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# Implementation of a productive and reliable laser-based directed energy deposition process for the Oil & Gas field

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## Abstract

Laser-based powder Directed Energy Deposition (DED-LB) is commonly used for rapid prototyping and repairing, but its productivity limitations have prevented widespread implementation for production in the Oil & Gas industry. To address this issue, an optimization procedure has been developed to increase deposition rates while maintaining good internal quality thick-walled structures. The procedure involves analyzing the effect of process parameters with a novel approach, and balancing them on productivity, efficiency, and clad shape. The heat input was limited as for conventional DED-LB. Furthermore, a monitoring system has also been implemented to ensure reliable process conditions without drifts. Finally, CNC gantry and articulated robot machines have been evaluated for geometric accuracy. The aim of this study is to demonstrate the viability of DED-LB in the Oil & Gas industry by increasing productivity and encouraging adoption, while maintaining high-quality standards.

Keywords: directed energy deposition; DED; laser metal deposition; LMD; process development; process monitoring; process optimization.

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## 1. Main text

Laser-based powder Directed Energy Deposition (DED-LB) has emerged as a promising technology for rapid prototyping and repair applications in various industries. It is capable of precisely depositing material layers using laser energy only where needed (Kanishka and Acherjee, 2023). This technology not only allows

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for the repair of damaged components but also enables the direct deposition of complex-shaped large size parts, offering a limited buy-to-fly ratio and lead time (Lehmann et al., 2021). Additionally, no molds are required, making the process suitable for producing custom-made, one-of-a-kind components (Frazier, 2014).

However, the productivity limitations associated with DED-LB have hindered its widespread implementation in the Oil & Gas industry, where efficiency and scalability are crucial (Tarancón et al., 2022). Developing a productive and reliable DED-LB process is a challenging task due to the numerous factors that need to be considered in order to achieve the desired outcome. The process is difficult to manage due to the multitude of controllable and uncontrollable input parameters that influence the quality of the deposited material and the overall performance of the deposition process (Shamsaei et al., 2015).

In order for the process to be appealing in high-end sectors such as Oil & Gas and Aerospace, it must meet certain requirements that are not always easy to fulfill simultaneously. The process should be productive and efficient in terms of deposition performance, while also ensuring that no predictable or unpredictable defects occur during production (Tang et al., 2020). For example, when dealing with large components like a turbine case with a diameter exceeding 1 meter, suboptimal deposition performance could significantly increase lead time or result in excessive material waste. Defects caused by poor tuning of process parameters or excessive heat accumulation can be even more detrimental, potentially leading to the rejection of an entire defective component (Svetlizky et al., 2021).

Developing a DED-LB process that meets these constraints requires a significant effort. This work presents the setup of a DED-LB process for the production of large gas turbine components using Inconel 718. Three main topics are discussed: the optimization of process parameters, the implementation of monitoring and control systems, and the evaluation and comparison of two different machines.

## 2. Materials and methods

The process was developed on a plasma atomized Inconel 718 powder by AP&C–GE Additive (Saint Eustache, CA). The powder granulometry ranged between 25 and 45  $\mu\text{m}$ . The substrates were instead made of AISI 304 stainless steel.

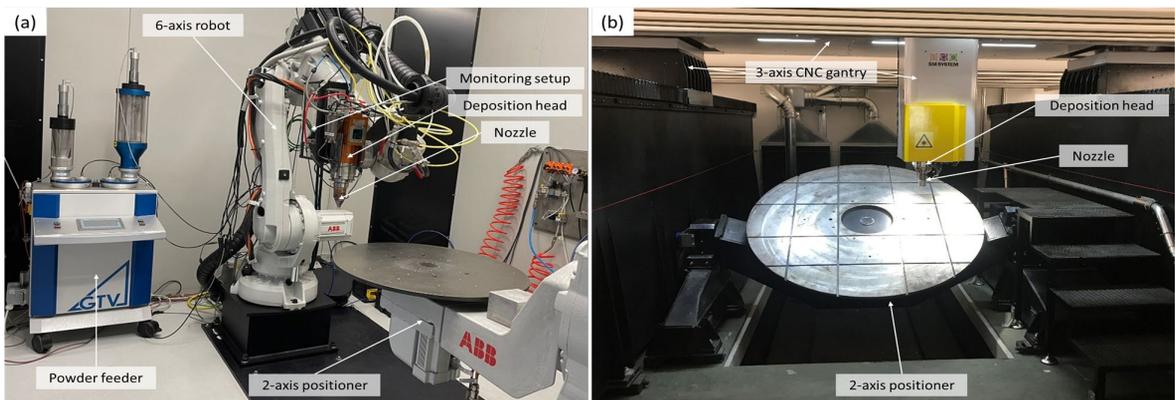


Fig. 1 The two DED-LB machines used throughout this study: (a) articulated robot, and (b) CNC gantry.

