Hybrid finishing of the additively manufactured tubular lattice structure for medical application

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Additive manufacturing (AM) has shown great potential in creating lattice structures with unique mechanical properties that are difficult to achieve through traditional manufacturing processes. However, the intrinsic surface defects in AM lattice structures can have a significant impact on their properties, including inferior mechanical strength, reduced specific energy absorption, and fatigue life. Therefore, it is essential to improve the surface quality of AM lattice structures to ensure their optimal performance and reliability. Existing finishing methods such as sandblasting, chemical etching, and electrochemical polishing may encounter problems such as inaccessibility to the internal lattice surfaces, uneven removal, or environmental issues. The finishing of lattice structures poses a unique set of challenges due to the fragility of the thin structures and the limited accessibility of conventional finishing tools. Hence, this paper aims to develop a novel hybrid finishing method for AM tubular lattice based on magnetic abrasive finishing and dry electrochemical polishing. Results have shown that the surface finish can be improved by more than 70% and the resultant surface is free from the major defects including the partially bonded particles and staircase effect. This study advances the surface finishing techniques of AM complex structures and provides an alternative post-processing method for the AM industry.

NOMENCLATURE

AM = Additive manufacturing
ECP = Electrochemical polishing
MAF = Magnetic abrasive finishing
SEM = Scanning electron microscopy

1. Introduction

Additive manufacturing (AM) has shown great potential in creating lattice structures with unique mechanical properties that are difficult to achieve through traditional manufacturing processes [1–6]. One of the key advantages of AM lattice structures is their high strength-to-weight ratio, which makes them ideal for applications that require lightweight yet strong materials [3,7,8]. Additionally, these lattice structures exhibit excellent shock absorption [9] and can provide on-demand stiffness control [10]. Furthermore, the increased surface area of AM lattice structures makes them suitable for use in various industrial and engineering applications [11,12]. However, it is important to note that the intrinsic surface defects in AM lattice structures can have a significant impact on their properties, including inferior mechanical strength, reduced specific energy absorption and fatigue life [13–15]. Therefore, it is essential to improve the surface quality of AM lattice structures to ensure their optimal performance and reliability [16].

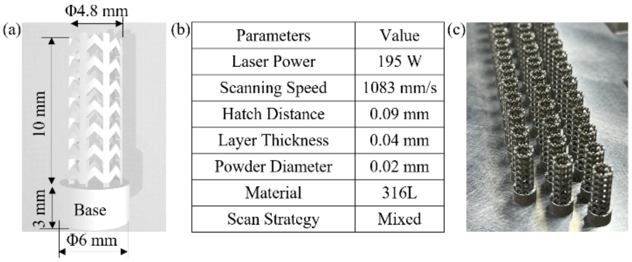
Existing finishing methods are mainly sandblasting [17,18], chemical etching [19] and electrochemical polishing [13,20,21]. Sandblasting or shot peening can effectively remove the partially bonded particles and the balling effect. It usually results in surface roughness from 1 to 5 μm Ra. However, it is difficult to access the internal lattice surfaces. And improper parameters may cause the beak and damage to the lattice. Chemical etching can remove some of the particles and usually results in uneven removal. Electrochemical polishing with optimized parameters may yield a good surface finish, but it has difficulty polishing internal surfaces.

The finishing of lattice structures poses a unique set of challenges due to the fragility of the thin structures and the limited accessibility of conventional finishing tools [22], especially the tubular lattice with a typical application as coronary stent implants. Hence, these paper aims to develop innovative and hybrid surface finishing techniques for AM metallic lattice structures. By achieving this goal, the project would contribute to the advancement of surface finishing technologies and the improvement of the quality and efficiency for AM components.

