Manufacturability of Ti-Al-4V Hollow-Walled Lattice Struts by Laser Powder Bed Fusion

J. NORONHA,¹ M. QIAN^{1,2}, , M. LEARY,¹ E. KYRIAKOU,¹
S. BRUDLER,¹ and M. BRANDT¹

1.—Centre for Additive Manufacturing, School of Engineering, RMIT University, Melbourne, VIC 3000, Australia. 2.—e-mail: ma.qian@rmit.edu.au

Hollow-walled lattices are novel cellular materials with lower densities than conventional dense-walled lattices. However, their manufacturability by laser powder bed fusion (LPBF) is not yet established. This study investigates the LPBF manufacturability of Ti-6Al-4V hollow-walled struts with respect to strut outer diameter, wall thickness (controlled by laser scan path), and inclination angle, while the strut length is purposely limited to 10–15 mm, typical of lattice unit dimensions. The manufacturability was reliable for outer diameters exceeding 0.5 mm and wall thicknesses exceeding 0.24 mm over the inclines of 22.5°–90°. To ensure a manufacturable hollow cylindrical channel by LPBF, we recommend a minimum inner diameter of 4Dv(90) according to the feedstock powder size distribution. The average inconsistency of 5.13% between the designed and manufactured outer diameters was substantially lower than that achievable by conventional manufacturing. The findings of this study provide necessary guidance for the future manufacture of hollow-walled lattices by LPBF.

INTRODUCTION

Metal hollow-walled lattice materials are a class of novel lattice materials, which have the potential to offer further weight reduction versus dense-walled lattice materials without significantly sacrificing the lattice strength or elastic modulus, or offer unique functionalities that are not possible for dense-walled lattice materials.¹ However, their manufacture is currently dominated by multistep fabrication processes,¹ which can allow ultralow relative densities down to 0.01%,² while the long lead time and processing complexity detrimentally impact both affordability and time efficacy. Furthermore, the multistep fabrication method commonly employs a self-propagating photopolymer waveguide (SPPW) process to fabricate the polymer template.¹ This SPPW process is limited to low-dimension arrays of ~ 2–5 unit cells in the vertical direction, which limits the functionality.³ These restrictions present an exciting opportunity for the

introduction of laser powder bed fusion (LPBF), a single-step metal additive manufacturing (AM) method, which may replace the current multistep processes.

As an emerging direction for lattice design, the first key question to answer is the manufacturability of these hollow-walled lattice materials in terms of the manufacturable “hollow” size, wall thickness, and orientation for the lattice struts by LPBF AM. This approach is common in the literature on LPBF AM of dense-walled lattice materials.^{4–7} Individual struts are often fabricated initially to enable a systematic understanding of the manufacturability for high-performance lattice builds. The literature information for LPBF hollow-walled struts, however, is currently scarce. Microlaser LPBF (μ LPBF) was once employed to fabricate vertical SS316L hollow microneedles with a wall thickness of 0.1 mm, an inner diameter of 0.16 mm, and a length of 1.2 mm.⁸ These struts, which were designed for drug delivery purposes, rather than for hollow-walled lattices, contained noticeable defects and provided limited insights into the strut manufacturability. Additionally, since the μ LPBF process employs very different operational parameters, the

(Received August 15, 2021; accepted September 13, 2021;
published online October 12, 2021)

geometrical restrictions observed do not apply to conventional LPBF. Hence, the manufacturability of hollow-walled lattices by LPBF remains an unexplored issue.

This study aims to fill this knowledge gap through detailed assessments of a variety of LPBF-manufactured Ti-6Al-4V hollow-walled struts. The purpose is to identify a reliable manufacturability range for LPBF of robust hollow-walled materials.

