Property Evaluation of Metal Cellular Strut Structures via Powder Bed Fusion AM

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Abstract

Cellular structures are widely used in many engineering applications, because of their light weight, high strength-to-weight ratio, high energy absorption, etc. Many previous research and development works are largely focused on structural design, while the material properties are often over-simplified. In this work, the relationships between process parameter and orientation on the geometrical and mechanical characteristics of the cellular struts fabricated via selective laser melting (SLM) were investigated. The results provide preliminary guidelines on the use of laser melting additive manufacturing process for the fabrication of cellular strut structures.

1. Introduction

Due to the desirable performance-to-weight ratios and greatly designable structures, cellular structures are widely regarded in various engineering applications. With additive manufacturing processes, the fabrication of cellular structures overcomes various limits in traditional manufacturing methods, which make it feasible for economical application of cellular structures. This promising prospect has become a driving force in the establishment of an integrated multi-scale model that enables accurate predictions of cellular structure performance as functions of process parameters, material selections and geometrical designs.

In order to achieve the multi-scale cellular structure designs, the multi-scale model could be potentially decoupled into (1) geometry-property model and (2) process-material model. This treatment is expected to allow for independent development of each design modules and the generalization of knowledge for the process optimization of thin-feature lightweight structures. Ultimately, the closed-loop process control can be realized via feedforward process optimization, which improves the quality control of the fabricated cellular structures.

In this study, investigation was focused on the relationship between process parameters and various quality characteristics of the single struts with thin features fabricated via selective laser melting (SLM) process.

2. Experiment planning with single struts

This study focused on Ti6Al4V thin struts fabricated via an EOS M270 direct metal laser sintering (DMLS) system. The process control of the SLM system involves a variety of parameters and scanning strategies. For each layer, the system is capable of performing three basic scanning operations including hatch, contour and edge (Fig. 1). Hatch scanning fills the interior selected region with parallel tracks; contour scanning is along the outline of selected scanning region; edge scanning performs as a single track with small dimensions, such as the sharp tip of the triangular area in Fig. 1(c).

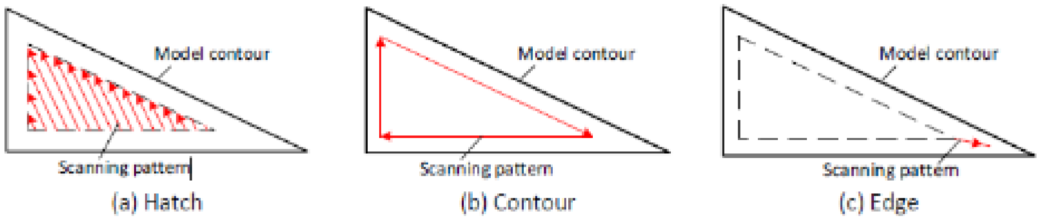


Fig. 1 Three basic scanning operations in SLM system

These three scanning operations can be used alone or in combination. For regular bulk structures, a hatch operation is applied to fill the volume of the structure, while a contour operation is used to better sketch boundaries and improve the surface quality of the final parts. From the previous study (Yang et al., 2014), for GP1 stainless steel (EOS GmbH), under default beam offset operations, thin features with dimensions larger than 0.3mm should be realized by a combination of contour and hatch. A combination of contour and edge is able to create thin features with dimensions between 0.1-0.3mm, although some dimensions may be more prone to defect generation. For the feature size smaller than 0.1mm, only edge operation is appropriate to result in single track scanning (Fig. 2).

