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Micro-blasting of 316L tubular lattice manufactured by laser powder bed fusion

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Abstract

The extraordinary capabilities of Laser powder bed fusion (L-PBF) technology such as customized manufacturing, short production cycle and ability to generate complex structures make L-PBF a perfect candidate technology for implant fabrication, e.g. hip bones, dental crowns, spine truss, etc. However, due to its nature of a layer-by-layer melting and solidification process, defects such as partially bonded particles, balling effect, staircase effect and ripple effect, greatly deteriorate the dimensional accuracy and surface finish of the L-PBF parts. Thus, appropriate post-processing is essential to improve form accuracy and surface quality of the L-PBF parts. To date, conventional finishing techniques such as machining, mechanical polishing, and electrochemical polishing have been applied for finishing L-PBF parts. However, more capable post-processing methods with high accessibility and efficiency are strongly demanded for high complexity of L-PBF parts such as tubular lattice structure which could be used as cardiovascular stents in medical implantology. To remove the partially bonded particles and balling on the L-PBF tubular lattice structure for further post-processing, automatic micro-blasting device was developed in this research. A systematic experimental work was conducted to investigate the effect of micro-blasting pressure, gap and coverage on dimension accuracy and material removal of L-PBF tubular lattice. The lattice diameter and strut width are evaluated and analysed. Material removal is characterized in micro-blasting as well for the sake of confirming proper tolerance in design phase.

Keywords: Post processing, additive manufacturing, sand blasting, surface finish, lattice structure

1. Introduction

Additive manufacturing (AM) technology makes it possible that complex components could be fabricated in a customized approach, e.g. tubular lattice structure used as cardiovascular stents. However, some disadvantages still impede further application of AM, such as poor surface finish and inadequate accuracy, which calls for attention in both academia and industry. Some techniques have been employed to address this challenge, such as chemical etching [1], magnetic abrasive finishing [2], vibration-assisted conformal finishing [3] etc. Löber *et. al* [4] compared different post processing methods for selective laser melted (SLM-ed) 316L cubes and concluded that the combination of mechanical pre-treatment and an electro or plasma polishing would result the best surface finishing. However, little research has been done on finishing complex AM-ed components. Since abrasive blasting is capable of modifying surface geometry and residual stress profile for complicate parts [5], micro abrasive blasting will be employed to finish tubular lattice structure fabricated by L-PBF in this paper, and the effect of blasting pressure, gap and coverage on material removal and dimension accuracy will be investigated.

2. Design of experiment

2.1. Tubular lattice structure design and fabrication

The design of tubular lattice structure is shown in Figure 1(a). The outer diameter (OD) is 4.8 mm and inner diameter (ID) is 4.2 mm. The strut cross section is a part of a ring with 150 µm width and 300 µm thickness, as seen in Figure 1(b). A 6 mm-diameter and 3 mm-height base was designed for clamping in micro-blasting process. The tubular lattice structures were printed by an EOS M 290 laser metal printer with 316L stainless steel powder. The printing parameters are listed Figure 1(c). The printed lattice structure is shown in Figure 1(d) with a close-up of struts. Totally 50 samples were printed and labelled by #1, #2, ... #50. The printed lattices were detached from substrate manually and no heat treatment was conducted after printing.

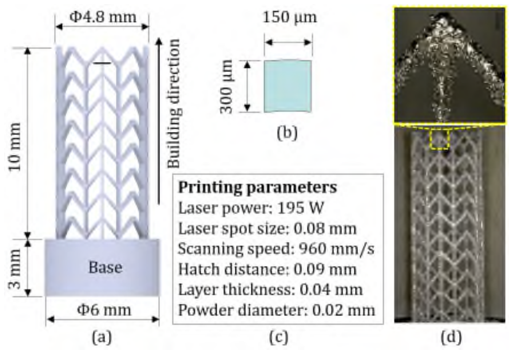

Figure 1. Designed and as-printed lattice structure: (a) tubular lattice structure and its dimension; (b) cross section of struts; (c) printing parameters; (d) as-printed lattice structure and a close-up of struts

2.2. Factorial design of experiments

An automatic micro-blasting setup based on IEPCO PEENMATIC 750 micro-blaster was developed, as seen in Figure 2. The tubular lattice was mounted on a motor with a constant rotation speed. Meanwhile, the motor could move linearly with a slide so that all the surface of lattice could be processed. Ceramic balls (spherical abrasives) with an average diameter of 150-200 µm was used and the SEM image was also shown in Figure 2. A 3^3 full-factorial experiment (Table 1) was designed to investigate the effect of three factors, i.e. gap, air pressure and coverage, on material removal and strut width reduction of L-PBF lattice in micro-blasting process. The coverage indicates the process cycles, e.g. a 100% coverage means the sample was micro-blasted for a whole cycle from right to left. The level of factors was chosen to ensure the partially bonded particles on the lattice could be removed while no apparent damage was seen on the lattice structure. The lattice mass, lattice diameter and strut width were measured and recorded before and after micro-blasting process. Surface topography was observed under a Keyence digital microscope VHX-1000. This microscope was also used to measure lattice diameter and strut width.

