Proceedings of the Canadian Society for Mechanical Engineering International Congress
32nd Annual Conference of the Computational Fluid Dynamics Society of Canada
Canadian Society of Rheology Symposium
CSME-CFDSC-CSR 2025
May 25–28, 2025, Montréal, Québec, Canada

Design and Deposition Sequence Approaches for Enhanced Residual Stress Management in Directed Energy Deposition

Marzia Saghafi[1], Bita Mohajernia[1], Ruth Jill Urbanic[1]
[1]Department of Mechanical, Automotive, and Materials Engineering, University of Windsor, Windsor, ON, Canada
*saghafi@uwindsor.ca

Abstract—*Directed Energy Deposition (DED) Additive Manufacturing (AM) offers significant advantages for fabricating complex geometries and repairing large metal components. However, frequent heating and cooling cycles during the process result in residual stress accumulation, adversely impacting mechanical properties and part reliability. This study investigates strategies to mitigate residual stress through geometric modifications and process optimization, focusing on substrate design, deposition sequences in junctions, and thin-wall structures. An experimentally validated FEM model in SYSWELD was employed to evaluate the effects of incorporating grooves into substrates, optimizing toolpath strategies, and redesigning thin-wall geometries. The results demonstrate that optimized substrate designs, deposition sequences, and geometric configurations for junctions and thin-wall structures effectively reduce residual stress and redirect high-stress regions, enabling enhanced post-processing and improved final part performance. These findings underscore the potential of integrating specialized design and process strategies to improve the reliability and quality of DED-manufactured components.*

Keywords-Additive Manufacturing; Directed Energy Deposition; Residual stress; Design for Additive Manufacturing; Additive Manufacturing Process

I. INTRODUCTION

Additive Manufacturing (AM), as defined by ISO/ASTM 52900:2015(E) [1], has revolutionized manufacturing by enabling the layer-by-layer fabrication of components directly from 3D model data. This approach facilitates the production of intricate geometries using specialized materials that are difficult or impossible to achieve with traditional manufacturing techniques, all with minimal human intervention. While AM offers numerous advantages, such as reduced production time and material waste, concerns about product reliability remain [2].

Among the various AM techniques, Directed Energy Deposition (DED) stands out for its effectiveness in manufacturing and repairing large metal parts. DED has been successfully applied in repairing components and fabricating complex geometries without the need for support structures, underscoring its unique capabilities. Recent studies have further explored automating the DED process for diverse geometries [3] and demonstrated its feasibility and high potential as a cost-effective alternative manufacturing approach [4].

DED employs a heat source to melt the substrate while depositing material into the molten pool, achieving significantly higher build rates compared to other AM methods. It accommodates both powder and wire feedstock and is categorized by energy sources, such as laser beam, electron beam, wire arc, and plasma arc. Hybrid manufacturing, which integrates machining operations with AM, combines AM's geometric design flexibility with machining's precision to address challenges like surface finish and dimensional tolerances. Additionally, DED AM enables the fabrication of components without support structures through innovative multi-axis toolpath and process planning strategies [5].

Despite its advantages, the DED AM process faces challenges arising from the inherent heating and cooling cycles caused by side-to-side and layer-by-layer deposition. These cycles result in repeated heating, melting, and solidification, leading to microstructural changes [6, 7] and the generation of residual stress and distortion [8], effects that become increasingly significant as part size grows. The formation of residual stress during DED is closely tied to microstructural behavior, as it induces microscopic crystal phase transformations that introduce plastic-straining energy into the material. These transformations significantly impact key mechanical properties, such as hardness and tensile strength. While compressive residual stresses are occasionally beneficial for hindering crack propagation [8], residual stress is generally regarded as a drawback, as it can lead to cracks and other nonconformities in the fabricated part, ultimately reducing the performance specifically in fatigue applications [9].

Crack formation in the DED process is influenced by heat dynamics and residual stress. Rapid cooling can lead to nonequilibrium solidification, increasing the risk of hot cracking, particularly in alloys where eutectic carbides form along grain boundaries, weakening them under stress [10]. Cold cracking, on the other hand, is driven by residual stress from constrained molten pool shrinkage during solidification [11]. Stress concentration at hot crack tips can further amplify localized residual stress, triggering cold crack propagation. Minimizing residual stress is crucial for enhancing the reliability and mechanical performance of DED-fabricated components.

Residual stress development during the AM process varies depending on process conditions and material behavior. At the initial stages of deposition, residual stress at the starting position of the scanning path is relatively small. As additional layers are deposited, stress patterns evolve based on thermal gradients and mechanical constraints. In many cases, compressive residual stress develops near the substrate due to repeated thermal contraction and strain accumulation during cooling cycles [12]. Conversely, tensile residual stress may form in the substrate if constrained thermal expansion dominates the deposition process. At the top of the deposition bead, localized cooling and solidification often induce compressive stress due to rapid cooling and thermal gradients [13]. These stress variations are influenced by deposition parameters, material properties, and substrate constraints, underscoring the complexity of residual stress formation in AM processes.

