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Procedia CIRP 00 (2023) 000–000

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17th CIRP Conference on Intelligent Computation in Manufacturing Engineering

An exploratory analysis on laser polishing of components by laser powder directed energy deposition

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Abstract

Directed Energy Deposition (DED) is one of the most challenging metal additive manufacturing (AM) processes on the market, still one of its main drawbacks is the poor surface characteristic. Laser polishing is an emerging technique for surface finishing of AM components, that can be easily integrated in laser powder directed energy deposition (LP-DED). Laser polishing can be used for reaching inner parts of complex shaped component during LP-DED production. In this study, an exploratory analysis on the most significant parameters involved in the laser finishing process is performed, providing a robust base for further optimization studies in the field.

Peer-review under responsibility of the scientific committee of the 17th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 12-14 July, Gulf of Naples, Italy

Keywords: Additive Manufacturing; Directed Energy Deposition; Surface finishing; Laser Polishing.

1. Introduction

Additive Manufacturing (AM) is defined as the *"process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing technologies"* [1]. Directed energy deposition (DED), as a metal additive manufacturing process, has recently gained interest from both industrial and academic perspectives [2,3]. The DED process is based on the action of an energy source, either laser, electron beam or plasma arc, locally heating up a substrate until the creation of a melt pool. Inside the melt pool, new filler material is delivered in the shape of powder or metallic wire. To this day, the process architecture receiving the largest attention on the market is the laser powder-directed energy deposition (LP-DED). LP-DED offers a better control of the process, with respect to the wire – directed energy deposition, leading to the fabrication of more complex geometries [4]. LP-DED is a flexible AM process, enabling the fabrication of components from scratches, the repairing of high value components and the deposition of functional graded materials [5]. As for every manufacturing process, LP-DED has limitations too. Poor surfaces characteristic is one of the main drawbacks of LP-DED, and more in general of all DED processes. It is well established in engineering technical literature the detrimental role of surface roughness in the fatigue life of components [6-8]. Thus, several studies have been conducted on the topic of surface roughness reduction for DED components.

Chan [9] stated that, in order to achieve better fatigue performances, surface roughness should be lowered at least below 1 µm. The objective of an improved surface characteristic can be achieved in different ways. Piscopo *et al.* [10] investigated the role of deposition strategy on surface roughness, finding that this factor does not play a major role on the topic. Notley *et al.* [11] also investigated the role of process parameters, in terms of laser power, travel speed and powder flow rate, on melt pool geometry and surface roughness of produced components. Again, they found out that surface roughness of deposited samples cannot be directly correlated to process parameters. Thus, at the moment and according to the

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authors' knowledge, no satisfactory results have been achieved in terms of surface roughness reduction by process parameters optimization. A second, and more obvious way of reducing surface roughness is through post processing operations, and the applicability to metal additive manufactured samples has been investigated by several authors. [12] compared the results of four different post processes applied to Ti6Al4V samples produced by laser powder bed fusion (LB-PBF): milling, blasting, vibro-finishing and micro machining. By milling, they achieved a surface roughness lower than 1 µm with an improved fatigue life, from 300 MPa to 775 MPa. Atzeni *et al.* [13] have assessed the capabilities of a vibro-finishing process on LB-PBF samples, in terms of surface quality improvement, cost and process duration. Souflas *et al.* [14] compared dry and cryogenic milling processes on DED components, noticing how the latter can reduce tool wear with only a limited influence on surface roughness. Atzeni *et al.* [15] applied on electron beam powder bed fusion (EB-PBF) samples two post processes, laser finishing and abrasive fluidized bed. They suggested that both treatments are able to improve surface finishing and fatigue behaviour when optimal process parameters are identified.