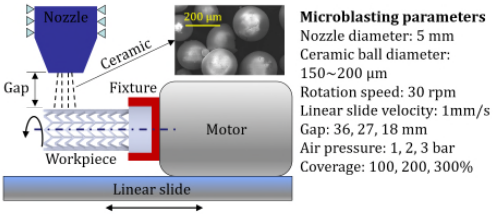

Figure 2. Schematic diagram of developed micro-blasting setup

Table 1 Design of experiment: 3^3 full factorial experiment

Gap (mm)	Pressure (bar)	Coverage (%) 100	200	300	Gap (mm)	Pressure (bar)	Coverage (%) 100	200	300
36	**1**	#1	#2	#3	**27**	**3**	#16	#17	#18
36	**2**	#4	#5	#6	**18**	**1**	#19	#20	#21
36	**3**	#7	#8	#9	**18**	**2**	#22	#23	#24
27	**1**	#10	#11	#12	**18**	**3**	#25	#26	#27
27	**2**	#13	#14	#15					

3. Results and discussion

3.1. Printing accuracy

The printing accuracy is evaluated in terms of lattice diameter and strut width, as seen in Figure 3(a) and (b). The results show that the average outer diameter measured is 4,731 μm which is only 1.4% lower than the designed value of 4,800 μm. This might be owing to the shrink after printing. On the other hand, the measured strut width is 241 μm which is 60.7% larger than designed value of 150 μm. This may be due to the fact that melting poor diameter is usually much larger than laser spot size.

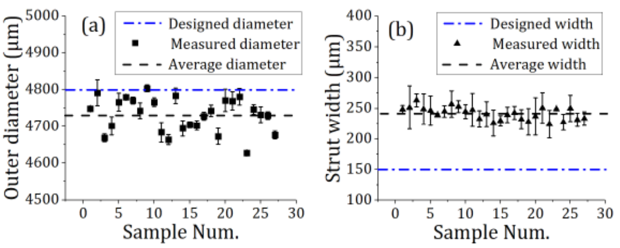

Figure 3. Comparison between designed and measured dimension: (a) tubular lattice outer diameter; (b) strut width

3.2. Analysis of variance for material removal and strut width

After micro-blasting, the average reduction of lattice outer diameter and strut width were 83 μm and 32 μm, respectively. Analysis of variance (ANOVA) was conducted to reveal the significant factors that affect material removal and strut width, with confidence level of 95%. The results are shown in Table 2 and 3. It is found that only factor B-gap has significant influence on mass loss and strut width reduction.

Table 2 ANOVA results for mass loss

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	306.28	6	51.05	2.04	0.1076
A-Coverage	21.14	2	10.57	0.4222	0.6613
B-Gap	217.08	2	108.54	4.33	**0.0273**
C-Pressure	68.05	2	34.03	1.36	0.2797
Residual	500.82	20	25.04		
Cor Total	807.10	26			

Table 3 ANOVA results for strut width reduction

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	3173.16	6	528.86	5.49	**0.0017**
A-Coverage	20.18	2	10.09	0.1047	0.9011
B-Gap	2864.23	2	1432.12	14.86	**0.0001**
C-Pressure	288.75	2	144.37	1.50	0.2476
Residual	1927.66	20	96.38		
Cor Total	5100.82	26			

3.3. Strut damage analysis

It is found that some struts were damaged after micro-blasting under microscope observation, as shown in Figure 4. The conditions leading to strut damage are highlighted by a symbol "×" in Table 4. It could be seen that the strut damage is mainly due to high air pressure. In this regard, it is suggested that lower pressure should be used during the micro-blasting of such fragile lattice structure generated by L-PBF process.

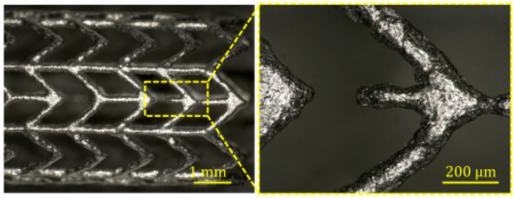

Figure 4. Strut damage after micro-blasting (Sample #6)

Table 4 Micro-blasting conditions leading to strut damage

Gap (mm)	Pressure (bar)	Coverage (%) 100	200	300	Gap (mm)	Pressure (bar)	Coverage (%) 100	200	300
36	**1**	#1	#2	#3	**27**	**3**	#16	**#17×**	**#18×**
36	**2**	**#4×**	**#5×**	**#6×**	**18**	**1**	#19	#20	#21
36	**3**	**#7×**	**#8×**	**#9×**	**18**	**2**	#22	#23	#24
27	**1**	#10	#11	#12	**18**	**3**	**#25×**	**#26×**	**#27×**
27	**2**	#13	#14	#15					

4. Summary

This work investigated the effect of micro-blasting parameters on material removal and strut width reduction. A 3^3 full-factorial experiment was conducted. The results showed that the average of as-printed outer diameter is only 1.4% lower than designed one while the measured strut width is 60.7% larger than designed value. The ANOVA results indicated that only gap between blaster nozzle and workpiece has significant influence on strut diameter reduction. Besides, pressure is the most significant factor leading to strut damage. In the future, theoretical work will be done to study the material removal mechanism of micro-blasting process on L-PBF parts.

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