

A Comprehensive Review of Parametric Optimization and FEM Simulation Techniques for T-Joint Welding Processes

Nitesh Gurav¹, R. M. Choudhari², P. V. Chopde³, Dr. Y. A. Kharche⁴

¹ P.G. Student, Mechanical Engineering, Padm. Dr. V. B. Kolte College of Engineering, Malkapur, India

^{2,3} Assistant Professor, Mechanical Engineering, Padm. Dr. V. B. Kolte College of Engineering, Malkapur, India

⁴ Associate Professor, Mechanical Engineering, Padm. Dr. V. B. Kolte College of Engineering, Malkapur, India

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ABSTRACT

Welding of thin plate T-joint structures is extensively used in structural, automotive, and fabrication industries; however, improper selection of welding parameters often leads to excessive residual stresses, distortion, and reduced joint strength. This thesis presents a comprehensive numerical investigation and optimization of welding parameters affecting the mechanical performance of thin T-joint plates using finite element method (FEM) integrated with statistical optimization techniques. A three-dimensional thermo-mechanical finite element model is developed in ANSYS to simulate the welding process of 2 mm thick steel plates arranged in a T-joint configuration. The influence of welding current, arc voltage, and welding speed on residual von Mises stress, total deformation, and ultimate tensile strength is systematically studied. Design of Experiments (DOE) based on Central Composite Design (CCD) is employed to minimize the number of simulations while capturing linear, interaction, and quadratic effects of process parameters. Finite element simulation results obtained from ANSYS are used to develop second-order response surface models. The statistical adequacy and significance of the developed models are validated using analysis of variance (ANOVA), which demonstrates high coefficient of determination values and insignificant lack-of-fit. Response surface plots are utilized to analyze the interaction effects of welding parameters. Multi-objective optimization is performed using the desirability function approach to minimize residual stress and deformation while maximizing tensile strength. Optimal welding parameters are identified, and confirmatory FEM simulations are conducted to validate the optimization results. The close agreement between predicted and simulated values confirms the reliability of the proposed methodology. The integrated FEM-RSM framework presented in this thesis provides an effective and economical approach for optimizing welding parameters and improving the mechanical performance of thin welded T-joint structures.

Keywords:- T-joint welding, Finite Element Method (FEM), Welding parameters, Residual stress, Deformation analysis

1. INTRODUCTION

Welding is one of the most widely used joining processes in manufacturing and structural engineering due to its ability to produce permanent joints with high strength and reliability. However, welding involves localized heat input, which generates steep thermal gradients in the weld zone and surrounding material. These thermal cycles lead to the development of residual stresses and distortion, which adversely affect dimensional accuracy, fatigue life, and structural integrity of welded components if not properly controlled [1], [2].

Among various joint configurations, T-joint fillet welds are extensively used in thin plate structures such as automotive frames, shipbuilding panels, and light structural assemblies. Thin plates are particularly sensitive to welding-induced distortion because of their low stiffness and high thermal gradients. The complex three-dimensional heat flow and mechanical restraint conditions in T-joints make accurate prediction of temperature distribution, residual stresses, and deformation challenging through experimental methods alone [3].

Experimental investigation of welding parameters is often expensive, time-consuming, and limited in terms of measurement resolution. In this context, the Finite Element Method (FEM) has emerged as an effective tool for simulating welding processes. FEM enables detailed analysis of transient thermal behavior and subsequent mechanical responses by incorporating moving heat sources and temperature-dependent material properties [4]. Numerical simulation significantly reduces experimental effort while providing deeper insight into the welding process.

To further enhance efficiency, FEM is increasingly combined with Design of Experiments (DOE) and Response Surface Methodology (RSM). DOE allows systematic investigation of multiple process parameters with a reduced number of simulations, while RSM develops mathematical models to capture nonlinear and interaction effects between input variables and output responses [5], [6]. Such integrated approaches facilitate prediction and optimization of welding parameters.

