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Enhancing surface finish of additively manufactured titanium and cobalt chrome elements using laser based finishing

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Abstract

Additive manufacturing (AM) offers the possibility of creating a complex free form object as a single element, which is not possible using traditional mechanical machining. Unfortunately the typically rough surface finish of additively manufactured parts is unsuitable for many applications. As a result AM parts must be post-processed; typically mechanically machined and/or and polished using either chemical or mechanical techniques (both of which have their limitations). Laser based polishing is based on remelting of a very thin surface layer and it offers potential as a highly repeatable, higher speed process capable of selective area polishing, and without any waste problems (no abrasives or liquids).

In this paper an in-depth investigation of CW laser polishing of titanium and cobalt chrome AM elements is presented. The impact of different scanning strategies, laser parameters and initial surface condition on the achieved surface finish is evaluated.

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH

Keywords: Additive manufacturing; laser polishing; laser finishing

1. Introduction

In recent past additive manufacturing (AM) has become a very intriguing solution for a lot of different areas of life due to its capability to overcome construction constraints that limit traditional manufacturing techniques as

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additive manufacturing is capable of creating three dimensional, free form surfaces. Unfortunately the surface finish produced by additive manufacturing might not be sufficient for certain specific applications, such as medical implants need that require a smooth surface to limit bacteria growth and prevent tissue damage. Currently AM parts are polished using either mechanical or electrochemical polishing, but both of those methods have their limitations. When considering mechanical polishing it struggles with highly complex free form parts and electrochemical polishing is insufficiently selective for creating highly customized microscale polished areas. Moreover both of these methods produce debris like abrasives or fluids. Laser polishing offers a potential solution without these limitations hence a number of research groups have investigated laser polishing of parts created with different additive manufacturing techniques as selective laser melting, sintering and laser metal deposition (Dadbakhsh, Hao, & Kong, 2010; J. A. Ramos; Lamikiz, Sanchez, et al., 2007; Lamikiz, Sánchez, López de Lacalle, & Arana, 2007; Rosa, Mognol, & Hascoët, 2015; Yasa, Deckers, & Kruth, 2011). In our research we present an investigation to determine optimal parameters of laser polishing of titanium and cobalt chrome parts created using selective laser melting. The influence of different laser parameters, various scanning strategies and initial surface condition is assessed.

2. Experimental setup

The laser used for polishing was a fibre laser manufactured by SPI, G3 40WH operating at the wavelength of 1064 nm with maximum operating power is 40 W. The beam profile is a type H (near flat top) with a beam quality factor, $M^2 = 3.1$. The beam is focused using an f-theta lens with focal length of 160 mm, generating a 40 µm diameter focal spot. However, during all of the experiments this beam was used out of focus to provide a divergent beam of 80 µm diameter. To prevent oxidization during the process, the samples were placed in a gas cell filled with argon. After processing, the samples were investigated using either a white light interferometer (Zygo NewView 5000), a surface profilometer (Alicona Infinite Focus) or an optical microscope (Leica DM6000 B). To eliminate waviness during the analysis, the surface was investigated in the different spatial frequency domains: (i) macro- ($\lambda \geq 80$ µm); (ii) meso- (80 µm $> \lambda >$ 10 µm); and (iii) micro-roughness ($\lambda \leq 10$ µm).

3. Experimental work

Experimental work focused on poslishing of lat surfaces of two different materials: titanium alloy – Ti6AL4V and cobalt chromium – CoCr. All of the parts were build using Renishaw AM250 SLM machine. Powder diameter was 10 – 20 µm with layer thickness of 30 µm. During the experimental work different scanning strategies were investigated to find the optimal scanning parameters for polishing of additively manufactured parts.

3.1. Ti6Al4V

An initial set of experiments was focused on testing whether an ablative process used before the laser polishing process provides any improvement to the processed part. The concept is to remove larger scale structures and as a result decrease the value of macro-roughness. To compare the influence of such a process both samples (with and without ablative process) were polished using continuous wave (CW) laser radiation using 1,2 and 3 polishing cycles (1 cycle = 4 laser polishing passes, at different angles (18°, 71°, 0°, 45°). Ablation process consisted of 8 laser passes - 250 ns pulse duration, 40 W power, 80 µm spot size and 75% pulse and live overlap. Laser polishing was carried out with 40 W laser power, 7.1 kJ/cm^2 energy density, 75% line overlap with 80 µm spot size. Fig. 1 shows values of roughness for each processed area and Fig. 2**Fig. 1** shows optical microscopy images of processed areas.