Laser polishing, also referred to as laser remelting or laser finishing, is an emerging finishing technique in the AM field. Laser polishing uses a laser wave, in either pulsed or continuous mode, to melt the outer surface of an existing samples. This process allows the molten metal coming from roughness crests to redistribute into the corresponding valleys under the combined actions of surface tension and gravity. Laser polishing does not require any contact with the component, i.e. laser polishing can be used to process hard metals without any tool wear apprehension. Moreover, laser polishing can ensure the finishing of complex shaped components, whose accessibility to conventional milling machines could be an issue. A growing number of articles on laser polishing of AM components are now available in the literature. Cho *et al.* [16] explored three process parameters, namely deposition direction, laser power and track overlap distance, to understand their role in laser polishing process. They identified the overlap as the main effect in terms of surface roughness and waviness reduction. Shen *et al.* [17] used picosecond laser machining and laser polishing to improve overall surface quality. Laser machining reduced surface waviness, removing part of the upper surface of the sample, whereas laser polishing reduced surface roughness. Bruzzo *et al.* [18] deposited thin wall samples and finished them with the same laser source soon after deposition. By testing deposition strategy, laser power, track overlap distance and angle of incidence, they were able to reduce surface roughness from Sa equal to 10.35 ± 0.42 µm to Sa equal to 1.92 ± 0.11 µm. Liu *et al.* [19] used a two-step laser process made of a first pulsed laser polishing followed by a continuous wave one. They were able to move from 15.75 µm to 0.23 µm after the two-step polishing. Finally, Dos Santos Paes *et al.* [20] tested the same laser polishing parameters on two different materials, pure iron AHC 100.29 and Inconel 625, and achieved a 30% and 70% reduction in roughness, respectively.

Although a consistent literature about laser polishing already exists, some gaps must still be covered. To the authors' knowledge, no previous work has performed a replicated exploratory campaign to uniquely identify the meaningful active parameters in this kind of process. Giving a strong statistical base to the experimental campaign performed allows other researchers to access reliable results. Moreover, most of the existing literature takes advantage of in-house experimental set-ups for both sample deposition and laser polishing. Thus, in this paper an exploratory experimental campaign, using a commercial DED system, is performed aimed at identifying the most significant parameters involved in laser finishing process.

2. Materials and methods

The LP-DED system used in this study was the LASERDYNE 430 by Prima Additive (Torino, Italy). The machine was equipped with a 5-axis rotary table and a continuous wave fibre laser CF1000 laser by Convergent Photonics (Torino, Italy) with a maximum nominal power of 1 kW, wavelength between 1070 nm and 1080 nm and laser spot diameter of 2 mm. The powder used for sample deposition was the MetcoAdd 316L-D by Oerlikon (Freienbach, Switzerland), that is an AISI 316L austenitic stainless steel with nominal granulometry in the range from 45 µm to 106 µm. Argon was both used as powder carrier and shielding gas.

Two plates of AISI 316L with dimensions $210 \times 210 \times 10$ mm^3 were used as substrates for sample depositions. Parallelepiped samples with dimensions $60 \times 30 \times 2$ mm^3 were deposited and used for laser polishing. A zigzag 0-90° deposition strategy was used for deposition, meaning the direction of deposition tracks rotates 90° each layer. Moreover, an island strategy was adopted to minimize residual stresses. Process parameters used for sample deposition were chosen based on previous authors' knowledge about the DED process and collected in Table 1.

The dimensions of the samples were consistent with surface characterization requirements. To allow surface roughness to be measured by means of a roughness meter, the dimension of the polishing area must respect the latest standard BS EN ISO 21920-3:2022 – Geometrical product specifications (GPS). Surface texture: Profile-Specification operators [21]. In the new version of the standard, evaluation length in terms of cut-offs length and number, only depends on the expected surface roughness value. Thus, the new standard removed any distinction between periodic and non-periodic profiles. Expecting a surface roughness below 10 µm after laser polishing, the roughness measurement would require 5 cut-off lengths of 2.5 mm, with an additional cut-off length for approaching the measure. Thus, a 15 mm evaluation length was considered for roughness measurement and the laser treatment was applied to a 20×20 mm^2 surface area. Each rectangular sample underwent two different laser finishing treatments, one on each side.

Table 1. Parameters used for sample deposition.

