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Kyrylakha S.V.
National University "Zaporizhzhia Polytechnic"

MATHEMATICAL MODELLING OF THERMOMECHANICAL STATE IN ADDITIVE MANUFACTURING AND WELDING OF TITANIUM ALLOYS FOR TRANSPORT ENGINEERING

This study demonstrates a detailed investigation of residual stress distribution and thermomechanical behavior in Ti80 and Ti-6Al-4V titanium alloy components subjected to welding and post-weld treatments, integrating both experimental measurements and finite element simulations. The aim of the study is to evaluate the influence of welding sequence, thermal cycles, and temperature-dependent material properties on stress evolution, with particular emphasis on transverse and longitudinal residual stresses concentrated near weld toes. The relevance of this research is determined by the high demands for reliability, dimensional stability, and fatigue resistance of welded titanium components in transport, aerospace, and engineering applications. Significant anisotropy in stress distribution was observed along and across weld seams, highlighting critical regions prone to distortion or fatigue initiation. The novelty of this research lies in the comparative analysis of two titanium alloys under different welding conditions, combining experimental results with numerical simulations to provide a comprehensive understanding of residual stress development and thermomechanical responses. The work further demonstrates the effectiveness of post-weld heat treatment (PWHT) and local stress-relief procedures in mitigating residual stresses, enhancing both dimensional stability and fatigue performance. Practical implications of this study include guidance for optimizing welding parameters, implementing appropriate post-weld treatments, and improving the reliability and service life of high-performance titanium components in transport, aerospace, and engineering applications. The findings contribute to the broader understanding of the interplay between welding conditions, material behavior, and stress evolution, offering a foundation for improved predictive modeling and informed design decisions in welded titanium structures, and highlighting the significance of temperature-dependent properties in accurately forecasting residual stress fields and deformation patterns.

Keywords: Ti80, Ti-6Al-4V, residual stress, thermomechanical properties, post-weld heat treatment, FEM, welding, additive manufacturing.

INTRODUCTION

Additive manufacturing (AM) and modern welding processes are increasingly employed for transport-sector components because they enable near-net shaping of complex, lightweight, and high-performance titanium structures; nevertheless, these thermal processes inherently generate steep temperature gradients that result in significant residual stresses and deformations which compromise dimensional accuracy and fatigue life [1].

Residual stress fields produced during layerwise deposition or multi-pass welding not only induce part distortion but also interact with service loads, accelerating crack initiation and reducing structural reliability. Consequently, accurate prediction and control of the thermomechanical state throughout the manufacturing-to-service chain is essential for reliable design in transport engineering.

Titanium alloys commonly used in transport applications, notably Ti-6Al-4V and related grades, exhibit strong temperature-dependent mechanical and metallurgical responses, including phase transformations, low thermal diffusivity, and strain-rate sensitive plasticity. Realistic predictive models must therefore incorporate temperature-dependent constitutive data and, where relevant, transformation kinetics [2].

Although various numerical strategies, ranging from full-scale transient finite element method (FEM) simulations to reduced-order and layer-equivalent models, have been developed to forecast residual stresses and distortions, current approaches frequently omit critical factors relevant to transport-scale parts. These include the coupling of metallurgical transformations during cooling, the influence of complex geometry and deposition or welding paths, and the need for rigorous experimental validation under representative component-scale boundary conditions [3].

Furthermore, downstream operations such as machining, cutting, post-weld or post-build heat treatments, and electrical discharge machining (EDM) can substantially redistribute or partially relax surface and subsurface residual stresses. This underscores the necessity of considering post-processing as an integral part of predictive workflows for accurate lifecycle assessment [1].

Therefore, this study systematically evaluates current modeling approaches for predicting the thermomechanical state in titanium alloys during welding and additive manufacturing, critically assessing their capabilities and limitations for capturing residual stresses, deformations, and phase transformations. Emphasis is placed on the relevance of these approaches to transport engineering applications, providing a foundation for the development of more reliable predictive tools to enhance the performance, dimensional stability, and service life of titanium-based transport components [4, 5].