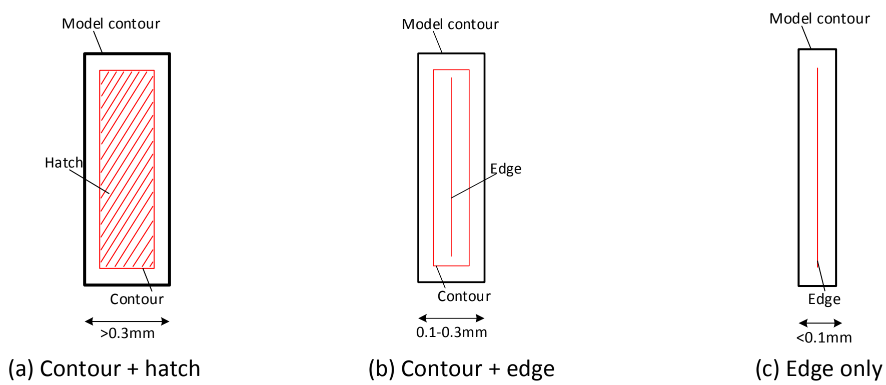


Fig. 2 Scanning strategies for thin features with different dimensions

For each scanning method, there are also various parameters to set up, such as scanning speed, power level, beam offsets, etc. Among these parameters, the scanning speed and laser power directly control the input energy density based on the energy density index (EDI) equation (Eqn. (1)), therefore determines the amount of powder melted. Beam offset compensates the scanning geometrical error caused by characteristic laser beam size. During this experiment, the laser beam size offset for Ti6Al4V is 40µm and the user defined in-process beam offset is 0. Besides, the spacing between the hatch pattern lines is 100µm and the layer thickness is 30µm by default.

$$E = \frac{P}{v \cdot h \cdot t} \tag{1}$$

In Eqn.(1), v indicates scanning speed, P indicates power level, h indicates hatch spacing, and t indicates layer thickness.

3. Process control and fabrication

Based on the design of decoupled multi-scale model of lightweight structures, the current study is focused on individual strut performance and characterization as functions of process parameters, material selections and geometrical features. The process control involves multiple parameters and scanning strategies.

1st iteration:

In the first iteration, the fabrication adopted the default process parameters for solid Ti6Al4V in EOS system (Power level of 170W, scanning speed of 1250mm/s) and assuming isotropic material properties, the first iteration was designed for length-width ratio ranging from 5 to 35, corresponding with the feature size ranging from 0.1mm to 2.0mm, and several build angles (tilt angle). The detailed design is shown in Table 1 and 3D model is shown in Fig. 3. The samples were fabricated in one batch.

Table 1 1st iteration of thin feature struts design

Factors	Design
Length l (mm)	2, 5, 10
Length-width ratio r	5, 10, 15, 35
Tilt angle (°)	15, 30, 45, 60, 75

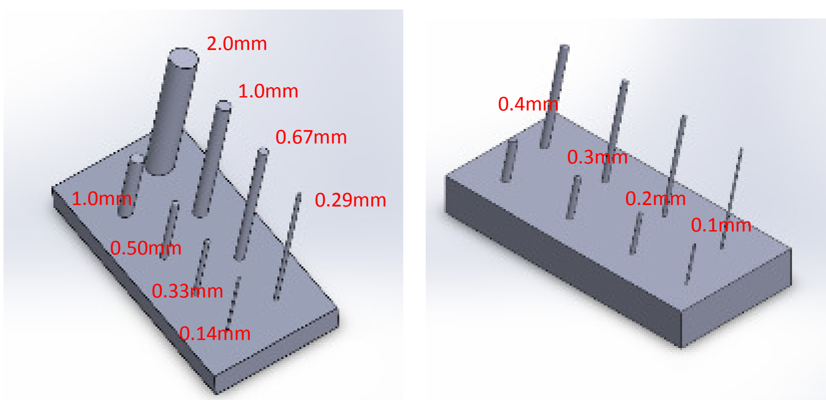


Fig. 3 Thin feature testing sample designs (1st iteration)

The fabricated samples were shown in Fig. 4. From the 1st build samples, for each orientation except for the 30° samples, struts with dimension of less than 0.14mm failed to build. Struts with diameter of 0.14mm or larger were fabricated successfully at all angles.

Fig. 4 1st build samples, a. 75°, b. 60°, c. 45°, d. 30°, e. 15°

2nd iteration:

In the 2nd iteration, the default process parameters for Ti6Al4V support structure in EOS system are selected as baseline for further investigation and comparison, since those parameters were used to generate support features with dimensions of 130-200 μm that possess mechanical strength for the restriction of thermal distortions of parts. In the 2nd iteration, both contour + edge and contour + hatch scanning strategies were investigated. For each scanning strategy, ±25% changes of power level and scanning speed based on baseline parameters were investigated. Also the built angle ranged from 15° to 90° and the diameter of struts ranged from 0.05mm to 2mm were investigated. The detailed design is shown in Table 2.