Several studies have examined the impact of process parameters on residual stress to develop optimized process plans aimed at minimizing its magnitude [14]. Various FEM and numerical models have been developed for this purpose. These studies indicate that reducing the local heat gradient is critical to decreasing residual stress. Effective strategies for minimizing temperature gradients include optimizing process parameters, maintaining ideal molten pool morphology and size, pre-heating the substrate, and employing an appropriate toolpath [15]. However, while these methods may influence residual stress values, they are often insufficient to fully address the issue in most cases as the component geometry and tool path are also statistically significant influence factors [16].

In addition to optimizing process parameters, several in-process and post-process methods have been introduced to control or minimize residual stress. In-process ultrasonic vibration has been shown to reduce residual stress, refine grain structures, and mitigate porosity in DED AM fabricated parts [17]. Mechanical techniques, such as deep rolling, ultrasonic impact peening, and microrolling, have also demonstrated effectiveness in reducing residual stress and tailoring microstructures to enhance material performance [18]. Post-process methods, including heat treatments and peening techniques such as laser shock peening, have likewise proven effective in alleviating residual stress [19]. Additionally, machining processes like grinding (which induces compressive stress), milling (which induces tensile stress), and magnetic field-assisted finishing have been shown to create beneficial compressive stress fields [20]. While these methods hold significant promise, they often require specialized machine setups, increase manufacturing time, and add to production costs, potentially making them impractical for certain applications.

Building on the applied physics underlying the DED AM process, strategies such as re-designing the substrate and implementing specialized design approaches for additive manufacturing hold significant potential for reducing residual stress in DED-fabricated parts. The concept of a "smart-substrate" has been introduced as a novel structural design to mitigate residual stress accumulation in DED-manufactured parts [21]. By incorporating specific geometric features, such as grooves, into the substrate, this approach effectively controls heat flow, minimizes temperature gradients, and promotes more uniform cooling. Additionally, the grooves act as stress-relief features in high-risk areas, preventing the buildup of stresses. Consequently, residual stress development is significantly reduced, enhancing the quality and reliability of the manufactured components [22].

Junctions and thin-wall structures are frequently used in applications that require lightweight designs. However, they pose unique challenges in the DED process, particularly due to the formation of residual stresses, which can lead to component failure. This study investigates modifications to substrate geometry and the re-design of junctions and thin-wall geometries as methods to minimize induced residual stress or strategically alter high-stress areas, making them more manageable through post-processing. Unlike other studies that focus on altering process parameters such as bead dimension, power, or speed, this work takes a different approach by re-thinking the problem through geometry modifications and deposition sequences. The objective is to evaluate the effectiveness of these specialized design strategies in enhancing final manufacturing outcomes by reducing residual stress levels, making them applicable in cases where the geometry limitations permit.

II. METHODOLOGY

In this study, various methods for reducing residual stress in DED-fabricated parts were explored. The simulations were performed using the FEM model in SYSWELD 2022. This FEM model had been previously validated through experimental results of residual stress measurements for single-bead and junction simulations [23, 24]. To ensure consistency, the same simulation setup parameters—such as heat source parameters, bead geometry, and the material—were utilized. Table 1 summarizes the assumed DED AM parameters. In all models, a single-bead, single-layer deposition is simulated on a substrate plate with a thickness of 5 mm

TABLE 1. PROCESS PARAMETERS AND MATERIALS

Bead width	**Layer height**	**Power (Watt)**	**Velocity (mm/s)**	**Material**
4 mm	1 mm	2500	10	X20Cr13 on S355J2G3

Two primary approaches were investigated: substrate modifications aimed at increasing flexibility and reducing residual stress, and specialized designs for additive manufacturing, focusing on junctions and thin-wall structures.

A. Substrate Modification

To reduce residual stress in DED-fabricated parts, an effective strategy involves the intentional design of the substrate, particularly by incorporating grooves. A hexagonal thin-walled structure was modeled using SYSWELD software to investigate the impact of substrate design on the mitigation of residual stresses (Fig 1(a)). The initial model utilized a solid substrate, which was then compared with a modified version where grooves were introduced at the back of the substrate, as shown in Figure 1(b). The residual stress distribution along path AB was analyzed for both the solid substrate and the grooved substrate scenarios.