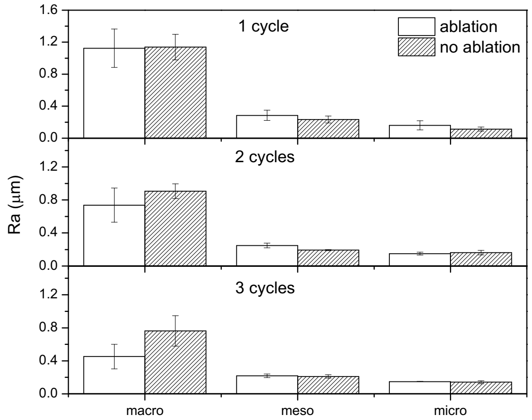


Fig. 1. Obtained values of micro-, meso- and macro- roughness for CW laser polishing of Ti6Al4V with and without ablation beforehand.

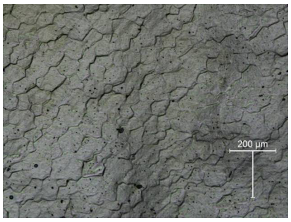
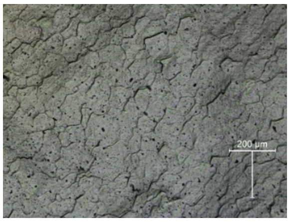
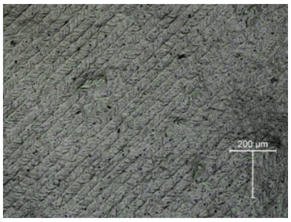
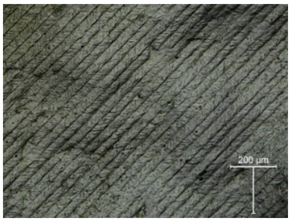
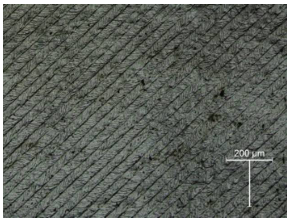
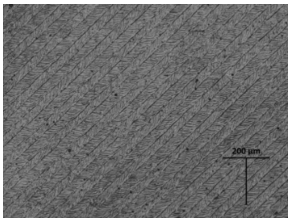
	1 cycle (4 scans) 18°, 71°, 0°, 45°	2 cycles (8 scans) 2 x 18°, 71°, 0°, 45°	3 cycles (12 scans) 3 x 18°, 71°, 0°, 45°
Only CW laser polishing			
Ablation + CW laser polishing			

Fig. 2. Optical microscopy images of surface obtained by CW laser polishing with and without pre-processing (laser ablation).

Analysis of the surface roughness reveals that the initial ablative process does indeed remove larger scale structures and decrease the value of macro-roughness. After three full laser processing cycles the value of roughness for the processed samples is half of that without the ablative process. The value of roughness in the micro and meso regimes is however no different. An alternative approach may be simply to polish with a more powerful laser, which would allow a larger spot size to be used, providing a larger melt pool, and hence smoothing of the larger scale features.

An additional set of experiments was carried out to compare a few different scanning strategies, with three different approaches tested: (i) simple raster scanning (0°, 0°, 0°, 0°); (ii) perpendicular scanning directions (0°, 90°, 0°, 90°); and (iii) a scanning approach using the halftone printing angles (18°, 71°, 0°, 45°). The best surface quality was achieved using the halftone printing scanning pattern. Fig. 3 shows the measured roughness values as a function of spatial wavelength for the surface polished using halftone scanning pattern and 3 laser polishing cycles. Application of the halftone scanning pattern provides a decrease in roughness of up to 85% when compared to unpolished surface.

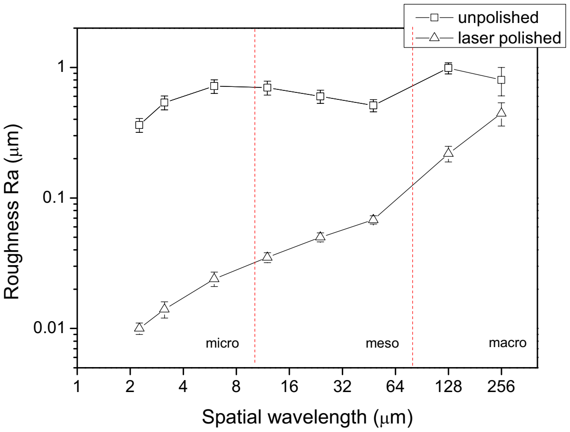


Fig. 3. Value of roughness achieved using 3 laser polishing cycles and halftone scanning pattern as a function of spatial wavelength. Spatial wavelength used to filter out the waviness of the surface: micro-roughnes – 2.25, 3.125 and 6 μm; mesoroughness: 12, 24 and 48 μm; macro-roughness: 128 and 256 μm.