2. Methodology

2.1 Sample preparation

This work investigated novel finishing methods for tubular lattice structures which have potential applications as stent implants. The design of the tubular lattice is shown in Fig. 1(a). It has a diameter of 4.8 mm and a length of 10 mm. The strut cross-section is a 500 µm × 500 µm square. A 6-mm diameter and 3-mm height base were designed for clamping in the post-processing stage. The tubular lattice structures were printed vertically by an EOS M290 laser metal printer with 316L stainless steel powder. The printing parameters are listed in Fig. 1(b). The printed lattice structures are shown in Fig. 1(c). The printed lattices were detached from the substrate manually and no heat treatment was conducted after printing.



Parameters	Value
Laser Power	195 W
Scanning Speed	1083 mm/s
Hatch Distance	0.09 mm
Layer Thickness	0.04 mm
Powder Diameter	0.02 mm
Material	316L
Scan Strategy	Mixed

Fig. 1 Design and fabrication of the tubular lattice structure: (a) design; (b) printing parameters and (c) printed tubular lattices on the substrate.

2.2 Finishing processes

Magnetic abrasive finishing (MAF) was employed to process the AM tubular lattice structure due to its high conformability and flexibility. The working principle of the MAF is shown in Fig. 2(a). A magnetic abrasive brush made of steel grit (G40, LESOON) is formed between two magnetic poles. The sample rotates and moves back and forth in the magnetic abrasive brush. The magnetized steel grits with high hardness and sharp corners serve as multiple-edge tools to remove the materials on the tubular lattice structure. The experimental setup based on a 3-axis motorized stage is presented in Fig. 2(b) and the zooming-in image of the functional part is shown in Fig. 2(c). The magnetic pole has a dimension of 20 mm × 10 mm × 5 mm and is an N35 grade NdB permanent magnet. The gap distance between the two poles is 10 mm. The rotation speed of the tubular lattice is 600 rpm and the feeding rate is 100 mm/min. The steel grits have an average diameter of 425 µm. Similar to the planar lattice, the surface roughness and the material removal in mass are measured by a 3D laser confocal microscope (Olympus OLS5000) and a precision balance (A&D GR200) after every 1- or 2-min polishing.

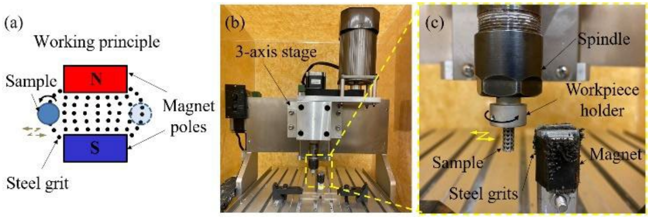


Fig. 2 Magnetic abrasive finishing of AM tubular lattice: (a) the schematic working principle of magnetic abrasive finishing; (b) the developed MAF setup on a 3-axis stage and (c) the functional part of the MAF setup showing the zooming-in image of the workpiece, steel grit and the magnet.

3. Results and discussion

The surface roughness and material removal in mass are plotted against the polishing time, as shown in Fig. 3. The material removal is large and the surface roughness decreases rapidly in the first 3 min polishing time. As the polishing time increases, the surface roughness tends to be stable and reaches a plateau of 2.35 µm Sa in the 18th min. This result is consistent with other abrasive finishing processes in the literature [23,24]. Fig. 4 shows the digital image of the tubular lattice before and after MAF. The top half of the tubular lattice becomes shiny while the bottom half is still gloomy. This is because the bottom half of the tubular lattice may not fully contact the magnetic abrasive brush, which may be addressed by using longer magnetic poles. The SEM images show that most partially bonded particles are removed after MAF and abrasive scratches are generated on the sample surface. The sample after MAF shows a much smoother surface than that of the as-printed sample, demonstrating the effectiveness of the developed MAF.