DESIGN OF HOLLOW-WALLED STRUTS

Both vertical and inclined struts have been designed for LPBF for assessment as intricate lattice unit cells which can comprise both types of struts. Our design or fabrication methodology for each hollow-walled strut is composed of two steps. We first define a strut outer diameter, illustrated as

the red circle in Fig. 1a, and then apply three different scan paths from the periphery towards the center referred to as single, double, and triple scan paths, to create three different wall thicknesses or three different hollow cores, as shown in Fig. 1a. More specifically, a single scan path corresponds to a thin wall, a triple scan path to a thick wall, and a double scan path to an intermediate wall. Fifteen outer diameters ranging from 0.2 mm to 1.6 mm were designed for vertical hollow struts, which are displayed in Fig. 1b. Each outer diameter will be fabricated with three scan paths, to give a total of 45 vertical hollow struts.

The manufacturability of inclined struts is assessed at inclination angles of 22.5°, 45°, and 67.5°. Strut designs at inclination angles below 20° have proved to be challenging for AM by both LPBF and electron beam PBF, even in the case of dense-

Fig. 1. (a) Three scan paths implemented for LPBF of hollow-walled struts, (b) vertical struts with different outer diameters for each scan path by CAD, and (c) inclined struts with different outer diameters for each scan path by CAD, at inclination angles of 22.5°, 45°, and 67.5° (Color figure online).

walled struts.^{4–6} For example, manufactured struts failed to achieve a uniform cylindrical shape below 20° by LPBF⁵ and below 25° by electron beam PBF.⁴ The same three scan paths are implemented for all inclined struts. However, the outer diameters are selected based on the successfully manufactured vertical struts. As will be shown below, this limits the inclined outer diameters to the ranges of 0.6–1.6 mm for single scan path, 0.8–1.6 mm for double scan path, and 1.1–1.6 mm for triple scan path, at intervals of 0.1 mm in each case, as illustrated in Fig. 1b. In total, 78 inclined hollow strut designs were manufactured at the three selected inclination angles (26 strut samples at each angle).

EXPERIMENTAL PROCEDURES

Materials and Manufacturing Process

Argon gas-atomized Ti-6Al-4V powder was used, whose powder size distribution was characterized using a Malvern Mastersizer (Malvern Instruments). The results are shown in Fig. 2 with $D_v(10) = 30.0 \mu\text{m}$, $D_v(50) = 44.6 \mu\text{m}$, and $D_v(90) = 66.2 \mu\text{m}$.

An SLM Solutions 250HL machine was used to fabricate all the designed strut specimens shown in Fig. 1, and the LPBF parameters used are detailed in Table I. After fabrication, the parts were cooled within the machine to room temperature (20°C). The parts were then manually removed from the build plate using a chisel and hammer.

Characterization

An FEI Quanta 200 scanning electron microscopy (SEM) facility was used to examine the hollow-walled strut specimens at an acceleration voltage of 30 kV with a spot size of 5.0 μm . This enabled the strut geometrical parameters to be derived, and the surface morphology to be quantified. For a comprehensive analysis of the internal geometry, powder flowability within the hollow cylindrical channel,

and frequency of internal defects in the experimental samples, microcomputed tomography (μCT) was implemented to examine selected samples using A Bruker Skyscan x-ray Micro CT, employing an x-ray tube current of 100 μA , and an acceleration voltage of 50 kV. The operational parameters for the analysis technology are displayed in Table II. To reconstruct the cross-sectional slices acquired from the μCT angular projections through the object, nRECON shadow image reconstruction software (Bruker) was used.

RESULTS AND DISCUSSION

Manufacturability of Vertical Struts

Figure 3 displays representative μCT (Fig. 3a, c, and e) and SEM observations (Fig. 3b, d, and f) of the vertically manufactured hollow-walled strut samples. Three classifications are defined according to the external structural integrity and internal cylindrical channel shape of each strut, namely failed, compromised, or successful. The external structural integrity refers to the level of stability along the external length of the strut. The internal cylindrical channel shape refers to the propensity of the strut to maintain a consistent internal wall thickness and hollow channel from end to end. The defects and abnormalities observed are consistent for all scan paths and outer diameters. The failure exemplified in Fig. 3a and b is due to the internal cylindrical channel of the strut being completely dense. This can be attributed to the excessive heat accumulated inside the cylindrical cavity, leading to the complete melting of the powder particles therein. This highlights a distinct difference between LPBF of hollow-walled and dense-walled struts, i.e., excessive heat must be avoided inside the cavity. The compromised strut as observed in Fig. 3c and d is manufacturable, but it contains a large volume of adhered internal powder particles. Their existence arises from two primary reasons, the non-uniformity of the internal cylindrical void

Fig. 2. Powder size distribution of the Ti-6Al-4V feedstock.

