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Performance assessment of a vibro-finishing technology for additively manufactured components

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Abstract

Metal components produced by Additive Manufacturing (AM) technologies usually exhibit a rough surface, that in certain applications can result detrimental for the part's functionality. Thus, it is of great interest to study the finishing processes that can be applied to the surfaces, both external and internal, of AM components. The aim of this work is the evaluation of the capabilities of a vibro-finishing process in the treatment of samples produced by Laser-Powder Bed Fusion (L-PBF) from AlSi10Mg powders. In this research, the abrasive media is identified, and the surface quality improvement is analysed in terms of surface roughness and modifications induced by the finishing treatment (i.e., edge rounding, material loss) against finishing duration. The cost of the treatment is also evaluated.

Keywords: Additive manufacturing; Laser-powder bed fusion (L-PBF); AlSi10Mg; Vibro-finishing; Surface roughness

1. Introduction

Additive Manufacturing (AM) has grown exponentially over the last seven years. From technology for prototypes, customer-oriented, it has become a viable industrial production system. In particular, the rapid rise of metal systems is well documented in the literature and consulting reports. Wohlers *et al.* [1] indicated a growth of 80% in the sale of metal AM systems. New systems producers enter the market, new technologies are developed with the aim of overcoming the barriers of the established technologies, in terms of productivity, part quality and costs. Industries are looking to capitalize the very high potential of AM processes, although currently undermined by lack of control and repeatability of the systems. The sustainable growth of AM processes is a challenge that has been taken up by large multinational companies, such as GE, HP or DMG MORI, who have allocated their numerous resources for the development and the supply chain of industrial AM techniques.

One of the critical points of AM is the finishing, which is inevitable for most components. In fact, despite the numerous advantages given by AM in terms of achievable geometric complexity, consolidated designs, optimization of the material use and product's added value, they suffer from drawbacks in terms of surface quality and dimensional accuracy. Consequently, it is often necessary to carry out machining operations on the AM components, in order to give the appropriate tolerances and tribological properties to the surfaces, or to improve the fatigue behavior, or to induce surface compressive stresses. Basically, the same aspects that are considered advantages in AM production represent challenges for finish machining: complex forms and light weighting can lead to difficulties in alignment and work-holding and could generate vibrations. Moreover, intricate shapes could be very difficult or impossible to cut. Thus, the research is focused on the study of finishing processes, alternative to machining, that can be applied to AM parts [2,3].

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The aim of this paper is to assess the capabilities of a vibro-finishing process in the treatment of AlSi10Mg samples fabricated by Laser-Powder Bed Fusion (L-PBF). The resulting quality at different treatment durations has been analysed in terms of surface roughness and geometrical modifications induced by the finishing treatment. Corresponding costs have been also evaluated.

2. Surface finishing of metal AM parts

The most commonly adopted post-processes to reduce surface finishing of metal AM parts can be mainly classified according to the energy source leading such processes: mechanical, thermal, chemical, and electrochemical [4].

2.1. Mechanical processes

Additionally to conventional machining, hot cutter machining and micro machining, processes such as grinding, blasting and water-jetting belong to mechanical finishing processes investigated in the last years [4]. Moreover, tribofinishing is gaining more and more attention due to its low unit cost and its capability of treating many components at the same time [5]. The mechanism underlying tribofinishing processes, such as vibratory bowl abrasion [6], centrifugal finishing, rotary barrel finishing, mass-finishing and drag finishing [5] is the removal of roughness peaks through plastic deformation and abrasion due to the relative motion between components and abrasive media. Different variants of finishing processes employing abrasive particles have been developed and are listed in the following. Abrasive Flow Machining (AFM), existing in different configurations [7], is indicated for difficult-to-access inner structures. Peng *et al.* [8] obtained a surface roughness S_a of 1.8 µm on an AlSi10Mg component whose as-built roughness was equal to 13-14 µm. Atzeni *et al.* [3] using Abrasive Fluidized Bed (AFB) obtained an average R_a of around 1.5 µm on AlSi10Mg parts realised through L-PBF. Yamaguchi *et al.* [9] processed the surfaces of a 316L steel part manufactured by L-PBF, changing the R_z-value from 100 to 0.1 µm through a Magnetic field-Assisted Finishing (MAF) process. With MAF, complex shapes can be processed in different regimes of machining by altering the magnetic tools. Tan and Yeo [10] used for the first time ultrasonic wave for surface modification purpose. In the process they named Ultrasonic Cavitation Abrasive Finishing (UCAF), the authors exploited the cavitation occurring in a liquid medium in which a high-frequency sinusoidal wave of pressure is induced. If micro-particles of abrasive media are added to the liquid medium, they act as nucleation sites for new bubbles, and enhance the erosion of the surface being accelerated against by the bubbles collapse. Witkin *et al.* [11] led chemically accelerated vibratory polishing, both eliminating surface defects and enhancing fatigue life of Ti6Al4V components made through Electron Beam Melting (EBM) and L-PBF.

