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Influence of Selected Finishing Technologies on the Roughness Parameters of Stainless Steel Manufactured by Selective Laser Melting Method

J. Hajnys, M. Pagac, J. Petru, P. Stefek, J. Mesicek, J. Kratochvil

***Abstract*—**The new progressive method of 3D metal printing SLM (Selective Laser Melting) is increasingly expanded into the normal operation. As a result, greater demands are placed on the surface quality of the parts produced in this way. The article deals with research of selected finishing methods (tumbling, face milling, sandblasting, shot peening and brushing) and their impact on the final surface roughness. The 20 x 20 x 7 mm produced specimens using SLM additive technology on the Renishaw AM400 were subjected to testing of these finishing methods by adjusting various parameters. Surface parameters of roughness Sa, Sz were chosen as the evaluation criteria and profile parameters Ra, Rz were used as additional measurements. Optical measurement of surface roughness was performed on Alicona Infinite Focus 5. An experiment conducted to optimize the surface roughness revealed, as expected, that the best roughness parameters were achieved through a face milling operation. Tumbling is particularly suitable for 3D printing components, as tumbling media are able to reach even complex shapes and, after changing to polishing bodies, achieve a high surface gloss. Surface quality after tumbling depends on the process time. Other methods with satisfactory results are shot peening and tumbling, which should be the focus of further research.

***Keywords*—**Additive manufacturing, selective laser melting, surface roughness, stainless steel.

I. Introduction

TODAY'S trend is to produce increasingly complex and high-quality parts. There are higher demands on production speed, accuracy and above all on the overall quality of the final product. To some extent, these new requirements are being met by a new progressive technology called SLM, which falls under the category of additive methods. One of the greatest challenges with this technology is the final surface quality of the component. The very rough surface of printed parts leads to the search for finishing applications that can quickly, efficiently and inexpensively finish the surface. It is also necessary to take into account the geometric complexity of the printed parts. The high roughness value is mainly determined by the size of the powder distribution, but also by process parameters such as layer height or scanning speed. The aim of this study is to experimentally test a number of selected finishing applications suitable for use after 3D printing of 316L.

Finishing applications are particularly important for finishing the final surface of the workpiece. However, there are the finishing methods, which change not only roughness of the surface, but also change the surface tension of the structure (from tensile to compressive stress). It is therefore necessary to take into account the stresses that occur in the workpiece. Contactless 3D surface area profilometers should be used when evaluating the surface roughness, as the surface texture of the printed part may vary in different locations and it is therefore not advisable to use profilometers with a contact tool. The greatest unevenness of the surface is achieved on ‘overhangs’ and areas where supports were present. Finishing applications include heat treatments that also significantly alter the internal structure.

II. Finishing Applications

Finishing applications still remain a necessary step in improving the final roughness parameter. Mechanical finishing applications are primarily methods that use a tool or abrasive media to finish a surface and affect a component by mechanical stress. Unconventional technologies do not come into physical contact with the body (no abrasive techniques are required), yet they can deform the surface or structure.

A. Finishing Machining

Machining is the first choice for finishing applications because of its ideal finish and controlled material removal, but they are cost-intensive and have limited machining movement. There are also ‘hybrid additive manufacturing (AM) machines’, combining the features of additive technology and machining in one machine. The principle of A/SM (additive/subtractive manufacturing) is to apply and bond a powder layer (locally) similar to the SLM process. However, after creating several layers (usually 30 layers), a milling tool comes in to level the surface after AM. Thus, the entire process continues until the final part is created. Complex internal structures, such as cooling ducts, etc., can also be created and machined in the A/SM process [1].

B. Grinding and Polishing

These technologies offer a high potential for achieving a smooth surface. We distinguish either manual or machine technologies. Lober et al. [2] compare various post-process technologies in relation to surface quality. One of these was grinding using different grinding wheels. They concluded that the grain size of the grinding wheel had a great influence on the final quality. Individual results are shown in Table I. Grinding achieved very good roughness parameter values;

Jiri Hajnys is with the VSB-Technical University of Ostrava, Czech Republic (e-mail: jiri.hajnys@vsb.cz).

however, it should be taken into account that the grinding was performed only on a flat surface.

