Joint Special Interest Group meeting between euspen and ASPE
Advancing Precision in Additive Manufacturing
TU Berlin, Germany, October 2025
www.euspen.eu

Sustainable dual-side deposition to mitigate substrate deformation in Directed Energy Deposition (DED)

Shubham Agarwal [1], Neel Kamal Gupta [1, *], Henning Zeidler [1]

[1]*Institute for Machine Elements, Engineering Design and Manufacturing (IMKF), Technische Universität Freiberg, 09599 Freiberg, Germany*

Neel.Gupta@imkf.tu-freiberg.de

Abstract

Components fabricated by Directed Energy Deposition (DED), particularly Wire Arc Additive Manufacturing (WAAM), often suffer from substrate deformation due to residual stresses generated by non-uniform thermal cycles. This study presents a dual-side deposition approach where the substrate is flipped after specific layer intervals, to mitigate this Z-axis substrate deformation. Al 6082 was used as the substrate and Al 4043 as the wire material, both commonly employed in aerospace and automotive industries. The Cold Metal Transfer (CMT) method by Fronius was used with a TPS 400i MIG welding system. Deposition parameters were optimized via the Taguchi method for maximum penetration depth. Computational studies were conducted in Simufact Welding to analyze deformation trends. Results showed that flipping the substrate after every layer reduced deformation by up to 70% compared to single-side deposition. In addition to minimizing distortion, dual-side deposition enabled substrate integration into the final component, reducing material waste, post-processing time, and overall carbon footprint. This study demonstrates that layer-wise substrate flipping is an effective strategy for distortion control in WAAM, especially in fabrication of larger components, where severe initial deformation can cause challenges for further deposition.

Directed Energy Deposition (DED); Dual Side Deposition; Residual Stress; Simufact; Substrate Deformation; Wire Arc Additive Manufacturing (WAAM)

1. Introduction

Additive Manufacturing (AM), commonly known as 3D printing, is a transformative approach to production that builds components layer by layer from digital models. It's useful for creating complex geometries and prototypes quickly. Directed Energy Deposition (DED) is a type of AM where focused thermal energy is used to fuse materials by melting as they are being deposited. DED-Arc (also known as Wire Arc Additive Manufacturing (WAAM)) is a classification of DED; wherein arc welding processes are used to build components layer by layer from a metal wire feedstock. WAAM is known for building large-scale, high-strength metal parts with high deposition rates [1]. Cold Metal Transfer (CMT) is an advanced variant of Metal Inert Gas WAAM, developed by Fronius International, designed to deliver highly controlled heat input and spatter-free welding.

Despite these advances, WAAM components commonly show defects such as porosity, cracking, residual stresses, etc. One of the subsequent defects of residual stresses is substrate deformation. Various studies have shown different methods to control these residual stresses and mitigate the resulting substrate deformation. These include path planning [2], preheating [3], deposition strategies [4], clamping strategies [5], inducing compressive stresses [6], etc.

Gupta et al. [4] conducted an experimental and simulation study on reducing WAAM substrate deformation using a dual-side deposition strategy. The component was split along the Z-axis; after depositing the first half on side-1, the substrate was flipped, and the second half was deposited on side-2, effectively counteracting prior deformation. Noticeable deformation could be seen after deposition on side-1. This method is further illustrated in Figure 1.

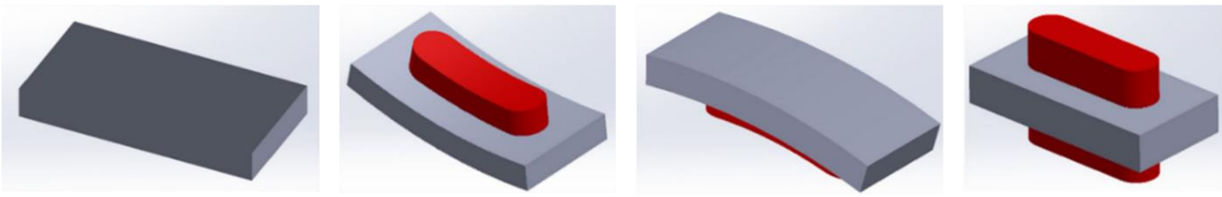

Figure 1: Dual side deposition strategy [4]

This paper combined simulations and experiments using a 10 mm Al 6082 substrate and Al 4043 wire. Deformation decreased from 0.17 mm to 0.02 mm in simulations and from 0.28 mm to 0.13 mm experimentally when switching from single- to dual-side deposition as shown in Figure 2.