Table 2 2nd iteration of thin feature struts design

Factors	Design
Power level (W)	60, 80, 100
Scanning Speed (mm/s)	300, 400, 500
Scanning Strategy	Contour + edge, Contour + Hatch
Tilt angle (°)	15, 30, 45, 60, 75, 90
Diameter (mm)	2.0, 1.5, 1.0, 0.8, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, 0.05

Fig. 5 2nd build samples

In the 2nd iteration, partial combinations of process parameters were selected under each of scanning strategies and build orientations. From the formation of the struts, it could be observed that at large tilt angles (i.e. strut aligns more along the build direction) it was difficult to fabricate even the struts relatively large diameters under no matter which scanning strategy (contour + hatch and contour + edge) used (Fig. 6). As the build angle getting smaller, the feasibility of fabrication increased in general. Also, it could be observed that for struts with tilt angle of 90°, some thin struts were fabricated successfully while the larger ones failed (Fig. 7). This phenomenon was also found at the angle of 75° and 60°. This suggested that the scanning strategy of contour + edge could fabricate struts with dimensions under 0.2mm. Under the investigated process parameters and scanning strategies, the fabrication quality was in general better at the built angles of 45° and 30°. However, at the tilt angle of 15°, the struts were significantly out of shape at the down-facing halves, although most dimensions were successfully fabricated (Fig. 8). This indicated that orientation significantly affected fabrication of thin struts. On one hand, the staircase effect becomes more significant at lower tilt angles, while on the other hand, for a strut with the same cross sectional area, smaller tilt angle would result in larger projection area in the build direction, which allows for easier fabrication.

Fig. 6 Formation at the tilt angle of 90°

Fig. 7 Fabricated samples (100W, 500mm/s, contour + edge)

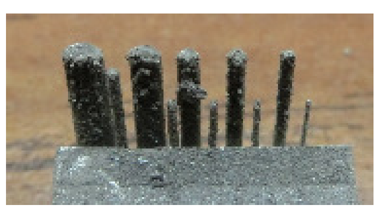


Fig. 8 Worn parts (80W, 500mm/s, contour + hatch)

3rd iteration:

As it was previously observed that lower power and lower energy density could potentially improve the thin feature manufacturability, based on the results from 2nd batch of fabrication, lower power levels and energy density input were employed in the 3rd iteration. The built angle ranging from 15° to 90° and the diameter of struts ranging from 0.05mm to 2mm were investigated. The detailed design is shown in Table 3.

Table 3 3rd iteration of thin feature struts design

Factors	Design
Power level (W)	40, 60, 80
Scanning Speed (mm/s)	400, 700, 1000
Scanning Strategy	Contour + edge, Contour + Hatch
Tilt angle (°)	15, 30, 45, 75, 90
Diameter (mm)	1.0, 0.8, 0.6, 0.5, 0.4, 0.3, 0.2, 0.16, 0.13, 0.1, 0.08, 0.05

The build quality of the struts in 3rd batch varied significantly with the build orientation. With larger build angle, fabrication failure occurred more commonly among all levels of EDI. As shown in Fig. 9, most struts at the tilt angle of 15° were built successfully; while at the tilt angle of 90°, it could be noticed that most of the struts failed to build under all parameter settings in the 3rd iteration. Even with several struts were built somehow, the build quality was not satisfying.

In addition, it was also seen that the processing conditions had significantly effect on the build quality. At a relative low energy density, such as power of 80W and scan speed of 1000mm/s (Fig. 9), the build quality is generally better. Also, under the same processing parameters, the struts built with contour + edge strategy were fabricated more successfully than contour + hatch at smaller build orientations. On the other hand, the use of contour + hatch appears to be more robust at larger build orientations.