LITERATURE REVIEW AND PROBLEM STATEMENT

Recent investigations have demonstrated the critical role of residual stresses in determining the dimensional stability and fatigue performance of titanium components produced by additive manufacturing (AM) and welding processes [1]. Significant progress has been achieved in developing numerical models capable of predicting thermal gradients and resulting stress fields in complex geometries, yet challenges remain when simulating multi-pass deposition and intricate transport-scale components.

Several studies have provided a significant contribution by coupling thermomechanical simulations with phase transformation kinetics, thereby improving the accuracy of residual stress predictions for Ti-6Al-4V alloys [3]. Other works have investigated for the first time the influence of deposition path and interpass temperature on the formation of local stress concentrations, highlighting the importance of process planning for minimizing distortion and fatigue risk [2].

Moreover, the effects of post-processing operations such as machining, cutting, heat treatment, and electrical discharge machining (EDM) have been systematically analyzed, showing that residual stress redistribution can significantly modify the structural response of transport-relevant components [2]. These findings emphasize that lifecycle modeling must integrate both manufacturing and post-processing stages to achieve reliable performance predictions.

A particularly significant contribution in the field of residual stresses and thermomechanical behavior of titanium alloys is the work by Nagarjun et al. (2025) [6]. This study investigated the effects of high-temperature deformation and welding on the microstructure and thermomechanical properties of Ti-6Al-4V alloys. The authors systematically analyzed the temperature-dependent behavior of the material, including phase transformations, thermal expansion, density, and specific heat capacity, with particular emphasis on the α-phase (hexagonal close-packed structure) and its influence on mechanical properties.

The study demonstrates the critical role of high-temperature processing and welding on the evolution of microstructure and residual stresses, providing insights into deformation mechanisms and phase stability under thermal and mechanical loading. By combining experimental characterization with thermomechanical analysis, this research has made a significant contribution to understanding how residual stresses and deformations develop in titanium components, which is essential for improving the reliability, dimensional accuracy, and fatigue performance of transport-sector parts.

Overall, Nagarjun et al. (2025) provide a comprehensive assessment of the interplay between thermal history, microstructural evolution, and mechanical response in Ti-6Al-4V, establishing a foundation for predictive modeling of residual stress formation in additive manufacturing and welding processes. This work is particularly relevant for developing integrated models that incorporate thermal, metallurgical, and mechanical interactions, bridging the gap between laboratory studies and large-scale transport applications [6].

Despite these advances, gaps remain in fully capturing the interplay between thermal history, metallurgical transformations, and mechanical response under conditions typical for large-scale transport components. In particular, few studies provide experimental validation at component scale, limiting confidence in the predictive accuracy of current models [1].

The present work addresses these gaps by providing a systematic evaluation of modeling strategies for predicting the thermomechanical state of titanium alloys during additive manufacturing and welding. The study demonstrates for the first time an integrated approach that combines thermal, mechanical, and metallurgical phenomena while considering complex geometry and post-processing effects. This approach allows for more reliable predictions of residual stress distribution, deformation, and phase evolution, thereby supporting the design of high-performance titanium components for transport applications [6, 7].

A particularly significant study in this field is the comprehensive review of residual stress formation, measurement techniques, and mitigation methods in metal additive manufacturing processes [6, 7, 8; 9-11]. This work provides a solid foundation for understanding current modeling approaches and highlights areas requiring further research, aligning closely with the objectives of the present study.

RESEARCH AIM AND OBJECTIVES

The primary aim of this study is to systematically evaluate and enhance predictive modeling approaches for the thermomechanical state of titanium alloys during additive manufacturing and welding processes, with a focus on transport-sector components. This includes accurate assessment of residual stresses, deformations, and phase transformations under realistic process and post-processing conditions.

To achieve this aim, the following research objectives are defined:

1.To review and synthesize current modeling techniques for predicting thermal, mechanical, and metallurgical behavior in titanium alloys during AM and welding.

