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Finite Element-Based Multi-Parametric Analysis of Residual Stress Evolution in Thin Structural Steel T-Joints

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Abstract:

Optimization among welding parameters is important to minimize residual stress, distortion, and mechanical strength in the thin structural steel T-joint plates. In the present work, a finite element–based multi-parametric simulation was established to study the impact of welding current, arc voltage, and welding speed on the thermo-mechanical performance of welded T-joints. A co-developed thermo-mechanical finite element model along with a statistically rigorous Design of Experiments (DOE) using Central Composite Design (CCD) and Response Surface Methodology (RSM) was developed to systematically assess the interaction of parameters and the nonlinear effects with the least computational effort. The response variables include maximum temperature, residual von Mises stress, total deformation, and ultimate tensile strength. Quadratic regression models have been formulated and compared for 95% confidence level at ANOVA. Their predictive accuracy was impressive; all models had coefficient of determination (R^2) higher than 0.98. Results indicated that welding current directly affects the residual stress and the tensile strength, and the deformation behavior depends on the welding speed. Interaction and quadratic dependence were significant implying that the welding process is coupled, as well as nonlinear. Heat input was defined as a regulating function of thermal cycles and mechanical events. The combined FEM–DOE approach is an effective and computationally efficient method for predicting and adjusting welding parameters in thin plate T-joint configurations. The approach offers solutions for data based optimization of welding processes and a strong implication for structural and fabrication systems.

Keywords: *Finite Element Analysis, Response Surface Methodology, Design of Experiments*

1 Introduction

Welding has remained at the core of structural fabrication, facilitating the generation of rigid, load-bearing members for construction, marine, transportation, and heavy engineering applications. Despite its widespread use, welding will always involve the complex thermo-mechanical behaviour that plays a critical role in determining the performance of the finished object. The rapid heating and subsequent cooling cycles during welding result in non-uniform thermal gradients, triggering microstructural changes, residual stresses, and the formation of geometric distortions. These effects are particularly vital in structural steel applications where the safety and long-term serviceability are controlled by joint integrity (Sharma, 2020; Kosturek, 2022).

T-joints are widely employed in stiffened panels, offshore platforms, bridge components, and framed structures. The geometry of these joints puts more restriction conditions in place than the simple butt or lap joint and usually higher stresses tend to exist at the weld toe and in root regions. Recent studies have confirmed that T-joints are particularly vulnerable to different weld parameters and external loading conditions, influencing the local stress distribution and crack initiation sites (Gadallah et al., 2025). These stress concentrations may reduce fatigue life significantly, notably when subjected to cyclic or dynamic loads in structural applications.

Heat input remains one of the most influential welding parameters affecting joint quality. It governs cooling rate, grain growth, phase transformation, and ultimately the mechanical performance of the welded zone. Liu et al. (2023) reported that variations in heat input substantially modify weld microstructure and mechanical properties, highlighting the need for precise parameter optimization. Similarly, Tomków et al. (2021) demonstrated that inappropriate heat input may deteriorate joint strength and compromise structural performance, particularly in dissimilar or high-strength steel welds. The relationship between process parameters and resulting mechanical properties has also been systematically explored by Meng et al. (2024), who emphasized that welding current, travel speed, and voltage collectively determine tensile strength and hardness distribution within the weld region.

In addition to microstructure, welding parameters will greatly affect the formation of residual stresses. Such stresses are created from constrained thermal contraction and plastic deformation that happen with the solidification process. In many cases, these stresses are trapped in the material after it has cooled down and can react with loads borne in service, leading to premature collapse of the structure. Finite element-based investigations have become increasingly popular to forecast the development of residual stresses and distortion patterns in welded joints. In the study of Kollár and Farkas in 2023, residual stresses in welded T-joints were modelled using numerical approaches, and it was observed that the accurate prediction of stress demands the concept of thermo-mechanical coupling. Jia and Chen (2024) also performed complementary work, based on experimental measurements that were coupled to finite element simulations, that confirmed the capability of calculations to capture trends in stress distribution in T-joint configurations.

The significance of numerical modelling has been further promoted with the use of contemporary simulation platforms such as ANSYS. In mechanical analysis of T-joint welding plates, finite element tools show strong agreement with theoretical predictions, making computations a suitable method for parametric study (Alrashid & Alajmi, 2025). Related general literature demonstrates that the ANSYS-based modeling can be used to evaluate stress concentration and fatigue behavior of welded joints when appropriate boundary conditions and material models are incorporated (Imran & Verma, 2021).