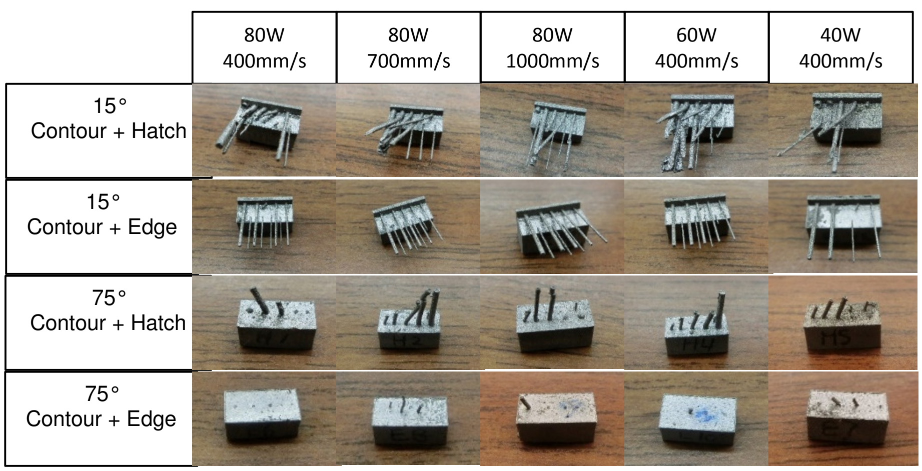
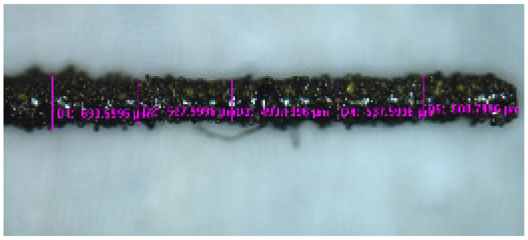


Fig. 9 3rd build samples

4. Geometrical accuracy

The dimensions of each sample strut were measured with an optical microscope (Olympus MX51). Because of surface sintering effect, the dimension of the thin feature was not uniform; also the smallest neck section becomes the critical location for the strength of the entire strut, therefore the minimum dimension from the measurements was taken as the thickness of the struts (Fig. 10).



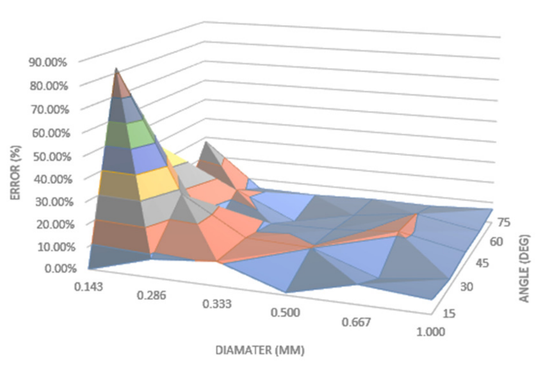


Fig. 10 Measurement of the thin feature dimensions

Fig.11 Dimension error in 1st iteration

Through the measurement, it was found that the default parameters used for bulk Ti6Al4V geometries in EOS could in general realize the fabrication of thin struts. However, from the trend of dimension error in Fig. 11, the fabrication error becomes significant at the dimension between 0.333mm and 0.5mm. As the dimension became smaller, the error increased sharply. On the other hand, the overall dimensional error reduced lightly as the build orientation became larger.

The fabrication errors in the second iteration exhibited a similar trend. As the dimension reduced to 0.5mm or so, the fabrication error became larger, for example, under 80W, 400mm/s and Contour+edge and 80W, 300mm/s and Contour+hatch (Fig. 12). On the other hand, the minimum strut size that could be achieved by the process appears to be around 0.1mm, although this dimension was only achievable when the design size was set at 0.05mm.

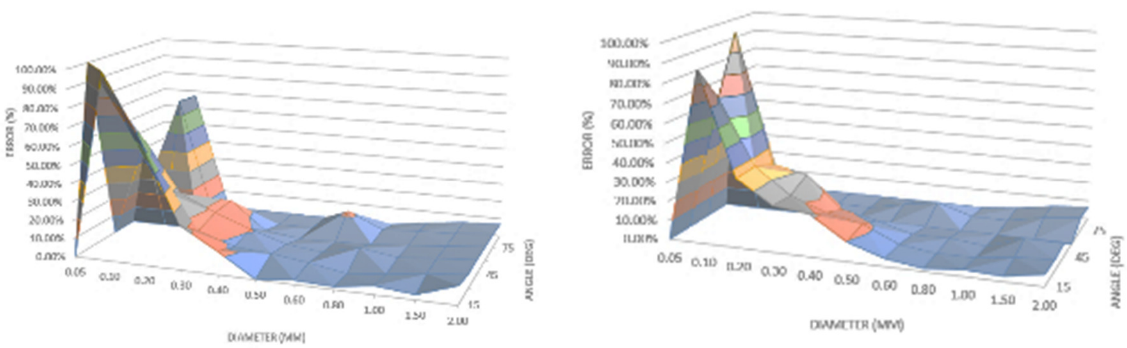


Fig. 12 Dimension error in 2nd iteration

(left: 80W, 400mm/s, Contour+edge; right: 80W, 300mm/s, Contour+hatch)

