



Laser Polishing of Polymer Parts Produced with Material Jetting Technology: Effect of Laser Scan Speed, Overlapping and Loop Cycles

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Received: 12 February 2023 / Accepted: 8 July 2023
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Abstract In the last year, the industrial production is characterized by the request of high level of product variety that generates a decrease of production volume changing manufacturing from mass production to mass customization. This trend let the conventional production processes, as forming, casting or moulding, expensive because of initial tools production cost that is not more amortized by the high-volume production. A solution to this scenario is to integrate Additive Manufacturing in tools production; this solution guarantees tools cost reduction also if post processes operations are needful to reduce the surface roughness produced by additive processes. Among additive processes, Material Jetting is able produce parts with guaranteed high accuracy and low average surface roughness (0.5 μm). However, these standards mainly refer to upfacing surfaces parallel to the print plate, and the roughness obtained on the other surfaces could increase up to 15 μm because of production mechanism. To improve parts roughness in this study, the laser polishing process was tested; different experimental tests were executed to investigate the effects of scan speed, overlapping and loop cycles. The results demonstrated that it is possible to improve the surface finish and reduce the roughness by 70% at the expense of dimensional accuracy.

Keywords Additive manufacturing · Material jetting · Laser polishing · Surface roughness

Introduction

Additive manufacturing (AM) technologies create components by adding layers of material one on top of the other [1]. Since this system allows easy creation of objects with high geometric complexity, the design freedom given by AM technologies makes them suitable for tasks in which a specific and optimized geometry is required [2]. In the biomedical sector, this technology is primarily used to develop customized prostheses and new tissues; it is also applied in the aerospace industry since it allows the creation of light components made with high-performance materials and in the automotive field for prototype production [3]. However, due to the layering strategy, AM technologies require longer production times than conventional processes such as injection moulding for plastic parts or machining processes for metals so that in the case of simple geometries, AM is not suited for mass production [4].

Currently, AM technologies are used in industrial environments to create tools for medium batch production (rapid tooling) [5], and the main advantages of implementing a rapid tooling approach are lower costs and reductions in time to market [6]. The main AM processes used for the rapid production of tools are selective laser melting (SLM) for steel tools and selective laser sintering (SLS) or fused filament fabrication (FFF) for polymer tools [7]. However, parts produced with these AM processes suffer from surface roughness caused by the staircase effect generated in layering production [8–10]. To counter this problem, several studies have been performed to analyse mechanical, chemical and laser treatments to improve the surface roughness generated by additive processes. Among these techniques, laser polishing (LP) avoids any surface orientation and tool wear, results in less pollution (no abrasive or liquids), and generates no debris; it is faster

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and cheaper than abrasive and chemical methods and can be easily implemented in a production line [11–13]. The LP technique consists of heating the surface with a laser beam to generate local melting, which reduces roughness and generates a homogenized surface [14].

For metallic components printed with the SLM technique, energy density was identified as the key parameter for a laser polishing process that guarantees a roughness reduction of 80% [15]; moreover, tests made with Ti6Al4V demonstrated that laser melting with high energy density increased surface microhardness [16]. In contrast, Obeidi et al., despite achieving a reduction in roughness from 10.4 to 2.7 μm , noticed that because of the balling effect (inhomogeneity of the surface due to powder particle sizes), some regions remained unmelted [17]. Moreover, some of the main advantages of LP for SLM parts are related to machine equipment; SLM machines usually work with continuous wave fibre lasers with a power equal to 1 kW, and parts are produced in chambers with an air content lower than 500 ppm; thus, polishing processes can be easily carried out in the same machine by adjusting the laser parameters to avoid oxidation [18]. This process could occur immediately after part production on surfaces facing upwards or on the whole surface after removing unmelted powder.

Regarding laser polishing of polymer parts made by FFF, Braun et al. tested acrylonitrile butadiene styrene (ABS) specimens with a quasi-top-hat scanning strategy with closed-loop temperature control, which provided an average roughness reduction from 4.25 to 0.23 μm [19]; moreover, the authors stated that drying of the material before laser polishing had a significant influence on the process. Chen et al. improved the surface quality of copper fibre/poly lactide acid (Cu/PLA) composite parts and reduced roughness by more than 91% (from 10.52 to 0.87 μm); the melting effect also closed possible voids formed between or within two lines that could initiate cracking [20]. Good results for surface smoothness were obtained after an LP treatment and were also obtained for PLA specimens made with FFF, and the final roughness values of these specimens were better than those obtained with other techniques; the extent of roughness reduction was 90.4% [21]. The influence of laser parameters on surface modifications of ABS and PLA samples was investigated by Chai et al. [22]. The maximum roughness reduction achieved was 68%, but the research highlighted the tendency of the ABS material to ball up rather than flatten during melting; this effect may occur because ABS has a higher surface tension than PLA. Moreover, the melting action of laser polishing improved not only surface quality but also mechanical behaviour,

such as Young's modulus, tensile strength [23] and flexural strength [24]; in contrast, a reduction in elongation at break was measured [25]. It must be noted that the results achieved refer to surfaces orthogonal to the build direction (z -axis), thereby avoiding problems related to the staircase effect.

As an alternative, for small batch production of plastic parts, vat photopolymerization (VT) processes could be used, which guarantee higher accuracy and lower surface roughness than FFF and reduce the need for postprocess operations; the typical average roughness achieved by the VT process is approximately 1.5 μm [26]. Similar to VT processes, material jetting is the AM technology that guarantees the best surface quality (0.5 μm) and the highest allowable part design complexity due to the degradable support material. Moreover, to make the technology suitable for rapid tooling applications, new photopolymers are available that can withstand high temperatures [27]. However, the reported surface qualities still refer to the x - y plane; on the z -axis, worsening of the surface occurred due to layering, and a roughness of 15 μm was achieved so that a polishing process was still necessary for three-dimensional part geometries [28]. This constraint limits the potential of material jetting for rapid tooling applications. In a previous study, the authors analysed how part orientation on the print plate is critical to produce inserts for micro injection moulding. The different surface roughnesses not only affected moulded part translucency but were critical for insert mechanical strength. In particular, the authors demonstrated that the best quality of moulded parts in terms of roughness corresponded to the worst insert tool life [29]. To enhance the potential of material jetting in rapid tooling, a challenge will be machining these new photopolymers with laser beams to reduce the surface roughness achieved by the layering effect.