B. Geometry and Process Design for AM in Junctions

Geometry and process design for AM, for junctions, has been investigated with a focus on residual stress as a function of deposition direction and order. The process parameters and material were kept consistent across all scenarios (Table 1). Three different junction configurations were analyzed: a three-joint junction, a modified cross structure with three joints, and a hexagonal shape as a thin walled structure will consist of a system of joints. The numbering for the toolpath directions and operation order for each configuration is shown in Figure 2.

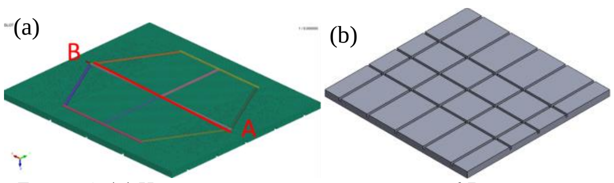


FIGURE 1. (A) HEXAGONAL DEPOSITION AND PATH AB CONSIDERED FOR STRESS MEASUREMENT, (B) SUBSTRATE WITH VERTICAL AND HORIZONTAL GROOVES ON THE BACK SURFACE

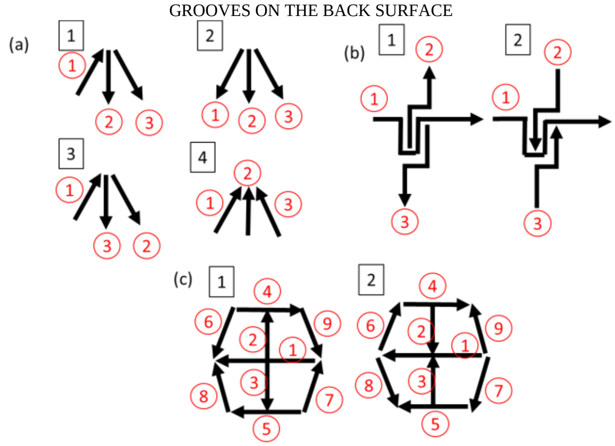
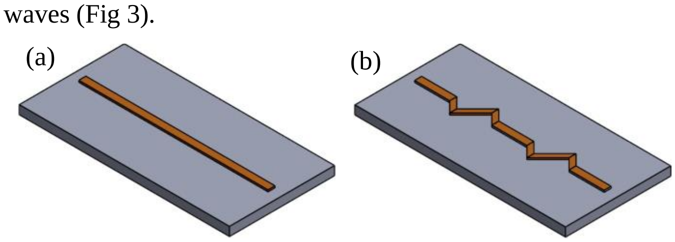


FIGURE 2. THE DEPOSITION SEQUENCE AND DIRECTION IN (A) THREE JOINTS JUNCTION, (B) MODIFIED THREE JOINTS JUNCTION, (C) HEXAGONAL SHAPE JUNCTION.

C. Geometry Design for AM in Thin Wall Structures

To explore the effect of geometry on the accumulation of residual stress in thin wall deposition, incorporating different wave shapes into the straight-line deposition was studied. The objective was to investigate the potential for reducing or redirecting residual stress away from the central line. This approach aims to facilitate the removal of high-residual-stress sections after deposition. In addition to the straight-line deposition, three distinct wave geometries were examined: triangular waves with 45° and 60° angles, as well as square waves (Fig 3).



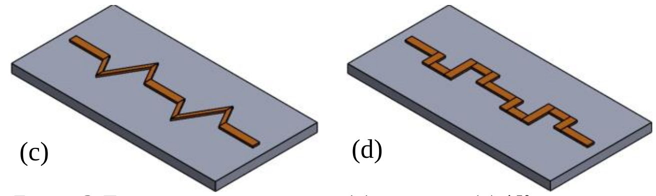


FIGURE 3. THIN-WALL GEOMETRIES IN (A) STRAIGHT, (B) 45⁰ TRIANGULAR, (C) 60⁰ TRIANGULAR, AND (D) SQUARE

III. RESULTS

The residual stress outcomes for each case, obtained using the experimentally validated FEM model, are presented below.

A. Substrate Modification

As depicted in Figure 4, a significant reduction in residual stress was observed in areas where the bead was deposited over the grooves along the path AB (Fig. 1(a)). Additionally, stress relaxation occurred at the junction between the deposited bead and the vertical groove, highlighting the effectiveness of substrate grooves in optimizing heat flux during deposition. This can be attributed to the improved heat flow facilitated by the grooves, which reduces the maximum temperature gradient during the DED process by controlling the cooling rate and minimizing thermal deformation.