Parameter	Value
Laser power, P	700 W
Travel speed, v	850 mm/min
Layer height, ΔZ	0.5 mm
Hatching distance, h_d	1 mm
Powder flow rate*, Q_P	4 g/min
Argon flow rate*, Q_{Ar}	6 L/min

* Environmental conditions: $T = 20$ °C and $p = 0.1$ MPa

Table 2. Factors and levels of the DoE.

Factor	Low level	High level
Linear energy density, LED (J/mm)	21	70
Hatching distance, h_d (mm)	1	2
Stand-off distance, s_d (mm)	8	28
Argon flow rate, Q_{Ar} (L/min)	2	10

Based on the conducted literature review, the need of a robust factor screening experimental campaign emerges. In the present study, four factors were tested on two levels, as commonly done in exploratory and screening analysis [22]. The four factors tested throughout the laser finishing experiment were: linear energy density, hatching distance, stand-off distance of the deposition head with reference to the substrate, and argon flow rate. The linear energy density (LED) is defined, as the name suggest, as the ratio between laser power and travel speed. LED is a synthetic parameter largely used in AM field, as well as in the welding one [23,24]. LED was chosen over its components to keep the number of investigated factors as low as possible. LED has been varied keeping the laser power constant at 700 W and changing the travel speed of the deposition head. The hatching distance (h_d) is the designed name for the distance between two adjacent depositions. Hatching distance was set to either 2 mm or 1 mm. The first choice of 2 mm theoretically implies no overlapping between depositions. On the other hand, a hatching distance of 1 mm implies a 50% overlapping between adjacent tracks. The stand-off distance (s_d) is the physical distance between deposition head and substrate throughout the deposition. A stand-off distance of 8 mm represents the normal working condition for the system in exam. With a stand-off of 8 mm the machine laser works on its focal plane. Moving away from its focal plane, laser beam spot is expected to grow, reducing its specific energy density. Based on previous investigations, a stand-off distance of 28 mm was chosen. It enlarged the laser beam spot up to 2.38 mm, marking an increase of around 40% in terms of laser beam spot area. Finally, the argon flow rate (Q_{Ar}) levels were set at 2 L/min and 10 L/min, working limits of the available powder delivering system.

These choices allowed for the selection of a full factorial design without the need of a prohibitive number of experiments. Full-factorial designs are more easily interpretable than fractional ones since no aliasing phenomenon is present. Table 2 collects investigated factors and corresponding levels. Working with a two-level factorial experiment, it is good practise to spread factors evaluated levels as much as possible to minimize nuisance effects. Three replicates of each experiment were performed, resulting in a 3×2^4 plan of 48 treatments. The presence of three replications of each treatment is extremely helpful in preventing nuisance factors from influencing the experiment. Considering that two laser polishing treatments were performed over one sample, 24 samples were deposited to accommodate all the treatments. Moreover, treatments were always performed perpendicularly to the direction of deposited tracks. This way a higher surface regularity was expected to be achieved. Fig. 1 represents the geometry and dimensions of the deposited sample, and the laser polishing area locations. Once all 24 samples were deposited, image acquisition and roughness measurement were performed to assess treatments initial condition. Leica S9i stereomicroscope by Leica (Wetzlar, Germany) was used for image acquisition. Leica S9i has an integrated camera with a planar resolution of 10 MP and a pixel size of 1.67×1.67 µm^2.

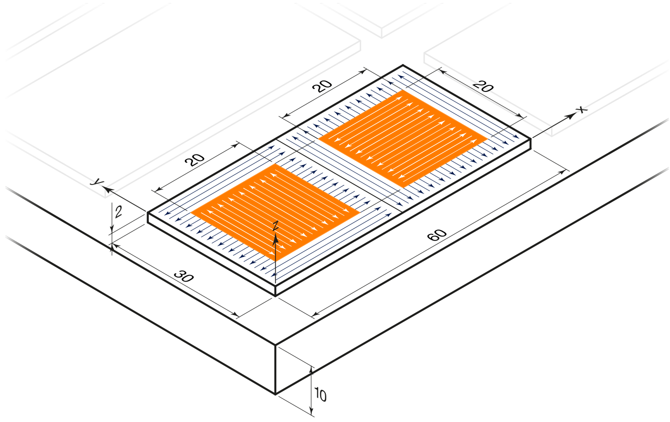

Fig. 1. Geometry and dimensions of the deposited sample, and the laser polishing area locations.

