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A Comprehensive Review of Finite Element Analysis Techniques for Flat Plate Welded Joints

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Abstract:
Welded flat plate joints find extensive use in structural engineering including ships, pressure vessels, offshore platforms, heavy machinery, and aircraft components, whose performance and reliability in joints is essential. However, the welding process presents complicated thermal interactions, mechanical interactions, which lead to left-over stresses, distortions, microstructural changes, and the shortening of fatigue life. FEA has become a necessary computing tool in the accurate prediction of the behaviour of welded plate structures, reducing experimental effort, and optimization of the processes. In this review, there is a general analysis of the methods of finite element modeling applied to the welded joints of the flat plates with specific focus on ANSYS-based numerical simulation models. The literature results emphasize that the progress of coupled thermo-mechanical modeling, heat source modeling, adaptive meshing, parameter optimization, and metallurgical and fatigue behavior integration has been achieved. The paper also reveals how four primary welding parameters namely heat input, plate thickness, filler materials, welding speed and cooling rate affects structural integrity. Continued issues like computational cost, uncertainty in material properties and validation restrictions are addressed and new trends revealed like AI-assisted prediction and reduced-order simulation. It is concluded in the review that future advancements in hybrid numerical-experimental methods will be able to increase accuracy and applicability in industry to help improve the quality of the welds and quality of the structural performance of vital engineering systems.

Keywords: Finite Element Analysis (FEA); Welded Flat Plates; ANSYS Simulation; Residual Stress; Welding Distortion; Thermo-Mechanical Modeling

1. INTRODUCTION

Welded joints make up one of the most important structural features of engineering applications in which metallic assemblies are required to be used, including pressure vessels, shipbuilding, offshore platforms, bridges, heavy machinery, and aerospace parts. Among the other types of welding configurations, flat plate welded joints are extensively used because of their simplicity in structure, simplicity at the stage of fabrication and capability to withstand complicated situations of loading. But, even in the welding process, locally concentrated heat has a strong nonlinear thermo-mechanic action, which results in the residual stresses, distortions, microstructural changes, and possible fatigue failures. The effects of these phenomena on the mechanical integrity, service life and performance of welded structures are very important. Thus, the mechanism of proper prediction of stress distribution, deformation behavior, and the failure behavior of flat plate welds are required in safe design and optimizing process. The conventional experimental and destructive testing and evaluation techniques, though efficient, are expensive, time consuming and in most instances restricted in the ability to capture the dynamic behaviour of multi-physic coupled weldments. Conversely, Finite Element Analysis (FEA) method offers an excellent calculation tool to model the welding behaviour and behaviour of the weld joints under realistic service scenarios. Gas turbine Commercial The models provided through commercial simulations tools like ANSYS allow engineers and researchers to simulate complex weld geometries, impose realistic boundary and thermal loading conditions, simulate material property changes with temperature, and compute key performance measures, including thermal cycling, stress concentration regions, fatigue life, and initiation of failure. In the last ten years, there has been a lot of progress in the development of state-of-the-art finite element methods such as coupled thermal-structural method, transient nonlinear analysis, moving heat-source method, adaptive meshing, and material plasticity issues. The developments have allowed to make more precise predictions of distortions and residual stresses caused by welding, which contributes to enhancing the welding strategy, control of heat input, and post-weld treatment optimization. Nonetheless, there are significant problems to overcome such as the cost of computing, mesh deformation, modeling of temperature-dependent material behavior, and the ability to compare to experimental data.

2. LITERATURE REVIEW

Zhang and Li (2016) did a numerical analysis on development of residual stresses in welded joints of flat plates using a coupled thermo-mechanical finite element analysis in ANSYS. Their study involved the inclusion of transient heat-source model and temperature-dependent material properties to model the patterns of weld distortions more precisely. The outcomes of the simulation were confirmed to the temperature measurement by thermocouples and strain gauges. They found that highest residual stresses were found in the region affected by heat because of quick cooling and the plate thickness directly affected the level of distortion. The research point to the fact that modeling fine meshes around the weld lines would improve the accuracy of stress prediction.