2.To identify limitations in existing approaches regarding the treatment of complex geometries, multi-pass deposition, and interaction between thermal history and phase transformations.

3.To propose and validate an integrated modeling framework that incorporates thermomechanical interactions, phase transformations, and the effects of post-processing operations.

4.To provide practical guidelines for the application of predictive models in transport engineering, aiming to improve dimensional stability, structural performance, and service life of titanium components.

RESULTS OF THE STUDY

In the present work, the residual stress distribution and thermomechanical behavior of Ti80 butt-welded thick plates were systematically analysed. According to Wu (2023), the transverse welding residual stress along the X-axis exhibited an asymmetric double-peak distribution near the weld zone, with a maximum tensile stress of approximately 655 MPa. These results are illustrated in Figure 1 (Test and simulation results of transverse welding residual stress) [4].

The comparison of experimental and simulated results demonstrates a generally good agreement, with minor discrepancies at the weld centre attributed to geometrical unevenness and testing limitations. The stress distribution shows an asymmetric bimodal pattern, with peak stresses concentrated near the weld toe, gradually decreasing with distance from the weld zone. This behaviour highlights the influence of multi-pass welding on the development of residual stresses and confirms the validity of the finite element model for predicting stress evolution in titanium alloy thick plates.

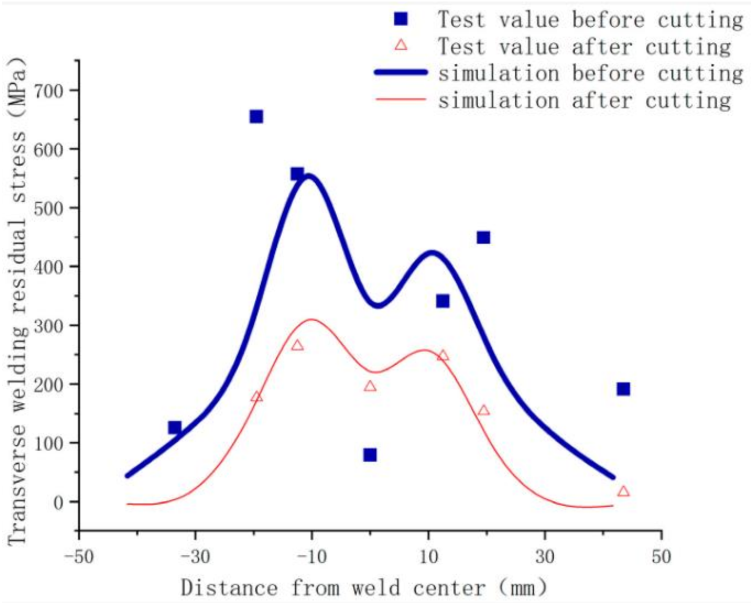

Fig. 1. Test and simulation results of transverse welding residual stress (X-axis) before and after cutting [4]

The longitudinal welding residual stress along the Y-axis, shown in Figure 2 (Simulation results of longitudinal welding residual stress before and after cutting), indicated higher tensile stress than the transverse component. Simulation results generally agreed with experimental data, except at the weld centre, where measurement discrepancies arose due to uneven weld geometry and X-ray focusing limitations. Peak longitudinal residual stresses were concentrated near the weld toe and decreased gradually with distance.

These findings indicate that longitudinal residual stresses are the dominant component in Ti80 butt-welded thick plates, with peak values substantially higher than transverse stresses. The redistribution observed after cutting reflects the stress relaxation mechanism, suggesting that post-weld operations such as machining significantly influence the residual stress state and may contribute to improved dimensional stability.