C. Blasting

Blasting technology is another mechanical finishing method that reshapes the surface. Morton et al. [3] designed blasting parameters to remove supports. However, their primary research was focused on the effect of blasting media on the final surface. In a blasting experiment on the surface of a component, they made an interesting discovery where delamination occurred in some places by the action of blasting medium containing glass beads. They explain this by blasting causing a so-called peening effect on the surface. Peening leads to local surface finishing plastically, resulting in compressive stresses in the surface layer and tensile stresses in the inner layer. Another observation was made on an aluminum oxide-containing medium. Thanks to this medium it was possible to remove the supporting structures and thus eliminate the manual work, but after removal the surface was still very rough. Blasting was also performed by Lober et al. [2], who reduced the surface roughness by 56% when using glass beads. Similar results were obtained with sand blasting (25-50 μm). They observed that larger sand particles (90-250 μm) lead to better results. Results of the roughness of mentioned experiments are given in Table I.

D. Tumbling

This technology is particularly suitable for shape-intensive components, as tumbling media can also enter the interior. Kaynak and Kitay [4] observe that for trailing tumbling the final quality is determined by the duration of the process. Longer times ensure better roughness of an average of 3.3 μm in 2 hours and 2.7 μm in 4 hours. For vibration tumbling technology, the average value was around 4.1 μm. Another experiment by Morton et al. [5] focused on rotary tumbling at various media and times. The first tested medium was a ceramic body, a part was inserted into it for 24 hours and measurements were taken every 4 hours. Minimal surface changes were observed. The second medium was stainless steel, where the difference was already apparent after 2 hours of tumbling, with a roughly 25% reduction in surface roughness, and 36% after another 2 hours. Corn bodies were the last medium. There were no significant changes in the roughness parameter observed, but the component was optically more bright and shiny.

E. Laser Ablation

Laser ablation is a very flexible process used for micro-finishing of forms and other micro-systems. The essence of the technology lies in the ablation operation causing the material to evaporate due to the interaction between the laser beam and the workpiece. Campanelli et al. [6] studied laser ablation. They designed DOE according to Taguchi, where they varied 4 parameters (laser power, pulse rate, scanning speed, and laser blur) to achieve the best surface roughness values for 316L after SLM manufacturing. They concluded that the surface roughness decreases significantly with the amount of ablation layers taken. Another conclusion was that the lower scanning speed (laser ablation) has no effect on the roughness.

F. Laser Polishing

A contribution from Rosa et al. [7] mainly deals with parameter values and polishing adjustment strategies. However, several conclusions have been drawn from the experiment. The presence of argon in the 3D printing process improves the conditions for laser polishing and thus overall surface integrity. The multi-pass strategy eliminates micro cracks on the surface. The laser polishing process makes it possible to smooth out thin areas created by 3D printing.

G. Plasma and Electrochemical Polishing

These two technologies are similar in many ways, and nearly identical surface roughness results have also been observed [2]. The advantage of plasma polishing is electrolytes with high efficiency and very long service life [8]. Lober et al. [2] achieved a 55% reduction in surface roughness when they applied plasma polishing. Furthermore, their experiment confirmed that plasma and electrochemical polishing are very similar and measured almost the same results. Another finding was that electrochemical polishing fails to remove sintered particles from the surface.

Leaving aside the effect of setting print parameters (which are essential, it is necessary to distinguish between volume and contour scanning), the application of finishing operations remains a necessary step to improve surface roughness parameters in relation to additive technology. It is possible to conclude from the research of expert articles [2], [9] that grinding and polishing should be chosen to reduce roughness. However, account must be taken of the fact that not all surfaces are capable of being treated by grinding, namely internal surfaces and rods with complicated shapes. For this reason, it seems that the best option is to use towing tumbling technology, which is also affordable. From the perspective of unconventional applications, laser polishing is the most advantageous. Literature [5] also shows that if there is a requirement for excellent surface treatment, the part should be oriented so that the surface is as vertical as possible (ideally 90° to the substrate).