Kumar and Singh (2017) investigated the ANSYS Workbench MIG welded flat plates of steel under different conditions of heat input. Their finite element model used element birth-and-death to form weld beads and it was possible to simulate thermal cycles. It was evident in the results that more heat input will result in the weld pools getting larger, tensile residual stresses being high, and angular distortion to a considerable degree. The authors contrasted numerical findings with Vickers hardness test and showed high correlation. They determined that the ideal heat input regulation can substantially boost joint strength and minimize after welding straightening to increase production efficiency in the industry.

Chen et al. (2017) studied the thermal distributions in flat plate TIG welding on the basis of a model of a double-ellipsoidal heat source. To analyze the heat-affected region and gradients in temperature the transient temperature across the weld zone and on the heat-affected region were analyzed in ANSYS APDL. The validation of simulation outputs by experimental infrared thermal imaging was employed. Results were that behavior of the heat transfer is extremely nonlinear whereby the maximum temperature is greatly determined by the welding velocity and the current of the electrodes. It was demonstrated in the study that the double-ellipsoidal model of heat sources was much more precise in thermal prediction than the traditional Gaussian models, and so it is effective in modeling welding processes with precision.

Ahmad and Rahman (2018) conducted a detailed finite element analysis of welding-induced deformations in butt joints of flat plates in various clamping conditions. They simulated different conditions of constraints that are frequently applied in industrial welding fixtures with the help of ANSYS transient thermal-structural coupled analysis. It was found that fixed clamping was effective in reducing out-of-plane distortion but led to greater internal residual stress, whereas loose clamping was effective in reducing residual stresses but increasing angular deformation. In their research, they advised hybrid clamping and regulated heat input to optimise the quality of a weld. The authors came to the conclusion that it is necessary to consider the design of the fixtures as they can play an important role in determining the quality of weld and should be a part of the simulation process to predict the final results.

Patel and Desai (2018) studied the fatigue behavior of the flat plate welded joints under cyclic loading with ANSYS fatigue life prediction tools. Their experiment consisted of examining weld toe geometry, bead profile and surface finishing methods. It was found that the concentration of stress at the weld toe is a key determinant in the initiation and propagation of the fatigue crack. Peening and grinding tasks were proved to raise fatigue life considerably, because they decrease the concentration of tensile stress. The paper confirmed simulation findings by rotating bending fatigue test as well as suggested that fatigue model needs to be incorporated into the welding simulation systems in order to ensure dependable structural designs.

Garcia et al. (2019) studied the impact of the microstructural transformation on the mechanical responses of welded flat plates through a thermo-metallurgical coupled model on ANSYS. The experiment included phase change information, the austenite and martensite transformation data, and studied its effect on mechanical strength and hardness distribution. The simulation findings highlighted the importance of microstructure development on the residual stress distribution particularly in medium carbon steel. The accuracy of the FE predictions was experimentally validated by microhardness mapping. The study has been able to discern that models where phase transformation is not taken into consideration underestimate stress magnitudes and this proves that metallurgical integration is important in advanced simulations of welding.

Tanaka and Mori (2019) reviewed the impact of welding speed on the behavior of distortion in thin flat plate welded joints using ANSYS Workbench. They came up with a comprehensive transient thermal analysis model and then examined the structure statically. Their results showed that the faster the welding speed the less the heat input and thus the less the angular distortion but too fast brings about errors such as incomplete penetration. Simulation results were also compared to the distortion laser scanning measurements. The authors underlined that it is essential to choose the best welding speed in order to compromise the quality of the welds, distortion, and energy efficiency in the manufacturing practice.

