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DED-LB powder additive manufacturing process set-up using multi-wavelength laser diode technology (IR + Blue) for multi-material copper-nickel components and early trials with IR disk laser

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Abstract

This study presents some early results about an innovative approach in laser beam directed energy deposition (DED-LB) technology exploiting a multi wavelength (multiWL) optic head that allows to combine on the same workpiece two laser sources, a blue diode laser beam (450 nm) and an infrared diode laser beam (915 nm), for a more efficient and sustainable DED manufacturing process of a multi material copper-nickel component. The reference scenario was developed using a commercial infrared disk laser and a single beam optic head. The growing complexity of aerospace and aeronautic multi-material products, fueled by the widespread adoption of additive manufacturing calls for solutions to streamline processes, enhance efficiency and cost-effectiveness. In this context, the EU-funded WAVETAILOR project aims to leverage modular laser sources and processing heads to facilitate high-precision manufacturing of complex material structures while minimising environmental footprint and to develop a flexible, energy-efficient photonic setup offering complete adaptability to suit various energy and resource requirements. This research paper illustrates the integration of novel solutions for multiWL DED-LB powder processes in a robotic cell and reports the initial results of multi-material processing with an infrared disk laser source to obtain a functional graded copper-nickel material as a reference scenario for future comparison with the multiWL approach.

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Keywords: laser beam directed energy deposition; diode lasers; multi wavelength; multi-material; metal additive manufactruing.

1. Introduction

Multi-wavelength laser delivery, especially hybrid blue (440-450 nm) and infrared (IR) (~1000 nm) beams, is emerging as a promising strategy to overcome reflectivity and heat-input limits in conventional IR-only DED-LB solutions. Blue diode lasers dramatically increase energy absorption in high-reflectivity metals like Cu (~9x compared to IR), enhancing melt pool stability and density at lower overall energy input, which reduces thermal waste and optics damage [1]. Combined blue/IR optic heads have already been proven effective in cladding applications, enabling similar geometries at reduced laser power and simultaneously strengthening in-line spectroscopic monitoring signals [2]. Recent research on coaxial hybrid blue-infrared DED (Hybrid laser DED) shows improved melt pool dynamics and defect control for Copper-

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Steel mixed materials, highlighting the efficiency of dual-wavelength approach for multi-material deposition [3]. Fundamental modelling efforts underpin the understanding of short-wavelength absorption and thermal transport in DED-LB melt pools, and this understanding informs the development of future high-efficiency optics [4]. Sustainability gains stem from lower energy footprints, higher deposition efficiency, and improved quality when integrating blue with traditional IR fiber or disk laser sources.

Within this context, functionally graded materials (FGMs) have emerged as an application area for DED-LB strategies. Those can be defined as novel engineered materials characterized by spatial variations in composition and therefore properties. Unlike conventional composites, they enable smooth transitions that can mitigate problems associated with sharp interfaces such as delamination or thermal stress [5]. As a result, FGMs have gained attention in recent years due to their promising applicability across a wide range of engineering fields, such as aerospace, biomedical, automotive or structural parts [6].

A key benefit of FGMs is their capacity to harness the distinct mechanical and physical properties offered by different base materials. Combinations such as CuCrZr and Inconel 625 are increasingly relevant for components requiring high thermal conductivity and mechanical strength, such as in aerospace and energy systems.

As previously mentioned, metal Additive Manufacturing (AM) is an enabling technology for producing FGMs, as this technology enables layer-by-layer deposition, offering precise special control over material distribution. This methodology is called Functionally Graded Additive Manufacturing (FGAM).

Recent advancements in FGAM, have demonstrated the successful production of IN625–CuCrZr graded structures, enabling the creation of defect-free components with controlled transitions between these two alloys [8,9].

2. Materials and methods

2.1. Feedstock Materials

Two commercially available gas-atomized powders were used as feedstock for this research: an Inconel 625 nickel-based superalloy produced by Additive Carpenter, and a CuCrZr alloy supplied by Metalpine. Both materials had a particle size distribution in the range of +45-106 µm.

The chemical composition of both materials was measured upon arrival and is presented in Table 1.

Table 1. Chemical composition of In625 and CuCrZr alloys used.