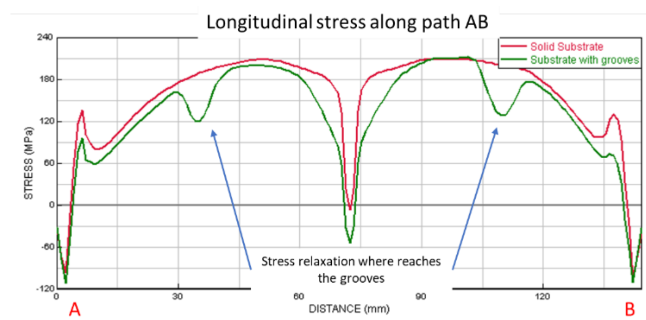


FIGURE. 4. COMPARISON OF LONGITUDINAL RESIDUAL STRESS ALONG PATH AB: RED CURVE REPRESENTS THE SOLID SUBSTRATE, AND GREEN CURVE REPRESENTS THE GROOVED SUBSTRATE

B. Design for AM in Junctions

The results of the study clearly indicate that deposition direction and the order of operations play a crucial role in the formation of residual stresses in junction structures fabricated using DED AM. Specifically, the path strategy employed in the deposition process has a significant impact on the mechanical and tensile properties of junctions, as it directly influences the thermal gradients and stress relaxation behavior. The study demonstrates that careful selection of deposition direction and operation order can reduce localized residual stresses.

As shown in Figure 5, the second scenario of the 3-joint junction exhibits the lowest tensile and compressive stresses, making it the most favorable tool path for this junction configuration. Figure 6 provides a comparison of the maximum and minimum tensile and compressive stresses for the two scenarios of the 3-joint junction and the hexagonal model. The stress results for the both scenarios of hexagonal shape are nearly identical and closely aligned with those of the second scenario of the 3-joint junction.

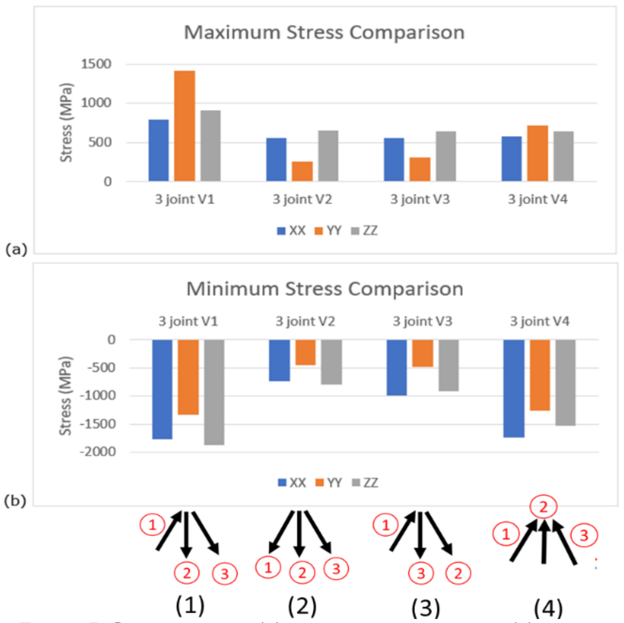


FIGURE 5. COMPARISON OF (A) MAXIMUM STRESSES AND (B) MINIMUM STRESSES IN THE MAJOR PLANES FOR THE THREE-JOINT JUNCTION SCENARIOS [25]

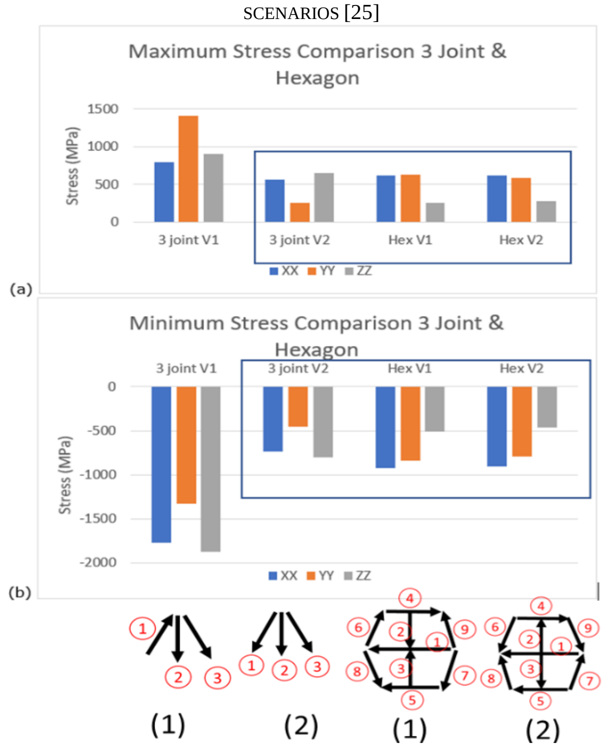


FIGURE 6. COMPARISON OF (A) MAXIMUM AND MINIMUM STRESSES ON MAJOR PLANES FOR THREE JOINT CASES AND THE HEXAGONAL MODEL CASE STUDY. [25]

The stress distribution in the modified 3-joint cross structure exhibits an almost identical pattern for both scenarios (Fig 7). This proposed toolpath deposition method aims to enhance mechanical bonding. Additionally, the concept of machining regions with higher residual stress should be explored in future studies to further optimize performance and durability.