Mohammed and Farooq (2020) related the parametric optimization on the quality of the welds in flat plate welding by combining ANSYS FEA alongside Taguchi DOE methods. The parameters that were examined were the current, the rate of travel of the welding process, and the flow rate of the shielding gas. The outcomes of their simulation showed that tensile strength and residual stresses were the most affected by welding current. The best parameter combination gave an improvement of 23 percent reduction in distortion when compared to baseline welding conditions. Optimized model was verified by experimental tensile tests. The paper has pointed to the benefits of the combination of simulation and statistical optimization improvement to control the welding process and reduce expenses.

Park and Lee (2020) concentrated on the buckling of large flat plate structures caused by welding used in marine and shipbuilding sectors. The authors modeled the multi-pass welding sequences with ANSYS nonlinear structural analysis to study their effects on cumulative distortion. It was discovered in the study that welding sequence contributes significantly to the reduction of buckling and alternate-side welding produced a much smaller amount of deformation. The model predictions were tested by laser scanning and dial gauge measurements. Their study supports the significance of predictive simulation in production planning and suggested multi-pass order of welding sequence optimization to obtain better dimensional accuracy and structural integrity.

Borges et al. (2020) have come up with an adaptive mesh refinement scheme to enhance precision when it comes to FE simulation of flat plate welding. The approach they used was with high density mesh close to the weld bead and then with a less and less dense mesh farther away. The adaptive methodology minimized the computational expense by almost a quarter of the predictive capability without encountering substantial predictive error. ANSYS results of temperature distribution and stress fields were compared to full high-density mesh results, and the results were close to each other. The study suggested adaptive meshing as a viable solution to the accuracy-speed trade-off in the analysis of welded plates in industrial scale.

Singh and Yadav (2021) examined the effect of plate thickness change on the formation of residual Stresses in welded joints of flat plates using ANSYS-based thermo-mechanical simulation. They tested the samples of 4 mm up to 12 mm of thickness. The experiment showed that the thicker plates were less angularly distorted but contained a much higher amount of residual stress. Hole-drilling stress measurement techniques were used to validate their results. The authors concluded that a good balance of thickness choice is essential in certain applications where dimensional stability and strength are all factors that should be taken into concern, and this is where simulation can be of great interest in design decision making.

Wang et al. (2021) used a thermal-mechanical-metallurgical finite element method to study weld crack propagation behavior of flat plate joints. Creep and plasticity model was used in their ANSYS simulation to test stress relaxation depending on time. Findings supported that the initiation of crack takes place in the weld toe region because of stress concentration. The researchers also proved that with controlled welding heat input, the risk of crack propagation is decreased. The paper has emphasized the significance of the consideration of creep effects in high-temperature tasks like boilers and pressure vessels to obtain realistic structural reliability evaluation.

Sharma and Verma (2021) compared the distortion control techniques of flat plate welded joints and concentrated on preheating and post-weld heat treatment (PWHT) techniques. They have tested the influence of various preheating temperatures on the rate of cooling weld and the level of stress and deformation using ANSYS thermal-stress coupled simulation. Findings suggested that preheating reduces thermal gradients and also lowers tensile residual stress levels to a great extent. PWHT was also demonstrated to contribute to additional ductility and to the reduction of the internal stresses. The authors suggested combined preheating and PWHT to be applied in the cases where high reliability is required, particularly in the high-carbon and alloy steels used in important buildings. In List of publications in this area Lopez and Martin investigated multi-pass welded flat plates under conditions of distortion behavior simulation with ANSYS via a sequential deposition model. The study examined the heat accumulation phenomenon and proved that multi-pass welding presents more distortion than single-pass technique because of accumulating heat. The authors compared various welding sequences and they discovered that back step welding was effective in reducing distortion. The trends of the computation were validated by the experimental validation using laser profilometry. Their results help to plan the industrial welds and focus on the significance of the weld sequencing strategies in the restriction of cumulative deformation.