For the samples from 3rd iteration, measurement was performed for struts with the built angle of 15°, since this size could be consistently realized and therefore characterized with more complete information about trend. Fig.13 shows the results from both scaning strategies. Note that due to the setting of zero beam offset, an approximately 0.8mm of additional error was expected to occur for the fabricated samples. Also, from this iteration it appears that the contour + hatch strategy is more accurate, which does not agree well with the results from previous iteration. One possible cause for this disagreement might come from the random error of the process, however more samples will need to be characterized in order to establish a statistically significant conclusion.

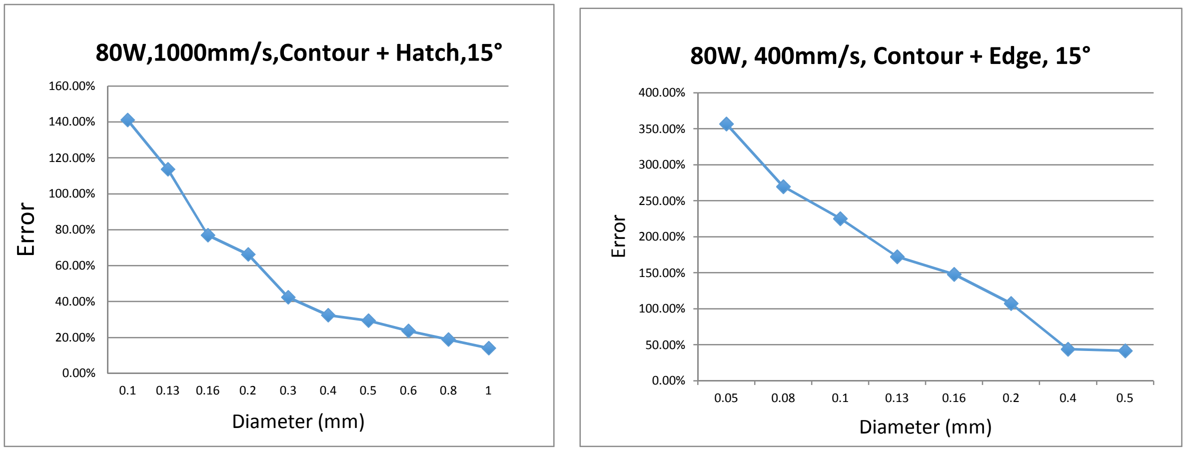
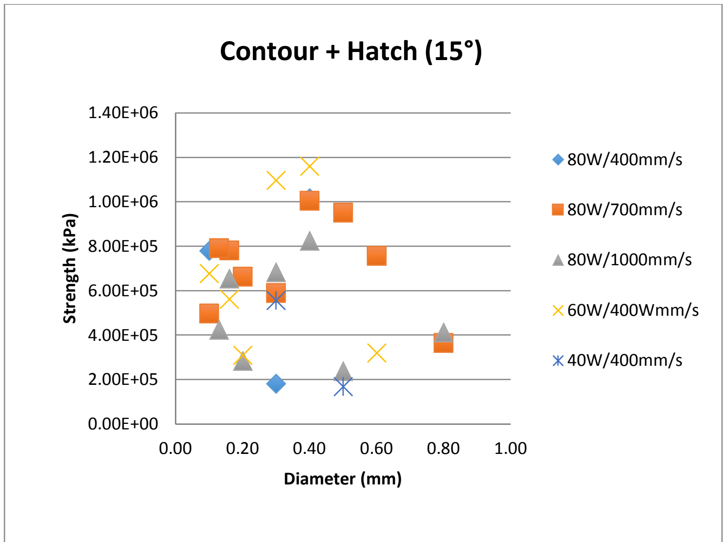


Fig. 13 Dimension error in 3rd iteration

(Left: 80W, 1000mm/s, Contour + Hatch; Right: 80W, 400mm/s, Contour + Edge)

5. Mechanical property

Based on the results of measurement in 3rd iteration, micro 3-point bending tests were carried out using the 10mm samples with build angle of 15° under an electromechanical universal tester (EZ-SX, Shimadzu), which has a maximum capacity of 500N. The mechanical property was characterized by ultimate strength of the thin features, shown in Fig. 14. From the graphs, it could be roughly observed that energy density input affected strength of the thin features. As the energy density reduced, the strength had a decreasing trend in general. However, in general the results were scattered over a wide range of values, which might be caused by both the random variation inherited in the fabrication process and the testing error that originated from the sample support and loading. Therefore no apparent correlation could be observed between the feature diameter and the mechanical properties, which will be investigated in more details in further studies.