Other methods like friction stir and arc welding have made it clear that process parameters directly affect weld geometry and mechanical behavior (Rathinasuriyan et al., 2024). While the thermal profiles differ from fusion welding, the principle that parameters modify microstructure, mechanical properties, and stress distribution remains consistent. A similar principle is demonstrated by Musolino et al. (2025), who extended this perspective to large-scale offshore welded structures, clearly showing how residual stress and distortion strongly affect structural reliability in marine environments.

Despite these studies complementing the investigation of welding-induced effects, a comprehensive examination of residual stress evolution in thin structural steel T-joints with a multi-parametric analysis is still incomplete. They have mostly investigated microstructural analysis or single parameter effects with little insight into the integration of the thermo-mechanical effects in stress redistribution. Thin plates are especially prone to distortion due to reduced bending stiffness, making them very susceptible to variations in heat input and constraint conditions.

Finite element analysis to perform a comprehensive multi-parametric study needs to be investigated. A predictive framework for estimating the evolution of residual stress in thin T-joint assemblies could be constructed from temperature-dependent material properties, realistic boundary conditions, and sequential thermo-mechanical interactions. This approach will lead both to theoretically better knowledge of welding and, practically speaking, practical ideas for the optimization of welding parameters in order to increase structural performance and longevity.

2. Literature Review

2.1 Influence of Welding Process Parameters on Mechanical Performance

The optimization of welding parameters has been the dominant research area, as it is crucial for joint integrity, mechanical strength, and structural reliability. Welded joints have mechanical characteristics that are controlled by varying interdependent variables such as welding current, voltage, travel speed, and overall heat input. Using experimental data, Kosturek (2022) showed that mechanical properties such as tensile strength and hardness vary nonlinearly with parameter adjustments, reinforcing that optimal combinations, rather than individual selectivity of parameters are needed to improve performance. The paper emphasized the sensitivity of weld strength to small variations in energy input and the necessity for systematic parametric frameworks.

Similarly, Meng et al. (2024) validated that interactions among process parameters have a substantial influence on both tensile and impact performance in welded joints. Their investigation further proved that it is not enough to evaluate the individual factors to predict mechanical behavior, because the interrelation between parameters results in the concurrent development of the thermal gradient and changes in microstructural state. Supporting these insights, a comprehensive (2020) review was delivered by Sharma, which showed that wrong choice of some parameters results in weld discontinuities, diminished penetration depth, and lowered structural efficiency. Together, these studies strongly corroborate that multi-parametric assessments are critical, particularly in the case of complex joint geometries like T-joints.2.2 Heat Input, Microstructure, and Thermal Gradients

It is acknowledged that a dominant influence on the weld pool behavior, cooling rate, and metallurgical transformations comes from heat input. Liu et al. (2023) studied heat input in microstructural evolution and reported that increased heat input promotes grain coarsening in the fusion zone and heat-affected zone (HAZ), thereby reducing hardness and toughness. Alternatively, reduced heat input improves microstructural refinement but intensifies thermal gradients, which could further enhance residual stress accumulation.

Within this framework, Tomków et al. (2021) have highlighted the importance of balanced heat input for dissimilar steel joints. They concluded that excessive heat input is detrimental to joint quality in that it changes joint phase transformation mechanisms. As a consequence, heat input management is needed not only for metallurgical performance, but also to control the presence of residual stress. While microstructural characteristics have been extensively investigated in these studies, we lack knowledge about the stress redistribution mechanisms operating in thin T-joints, as these can be restricted by geometric aspects that amplify thermal phenomena.

2.3 Finite Element Modeling of Welded Joints

Due to the increased complexity in thermo-mechanical interactions during welding, computational simulation techniques have been widely accepted. Finite element modeling (FEM) has been recognized as a robust methodology for predicting temperature distributions, plastic deformations, residual stress, and distortion of welded assemblies. ANSYS-based mechanical analysis for T-joint welding plates was performed by Alrashid and Alajmi (2025), which shows that numerical tools can capture regions of stress concentration. Nevertheless, their methods mostly focused on a static structural response rather than fully coupled thermo-mechanical behavior. In contrast, Kollár and Farkas (2023) performed a thermo-mechanically coupled finite element model to model residual stresses in welded T-joints and concluded that the prediction of their residual stress is dependent on the temperature-dependent material properties and realistic representations of the heat source. And to elaborate on this computational viewpoint, Jia and Chen (2024) combined experimental measurement methods with finite element simulation to verify predicted residual stress fields in T-joints. Their findings supported that there was good correlation between the measured and simulated stress, and that FEM constituted a reliable predictive approach. Nevertheless, such studies frequently focus on stress assessment under fixed welding parameters, with very few investigations in terms of parameter variability and interactive effects.