III. Material and Experimental Methods

The test material was stainless steel AISI 316L (1.4404), which is a non-magnetic austenitic stainless steel that contains a very low percentage of carbon and is alloyed with chromium, nickel, molybdenum and other negligible elements (see Table II). The steel workpiece was converted by means of gas atomization to a metallic powder which was used for printing the test samples. Powder sieved several times has been used in the sample production, which may affect the resulting surface quality; however, according to [12] the mechanical properties are the same as the virgin powder even after ~ 30 sieves and can be used.

TABLE I
OVERVIEW OF FINISHING APPLICATIONS AFTER 3D PRINTING IN RELATION TO SURFACE ROUGHNESS

Method	Process parameters	Ra [μm]	Equipment	Source
	316L stainless steel			
	Surface after printing – 14.45 ± 0.06 μm			
Finishing machining	v_c = 200 m·min^{-1}, a_p = 0.4 mm, f = 0.15 mm	***1.7***	Renishaw AM250	[4]
Grinding	P80	***2.22 ±0.02***	SLM 250	[2]
	P240	***1.15 ±0.06***	SLM 250	[2]
	P300	***0.52 ±0.03***	SLM 250	[2]
	P500	***0.43 ±0.01***	SLM 250	[2]
	P800	***0.34 ±0.01***	SLM 250	[2]
Grinding and polishing	N/A	***0.05***	Renishaw AM400	[9]
Blasting	30s aluminum oxide, then class 10 glass beads	***3.84***	-	[3]
	30s aluminum oxide mixed with class 13 glass beads	***4.83***	-	[3]
	Coarse blasting of class 20 aluminum oxide (removal of supports)	***9.35***	-	[3]
	glass (50–150 μm)	***8.85 ±0.03***	Renishaw AM400	[9]
	sand (90–250 μm)	***3.87 ±0.06***	Renishaw AM400	[9]
	sand (25-50 μm)	***8.28 ±0.09***	Renishaw AM400	[9]
Tumbling	towing (2 hours)	***3.3***	Renishaw AM250	[4]
	towing (4 hours)	***2.7***	Renishaw AM250	[4]
	Vibratory	***4.1***	Renishaw AM250	[4]
Laser ablation	P = 20 W, v = 700 mm/s, defocus = 2 mm	***5.0***	-	[6]
Laser polishing	E = 525 J·cm^{-2}, P = 210 W, V_f = 000 mm·min^{-1}, Of = 0 mm and overlap (Ov) = 60%.	***0.79***	ALM	[7]
Plasma polishing	96% water and 4% ammonium salts, 80°C, 300V DC	***8.54 ±0.04***	SLM 250	[2]
Electrochemical polishing	65-85% ethanol, 10-15% butoxyethanol and 5-15% water for 4 min, 12V DC	***9.28 ±0.07***	SLM 250	[2]
Magnetic polishing	Magnetic abrasive 80 μm, 60 min	***7.35***	-	[10]

TABLE II
CHEMICAL COMPOSITION OF 316L DECLARED BY THE MANUFACTURER [11]

Element	Mass [%]
Fe	Balance
Cr	18
Ni	14
Mo	3
Mn	< 2
Si	< 1
N	< 0.1
O	< 0.1
P	< 0.045
C	< 0.03
S	< 0.03

The surface roughness parameter Sa was chosen as the evaluation criterion. Research has focused on methods that are not commonly available. All samples were printed under the same conditions (P = 250 W, v_{scan} = 650 mm·with^{-1}, t_{layer} = 50 μm) for final comparison of individual methods. A total of 50 samples were printed covering the entire build-up area. The samples were cuboid with dimensions 20 × 20 × 7 mm. Non-adjacent samples were selected for each method to ensure repeatability and error elimination. In addition, for each method, samples were tested at different parameters, further enhancing the impact of the experiment. Individual finishing applications and their set parameters are shown in Table III. The layout of the samples produced is shown in Fig. 1.