Element (wt.%)	Cu	Cr	Zr	Ni	Mo	Ti	Nb	Fe	N
In625	-	21,5	-	Bal	8,7	0,2	4,1	1,9	0,009
CuCrZr	Bal	0,85	0,081	-	-	-	-	<0,03	-

2.2. Experimental set-up

CuCrZr alloy and a Nickel-based alloy IN625 powders were processed by LORTEK using a robotic DED-LB station equipped with a 6-axis Fanuc robot arm and a 2-axis positioner table and a Human Machine Interface (HMI) developed for their operation in a flexible manufacturing cell concept. For the reference scenario a solid-state 6 kW disc laser source (Trumpf TruDisk 6002, Ditzingen, Germany) operated in continuous wave (CW) mode with a wavelength of 1030 nm was also used. The laser beam is guided through an optic fibre of 400 µm. The LMD robotic station was equipped with a fixed Trumpf BEO D70-90° optic head (Ditzingen, Germany) with a collimation/focal length of 200/200 mm and an annular continuous coaxial HighNo4.0 nozzle manufactured by Harald Dickler GmbH (Übach-Palenberg, Germany) operated with a stand-off distance of 9 mm. For WAVETAILOR research project a new multiWL dual laser optic head with two collimators and one focusing lens with a 4-jet discrete nozzle (see Fig. 1) were developed and manufactured by PRIMA Additive (now AltForm). Two laser concepts are used for comparison: A modular multiWL dual laser concept, which is composed of an innovative IR diode laser source with a wavelength of 915 nm, developed and manufactured by nLIGHT Europe (Torino, Italy), and a blue laser manufactured by NUBURU Inc. (Colorado, USA). The mentioned IR diode laser source allows a rapid laser power measurement with a latency of 10 µs. Both lasers operate in continuous wave (CW) mode and are commanded by the HMI at cell level.

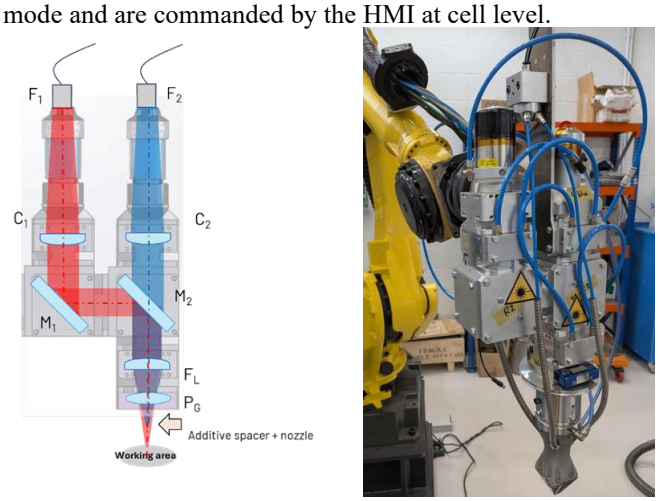


Fig 1. MultiWL dual laser DED optic head developed and manufactured by PRIMA Additive (Now AltForm).

For powder delivery and enabling the multi-material deposition, the DED-LB station has a twin powder feeder Oerlikon-Metco Twin 150 (Wohlen, Switzerland) with two 5 L heated hoppers and a mixing chamber. Argon Q1 was used as protective (9 l/min) and carrier gas (2 l/min flow at 2 bars) for powder particles delivery to powder distributor and the nozzle.

2.3. Methods

A thin single-track wall (Fig. 2) was built on a build plate inclined 5º to minimise laser reflection to the optics in the head. The experimental setup is shown in Fig 3 and the process parameters used for the fabrication of the specimen is shown in Table 2, as it can be observed for this study, a five-step compositional gradient was implemented**Fehler! Verweisquelle konnte nicht gefunden werden.**. A unidirectional scan strategy (laser switch on at one extreme of

the track for each layer) was employed for the fabrication of the thin wall.

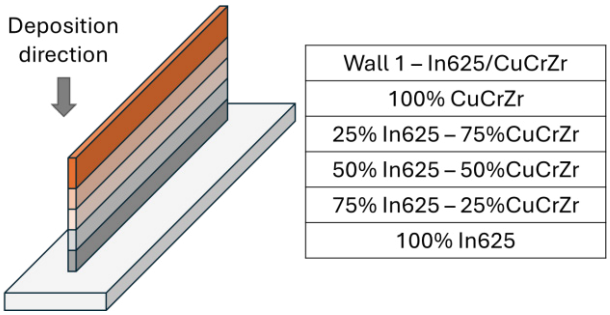


Fig. 2. Schematic representation of the deposition strategy for the development of the FGM In625-CuCrZr

After fabrication, the thin wall was sectioned, polished and analised in their cross-section. Metallographic characterisation of the section across the height of the FGM walls was performed using light optical microscopy, SEM, EDX and HV.

Standard metallographic preparation procedures, including cutting, mounting, grinding and polishing, were carried out, followed by chemical etching for 12 s with a reagent composed of 7 ml HF, 3 ml HNO3, and 5 ml of H2O to reveal the microstructural features.