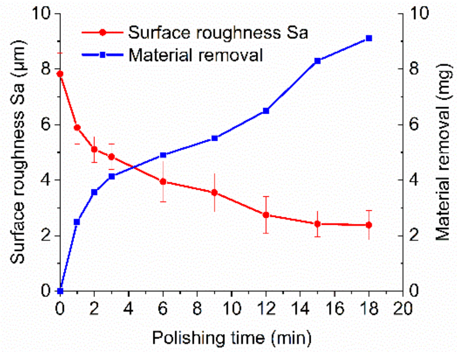


Fig. 3 Surface roughness and material removal in mass against the polishing time for the tubular lattice during MAF.

To benchmark the effect of various post-finishing methods on the surface quality improvement of the AM lattice structures, sandblasting and dry electrochemical polishing (ECP) processes were employed. The sandblasting process was conducted on IEPCO PEENMATIC 750 with an air pressure of 2 Bar and 200-µm steel balls. The ECP was conducted on GPAINNOVA DLyte 1+Ti dry electrochemical polishing machine with stainless steel polishing media. The polishing time was set as 40 min. The finishing results are shown in Fig. 5. The blasting can achieve a surface roughness of 2.77 µm Sa. The direct ECP has a neglectable effect on surface finish improvement while the surface pro-processed by blasting and MAF can reach <2 µm surface roughness after ECP. Moreover, the MAF + ECP produces the best surface finish. The above results demonstrate that MAF is a promising candidate for finishing AM-ed tubular lattice structures.

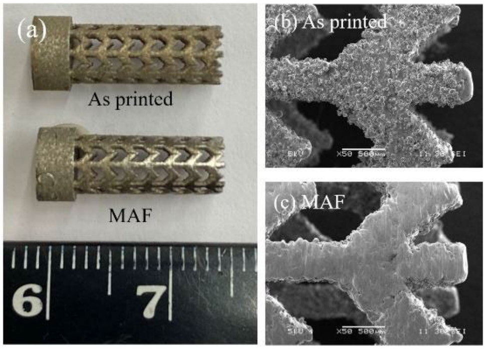


Fig. 4 Tubular lattice before and after MAF: (a) a digital image of the overall sample; (b) the SEM image of the sample tip before MAF and the SEM image of the sample tip after MAF.

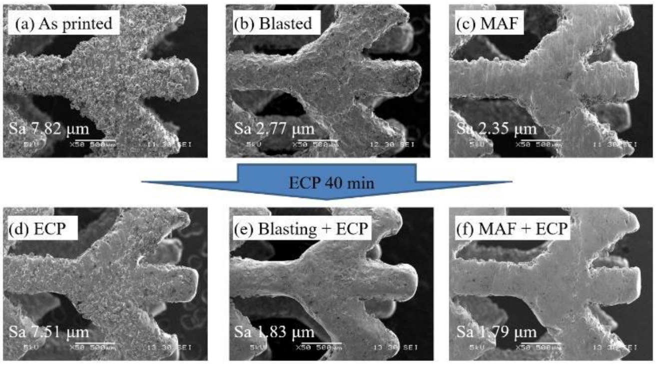


Fig. 5 SEM images of the tubular lattice by different finishing methods: (a) as printed; (b) blasted; (c) MAF; (d) ECP; (e) blasting + ECP and (f) MAF+ECP.

The benchmarking of different finishing processes for AM-ed lattice structure is presented in Table 1. ECP could not be directly applied for as-printed lattice structures due to its low material removal rate. Blast is a cost-effective and efficient method as the pre-finishing technique for ECP. MAF outperforms blasting regarding the achievable surface finish. Most importantly, MAF+ECP leads to the best surface finish as low as 1.79 μm Sa among all evaluated finishing methods.

