

Research Paper

Controlling and testing anisotropy in additively manufactured stochastic structures

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ARTICLE INFO

Keywords:

Additive manufacturing
Powder bed fusion
Stochastic
Porous
Isotropy
Biomaterial

ABSTRACT

Additive manufacturing (AM) enables fine control over the architecture and mechanical properties of porous lattice structures. Typical periodic unit cells used in porous structures are inherently anisotropic, may not be suitable for multi-axial applications and cannot reliably create features or struts with low build angle. This study used laser powder bed fusion (PBF) to create isotropic stochastic porous structures in stainless steel (SS316L) and titanium alloy (Ti6Al4V), with modifications that aimed to overcome PBF manufacturing limitations of build angles. The structures were tested in uniaxial compression ($n = 5$) in 10 load orientations relative to the structure, including the three orthogonal axes. The testing verified that no hidden peaks in elastic modulus existed in the stochastic structure. Modification to the structure reduced the standard deviation of the 10 elastic modulus values from 249 MPa to 101 MPa when made in SS316L and from 95.9 MPa to 52.5 MPa for Ti6Al4V, indicating the structures were more isotropic. These modified stochastic structures have improved stiffness isotropy and could be used for lightweighting and biomaterial applications, reducing the dependence of performance on build orientation, and allowing more flexibility for component orientation on the build platform.

1. Introduction

Additive manufacturing (AM) methods enable fine control of porous lattice structures made from metallic alloys [1–5]. This control allows the internal architecture of an additively manufactured component to be specified and optimised for specific mechanical performance, such as tailored stiffness properties. This has applications for lightweighting and energy absorbing components in the aerospace industry [4,6], as well as for AM biomaterials that stimulate bone strengthening by influencing strain [7,8].

The vast majority of AM lattice structures in the literature use a repeating cubic unit cell, which is tessellated in 3D space. These can be based on Platonic and Archimedean solids, or strut-based structures based on crystal packing, such as body-centred-cubic (BCC) or face-centred cubic (FCC) structures [9]. Other unit cells are based on triply-periodic minimal surfaces (TPMS) [10], or use topology optimisation to create unit cells with specific mechanical properties [11–13]. Uniaxial compression testing is used to evaluate the mechanical performance, often plotting the change in stiffness as a function of the relative density of the lattice. However, this testing is usually only

conducted in one direction. Therefore, any change in lattice stiffness in off-axis directions is often unaccounted for.

Repeating unit cell lattice structures have been shown to vary in stiffness by 2.5–6 times depending on the orientation [4,14–16], and potentially more depending on the lattice dimensions used [17,18]. Some unit cells, such as the gyroid show less stiffness variance varying by up to 1.7 times [19]. Testing in multiple directions has demonstrated the anisotropy of repeating unit cells [20] and FEA has demonstrated changes in stress distributions under multidirectional loads [21]. Therefore, unit cells have varying degrees of anisotropy, some with highly varying stiffness which could compromise the mechanical performance of components that use them. This is a cause for concern as porous lattices are often used as ‘space-filling’ geometry within a component.

Some work has attempted to control anisotropy in a unit cell based AM lattices. Plate based lattices in polymer materials based on crystal packing planes have been proposed [9] and FEA simulations of strut-based unit cells have been performed [4,22], but without mechanical testing to prove their behaviour when manufactured. Topology optimisation has been used to achieve isotropic mechanical behaviour,

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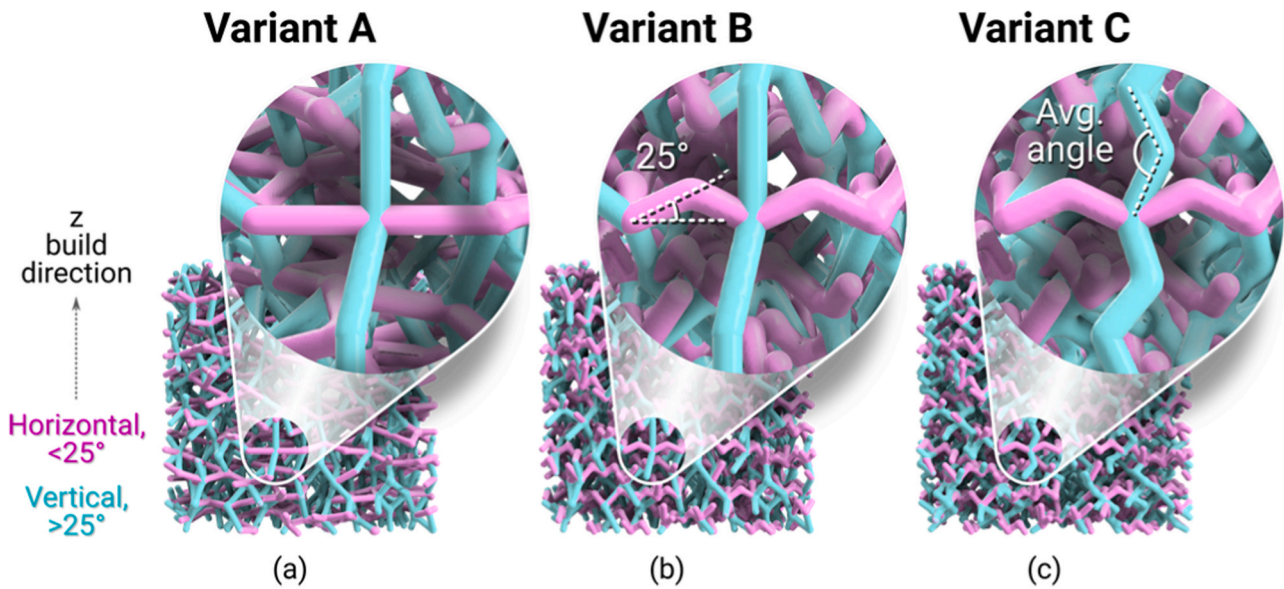