While the dual-side deposition strategy significantly reduced substrate deformation, flipping the substrate only after completing deposition on side-1 can still lead to issues. In some cases, the resulting deformation may exceed acceptable limits, making it difficult to continue deposition effectively on side-2. Moreover, severe warping of the substrate can distort the geometry of the part being fabricated, compromising overall build quality. To address this challenge, the current study introduces the concept of intermediate flipping intervals. By flipping the substrate after each layer and analyzing the effects of various flipping frequencies. This approach aims to find an optimal balance between minimizing deformation and maintaining process efficiency throughout the build.

The next sections explain the materials, simulation model and experiment setup used for this study, followed by results and conclusion and finally exploring the future scope of the work.

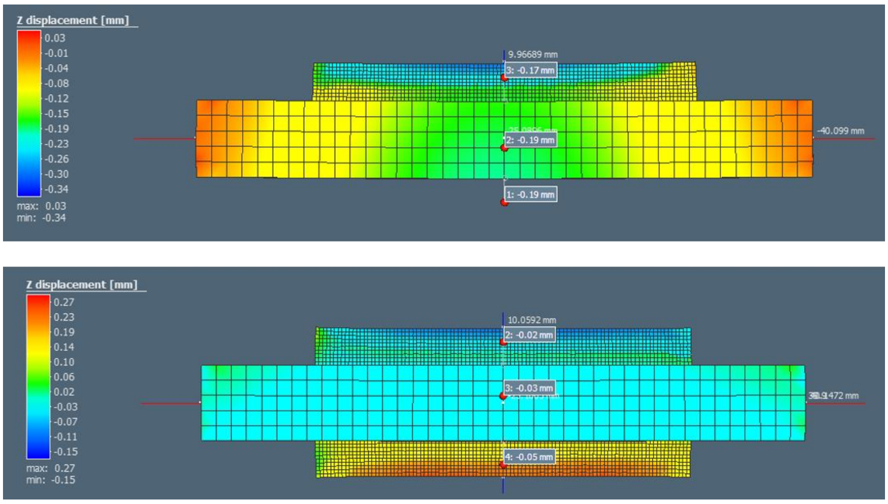

Figure 2: Substrate deformation, single side vs dual side [4]

2. Methodology

2.1. Materials and deposition parameters

For this study, a 10 mm thick, Al 6082 substrate was used, upon which 10 layers were deposited with a 1 mm wire of Al 4043. The dimensions are shown in Figure 3. The deposition parameters: current, torch speed, gas flow rate, and contact tip distance were optimized using the Taguchi method for maximum bead penetration.

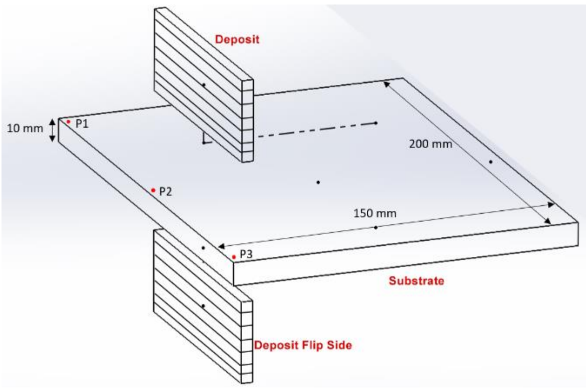

Figure 3: Substrate dimensions and measurement points

2.2. Computational and experimental setup

The Goldak heat source model [7] was used to estimate the heat source in SIMUFACT Welding software. The substrate was clamped at one end. A Fronius TPS 400i welding setup, with a robot-controlled MIG torch, was used for deposition. 99.99% pure Argon was used as the shielding gas.

The Z-axis deformation was measured using a dial gauge, mounted to the robotic arm as shown in Figure 4. Measurements were done at 3 distinct points, as seen in Figure 3.