Table 1 Benchmarking of techniques to finish AM-ed lattice structures

Processes	A	B	C	D	E
Sa (μm)	7.51	2.77	1.83	2.35	1.79
Improvement	4%	64%	76%	70%	77%
Efficiency	+	++++	++++	+++	+++
Cost	High	Medium	High	Low	High
Environmentally friendly	+	++	+	+++	+

*A = ECP, B = Blasting, C = Blasting + ECP, D = MAF, and E = MAF + ECP

3. Conclusions and outlook

In this paper, a rotational magnetic abrasive finishing (MAF) method, was developed to finish the additively manufactured tubular lattice structure produced by laser powder bed fusion. MAF can remove the initial defects efficiently. By combining electrochemical polishing as a sequent finishing method, the surface quality improvement of the tubular lattice can be as high as 77% in only 1 hour. These results demonstrate the effectiveness of the developed finishing processes and their potential for advancing the field of manufacturing. The research is expected to contribute to the development of innovative finishing techniques that can significantly enhance the quality and efficiency of AM processes.

In the future, alternative methods such as abrasive flow machining or abrasive jet finishing can be further explored. Additionally, it is important to evaluate the mechanical properties of the finished product in order to determine the effectiveness of the finishing process. Finally, efforts should be made to improve the technology readiness level of these techniques and explore potential commercialization opportunities, in order to bring these advancements to market and benefit society as a whole.

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REFERENCES

[1] C. Yan, L. Hao, A. Hussein, D. Raymont, Evaluations of cellular lattice structures manufactured using selective laser melting, Int. J. Mach. Tools Manuf. 62 (2012) 32–38.

[2] M. Bici, S. Brischetto, F. Campana, C.G. Ferro, C. Seclì, S. Varetti, P. Maggiore, A. Mazza, Development of a multifunctional panel for aerospace use through SLM additive manufacturing, Procedia CIRP. 67 (2018) 215–220. https://doi.org/10.1016/j.procir.2017.12.202.

[3] S. AlMahri, R. Santiago, D.W. Lee, H. Ramos, H. Alabdouli, M. Alteneiji, Z. Guan, W. Cantwell, M. Alves, Evaluation of the dynamic response of triply periodic minimal surfaces subjected to high strain-rate compression, Addit. Manuf. 46 (2021) 102220. https://doi.org/10.1016/j.addma.2021.102220.

[4] L. Hao, D. Raymond, C. Yan, A. Hussein, P. Young, Design and additive manufacturing of cellular lattice structures, in: Int. Conf. Adv. Res. Virtual Rapid Prototyp. (VRAP). Taylor Fr. Group, Leir., 2011: pp. 249–254.

[5] D. Shamvedi, O.J. McCarthy, E. O'Donoghue, C. Danilenkoff, P. O'Leary, R. Raghavendra, 3D Metal printed heat sinks with longitudinally varying lattice structure sizes using direct metal laser sintering, Virtual Phys. Prototyp. 13 (2018) 301–310. https://doi.org/10.1080/17452759.2018.1479528.

[6] J. Bai, G. Bu, Progress in 4D printing technology, J. Adv. Manuf. Sci. Technol. 2 (2022). https://doi.org/10.51393/j.jamst.2022001.

[7] J. Zhang, R. Hong, H. Wang, 3D-printed functionally-graded lattice structure with tunable removal characteristics for precision polishing, Addit. Manuf. 59 (2022) 103152. https://doi.org/10.1016/j.addma.2022.103152.

[8] S. Daynes, S. Feih, W.F. Lu, J. Wei, Optimisation of functionally graded lattice structures using isostatic lines, Mater. Des. 127 (2017) 215–223.

[9] X. Li, X. Yu, W. Zhai, Additively Manufactured Deformation-Recoverable and Broadband Sound-Absorbing Microlattice Inspired by the Concept of Traditional Perforated Panels, Adv. Mater. 33 (2021) 2104552.

https://doi.org/10.1002/adma.202104552.

[10] Y. Wang, L. Li, D. Hofmann, J.E. Andrade, C. Daraio, Structured fabrics with tunable mechanical properties, Nature. 596 (2021) 238–243.

[11] V.A. Beck, A.N. Ivanovskaya, S. Chandrasekaran, J.B. Forien, S.E. Baker, E.B. Duoss, M.A. Worsley, Inertially enhanced mass transport using 3D-printed porous flow-through electrodes with periodic lattice structures, Proc. Natl. Acad. Sci. U. S. A. 118 (2021). https://doi.org/10.1073/pnas.2025562118.