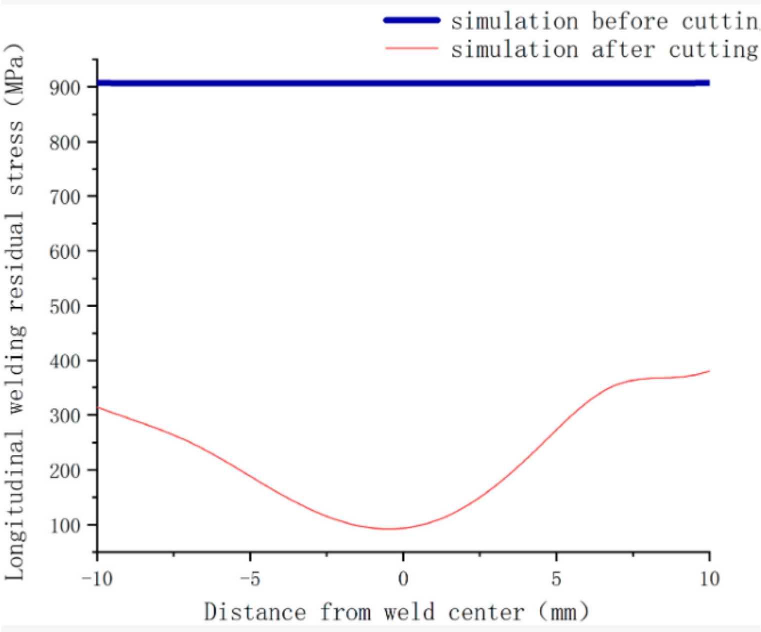

Fig. 2. Simulation results of longitudinal welding residual stress (Y-axis) before and after cutting [4]

Material properties of Ti80 were characterised by a yield strength of approximately 800 MPa, tensile strength of 913 MPa, yield-to-tensile ratio of 0.87, and Poisson's ratio of 0.3 at room temperature. Stress–strain relationships at various temperatures, presented in Figure 3 (Stress versus strain plots for Ti80 at different temperatures), demonstrate the temperature-dependent mechanical behaviour, highlighting a reduction in yield and tensile strength with increasing temperature [9].

The stress–strain behaviour confirms that Ti80 exhibits excellent strength at ambient conditions but undergoes pronounced thermal softening at elevated temperatures. This temperature dependence is critical for welding simulations, as it directly affects the development of residual stresses and potential distortion. The results also validate the material model used in the finite element analysis, ensuring accurate prediction of thermomechanical responses under realistic welding conditions.

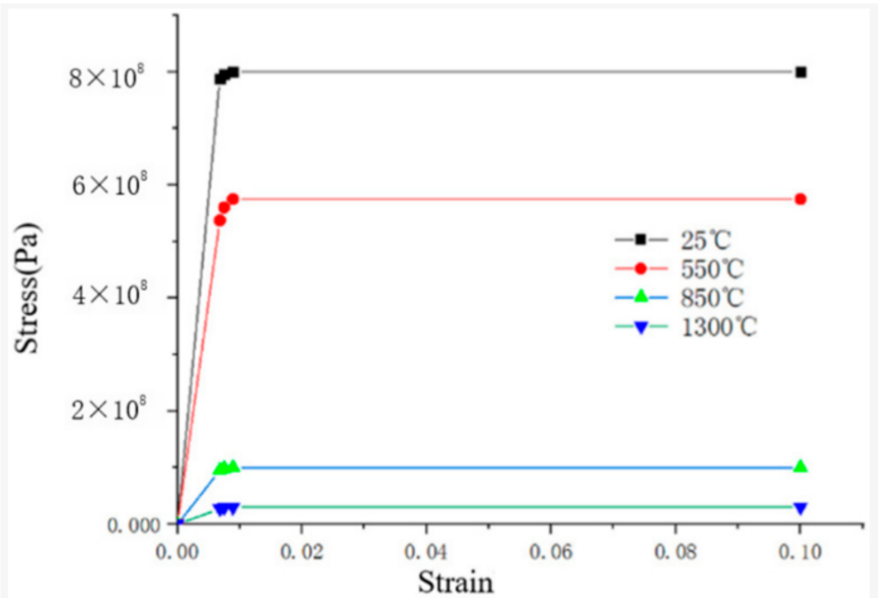

Fig. 3. Stress versus strain plots for Ti80 at different temperatures [10]

Key observations from the analysis include:

1. The weld zone exhibits pronounced residual tensile stress concentration, primarily in regions adjacent to the weld toe.