In this research, a laser polishing process was tested to improve the surface roughnesses of parts produced via material jetting technology. Different experimental tests were performed to investigate the effects of scanning speed, track overlap and number of loops in order to measure their variation effect on the material surface roughness. The results highlighted the benefits and critical aspects of the LP technique which improves surface quality by removing a small layer of material.

Materials and Methods

The experimental procedures were divided into three main steps: sample design and production, laser polishing, and polishing performance analysis.

For the sample design step, cubes with lengths of 20 mm were produced with a material jetting process. Cubic samples were printed with a ProJet 2500 Pro machine (3D Systems, South Carolina, US) [30]. The resin selected was commercial VisiJet® M2S-HT250 provided by 3D Systems [31]. Due to the material jetting mechanism, the produced cubes had three different surface morphologies depending on the orientation on the build plate. During part fabrication, the printing head deposited small drops of resin along a line in the y direction; this process is known as filling (Fi). When line filling was concluded, the print head moved in the x direction to start a new line; this movement is called feeding (Fe); finally, when an XY layer was completed, the printing table moved down in the z direction, and the process was restarted, which is called layering (La). Figure 1a shows a representative scheme for the material jetting deposition mechanism.

The consequences of these printhead and plate movements were different morphologies generated on cube faces: faces in the XY plane had the best surface roughness since they were not affected by layering, and the surfaces were

classified as low; in the XZ plane, there were medium surfaces since there was only the effect of layering, while the YZ plane contained the worst surfaces because of the combined effects of layering and feeding, and these were named the high surfaces. Based on this definition, the cubes produced had 2 faces each with low, medium and high surfaces. Figure 1b shows a produced cube.

For the laser polishing step, an LEP-V20MQG (Lee Laser, Florida, US) was used; the lasing medium was Nd:YVO₄ pumped with a diode laser with a maximum power of 8 W operating in continuous wave (CW) or q-switched mode at a wavelength of 532 nm. The outgoing laser beam was collimated in the galvo system Prowriter D8G (Control Laser Corporation, Florida, US) equipped with an f-theta lens (focal length 160 mm) to impose remote control and a beam diameter equal to 0.1 mm. The cubic samples were locked on a mechanical vice fixed on a support to set the distance from the galvo head equal to the focal distance. Because the energy distribution had a Gaussian profile, a mechanical filter was applied to eliminate the Gaussian tails and reduce the spot to 0.06 mm. Air was chosen as the assist gas; gas

Fig. 1 Material jetting part production mechanism **a** and cubic sample produced **b** (Color figure online)

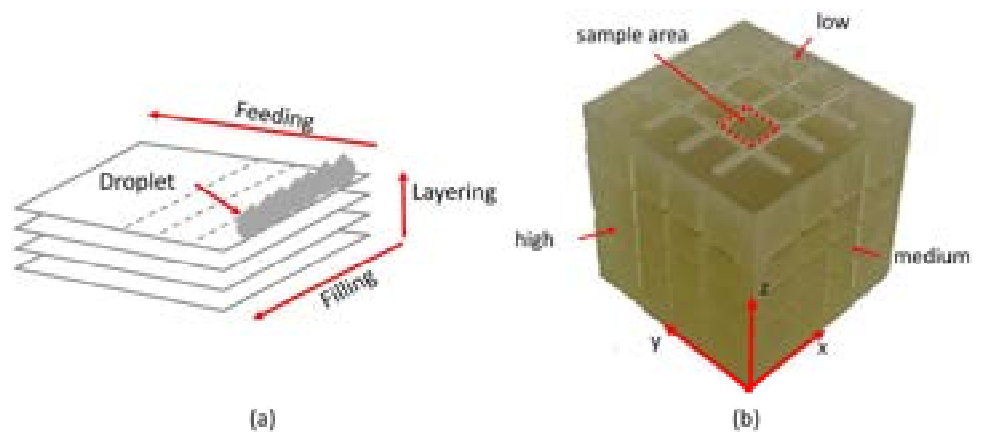
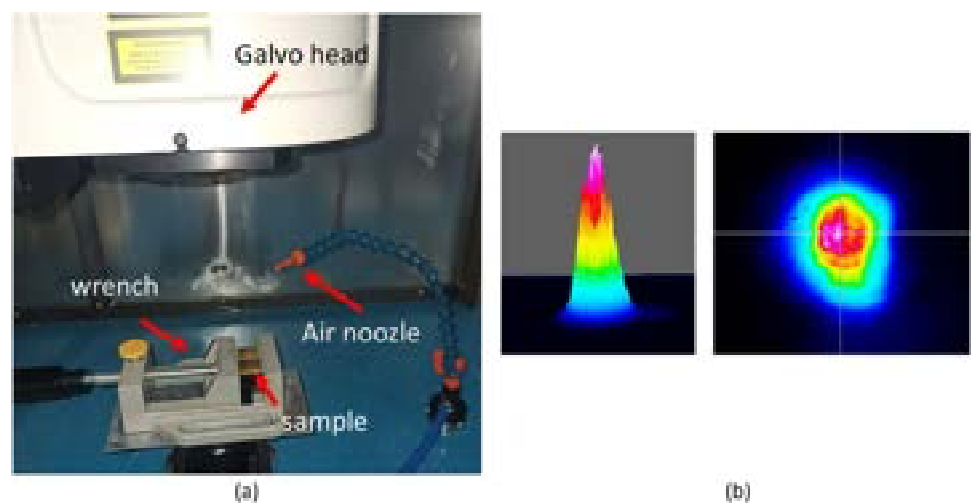


Fig. 2 Laser polishing set up **a** and laser beam power distribution **b** (Color figure online)



feeding was realized with a tube fixed on a support to obtain a homogeneous flux oriented at 45° with respect to the specimen. Figure 2a shows a scheme for the laser setup.