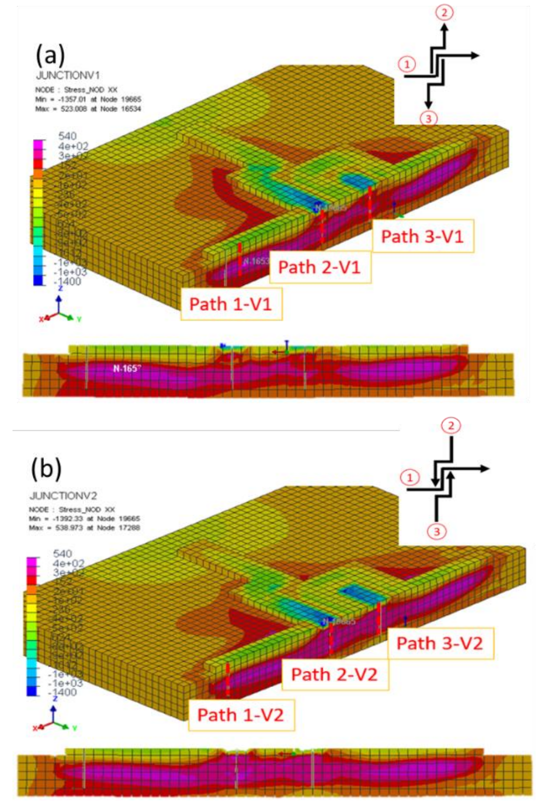


FIGURE. 7. RESIDUAL STRESS DISTRIBUTION IN MODIFIED 3-JOINTS CROSS STRUCTURE

C. *Design for AM in Thin Wall Structures*

The first principal stress was used as the output parameter to compare various thin-wall designs against the straight-line deposition. All configurations were evaluated after the deposition process and 100 seconds of cooling at ambient temperature.

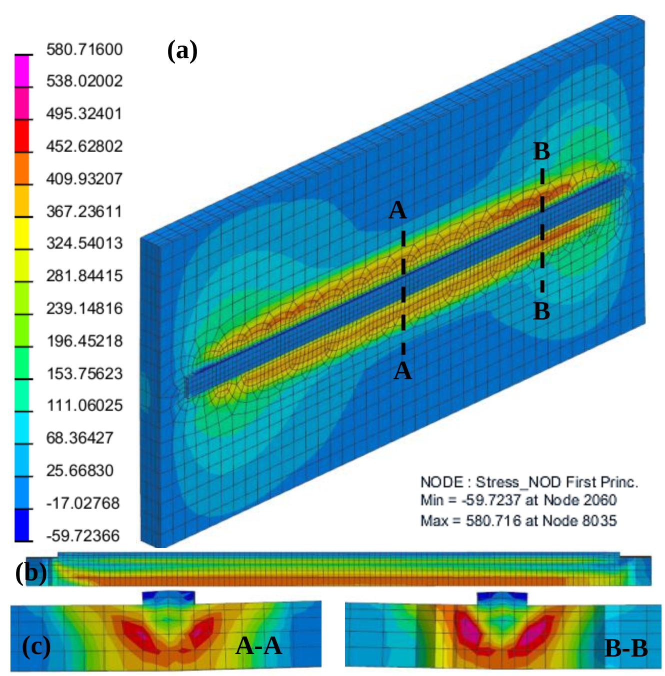


FIGURE 8. (A) RESIDUAL STRESS DISTRIBUTION IN STRAIGHT LINE, (B) ALONG WITH DEPOSITION, (C) IN BEAD CROSS SECTION

Figure 8 illustrates the stress distribution across the entire structure for the straight-line deposition, along the deposition bead (Fig 8(b)), and at the bead cross-sections (Fig 8(c)). The results indicate a maximum tensile stress of 580 MPa in the substrate and a maximum compressive stress of 60 MPa in the deposited bead.

The results for the triangular wave deposition indicate a similar range of residual stress compared to the straight-line deposition; however, a larger area of the substrate is affected by these stresses (Fig 9). For the triangular wave with a higher angle (Fig 10(a)), the maximum residual stresses are slightly lower, the stress-affected region is broader, and the high tensile stress zones in the substrate are farther from the deposition bead (Fig 9 (a),(c), Fig 10 (a), (b)).