2.2. Thermal processes

Laser polishing and Electron Beam (EB) irradiation [4] provide thermal energy to surface apexes, whose material melts and in the liquid state is redistributed at the same horizontal level due to gravity and surface tension [6]. Both the processes are contactless, with no limitations due to tool wear. In particular, laser polishing offers the possibility of easy integration and high automation [6]. Gora *et al.* [12] laser polished parts produced by L-PBF. The achieved results were a reduction in the roughness of 85% on Ti6Al4V samples and of 85-96% for CoCr ones. Bhaduri *et al.* [13] reported a list of the key publications on laser polishing, from 1997 to 2016 with details on laser systems used. The most investigated are CO_2, Nd:YAG and fiber lasers [6,13]. Although, the use of shorter wavelength lasers (UV lasers in the range of 350 to 250 nm) used in micro-machining is getting attention, as they can perform the so-called Cold Laser Machining (CLM) or photochemical ablation [6]. Also the laser pulse regime is a key parameter, since in ultrashort ones the laser beam interacts with the material on a much greater timescale than the one of thermal diffusion, enabling the production of precise and clean features reducing the heat-affected zone [14]. Ma *et al.* [15] used a nanosecond pulsed fiber laser (wavelength 1060 nm and pulse duration 220 ns) to polish a surface cut by wire-electrode of additively manufactured titanium alloys. Worts *et al.* [14] employed femtosecond lasers to micromachine Ti6Al4V parts made by a L-PBF process. Femtosecond laser systems are forecast to be integrated into L-PBF systems, as they can operate at identical wavelengths (about 1040 nm) of high average power Yb-fiber lasers employed in those AM processes (L-PBF), according to the gain medium used.

2.3. Chemical and electrochemical processes

Chemical polishing (or chempolishing) consists of material removal by dissolution. The surface is considered chemically polished when the layer formation rate and its dissolution are the same [16,17]. Such post-processes have the capability of improving the roughness of outer and inner complex surfaces simultaneously [18]. Tyagi *et al.* [17] obtained uniform roughness distribution on 316 stainless steel, reaching values from 5.0 to 0.4 µm for outer surfaces, and 15 to 0.4 µm inner ones. Wysocki *et al.* [19] chemically polished titanium scaffolds to remove not fully melted particles using various HF and HF-HNO_3 acid solutions. Łyczkowska *et al.* [20] reviewed chemical polishing techniques for Ti6Al7Nb scaffolds. Electrochemical Polishing (ECP) [4] and Plasma Electrolytic Polishing (PeP) exploit electrolytic processes where the AM part acts as the anode, specifically PeP is considered a particular case of anodic dissolution [21]. A counter electrode is needed near the to-finish surface [18]. Urlea and Brailovski [22] and [23] electro-polished selectively laser-melted Inconel 625 and Ti6Al4V parts. Jung *et al.* [24] instead, tested titanium plates manufactured through EBM.

