Master thesis proposal in Civil and/or Architectural Engineering
2024-2025

Tentative title of the master thesis

Process parameter optimization for 3D printing of Functionally Graded rocket nozzle through Directed Energy Deposition process.

Context of the master thesis

3D printing is a very popular additive process during which layers of material are superposed to create a 3D part. In the past decade it gained a lot of interest due to an important increase in accessibility.

Directed Energy Deposition (DED) [**1**] is a specific metal additive manufacturing (AM) or 3D printing technique which uses a focused laser source to melt metal powder which is simultaneously fed by a nozzle.

The Additive Manufacturing Research Lab (AM-lab) of the VUB developed an in-house hybrid DED machine, called the MiCLAD, which is extensively presented in [**2**]. It is equipped with a 3-axis CNC control and has the particularity to allow the combination of and fast change between DED additive deposition and subtractive drilling/milling operations for the production of a part. An in-situ monitored image of the process is shown in Fig. 1 on which the nozzle, and the melt pool (high intensity spot) are visible.

Fig. 1 : MiCLAD DED process during rocket nozzle manufacturing.

Functionally Graded Materials (FGM) are components with gradual changes in composition or structure across their volume, designed to optimize mechanical or thermal performance. In DED, FGMs are produced by dynamically adjusting the metal powder or wire feed rates during the deposition process. This enables smooth transitions between different metal alloys (e.g., stainless steel to copper), reducing residual stresses and improving bonding. Such FGMs are ideal for applications requiring a combination of properties like high strength, corrosion resistance, and thermal stability within a single part.

Rocket nozzles need FGMs to withstand extreme thermal and mechanical stresses by gradually transitioning from heat-resistant materials at the throat to tougher structural metals, improving durability, reducing thermal mismatch, and preventing failure. This is why rocket nozzles are manufactured with a graded transition from 316L or Inconel to copper as shown on Fig. 2-3.

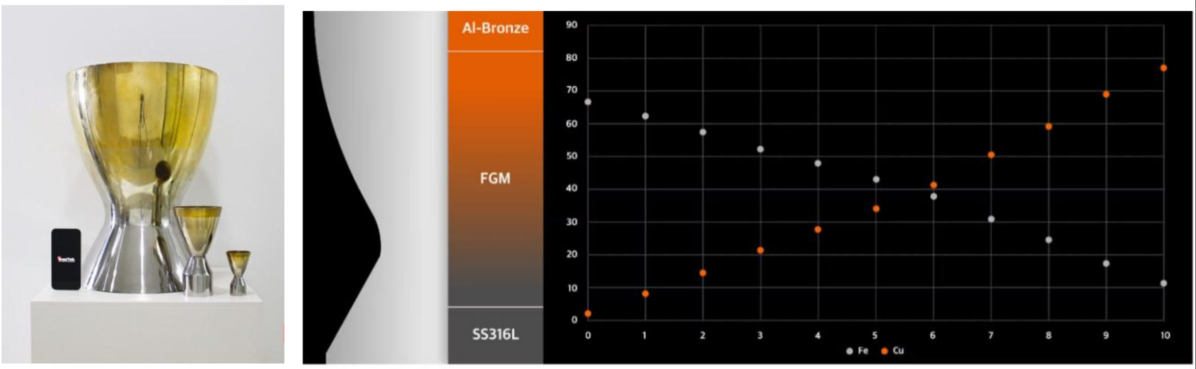

Fig. 2-3 : Functionally Graded rocket nozzle with composition evolution from 316L to copper.

The **BE-Rocket Team** [**3**] is a Belgian inter-university student initiative (VUB, KU Leuven, ULB, RMA, Liège, Mons, Bruges) aiming to design, build, test, and launch amateur solid-fuel rockets to compete in the European Rocketry Challenge (EuRoC). The 21st of October 2024, Be-Rocket successfully launched their first rocket, Bossart-I, at the military base of Elsenborn in Belgium. Fig. 4-6 shows the rocket during boost phase, and the nozzle design that was used for the tests. However, the nozzle has been conventionally manufactured and doesn't rely yet on the FGM technology.

Fig. 4-6 : Boost phase of Bossart-I rocket BE-rocket launch and used nozzle design.

In parallel at the AM-Lab of VUB, preliminary experiments have been performed for the production of miniature rocket nozzles. During the DED process, the thermal history of the part is critical to the final quality and directly influences residual stresses. Many interconnected physical phenomena occur, and the process is defined by several parameters such as laser power, scan speed, powder feed rate, scanning path, track overlap, and more. When printing FGMs, these parameters increase in number and must be actively tuned during the build as the material transitions from one type to another. The results of the manufacturing of the miniature FGM rocket nozzle are shown in Fig. 7-10. However, several processing challenges remain, including dripping, crack formation, lack of fusion, and other microstructural defects. These issues highlight the need for further process optimization to produce a high-quality rocket nozzle.