2. The transverse residual stress distribution shows an asymmetric bimodal profile, reflecting the influence of the welding sequence and surface geometry.

3. Longitudinal residual tensile stress exceeds the transverse tensile stress, indicating anisotropy in stress development along and across the weld seam.

4. Numerical simulations capture the overall stress distribution trends effectively, providing reliable insight into the thermomechanical state of the welded component.

Analysis: Residual stress is highly localized near the weld toe and sensitive to welding parameters. The asymmetry in the transverse stress distribution suggests that even minor variations in welding sequence or surface geometry can produce significant differences in stress concentration. Stress–strain curves reveal a pronounced temperature dependence of Ti80, which must be considered in predictive modelling of deformation and residual stress evolution. Integration of transverse and longitudinal stress data provides a comprehensive understanding of potential sites for distortion or fatigue initiation in transport-sector titanium components.

In conclusion, these results emphasize the importance of combining experimental validation with numerical simulation to accurately predict residual stress fields, thereby informing design and post-processing strategies for high-performance titanium parts. In the analysis of TIG-welded Ti-6Al-4V plates subjected to local post-weld heat treatment (PWHT), the finite element model included 93,950 3D elements and 107,678 nodes. According to Liu et al. (2023), the thermal and mechanical properties of the material varied with temperature, obtained through interpolation and extrapolation of low-temperature performance parameters, as illustrated in Figure 4 (Temperature-dependent thermo-physical and thermo-mechanical material properties of Ti-6Al-4V) [11].

The results presented in Figure 4 (Temperature-dependent thermo-physical and thermo-mechanical material properties of Ti-6Al-4V used in the finite element model) [11] clearly demonstrate the strong temperature sensitivity of Ti-6Al-4V during welding and subsequent post-weld heat treatment. As shown in the thermo-physical data (Figure 4a), both thermal conductivity and specific heat capacity increase substantially with temperature, which directly influences heat flow and cooling rates across the weld zone. This behavior is particularly critical for predicting transient temperature fields and resulting microstructural evolution, as higher conductivity at elevated temperatures promotes more uniform heat distribution, while increased specific heat moderates the thermal gradients.

The thermo-mechanical properties (Figure 4b) further highlight the pronounced reduction in elastic modulus and yield strength with increasing temperature, accompanied by significant changes in thermal expansion coefficients. Such temperature-dependent softening directly affects stress development, making the alloy more susceptible to plastic deformation under residual stress accumulation during multi-pass welding. Importantly, the finite element implementation of these properties ensures more realistic simulation outputs, as constant material parameters would underestimate stress redistribution and distortion effects. These findings confirm that accurate incorporation of temperature-dependent material behavior is indispensable for reliable prediction of thermomechanical responses in welded titanium alloys. Moreover, the data underscore the necessity of localized stress-relief treatments, since mechanical performance degradation at high temperatures may exacerbate residual stress concentrations if left unmitigated.

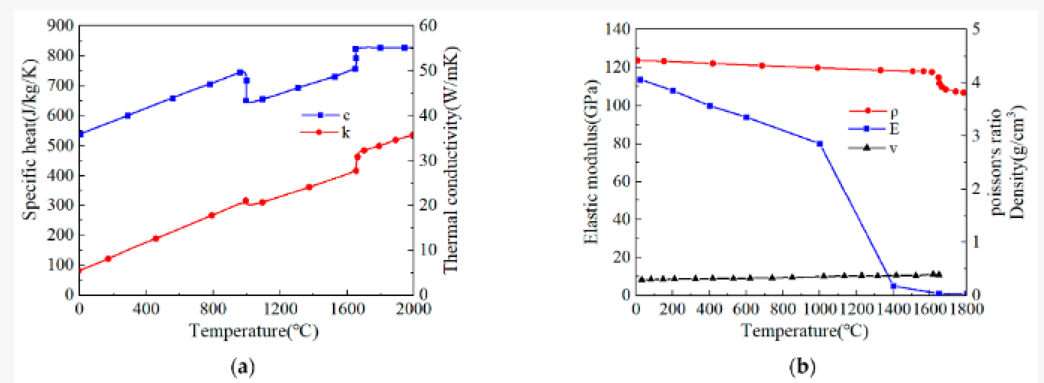

Fig. 4. Temperature-dependent (**a**) thermo-physical and (**b**) thermo-mechanical material properties of Ti-6Al-4V used in the finite element model [11]