Fig. 1. Stochastic structure variations, (a) variant A, no change, (b) variant B, low angles kinked, and (c) variant C, all angles kinked. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with one study using a unit cell similar to a TPMS Schwarz-p primitive structure [11], but the structure has little open porosity and may not be suitable for applications where flow through the lattice is required. Stochastic structures offer an alternative approach. These do not use a regular unit-cell approach, and instead use distributions of points that are generated algorithmically, closer resembling traditional open-cell metallic foams [23], and thus have no hidden planes of high stiffness [24–26]. In our study we use a stochastic structure to take advantage of this and aim to create an isotropic stiffness structure.

A major challenge in creating a stochastic structure using laser PBF is in building struts at low angles to the build plate. Previous PBF structures were built without struts with an angle lower than 30° to the build platform [25,26]. This results in higher anisotropy, with a higher stiffness in the build direction versus in the plane of the build platform [27]. Removal of these struts forfeits the advantage stochastic structures have over unit cell based lattices, whereby material is distributed evenly in every direction. There is an increasing interest in stochastic structures with controlled anisotropy [28], and our study presents a way to manufacture these low angle struts such that they contribute to the overall structure stiffness in that direction.

The aim of this paper is to create a stochastic structure with isotropic stiffness properties. To achieve this, we must overcome the manufacturing limitations of low angle struts in laser PBF. Uniaxial compression testing is used in multiple directions, to find mechanical properties and verify the anisotropy of the structure. Two materials are

used, stainless steel (SS316L) and a titanium alloy (Ti6Al4V), to cover a broad range of engineering applications.

2. Materials and methods

2.1. Specimen design and manufacture

A stochastic structure was created using Rhinoceros 5.0 and the Grasshopper plugin (Robert McNeel & Associates). A volume was populated with pseudo-random points using the Populate 3D component, which uses a conditional random insertion algorithm to generate uniform points, whilst maintaining a specific minimum proximity. The points were then joined by lines (struts) subject to three parameters:

1. The number of connections to make at a node
2. The minimum length of a connection
3. The maximum length of a connection

such that a certain ‘connectivity’ was achieved, defined as the number of struts terminating at a given node. This method is identical to that used by Ghouse et. al. [25], although in that case a Poisson-disc sampling algorithm was used to generate initial points. The minimum distance that was allowed as a strut connection was 0.4 mm, allowing space between nodes and creating a pore size of around 400 μm. The density of

Table 1
Comparison of each variant and the distribution of struts in each direction.

	Variant A	Variant B	Variant C
Node locations	Same	Same	Same
Strut density (struts/mm ³)	4.06	4.06	4.06
Average connectivity	5.80	5.80	5.80
Diagram showing average length of strut segment in millimetres in each direction from horizontal (0°) to vertical (90°)	90 0.5 0	90 0.5 0	90 0.5 0