Macrostructural integrity, porosity and layer morphology were evaluated through optical microscopy (Olympus GX51 optical microscope with an image acquisition system via digital camera). Grain boundaries and phase distribution were evaluated through FESEM (Zeiss Ultra Plus model, equipped with an X-ray detector from Oxford Instruments (X-Max)). Elemental distribution along the height of the thin walls by conducting elemental composition profiles via EDX. Finally, a hardness profile using a Buehler MacroMet 5112 durometer, with a load of 500 g (HV0.5 scale) was performed.

3. Results and discussion

3.1. Integration of multiWL optic head and Blue + IR diode laser sources in a Robotic DED-LB powder cell

The materials were processed first with current capabilities at LORTEK, using an IR disk laser and a commercial optic head (Trumpf BEO D70-90º), which are the results presented in this study, and then the multiWL dual laser DED optic head and multiWL laser sources were integrated into the DED-LB robotic cell at LORTEK (See Fig. 3).

Table 2. DED-LB Process parameters and FGM material ratio composition grades for each step gradients

	Mixing ratio, wt.%	Powder flow, g/min	Deposition speed, mm/s	Power, W	Layer thickness, mm	Total layers
1	100 In625 0 CuCrZr	10.5 --	17	580	0.6	7
2	75 In625 25 CuCrZr	8.4 2.4	17	640	0.6	7
3	50 In625 50 CuCrZr	5.4 5.8	17	690	0.6	7
4	25 In625 75 CuCrZr	2.3 9.2	17	720	0.6	7
5	0 In625 100 CuCrZr	-- 11.5	17	720	0.6	7

For this work, a powder mixing chamber, rapid switches for automatic hopper switching, and a powder flow watch sensor were incorporated into the Twin powder-feeder system. The operating parameters were adjusted to achieve a controlled powder flow rate totaling a mass flow rate of ~11 g/min (CuCrZr + IN625 mix). The manufacturing process parameters used were a laser spot diameter of 1.6 mm, laser power of 580-770 W, and a linear deposition speed of 17 mm/s. The final dimensions of the manufactured single track walls were a total length of 75 mm, thickness of ~1.80 mm and a height of 21 mm. As build plate, rectangular pieces (100x50x10 mm3) of stainless steel type 304L were used.

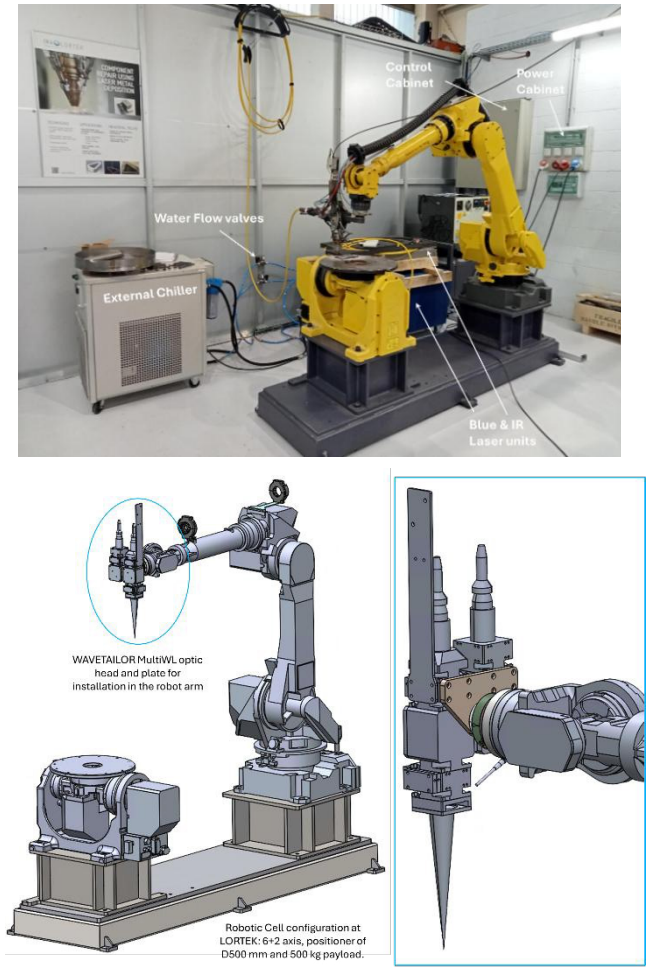


Fig. 3. Hardware modifications in DED-LB robotic cell at LORTEK (Top) and Virtualization of the cell with the new multiWL optic head (Bottom)

The DED-LB robotic cell has been prepared to work with both diode laser systems, all the signals have been wired and mapped to the industrial PC master. The software and new modules in the HMI are prepared to work with both lasers and additional ones, controlling the cooling system and the Twin powder feeder to enable multi-material deposition. To achieve this level of automation, it was necessary to acquire new hardware and materials (communication cards for the two new lasers units) and expand the communication architecture.