Roughness measurement was performed by means of an RTP-80 by SM Metrology Systems (Volpiano, Italy). The RTP-80, together with the translator TL 90, offers a measuring range of ±500 µm, a resolution of 0.001 µm and a measuring length up to 50 mm. Minitab 21 statistical software, by the National Institute of Standards and Technology (Gaithersburg, Maryland, US) was used for all the statistical analysis and elaboration on acquired data. For every as-built sample and on both sides, roughness was measured five times at different locations (Fig. 2) and the average value assumed as response variable. This time, expecting a higher initial roughness, the measure required 5 cut-off lengths of 8 mm, justifying the decision of using relatively large samples. Not respecting the BS EN ISO 21920-3:2022 [21], and using smaller evaluation lengths than prescribed ones, could lead to severe surface roughness underestimations. An ANOVA test was performed to certify the equivalence of samples initial conditions.

At the end of the laser polishing activity, image acquisition and roughness measurement were performed once again. Again, five repeated roughness measurements were performed for every polished surface. The values coming from the five measurements were always averaged and the mean value considered as response variable for further investigations. Ra was measured perpendicularly to laser polishing direction, as previously done. In this study the focus is limited to the Ra parameter for the sake of simplicity. Similar studies will be conducted, in future works, on other roughness and waviness descriptive parameters such as Wa and Rt. Finally, a second ANOVA test was conducted on the results of the performed experiments and active factors distinguished from inactive

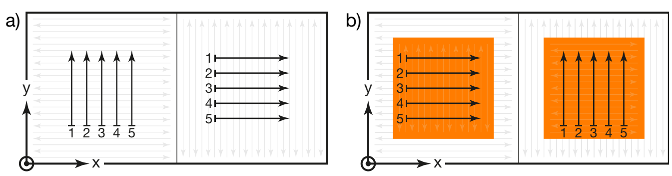

Fig. 2. Surface roughness measurement locations for (a) as built samples and (b) after laser polishing treatment.

ones. The active factors will be considered for future optimization experimental campaigns to find a set of parameters granting minimum surface roughness.

3. Results and discussion

The first step has been sample deposition and characterization. Fig. 4 represents the as-built condition of a deposited sample. It can be seen how partially sintered powder certainly plays a major role in defining surface roughness. Five repeated roughness measurements were then performed on every sample at different locations. The overall mean of the measured samples roughness was 23.9 µm, with a standard deviation of 1.2 µm. These values are in accordance with the usual surface quality achieved with LP-DED processes. To certify the equivalence of laser polishing initial conditions, an ANOVA test was performed on the measured surface roughness. The test did not highlight any meaningful difference between the 24 samples at a level of confidence of 95%. Thus, from a statistical standpoint, all samples were assumed to represent the same initial condition.

That said, laser polishing treatments were performed, two treatments for every sample and always perpendicular to the deposition direction of sample last layer. The considered response variable was Ra measured perpendicularly to the laser polishing direction since it is usually considered more critical than the corresponding parallel measure. Fig. 3 reports a bar chart collecting sample roughness data after laser polishing treatments. Each of the 16 proposed laser polishing treatments is a combination of the 2^4 factors investigated. The eight of every bar of the chart is equal to the mean of roughness measured on the three replications of the treatments. The error bars associated to every treatment span ±2σ, were σ is the standard deviation of replicated treatments. This way the interval [*mean* – 2σ, *mean* + 2σ] collects around the 95% of possible observations and gives a clear indication about process variability. In particular, the observed process variability is considered acceptable for almost every laser polishing treatment, and overall consistent roughness improvements were observed after laser polishing. The highest roughness reduction was measured for the Treatment No. 2, with an initial roughness reduction of 89%. Even the Treatment No. 15, that is the worst in terms of final surface roughness, marked a meaningful 54% reduction of the initial roughness value.