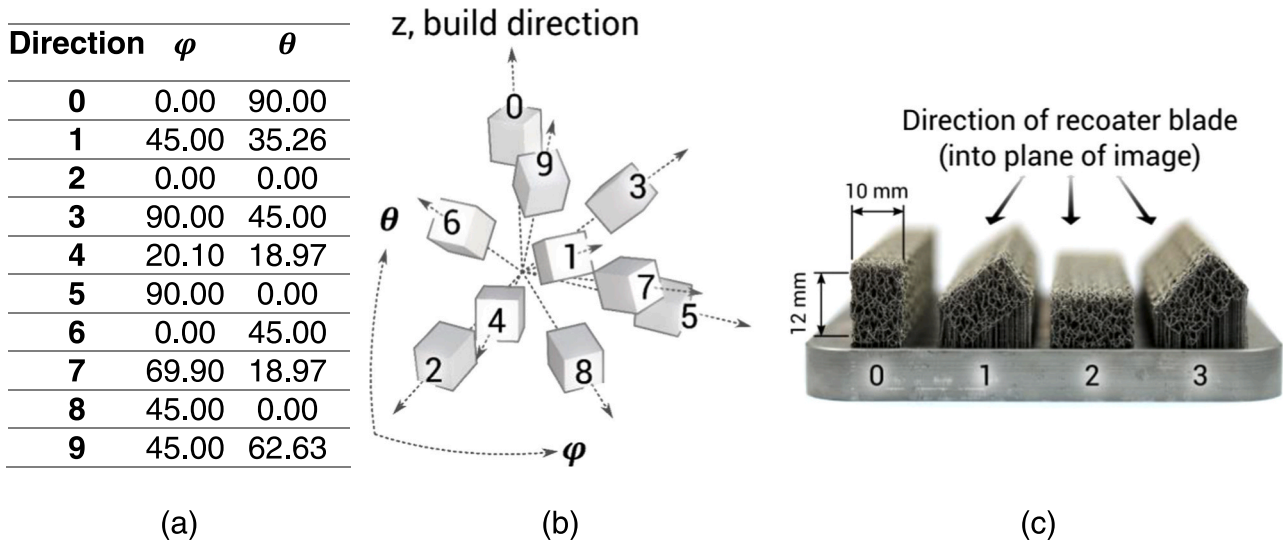


Fig. 2. Test directions for structures, (a) shows spherical coordinates, (b) shows specimen orientations and (c) shows printed specimens. Airflow direction is from left to right, perpendicular to recoater blade direction.

the structure was 4.06 struts/mm³ and with an average connectivity at each node of 5.80.

2.1.1. Stochastic structure variations

Three variants of the stochastic structure were generated. The first variant, variant A, was as described above with no further action, including horizontal or low angle struts relative to the build direction (see Fig. 1a).

A second variant, variant B, was created where all struts with an angle less than 25° to the horizontal plane were identified as ‘close to horizontal’ and potentially prone to building poorly (shown in pink in Fig. 1). These struts are split into two parts and redrawn in a ‘kinked’ configuration, such that the strut subtends the same points but now kinks upwards to increase the angle of the strut to the horizontal to at least 25° (Fig. 1b). This is to help improve the building of this connection between two nodes, as the overhang is built at an angle layer by layer, until reaching the midpoint of the kinked strut.

A third variant, variant C, was created where in addition to the kinked horizontal struts, all remaining struts with an angle more than 25° to the horizontal direction (identified as ‘vertical’ and highlighted in blue in Fig. 1) were kinked to an angle matching the average resulting angle of the horizontal kinking in the second variant (Fig. 1c).

The resulting change in the distribution of strut ‘directions’ in each variant of the lattice structure is shown in the last row of Table 1 below. The diagrams show the average length of strut segment at a given orientation to the build platform, as measured from the CAD files.

2.1.2. Printed specimens

Cuboid compression specimens were generated containing the structure variants aligned in 10 different directions to the testing axis, as shown in Fig. 2 below. Five specimens were tested per direction. Specimen dimensions were 10 × 10 × 12 mm and conformed to ISO 13314:2011 [29].

2.2. Materials and manufacturing

All specimens were printed using a Renishaw AM250 PBF additive manufacturing system, (spot size of 70 μm and wavelength of 1.07 μm). Solid STL geometry is usually printed using a contour-hatch printing strategy [25]. For this small-scale line geometry, the contour-only method was used to melt the required cross section of each strut as described by Ghouse et. al. [25]. Contours are traced with individual points, holding the laser at a point for a specified exposure time and then

moving to the next point in the sequence. Slice data (build files) were generated at 50 μm layer thickness using Material Engine 1.0 (Betatype Ltd).

Both stainless steel (SS316L) and titanium alloy (Ti6Al4V ELI, Grade 23) spherical powder of particle size range 10–45 μm were used to create specimens, supplied by Carpenter Additive Ltd. The build chamber was vacuumed to −960 mbar and then back filled with 99.995% pure Argon to 10 mbar with an O content of ~0.1%. For SS316L, laser power was constant at 200 W whilst exposure times varied from 30 to 60 μs to maintain a constant strut thickness. For Ti6Al4V, laser power was constant at 50 W whilst exposure times varied from 100 to 150 μs.

Specimens were removed from the build platform using wire erosion, ensuring that the wire path preserved the intended part geometry, then cleaned using ultrasonic bath and air jet. Each specimen was individually measured thrice in each dimension using Vernier caliper, and dry weighed thrice at normal atmospheric conditions. The relative density was then calculated by dividing the specimen weight by the bulk weight of the metal that corresponds to the specimen macro volume. A density of 8.1 g/cm³ was used for SS316L, and for Ti6Al4V ELI, 4.42 g/cm³.

A selection of Ti6Al4V specimens to be tested in direction ‘0’ were imaged using a Hitachi S-3400N scanning electron microscope to compare the structure variations.

2.3. Mechanical testing

A materials testing machine (Instron 8872) with a 10 kN load cell was used to perform quasi-static compression testing at an extension rate of 2 mm/min, which corresponds to a strain rate within standard limits [29]. Displacement was measured using LVDTs to reduce any compliance effects from the test apparatus. A sampling rate of 30 Hz was used. The platens of the machine were lubricated to reduce any frictional effects. Stress-strain curves were obtained using the individual macro dimensions of each specimen.