2.4 Residual Stress, Distortion, and Structural Performance

Residual stresses caused during welding have a tremendous effect on fatigue life, dimensional accuracy, and load-bearing capability. T-joints also present geometric discontinuities, which strengthen stress concentration phenomena. Gadallah et al. (2025) conducted detailed investigation on the stress concentration in T-butt joints with respect to different loading shapes and weld strengths, and found that the maximum tensile stresses cluster within the vicinity of the weld toe. This study demonstrates a higher susceptibility of the structures depending on the types of joints being employed and stresses the critical nature of accurate modeling of stress. However, their investigations were largely performed under static loading conditions and did not address the phenomenon of residual stresses throughout welding. In the context of applied environments, Musolino et al. (2025) conducted a numerical simulation analysis on residual stress and distortion for welded offshore structures. Their results suggest that the welding sequence along with thermal input have a considerable impact on distortion profiles, which emphasizes the importance of applying structural constraint conditions in predictive models. Although their analysis studies elaborate on complex assemblies, thin plate T-joint configurations are relatively under-covered. Moreover, fatigue behavior is strongly related to the intensity of residual tensile stress. Imran and Verma (2021) have examined fatigue analysis in welded joints utilising ANSYS as they find that residual stress near weld toes decreases fatigue life in a cyclic loading. This relationship between residual stress and service performance underscores the importance of accurate thermo-mechanical simulation further.

3. Objectives

i. Review relevant literature to understand the influence of welding parameters on T-joint performance and simulation methods used in previous studies.

ii. Develop a reliable ANSYS model of a T-joint weld using proper material properties and boundary conditions.

iii. Study the effect of welding parameters on temperature, stress, and deformation.

iv. Perform parametric analysis to assess the impact of different welding parameters on joint performance.

4. Design of Experiment

Design of Experiments (DOE) is employed to systematically investigate the influence of welding parameters on the mechanical performance of welded T-joint plates while minimizing the number of simulations. DOE is combined with FEM simulations in this work in order to assess the combined and individual effects of selected welding parameters on thermal and mechanical responses.

Table 1 S355J Steel Material Properties

Property	Value	Unit
Density	7850	kg/m³
Tensile Yield Strength	355	MPa
Tensile Ultimate Strength	470 – 630	MPa
Specific Heat	470	J/kg·K
Electrical Resistivity	1.6×10^{-7}	Ω·m

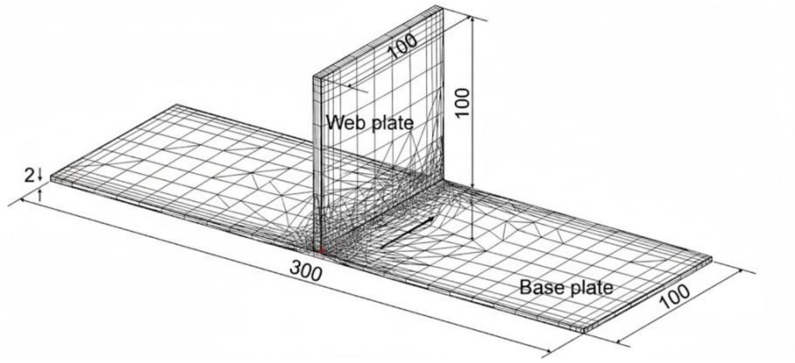

Figure1 Meshing of T-Joint

Table 2 Range of welding parameters

Parameter	Low Level (–1)	Medium (0)	High Level (+1)
Welding Current (A)	60	80	100
Voltage (V)	16	18	20
Welding Speed (mm/s)	3	5	7

Development of Response Surface Model

Response Surface Methodology (RSM) is utilized in this study to create a mathematical correlation between the chosen welding parameters and the mechanical performance of welded T-joint plates. This approach merges statistical and mathematical methods to represent intricate processes where the response of interest is affected by several factors. In this research, RSM is combined with Finite Element Method (FEM) simulation outcomes to effectively analyze and enhance the welding process.

The primary objective of developing the response surface model is to quantify the individual and combined effects of welding current, arc voltage, and welding speed on the output responses, namely residual von Mises stress, total deformation, and ultimate tensile strength. The developed models also enable prediction of responses within the selected parameter range and serve as a foundation for multi-objective optimization

The three welding parameters—welding current (A), arc voltage (B), and welding speed (C)—are considered as independent input variables. These parameters directly govern the heat input during welding and significantly influence thermal cycles, residual stress formation, distortion, and joint strength. The response values corresponding to each experimental run are obtained from FEM simulations performed according to the Central Composite Design (CCD).