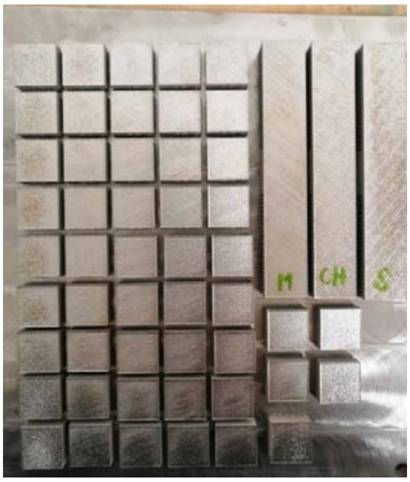

Fig. 1 Sample layout on the base plate

IV. RESULTS AND DISCUSSION

The professional Alicona Infinite Focus 5 was used to evaluate the surface roughness parameters. The main element of the Infinite Focus 5 is precision optics containing objectives that allow different resolution measurements. The instrument ensures high accuracy and repeatability of the whole measurement. This instrument was chosen for contactless measurement of surface irregularities, which is ideal for evaluating components after 3D printing. This is because contact profilometers are unable to accommodate the surface structure of the surface, which may vary from place to place. The surface roughness parameter Sa was chosen as the decisive evaluation criterion and the profile parameter Ra was measured as an additional measurement. 3D surface parameters are defined by the standard ČSN EN ISO 25178-2.

End mill (12 mm diameter) was used for face milling. Since machining creates a completely new surface, very good roughness parameters can be expected. The individual measurement results for the different machining parameters are shown in Table III. The mill has left traces that can be seen in Fig. 2.

When applying the tumbling finishing operation, the determining factors of the surface roughness were the tumbling time and the abrasive media used. Namely, it was disc centrifugal wet tumbling. This technology mechanically aligns the surface peaks into a plane. The roughness parameter improved with the time spent in the machine up to 120 min, after which the surface no longer improved, see Fig. 3.

Sand blasting refines the surface and imparts internal stress to it by external mechanical force. In terms of surface roughness, it can be stated that the best values are obtained in the wet process with medium pressure and large fraction, see Fig. 4.

The essence of shot peening is very similar to the previous sanding operation; again, no new surface is formed, but the existing surface is refined. Due to the impact of the balls, the surface is hardened and the roughness is improved, when the surface micro-irregularities are plasticized. Fig. 5 shows traces of the balls.