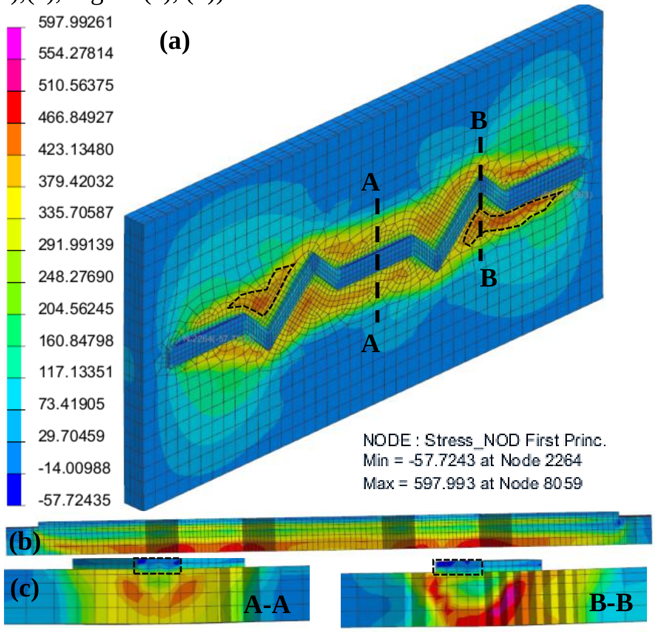


FIGURE 9. (A) RESIDUAL STRESS DISTRIBUTION IN 45° TRIANGULAR WAVE, (B) ALONG WITH DEPOSITION, (C) IN BEAD CROSS SECTION

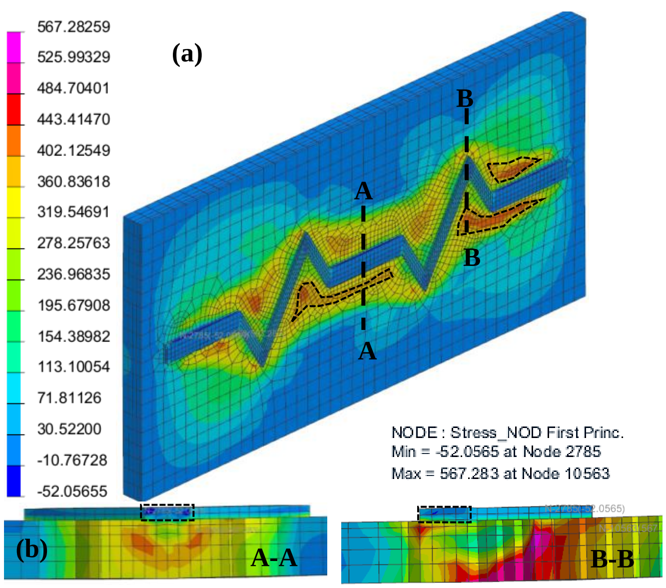


FIGURE 10. (A) RESIDUAL STRESS DISTRIBUTION IN 60° TRIANGULAR WAVE, (B) IN BEAD CROSS SECTION

In the square wave scenario, the maximum compressive stress at the ends of the deposited sections is significantly higher. However, the redirection of high-stress areas away from the deposition bead is less pronounced in this scenario (Fig. 11).

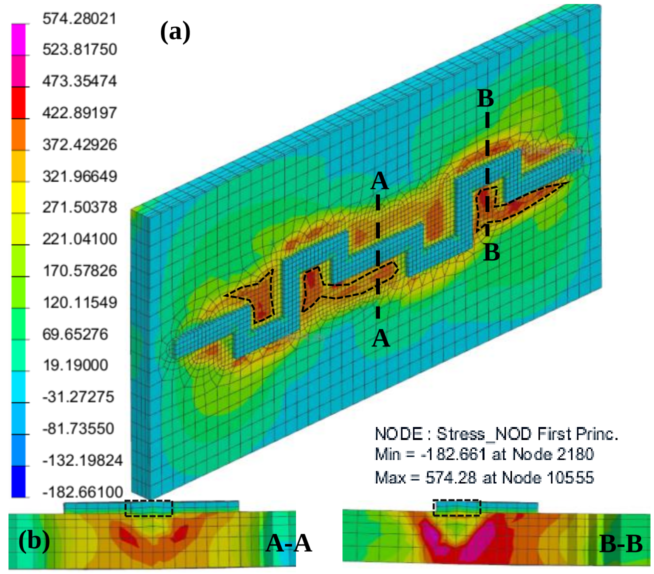


FIGURE 11. (A) RESIDUAL STRESS DISTRIBUTION IN SQUARE WAVE, (B) IN BEAD CROSS SECTION

IV. DISCUSSION

While DED AM has made significant advancements in process planning and facilities, several concerns persist regarding the reliability of fabricated parts, largely due to the frequent heating and cooling cycles inherent in the process. A key challenge is the accumulation of residual stress within the part, which is often detrimental due to its adverse effects on mechanical properties and fatigue performance.