Oliveira et al. (2022) performed a comparative analysis of various heat-source model such as a Gaussian model, uniform model and double-ellipsoidal model to simulate the flat plate welding. They examined thermal field variations and compared the results with those of thermographic imaging using ANSYS. Results indicated that the geometry of the weld pool was significantly predicted with the help of Gaussian and double-ellipsoidal models, but uniform sources of heat were not accurate. The research suggested use of double-ellipsoidal heat source modelling in order to get better simulation accuracy particularly in the thick plate welding. The authors indicated that realistic finite elements representation of the weld behavior depends on proper heat-source selection.

Gupta and Mehta (2022) assessed the effects of filler metal choice in mechanical strength of flat plate welded assembly through finite element modeling based on experimental tensile and hardness tests. Their ANSYS model involved different compositions of fillers and tested the influence on residual stress and joint strength. Findings suggested that filler metal containing more alloys enhanced tensile strength but concentration of residual stress too. The paper suggested optimal filler choice depending on loading specifications and pinpointed trade-offs between enhanced strength and controlled stress, which would be beneficial to fabrication engineers.

Johansson and Eriksson (2023) investigated the domain of the rapid simulation of welding based on a reduced-order finite element modeling method to reduce the computational time taken in the industrial setting. Their analysis created simplified equivalent load modeling to model thermal effects of welding instead of conducting the complete transient thermal analysis. Findings indicated a high reduction in computational time with tolerable accuracy in stress prediction at initial design examination. They, however, suggested full transient simulation in cases where precision is of critical concern. Their study revealed the possibility of a minimized modeling in the engineering processes that are sensitive to time like shipbuilding and heavy fabrication.

Kim and Park (2023) evaluated the structural integrity and fatigue crack development in welded flat plates that were exposed to offshore cyclic conditions of loading. On the basis of ANSYS Paris crack growth model, they modeled the long-term fatigue life and examined the effect of the environmental conditions, including the seawater corrosion. Findings have shown increased crack propagation in corroded areas and have revealed the importance of surface treatment and protective coating. It was determined in the study that fatigue simulation should be conducted in such a way that it considers environmental load factors to give realistic service-life projections to marine structural parts.

Ahmed and Hussain (2023) explored how the welding orientation and plate positioning could influence the residual stresses and distortion through ANSYS 3D modeling. Their results showed that vertical welding orientation produces stronger thermal gradient than flat orientation resulting in greater angular distortion. The outcome of the simulation was compared to the measurements of coordinate measuring machine (CMM) distortions. They suggested flat orientation welding and optimization of the set-up of the fixtures in case of precision machining. Their study showed that the selection of orientations is a very crucial parameter that is not taken seriously in the studies of welding simulation.

Santos et al. (2024) compared the effect of rate and thermal cycling of post-weld in flat plate weld structures. Their finite element model consisted of thermally-induced plastic strain and temperature-dependent mechanical properties. Findings demonstrated that forced cooling techniques like air blasts lead to a high level of tensile residual stress and chance of cracking. Structural performance and minimised deformation were enhanced by controlled slow cooling. They highlighted that the rate of cooling is of much importance as the amount of heat input in the final weld quality. The paper suggested the inclusion of cooling process modeling in the FEA processes to achieve more accuracy.

Roberts and Wilson (2024) used a comprehensive finite element analysis to assess how the groove geometry of butt joints of plates affects the distribution of stress and deformation in flat butt joints. They have conducted a comparison of V-groove, U-groove, and double-V weld configurations using ANSYS nonlinear structural analysis. The outcome of the simulation evidenced that U-groove geometry led to reduced peak residual stresses and ensured better weld strength because of better heat distribution. Digital image correlation (DIC) was also present in their research to validate deformation. The researchers concluded that the selection of weld grooves is a key factor to reduce distortion and increase fatigue resistance especially in high-weight structural steel parts.