Residual stresses were investigated along multiple observation paths on the weldments, divided into three main regions. The first region included paths P1–P4 on the top side of the weld, with distances from the weld centerline of 0, 5.5, 7.5, and 10.4 mm. The second region covered paths P5–P8 on the bottom side, at similar distances from the weld centerline. Figures 5 present the distribution of longitudinal and transverse residual stresses along paths P9 and P10 after welding, with and without stress relief treatment (SSPT) [11].

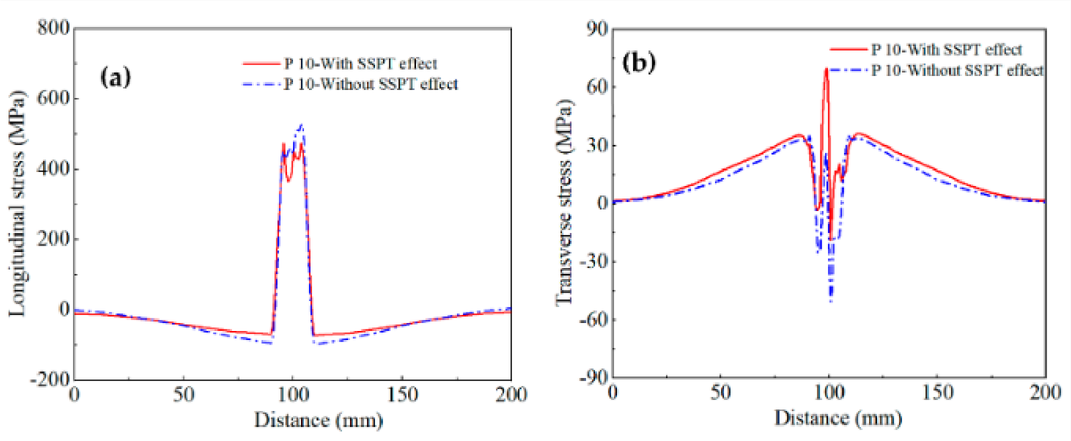

Fig. 5. Distribution of (**a**) longitudinal and (**b**) transverse residual stress along path P10 after welding with and without SSPT [11]

The stress distributions along path P10 (Figure 5) reveal pronounced and spatially localized residual tensile peaks in both longitudinal and transverse components immediately adjacent to the weld seam following welding, while application of synchronous servo press treatment (SSPT) produces a clear and systematic reduction of these peaks [11]. Quantitatively, SSPT reduces the maximum longitudinal tensile stress more substantially than the transverse component, producing a flatter, more uniform profile along the analysed path and shifting the stress field toward lower tensile (or more compressive) mean values. Spatially, the longitudinal stresses display sharper gradients near the weld toe compared with the transverse stresses, indicating that load-parallel (along-seam) directionality concentrates strain and locking-in of tensile residuals more effectively than the cross-seam direction. The post-treatment profiles also evidence partial redistribution of stresses away from the immediate toe region toward broader, lower-magnitude fields, which is consistent with plastic relaxation and controlled constraint introduced by SSPT. From an engineering perspective, these changes imply a reduced risk of fatigue crack initiation at the weld toe and a lower propensity for out-of-plane distortion; they also validate SSPT as an effective localized stress-relief measure for welded Ti alloys. For predictive modelling, the results underscore the need to include both the mechanistic effect of localized mechanical compression (as in SSPT) and temperature-dependent plasticity in simulations to reproduce post-treatment stress redistribution accurately.