2.4. Comparison and limitations

Each post-process owns pros and cons, according to the specific case. For example, electropolishing returns smoother surfaces than chemical polishing, but at the same time the electrode used encounters limits on the accessibility to the workpiece in narrow inlets reachable through chempolishing [17]. In a similar way, micromachining, grinding and blasting, as well as EB irradiation and PeP, require a line of sight [4]. Processes such as EB irradiation, electropolishing and chemical etching, instead, do not allow finishing of limited areas of a surface since they are not selective [4]. Tyagi *et al.* [17] found different morpologhical surfaces after adopting electropolishing and chempolishing, especially in the quantity of retaining sub-micrometric cavities. Witkin *et al.* [11], by comparing abrasive and laser polishing operations on Inconel 625 parts fabricated using L-PBF, highlighted that removing material by abrasion or by re-melting could have different outcome on fatigue life, since in the first case the defect roots could not be always successfully removed. All of these peculiarities have to be considered during the choice of the proper finishing post-process, according to the geometry of the component and the load it will bear [17], even in the early stages of its design process [4].

3. Material and methods

The fabrication and finishing of the aluminum alloy samples produced by AM is detailed in the following Sections. The methodology adopted for the evaluation of the surface quality is also described.

3.1. Fabrication of the samples

Direct Metal Laser Sintering (DMLS) process by EOS GmbH (Krailling, Germany) was used to build three AlSi10Mg $15 \times 15 \times 10$ mm^3 parallelepiped-shaped samples as shown in Fig. 2a. The EOSINT M 270 Dual Mode machine, equipped with a 200 W Yb-fiber laser source focused on a 0.1 mm spot diameter, allows to process reactive materials in an argon environment, to prevent oxidation of the material. The building process begins with the deposition of a powder layer onto the building platform. Then, the laser selectively melts the powder according to the section

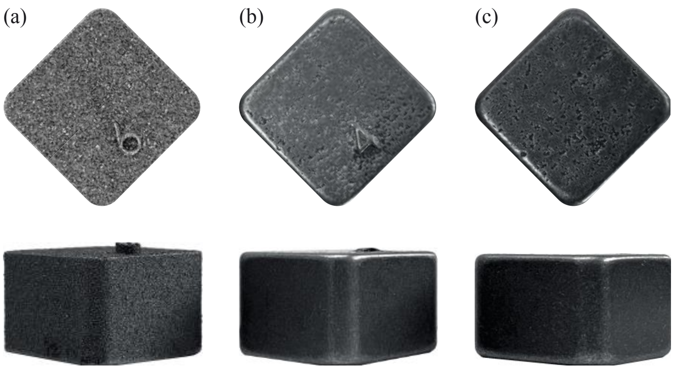

Fig. 2. Top and later view of (a) the as-built sample, (b) the sample after Test #1 and (c) the sample after Test #2.

Fig. 1. AV 40 vibro-finishing machine (Best Finishing Srl, Italy).

geometry. Thereafter, the building platform is lowered, and the sequence is repeated, layer by layer, up to the complete fabrication of the parts. Commercial EOS Aluminium AlSi10Mg material was used and standard process and exposure parameters, optimized by the system producer for this material type and EOSINT systems, were adopted. Thus, the layer thickness was set to 30 μm, the building platform was maintained at 100 °C and the scan strategy was a stripe pattern, rotated by 67° at each new layer. The standard scan strategy uses different exposure parameters for the upper and bottom layers, the core and the skin. Samples were anchored to the platform with a saw-toothed 5 mm high support structure. After the fabrication and before the manual parts removal, the platform with samples was subjected to a stress relieving thermal treatment, at 310 °C for one hour.

3.2. Finishing process

The REM Isotropic Superfinishing (REM ISF®) process was carried out in Best Finishing Srl (Gessate, Milano, Italy) by means of an AV 40 vibro-finishing machine shown in Fig. 1 filled with FMX 3/8” TC abrasive inserts. The process was executed in two subsequent steps of (*i*) finishing and (*ii*) polishing. A commercial ALUMIL 241 medium with 10:100 dilution in water was used in the finishing step, and the flow rate was fixed to 1 liter/h. The finishing step lasted for 38 h and 62 h for Test #1 and Test #2, respectively. This process was followed by a polishing step, in which an FBC 50 medium with 1.5:100 dilution in water and a flow rate of 5 liter/h was used. The polishing step lasted 2 h for both Test #1 and Test #2. At the end of the vibro-finishing process, the specimens were extracted from the machine, washed in water and dried with hot air.

