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Procedia CIRP 124 (2024) 210–213

www.elsevier.com/locate/procedia

13th CIRP Conference on Photonic Technologies [LANE 2024], 15-19 September 2024, Fürth, Germany

Energy consumption monitoring in DED-LB for enhancing the process sustainability

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Abstract

Energy efficiency is a highly relevant aspect in modern manufacturing processes, not only for economic reasons, but also because of the environmental impact it generates. With the aim of contributing to a more efficient and environmentally friendly manufacturing process, this research analyses the energy consumption of the Laser Directed Energy Deposition (DED-LB).
First, the energy efficiency of the laser generator is characterized. In a second step, the deposition process is evaluated, which enables to categorize the process according to the amount of energy required per gram of material deposited, and the mass-deposition efficiency. For this purpose, a 3-level design of experiment (DOE) is performed in order to study the effect of the laser power, mass rate, and machine feed rate on the process efficiency. Besides, a metallographic study is also performed to ensure the metallurgical quality. Energy and material saving of 35% are obtained without influencing the clad quality.

Keywords: Energy Consumption; Monitoring; DED-LB; Sustainability

1. Introduction

There is no doubt that sustainability is fundamental in modern industrial production processes. The growing awareness of the impact that production has on the environment and social spheres has promoted a paradigm shift in the conception and implementation of industrial activity [1]. Manufacturers are therefore adopting environmentally friendlier practices, such as optimizing natural resources and reducing emissions. In this line, one of the key strategies is to improve the energy efficiency, as this not only implies a more responsible use of resources but also translates into greater competitiveness and stability for companies [2].

Reducing industrial energy consumption is a key measure to mitigate the impact of climate change. In addition, reducing the countries' energy dependence and achieving the goa ls of the European Green Deal is also crucial [3].

Achieving the commitments of the Green Deal requires a profound change in how industrial processes are conceived and executed. The aim of the Green Deal is based on prioritizing clean technologies, sustainable practices, and efficient energy management as fundamental pillars towards a greener and more prosperous future. Thus, Directive (EU) 2018/2002 establishes ambitious objectives to improve energy efficiency, particularly to reduce primary energy consumption in the EU by at least 32.5% by 2030 compared to current projections [1].

Besides, due to the war in Ukraine and other international conflicts, fossil fuels used for electricity production, namely oil and gas, have become more expensive, directly affecting electricity prices (Fig. 1). This energy cost increasing have forced some industries to cut production by 50% or even halt the production completely [4]. Therefore, efficient use of electricity not only helps conserve natural resources and mitigate climate change but can also be a significant competitive advantage. By implementing more efficient

10.1016/j.procir.2024.08.101

production technologies and optimizing energy management systems, companies can reduce long-term operating costs as well as improve their corporate image by meeting the growing sustainability expectations of consumers and regulators.

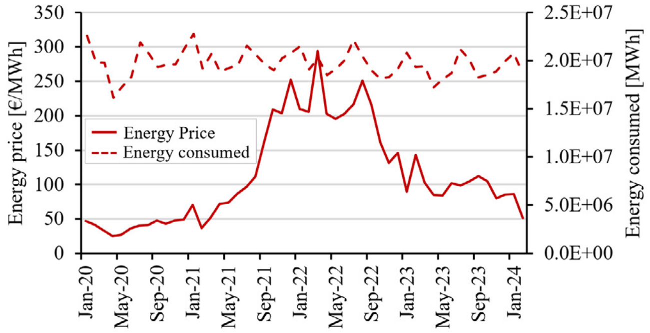

Fig. 1. Energy price and consumption between 01/ 2020 and 03/ 2023 in Spain [5].

In this regard, additive manufacturing (AM) processes have become a highly sustainable alternative to traditional industrial manufacturing processes [6]. AM is known for its ability to create products by adding successive layers of material, which significantly reduces material waste compared to subtractive manufacturing methods.

In order to assess the sustainability of AM, the environmental impact of the whole process needs to be studied, from the extraction of raw materials and the production of powder, to the post processing. Research data shows that, in the case of the laser Directed Energy Deposition process (DED-LB) and compared to other aspects, the majority of the energy consumption derives from the deposition process itself [7]. Therefore, both the operating cost of the company and the carbon footprint of the production process would be greatly reduced by increasing the energy efficiency of the manufacturing process.

However, the energy efficiency of the process has not been often studied, and large variations can be found in the energy consumed per gram of additively manufactured material [8].

In view of this necessity, in the present research, the energy and mass efficiency of the DED-LB process is studied at different stages and the optimal parameter set for boosting them are concluded.

