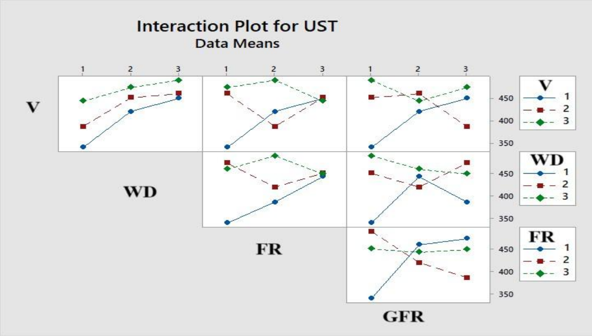

Figure 13. Interaction effect plots of UTS.

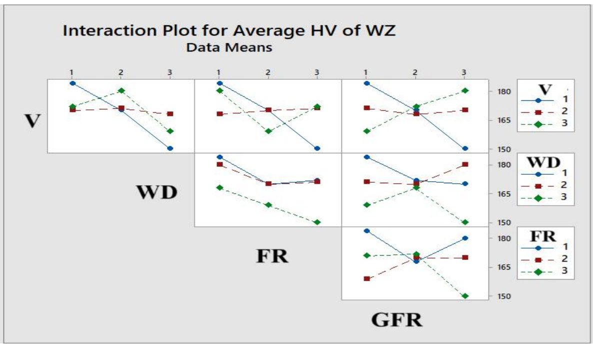

Figure 14. Interaction effect plots of HV of WZ.

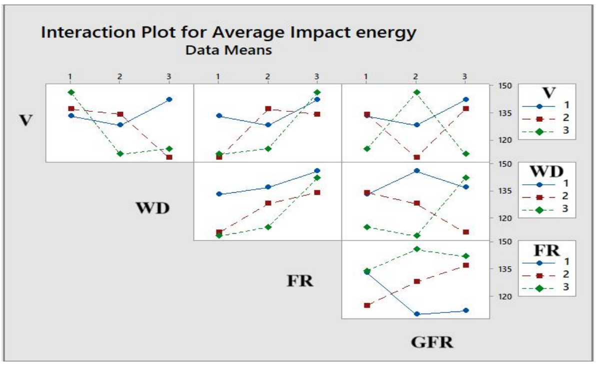

Figure 15. Interaction effect plots of impact energy.

Figures 16-18 present three-dimensional response surface plots that further illustrate how welding parameters impact UTS, HV and impact energy. Figure 16 demonstrates that UTS increases with higher voltage, wire diameter, and feed rate, reaching its maximum at elevated levels of these parameters. This suggests that optimizing these factors enhances tensile strength, which is crucial for ensuring weld durability and structural integrity. Figure 17 illustrates the response surface for HV, showing that the highest hardness values are achieved at higher voltage levels. However, an increase in wire diameter, feed rate, and gas flow rate results in decreased hardness. This indicates that while voltage plays a dominant role in enhancing hardness, excessive increases in the other parameters may negatively impact the weld's hardness characteristics. Figure 18 shows the interaction effects on impact energy, where the highest values are observed at lower voltage, wire diameter, and feed rate levels. However, an increase in gas flow rate positively contributes to weld hardness. The results suggest that increasing wire diameter, feed rate, and voltage leads to a reduction in impact energy, which may affect the weld's ability to withstand dynamic loading. On the other hand, a higher gas flow rate enhances weld hardness, indicating its role in stabilizing the weld structure. These findings highlight the complex interplay between welding parameters and their influence on mechanical properties. Understanding these interactions allows for the optimization of welding conditions to achieve a balance between tensile strength, hardness, and impact resistance, ensuring optimal performance for specific applications.

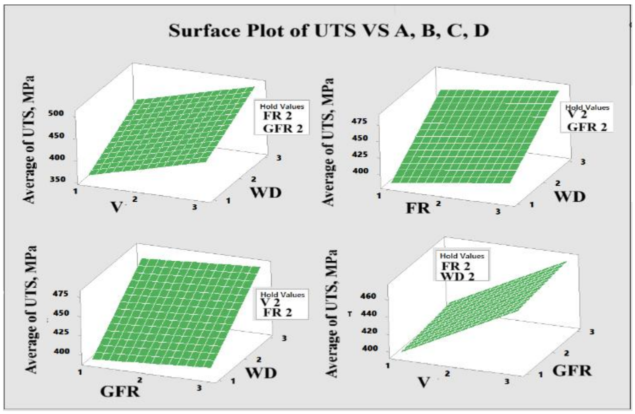

Figure 16. Three-dimensional surface plot for UTS for MAG welding parameters.