3.3. Surface quality evaluation

Measurements of surface profiles of the samples, before the finishing treatment, were conducted by using a MarSurf XR 20 with GD25 roughness measuring station. Traversing length was 5.6 mm, with a step size of 0.5 μm and processed with five cut-offs of 0.8 mm. Traversing speed was 0.5 mm/s. In addition, surface roughness and texture were analysed on each sample, before and after the finishing treatment, by using a MarSurf CM mobile confocal microscope with an 800XS objective. The measured area was 2 × 2 mm², with sampling intervals of 5 µm. From surface data, roughness profiles were also extracted. A Gaussian filter was applied. Changes in the edge radius of the samples were evaluated by retrieving the actual geometry with the 3D scanner Picza PIX-3. It is a contact-type scanner, equipped with a piezoelectric sensor. Scanning steps were 25 µm in height (Z-axis) and 50 µm in width (X-axis) and depth (Y-axis).

4. Results and discussion

The results achieved in terms of surface roughness, edge roundness and finishing costs are presented and discussed in the following sections.

4.1. Geometry and mesh

Bi- and tri-dimensional observations of the morphology of as-built and finished surfaces are shown in Fig. 3 . For the sake of clarity, it is worth to remark that the scale axis is different per each picture, with the aim to better present the results and the surface features. The observed changes in surface morphology are consistent with those typical of the chemically accelerated REM ISF® process. The treatment is progressive, and the roughness is reduced by leveling the most exposed peaks with the formation of an isotropic surface. As the duration of the finishing process increases (as highlighted by the differences between Test #1 and Test #2), even the deepest valleys can be gradually removed.

The surface roughness parameters (computed in compliance with the ISO 25178 standard) are resumed in Table 1. In comparison with the results concerning the as-deposited samples, a significant reduction in the height parameters S_a, S_q, S_z, S_p and S_v was noticed. As expected, the longer the finishing step is, the better the surface quality. The surface skewness (S_{sk}) is slightly negative, and its value decreases with the increase of the duration of the finishing process, while the Kurtosis (S_{ku}) and the areal material ratio (S_{mr}) parameters both slightly increase.