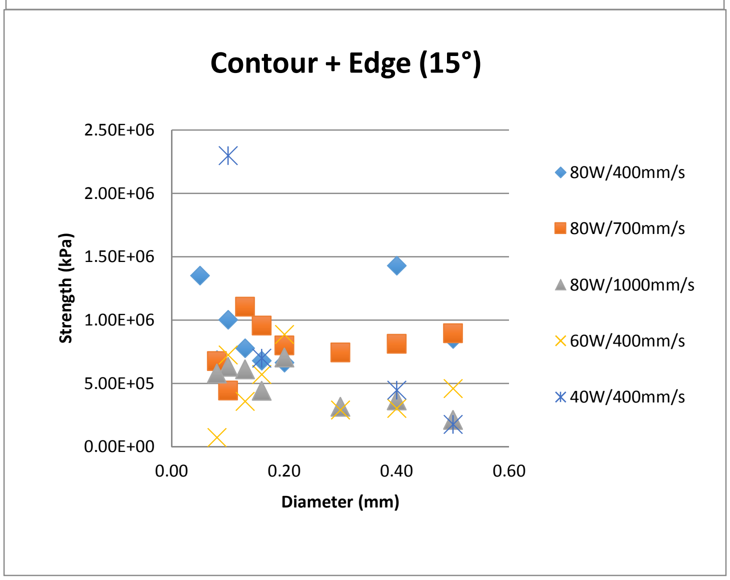


Fig. 14 yield strength of thin features (Left: Contour + hatch; right: contour + edge)

6. Microstructural characterization

The microstructure of the Ti6Al4V bulk sample fabricated with default process parameter was observed under the optical microscope (200 magnification, Fig. 15). It shows that the grain columns grew along the build direction, and the width of the columnar grain was around 130µm.

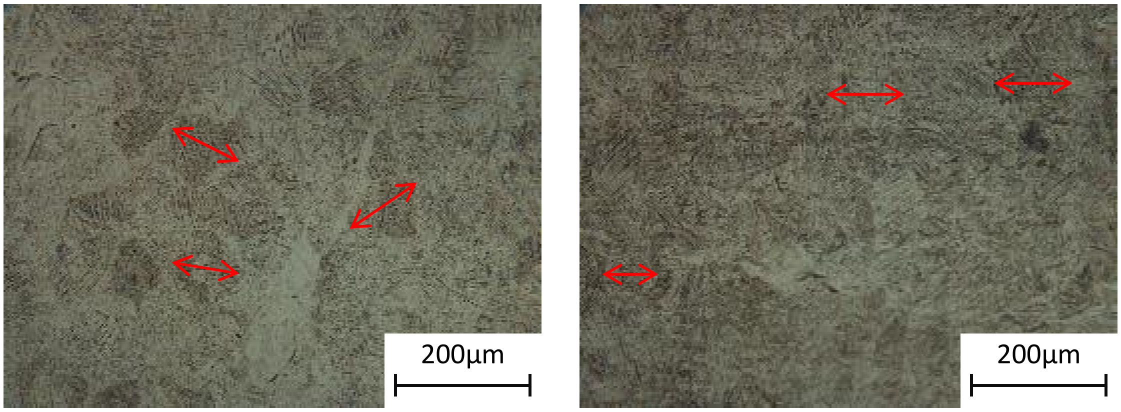


Fig. 15 Optical microstructures of the cross-section surfaces of Ti6Al4V (bulk) sample (Left: top; Right: side)

For the thin-feature struts fabricated via the default parameters, it was also found (Fig. 16) that the columnar grains orient generally along the build direction regardless of the tilt angle of the strut geometries. This clearly indicates that the dominant temperature gradient under the investigated process parameters remains largely identical to that with bulk geometries. It was speculated that the strut orientation factor might become significant if a slower scanning speed is used. As the size of struts reduces, the width of columnar grains becomes smaller as shown in Fig. 16 and Fig 17. In addition, at 75° orientation, the widths of the grains in the center interior of the strut were significantly larger than those located near the boundaries of the struts, indicating that the thermal conditions could still become significant even for the small structures (Fig. 18).