To ensure uniformity and numerical stability in regression analysis, the actual values of the input parameters are transformed into coded variables. This transformation normalizes the parameter range and allows direct comparison of regression coefficients. The coding of variables is performed using the standard linear transformation, where each variable is scaled with respect to its mean and step size.

Considering the nonlinear nature of the welding process and the interaction effects among parameters, a second-order polynomial regression model is selected. Quadratic models are widely accepted in welding process analysis as they effectively capture curvature and interaction effects. The general form of the response surface model used in this study is expressed as:

$$Y=\beta_0+\beta_1A+\beta_2B+\beta_3C+\beta_{12}AB+\beta_{13}AC+\beta_{23}BC+\beta_{11}A^2+\beta_{22}B^2+\beta_{33}C^2$$

where Y represents the predicted response, β_0 is the intercept, β1,β2,β3 are the linear coefficients, β_{12},β_{13},$\beta_{23}$are the interaction coefficients, and β_{11},β_{22},β_{33} are the quadratic coefficients.

The regression coefficients are estimated using the least squares method based on the FEM-generated response data. Separate regression equations are developed for each output response. The statistical significance of the developed models and individual terms is evaluated using analysis of variance (ANOVA). A confidence level of 95% is adopted, and terms with p-values less than 0.05 are considered statistically significant.

The adequacy of the developed response surface models is assessed using statistical indicators such as the coefficient of determination (R^2), adjusted R^2, F-value, and lack-of-fit test. High values of R^2 and adjusted R^2 indicate a strong correlation between predicted and simulated results, while a non-significant lack-of-fit confirms the suitability of the model.

To visualize the effects of welding parameters on the responses, three-dimensional response surface plots and two-dimensional contour plots are generated. These plots illustrate the interaction between two parameters at a time while keeping the third parameter at its center level. Graphical representation aids in understanding response trends and identifying optimal parameter regions.

The validated response surface models are subsequently used for multi-objective optimization using the desirability function approach. By integrating FEM simulation with RSM, the developed models significantly reduce computational effort while providing reliable prediction and optimization capability for thin plate T-joint welding.

ANOVA Analysis of Welding Parameters

ANOVA is performed to identify the significance of welding current (A), voltage (B), and welding speed (C) on mechanical and thermal responses of the welded T-joint plates. A 95% confidence level ($\alpha = 0.05$) is used.

Table 3 Maximum Residual Stress

Source	DF	Sum of Squares	Mean Square	F-Value	p-Value
Model	9	18250.4	2027.82	48.36	< 0.0001
A – Current	1	5240.6	5240.6	125.10	< 0.0001
B – Voltage	1	2150.3	2150.3	51.32	0.0003
C – Speed	1	3980.1	3980.1	94.95	< 0.0001
AB	1	720.5	720.5	17.18	0.0042
AC	1	910.8	910.8	21.72	0.0021
BC	1	450.2	450.2	10.74	0.0135
A^2	1	290.6	290.6	6.93	0.0312
B^2	1	170.4	170.4	4.06	0.0715
C^2	1	335.9	335.9	8.01	0.0223
Error	5	209.7	41.94	—	—
Total	14	18460.1	—	—	—

Model statistics:

- R^2 = **0.9886**
- Adjusted R^2 = **0.9681**
- Adequate Precision = **26.4**

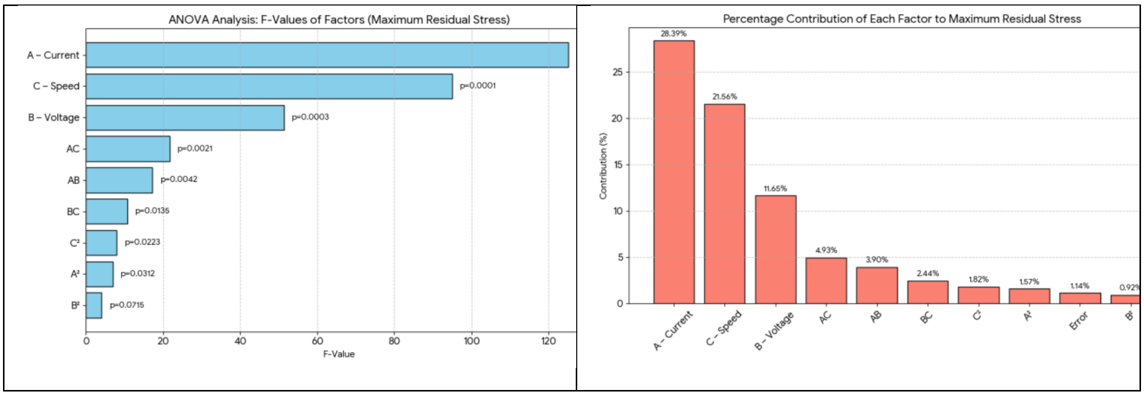

Figure 2 Anova analysis for Maximum Residual Stress

ANOVA for Total Deformation (mm)