In this study, various re-design strategies, including geometric modifications and deposition sequence adjustments, were explored to mitigate high levels of residual stress in DED-fabricated parts, specifically for junctions and thin-wall structures. The simulation results demonstrate promising opportunities for re-designing the deposition sequences and geometries of substrates, junctions, and thin-wall structures to effectively reduce residual stress in the final fabricated parts.

One key approach involved modifying substrate geometry to introduce grooves aimed at reducing temperature gradients and enhancing mechanical flexibility. The results revealed that these grooves effectively alleviated stress concentrations, leading to a more uniform stress distribution. Furthermore, the changes in substrate stiffness, enabled by the groove geometry, reduced mechanical constraints that typically hinder thermal deformation. These findings suggest that incorporating such geometric features into substrate designs could be a promising strategy for mitigating residual stress, improving thermal management, and enhancing the overall quality of DED-manufactured components, particularly when these features are strategically designed to address high-stress areas.

The study also highlighted the critical role of deposition sequence in managing residual stress in junction structures. The findings demonstrate that effective toolpath strategies and optimized deposition order are essential for minimizing residual stress in thin-walled junction components. As this research extends to multi-layer scenarios, it will provide a more comprehensive understanding of the challenges associated with fabricating complex thin-walled junction structures, laying the groundwork for further process planning and design optimization.

For thin-wall structures, although the maximum tensile and compressive stresses remained relatively constant, the use of triangular wave shapes in the thin wall successfully redirected high tensile stress areas away from the deposition bead. This configuration could facilitate modifications to substrate geometry or enable the removal of high-stress regions post-process, potentially reducing residual stress in the final fabricated part. Similarly, for the redesigned 3-joint junction geometry, high-stress regions remained localized, particularly in components with multiple junctions. This study emphasizes that managing these localized high-stress regions will require strategic post-processing techniques, such as machining, to mitigate the cumulative effects of residual stress while preserving structural integrity.

V. CONCLUSION

Overall, this study underscores the importance of integrating geometric and process design strategies to reduce residual stress or relocate high-stress areas in DED-manufactured components. This approach can optimize the design for AM and enhance DED process planning to achieve desired properties in the final fabrication. Although this study focused on thin-wall structures and single-layer depositions, these insights pave the way for future research into multi-layer depositions and complex geometries, further improving the reliability and performance of DED-fabricated parts.

ACKNOWLEDGMENT

This work was supported by CAMufacturing Solutions, and Mitacs through the Mitacs Accelerate program (Grant number IT16938).

REFERENCES

[1] ISO/ASTM 52900:2015 Additive manufacturing — General principles — Terminology, 2015

[2] F. Marinho de Brito, G. da Cruz, E. M. Frazzon, J. P. T. V. Basto and S. G. S. Alcalá, "Design Approach for Additive Manufacturing in Spare Part Supply Chains," in IEEE Transactions on Industrial Informatics, v17 (2), pp. 757-765, 2021, doi: 10.1109/TII.2020.3029541.

[3] Saghafi, M., Urbanic, R. J., Hedrick, B., & Ramezani, H. (2024). Geometry-Based Decomposition Rules and Programming Strategies for Complex Components in Additive and Hybrid Manufacturing. The International Journal of Advanced Manufacturing Technology.

[4] Mandolini, M., Sartini, M., Favi, C., & Germani, M. (2022). An Analytical Cost Model for Laser-Directed Energy Deposition (L-DED). Lecture Notes in Mechanical Engineering, 893-906. Springer. https://doi.org/10.1007/978-3-031-15928-2_87&#8203

[5] Urbanic, R., Hedrick, B., Ramezani, H., El Moghazi, S., & Saghafi, M. (2022). Hybrid manufacturing decomposition rules and programming strategies for service parts. In Proceedings of the ASME 2022 International Mechanical Engineering Congress and Exposition (IMECE2022), Columbus, Ohio. https://doi.org/10.1115/IMECE2022-95560.

[6] B. Mohajernia and R. Urbanic, "Exploring computational techniques for simulating residual stresses for thin wall multi-joint hexagon confgurations for a laser directed energy deposition process," The International Journal of Advanced Manufacturing Technology, vol. 126, p. 2745–2763, 2023.

[7] M. Saghafi, S. E. Mirazimzadeh, R. J. Urbanic, and A. Alpas, "Evaluating Bead Geometry, Hardness, and Residual Stress for a Multi-Layer 316L Laser-Wire Based DED Block," in Proceedings of the ASME International Mechanical Engineering Congress and Exposition (IMECE), Portland, OR, USA, Oct. 27–31, 2024, Paper No. IMECE2024-145699, doi: 10.1115/IMECE2024-145699

[8] P. Kattire, S. Paul, R. Singh, and W. Yan, "Experimental characterization of laser cladding of CPM 9V on H13 tool steel for die repair applications," Journal of Manufacturing Processes, vol. 20, pp. 492–499, 2015.