2. Methodology

2.1. Experimental tests

The energy and mass efficiency are analysed in three steps, in order to increase progressively the complexity of the studied situation.

First, the energy efficiency of the Coherent Highlight FL 1000 laser generator is analysed. On the one hand, the real power emitted by the laser is measured at the DED-LB nozzle exit with a Coherent PM3K–100 power meter, where the power losses due to the fiber transportation and the optical path within the DED-LB head are considered. On the other hand, the energy consumption from the network is measured using a Fluke 1732 three-phase analyzer, which enables to define the wall-plug efficiency.

The whole power range, up to a 1000 W nominal laser power, is evaluated in 100 W steps. In each situation the laser is maintained at a constant power approximately during 60 s, which is sufficient to ensure that the network power consumption is stable. After the whole range is studied, the laser is restarted, and the central value of 500 W is repeated to study the measurement repeatability.

In a second step, the energy efficiency of the DED-LB nozzle is evaluated through the laser beam attenuation. The same Coherent PM3K–100 power meter as in the previous step is employed according to the setup detailed in Fig. 2. At the focal plane a 1 mm thick steel plate is installed, with a 5 mm diameter hole where the laser beam is centered. At the lower face, an air jet is installed, which blows the powder particles as soon as they pass the hole in the steel plate. These particles are suctioned with a vacuum system. The power meter is positioned at a 250 mm distance from the nozzle tip and is covered with a protective glass. Besides, it is constantly cleaned with a lateral cross jet to avoid posing powder particles on the glass that could induce measuring errors.

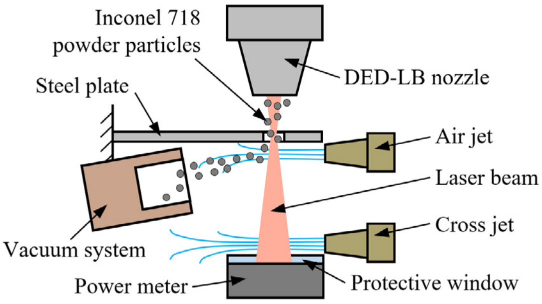

Fig. 2. Experimental setup for the laser beam attenuation measurement.

In a third step, the mass and energy efficiency during the DED-LB process are measured. For this purpose, a 3-level DOE experimental design is performed. Laser power (P), machine feed rate (F), and powder mass rate (M) are varied a 20% around the central values of 600 W, 525 mm·min^{-1}, and 5.5 g/min, respectively. The central value is repeated twice to ensure the process and measurements reliability, test 1 and 8.

Table 1. DED-LB experimental tests for process efficiency measuring.

Test	P [W]	F [mm·min^{-1}]	M [g/min]
1	600	525	5.5
2	720	525	5.5
3	480	525	5.5
4	600	420	5.5
5	600	630	5.5
6	600	525	4.4
7	600	525	6.6
8	600	525	5.5

Base material is a 100x80x10 mm^3 Inconel 718 plate and filler material for DED-LB tests is gas atomized Inconel 718 powder with a particle size between 45 μm and 90 μm. The nozzle is located 15 mm above the working plane and the laser spot diameter is 1.5 mm. Argon with a 99.99% purity is employed for drag and shielding.

Individual clads have a 80 mm length and 3 cross sections are extracted from each test to measure the average clad width (W), height (H), and area (A). Individual specimens are prepared following the appropriate metallographic procedure, and Kalling´s 2 reagent is employed for revealing the Inconel 718 microstructure. Finally, a Leica DCM-3D optical microscope is employed for analysing the cross sections.

3. Results and discussion

3.1. Laser Generator Efficiency Analysis

The Fluke 1732 three-phase analyser provides an instantaneous network power consumption reading every 1 s. In Fig. 3 the active power consumption from the network is shown in real time. The laser presents a 0.38 kW residual power consumption, which initiates automatically once the laser is switched on. In the individual tests, after an initial peak, the consumed power stabilizes rapidly, and an increasing network power consumption is detected with an increasing nominal power of the laser. Finally, the 500 W test is repeated after the laser is restarted, this is the reason why the network consumption drops to almost zero between the 1000 W test and the final 500 W test. The whole procedure is repeated twice and differences between lectures below 1% are obtained, what ensures the repeatability of the process and the extrapolation of the present results to future tests.

