Control of Distortions and Residual Stresses for the Repair of Parts by Additive Manufacturing Using Laser Directed Energy Deposition

Context and Objective

Additive manufacturing (AM) processes of the L-DED (Laser Directed Energy Deposition) type, whether using powder or wire, are particularly well suited for repairing damaged or worn metallic parts. They are already used for the repair of turbine blades [1] in the civil sector, and several national and European projects are currently focusing on this topic. However, it is still very difficult to predict, optimize, and control the distortions and residual stresses introduced by these deposits in the often complex repaired parts. This constitutes a major obstacle to the qualification of repaired components. The reasons are mainly three scientific challenges:
(1) macroscale numerical models that are fast enough are often insufficiently predictive;
(2) microscale models are inapplicable to full 3D part simulations due to their computational cost—yet this is essential in a repair context;
(3) in-situ data and measurements to validate numerical approaches and control the process in real time across a wide range of parameters (e.g., laser power, scan speed and strategy, use of the laser or argon flow to perform heat treatments during nozzle repositioning between layers, etc.) remain scarce.

The PhD fits into the project *“Limiting residual distortions during repairs by additive manufacturing”* (LIDRES), funded by the *Centre Interdisciplinaire d’Études pour la Défense et la Sécurité* (CIEDS), which aims to remove the scientific obstacles identified above. The simplified, fast large-scale L-DED process models developed at LMS constitute a solid initial foundation but need to be extended and integrated into a numerical process-parameter optimization strategy and a neural network training workflow to develop a fast digital twin of the process.

In addition, in-situ measurements on the BeAM machine (X-ENSTA, mechanics department) are being developed at LMS and will continue during the LIDRES project through a post-doctoral position. These measurements will not only allow model validation under varied and complex conditions but also enable the establishment of real-time process-control loops, thus helping to remove the third obstacle.

PhD Topic

Digital Twin.

Research conducted at LMS over the past five years provides a foundation for developing a global, extremely fast model of the complete process. Several computational codes have been developed and must be extended as part of the PhD:

- **ScanFast [2–4]** allows rapid calculation of thermal kinetics during DED processes under the assumption of a thin-wall structure (i.e., a single bead through the thickness). The theoretical and numerical extensions will expand its validity to more complex multi-track situations (multiple beads through the thickness).
- **QuadWire [5–7]** is a one-dimensional theoretical mechanics model specifically designed for additive manufacturing problems where a highly slender bead is deposited to form a bulk part. We

have shown that this model drastically reduces the total number of degrees of freedom needed to simulate structures during printing. Future developments must incorporate elastoplastic behaviors adapted to the L-DED process.

These codes are currently developed separately in Python. They will be unified into a single, easy-to-use tool, forming a complete digital twin of the process. This twin will be experimentally validated through tests conducted in the associated post-doctoral project. Furthermore, optimization strategies for process parameters will be developed to minimize residual stresses and distortions using the digital twin.

Interfaces Between the Part and the Repair.

One specific feature of repair, compared with standard additive manufacturing, is that the printing support is no longer a simple plate substrate with easily defined boundary conditions but a larger, more complex part relative to the repair dimensions, which must be considered. Thus, a modular approach must be developed, where the part to be repaired is not simulated in detail but reduced in scale as an equivalent substrate with the correct exchange conditions with the printed region.

Real-Time Control.

The intrinsic variability of processes and of the parts to be repaired leads to a discrepancy between simulations and the actual fabrication/repair. It is therefore essential to control the process in real time to avoid deviating from the desired characteristics. Since the digital twin is sufficiently fast, it can be used to generate a large database and thus train a neural network. This network must be trained specifically to adjust process parameters based on the deviation between a target and a measurement. During the PhD, this task will initially be performed entirely numerically using synthetic measurements.

Keywords: Additive manufacturing; repair; fast simulation; residual stresses and distortions; digital twin

Desired Profile

Strong knowledge in thermo-mechanics and numerical simulation is required. An interest in additive manufacturing processes is desirable, along with scientific rigor, curiosity, and good autonomy.

The recruited candidate will primarily be based at the *Laboratoire de Mécanique des Solides* (LMS, École polytechnique) in Palaiseau (91).

Desired start date: Autumn 2025

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Compensation

Gross PhD salary (2200 euros until 31/12/2025, then 2300 euros starting 01/01/2026)

References

[1] Guevenoux, C. (2021). *Réparation de pièces métalliques par Directed Energy Deposition: gradient microstructural, comportement mécanique et tenue en fatigue* (Doctoral dissertation, Institut polytechnique de Paris).

[2] Weisz-Patrault, D. (2020). Fast simulation of temperature and phase transitions in directed energy deposition additive manufacturing. Additive Manufacturing, 31, 100990.

[3] Weisz-Patrault, D., Margerit, P., & Constantinescu, A. (2022). Residual stresses in thin walled-structures manufactured by directed energy deposition: In-situ measurements, fast thermo-mechanical simulation and buckling. Additive Manufacturing, 56, 102903.

[4] Gaudez, S., Weisz-Patrault, D., Abdesselam, K. A., Gharbi, H., Honkimäki, V., Van Petegem, S., & Upadhyay, M. V. (2025). Estimating elastic and thermal contributions to lattice strains from operando x-ray diffraction measurements using fast simulations. Additive Manufacturing, 104674.

[5] Preumont, L., Viano, R., Weisz-Patrault, D., Margerit, P., & Allaire, G. (2024). QuadWire: An extended one dimensional model for efficient mechanical simulations of bead-based additive manufacturing processes. Computer Methods in Applied Mechanics and Engineering, 427, 117010.

[6] Viano, R., Margerit, P., Mesnil, R., Weisz-Patrault, D., & Caron, J. F. (2024, September). Shrinkage characterization and compensation for 3DPC. In Digital concrete.

[7] R Viano, L Demont, P Margerit, R Mesnil, JF Caron, D Weisz-Patrault. Residual stress control in large format polylactic acid additive manufacturing via fast thermomechanical simulation and in-operando imaging techniques (2025 submitted)