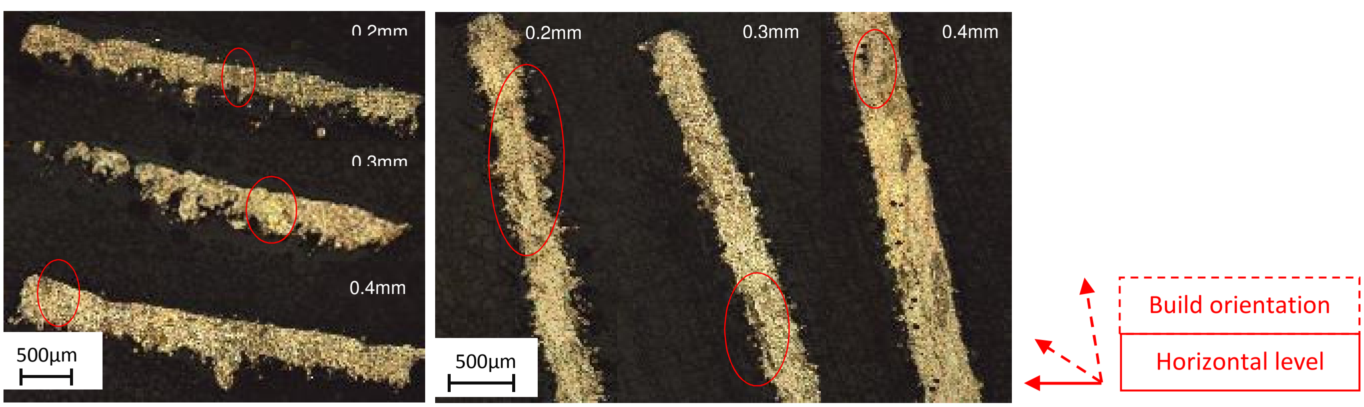


Fig. 16 Side cross-section of thin feature struts (Left: 15°; Right: 75°)

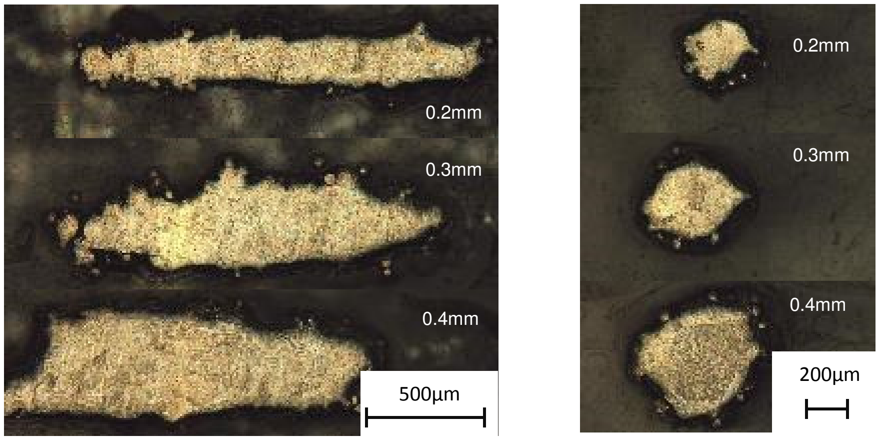


Fig. 17 Top cross-section of thin feature struts (Left: 15°; Right: 75°)

From Fig. 18 it could also be observed that the grain size did not show significant dependence on the tilt angle. The grain sizes for the 15° struts and the interior grain sizes for the 75° struts exhibit very similar values at the range of strut diameters investigated. On the other hand, the boundary grain sizes for the 75° struts were approximately 50% of that from interiors.