The laser machine and galvo head were controlled by software, and it was possible to set the scan speed, beam mode, scan strategy, overlap (distance between two consecutive tracks), loop number and laser power. For the laser path, a parallel line strategy was adopted. The outgoing laser beam power distribution was previously measured with a CCD12 beam profiler (Gentec Electro-Optics, Quebec, Canada) [32]. The power density of the laser spot exhibited a Gaussian distribution, as shown in Fig. 2b.

To evaluate the effects of laser processing parameters and conditions, three different experimental tests were run on high cube faces to investigate the effects of laser scan speed, overlap and loop cycles. The aim was to investigate process conditions that minimize working time (laser scan speed), reduce the tail effect induced by Gaussian distribution that could generate irregular polishing (overlap) and assess the possibility of reducing roughness by superimposing the polishing effect (loop cycles). Each test was executed within a $3 \times 3 \text{ mm}^2$ area (Fig. 1b). Three replicates of each experiment were performed. The set process parameters were selected after preliminary tests and are shown in Table 1.

After the polishing step for each experiment, the following methods were executed:

- Image analysis was performed at the boundary with the as-printed surface to inspect the polishing effect and evaluate the presence of localized burned resin, ablations or other defect phenomena. Images of the surfaces were acquired with an optical 3D microscope RH2000 (Hirox, Tokyo, Japan).
- The average surface roughness (S_a) and maximum peak-to-valley height (S_z) were evaluated to plot the false surface colour maps and quantify the laser polishing action; the average linear roughness (R_a) and maximum peak-to-valley linear height (R_z) were evaluated to plot the polished surface profile with respect to the as-printed profile and for the statistical analysis. The roughness parameters were evaluated according to the ISO standard 25,178 [33]. Measurements were performed with the point autofocus probe surface texture measuring instrument PF-60 (Mitaka, Tokyo, Japan). Surface roughness values were acquired for an area of 1 mm^2 in the centre of the cubic sample by imposing a pitch (distance between two consecutive linear scans) of $10 \text{ }\mu\text{m}$ and a scanning speed of 50 mm/s . Ten replicates of linear roughness values (R_a , R_z) were acquired on a length of 1 mm . All measurements were analysed with Mountain Map software (Digital Surf, Besançon, France) to find the roughness values after removing the shape error.
- R_a and R_z were assessed with the following statistical approaches: analysis of variance (ANOVA) to analyse the differences among means and Tukey's range test (Tukey's) for the first experimental campaign to find means that are significantly different from each other.
- To compare the results with the as-printed morphology, a preliminary analysis was also executed.

Results

The results of the preliminary analyses focussing on printed cubes are reported in Fig. 3 and Table 2. As discussed in the previous section, the produced cubes were characterized by three different morphologies and related roughness values. In Fig. 3, it is possible to observe the low (a), medium (b) and high (c) surfaces of cube faces. As shown in Table 2, there were significant differences in roughness obtained both in terms of average value and standard deviation.

In the first experiments, three scanning speeds were tested: 10 , 15 and 20 mm/s . Figure 4 and Table 3 summarize the main results.

- Regarding surface morphology, it was possible to observe burned zones highlighted by the presence of darker and glossier areas in the images presented in Fig. 4a. Moreover, all experiments were characterized by the presence of fumes produced during polishing operations.
- In comparing the results shown in Fig. 4b, c and Table 3, it was possible to conclude that increases in laser speed generated uniform surfaces with lower S_a and S_z values; S_a in particular is the parameter that exhibited the best

Table 1 Fixed and investigated parameters for each experimental test

	First	Second	Third
Power [W]	2.5	2.5	2.5
Laser beam diameter [mm]	0.06	0.06	0.06
Path	Parallel line strategy	Parallel line strategy	Parallel line strategy
Focus distance [mm]	160	160	160
Beam mode	CW	CW	CW
Surface morphology	High	High	High
Orientation on the print plate	yz	yz	yz
Speed [mm/s]	10/15/20	20	20
Overlap [%]	50	25/50	25
Number of loops	1	1	1/2
Replicates	3	3	3