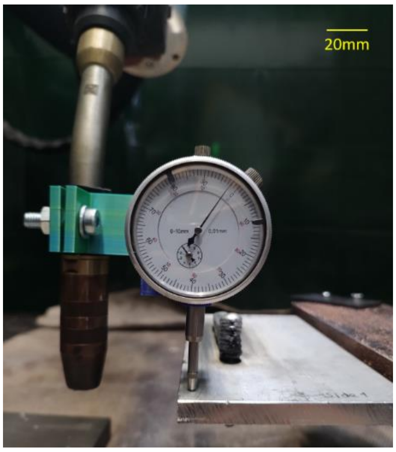

Figure 4: Measurement setup using dial gauge

3. Results and Discussion

Maximum deformation of 0.53 mm (simulation, as shown in Figure 5) and 0.48 mm (experimental) was observed at Point 1, after complete deposition of 10 layers on side 1. This is in accordance with the literature review, which showed that single-side deposition causes substrate warping due to residual stresses generated as a result of the heat input and subsequent uneven cooling cycles.

By flipping the substrate after every layer, the end deformation was noted to be 0.03 mm (simulation, as shown in Figure 6) and 0.01 mm (experimental). This suggests that the deformation after deposition on one side-1, is effectively cancelled out by depositing the next layer on side-2. Moreover, maximum deformation was observed after the deposition of first layer: 0.14 mm (simulation) and 0.16 mm (experimental), which then kept on decreasing as further layers were deposited alternately, as shown in Table 1. This is attributed to the limited heat input on a single side and balancing it by flipping the substrate and depositing on the other side. This method reduced the maximum substrate deformation by about 70% in comparison to flipping the substrate only after complete deposition on side-1.

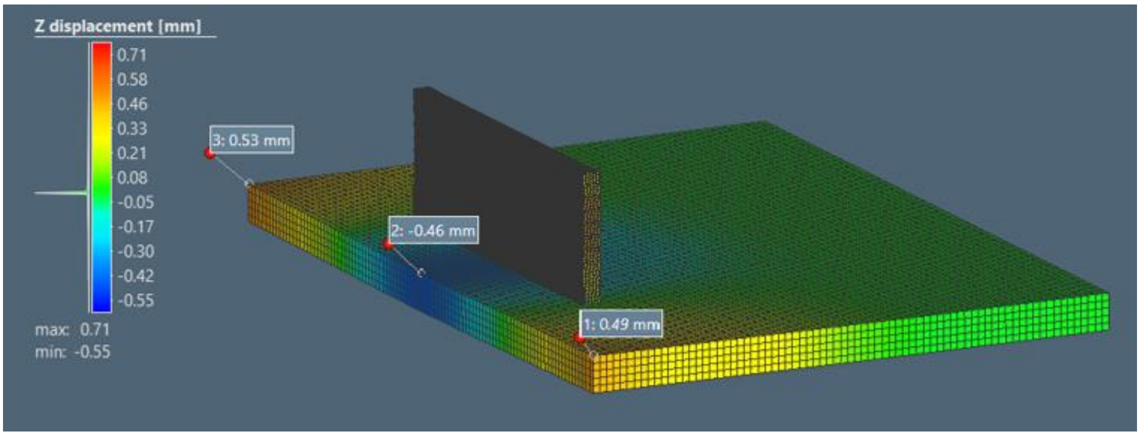

Figure 5: Deformation – after complete deposition of 10 layers on one side

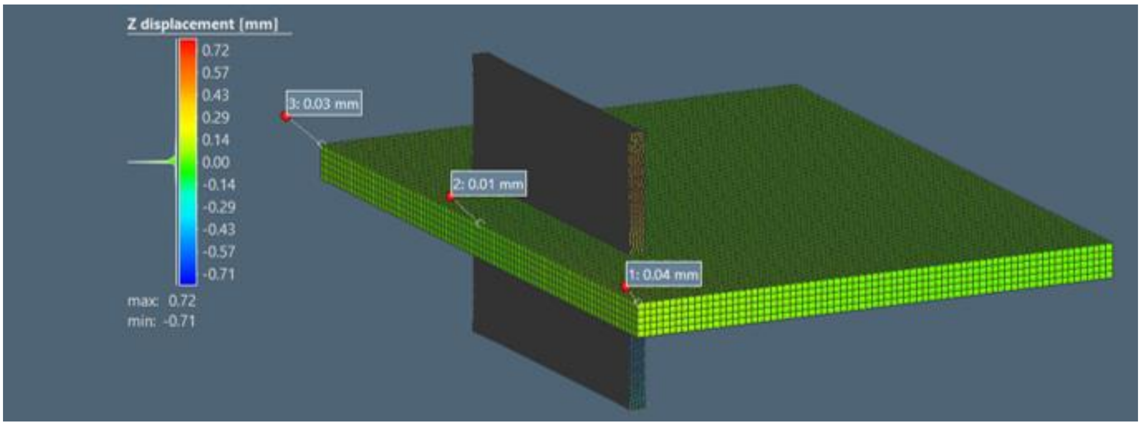

Figure 6: Deformation - after complete deposition with flipping after every layer