The loading regime includes a hysteresis loop to account for localised yielding within the porous structure. This was carried out from 70% of the yield stress (σ_{70}), to 20% of the yield stress (σ_{20}) and then the specimen is fully compressed to a high strain [29]. A preliminary specimen was compressed to 50% strain at 2 mm/min to find the required reference stresses for both materials. The elastic modulus is then calculated using a linear regression analysis of the hysteresis loop. For all specimens, the 1% offset yield stress was calculated to define the yield properties, as recommended by ISO standard [29]. The strength to

Table 2
Manufactured specimen dimensions compared to intended dimensions.

Specimens	Average width $\pm$ SD (mm)	Average depth $\pm$ SD (mm)	Average height $\pm$ SD (mm)	Average relative density $\pm$ SD (%)
Intended	10 $\pm$ 0	10 $\pm$ 0	12 $\pm$ 0	12.57 $\pm$ 0.73
SS316L	10.25 $\pm$ 0.20	9.76 $\pm$ 0.22	11.95 $\pm$ 0.04	13.00 $\pm$ 0.98
Ti6Al4V	10.00 $\pm$ 0.20	10.23 $\pm$ 0.20	11.95 $\pm$ 0.05	12.51 $\pm$ 0.48

stiffness ratio was also calculated to see if the modifications to the structure affected one property more than the other. To quantify the variation in the results over each direction, the standard deviation for each variant was also calculated for each mechanical property.

3. Results

Table 2 details the average outer dimensions of the final specimens built SS316L and Ti6Al4V, as well as the relative density of the final specimens. These values are compared to the intended dimensions and average intended relative density, calculated using the volumes of the CAD geometry of all designed specimens.

3.1. Mechanical testing

Example stress strain curves for a variant C specimen in direction '0'

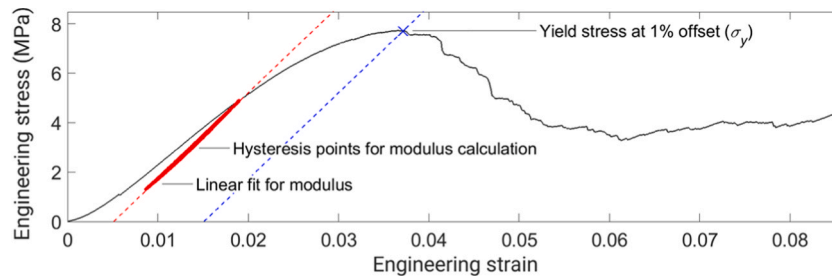


Fig. 3. Stress strain curve for a Ti6Al4V specimen of variant C in the '0' direction.

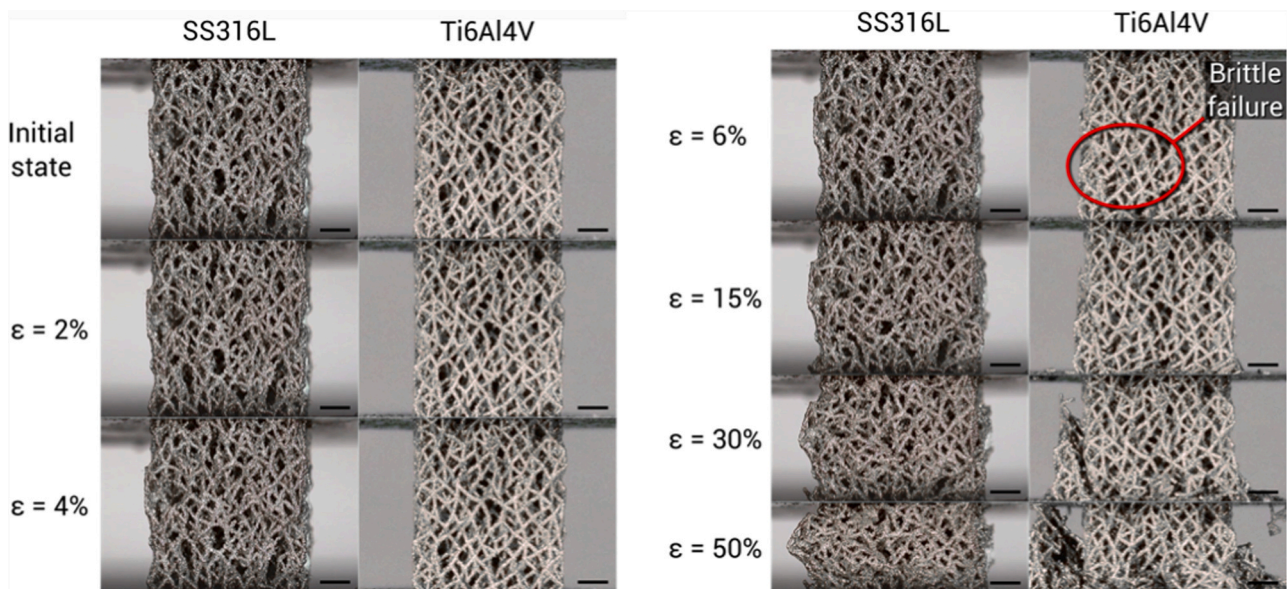


Fig. 4. Photographs of variant A specimens in the '0' direction for both SS316L and Ti6Al4V undergoing compression. The start of brittle failure can be seen in Ti6Al4V at $\epsilon = 6\%$ (highlighted in red). Black scale bar on bottom right of images is 2 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

is shown in Fig. 3 below, for the Ti6Al4V material.