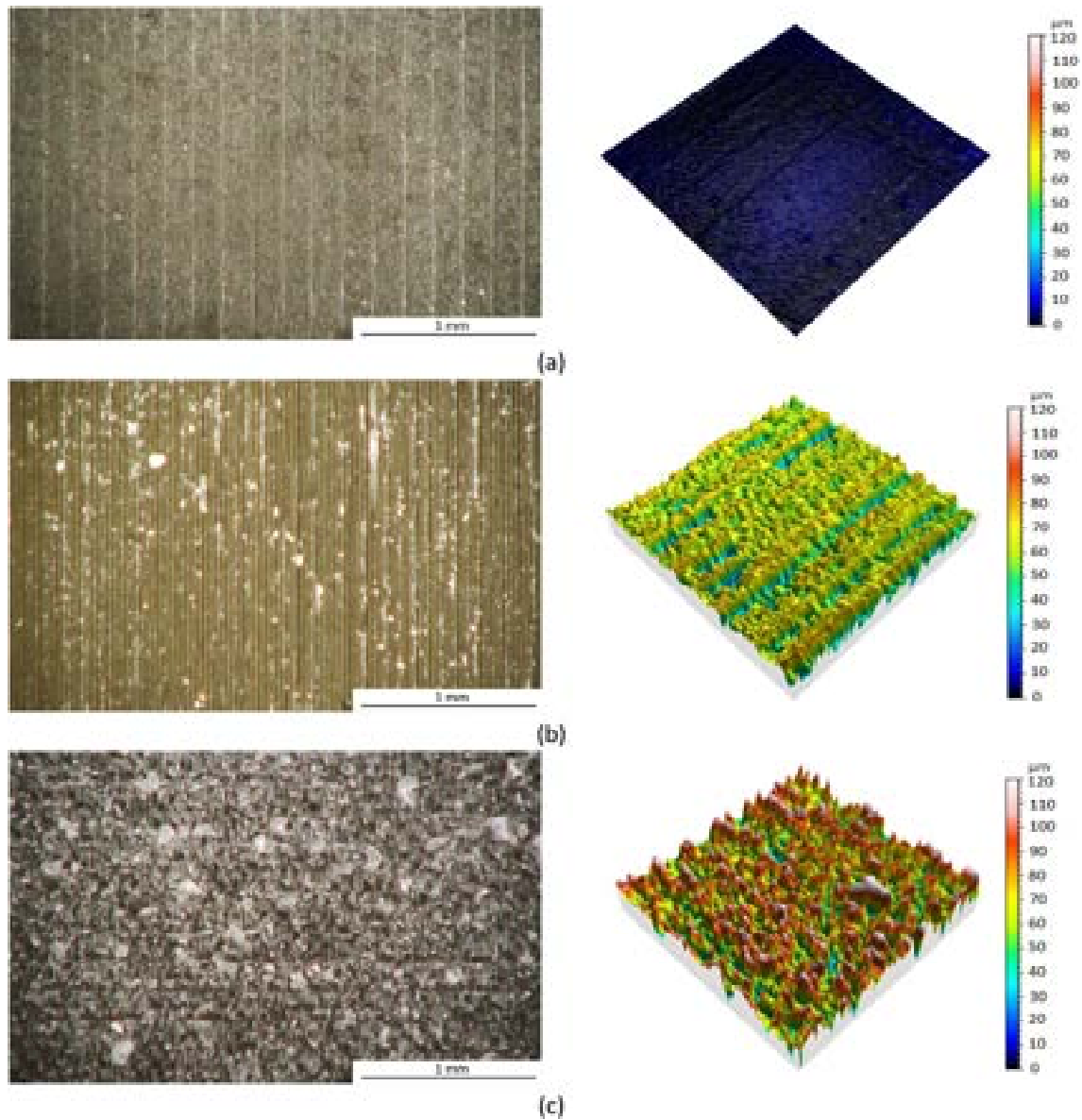


Fig. 3 As-printed morphologies and false map surface map for low **a**, medium **b** and high **c** surfaces (Color figure online)

Table 2 Surface roughness measures of as-printed samples

	Surface morphology		
	Low	Medium	High
Sa [μm]	0.56 ± 0.07	7.95 ± 1.78	15.36 ± 3.50
Sz [μm]	8.64 ± 0.64	88.48 ± 6.36	135.70 ± 12.30

reduction (46%) when the laser scan speed was increased from 10 to 20 mm/s.

The results of the statistical analysis are reported in Fig. 5. ANOVA and Tukey reported no significant effect of laser scan speed on Ra (p value > 0.05); in contrast, for Rz, Tukey identified a difference between speeds of 10 and 20 mm/s but not between speeds of 15 and 20 mm/s.