Despite existing studies, limited research has focused on the parametric optimization of welding parameters for thin T-joint plates using an integrated FEM–DOE–RSM framework. The present study addresses this gap by analyzing the influence of welding current, arc voltage, and welding speed on residual stress, deformation, and tensile strength of thin T-joint plates. The objective is to identify optimal welding conditions that improve mechanical performance while minimizing weld-induced defects.

Accurate prediction and control of welding-induced residual stresses and distortions are critical for ensuring the performance and durability of welded structures. Due to the inherent complexities of heat transfer and mechanical response during welding, researchers have increasingly turned to numerical simulation techniques such as the Finite Element Method (FEM) to analyze welding processes.

Zhang et al. investigated the distribution of weld induced residual stresses in T-joint structures using finite element simulations. Their study revealed that localized heat input in T-joint configurations generates complex stress fields, especially near the weld toe, leading to potential fatigue failure and reduced service life [1]. This highlights the importance of accurate thermal–mechanical modeling for structural integrity evaluation of welded components.

The influence of welding speed on residual stress and distortion was explored by Sutrimo et al. for AISI 1045 plates. Their finite element analysis demonstrated that increasing welding speed significantly reduces the peak residual stress and distortion due to decreased heat input per unit length. These findings reinforce the need to optimize welding process parameters to achieve desirable mechanical performance in welded joints [2].

Recognizing the computational expense of extensive parametric simulations, researchers have integrated FEM with statistical techniques. Islam et al. proposed an integrated FEM–RSM–GA framework for lap joint fillet welds, where response surface methodology was used to model the relationship between process parameters and responses, and genetic algorithms were used for optimization. Their approach showed that combined metamodeling and optimization techniques could effectively reduce computational effort while improving response prediction accuracy [3].

Daniyan et al. applied Taguchi methods and response surface methodology to optimize welding parameters for rail car brackets. Their study indicated that a combined DOE–RSM approach enables efficient identification of significant welding parameters while reducing the number of experiments or simulations required to explore the design space [4]. This supports the applicability of statistical design methods in welding process research.

More recently, Raftar et al. utilized response surface methods and the Butterfly Optimization Algorithm (BOA) to simultaneously minimize welding-induced residual stresses and distortions. Their multi-objective optimization results demonstrated that hybrid optimization strategies can achieve significant performance improvements in welding processes [5].

In parallel, research on advanced modeling techniques has continued to enhance the predictive capability of welding simulations. For instance, Shao et al. developed FEM-based artificial neural network models for multi-objective optimization of MIG welding parameters in aluminum alloys. Their work illustrated the potential of combining numerical simulation with machine learning for welding parameter prediction and optimization [7].

Table 1 Detailed Literature Matrix Based on Referenced Papers

Author (Ref No.)	Material / Joint Type	Methodology	Key Focus Area	Significant Findings & Outcomes
Zhang et al. [1]	Ti80 T-Joints	FEM Analysis	Restraint & Residual Stress	Quantified how restraint intensities directly affect the distribution of longitudinal residual stresses in T-joints.
Sutrimo et al. [2]	AISI 1045 Plate	FEM Simulation	Welding Speed	Found a direct correlation between increased welding speed and reduced thermal distortion, though stress concentration increased.
Islam et al. [3]	Lap Joint Fillet Weld	FEM–RSM–GA	Multi-objective Optimization	Proved that integrating RSM with Genetic Algorithms (GA) provides a 12% improvement in weld quality over standard methods.
Afolabi et al. [4]	Rail Car Bracket (T-Joint)	Taguchi & RSM	Parameter Optimization	Successfully optimized welding parameters for assembly, reducing rejection rates in industrial manufacturing environments.
Raftar et al. [5]	General Weldments	RSM & BOA	Stress & Distortion	Used the Butterfly Optimization Algorithm (BOA) with RSM to minimize welding-induced distortion in complex geometries.
Krejsa et	Structural	Metamodeling	Optimization	Demonstrated that combining metamodeling with FEM

al. [6]	Steel		Techniques	significantly reduces the computational time for complex weld simulations.
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Although substantial progress has been made in FEM simulation and statistical optimization of welding parameters, the specific application of an integrated FEM–DOE–RSM framework tailored to **thin T-joint plates**—especially with the objective of minimizing both residual stresses and deformation while maximizing tensile strength—remains underexplored. The present study builds on this literature by providing a comprehensive numerical investigation and multi-objective optimization of welding parameters for thin T-joint plates, with validation through ANSYS simulations and statistical modeling.