Key observations from the analysis of these figures include:

1. Longitudinal residual stresses along both top and bottom paths were generally higher than the transverse residual stresses, indicating anisotropy in residual stress development.
2. Application of SSPT significantly reduced both longitudinal and transverse residual stresses across all observation paths, demonstrating the effectiveness of local post-weld heat treatment in mitigating stress concentrations.
3. The residual stress distributions exhibited notable variations along the different paths, reflecting the combined effects of welding sequence, thermal cycles, and geometry of the weldments.
4. Temperature-dependent material properties strongly influenced stress redistribution, as regions with higher local temperatures showed more pronounced stress relaxation.

Analysis: These results indicate that post-weld heat treatment is a critical factor in controlling residual stresses in TIG-welded Ti-6Al-4V components. The anisotropy between longitudinal and transverse stress components underscores the importance of path-specific analysis for predicting potential distortion or fatigue-prone areas. The combination of top- and bottom-side observation paths provides a comprehensive understanding of residual stress fields, which is essential for the design and maintenance of transport-sector components. Furthermore, integrating temperature-dependent properties into the simulation ensures more accurate predictions of stress evolution under realistic thermal cycles.

In summary, the study demonstrates the significant influence of PWHT on the reduction of residual stresses and highlights the necessity of considering temperature-dependent material behavior in predictive modelling of welded titanium components.

DISCUSSION OF RESULTS

The combined analysis of residual stress distributions and thermomechanical behavior in Ti80 and Ti-6Al-4V welded components reveals several key patterns and implications for welding and post-weld treatment strategies.

Ti80 butt-welded thick plates exhibit pronounced residual tensile stress concentrations near the weld toe, with transverse residual stress showing an asymmetric double-peak distribution and longitudinal residual stress exceeding the transverse component. Stress–strain behavior across different temperatures indicates a reduction in yield and tensile strength with increasing temperature, emphasizing the importance of temperature-dependent properties in predictive modeling.

In TIG-welded Ti-6Al-4V plates, post-weld heat treatment (PWHT) effectively reduces both longitudinal and transverse residual stresses along multiple observation paths. Temperature-dependent material properties strongly influence stress redistribution, with higher local temperatures promoting stress relaxation. The distribution of residual stresses along different paths indicates that weld sequence, geometry, and thermal cycles significantly affect stress localization.

Comparative analysis of these studies highlights several critical observations:

1. Longitudinal residual stresses consistently exceed transverse stresses in both materials, reflecting directional sensitivity of stress accumulation relative to the weld seam.
2. Peak tensile stresses are concentrated near weld toes, which are potential sites for distortion or fatigue initiation.
3. Reduction of material strength with increasing temperature and the facilitation of stress relaxation via PWHT underscore the necessity of incorporating temperature-dependent properties into simulations and post-weld design strategies.
4. Post-weld heat treatment significantly mitigates residual stress concentrations, enhancing fatigue performance and dimensional stability.
5. Numerical simulations align closely with experimental measurements, validating FEM approaches and confirming reliable prediction of residual stress patterns when thermal and mechanical material behaviors are accurately represented.

Own interpretation and implications: The integration of results from both studies indicates that advanced welding process control combined with post-weld treatments is essential to ensure the structural integrity of high-performance titanium components. The observed anisotropy and localization of residual stresses underscore the need for path-specific analysis in component design and maintenance. Temperature-dependent material properties must be explicitly considered in simulations to predict deformation accurately and optimize welding sequences. Additionally, post-weld heat treatment strategies provide a practical means to reduce residual stress concentrations, thereby enhancing fatigue performance and dimensional stability.

Overall, these findings contribute to a deeper understanding of the interplay between welding parameters, thermal cycles, material behavior, and residual stress evolution in titanium alloys. They provide guidance for future design, simulation, and experimental studies aimed at improving the performance and reliability of welded titanium components in transport and engineering applications.