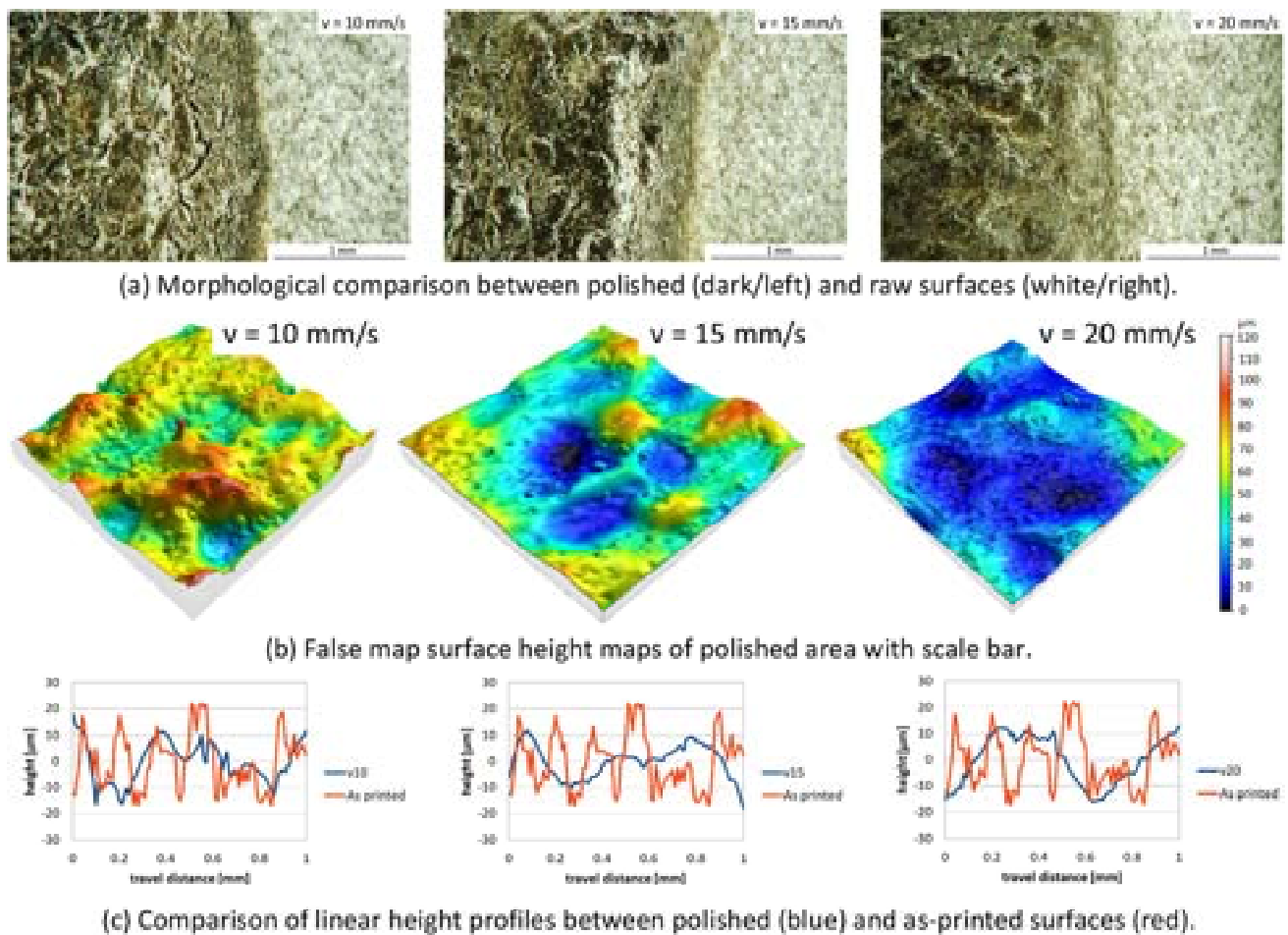


Fig. 4 Main results of first experimental tests as a function of laser scan speed. **a** Morphological comparison between polished (dark/left) and raw surfaces (white/right). **b** False map surface height maps of

polished area with scale bar **c** Comparison of linear height profiles between polished (blue) and as-printed surfaces (red) (Color figure online)

Table 3 Surface roughness comparisons for the first experimental tests

	Laser scan speed [mm/s]		
	10	15	20
Sz [μm]	121.70 ± 5.09	104.99 ± 11.33	98.72 ± 0.73
Sa [μm]	15.28 ± 0.64	9.91 ± 1.53	8.25 ± 0.92

Considering the time factor, a level of 20 mm/s was assumed as the optimum laser scan speed.

By analysing the second experimental tests reported in Fig. 6 and Table 4, it was possible to assert the following:

- Reducing the overlap from 50 to 25% generated a surface without burned areas (Fig. 6a) and produced uniform heights (Fig. 6b) and a flatter linear profile (Fig. 6c).
- ANOVA confirms the significant effect of the overlap factor (Fig. 7).
- Table 4 reports that Sa and Sz were significantly reduced by 56% and 70%, respectively.

In the third set of experimental tests designed to further improve surface roughness, the effect of the number of loops was tested; comparisons between one and two loops are reported in Fig. 8 and Table 5. Figure 8a shows the presence of spotted melting zones, which resulted in worsening of the surface morphology, as confirmed by the graphs shown in Figs. 8b and c. The ANOVA results shown in Fig. 9 confirm that increasing the loop cycle results in a significant change

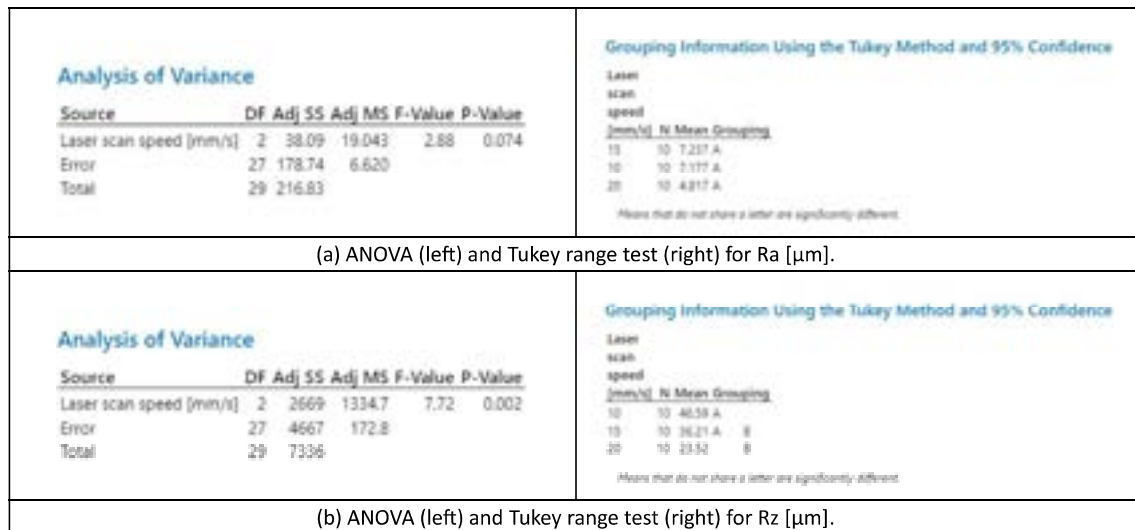


Fig. 5 Main results of statistical analysis of the first experimental campaign

in Ra and Rz. As reported in Table 5, the average surface roughness Sa changed from 4.51 to 12.11 μm , indicating an increase of 100%; coherent behaviour was measured for Sz. The deterioration observed in the surface quality can be attributed to the physics of laser material interaction. Following the initial polishing cycle, the surface temperature increases, and the low thermal conductivity of the polymer inhibits efficient cooling. Furthermore, the increased temperature leads to a higher absorption coefficient. As a consequence, during the second laser scan, an ablation process occurs rather than a polishing process, resulting in the formation of bubbles and a degraded surface, as commonly observed in such phenomena [34].

Discussion

The main results achieved with each experimental test and percentage comparisons with the as-printed data are reported in Fig. 10. The tests were named with the following coding: *laser scan speed _ overlapping percentage _ loop cycle* (for example, test 15_0.50_1 refers to a scan speed of 15 mm/s, an overlap between consecutive scans of 50% and 1 loop cycle).