SS316L specimens failed in a ductile manner and were gradually compressed until densification. Ti6Al4V specimens failed in a brittle manner and never recovered the same strength after yielding. Fig. 4 compares the progression of specimen failure SS316L and Ti6Al4V specimens of variant A in the '0' direction, showing how the Ti6Al4V specimens fracture as in Fig. 3 above.

The results for the mechanical testing below show the values for each direction in order of increasing angle to the build platform, i.e. from horizontal directions to vertical. The directions are described in Fig. 2 above.

3.1.1. Elastic modulus

Elastic modulus results are shown in Fig. 5. For SS316L specimens, the moduli of each direction for variant A (no change) ranged from 384 MPa to 1058 MPa, with a standard deviation (SD) of 249 MPa. The overall elastic modulus of the structure increased with variant B (kinking low angle struts) to an average of 1191 MPa, whilst reducing the SD to 135 MPa. Variant C (kinking all struts) had a lower average modulus of 973 MPa, but also a lower SD of 101 MPa.

For Ti6Al4V specimens, the average elastic modulus was reduced with each succeeding variant, going from 680 MPa for variant A to 500 MPa for variant B, and then to 350 MPa for variant C. The SD did decrease going from variant A to C, from 95.9 MPa to 52.5 MPa, although not as considerably as SS316L. When modifying only the horizontal struts in variant B however, the SD was increased to 111 MPa.

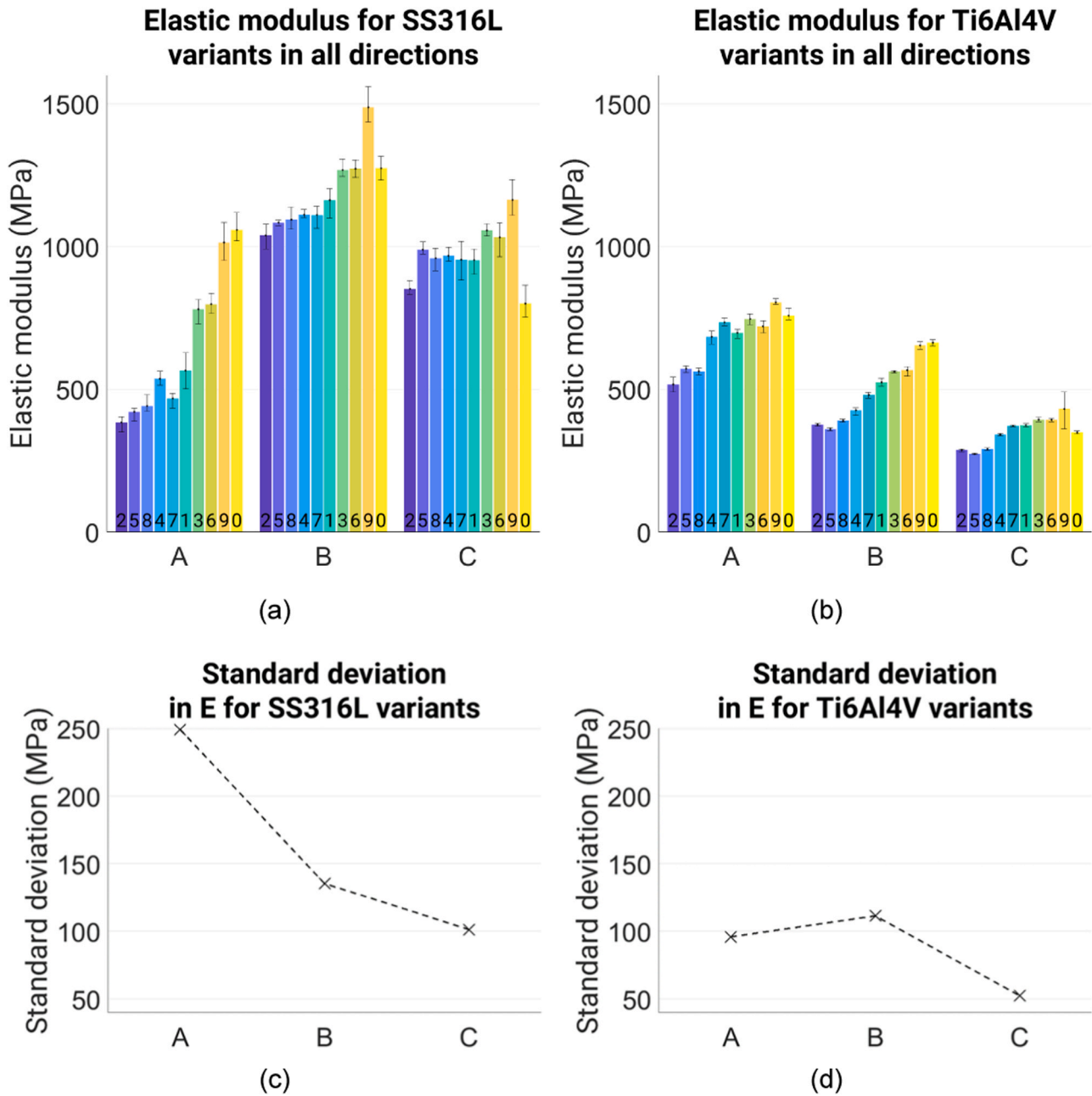


Fig. 5. Elastic modulus vs test directions. Directions are grouped by the structure variant A, B and C for (a) SS316L and (b) Ti6Al4V specimens. Standard deviation for each variant shown for (c) SS316L and (d) Ti6Al4V specimens.