Table I. LPBF parameters implemented to fabricate hollow-walled strut specimens.

Parameters	Feedstock material	Spot size (μm)	Laser power (W)	Layer thickness (μm)	Scan speed (mm/s)	Platform temp ($^{\circ}\text{C}$)	Focus offset (μm)	Support structure (Y/N)	Number of specimens
Vertical struts	Ti-6Al-4V	80	100	30	750	200	0	N	45
Inclined struts (22.5°, 45°, 67.5°)	Ti-6Al-4V	80	100	30	750	200	0	N	78

Table II. μCT parameters implemented for characterizing hollow-walled struts

Parameters	Source voltage (kV)	Source current (μA)	Image pixel size (μm)	Rotation Θ ($^{\circ}$)	Rotation step Θ ($^{\circ}$)	Filter
Vertical struts	50	100	7-12	360	0.4	Aluminum 1 mm
Inclined struts	50	100	7-12	360	0.3	Aluminum 1 mm

and the partial melting and/or sintering of the powder particles due to excessive heat accumulation. This raises another manufacturability issue that differs from the case of dense-walled struts, i.e., to ensure a uniform cylindrical cavity and to avoid internal melting or sintering. A successful fabrication is shown in Fig. 3e and f, which leads to a completely hollow and uniform internal cylindrical channel (Fig. 3e) and high wall-thickness structural integrity. These struts show the right combination of geometrical design and LPBF processing.

Table III summarizes the reliable manufacturability range for the vertical struts. For a single scan path, the outer diameters between 0.6 mm and 1.6 mm were fabricated successfully. For a double scan path, the outer diameters between 0.8 mm and 1.6 mm led to successful fabrication but with minor abnormalities. For a triple scan path, the outer diameters between 1.1 mm and 1.6 mm worked consistently and resulted in the desired fabrication. The external structural integrity remained consistently stable for all of the struts regardless of outer diameter or scan path.

For each of the hollow-walled struts, the wall thickness was measured through the cross-sectional SEM and μCT data and subsequently averaged. The single scan path samples achieved an average wall thickness of 0.236 mm with adhered powder and 0.137 mm without powder. The double scan path samples were observed to have an average wall thickness of 0.332 mm with adhered powder and 0.221 mm without powder. The triple scan path samples maintained an average wall thickness of 0.415 mm with adhered powder and 0.308 mm without powder. It should be noted, however, that

increasing the outer diameter reduced the wall thicknesses regardless of the scan path. On average, the wall thickness observed a decrease of $\sim 40 \mu\text{m}$ between the thinnest hollow-walled strut manufacturable (typically compromised) and the thickest hollow-walled strut (successfully manufactured).

The above SEM and μCT assessments defined the reliable manufacturability ranges for vertical hollow-walled struts. The variations of $\sim 100 \mu\text{m}$ measured in wall thicknesses with and without considering the adhered powder are not surprising, given that the powder has $2\text{Dv}(50) \approx 90 \mu\text{m}$ and $2\text{Dv}(90) \approx 130 \mu\text{m}$. In that regard, the hollow cylindrical channel diameter should be sufficiently larger than $2\text{Dv}(90)$. Furthermore, the lowest successfully fabricated internal diameter for each scan path is estimated to be: $250 \mu\text{m}$ or $3.85\text{Dv}(90)$ for the single scan path, $420 \mu\text{m}$ or $6.5\text{Dv}(90)$ for the double scan path, and $460 \mu\text{m}$ or $7.1\text{Dv}(90)$ for the triple scan path. Therefore, we recommend a minimum of $4\text{Dv}(90)$ or $2 \times 2\text{Dv}(90)$ for the manufacturable hollow cylindrical internal channel diameter by LPBF. In the extreme case, this allows the fabrication of a hollow cylindrical channel with a diameter of $2\text{Dv}(90)$. The $4\text{Dv}(90)$ criterion is subject to optimization by considering the thermal history of each hollow-walled strut through simulation, which will be pursued in our future research. The increase in inner diameter required to ensure uniform hollow internal channels for each additional scan path is also related to the thermal history, where internal powder particles may increasingly adhere to the walls by sintering during each additional laser scan path.