By analysing the results shown in Fig. 10, it is possible to appreciate the benefits of laser processing parameters and conditions; in particular, test 20_0.25_1 showed a reduction in the average roughness to 4.5 μm (68%) and the maximum peak-to-valley height to 43.15 μm (69%). Despite the

benefits, melting phenomena could occur when the input energy (i.e., scan speed) was increased or surfaces were irradiated more times (high overlap or excess loop cycles), causing a worsening of surface roughness. This causes an increase in the average track depth and a worsening of the polishing quality, as confirmed by test 10_0.50_1 shown in Fig. 10. The main effect of imposing looped cycles is to generate localized burning areas, which results in loss of performance for Sa, but no significant effect has been recorded for Sz. Overlap seems to be the fundamental parameter for a correct polishing process. These considerations are consistent with prior studies: a roughness reduction equal to 90% was measured when working with a CO₂ laser [19, 22, 23] or with a fibre laser [20, 21, 25]. The main difference is the set scan speed, which is lower than that set with a fibre laser (150–200 mm/s) [20, 21]. However, it must be highlighted that these results have been found for thermoplastic polymers fabricated via FFF technology; in contrast, the material tested in this research is a photopolymer with thermoset behaviour, and it was polished by a laser with a wavelength equal to 532 nm (half that of the fibre laser). Another consideration was addressed to the surface colour changing due to the polishing effect; this phenomenon occurs because the loss of roughness is correlated to a change of material light reflection but it was not considered as critical because the research investigate on the application of material jetting technology to rapid tooling and not product production.

To test the 20_0.25_1 solution on higher areas and on different surface morphologies, a validation test was executed by

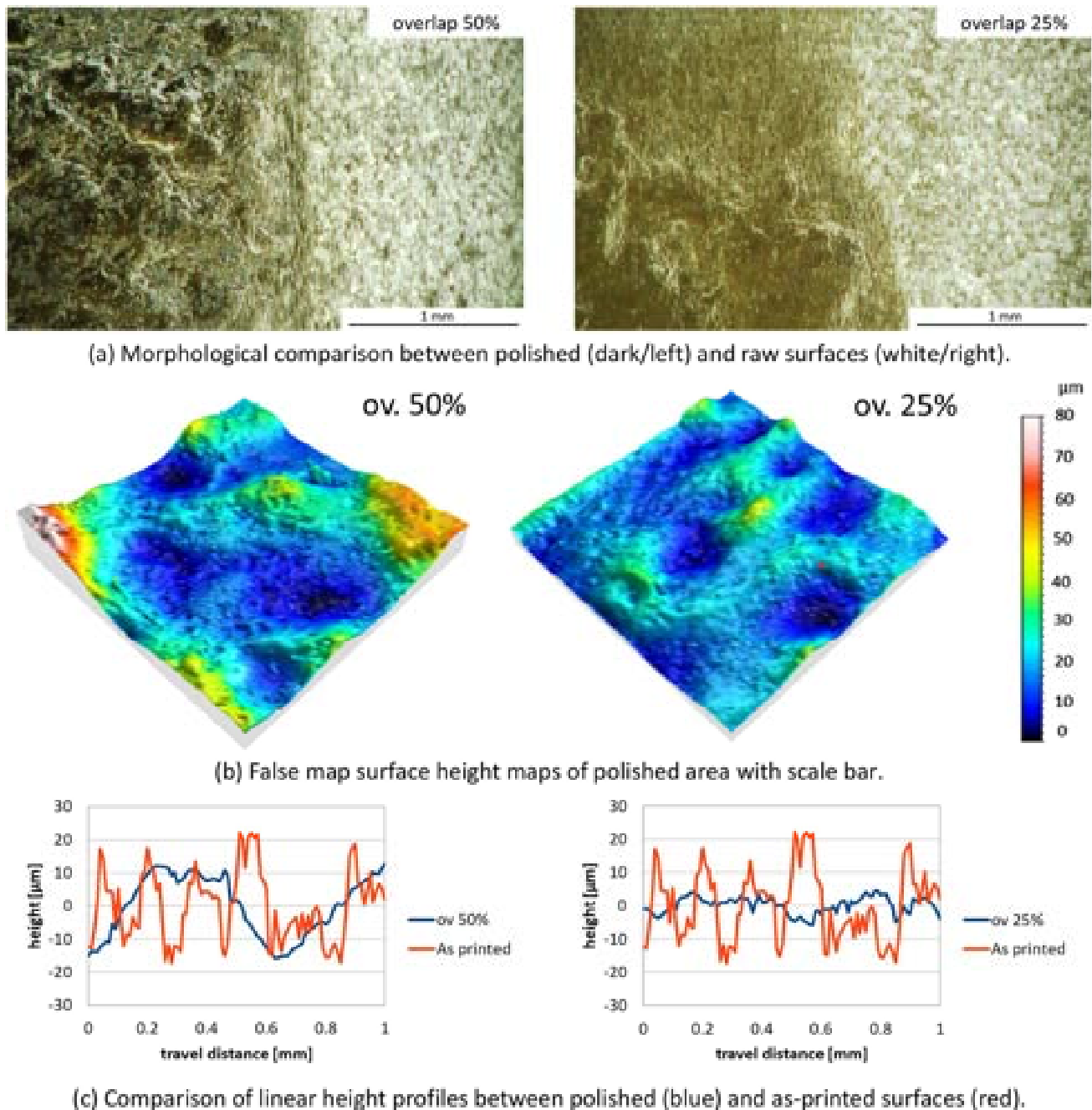


Fig. 6 Main results of second experimental tests as a function of overlap (Color figure online)

Table 4 Surface roughness comparisons for the second experimental tests

	Overlap percentage between consecutive scans	
	50%	25%
Sz [μm]	98.72 ± 0.73	41.95 ± 0.06
Sa [μm]	8.25 ± 0.92	4.44 ± 0.10

setting a scanned surface measuring 15×15 mm on high and medium faces. Figure 11 shows the results for the high (left) and medium (right) surfaces. The measured area includes a printed zone; Sa and Sz are reported for sub surfaces with dimensions of 1×1 mm located in the polished area. From Fig. 11, two main conclusions can be drawn:

- The polishing process was also effective for medium surfaces, generating a smoother surface, avoiding burning