This study was conducted using two different, yet similar, DED-LB machines. These machines share similar laser and powder systems. Specifically, they are both equipped with an IPG Photonics (Oxford, MI, USA) high-

power fiber laser operating at a wavelength of 1070 nm. Additionally, both machines are fitted with the same KUKA (Augsburg, DE) deposition head, which incorporates a coaxial powder nozzle from Fraunhofer ILT (Aachen, DE). By adjusting the position of the collimation lens, the same laser spot diameter can be achieved at the working plane.

The primary difference between the two machines lies in their motion systems. One machine utilizes an articulated robot manufactured by ABB (Västerås, SE) to move the deposition head, while the other machine employs a CNC gantry system manufactured by SM Systems (Torre Canavese, IT). Finally, both the machines are equipped with a 2-axis positioned that can rotate and tilt. The two DED-LB systems are shown in Fig. 1 and are more in-depth described in (Maffia et al., 2023a).

### 3. Process development strategy

As anticipated, the development problem of the DED-LB process was approached by dividing it into three perspectives: parameter optimization, implementation of monitoring systems, and evaluation of the geometrical accuracy of two different machines.

#### 3.1. Parameter optimization

It is commonly reported that the DED-LB process with powder achieves deposition rates of only 300-500 g/h when using Inconel 718, which is insufficient in terms of productivity when considering the production of large components. Additionally, these results are obtained with a 50% powder catchment efficiency, meaning that 50% of the blown powder is wasted. This level of wastage is not acceptable, especially when dealing with expensive materials.

One possible approach to overcome this limitation is to utilize very high laser power levels (above 3 kW), large laser spots (diameter > 4 mm), and high powder feed rates (above 3 kg/h). This allows for deposition rates exceeding 2 kg/h. However, this approach requires an unconventional setup, and since the process conditions differ significantly from conventional ones, the underlying mechanisms of the process also change. This necessitates further studies on thermal behavior and heat treatments. Additionally, with such high power levels, interlayer pauses should be considered during the deposition of wall-like structures to prevent excessive heat accumulation.

Another approach to enhance the productivity of the DED-LB process would be to stick with a conventional setup but conduct a thorough experimental campaign aimed at maximizing the deposition rate. The reported deposition rates of 300-500 g/h are obtained under conditions that are not optimized for productivity. Therefore, these values may not reflect the true potential of the technology. To address this, a series of experiments were designed and conducted to maximize the deposition rate using the standard setup. The experiments involved the deposition and analysis of single tracks and thick walls, with considerations for powder catchment efficiency and internal deposit quality (preventing porosities). Only process conditions that produced single tracks with a contact angle below 60 degrees were considered to ensure the absence of lack of fusion. The strategy was to investigate the effects of process parameters on the deposition rate and employ a multi-objective optimization approach to find the optimal process parameter sets that maximize productivity and efficiency while avoiding lack of fusion. Throughout the experimental campaigns, a wide range of process parameters were tested, including laser power between 575 W and 2000 W, scan speed between 420 mm/min and 1980 mm/min, and powder feed rate between 270 g/h and 2115 g/h.

### 3.2. Process monitoring

It is not uncommon to run the DED-LB process without real-time monitoring, as properly tuned process parameters can lead to successful outcomes without the need for adjustments. However, these process parameters are typically optimized using simple-shaped samples such as single tracks, thick walls, or cubes, which can significantly differ from real components. Consequently, even if the process appears stable, heat may unexpectedly accumulate when depositing complex or unfavorable geometries, resulting in internal defects such as porosities or deviations from the desired microstructure. These defects render the deposited part non-compliant and ultimately lead to its rejection.

Process monitoring systems play a crucial role in tracking the entire deposition process and capturing its history. Various strategies can be employed to collect data during deposition, utilizing different sensors and configurations to record various process signatures. In this study, it was decided to directly monitor the characteristics of the molten pool, including the molten pool height, area, and temperature. To achieve this, three sensors were employed: a green laser triangulator, a near-infrared camera, and a ratio pyrometer. The preferred approach for these measurements was to implement the sensors coaxially rather than laterally. To accomplish this, the lateral optical door of the deposition head was utilized. Fig. 2 shows the monitoring setup and its optical scheme.