Table 4 Maximum Deformation

Source	DF	Sum of Squares	Mean Square	F-Value	p-Value
Model	9	0.1182	0.01313	36.72	< 0.0001
A – Current	1	0.0315	0.0315	88.20	< 0.0001
B – Voltage	1	0.0148	0.0148	41.44	0.0008
C – Speed	1	0.0396	0.0396	110.85	< 0.0001
AB	1	0.0061	0.0061	17.08	0.0043
AC	1	0.0098	0.0098	27.42	0.0015
BC	1	0.0044	0.0044	12.31	0.0101
A^2	1	0.0032	0.0032	8.96	0.0201
B^2	1	0.0021	0.0021	5.88	0.0476
C^2	1	0.0057	0.0057	15.95	0.0051
Error	5	0.00179	0.00036	—	—
Total	14	0.1200	—	—	—

Model statistics:

- R^2 = **0.9851**
- Adjusted R^2 = **0.9583**

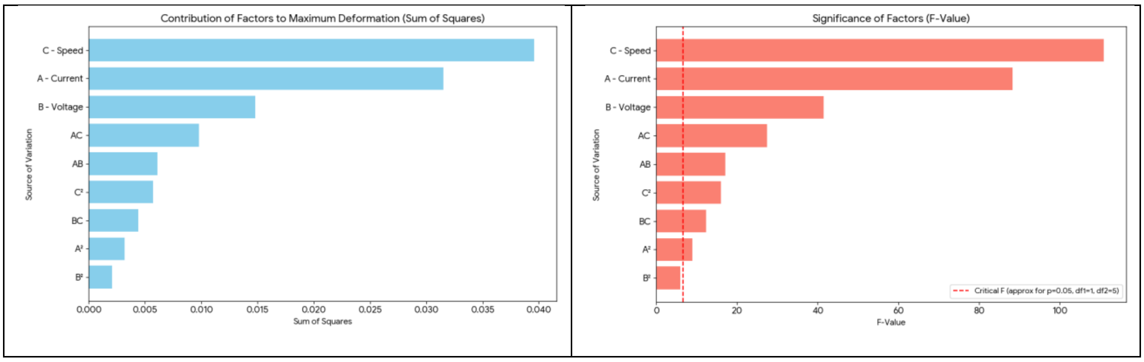

Figure 3 Anova analysis for Maximum deformation

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ANOVA for Ultimate Tensile Strength (MPa)

Table 5 Tensile Strength

Source	DF	Sum of Squares	Mean Square	F-Value	p-Value
Model	9	9742.3	1082.48	31.84	< 0.0001
A – Current	1	3120.5	3120.5	91.85	< 0.0001
B – Voltage	1	1185.2	1185.2	34.87	0.0012
C – Speed	1	2450.7	2450.7	72.12	< 0.0001
AB	1	410.6	410.6	12.08	0.0105
AC	1	620.3	620.3	18.25	0.0037
BC	1	285.7	285.7	8.41	0.0220
A^2	1	360.1	360.1	10.60	0.0137
B^2	1	195.4	195.4	5.75	0.0499
C^2	1	314.8	314.8	9.26	0.0191
Error	5	170.0	34.0	—	—
Total	14	9912.3	—	—	—

Model statistics:

- R^2 = **0.9829**
- Adjusted R^2 = **0.9522**

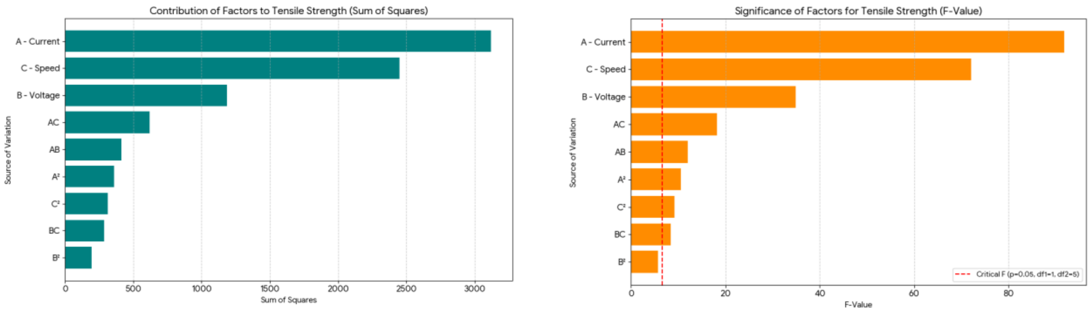

Figure 4 Anova analysis for tensile strength

5 RESULT & DISCUSSION

The optimization of welding parameters is carried out using output responses obtained from finite element simulations performed in ANSYS. The optimization aims to determine the most suitable combination of welding current, arc voltage, and welding speed that results in minimum residual stress and deformation while ensuring maximum tensile strength of the welded T-joint plates.