Fig. 7-10 : Miniature FGM rocket nozzle manufactured on the VUB DED MiCLAD machine.

The aim of this master thesis will be to manufacture a structurally sound rocket nozzle for the next Be-Rocket student rocket, the design of which is shown in Fig. 6. The work will involve conducting an extensive parametric study to enable the production of a high-quality miniature nozzle demonstrator, meeting criteria such as dimensional accuracy, appropriate microstructure, and minimal defects like pores, cracks, or lack of fusion. Various manufacturing strategies available in our lab must considered be explored (for example regulation of melt pool temperature, etc.).

The results of these strategies will need to be compared to identify the most efficient manufacturing approach for manufacturing a real size nozzle. The best demonstrator will then be on the test bench for solid rocket motors at the rocket propulsion test facility of the ULB, as shown on Fig. 11-12.

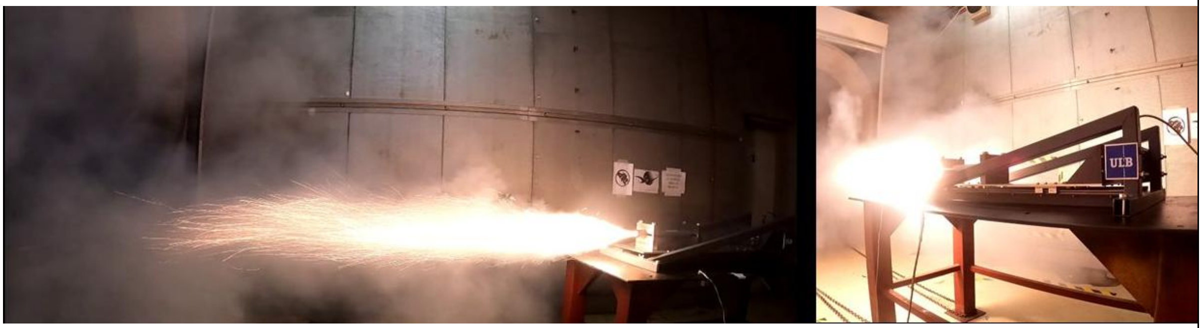

Fig. 11-12 : Rocket propulsion test facility ULB.

Upon successful completion of the master thesis, the continuation in a PhD position is a possibility to be evaluated.

References

[1] *Thompson, S. M., Bian, L., Shamsaei, N., & Yadollahi, A. (2015). An overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modeling and diagnostics.* Additive Manufacturing, 8*, 36-62.*

[2] *Ertveldt, J., Guillaume, P., & Helsen, J. (2020). MiCLAD as a platform for real-time monitoring and machine learning in laser metal deposition.* Procedia CIRP, 94*, 456-461.*

[3] *https://www.berocket.be/*

Objectives of the master thesis

- *Understanding of current DED toolpath generation solution CamLink and use for new toolpath generation for BE-rocket design.*
- *Process parameter optimization to reach a defect-free demonstrator.*
- *Investigation effect of controlled melt-temperature (and eventually other strategies) on final demonstrator.*
- *Microstructure and defect analysis of nozzle along deposition height*
- *Manufacturing of final nozzle demonstrator with optimized parameters.*
- *Testing of the final nozzle demonstrator on propulsion test facility and analysis of nozzle performance during test.*
- *The reporting of the followed methodology and analysis of the results is expected in the final master thesis manuscript.*

Supervisor[1] *Zoé Jardon (zoe.jardon@vub.be) - MECH* **Co-supervisor**[2] (optional) *Michaël Hinderdael (michael.hinderdael@vub.be@vub.be) - MECH*	**Other contact persons (Advisors**[3]**)**: *Aurélie Bellemans (aurelie.bellemans@vub.be) - FLOW*
Working language English/Dutch/French *(three languages possible)*	
Student profile Civil Engineering/Mechanical Engineering	
Design part In case the topics would be selected by a student in Architectural Engineering, please indicate if an integrated design part is coupled to the research part (to be eventually approved by the MA2 Design Studio module coordinators): ☐ YES ☒ NO ☐ TO BE CONSIDERED LATER	
Prerequisites/special skills (optional) *Interest in numerical simulations and metal additive manufacturing and proactive attitude are required.*	

[1] The main supervisor must hold an academic position in VUB or ULB Faculty of Engineering
[2] The co-supervisor must hold a PhD or an academic position
[3] An advisor must hold an academic, a research position or a lab technician position.