3.1.2. Yield strength

Fig. 6 shows similar results for the plastic properties of both materials as for the elastic properties in Fig. 5. For SS316L specimens, the average 1% offset yield stress increases from variant A at 4.45 MPa to 6.80 MPa for variant B. This decreases slightly again to 6.56 MPa for variant C. The SD shows the same trend as before, decreasing from 0.715 MPa to 0.395 MPa.

For Ti6Al4V specimens, the average 1% offset yield stress decreases from 11.76 MPa for variant A, to 9.24 MPa for variant B, and then to 7.72 MPa for variant C. The SD again increases for variant B to 1.39 MPa. However, the overall SD increases slightly from variant A to C, going from 0.863 MPa to 0.870 MPa.

3.1.3. Strength over stiffness ratio

Fig. 7 shows the strength to stiffness ratio for both materials. This ratio compares how the plastic strength properties are affected

compared to the elastic stiffness properties, with the changes to the structure made by each variant. For SS316L specimens, the ratio does not change dramatically with each variant. The average ratio decreases by 9% going from variant A to C, showing that there is some small loss in strength/stiffness by modifying the structure.

For Ti6Al4V, the ratio steadily increases going from variant A to C, increasing by 27% overall. Whilst both strength and stiffness decrease for Ti6Al4V variants, the stiffness or elastic properties are decreased more readily than the plastic strength properties.

The strength to stiffness ratio plotted in Fig. 7 demonstrates that the modifications do not disproportionately affect the elastic over the plastic properties or vice versa, especially for SS316L. The ratio does increase by 27% for Ti6Al4V variant C specimens however, and whilst both the strength and the stiffness do decrease going from variant A to C, the strength decreases less as the modifications are made. This is useful improvement for musculoskeletal applications.