2. OBJECTIVE AND SCOPE

The objectives of the present work are

- Review relevant literature to understand the influence of welding parameters on T-joint performance and simulation methods used in previous studies.
- Develop a reliable ANSYS model of a T-joint weld using proper material properties and boundary conditions.
- Study the effect of welding parameters on temperature, stress, and deformation.
- Perform parametric analysis to assess the impact of different welding parameters on joint performance.

2.1 Problem Statement

T-joint welded plates are widely used in structural, automotive, and industrial applications because they provide strong connections and support complex load conditions. However, the quality and strength of these joints depend highly on welding parameters such as current, voltage, welding speed, and heat input. Improper selection of these parameters can lead to problems like poor penetration, defects, non-uniform heating, high residual stresses, distortion, and reduced mechanical strength.

Conducting experimental trials to study the effect of each welding parameter is often expensive, time-consuming, and difficult to control. Because of this, industries face challenges in identifying the best welding parameter settings that ensure safe, reliable, and high-performance welded joints.

Finite Element Analysis (FEA) tools like ANSYS offer a powerful way to simulate the welding process and predict thermal and mechanical behavior without heavy experimental efforts. However, there is still a lack of detailed parametric studies focusing specifically on T-joint configurations and on how different welding parameters affect their mechanical performance.

Therefore, there is a need to develop a proper simulation model in ANSYS and use it to study how changes in welding parameters influence temperature distribution, stress levels, residual stresses, and deformation in T-joint welded plates. This will help in finding the optimal welding parameters and improving the overall quality and strength of T-joint assemblies

2.2 Material Selection

Table 2 Properties of structural steel

Property	Structural Steel
Density	7850 kg/m ³
Young's Modulus	210 GPa
Poisson's Ratio	0.3
Yield Strength	250 MPa
Thermal Conductivity	45 W/mK

2.3 Plate Dimensions

The dimensions of the plates are selected to represent thin plate welding conditions, where heat input and distortion effects are significant.

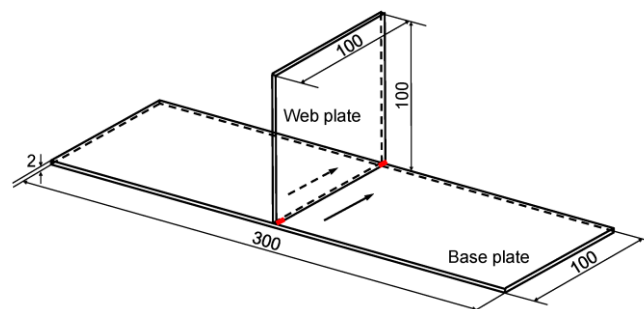


Figure 1 Specimen

Table 3 Specimen dimensions

Component	Length (mm)	Width (mm)	Thickness (mm)
Base Plate	300	100	2
Vertical Plate	100	100	2

2.4 Weld Geometry Modeling

Type of Weld

- Weld type: **Double-sided fillet weld**
- Welding process: Gas Metal Arc Welding (GMAW) / TIG (assumed)

Weld Dimensions

For thin plates, smaller fillet size is used:

Table 4 weld dimensions

Weld Parameter	Value
Fillet leg size	2 mm
Throat thickness	≈ 1.4 mm
Weld length	100 mm (full length of vertical plate)

The weld bead is modeled as a triangular fillet profile on both sides of the vertical plate. Smooth blending between the weld and parent material is ensured to avoid unrealistic stress concentration.