Finally, the HMI was updated in their CONFIG, DATALOGGER and SAFETY modules (Fig 4) to work with the multiWL dual laser concept.

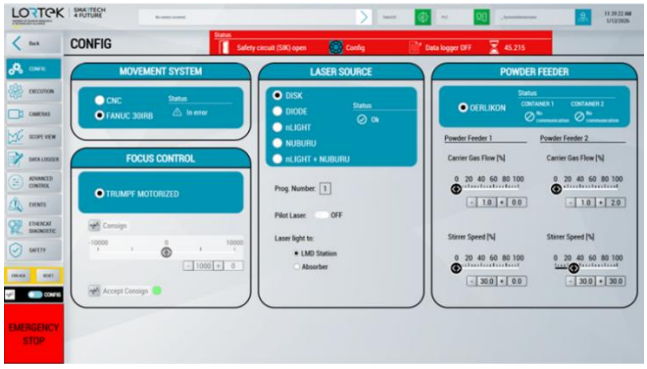


Fig. 4. Update of the HMI Config module to work with current scenario and new laser source units (Disk, LL IR diode, nLIGHT IR diode and Blue diode) at LORTEK DED-LB robotic cell.

3.2. Process development for FGMs with IR disk laser (reference scenario)

Figure 5 shows a macrographic examination of a cross section of the fabricated thin wall, with its corresponding FGM mixing ratio (showing the five-step gradients). As can be seen, there is no visible lack of fusion or porosity throughout its cross section, but small cracks are visible on some surfaces.

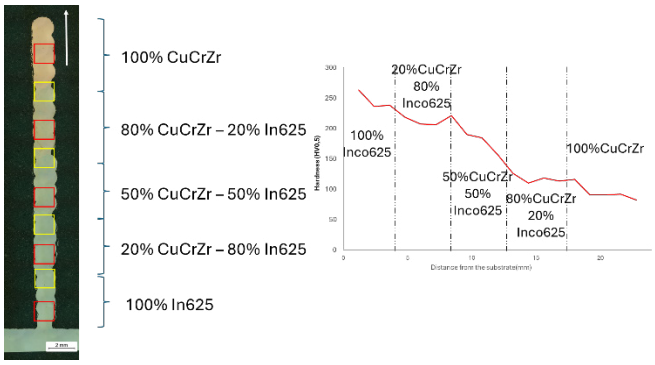


Fig 5. Macrographic examination of the fabricated FGM (left), and Hardness distribution across the cross section of the fabricated wall (right)

To assess the spatial distribution of the mechanical properties obtained after fabricating the wall, hardness indentations were performed on the material, with measurements taken every mm from the substrate to the top of the wall. The results obtained and showed in Fig. 5, which presents the hardness variation as a function of the distance from the substrate, along with the corresponding feed mixture in each of the five sections.

In the 100% Inconel 625 region, the hardness is approximately 250 HV0.5 and decreases, as expected, linearly with a transition gradient to about 70 HV0.5 in the 100% CuCrZr region. This is an expected and desirable behavior of an FGM.

4. Conclusions

In this study, the development of the DED-LB powder AM process for multi-material copper and nickel components using a single-beam IR disk laser was investigated, as well as advancements in the implementation of multi-wavelength (IR + blue) laser diode technology. Based on the initial results obtained, we were able to draw the following conclusions:

- The development of the DED-LB powder process for obtaining FGM Cu-Ni has been achieved, resulting in a single tracks wall with minimal defects and an adequate transition between the chemical compositions of both materials deposited. A smooth gradient in hardness demonstrates a controlled compositional transition, confirming the formation of a stable and homogeneous material combination.
- The HMI system at cell level has been updated, only the final test and validation is pending (to be done after new laser sources commissioning and start-up) to manufacture the multi-material aerospace demonstrator component. using multiWL dual laser optic head and modular laser unit combining Blue and IR laser beams brings a flexible and energy-efficient photonic setup in comparison with current single beam IR fiber or disk laser approach.
- The reported results is for IR disk laser processing (reference scenario). The full implementation and validation of multiWL solutions developed in WAVETAILOR project is in progress and benefits will be evaluated on a multi-material aerospace component at end of the project.

Acknowledgements

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