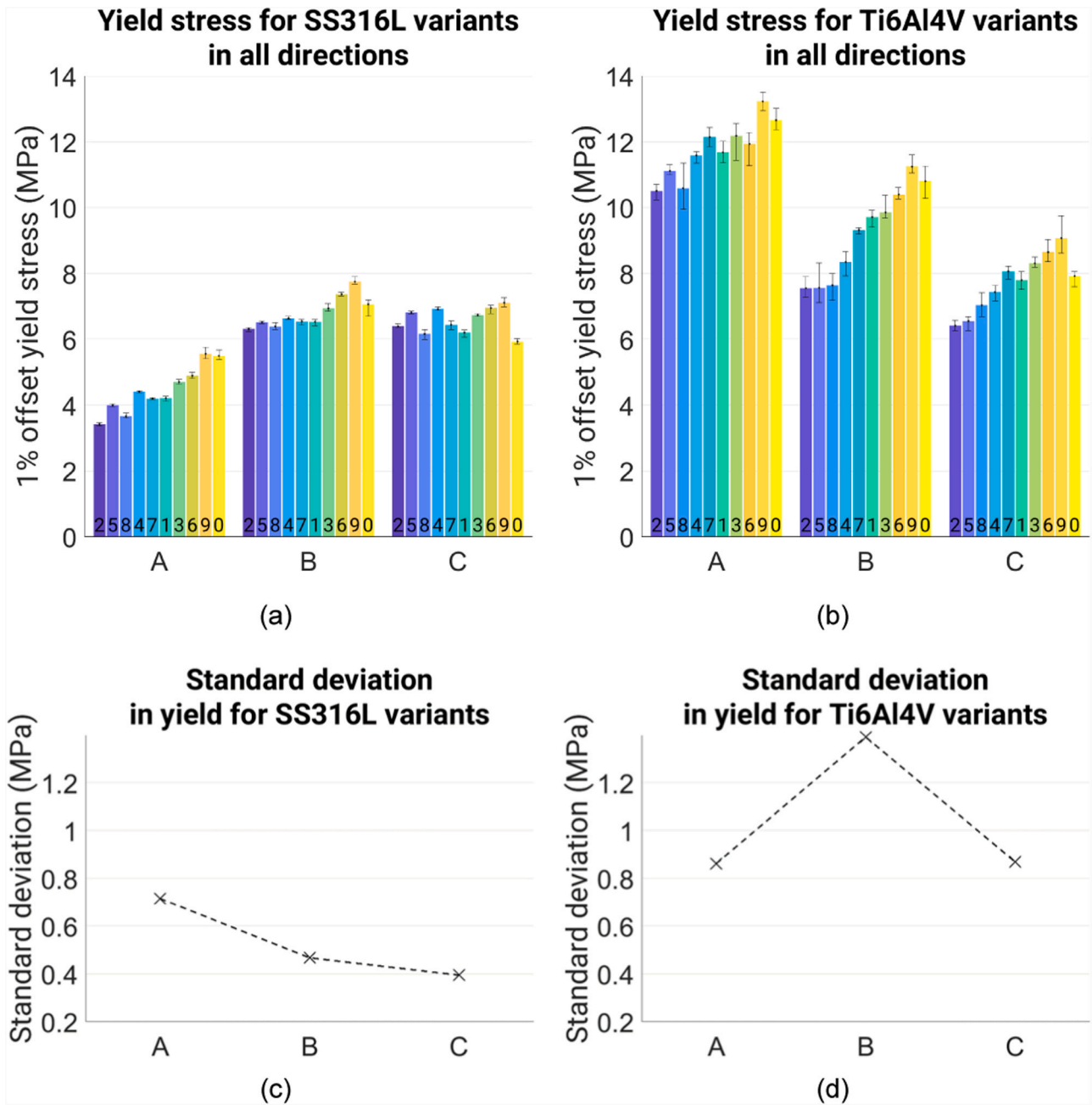


Fig. 6. Yield stress vs test directions. Directions are grouped by the structure variant A, B and C for (a) SS316L and (b) Ti6Al4V specimens. Standard deviation for each variant shown for (c) SS316L and (d) Ti6Al4V specimens.

SEM images in Fig. 8 show the effect of each modification from variant A to C on the print quality and final geometry of the printed structure. A failed horizontal strut in variant A can be seen having been successfully built in variants B and C due to the kinking process.

4. Discussion

This work shows that a modified stochastic structure can overcome the mechanical anisotropy inherent in lattice structures due to unit cell geometry. For SS316 and Ti6Al4V, testing these properties in 10 directions verifies that there are no hidden peaks in elastic modulus or yield stress, as opposed to traditional unit cell based lattices [4,14]. The stiffness and strength of the variant C structures were within $\pm 10\%$ for all 10 directions tested. In all cases, the stress-strain curve of our stochastic structures was similar to that of a continuum material. There are

no failure planes that could occur from a repeating unit cell, where the same part of the cell fails at once under a critical load (a shear band-type global failure) [30]. This work also demonstrates a method of creating load bearing struts in the direction parallel to the build surface, enabling increased flexibility in orienting components on the build platform, in order to reduce cost and increase manufacturing capacity. Although our goal was to improve isotropy, the structure could easily be modified to a desired anisotropy by increasing or decreasing the strut diameters at the required angles.

For AM porous lattices, both the varying morphology of struts and microstructural effects have an impact on mechanical properties in different loading directions. Individual struts built at a low angle to the build platform have worse roughness and build quality (morphology) than those built in a vertical direction [31–33]. This is due to the layer-by-layer fabrication inherent to PBF, leading to changing