4. Cobalt-chrome

The second material investigated is cobalt chrome. In this case the parts were L-brackets, specially selected to provide both top and bottom angled surfaces, and hence a range of different surface finishes – see Fig. 4. , with the best quality being on the top surface; the bottom surface includes grains of powder that were only partially melted. Similar scanning strategies were tested as with Ti6Al4V; in this case four different approaches were used: (i) raster scan with alternating direction (0°, 180°, 0°, 180°); (ii) perpendicular scanning directions (0°, 90°, 0°, 90°); (iii) scanning with increasing angle (0°, 45°, 90°, 135°); and (iv) halftone printing angles (18°, 71°, 0°, 45°). Laser processing parameters were kept constant during laser polishing of both the top and bottom surfaces. The energy density was set at 3 kJ/cm^2, scanning speed of 16.5 mm/s, power of 40 W and spot size of 80 μm. Fig. 5 shows the topography of the unprocessed and laser polished surfaces (using different scanning strategies) of the bottom surface of the AM CoCr part. **Fig. 6**Fig. 6, meanwhile, shows the topography of the unprocessed and laser polished surfaces (using different scanning strategies) of the bottom surface of the AM cobalt-chrome part. The size of the polished area was 5 mm by 5mm.

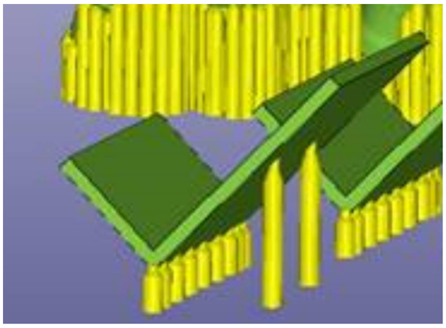
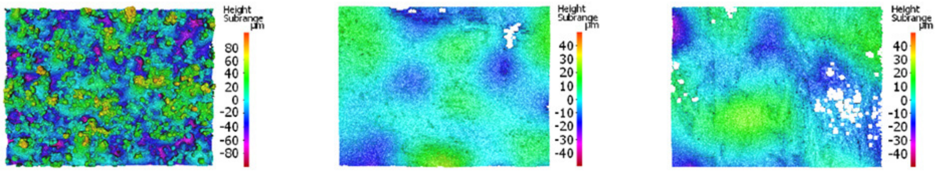


Fig. 4. Orientation of the AM parts during the SLM.

Unprocessed surface | Raster scan with alternating direction 0°, 180°, 0°, 180° | Perpendicular scanning directions 0°, 90°, 0°, 90°



Scanning with increasing angle 0°, 45°, 90°, 135° | Scanning imitating halftone printing 18°, 71°, 0°, 45°

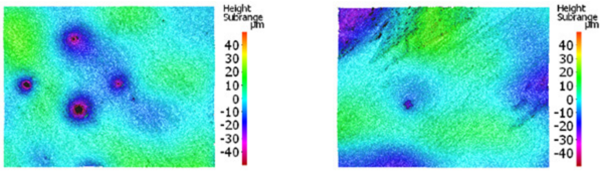
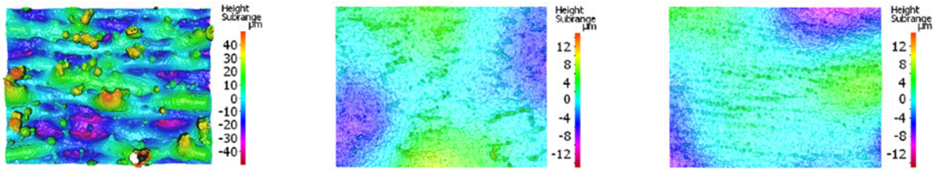


Fig. 5. Surface profiles of the unprocessed initial surface (bottom side of the sample - worse) and for laser polished areas after 4 consecutive laser passes using respective laser scanning approaches. Note that the surface height (colour) scales are different for each image.