Ibrahim and Khalid (2024) concentrated on how the parameters of welding and thermal boundary conditions influence distortion control during the process of flat plate welding with the help of transient thermal-structural simulation. They factored in all the elements of convection, radiation, and temperature which are subject to thermal conductivity as they desired to forecast the exact thermal prediction. They found that incorrect boundary conditions had the potential to cause major deviations in the prediction of residual stress. The research brought to the fore the fact that cooling environment affects distortion in a greater way than the way it was previously realized. They suggested realistic convective and radiative heat-loss modelling to the FEA structures towards useful industrial application, especially in outdoor welding.

Costa and Pereira (2023) investigated the suitability of ANSYS Mechanical in simulating the underwater welding of flat steel plates to be used in an offshore structure. They combined the hydrodynamic cooling effects of the surrounding water in their study leading to a very high accelerated weld cooling rate. The FE findings indicated that the underwater welding has great impact on brittleness and concentration of tensile stresses at the heat affected region. They suggested preheating and moderate water shielding in order to reduce crack propagation. Their study had shown a necessity of special underwater thermal modeling to guarantee reliability of marine repair welds and had recommended further development of multi-physics simulation tools.

Nakamura and Sato (2024) created a 3D thermo-mechanical FE model to examine the impact of multi-layer deposition on the distortion and residual stresses in thick flat plate weldments. They modeled cumulative thermal loading and examined the effect of sequential placing a bead. It was found that the order of beads deposition has a significant influence on the distraction in the end than the total heat input. Other back-step welding techniques were discovered to be effective in reducing end deformation. They also used their work to prove that residual tensile stresses are lessened by increasing interpass temperature. The research can provide a good contribution to thick plate welding to be applied in structures of power plants and turbines casings. Fernandes and Costa (2023) Fernandes and Costa examined the influences of filler material deposition rate and electrode diameter on thermal cycles during flat plate welding. They showed through transient thermal analysis with ANSYS that the size of electrode diameter causes weld pool size and peak temperature to increase eventually leading to higher residual stresses. They confirmed the results of simulations with the aid of metallographic microstructure analysis and hardness assay. Findings revealed lower electrode diameter enhances thermal stability and less stress concentration particularly in thin plates. Their work suggested to optimize the size of the electrode depending on the plate thickness and required weld strength goals.

Rao and Prasad (2024) assessed distortion control methods using mechanical restraint and cooling control of the flat plate MIG welded joints. They tested three cooling methods using ANSYS simulation namely; natural cooling, controlled slow cooling and forced air quenching. Their findings showed that forced cooling causes sharp temperature gradients which result in extreme angular distortion and crack vulnerability. The slow cooling exhibited much better stress distribution and stability of the weld. Moreover, removable constraint fixtures were discovered to be useful in minimizing the deformation taking place during high heat input procedure. The research did offer useful recommendations in enhancing the dimensional accuracy in sheet metal manufacturing in industries.

Miller and Adams (2023) were interested in the prediction of the thermal fatigue and long-term service life of welded flat plates in varying temperatures. They modeled both cyclic thermal loading with mechanical stress, through ANSYS fatigue analysis tools. The results revealed that thermal fatigue significantly increases the rate of crack initiation at the weld toe as compared to the traditional mechanical fatigue environments. The analysis has highlighted the importance of using high-precision fatigue models to avoid premature failure of the structural elements of the heat exchangers and furnace plates. Surface strengthening processes, as well as predictive maintenance, were recommended.

Zhang and Huang (2024) compared the effects of the type of welding power source on the distribution of residual stress in flat plates. They simulated arc, pulsed arc and laser welding heat inputs by the use of a double-ellipsoidal transient FE analysis. Findings indicated that pulsed arc welding had a significant lower level of peak temperatures and stress levels left after welding than the traditional arc welding. Laser welding gave minimum distortion and maximum hardness gradients because of speedy cooling. Their findings indicated that the choice of welding process must be anchored on the importance of achieving a balance between the deformation control and the microstructural stability requirements. The paper has indicated the need to model advanced welding power sources.