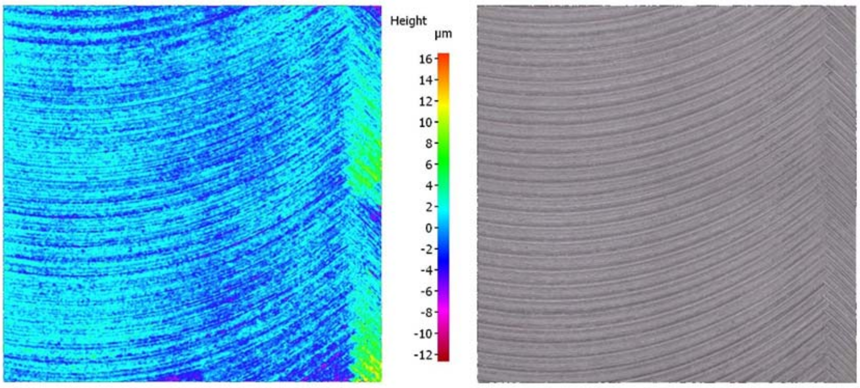

Fig. 2 Face milling

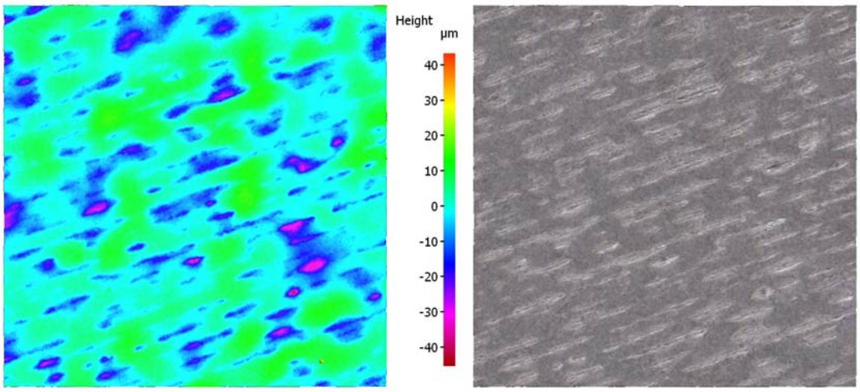

Fig. 3 Tumbling

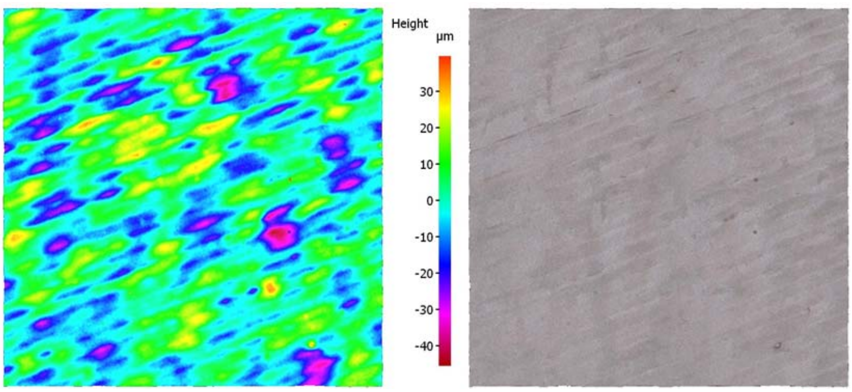

Fig. 4 Sandblasting

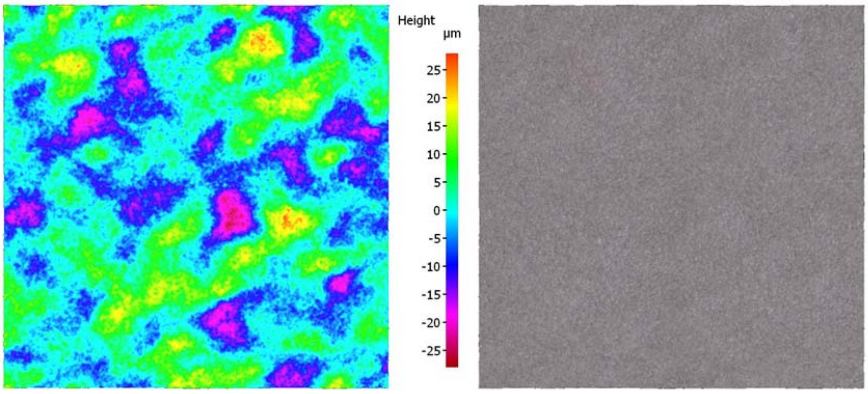

Fig. 5 Shot peening

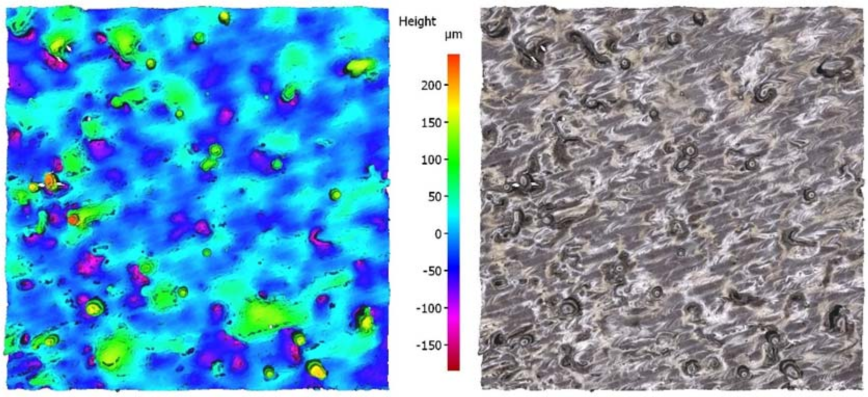

Fig. 6 State after printing

TABLE III
SELECTED FINISHING APPLICATIONS AND MEASURED RESULTS

Method	Parameters	Sa [µm]	Sz [µm]	Ra [µm]	Rz [µm]
Face milling	v_c = 100 m·min^{-1}, a_e = 11 mm, f_z = 0.1 mm, a_p = 0.5 mm	1.506	20.569	1.234	11.028
	v_c = 150 m·min^{-1}, a_e = 11 mm, f_z = 0.1 mm, a_p = 0.5 mm	1.623	23.369	1.291	13.414
	v_c = 200 m·min^{-1}, a_e = 11 mm, f_z = 0.1 mm, a_p = 0.5 mm	1.521	25.077	1.390	12.244
	v_c = 250 m·min^{-1}, a_e = 11 mm, f_z = 0.1 mm, a_p = 0.5 mm	1.380	20.619	1.078	9.644
	v_c = 100 m·min^{-1}, a_e = 11 mm, f_z = 0.05 mm, a_p = 0.5 mm	1.512	28.467	1.334	11.155
	v_c = 150 m·min^{-1}, a_e = 11 mm, f_z = 0.05 mm, a_p = 0.5 mm	1.402	25.506	1.187	11.054
	v_c = 200 m·min^{-1}, a_e = 11 mm, f_z = 0.05 mm, a_p = 0.5 mm	1.344	31.826	1.233	11.672
	v_c = 250 m·min^{-1}, a_e = 11 mm, f_z = 0.05 mm, a_p = 0.5 mm	1.117	22.694	0.921	8.923
Tumbling	t = 60 min, ceramic media	7.658	103.413	8.585	50.966
	t = 120 min, ceramic media	4.299	57.628	5.506	33.067
Tumbling	t = 180 min, ceramic media	3.850	78.797	4.435	28.565
	t_1 = 180 min, ceramic media; t_2 = 60 min. plastic	4.986	74.520	5.623	35.942
Sandblasting	p = 0.25 MPa; Rossler Media	6.264	74.496	6.189	48.241
	p = 0.5 MPa; fraction = 180/220	5.984	67.477	6.153	37.462
	p = 0.4 MPa; fraction = 240/280	5.695	69.235	6.020	43.326