CONCLUSIONS

Based on the integrated analysis of residual stress distributions and thermomechanical behavior in Ti80 and Ti-6Al-4V welded components, the following conclusions can be drawn:

1. Both Ti80 and Ti-6Al-4V welded plates exhibit pronounced residual tensile stress concentrations near weld toes, with longitudinal stresses exceeding transverse stresses, indicating anisotropic stress accumulation along and across weld seams.
2. The asymmetric distribution of transverse residual stresses in Ti80 and the variations along different observation paths in Ti-6Al-4V highlight the significant influence of welding sequence, geometry, and thermal cycles on stress localization.
3. Temperature-dependent material properties critically affect stress development and redistribution. Incorporating these properties into predictive models is essential for accurate simulation of thermomechanical behavior.
4. Post-weld heat treatment (PWHT) and local stress-relief techniques, such as synchronous servo press technology (SSPT), are highly effective in mitigating residual stress concentrations, enhancing fatigue performance, and improving dimensional stability of welded titanium components.
5. The combination of experimental validation and numerical simulations provides a reliable framework for predicting residual stress evolution, informing design strategies and post-processing requirements for high-performance titanium alloys in transport and engineering applications.

6.These findings contribute to a deeper understanding of the interplay between welding parameters, thermal cycles, material behavior, and residual stress evolution, providing guidance for optimizing welding processes, reducing distortion, and improving service performance of welded titanium components.

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Кирилаха С.В. **Математичне моделювання термонапруженого стану при адитивному виготовленні та зварюванні титанових сплавів для транспортного машинобудування**

У роботі показано детальне дослідження розподілу залишкових напружень та термомеханічної поведінки компонентів із титанових сплавів Ti80 та Ti-6Al-4V, які піддавались зварюванню та післязварювальній обробці, із інтеграцією експериментальних вимірювань та чисельного моделювання методом скінченних елементів. Метою дослідження є оцінка впливу послідовності зварювання, термічних циклів та температурозалежних властивостей матеріалу на еволюцію напружень, з особливим акцентом на поперечні та поздовжні залишкові напруження, зосереджені біля швів. Актуальність роботи визначається високими вимогами до надійності, геометричної стабільності та втомостійкості зварних титанових компонентів у транспортній, авіаційній та інженерній галузях. Виявлено значну анізотропію розподілу напружень уздовж та поперек швів, що дозволяє виділити критичні ділянки, схильні до деформацій або початку втомних тріщин. Новизна дослідження полягає у порівняльному аналізі двох титанових сплавів за різних умов зварювання, який поєднує експериментальні дані та чисельні моделі для комплексного розуміння формування залишкових напружень та термомеханічної поведінки. У роботі також показано ефективність післязварювальної термічної обробки (PWHT) та локальних методів зниження напружень у зменшенні залишкових напружень, підвищенні геометричної стабільності та втомостійкості. Практичне значення роботи полягає у формуванні рекомендацій щодо оптимізації параметрів зварювання, застосування післязварювальної обробки та підвищення надійності і ресурсу експлуатації високопродуктивних титанових компонентів у транспортній, авіаційній та інженерній сферах. Отримані результати сприяють кращому розумінню взаємодії між умовами зварювання, поведінкою матеріалу та еволюцією напружень, закладаючи основу для вдосконалення прогнозного моделювання та обґрунтованого проектування зварних титанових конструкцій, а також підкреслюють значення температурозалежних властивостей для точного передбачення полів залишкових напружень і деформаційних процесів.

Ключові слова: Ti80, Ti-6Al-4V, залишкові напруження, термомеханічні властивості, післязварювальна обробка, FEM, зварювання, адитивні технології.

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Svitlana KYRYLAKHA, PhD student in the specialty of Materials Science, Department “Composite Materials, Chemistry and Technologies, master’s student in the specialty G9 “Applied Mechanics” at the Department of “Integrated Welding Technologies and Structural Modelling, ”National University "Zaporizhzhia Polytechnic e-mail: lanakirilaha@gmail.com ORCID: https://orcid.org/0009-0001-5688-5616

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