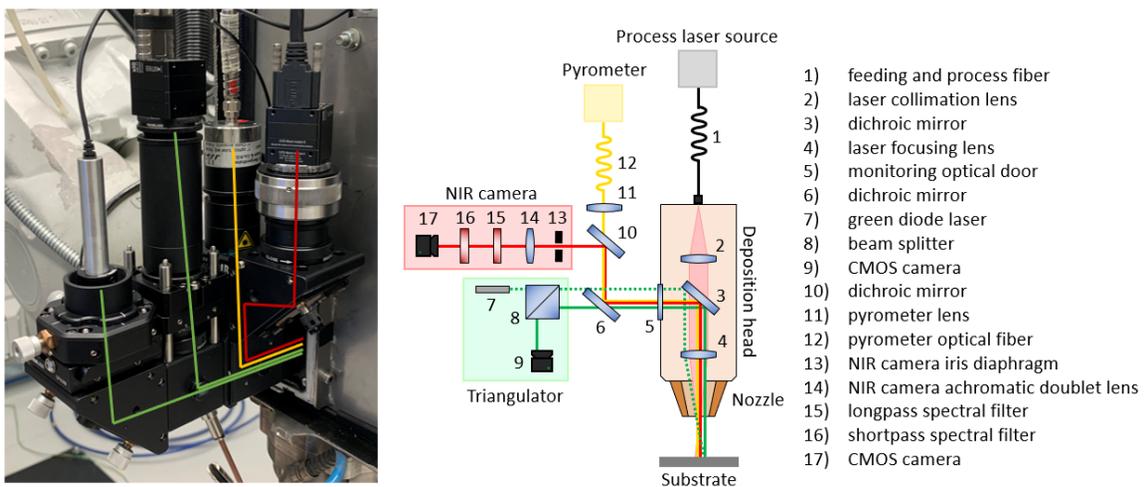


Fig. 2 The coaxial monitoring optical system and its optical scheme (Maffia et al., 2023b).

To assess the effectiveness of the proposed monitoring solution, an experimental campaign was conducted on thin walls. The campaign involved varying the laser power and scan speed, following the scheme outlined in Fig. 3. A 2-factors 2-levels experimental design was employed for this study, with three replicates and the inclusion of a central point. The measured outputs from the experiments were collected and presented in main effect plots. These plots were analyzed to evaluate their ability to identify and distinguish different process conditions.

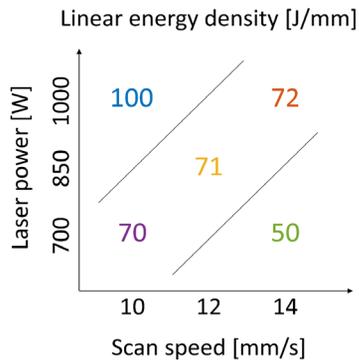


Fig. 3 Process parameters and resulting linear energy density to assess the performance of the monitoring setup (Maffia et al., 2023b).

### 3.3. Comparison of the geometrical accuracy of the two machines

For this test, a case study was developed using an axisymmetric gas turbine component with a diameter of approximately 400 mm. The component was selected to be printed on both machines using the same set of process parameters. By utilizing the same parameters and considering the similarities between the laser and powder systems used in both machines, any differences in the geometry of the deposited components can be attributed to the accuracy performance of the machines.

The CNC gantry machine offers higher accuracy compared to the articulated robot but is also significantly more expensive. After the deposition of the two components, 3D laser scanning was performed using a FARO Technologies scanner (Lake Mary, FL, USA), and the scans of the two components were compared to evaluate possible differences.

While the CNC gantry machine may exhibit greater accuracy, this improved precision may not be crucial for the DED-LB process, especially when fabricating large structures where the use of relatively large laser spots is preferred, which reduces the process resolution. However, higher geometrical accuracy can still be advantageous as it may allow for a reduction in stock material.

If no significant differences are observed between the two components, it suggests that using robots for this application could be a viable alternative to CNC systems. This would not only reduce the cost of the machine itself but also the overall process expenses (Maffia et al., 2023a).