[9] U. Kumar, S. Al-Saadi, A. K. Das, and R. K. S. Raman, "Corrosion and stress corrosion cracking characteristics of 4043 aluminium alloy fabricated through directed energy deposition process," Journal of Alloys and Compounds, vol. 934, p. 168021, 2024.

[10] F. Khodabakhshi, M. H. Farshidianfar, S. Bakhshivash, A. P. Gerlich, and A. Khajepour, "Dissimilar metals deposition by directed energy based on powder-fed laser additive manufacturing," Journal of Manufacturing Processes, vol. 43, pp. 83–97, 2019.

[11] G.-W. Park et al., "Analysis of solidification microstructure and cracking mechanism of a matrix high-speed steel deposited using directed-energy deposition," Journal of Alloys and Compounds, vol. 907, p. 164523, 2022.

[12] C. Selcuk, "Laser metal deposition for powder metallurgy parts," Powder Metallurgy, vol. 54, no. 2, pp. 94–99, 2011.

[13] S. Zhang, X. Lin, J. Chen, and W. Huang, "Influence of heat treatment on residual stress of Ti-6Al-4V alloy by laser solid forming," Rare Metal Materials and Engineering, vol. 38, no. 5, pp. 774–778, 2009.

[14] R. Ghanavati, H. Naffakh-Moosavy, M. Moradi, E. Gadalińska, and A. Saboori, "Residual stresses and distortion in additively-manufactured SS316L-IN718 multi-material by laser-directed energy deposition: A validated numerical-statistical approach," Journal of Manufacturing Processes, vol. 85, pp. 1–15, 2023.

[15] . Rangaswamy et al., "Residual stresses in LENS® components using neutron diffraction and contour method," Materials Science and Engineering: A, vol. 399, no. 1–2, pp. 72–83, 2005.

[16] S. Pazireh, E. Mirazimzadeh, R. J. Urbanic, and B. Hedrick, "Analysing the Influence of Geometry and Tool Paths for a Laser-Based DED Application," presented at the ASME 2024 International Mechanical Engineering Congress and Exposition, January 2025, doi: 10.1115/IMECE2024-145556.

[17] W. Zhang, C. Xu, C. Li, and S. Wu, "Advances in Ultrasonic-Assisted Directed Energy Deposition (DED) for Metal Additive Manufacturing," Crystals, vol. 14, no. 2, p. 114, 2024.

[18] C. J. Müller, K. Büßenschütt, A. Schwedt, J. H. Schleifenbaum, and M. Sudmanns, "Enabling tailored microstructures by hybrid directed energy deposition processing of a nickel-based superalloy," Additive Manufacturing Letters, vol. 4, p. 100248, 2024.

[19] R. Boillat-Newport, S. P. Isanaka, J. Kelley, and F. Liou, "Heat Treatments for Minimization of Residual Stresses and Maximization of Tensile Strengths of Scalmalloy® Processed via Directed Energy Deposition," Materials, vol. 17, no. 6, p. 1333, 2024.

[20] A. M. Souza, E. J. da Silva, and H. Yamaguchi, "Effects of post-processing operations on directed energy deposited 316L stainless steel surfaces," International Journal of Advanced Manufacturing Technology, vol. 125, pp. 1–15, 2023.

[21] A. S. Alghamdi, M. A. Alrbaey, and M. A. Alkahari, "Smart-Substrate: A Novel Structural Design to Avert Residual Stress in Additive Manufacturing," Virtual and Physical Prototyping, vol. 18, no. 3, pp. 1–15, 2023.

[22] X. Lu et al., "Substrate design to minimize residual stresses in Directed Energy Deposition AM processes," Materials & Design, vol. 202, p. 109525, Apr. 2021.

[23] N. Nazemi and R. J. Urbanic, "A numerical investigation for alternative toolpath deposition solutions for surface cladding of stainless steel P420 powder on AISI 1018 steel substrate," The International Journal of Advanced Manufacturing Technology, vol. 97, no. 5, pp. 2021–2036, 2018, doi: 10.1007/s00170-018-1840-1.

[24] M. Saghafi, R. J. Urbanic, and B. Hedrick, "VoxeLogic Heat Dynamics Modeler: A Fast, Mesh-Free, Physics-Logic-Based Heat Prediction Approach for DED Simulations," under review.

[25] B. Mohajernia and R. J. Urbanic, "Residual Stress Modeling of Junction Structures Using Powder Injection Laser Cladding of Martensitic Stainless Steel on Low Alloyed Carbon Steel Substrate," *Computer-Aided Design and Applications*, vol. 19, no. 6, pp. 1070–1092, 2022.