Fig. 3. μ CT and SEM images of vertically built hollow-walled strut samples. (a) μ CT of strut with triple scan path, outer diameter: 0.8 mm, (b) a cross-sectional SEM view of strut (a), (c) μ CT of strut with triple scan path, outer diameter: 1.0 mm, (d) a cross-sectional SEM view of strut (c), (e) μ CT of strut with triple scan path, outer diameter: 1.1 mm, (f) A cross-sectional SEM view of strut (e).

Geometrical Accuracy of Vertical Struts

Figure 4 quantifies the average geometrical inaccuracy between the designed and manufactured outer diameters of each successfully manufactured hollow-walled strut sample through SEM and μ CT. An average departure of 2.15% was observed without considering the powder adherence, while an average error of 5.13% was found when adhered powder particles were included. As the outer diameter increased, the manufactured and designed outer diameters became closer to each other, with the single scan path 1.6-mm samples achieving the lowest variance of 0.7%.

The scan path was positioned with an offset of 60 μ m from the designed outer diameter to account for the scan path width. This value was derived by halving the resulting scan path width ($\sim 120 \mu$ m) examined in a preliminary experiment. This offset appears to have enabled the high accuracy of 2.15%

and 5.13%. Additionally, the wall thickness was found to be $\sim 140 \mu$ m for a single scan path width through the results discussed in “[Manufacturability of Vertical Struts](#)” section. However, future strut experiments with thermal history examinations are needed to confirm the effects of this scan path offset to improve the accuracy.

The high level of geometrical accuracy achieved by the LPBF process is uncommon in hollow-walled lattice designs fabricated through the multistep method. Manufactured Ni BCC hollow-walled lattices fabricated saw a departure of $\pm 15\%$ from the designed outer diameter.⁹ Additionally, a standard error analysis indicated uncertainty of 18% in the wall thickness-to-outer diameter ratio. A honeycomb hollow-walled lattice also observed large geometric deviance,¹⁰ where, due to non-uniform wall thickness, the relative density of the experimental lattice deviated from the designed samples by up to

Table III. The manufacturability of hollow-walled struts at 90° where green, yellow, and red indicate successful, compromised, and failed struts (Color figure online)

Single scan path	Outer diameter, <i>Do</i> (mm)															
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	
External structural integrity																
Internal cylindrical channel shape and inner diameter					0.15	0.25	0.37	0.48	0.59	0.69	0.80	0.89	1.00	1.11	1.19	
Double scan path	Outer diameter, <i>Do</i> (mm)															
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	
External structural integrity																
Internal cylindrical channel shape and inner diameter								0.27	0.42	0.46	0.61	0.73	0.80	0.92	0.97	
Triple scan path	Outer diameter, <i>Do</i> (mm)															
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	
External structural integrity																
Internal cylindrical channel shape and inner diameter										0.35	0.46	0.55	0.66	0.77	0.82	

Inner diameter reported for successful struts.

40%. For dense-walled Inconel 625 BCC, BCCZ, FCC, and FCCZ lattices, geometrical inaccuracy from the struts and nodes caused a relative density deviation of 13–44% from the designed lattices.⁶

Manufacturability of Inclined Struts

Figure 5 displays representative SEM observations of the hollow-walled inclined strut samples. Similar to the case of the vertical struts, we classify the as-manufactured hollow-walled inclined struts into three categories according to their external structural integrity and internal cylindrical channel shapes, namely failed, compromised, or successful. A failed hollow-walled strut sample is displayed in Fig. 5a and b, due to external wall integrity defects or cavities (see red circles), which can significantly weaken its structural integrity. These cavities are exclusive to single scan path struts inclined at 22.5°. In principle, they can be regarded as lack-of-fusion-induced cavities due to the use of a single scan path. Figure 5c shows a compromised strut, which is manufacturable but exhibits non-uniform cross-sectional profiles at the end of the struts (see yellow lines). Additionally, Fig. 5e and f display compromised struts with cavities at the inner edge of the strut (see yellow circles). The presence of these minor defects at the end of the struts appears to be random, occurring at all inclination angles and scan paths. However, the frequency of their occurrences