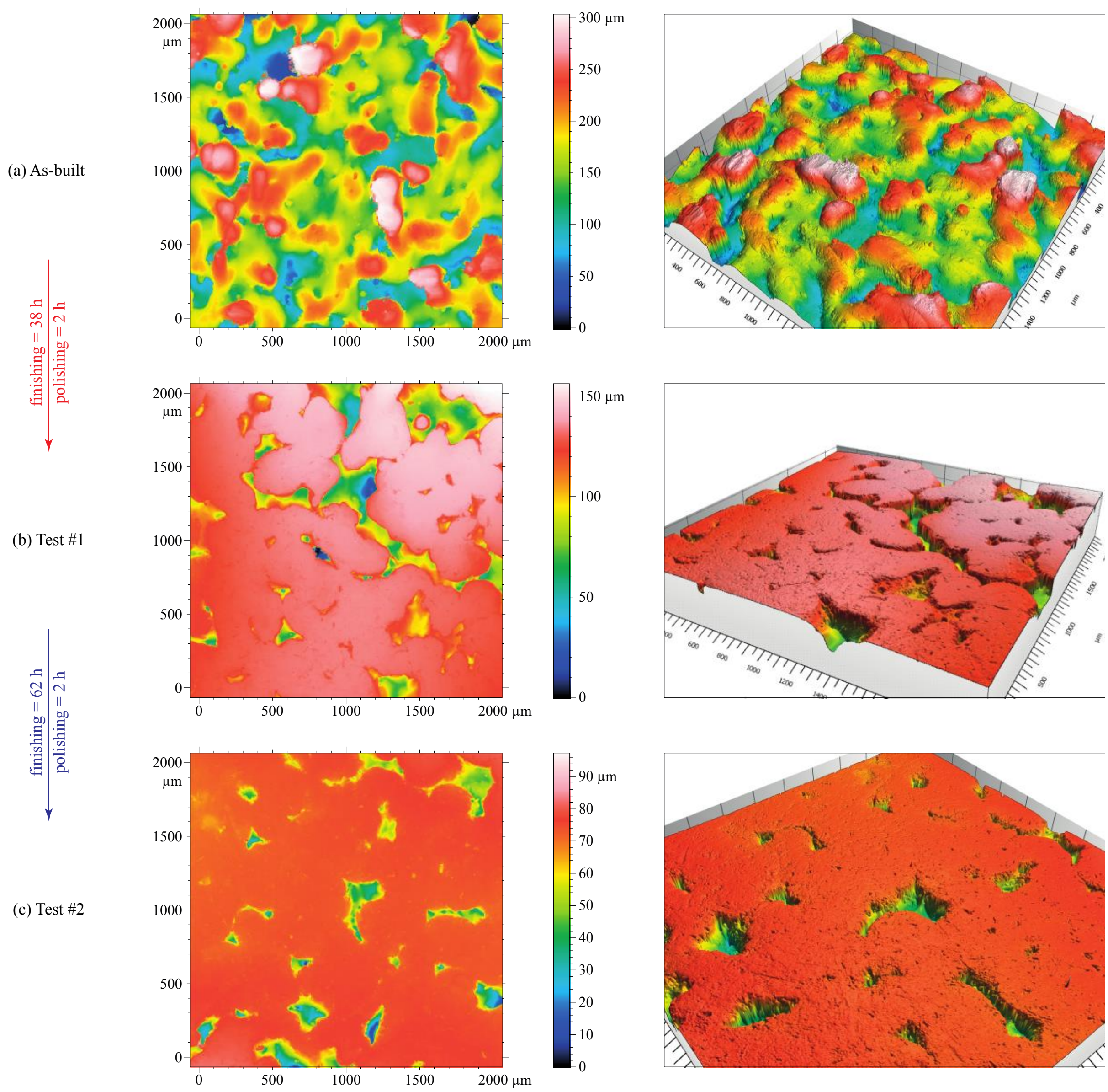

Fig. 3. Bi- and tri-dimensional observations of the morphology of a sample in (a) as-build state, after Test #1 and (c) after Test #2.

Table 1. Typical surface roughness results.

Parameter (ISO 25178)	As built	After Test #1	After Test #2
S_a (µm)	44.0	12.1	4.25
S_q (µm)	54.1	18.8	7.96
S_z (µm)	304	156	97.3
S_p (µm)	130	30.7	25.6
S_v (µm)	174	126	71.7
S_{sk}	−0.21	−2.35	−3.66
S_{ku}	2.56	9.36	18.3
S_{mr} (%)	5.13	6.23	7.51

4.2. Edge roundness

The scanning operations allowed to perform measurements on the samples. Moreover, samples were weighted to determine the loss of weight due to the finishing treatments. Results are shown in Table 2 and in Fig. 4. The abrasive finishing operations generated an edge radius of about 0.6 mm on the treated samples. This radius was observed after Test #1, and it did not vary after Test #2 increasing the finishing treatment time. Similarly, a reduction in edge length by 0.27 mm (1.8%) was observed for Test #1, and the longer finishing time had a negligeable effect on this dimension, being the measured variation comparable with the accuracy of the scanner (0.05 mm). As regards the lateral radius, it is observed that the original radius was not significantly changed. The weight measurements confirmed these results: the weight reduction was about 3%, and the weight of the two treated samples are comparable to each other.