Fig. 7 Main results of statistical analysis of the second experimental campaign

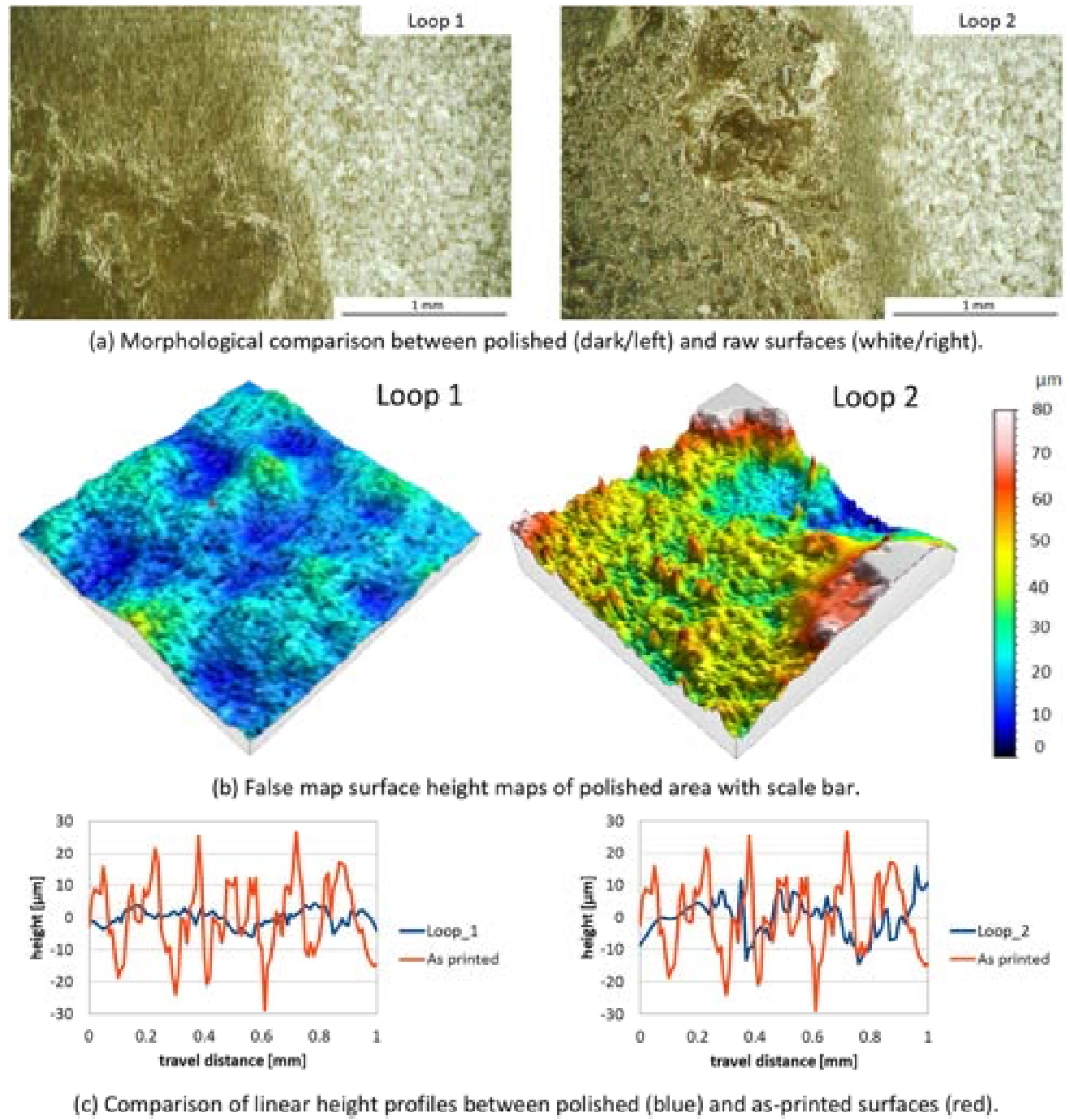


Fig. 8 Main results of third experimental tests as a function of the number of loops (Color figure online)

Table 5 Surface roughness comparisons of the third experimental tests

	Loop cycles	
	1	2
Sz [μm]	41.95 ± 0.06	80.23 ± 8.92
Sa [μm]	4.44 ± 0.10	9.12 ± 1.19

phenomena (Fig. 11a) and achieving an average roughness equal to $4.1 \mu\text{m}$ and a Sz equal to $38.60 \mu\text{m}$. Moreover, it was possible to observe how laser irradiation removed any orientation due to the printing process and created surfaces exhibiting isotropic roughness. By comparing the surface colour maps and the related roughness parameters, it was possible to see that the action of the laser was not affected by the starting surface morphology; indeed, the same results were achieved for both surfaces.

- Despite all the benefits, a loss of thickness equal to $150 \mu\text{m}$ was measured due to the laser polishing effect, as shown in Fig. 11c; thus, ablation occurred during the polishing process and affected part accuracy.

However, the material losses were the same for the medium and high surfaces, which indicated that the process is suitable for complex part geometries where the surface roughness could change in space because it is possible that

the part orientation on the print plate is not parallel to the x-, y- or z-axis.