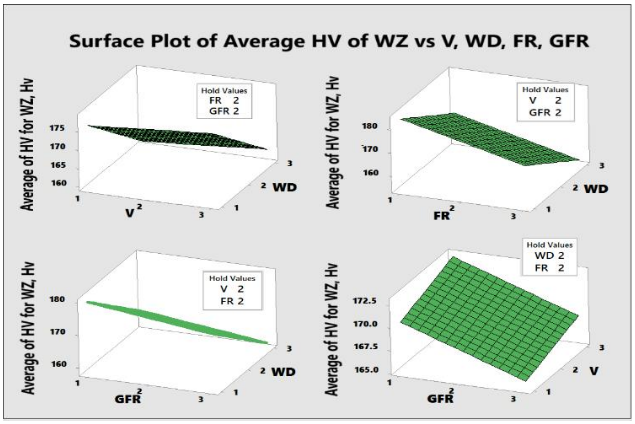

Figure 17. Three-dimensional surface plot for average HV welding zone for MAG welding parameters.

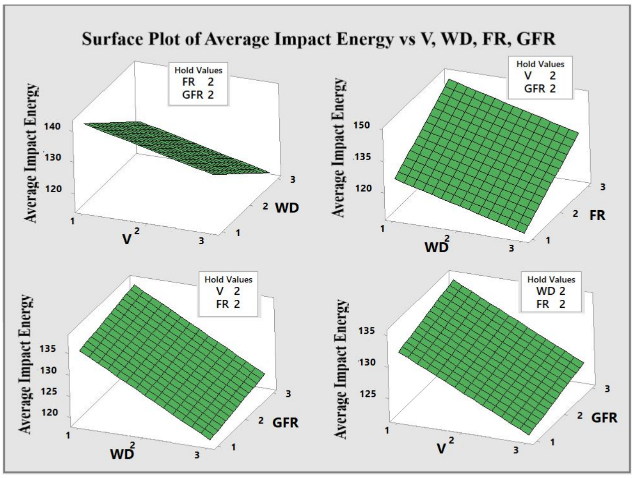

Figure 18. Three-dimensional surface plot for average impact energy for MAG welding parameters.

7. Conclusion and Further Work

The TSS method integrates the structured framework of six sigma with the robust statistical capabilities of the Taguchi approach and ANOVA, making it a powerful tool for process optimization. In this study, the Taguchi method was effectively applied to optimize the process parameters of MAG welding for ST37 steel. The results demonstrate that this approach is highly efficient in determining optimal welding parameters, leading to improved mechanical properties, including UTS, hardness of welded joints, and impact energy.

Based on the S/N ratio analysis, the optimal parameters for maximizing UTS were identified as a voltage of 30 V, a wire diameter of 1.6 mm, a feed rate of 6 m/min, and a gas flow rate of 15 L/min. For achieving optimal HV in the welding zone, the best parameters were determined to be a voltage of 30 V, a wire diameter of 0.8 mm, a feed rate of 2 m/min, and a gas flow rate of 10 L/min. Similarly, for maximizing impact energy, the optimal settings included a voltage of 20 V, a wire diameter of 0.8 mm, a feed rate of 6 m/min, and a gas flow rate of 20 L/min.

ANOVA results further highlighted the significance of welding parameters. Wire diameter was identified as the most influential factor affecting UTS and hardness in the welding zone, while feed rate was found to have the greatest impact on impact energy. In contrast, gas flow rate and voltage were observed to be the least significant parameters in affecting these mechanical properties.

The findings of this study provide valuable insights that can be utilized for future research and industrial applications. Moving forward, the author aims to extend this research by integrating the taguchi-based LSS methodology into various manufacturing processes across different case studies.

Future research should focus on enhancing the robustness of the optimization process by integrating LSS techniques, advanced statistical modeling, and real-time monitoring. Additionally, further studies should investigate the impact of advanced welding materials, shielding gases, and environmental conditions on weld quality and process stability.

Acknowledgements

Not applicable.

Ethics Statement

Not applicable.

Data Availability Statement

All data supporting this study are contained within the article.

Author Contributions

The authors contributed to the research and writing of this article and have read/agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Generative AI Statement

The authors declare that no generative AI tools were used in the writing, analysis, or preparation of this manuscript.

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