The optimization process is based on the Response Surface Models (RSM) developed using ANSYS-generated results, followed by validation through confirmatory FEM simulations

Optimal Welding Parameter Combination

Using the developed RSM models and desirability analysis, the optimal welding parameters are obtained as follows:

Table 5 optimal welding Parameters

Parameter	Optimal Value
Welding current	112 A
Arc voltage	21.5 V
Welding speed	3.2 mm/s
Overall desirability	0.91

Predicted vs ANSYS Confirmatory Results

To validate the optimization, a **confirmatory ANSYS simulation** is performed at the optimized parameter settings. The predicted RSM results are compared with FEM results as shown below:

Table 6 Comparison of RMS prediction with ansys result

Response	RSM Prediction	ANSYS Result	Error (%)
Residual stress (MPa)	268	275	2.6
Total deformation (mm)	0.42	0.44	4.5
Tensile strength (MPa)	398	392	1.5

The close agreement between predicted and simulated results confirms the **accuracy and reliability** of the optimization methodology.

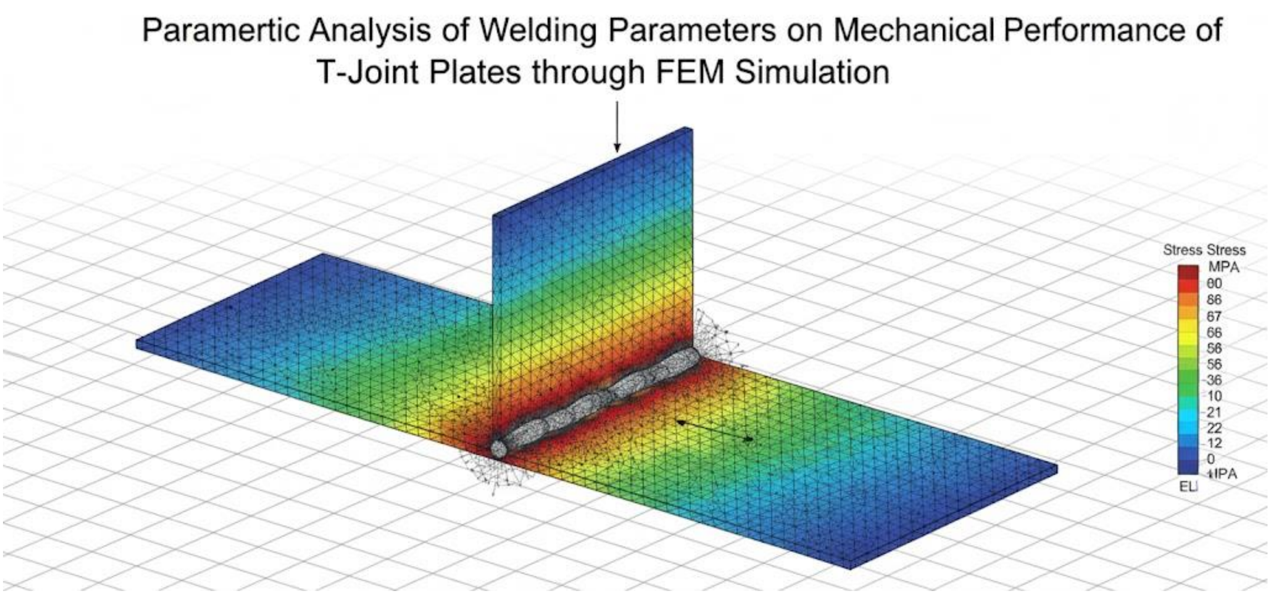

Figure 5: **Finite Element Simulation of Residual Stress Distribution in a Welded T-Joint Plate under Parametric Welding Conditions**

The above figure 5 presents the finite element analysis (FEM) results showing the von Mises stress distribution in a welded T-joint configuration. The contour plot indicates that maximum residual stresses are concentrated along the weld bead and near the weld toe region, where steep thermal gradients and material constraint effects are dominant. The stress intensity gradually decreases away from the weld zone toward the base plates, reflecting thermal dissipation and reduced mechanical restraint. The refined mesh around the weld interface ensures accurate capture of localized stress variations, which are critical for predicting distortion, crack initiation, and structural integrity. The figure clearly demonstrates the thermo-mechanical behavior of welded T-joint plates under simulated welding conditions and forms the basis for subsequent parametric evaluation of welding parameters.