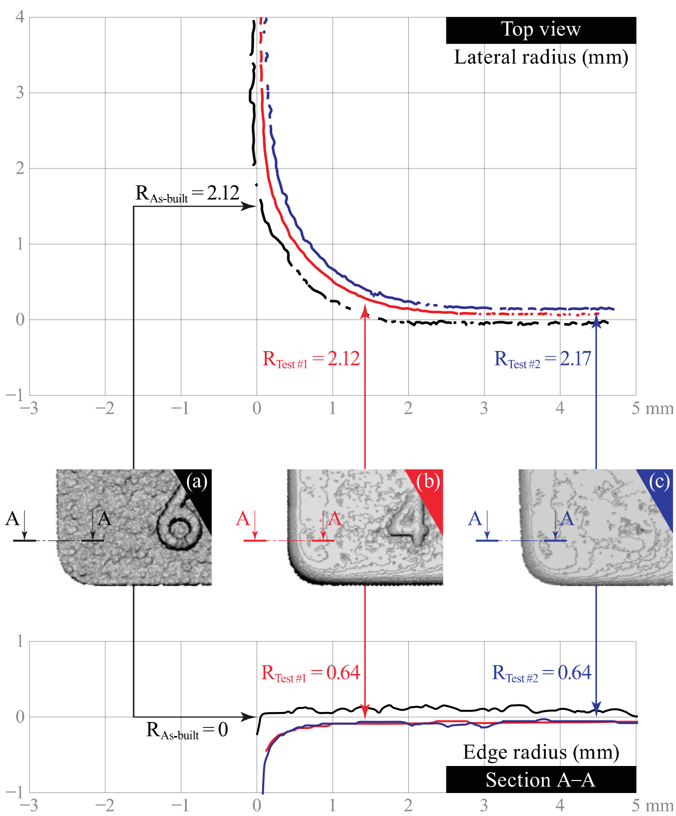

Fig. 4. Lateral and edge radius of (a) the as-built sample, (b) the sample after Test #1 and (c) the sample after Test #2.

Table 2. Weight and dimensions of the samples.

Parameter	As built	After Test #1	After Test #2
Weight (g)	5.75	5.57	5.60
Lateral radius (mm)	2.12	2.12	2.17
Edge length (mm)	15.12	14.85	14.83
Edge radius (mm)	0	0.64	0.64

4.3. Finishing costs

The costs for the REM ISF® vibro-finishing were computed by accounting for the (*i*) indirect costs, (*ii*) processing costs and (*iii*) labour costs, under the hypothesis of simultaneously finishing 50 identical parts per each cycle in order to saturate the working volume of the AV 40 machine. The indirect costs add up the administrative/production overheads as well as the purchase and maintenance costs of the machine, and they were allocated through the total part finishing time. An indirect cost rate [25] of 5.76 €/h was supposed by assuming: (*i*) a purchase cost for the AV 40 machine of 2,270 €; (*ii*) a depreciation period of 2 y; (*iii*) an annual operating time of 4,680 h/y, which was computed by assuming an 18-h/d use over 260 working days per year; (*iv*) a maintenance cost of 100 €/y; (*v*) an administrative/production overhead rate of 5.5 €/h. The labour charge rate was 16.45 €/h, since a full annual labour cost of 30,000 € was considered for 228 8h/d-working days (net of holidays) per year. The operator's working time was obtained by supposing an employment due to manual and supervision operations equal to 3% of the total finishing time. As far as the processing costs are concerned, the AV 40 machine was filled with 16 kg of FMX abrasive inserts, the purchase cost of which was 5.75 €/kg and the consumption rate when finishing was quantified in 0.06 %/h. The purchase costs of the ALUMIL 241 and FBC 50 media were 7.50 €/liter and 4.00 €/liter, respectively. The AV 40 machine is equipped with an electric engine, and its constant power demand was assumed to be 0.15 kW. The cost of electric energy was fixed to 0.25 €/kWh. The cost for the disposal of waste fluids was esteemed to be 0.12 €/liter. The cost assessment is detailed in Table 3. Under the above mentioned assumptions, the costs per finished part are equal to 5.77 € and 9.24 € for Test #1 and Test #2, respectively. These values are dominated by the indirect costs. It is worth

Table 3. Cost assessment for vibro-finishing operations.