Table 1: *Maximum deformation after every layer (Sim-Simulation, Exp-Experimental)*

Layer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Side	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Sim P3 (mm)	0.14	0.02	0.07	0.02	0.08	0.02	0.08	0.02	0.08	0.02	0.08	0.02	0.07	0.03	0.06	0.03	0.06	0.03	0.05	0.03
Exp P3 (mm)	0.16	0.01	0.1	0.01	0.03	0	0.02	0.01	0.02	0	0.03	0	0.02	0.01	0.03	0	0.03	0	0.01	0.01

4. Conclusions

This study shows that deposition on a single side causes significant substrate deformation (0.53 mm), which is reduced to just 0.03 mm by using the dual side approach. Additionally, the peak deformation observed was 0.14 mm, which shows that the substrate never undergoes severe warping, which may have caused challenges in further deposition. Thus, the results support that dual side deposition is an effective method in mitigating substrate deformation in WAAM.

Usually, the substrates are discarded and only the deposited components are used. The dual-side deposition approach also facilitates direct substrate integration, as illustrated in Figure 7. This integration not only expedites the overall build process by reducing deposition time but also contributes to material efficiency and a lower environmental impact through minimized waste and reduced carbon footprint.

Because of this substrate integration, variations are expected between the substrate-integrated regions and the deposited layers due to differences in thermal history, solidification conditions, and potential metallurgical bonding characteristics. This microstructural disparity necessitates further investigation to understand its implications on the component's performance.

In particular, the influence of substrate integration on mechanical properties must be rigorously evaluated. Comprehensive mechanical testing, such as uniaxial tensile, compressive, and fatigue strength assessments, will be required to quantify any changes in strength, ductility, and durability associated with the integrated design.


Figure 7: *Substrate integrated into deposited sample*

References

[1] Gupta, N. K., S, S., Karade, S. R., G, G., Gote, G. D., Dubey, S., & Karunakaran, K. P. (2025). Enhancing 5-axis deposition with a double slicing method in wire arc additive manufacturing. *Rapid Prototyping Journal*, *31*(6), 1264-1279. https://doi.org/10.1108/RPJ-03-2024-0116

[2] C. Zhang, C. Shen, X. Hua, F. Li, Y. Zhang, Y. Zhu. (2020). Influence of wire-arc additive manufacturing path planning strategy on the residual stress status in one single buildup layer, International Journal of Advanced Manufacturing Technology 111 797–806. https://doi.org/10.1007/S00170-020-06178-W.

[3] Gupta, N. K., Ganesan, G., Siddhartha, S., Karade, S. R., Paul, A. K., Dubey, S., ... & Karunakaran, K. P. (2024). In situ pre-heating in wire arc additive manufacturing: design, development, and experimental investigation on residual stresses and metallurgical and mechanical properties. Journal of Materials Engineering and Performance, 34(12), 12256–12267. https://doi.org/10.1007/s11665-024-10011-w.

[4] N.K. Gupta, G. Ganesan, S. Siddhartha, S.R. Karade, S.D. Singh, K.P. Karunakaran, (2024). A Dual-Side Deposition Technique to Mitigate Deformation in Wire Arc Additive Manufacturing, Transactions of the Indian Institute of Metals, 77(11), pp 3425-3434. https://doi.org/10.1007/s12666-024-03350-8.

[5] J. West, E. Betters, T. Schmitz, (2023). Limited-constraint WAAM fixture for hybrid manufacturing, Manuf Lett 37, 66–69. https://doi.org/10.1016/J.MFGLET.2023.08.139.

[6] N.E. Uzan, S. Ramati, R. Shneck, N. Frage, O. Yeheskel, (2018). On the effect of shot-peening on fatigue resistance of AlSi10Mg specimens fabricated by additive manufacturing using selective laser melting (AM-SLM), Addit Manuf 21, 458–464. https://doi.org/10.1016/J.ADDMA.2018.03.030.

[7] J. Goldak, A. Chakravarti, M. Bibby, (1984). A new finite element model for welding heat sources, Metallurgical Transactions B 15, 299–305. https://doi.org/10.1007/BF02667333/METRICS.