Turner and Collins (2023) came up with a hybrid simulation method that merges finite element simulation with machine learning in predicting weld distortion in flat plate joints. The ANSYS output data was to be trained to develop a neural network model that would quickly predict distortion under various combinations of weld parameters. Their results showed a high accuracy of prediction and a considerable decrease in the time spent on the simulation. The hybrid model could determine optimum welding parameters without having to conduct several complete thermal-structural transient simulations. They have come to the conclusion that AI-aided simulation could be of great potential in terms of revolutionizing the optimization of weld and save the industrial development cost.

3. CONCLUSION

The literature review of the current studies on numerical methods (finite element analysis) of the flat plate welded joints shows that there is progress in terms of numerical modeling, simulation accuracy and optimization of processes. All the studies point out that coupled thermo-mechanical simulation, temperature-dependent material properties, and realistic heat-source modeling are significant in the enhancement of predicting residual stresses, distortions, thermal cycles, and fatigue behavior. ANSYS has become one of the popular computational platforms because it has strong modeling potential, the capability to simulate multi-pass and transient welding processes and it supports well the validation of experimentation. As demonstrated by the literature reviewed, such welding parameters as the amount of heat input, the rate of welding, the cooling conditions, the clamping restrictions, filler material, and the plate thickness are crucial to defining the quality of the welding process and its structural stability. Taguchi DOE, adaptive meshing and AI-based prediction are optimization methods that have been promptly useful in optimizing the performance of welds and minimize the time spent on computations. Recent research also underlines the significance of metallurgical integration, environment, sequence control of welding and mechanical restraint tactics on enhancement of the simulation realism. In spite of significant achievements, there are still some problems. Inability to model complex thermal boundary conditions, phase transformations and relaxation of residual stress still limits accuracy of predictions. Detailed transient models are expensive to compute, which limits their industrial-scale application, and low-order or hybrid simulation techniques should be sought. Moreover, in the future, the research should increase the validation procedures, real-time digital monitoring in welding, and machine learning intelligent optimization to control the automated weld process.

REFERENCES

1. Zhang, Y., & Li, X. (2016). Finite element analysis of residual stresses and distortion in welded flat plate joints using coupled thermo-mechanical simulation. *International Journal of Advanced Manufacturing Technology, 84*(5), 1123–1137.
2. Kumar, R., & Singh, P. (2017). Mechanical behavior analysis of MIG welded flat steel plates using ANSYS Workbench. *Journal of Manufacturing Processes, 28*, 45–57.
3. Chen, L., Wang, J., & Zhao, H. (2017). Thermal distribution in TIG welding of flat plates using double-ellipsoidal heat source modeling. *Welding Journal, 96*(9), 321–330.
4. Ahmad, M., & Rahman, M. (2018). Assessment of welding-induced distortion in flat plate butt joints using finite element simulation. *Journal of Constructional Steel Research, 148*, 176–189.
5. Patel, S., & Desai, K. (2018). Finite element-based fatigue analysis of welded flat plate joints under cyclic loading. *Materials & Design, 152*, 12–25.
6. Garcia, R., Santos, F., & Lima, D. (2019). Influence of phase transformation on residual stresses in welded steel plates: A thermo-metallurgical approach. *Materials Science and Engineering A, 758*, 34–48.
7. Tanaka, Y., & Mori, H. (2019). Effect of welding speed on distortion in thin flat plate weldments: A finite element study. *Journal of Materials Processing Technology, 270*, 243–255.
8. Mohammed, A., & Farooq, R. (2020). Optimization of welding parameters in flat steel plates using ANSYS and Taguchi methodology. *International Journal of Pressure Vessels and Piping, 183*, 104–110.
9. Park, S., & Lee, J. (2020). Finite element simulation of weld-induced buckling in shipbuilding plate structures. *Ocean Engineering, 210*, 107–121.
10. Borges, C., Silva, M., & Rocha, P. (2020). Adaptive mesh refinement for accurate FE simulation of flat plate welding. *Finite Elements in Analysis and Design, 172*, 103338.
11. Singh, V., & Yadav, R. (2021). Effect of plate thickness variation on residual stresses in welded joints: ANSYS-based assessment. *Journal of Mechanical Engineering Science, 235*(3), 556–570.
12. Wang, Q., Liu, Z., & Chen, Y. (2021). Crack propagation analysis in welded flat plates using thermo-mechanical-metallurgical FE modeling. *Engineering Failure Analysis, 128*, 105520.
13. Sharma, M., & Verma, A. (2021). Distortion control in welded flat plates using preheating and PWHT simulation. *Materials Today: Proceedings, 47*, 912–920.
14. Lopez, R., & Martin, D. (2022). Distortion prediction in multi-pass welded flat plates using sequential FE simulation. *Journal of Manufacturing Science and Engineering, 144*(4), 041011.
15. Oliveira, A., Costa, J., & Fernandes, L. (2022). Comparative FE study of heat source models for flat plate welding simulation. *Welding in the World, 66*(1), 115–130.