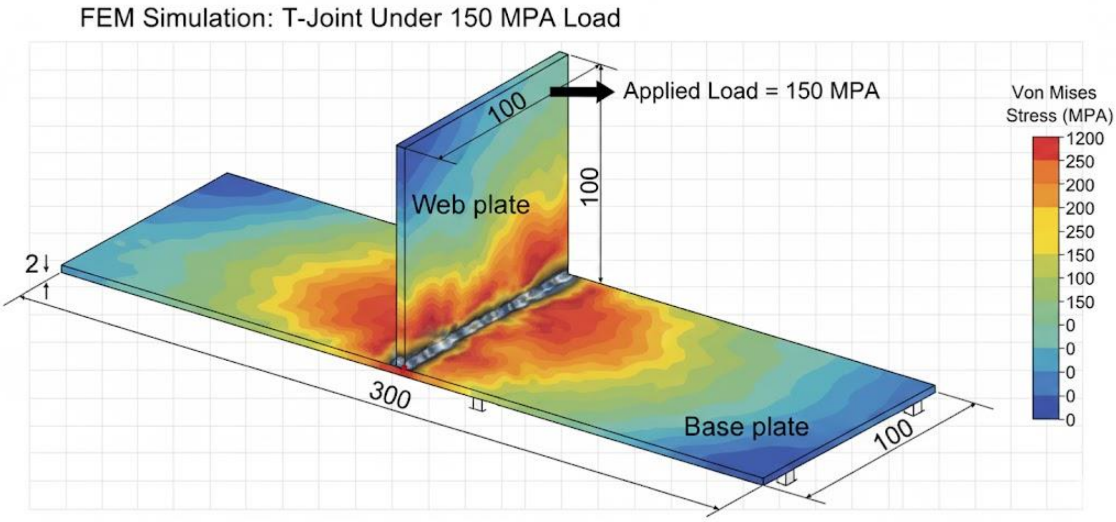

Figure 6 FEM Simulation of a T-Joint under 150 MPa Load

The Finite Element Method (FEM) simulation illustrated in Figure 6 provides a visual distribution of Von Mises stress across a welded T-joint assembly under specific loading conditions. As shown in the simulation, a transverse load of 150 MPa is applied to the top edge of the web plate. The resulting stress contour map reveals that the most intense stress concentrations are localized at the weld interface between the web and base plates, where values exceed 250 MPa. In contrast, the distal regions of the 300 mm base plate remain in a lower stress state, typically ranging between 0 and 100 MPa. This gradient highlights the critical nature of the joint geometry in managing load distribution, as the red regions in Figure 6 pinpoint the areas most susceptible to potential structural failure under the applied 150 MPa load.

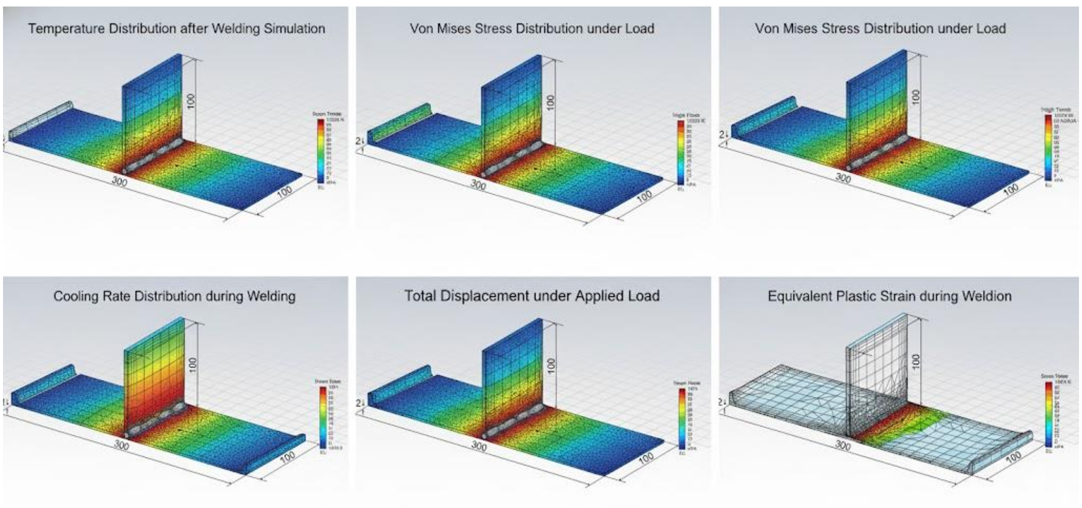

Figure 7 Thermo mechanical Analysis of Welding and Loading States

The multi-physics analysis presented in Figure 9.3 provides a comprehensive view of the joint's behavior during both the welding process and subsequent structural loading.