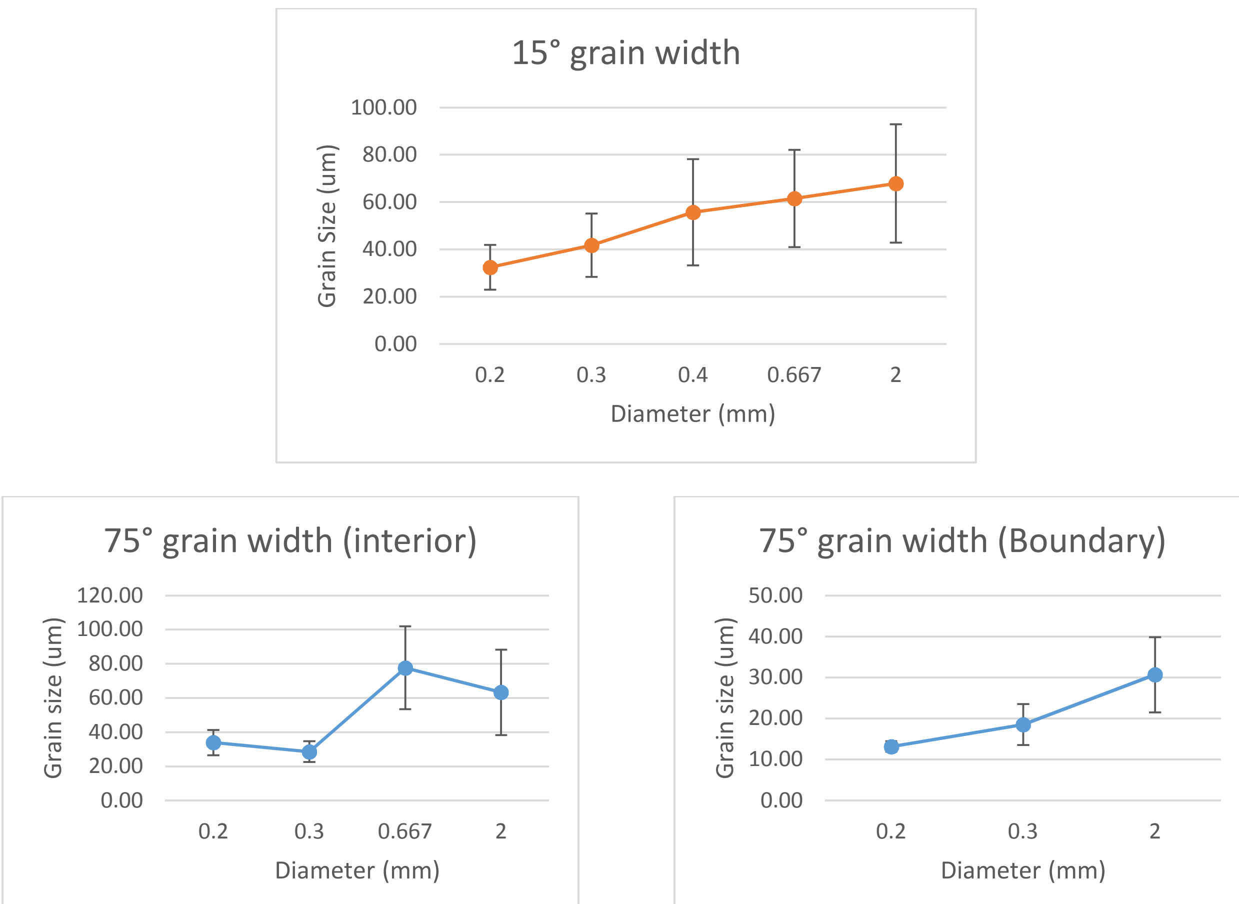


Fig. 18 grain widths of thin feature struts

6. Conclusions

Through this study, it was found that scanning strategies significantly affect the fabrication of thin feature Ti6Al4V struts in SLM. It appears that the default process parameters for bulk materials could be used to generate some thin feature structures, although the minimum achievable size is rather coarse. With high fabrication failure rate, the experimental study was insufficient to verify the effect of different scanning strategy on the quality of the thin strut parts. The minimum feature size that could be achieved under various process conditions is approximately 0.12mm, although this was realized when the design dimension was significantly smaller (0.05mm), and is also significantly affected by the build orientation.

The mechanical properties of the struts appear to be dependent on the input energy density, although the results from this study exhibit significant standard deviation that requires further study to address. The microstructure of the fabricated struts exhibit columnar grain that aligns along the build direction, and the sizes of the grains appear to have linear dependency on the strut dimensions.

Acknowledgement

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Reference

Li Yang, Haijun Gong, Samuel Dilip, Brent Stucker. An investigation of thin feature generation in direct metal laser sintering systems. Proceedings of the Solid Freeform Fabrication Symposium, Austin, TX, USA. 2014.