Beading	p = 0.35 MPa	3.459	35.630	5.080	31.447
After printing	P = 250 W, v_{scan} = 650 mm · s^{-1}, t_{layer} = 50 µm	12.875	406.623	27.040	239.635

For comparative purposes, 5 samples were selected, which remained in the state after printing without further adjustments. The unevenness of the surface and the individual laser scanning paths is shown in Fig. 6. Placement in the working chamber also affects the quality of the surface.

An experiment conducted to optimize the surface roughness revealed that, as expected, the best roughness parameters were achieved through a face milling operation. Milling was also the only operation that created a new surface and removed a layer of material. For this reason, when applying it, it is necessary to think about creating additions. Other methods with satisfactory results are shot peening and tumbling, which should be the focus of further research. Tumbling is particularly suitable for 3D printing components, as tumbling media are able to reach even complex shapes and, after changing to polishing bodies, achieve a high surface gloss. Surface quality after tumbling depends on the process time. On the other hand, the worst results were measured with sandblasting. Sandblasting by its very nature only removes a layer of e.g. paint or corrosion and is therefore not suitable for surface improvement. All measured results are shown in Table III.

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J. Hajnys is with the VSB - Technical University of Ostrava, Faculty of Mechanical Engineering, 70800, Ostrava, Czech Republic (phone: +420737931676; e-mail: jiri.hajnys@vsb.cz).