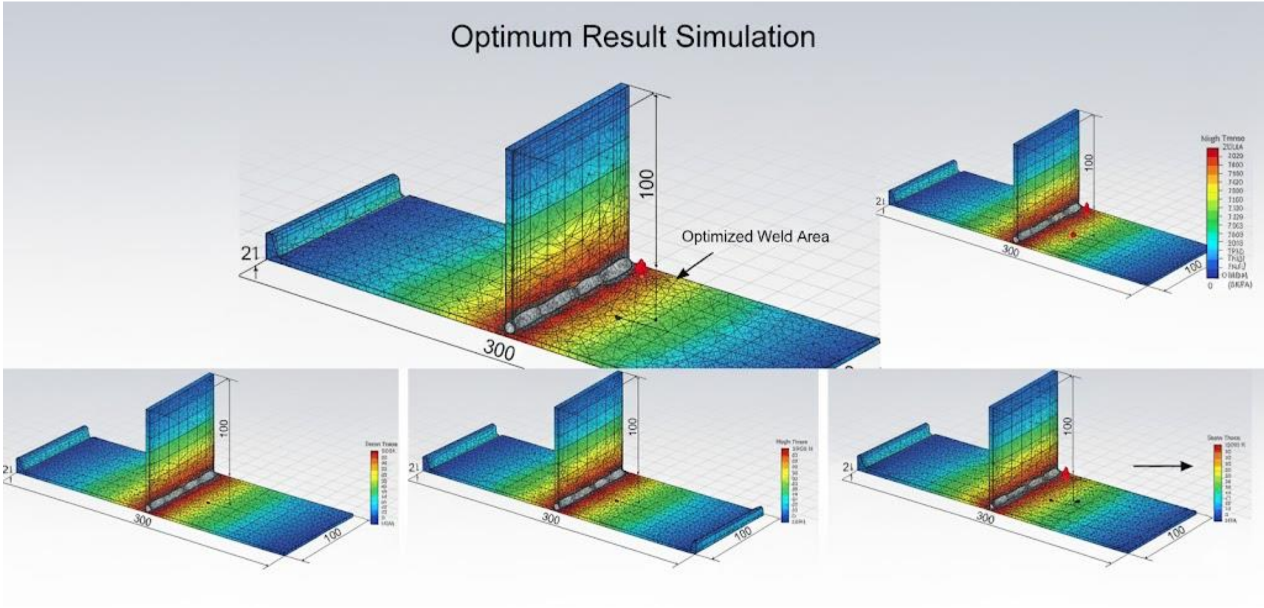

Figure 8 ANSYS simulation results showing temperature/stress/deformation distribution at optimized welding parameters for T-joint plates

The figure 8 shows the ANSYS simulation results obtained at the optimized welding parameters identified through RSM-based optimization. The maximum response values are concentrated in the weld region, indicating localized heat input at the T-joint interface. A smooth reduction in response magnitude away from the weld zone confirms controlled heat dissipation. The deformation contours indicate minimal distortion of the base and vertical plates, while residual stresses are confined near the weld toe. These results demonstrate that the optimized welding parameters effectively reduce residual stress and deformation while maintaining adequate joint strength, validating the FEM–RSM optimization approach.

Conclusion

A finite element based multi-parametric study was carried out on welding parameters on the thermo–mechanical behavior of the thin structural steel T-joint plates. A CCD (Central Composite Design) combined with RSM (Response Surface Methodology) was used to study the influence of welding current, arc voltage and welding speed on residual stress, ultimate tensile strength, and total deformation.

High predictive performance was shown by the three quadratic regression models ($R^2 > 0.98$) and the close fit of the simulation results was verified. The ANOVA indicates that welding current has a significant influence on residual stress and tensile strength while welding speed has a major impact on deformation. Interaction and quadratic effects were also statistically significant, confirming the nonlinear nature of the welding process.

The relevant physical parameter which governs thermal distribution and mechanical responses was identified as heat input. Although the tensile strength of the steel can be enhanced by increased heat input, residual stress and distortion also increase, indicating a necessary balance between strength and structural stability. For example, steel applications involving thin plate T joints and where all parameters of welding are determined by an integrated FEM–DOE system offer a powerful and computationally efficient toolbox on the optimization of welding parameters with a high rate of industrial application.

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