Variable	Test #1	Test #2
Duration of finishing + polishing process (h)	38 + 2	62 + 2
Cost of FMX 3/8" TC abrasive inserts (€)	2.21	3.53
Cost of ALUMIL 241 medium (€)	28.50	46.50
Cost of FBC 50 medium (€)	0.60	0.60
Cost of electric energy (€)	1.50	2.40
Cost of waste disposal (€)	5.76	8.64
Processing costs, per batch (€)	38.57	61.67
Indirect costs, per batch (€)	230.40	368.64
Labour costs, per batch (€)	19.74	31.58
Total costs, per batch (€)	288.71	461.89
Total costs, per part (€)	5.77	9.24

to underline that, when excluding the administrative/ production overheads from the calculation (i.e., by including in the assessment of the indirect cost rate only the purchase and maintenance costs of the machine), the costs per finished part would be noticeably reduced to 1.37 € and 2.20 € for Test #1 and Test #2, respectively.

5. Conclusions

A vibro-finishing process in the treatment of AlSi10Mg samples fabricated by L-PBF was assessed. Two different treatment durations were applied while keeping the same abrasive media, which were selected as a function of the specific material and the acquired knowledge on finishing of additively manufactured parts. The finishing performance capabilities were quantified in terms of surface topology and roughness, edge roundness and process costs. The experiments show that the finishing process is suitable to reduce the average surface roughness, S_a, to one-tenth of the as built one, resulting in an S_a of about 4 μm. The treatment progressively reduces the roughness by leveling the most exposed peaks with the formation of an isotropic surface. Even the deepest valleys can be gradually removed by increasing the duration of the finishing process. Moreover, while retaining the original geometrical shape, the as-built sharp edges are rounded. This phenomenon is particularly evident in the earlier phases of the abrasive process. Overall, it was possible to estimate a needed allowance of 0.3 mm to account for the material removal. The cost for the finishing process is not expected to significantly increase the total costs of the whole manufacturing route.