[12] D. Steffen, 3D printing a rocket engine, (2019). https://www.etmm-online.com/3d-printing-a-rocket-engine-a-886960/.

[13] S. Chang, A. Liu, C.Y.A. Ong, L. Zhang, X. Huang, Y.H. Tan, L. Zhao, L. Li, J. Ding, Highly effective smoothening of 3D-printed metal structures via overpotential electrochemical polishing, Mater. Res. Lett. 7 (2019) 282–289. https://doi.org/10.1080/21663831.2019.1601645.

[14] G. Strano, L. Hao, R.M. Everson, K.E. Evans, Surface roughness analysis, modelling and prediction in selective laser melting, J. Mater. Process. Technol. 213 (2013) 589–597. http://dx.doi.org/10.1016/j.jmatprotec.2012.11.011.

[15] J. Zhang, A. Chaudhari, H. Wang, Surface quality and material removal in magnetic abrasive finishing of selective laser melted 316L stainless steel, J. Manuf. Process. 45 (2019) 710–719. https://doi.org/10.1016/j.jmapro.2019.07.044.

[16] H. Wang, Y.J. Lee, Y. Bai, J. Zhang, Post-Processing Techniques for Metal-Based Additive Manufacturing, 1st ed., CRC Press, New York, 2023. https://doi.org/10.1201/9781003272601.

[17] J. Zhang, Micro-blasting of 316L tubular lattice manufactured by laser powder bed fusion, in: Eur. Soc. Precis. Eng. Nanotechnology, Conf. Proc. - 19th Int. Conf. Exhib. EUSPEN 2019, Bilbao, ES, 2019: pp. 254–255. https://www.euspen.eu/knowledge-base/ICE19107.pdf.

[18] A.Q.A. Teo, L. Yan, A. Chaudhari, G.K. O'neill, Post-processing and surface characterization of additively manufactured stainless steel 316l lattice: implications for biomedical use, Materials (Basel). 14 (2021) 1–23. https://doi.org/10.3390/ma14061376.

[19] E. Lyczkowska, P. Szymczyk, B. Dybała, E. Chlebus, Chemical polishing of scaffolds made of Ti-6Al-7Nb alloy by additive manufacturing, Arch. Civ. Mech. Eng. 14 (2014) 586–594. https://doi.org/10.1016/j.acme.2014.03.001.

[20] A.G. Demir, B. Previtali, Additive manufacturing of cardiovascular CoCr stents by selective laser melting, Mater. Des. 119 (2017) 338–350. https://doi.org/10.1016/j.matdes.2017.01.091.

[21] Y. Bai, C. Zhao, J. Yang, J.Y.H. Fuh, W.F. Lu, C. Weng, H. Wang, Dry mechanical-electrochemical polishing of selective laser melted 316L stainless steel, Mater. Des. 193 (2020) 108840. https://doi.org/10.1016/j.matdes.2020.108840.

[22] J. Zhang, H. Wang, A. Senthil Kumar, M. Jin, Experimental and theoretical study of internal finishing by a novel magnetically driven polishing tool, Int. J. Mach. Tools Manuf. 153 (2020) 103552. https://doi.org/10.1016/j.ijmachtools.2020.103552.

[23] F. Hashimoto, H. Yamaguchi, P. Krajnik, K. Wegener, R. Chaudhari, H.W. Hoffmeister, F. Kuster, Abrasive fine-finishing technology, CIRP Ann. - Manuf. Technol. 65 (2016) 597–620. https://doi.org/10.1016/j.cirp.2016.06.003.

[24] H. Yamaguchi, J. Kang, F. Hashimoto, Metastable austenitic stainless steel tool for magnetic abrasive finishing, CIRP Ann. Technol. 60 (2011) 339–342.