## 4. Results and discussion

The objective of this work was to make the DED-LB process viable for the production of large components, particularly for the Oil & Gas industry. To achieve this, the productivity and efficiency of the process needed to be improved without compromising the internal quality of the deposited parts. It was also crucial to identify and prevent unwanted heat accumulation or other defects resulting from the shape and size of the components. Additionally, the selection of the appropriate DED-LB machine configuration needed to strike a balance between cost and geometrical accuracy.

The study demonstrated that the deposition rate is significantly influenced by the laser power and powder feed rate. To increase process productivity, both of these parameters should be maximized. However, it is important to note that excessively high powder feed rates can lead to a reduction in efficiency. Interestingly, the scan speed did not have a significant impact on either productivity or efficiency. This is because increasing the speed tends to reduce the shape and cross-section area of the deposited track, effectively canceling out any effects on productivity and efficiency. However, in terms of ensuring the

internal quality of the parts, it was found that imposing an upper limit on the contact angle of the single track was effective in preventing the formation of lack of fusion voids between adjacent tracks, as it allows for proper material melting.

However, when increasing the powder feed rate to enhance process performance, the contact angle of the single tracks also increases. Therefore, the powder feed rate needs to be limited. Alternatively, increasing the scan speed can help in depositing tracks with lower contact angles. By utilizing high levels of both the powder feed rate and scan speed, deposition rates of 1.5 kg/h, with a deposition efficiency of 70% and no internal defects, can be achieved with Inconel 718.

Fig. 4 displays the main effect plots generated during the monitoring activity. The three monitored process signatures—molten pool height, area, and temperature—exhibit similar behavior as the process parameters are adjusted. All three responses increase with higher laser power and decrease with higher scan speed. However, it is evident that the scan speed has the strongest influence on the molten pool height, while the laser power has the strongest impact on the molten pool area and temperature.

The implemented coaxial monitoring setup, consisting of three sensors, effectively detects variations in the process conditions and provides real-time information about the deposition status. In this study, variations in process conditions were achieved by directly manipulating the process parameters. However, the monitoring system is also capable of capturing variations resulting from external and uncontrollable factors.

Overall, the monitoring system demonstrated its ability to accurately track changes in the process conditions and provide comprehensive insights into the deposition process (Maffia et al., 2023b).

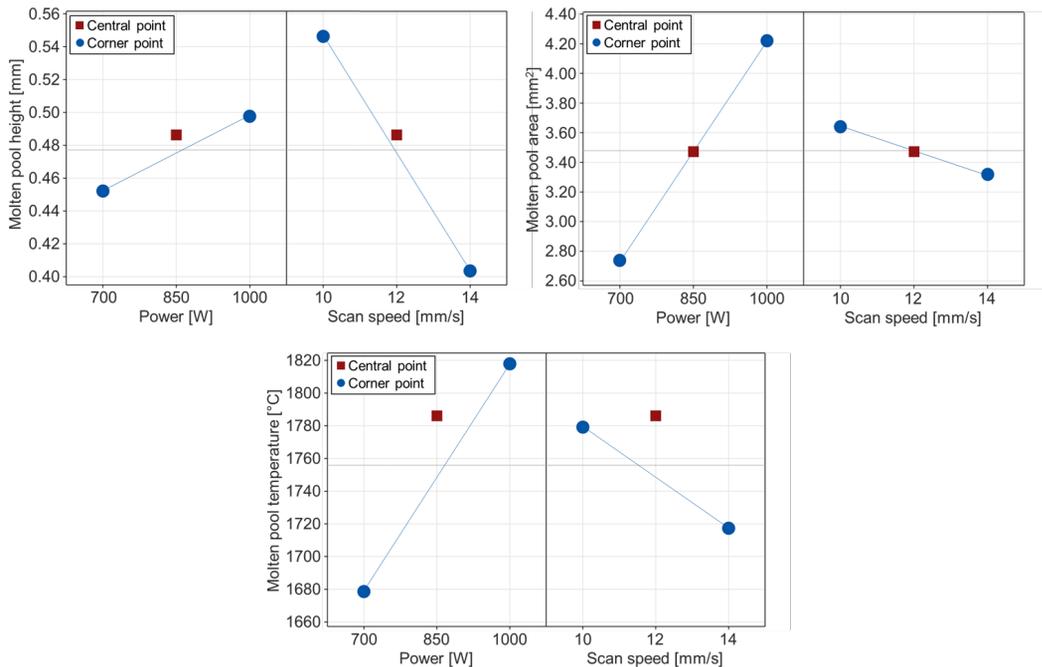


Fig. 4 Main effect plots of the molten pool height, area, and temperature (Maffia et al., 2023b).