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References

[1] Wohlers T, Caffrey T, Campbell RI, Diegel O, Kowen J. Wohlers Report 2018: 3D Printing and Additive Manufacturing State of the Industry; Annual Worldwide Progress Report: Wohlers Associates; 2018.
[2] Ribezzo A, Calignano F, Salmi A, Atzeni E, Pietrobono F, Trovalusci F, Rubino G. Finishing of metal additive manufactured parts by abrasive fluidized bed machining. European Society for Precision Engineering and Nanotechnology, Conference Proceedings - 18th International Conference and Exhibition, EUSPEN 2018. p. 271-2.
[3] Atzeni E, Barletta M, Calignano F, Iuliano L, Rubino G, Tagliaferri V. Abrasive Fluidized Bed (AFB) finishing of AlSi10Mg substrates manufactured by Direct Metal Laser Sintering (DMLS). Additive Manufacturing. 2016;10:15-23.
[4] Gordon ER, Shokrani A, Flynn JM, Goguelin S, Barclay J, Dhokia V. A Surface Modification Decision Tree to Influence Design in Additive Manufacturing. Sustainable Design and Manufacturing 2016. p. 423-34.
[5] Salvatore F, Grange F, Kaminski R, Claudin C, Kermouche G, Rech J, Texier A. Experimental and Numerical Study of Media Action During Tribofinishing in the Case of SLM Titanium Parts. Procedia CIRP. 2017;58:451-6.
[6] Kumbhar NN, Mulay AV. Post Processing Methods used to Improve Surface Finish of Products which are Manufactured by Additive Manufacturing Technologies: A Review. Journal of The Institution of Engineers (India): Series C. 2018;99:481-7.
[7] Ali P, Dhull S, Walia RS, Murtaza Q, Tyagi M. Hybrid Abrasive Flow Machining for Nano Finishing - A Review. Materials Today: Proceedings. 2017;4:7208-18.
[8] Peng C, Fu Y, Wei H, Li S, Wang X, Gao H. Study on Improvement of Surface Roughness and Induced Residual Stress for Additively Manufactured Metal Parts by Abrasive Flow Machining. Procedia CIRP. 2018;71:386-9.
[9] Yamaguchi H, Fergani O, Wu P-Y. Modification using magnetic field-assisted finishing of the surface roughness and residual stress of additively manufactured components. CIRP Annals. 2017;66:305-8.
[10] Tan KL, Yeo SH. Surface modification of additive manufactured components by ultrasonic cavitation abrasive finishing. Wear. 2017;378-379:90-5.
[11] Witkin DB, Patel DN, Helvajian H, Steffeney L, Diaz A. Surface Treatment of Powder-Bed Fusion Additive Manufactured Metals for Improved Fatigue Life. Journal of Materials Engineering and Performance. 2018;28:681-92.
[12] Gora WS, Tian Y, Cabo AP, Ardron M, Maier RRJ, Prangnell P, Weston NJ, Hand DP. Enhancing Surface Finish of Additively Manufactured Titanium and Cobalt Chrome Elements Using Laser Based Finishing. Physics Procedia. 2016;83:258-63.
[13] Bhaduri D, Penchev P, Batal A, Dimov S, Soo SL, Sten S, Harrysson U, Zhang Z, Dong H. Laser polishing of 3D printed mesoscale components. Applied Surface Science. 2017;405:29-46.
[14] Worts N, Jones J, Squier J. Surface structure modification of additively manufactured titanium components via femtosecond laser micromachining. Optics Communications. 2019;430:352-7.
[15] Ma CP, Guan YC, Zhou W. Laser polishing of additive manufactured Ti alloys. Optics and Lasers in Engineering. 2017;93:171-7.
[16] Mohammadian N, Turenne S, Brailovski V. Surface finish control of additively-manufactured Inconel 625 components using combined chemical-abrasive flow polishing. Journal of Materials Processing Technology. 2018;252:728-38.
[17] Tyagi P, Goulet T, Riso C, Stephenson R, Chuenprateep N, Schlitzer J, Benton C, Garcia-Moreno F. Reducing the roughness of internal surface of an additive manufacturing produced 316 steel component by chempolishing and electropolishing. Additive Manufacturing. 2019;25:32-8.
[18] Tyagi P, Goulet T, Riso C, Garcia-Moreno F. Reducing surface roughness by chemical polishing of additively manufactured 3D printed 316 stainless steel components. The International Journal of Advanced Manufacturing Technology. 2018;100:2895-900.
[19] Wysocki B, Idaszek J, Szlązak K, Strzelczyk K, Brynk T, Kurzydłowski K, Święszkowski W. Post Processing and Biological Evaluation of the Titanium Scaffolds for Bone Tissue Engineering. Materials. 2016;9.
[20] Łyczkowska E, Szymczyk P, Dybała B, Chlebus E. Chemical polishing of scaffolds made of Ti–6Al–7Nb alloy by additive manufacturing. Archives of Civil and Mechanical Engineering. 2014;14:586-94.
[21] Nestler K, Böttger-Hiller F, Adamitzki W, Glowa G, Zeidler H, Schubert A. Plasma Electrolytic Polishing – An Overview of Applied Technologies and Current Challenges to Extend the Polishable Material Range. Procedia CIRP. 2016;42:503-7.
[22] Urlea V, Brailovski V. Electropolishing and electropolishing-related allowances for powder bed selectively laser-melted Ti-6Al-4V alloy components. Journal of Materials Processing Technology. 2017;242:1-11.
[23] Urlea V, Brailovski V. Electropolishing and electropolishing-related allowances for IN625 alloy components fabricated by laser powder-bed fusion. The International Journal of Advanced Manufacturing Technology. 2017;92:4487-99.
[24] Jung J-H, Park H-K, Lee BS, Choi J, Seo B, Kim HK, Kim GH, Kim HG. Study on surface shape control of pure Ti fabricated by electron beam melting using electrolytic polishing. Surface and Coatings Technology. 2017;324:106-10.
[25] Priarone PC, Campatelli G, Montevecchi F, Venturini F, Settineri L. A modelling framework for comparing the environmental and economic performance of WAAM-based integrated manufacturing and machining. CIRP Annals – Manufacturing Technology. In press.