is closely related to the hollow channel diameter, where diameters near the lower boundaries of the reliable manufacturability range corresponded to higher frequencies at all inclination angles, as displayed in Table IV. Nonetheless, these internal cylindrical channels were confirmed to be still consistently hollow by μ CT analyses with stable wall thicknesses. Furthermore, in hollow-walled lattice fabrication, the addition of strut connections should negate these minor defects, and render some of those ‘compromised struts’ in Table IV fully manufacturable (e.g., those inclined at 67.5°). Successful struts, exemplified in Fig. 5d, are featured by a uniform hollow internal cylindrical channel and high structural integrity. They realise the designed strut geometry by LPBF processing.

Table IV summarizes the manufacturability range for the inclined struts. For a single scan path, the majority of outer diameters between 0.6 mm and 1.6 mm were fabricated successfully at the inclines of 45° and 67.5°. In contrast, the incline of 22.5° was found to be less practical with a single laser scan path due to the frequent occurrence of wall integrity defects and geometrical inaccuracies. The double scan path worked satisfactorily for the majority of outer diameters between 0.9 mm and 1.6 mm and resulted in the desired fabrication at all inclines. The

Fig. 4. Outer diameters of hollow-walled struts: measured versus designed: (a) single scan path, (b) double scan path, (c) triple scan path. The red solid line displays the idealised relationship where the measured parameters equal the designed parameters.

manufacture of struts with triple scan paths, was reliable for the outer diameters between 1.1 mm and 1.6 mm at all inclines. Since the strut length was only 10 mm, no support material was used for all hollow-walled struts inclined at 22.5°, 45°, and 67.5°. However, unlike the vertical hollow-walled struts, no inclined hollowed-walled struts displayed the abnormalities shown in Fig. 3a and c.

CONCLUSION

LBPF presents an efficient single-step fabrication method for hollow-walled struts and subsequently hollow-walled lattices. Through the systematic fabrication and analysis of the experimental hollow-walled struts, reliable manufacturability ranges have been established.

- Vertical hollow-walled struts with the wall thickness in the range of 0.24–0.41 mm and

Fig. 5. Examples of failed, compromised, and successful hollow-walled strut samples by LPBF (SEM images): (a) failed, single scan path; outer diameter: 1.3–1.5 mm; inclination angle: 22.5°, (b) failed, single scan path; outer diameter: 1.4 mm; inclination angle: 22.5°, (c) compromised, single scan path; outer diameter: 0.6 mm; inclination angle: 22.5°, (d) successful, double scan path; outer diameter: 1.6 mm; inclination angle: 22.5°, (e) compromised, triple scan path; outer diameter: 1.1 mm; inclination angle: 67.5°, and (f) compromised, triple scan path; outer diameter: 1.1 mm; inclination angle: 22.5°.

Table IV. The manufacturability of hollow-walled struts at varying inclination angles where green, yellow, and red indicate successful, compromised, and failed struts (Color figure online)

Single scan path	$\theta(^{\circ})$	Outer diameter, Do (mm)										
		0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6
External structural integrity	22.5°											
	45°											
	67.5°											
Internal cylindrical channel shape	22.5°											
	45°											
	67.5°											
Double scan path	$\theta(^{\circ})$	Outer diameter, Do (mm)										
		0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6		
External structural integrity	22.5°											
	45°											
	67.5°											
Internal cylindrical channel shape	22.5°											
	45°											
	67.5°											
Triple scan path	$\theta(^{\circ})$	Outer diameter, Do (mm)										
		1.1	1.2	1.3	1.4	1.5	1.6					
External structural integrity	22.5°											
	45°											
	67.5°											
Internal cylindrical channel shape	22.5°											
	45°											
	67.5°											

outer diameters between 0.6 mm and 1.6 mm are attainable at lengths ranging from 10 mm to 15 mm by LPBF.