Unprocessed surface | Raster scan with alternating direction 0°, 180°, 0°, 180°, | Perpendicular scanning directions 0°, 90°, 0°, 90°



Scanning with increasing angle 0°, 45°, 90°, 135° | Scanning imitating halftone printing 18°, 71°, 0°, 45°

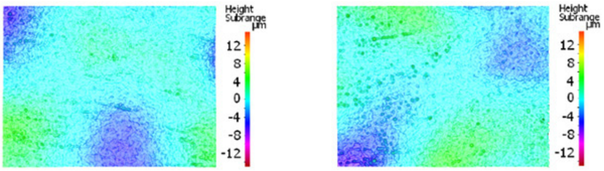


Fig. 6. Surface profiles of the unprocessed initial surface (top side of the sample - better) and for laser polished areas after 4 consecutive laser passes using respective laser scanning approaches. Note that the surface height (colour) scales are different for each image.

The lowest value of surface roughness (R_a) was achieved in each case when the scanning pattern imitating halftone printing was used 4 consecutive times. Table 1 shows the values of micro-, meso- and macro-roughness for both top and bottom surfaces of the cobalt chrome AM part. When considering bottom surface of the AM part, with worst initial surface quality, it was possible to decrease the micro-roughness by 90%, meso-roughness by 93% and macro-roughness by 96%. As for the top surface of the AM part, with better initial quality it was possible to decrease value of surface micro-roughness by 85%, meso-roughness by 90% and macro-roughness by 95%.

Table 1. Value of roughness (Ra) after four laser scans at halftone printing angles.

	Bottom surface – Worse initial surface quality			**Top surface – better initial surface quality**		
	Pre-polishing	Post-polishing	Improvement	Pre-polishing	Post-polishing	Improvement
Micro-roughness (cut-off 5 µm)	229 ± 46 nm	23 ± 1.8 nm	90%	76±34 nm	11.7±1.02 nm	85%
Meso-roughness (cut-off 50 µm)	3.91 ± 0.5 µm	290 ± 30 nm	93%	1.36±0.595 µm	136±10 nm	90%
Macro-roughness (cut-off 250 µm)	12.89 ± 3.1 µm	570 ± 40 nm	96%	5.13±1.54 µm	234±30 nm	95%

5. Conclusions

Results of CW laser polishing of additively manufactured cobalt-chrome and titanium are presented. For both of the materials the best results were achieved when using a scanning pattern that imitates angles used for halftone printing (18°, 71°, 0°, 45). For the titanium (Ti6Al4V) part it was possible to decrease the roughness up to 85% of the initial value. For cobalt-chrome parts the surface roughness was decreased by 85% to 96% depending on the spatial filtering chosen and the initial surface finish. Even with initial surfaces of significantly different surface quality (3 times difference in Ra), identical parameters worked best in each case; however a better quality finish could be obtained with the higher quality initial surface.

Acknowledgements

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References

Dadbakhsh, S., Hao, L., & Kong, C. Y. (2010). Surface finish improvement of LMD samples using laser polishing. Virtual and Physical Prototyping, 5(4), 215-221. doi: 10.1080/17452759.2010.528180

J. A. Ramos, D. L. B., J. J. Beaman. Surface Over-Melt during Laser Polishing of Indirect-SLS Metal Parts. Paper presented at the Rapid Prototyping Technologies.

Lamikiz, A., Sanchez, J. A., Lacalle, L. N. L. D., Pozo, D. D., Etayo, J. M., & Lopez, J. M. (2007). Laser polishing techniques for roughness improvement on metallic surfaces. International Journal of Nanomanufacturing, 1(4), 490-498. doi: doi:10.1504/IJNM.2007.014568

Lamikiz, A., Sánchez, J. A., López de Lacalle, L. N., & Arana, J. L. (2007). Laser polishing of parts built up by selective laser sintering. International Journal of Machine Tools and Manufacture, 47(12–13), 2040-2050. doi: http://dx.doi.org/10.1016/j.ijmachtools.2007.01.013

Rosa, B., Mognol, P., & Hascoët, J.-y. (2015). Laser polishing of additive laser manufacturing surfaces. Journal of Laser Applications, 27(S2), S29102. doi: doi:http://dx.doi.org/10.2351/1.4906385

Yasa, E., Deckers, J., & Kruth, J. P. (2011). The investigation of the influence of laser re-melting on density, surface quality and microstructure of selective laser melting parts. Rapid Prototyping Journal, 17(5), 312-327. doi: doi:10.1108/13552541111156450