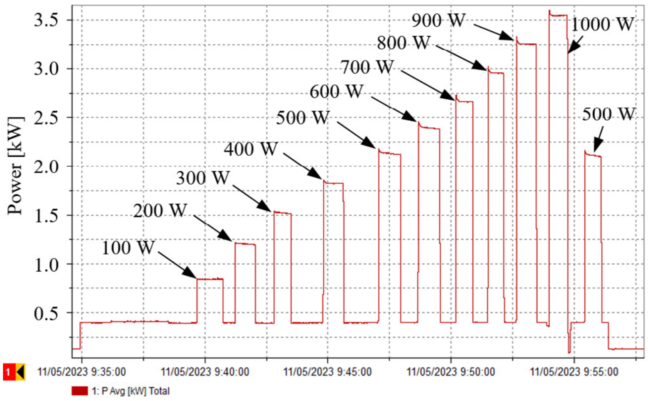

Fig. 3. Network energy consumption for different nominal laser powers.

The laser beam losses in the optical path and laser DED-LB head are almost linear and a power loss of between 5 and 7% is measured in the whole studied range, solid line in Fig. 4. The power consumption from the network, on the contrary, has a low residual value and presents a decreasing slope, as shown in Fig. 4 by the dashed curve, which means that the efficiency of the laser generator is variable depending on the nominal laser power.

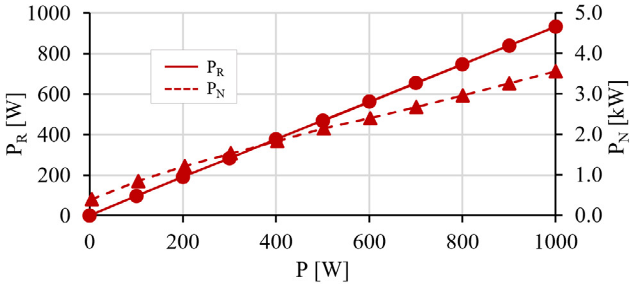

Fig. 4. Relation between the power consumption from the network (P_N), real laser power (P_R), and nominal laser power (P).

The wall-plug efficiency (η_L) for the whole laser system, generator plus optical path, is defined according to eq. (1). At 0 W nominal laser power, the laser presents a zero efficiency, because despite having a residual power consumption no radiation is emitted. However, as the nominal power of the laser is increased, a higher efficiency is obtained, see Fig. 5. For instance, working at an 800 W laser power instead of 400 W, implies an 22.82% improvement of the laser efficiency, or what is the same, almost a quarter of the consumed energy is saved.

$$\eta_L = \frac{P_R}{P_N} \cdot 100 \tag{1}$$

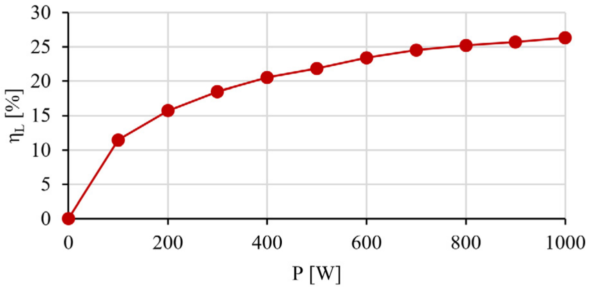

Fig. 5. Laser generator efficiency (η_L) vs. nominal laser power (P).

3.2. Laser Beam attenuation

The real laser power measured in the previous section corresponds to the situation where no powder-shaped filler material is injected. However, in the DED-LB process powder filler material generates a cloudy area at the nozzle exit, which attenuates the laser beam and reduces the effective power that reaches the surface of the substrate. In the present case the laser power attenuation is measured as shown in Fig. 6. A thermal camera is employed for ensuring that the setup works properly. No heat is lost through the steel plate and the only heat attenuation source are the in-flight powder particles.

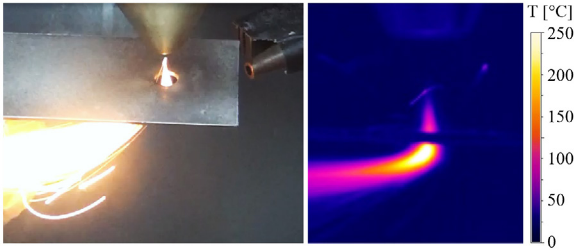

Fig. 6. Laser beam attenuation by the in-flight powder particles.

The employed drag and shielding gas flows have a dominant effect in the powder distribution at the nozzle exit, hence in the laser attenuation. For this reason, in the present study they are kept fixed and only the powder mass rate is modified. Three different scenarios are studied: 4.4 g·min^{-1}, 5.5 g·min^{-1}, and 6.6 g·min^{-1} and attenuation values of 16.81%, 21.02%, and 25.22% are measured, respectively.

3.3. DED-LB process efficiency

The energy consumption measured during the deposition of each clad is averaged and all the values are shown in Table 2, where active power (P_{ac}), reactive power (Q), and apparent power (S) are differentiated. An excess of reactive power consumption increases the power factor of the machine, cos (θ), and reduces its ability to operate optimally. In the present case, power factor values close to the unit value are obtained, which is considered appropriate and no corrective measures to improve power factor are required.