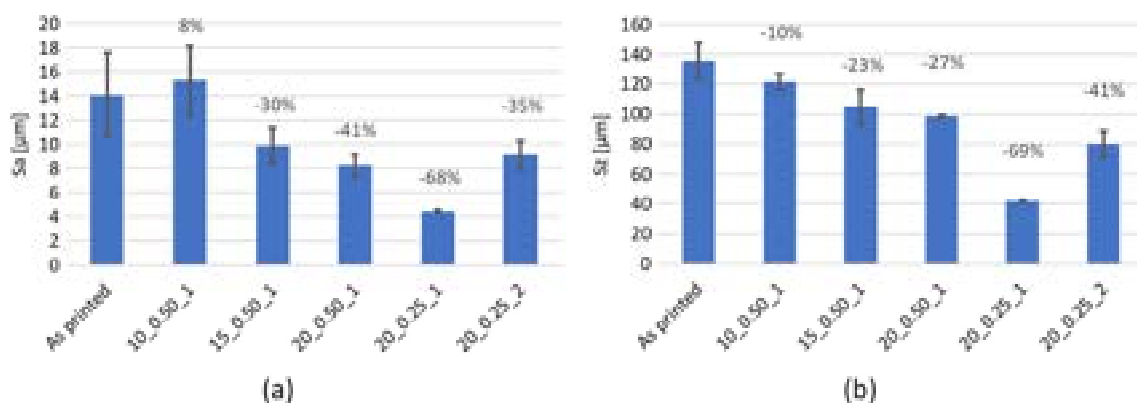
Conclusion

Laser polishing of photopolymers printed with material jetting technology was investigated. A final average roughness value of $4.5 \mu\text{m}$ was achieved for both medium and high surfaces, which corresponded to a maximum reduction in roughness equal to 70%. These results were achieved by imposing a laser power equal to 2.5 W, spot diameter of 0.06 mm , scan speed of 20 mm/s and overlap of 25% between consecutive scans. In addition, the laser process eliminated any orientations caused by the additive production mechanism and generated the same surface morphology independent of the starting surface roughness. These results enhance the possibility of using material jetting technology to produce tools with homogeneous surface finish. Despite these benefits, a loss of accuracy was measured because of ablation caused by the thermal energy absorbed. However, this phenomenon was regular and not dependent on the starting surface texture.

Activities are ongoing to test the chemical and mechanical properties of polished parts, to investigate on new set of process parameters to limit vaporisation and to develop new approaches to part designs utilizing a stock material to compensate for losses due to laser irradiation.

Fig. 9 Main results of statistical analysis of the third experimental campaign

Analysis of Variance						Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value	Source	DF	Adj SS	Adj MS	F-Value	P-Value
Loop	1	25.21	25.206	6.11	0.024	Loop	1	1310	1309.9	6.07	0.024
Error	18	74.29	4.127			Error	18	3887	215.9		
Total	19	99.50				Total	19	5197			

(a) ANOVA result for Ra [μm].(b) ANOVA result for Rz [μm].**Fig. 10** Histograms for Sa **a** and Sz **b** for all the experimental tests

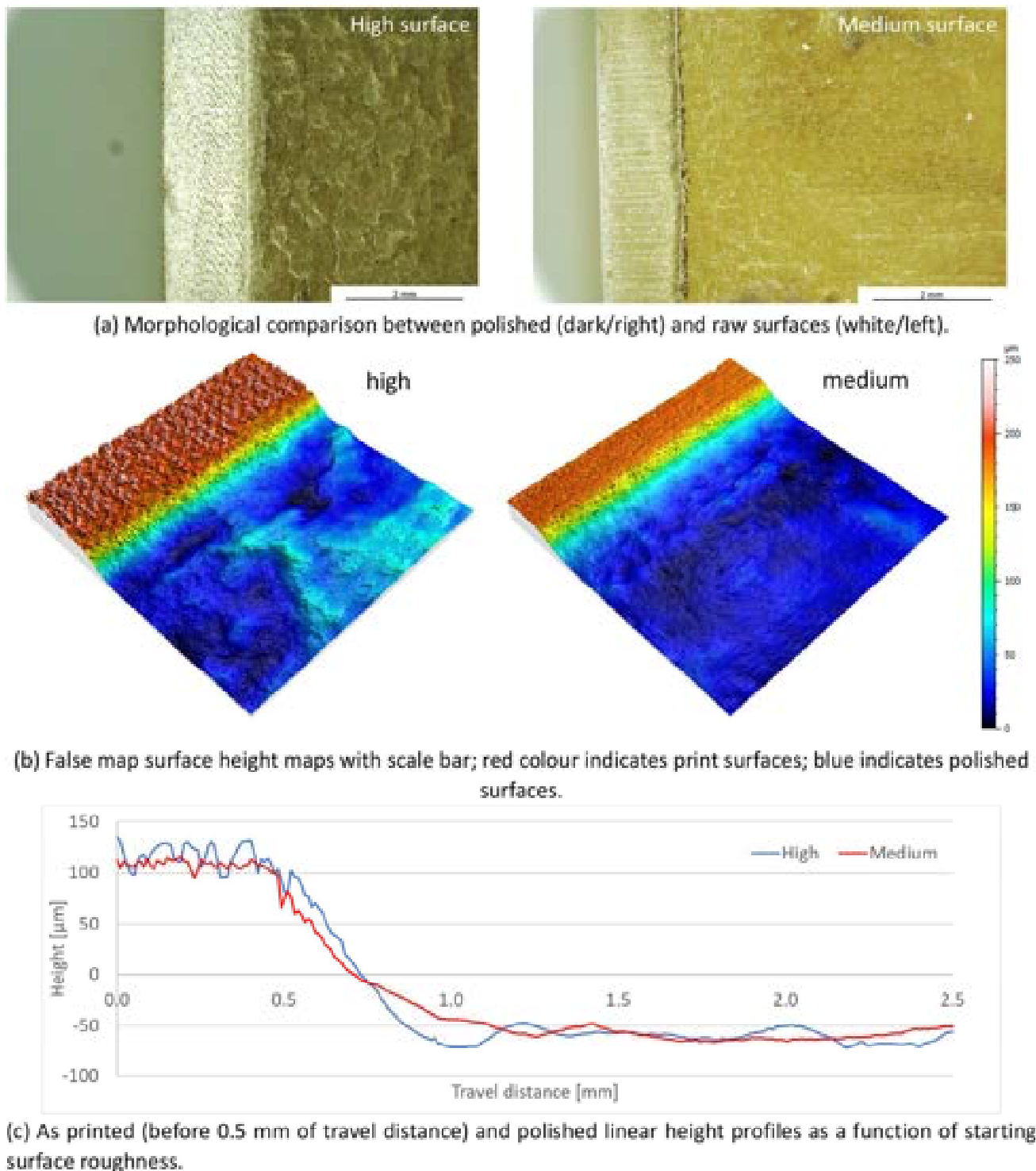


Fig. 11 Comparison of laser polishing performance for a $15 \times 15 \text{ mm}^2$ scanned area (Color figure online)

Acknowledgements The authors would like to mention that the present work has been carried out in the framework of the AITeM-PromozioneL@ser association.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by LG, MR. The first draft of the manuscript was written by MR and LG commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by Università degli Studi di Brescia within the CRUI-CARE Agreement. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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