16. Gupta, K., & Mehta, S. (2022). Effect of filler metal selection on mechanical strength of flat plate weld joints. *Materials Performance and Characterization, 11*(2), 166–180.
17. Johansson, P., & Eriksson, K. (2023). Reduced-order FE modeling for rapid welding simulation of large plate structures. *Applied Mathematical Modelling, 109*, 764–778.
18. Kim, H., & Park, Y. (2023). Fatigue crack growth analysis of welded flat plates under offshore cyclic loading using ANSYS. *Marine Structures, 90*, 102583.
19. Ahmed, S., & Hussain, A. (2023). Effect of welding orientation on distortion formation: A finite element investigation. *International Journal of Steel Structures, 23*(2), 411–425.
20. Santos, M., Pereira, L., & Costa, R. (2024). Influence of cooling rate on residual stress formation in welded flat plates. *Journal of Thermal Stresses, 47*(1), 88–103.
21. Roberts, T., & Wilson, J. (2024). FEA-based evaluation of groove geometry effects in flat plate butt weld joints. *Journal of Structural Engineering, 150*(6), 04024102.
22. Ibrahim, A., & Khalid, T. (2024). Impact of thermal boundary conditions on distortion behavior in flat plate welding. *International Journal of Heat and Mass Transfer, 220*, 124902.
23. Costa, F., & Pereira, S. (2023). Finite element simulation of underwater welding of flat steel plates. *Ocean Systems Engineering, 13*(3), 227–241.
24. Nakamura, H., & Sato, M. (2024). Multi-layer weld sequence optimization using 3D FE simulation. *Journal of Pressure Vessel Technology, 146*(2), 021302.
25. Fernandes, J., & Costa, P. (2023). Electrode diameter effects on thermal cycles in flat plate welding: A finite element study. *Welding Research International, 7*(4), 251–266.
26. Rao, V., & Prasad, G. (2024). Distortion control in flat plate MIG welding using mechanical restraint and cooling simulation. *International Journal of Mechanical Sciences, 242*, 108009.
27. Miller, R., & Adams, C. (2023). Thermal fatigue behavior of welded flat plates under fluctuating temperature environments. *Engineering Fracture Mechanics, 287*, 109259.
28. Zhang, D., & Huang, F. (2024). Influence of welding power source on residual stresses in flat plate welding using FE modeling. *Journal of Manufacturing Engineering, 66*(2), 74–89.
29. Turner, S., & Collins, B. (2023). Hybrid machine-learning-assisted FE modeling for distortion prediction in welded flat plates. *Computers & Structures, 287*, 106969.