Table 2. Average network power consumptions measured during the deposition tests.

Test	P [W]	F [mm·min^{-1}]	M [g/min]	P$_{ac}$ [kW]	Q [kVAr]	S [kVA]	cos(θ) [-]
1	600	525	5.5	2.46	3.55	2.56	0.82
2	720	525	5.5	2.76	3.93	2.80	0.82
3	480	525	5.5	2.07	3.05	2.24	0.83
4	600	420	5.5	2.47	3.54	2.54	0.82
5	600	630	5.5	2.46	3.55	2.56	0.82
6	600	525	4.4	2.49	3.62	2.62	0.82
7	600	525	6.6	2.47	3.57	2.58	0.82
8	600	525	5.5	2.41	3.49	2.53	0.82

In Fig. 7 an example of a cross section for each test is shown. As it can be seen, they present different shapes, clad width and heights, but all of them are free of defects such as internal porosity or lack of adhesion.

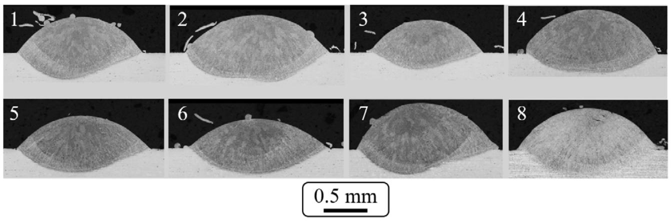

Fig. 7. Cross sections of the deposited clads.

In order to evaluate the efficiency of the DED-LB process, mass efficiency (η_M) and energy efficiency (η_E) have been calculated according to equations (2) and (3), where ρ is the Inconel 718 density and A is the clad area. These efficiencies represent the percentage of feed powder that is trapped into the melt pool and becomes part of the deposited clad, and the required amount of energy in kJ to deposit a gram of material, respectively. In Table 3 the detailed results for each test are shown.

$$\eta_M = \frac{\rho \cdot A}{F \cdot M} \cdot 100 \tag{2}$$

$$\eta_E = \frac{P_{ac}}{\rho \cdot A \cdot F} \tag{3}$$

Table 3. Mass and energy efficiencies measured during clad deposition.

Test	W [mm]	H [mm]	A [mm^2]	η_M [%]	η_E [kJ/g]
1	1.58	0.74	0.37	29.09%	92.26
2	1.81	0.81	0.50	38.92%	77.37
3	1.43	0.64	0.29	22.82%	98.97
4	1.68	0.79	0.44	27.52%	97.91
5	1.54	0.65	0.32	29.87%	89.83
6	1.57	0.65	0.33	32.51%	104.43
7	1.57	0.79	0.41	26.43%	84.96
8	1.59	0.74	0.38	29.95%	87.78

The highest powder efficiency is obtained in test 2, which corresponds to the highest laser power. This is because if the rest of the factors are maintained constant, a higher laser power generates a wider melt pool and hence, it catches more powder. On the contrary, lower laser powers reduce the mass efficiency.

Also, test 2 is the most efficient in terms of energy, because it presents the lowest energy cost per gram of deposited Inconel 718. Comparing this last test results with the central parameters, test 1, it presents a 19.25% lower energy consumption and the energy saving is increased up to the 35% in comparison to test 6, which corresponds to the least energy-efficient case.

4. Conclusions

Hereafter the main conclusions reached after the present study are summarized:

On the one hand, the analyzed laser presents a non-constant wall-plug efficiency. Higher laser powers enable a better energy use. On the other hand, powder attenuation can absorb over a 25% of the laser energy before it reaches the melt pool, for the studied process parameters. Consequently, higher powder mass rates reduce the amount of energy introduced into the baseplate to generate the melt pool. This point is especially critical if the employed nozzle presents a low mass efficiency, because in that case the heated particles are lost, together with the heat absorbed by them.

To summarise, for the studied process parameter window and material, higher laser powers improve both the energy efficiency, by enhancing the laser generator efficiency, and the mass efficiency by improving the powder catchment. Based on these results, it is concluded that more aggressive process parameters (with higher mass rates, laser powers, and feed rates) promote an increase in the energetic efficiency of the DED-LB process regardless of the employed material.

Acknowledgements

Grant TED2021-130543B-I00 funded by the MCIN/AEI/10.13039/501100011033 and the European Union NextGenerationEU/PRTR. Grant PID2022-141946OB-C21 funded by MCIN/AEI/10.13039/501100011033/and by ERDF A way of making Europe.

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