- To ensure a manufacturable hollow cylindrical channel within the strut by LPBF, we recommend a minimum inner diameter of $4D_v(90)$ according to the feedstock powder size distribution.
- A high level of consistency was achieved between the designed and manufactured outer diameters for hollow-walled struts. The average variation equated to 5.13% with the inclusion of adhered powder. This level of consistency is vastly superior to hollow-walled strut samples fabricated by existing multistep methods. The reliable manufacturability range for the incline struts is consistent with those established for the vertical struts.
- Inclination angles affect the manufacturability of hollow-walled struts. A high failure frequency was observed for those inclined at 22.5° with the thinnest wall thickness due to the occurrence of wall integrity defects. This is particularly the

case when a single laser scan path is used.

- The wall integrity is important to hollow-walled struts. To minimize the occurrence of lack-of-fusion-induced cavities in the strut walls, we recommend the use of a double scan path rather than a single scan path.

CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

ACKNOWLEDGEMENTS

This project was funded by the Australian Research Council (ARC) through DP200102666. The authors acknowledge the scientific and technical support of the RMIT Advanced Manufacturing Precinct and the RMIT RMMF microscopy facility.

AUTHOR CONTRIBUTIONS

Jordan Noronha: critical analysis, conceptualization, visualization, compilation, investigation of data, writing—initial draft, and writing—review

and editing. Ma Qian: conceptualization, visualization, writing—review and editing, supervision, critical analysis, project administration, funding acquisition. Milan Brandt: conceptualization, visualization, editing, supervision, resources, funding acquisition, critical analysis. Martin Leary: conceptualization, visualization, writing—review and editing, supervision, critical analysis, project administration, funding acquisition. Elizabeth Kyriakou: project administration, review, supervision, critical analysis. Simon Brudler: conceptualization, and visualization.

REFERENCES

1. J. Noronha, M. Qian, M. Leary, E. Kyriakou, and M. Brandt, *Curr. Opin. Solid State Mater. Sci.* 25, 100940. (2021).
2. T. Schaedler, A. Jacobsen, A. Torrents, A. Sorensen, J. Lian, J. Greer, L. Valdevit, and W.B. Carter, *Science* 334, 962. (2011).
3. L. Salari-Sharif, S. Godfrey, M. Tootkaboni, and L. Valdevit, *Addit. Manuf.* 19, 51. (2018).
4. X. Zhang, H. Tang, M. Leary, T. Song, L. Jia, and M. Qian, *JOM* 70, 1870. (2018).
5. M. Mazur, M. Leary, S. Sun, M. Vcelka, D. Shidid, and M. Brandt, *Int. J. Adv. Manuf. Technol.* 84, 1391. (2015).
6. M. Leary, M. Mazur, H. Williams, E. Yang, A. Alghamdi, B. Lozanovski, X. Zhang, D. Shidid, L. Farahbod-Sternahl, G. Witt, I. Kelbassa, P. Choong, M. Qian, and M. Brandt, *Material. Des.* 157, 179. (2018).
7. A. Alghamdi, B. Lozanovski, M. McMillan, R. Tino, D. Downing, X. Zhang, I. Kelbassa, P. Choong, M. Qian, M. Brandt, and M. Leary, *Int. J. Adv. Manuf. Technol.* 105, 2501. (2019).
8. M. Gieseke, V. Senz, M. Vehse, S. Fiedler, R. Irsig, M. Hustedt, K. Sternberg, C. Nölke, S. Kaierle, V. Wesling, J. Tiggesbäumker, K.-H. Meiwes-Broer, H. Seitz, K.-P. Schmitz, and H. Haferkamp, *Biomed. Tech. (Berl.)* 57, 398. (2012).
9. A. Torrents, T. Schaedler, A. Jacobsen, W. Carter, and L. Valdevit, *Acta Mater.* 60, 3511. (2012).
10. S. Yin, H. Wang, J. Hu, Y. Wu, Y. Wang, S. Wu, and J. Xu, *Compos. B* 179, 107522. (2019).

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.