Fig. 5 collects the acquired roughness profiles of the sample subjected to Treatment No. 2 before and after laser polishing treatment, and details of the surface as observed with the stereomicroscope. It can be clearly seen the dramatic difference a single laser polishing step has on the surface characteristic of

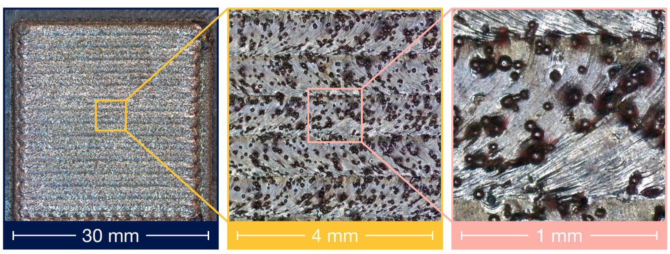

Fig. 4. As-built surface characterization and sintered powder particles details.

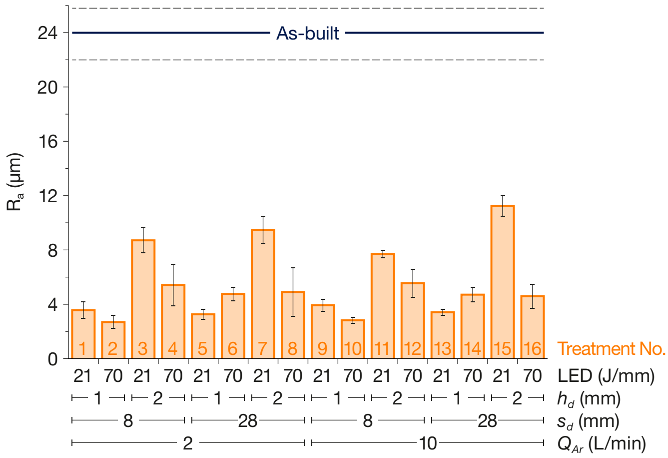

Fig. 3. Sample surface roughness after laser polishing treatments.

the sample. Finished areas exhibit a smooth surface and complete absence of partially sintered powder particles.

In order to distinguish active factors from inactive ones, a second ANOVA test was performed. The considered response variable was Ra measured perpendicularly to the deposition direction. Roughness was measured five times for each sample and arithmetic mean of the measurement considered as an aggregate value. Moreover, recalling that every treatment was replicated three times, the three mean roughness values were further averaged, and this final value considered as the ANOVA response variable. The model obtained this way optimally described the system, the R^2 and R^2_{adj} parameters were respectively equal to 98.07% and 97.16%. A good match between these two terms indicates that no useless experiments were performed during the campaign. Moreover, R^2_{pred} equal to 95.65% ensures a good capability of the system to predict new values in the explored variable space, and not only to describe current data. Beware that this prediction ability of the model ensures a good interpolation of new values, but generally does not ensure a good extrapolation too. This means that the actual model, in general, should not be trusted outside the explored factorial space.

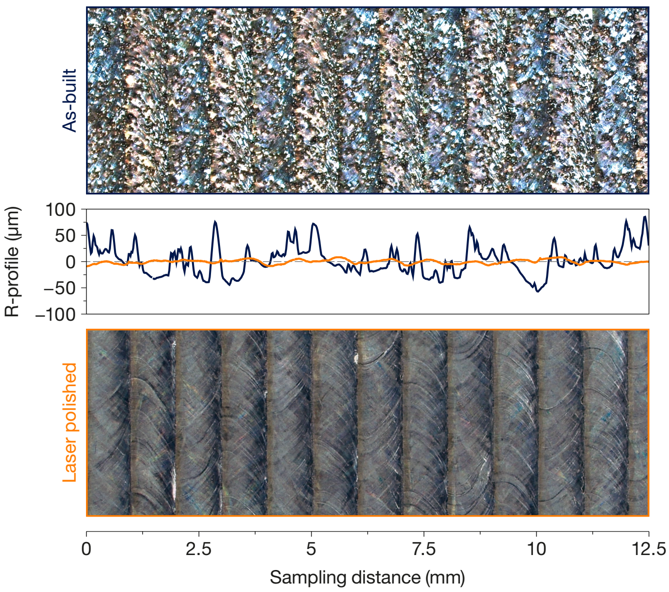

Fig. 5. Comparison between as built and polished surface roughness profiles.