Fig. 5 illustrates the pseudo-color geometrical comparisons between the 3D scans of the components deposited using the two machines, as well as the comparison with the original CAD file. Additionally, a

comparison between the two component scans is shown. It is evident that both components exhibit a deformation towards the center, resulting in a geometrical mismatch of approximately 2 mm in the internal side wall compared to the CAD model. This deformation is caused by the residual stresses induced during the DED-LB process, which is known for its rapid cooling rate.

However, considering that the two machines are identical in terms of laser and powder management, and that the same set of process parameters was employed, it is reasonable to assume that the deformation caused by thermal residual stresses is similar in both components. When comparing the two 3D scans, the dimensional mismatch between them is very small, within the range of  $\pm 0.5$  mm. This finding suggests that, for large axisymmetric components in the DED-LB process, the lower geometrical accuracy typically associated with articulated robots is not significant. Therefore, using an articulated robot instead of a CNC gantry system to handle the deposition head could be a viable approach to reduce the costs of the DED-LB machine and ultimately lower the overall process expenses (Maffia et al., 2023a).

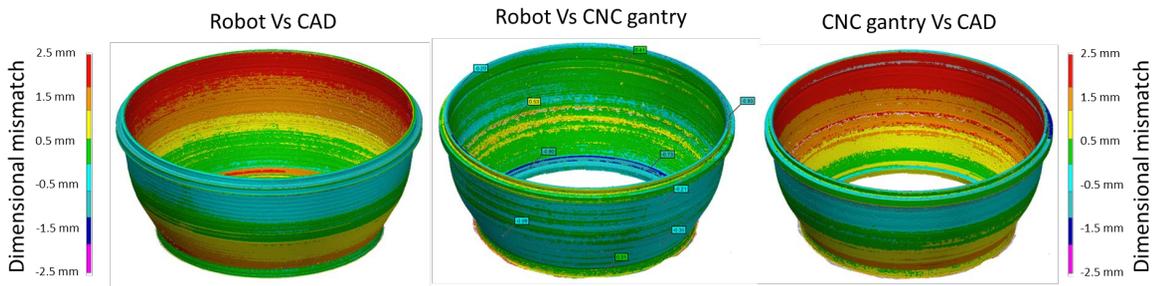


Fig. 5 The comparisons of the two 3D scans to the original CAD file and between themselves (Maffia et al., 2023a).

## 5. Conclusions

This work focused on developing a conventional DED-LB process suitable for manufacturing large gas turbine components using Inconel 718, specifically targeting the Oil & Gas sector. The development process was divided into three main activities: process optimization, implementation of a monitoring system, and evaluation of the geometrical accuracy of different DED-LB machines.

- In terms of process optimization, several experimental campaigns were conducted to enhance the deposition rate, efficiency, and internal quality of the parts. The results achieved were significant improvements compared to the standard setup, with a productivity of 1.5 kg/h, 70% powder catchment efficiency, and fully dense deposited material. These outcomes make the process feasible for efficiently producing large components within a reasonable timeframe.
- The implementation of a monitoring system played a crucial role in this work. A coaxial 3-sensor setup consisting of a triangulator, a near-infrared camera, and a ratio pyrometer was mounted on the deposition head. This system enabled real-time measurement and monitoring of the molten pool height, area, and temperature, respectively. By capturing variations in the process conditions, the monitoring system could help identify and mitigate issues such as heat accumulation or material defects that may occur during the deposition of complex-shaped large structures.
  - The evaluation of the geometrical accuracy of two DED-LB machines, one utilizing a CNC gantry system and the other an articulated robot, revealed that despite the CNC gantry machine being inherently more accurate, no significant difference in geometrical accuracy was observed for the axisymmetric component. Both machines exhibited the same deformation pattern, indicating that for this specific

application, a cheaper articulated robot could be successfully employed, reducing the overall cost of the DED-LB machine.

The successful implementation of the DED-LB process in the Oil & Gas field opens up opportunities for future development. Further research can explore the process with other alloys and non-axisymmetric geometries to expand its applicability. Additionally, based on the presented monitoring system, a feedback control system has been designed and is currently undergoing testing, paving the way for advanced process control and optimization.

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