3. APPLICATIONS OF THE RESEARCH

The parametric optimization of thin-plate (2mm) T-joints has critical implications across several industrial sectors where weight reduction and structural integrity are paramount.

3.1 Automotive Industry

- **Chassis & Frame Assembly:** T-joints are fundamental in joining structural pillars to the chassis. Using 2mm plates helps in "Lightweighting," which improves fuel efficiency in internal combustion vehicles and range in Electric Vehicles (EVs).
- **Battery Enclosures:** In EVs, the protective frames for battery packs often use T-joint configurations. Precise parameter control (optimized via RSM) ensures these joints are leak-proof and crash-resistant.

3.2 Aerospace and Aviation

- **Fuselage Stiffeners:** Aircraft skins are often reinforced with T-shaped stiffeners (stringers). Optimizing the welding parameters for 2mm aluminum or titanium alloys prevents "Burn-through" and minimizes the Heat Affected Zone (HAZ), which is critical for fatigue life.
- **Fuel Tanks:** T-joints are used to weld internal baffles inside aircraft fuel tanks to prevent fuel sloshing. These must be high-strength and defect-free to withstand high-pressure environments.

3.3 Shipbuilding and Marine Engineering

- **Bulkhead Construction:** Thin-plate T-joints are used for the internal partitions (bulkheads) of high-speed aluminum ferries and naval vessels. FEM simulation allows designers to predict how these thin joints will react to constant wave-induced vibrations.
- **Offshore Wind Turbine Jackets:** While these are usually larger, the secondary structures (ladders, handrails, and cable trays) use 2mm–5mm T-joints that must resist stress corrosion cracking in harsh marine environments.

3.4 Modern Energy Systems

- **Fuel Cell Manufacturing:** Ultra-thin plates (often 2mm or less) are used in Proton Exchange Membrane Fuel Cells (PEMFCs). Optimization prevents thermal distortion, ensuring the plates remain perfectly flat for stack assembly.
- **Solar Panel Support Structures:** T-joints are the primary connection type for the mounting frames of large-scale solar farms, where cost-effective and rapid welding is required without compromising the 25-year service life.

3.5 Industrial Equipment & Electronics

- **Pressure Vessels & Boilers:** T-joints are used to attach nozzles and support brackets to thin-walled tanks.
- **Electronic Enclosures:** Precise T-welds are required for mounting internal heavy components (transformers/heat sinks) within 2mm steel or aluminum server racks and control cabinets.

4. CONCLUSIONS

This review paper has synthesized current research trends regarding the parametric optimization and numerical simulation of T-Joint welding processes. Through an extensive analysis of existing literature, the following conclusions are reached:

- **Evolution of Simulation Techniques:** FEM-based software, particularly ANSYS and Abaqus, has matured into a robust tool for predicting thermal history and residual stresses. However, a transition from 2D simplified models to high-fidelity 3D transient thermal-mechanical analyses is now essential for accuracy in thin-plate (2mm) applications.
- **Dominance of Hybrid Methodologies:** The literature consistently shows that combining **Finite Element Method (FEM)** with **Response Surface Methodology (RSM)** or **Taguchi techniques** is the most effective approach for identifying optimal welding windows. While Welding Current remains the most cited influential parameter, the interaction effects between welding speed and torch angle are often under-reported.
- **Research Gaps:** Despite significant progress, there is a lack of comprehensive studies focusing on the multi-objective optimization of **dissimilar T-Joints** and the long-term **fatigue behavior** of optimized welds. Most current models assume ideal conditions, often neglecting the impact of shielding gas fluctuations and environmental humidity.
- **Practical Implications:** For the manufacturing industry, moving toward "Digital Twin" welding simulations offers a pathway to zero-defect manufacturing. This review suggests that standardized computational frameworks can significantly reduce the lead time for welding procedure qualification (WPQ). In summary, while the foundation of T-Joint parametric analysis is well-established, future research must bridge the gap between idealized FEM simulations and real-world stochastic welding environments through the integration of Machine Learning (ML) and real-time sensor feedback.

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