Table 3. Analysis of Variance (ANOVA) of the performed exploratory experimental campaign.

		DF	Adj SS	Adj MS	F-value	p-value	η^2
Linear Terms	LED	1	47.088	47.088	263.94	0.000	0.477
	h_d	1	151.201	151.201	847.53	0.000	0.148
	s_d	1	6.708	6.708	37.60	0.000	0.021
	Q_{Ar}	1	0.261	0.261	1.46	0.235	0.001
2-Way interactions	LED · h_d	1	57.063	57.063	319.86	0.000	0.180
	LED · s_d	1	0.182	0.182	1.02	0.320	0.001
	LED · Q_{Ar}	1	0.340	0.340	1.91	0.177	0.001
	$h_d \cdot s_d$	1	0.019	0.019	0.11	0.744	0.000
	$h_d \cdot Q_{Ar}$	1	0.001	0.001	0.00	0.950	0.000
	$s_d \cdot Q_{Ar}$	1	0.702	0.702	3.94	0.056	0.002
3-Way Interactions	LED · $h_d \cdot s_d$	1	20.888	20.888	117.08	0.000	0.066
	LED · $h_d \cdot Q_{Ar}$	1	0.041	0.041	0.23	0.633	0.000
	LED · $s_d \cdot Q_{Ar}$	1	1.883	1.883	10.55	0.003	0.006
	$h_d \cdot s_d \cdot Q_{Ar}$	1	1.405	1.405	7.87	0.008	0.004
4-Way interactions	LED · $h_d \cdot s_d \cdot Q_{Ar}$	1	1.952	1.952	10.94	0.002	0.006
Error		32	5.709	0.178			
Total		47	295.443				

Another meaningful indication on the good quality of acquired data is given by normal probability plot of residuals reported in Fig. 6. In the graph an almost normal behaviour of residuals can be observed, suggesting the absence of systematic errors in acquired data. Table 3 is the Minitab output for the performed ANOVA the experimental campaign. Focusing on the p-value test in the last column and recalling that a factor is usually considered statistically significant if its p-value is lower than 0.05, the three active factors can be clearly seen: hatching distance, linear energy density and stand-off distance. The confidence level is expressed by the one hundred's complement of the p-value. Thus, the lower the p-value, the higher the significancy of the factor. Reported p-value less than 0.001 simply indicate a confidence level above 99.99%. Moreover, among the six two-way interactions, only the interaction between LED and hatching distance is significant, with a confidence level above 99.99%. As for higher order interaction, the three-way interaction between LED, hatching distance and stand-off distance is the only active interaction worth considering, with a confidence level above 99.99%. Other three-way interactions and the four-way interaction bring

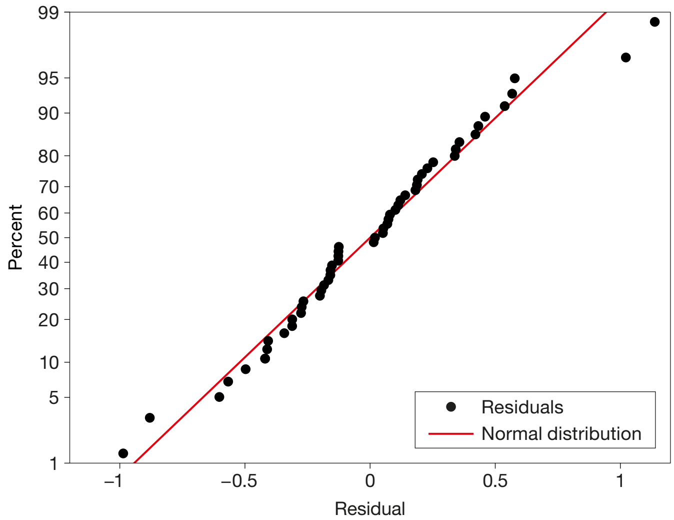

Fig. 6. Normal probability plot of residuals.

an almost negligible contribution to model variability, even if statistically significant. This can be easily evaluated looking at factors effect sizes, η^2, computed as Adj SS_{factor} /Adj SS_{total} [25]. This last column parameter completes the information given by the p-value and states the percentage of model variability explained by the single term.

Although the presence of a strong interaction between the two main effects is suggested, hatching distance and LED, this paper focused on the simple identification of the active single factors. Interactions influence over the response of the system will be delegated to further investigations. Fig. 7 reports the main effect plots computed by Minitab, i.e. how the change in a specific factor level influences the chosen response variable. High slope segments generally refer to active and large effect size factors, whereas almost horizontal segments refer to irrelevant factors. At first glance it is straightforward to confirm that hatching distance and LED play a major role in surface roughness definition of treated samples. Another important indication coming from main effect plots is the way in which factors changing influences the response variable. Thus, high linear energy density and low hatching distance ensure low surface roughness. On the other hand, argon gas flow rate does not have a real impact on surface roughness definition. Lastly, the deposition head stand-off distance is an active but detrimental factor. From the analysis, it is clear how higher stand-off distance values induce higher surface roughness on the treated samples. Thus, this defocusing factor will be excluded from further experimental campaigns.

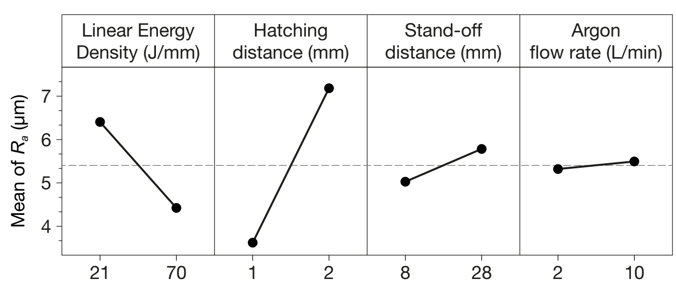

Fig. 7. Main effects plots.

4. Conclusions

In this paper an exploratory campaign of LP-DED laser polished components has been reported. The main goal of this exploratory campaign was the identification of the active factors between four selected ones: linear energy density (LED), hatching distance, stand-off distance and argon flow rate. The main difference between this study and similar ones already available in literature is the statistical approach powering the same study. No judgments on results were performed by naked eyes, without questioning reliability and repeatability of the results. At the end of the campaign, it was evident how:

- the presence of replication, i.e. the high number of error degree of freedom, gave the model high reliability and prediction ability. This is summarized in the coefficient $R^2 = 98.08\%$ and $R^2_{pred} = 96.65\%$;
- hatching distance and LED are the active factors which will be considered for further investigations. Lower hatching distances and higher LED should bring to lower roughness;
- argon gas flow rate had no meaningful impact on the process. This means it could be tuned according to the needs. Low levels of argon flow rate allow cheaper processes, higher levels of argon flow rate should avoid any kind of possible oxidation;
- Stand-off distance is an active but detrimental factor, meaning it should not be considered if low levels of surface roughness are desired. Further investigations will leave the stand-off distance to the standard 8 mm.

Finding an optimum for laser polishing of LP-DED components, with comparable surface quality to conventional machining processes, would allow laser polishing to be considered for real industrial application, strongly changing the whole LP-DED manufacturing chain. After the current experimental campaign, concluded with the identification of active factors, an optimization campaign will follow. The subsequent optimization campaign will aim at finding the set of parameters granting minimum surface roughness.

Acknowledgements

The authors would like to thank for the financial support the Interdepartmental Centre for Integrated Additive Manufacturing (IAM@PoliTo) at the Politecnico di Torino, Torino, Italy.

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