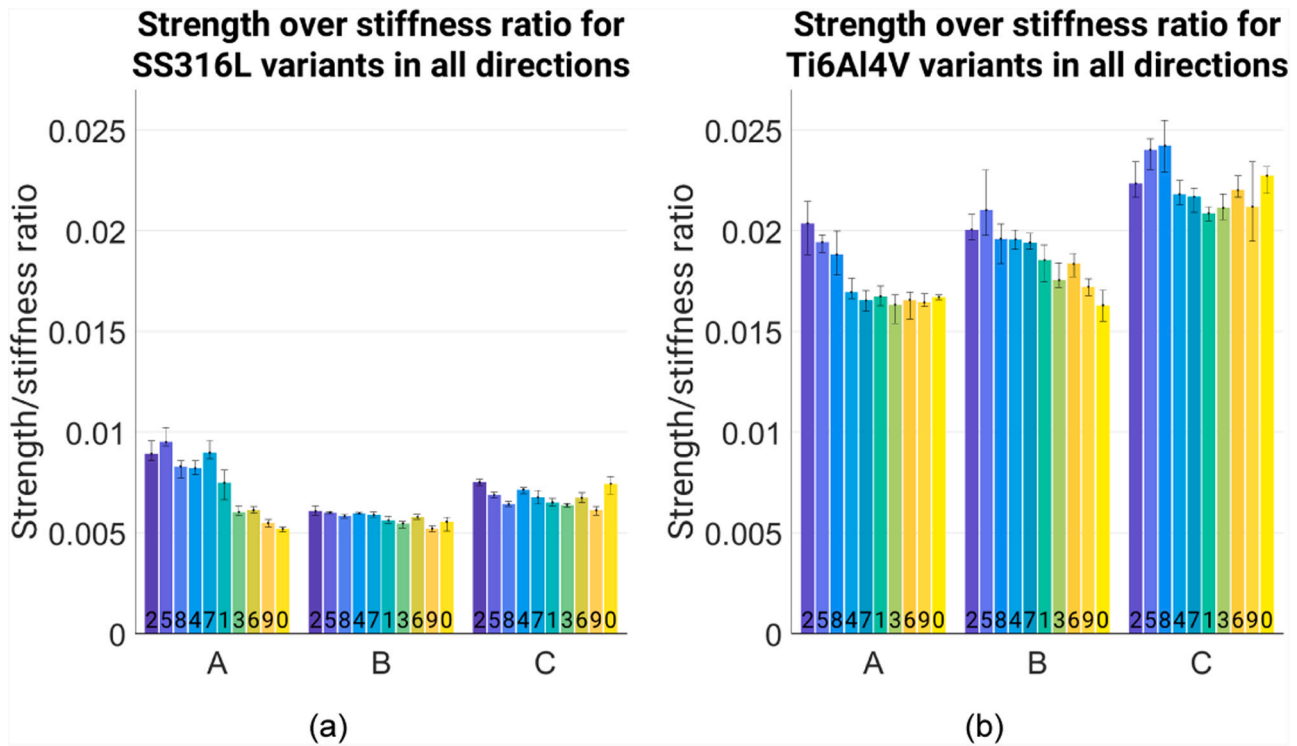


Fig. 7. Strength over stiffness ratio vs test directions. Directions are grouped by the structure variant A, B and C for (a) SS316L and (b) Ti6Al4V specimens.

performance of lattices in different orientations [34]. Also, even in solid AM components, the orientation and size of the grains relative to the build angle effects strength and ductility. So, whilst the kinking procedure may make the structure more geometrically isotropic, microstructural effects will still apply. Different materials will be impacted differently in this respect. Material datasheets by Renishaw quantify the different ratios of mechanical properties in the build directions versus in perpendicular directions, for both SS316L and Ti6Al4V [35,36].

The variation in the yield properties for Ti6Al4V specimens did not necessarily improve as modifications were introduced as compared to SS316L (shown in Fig. 6d), and this may be due to the two effects discussed. Ti6Al4V struts built at a low angle have been shown with SEM imaging to have more surface cracks and stress concentrations [25]. Due to the brittle nature of Ti6Al4V, these struts may be prematurely yielding due to poorer morphology and impacting the performance of the lattice, even in the elastic regime. There is also higher levels of residual stress in the Ti6Al4V lattices. By contrast, SS316L strain hardens and the steel struts may therefore have been able to sustain more load post-yield. Where the lattice yields locally in the elastic regime, strain hardening may improve the performance even in directions perpendicular to the build direction. Using post processing techniques such as chemical etching may smooth out stress concentrations and roughness present in the lattice [37–39], which disproportionately affect low angle struts. However, maintaining an equal application of the etching within the interior of the lattice may present an extra challenge.

Our isotropic lattices compare well to other isotropic work in the literature. Standard unit cell designs, such as an FCC structure, have shown anisotropies in stiffness of over 6 [16]. Prior work aiming to create isotropic lattices either mix multiple unit cell designs, optimising the beam diameters or plate thicknesses to reach elastic isotropy [9,22], or the unit cell undergoes topological optimisation [4,11,40]. The results for these lattices have shown highly isotropic behaviour. In our study we were able to create an isotropic stiffness structure (variant C) to within $\pm 10\%$, but an advantage of our study is that we experimentally demonstrated the stiffness in different directions whereas prior work has relied on FEA methods which may not capture the limitations in build

angle, strain hardening or altered mechanical properties due to the thin strut morphology.

Unit cells produced using optimisation can potentially present a challenge to manufacture using PBF due to the presence of horizontal beams [4,22], or of closed cavities that may trap metal powder [9]. The topology-optimised unit cell presented by Takezawa et. al [11] resembles a Schwarz P minimal surface and so would be better able to self-support during manufacturing. A general disadvantage for these structures is the need to re-optimize the structures for higher relative densities, and higher stiffnesses. The modifications to the stochastic structure shown in this study helped improve the fabrication of low-angle struts. Another approach would simply be to remove low angle struts, whilst maintaining a connected stochastic structure. Previous work by the authors has shown that doing so reduces the stiffness of the lattice in the x-y plane substantially, resulting in a ratio of maximum to minimum stiffness of 4.6 [41].

All open cell, strut-based isotropic lattice designs will have their properties dictated in some way by the AM technique used. For example, the pilot data for this work indicated that the 25° critical angle was appropriate for our setup, and this may not be the case for different materials, build parameters or manufacturing method. Other limitations of the work presented here relate to the manufacturing process. The specimens generated in the orientations seen in Fig. 2b are rotated before printing as in Fig. 2c, to face one direction for easier removal using electro-discharge machining/wire erosion. Therefore, the direction of the recoater blade varies with respect to the structure and is not kept constant. This may have an effect on the morphology of individual struts within the lattice [42], and therefore have an effect on the mechanical properties of the structure, causing variation in the results when comparing directions at the same angle to the build platform (i.e. directions 2, 5 and 8). However, it is expected that these effects are small with correct functioning of the recoater blade.

When creating porous lattices with feature sizes from 100 to 300 μm using PBF manufacturing, factors such the slicing method, and the quality of air filtration/optical train all influence the lattice performance. These may vary from printer to printer, so further tests would be

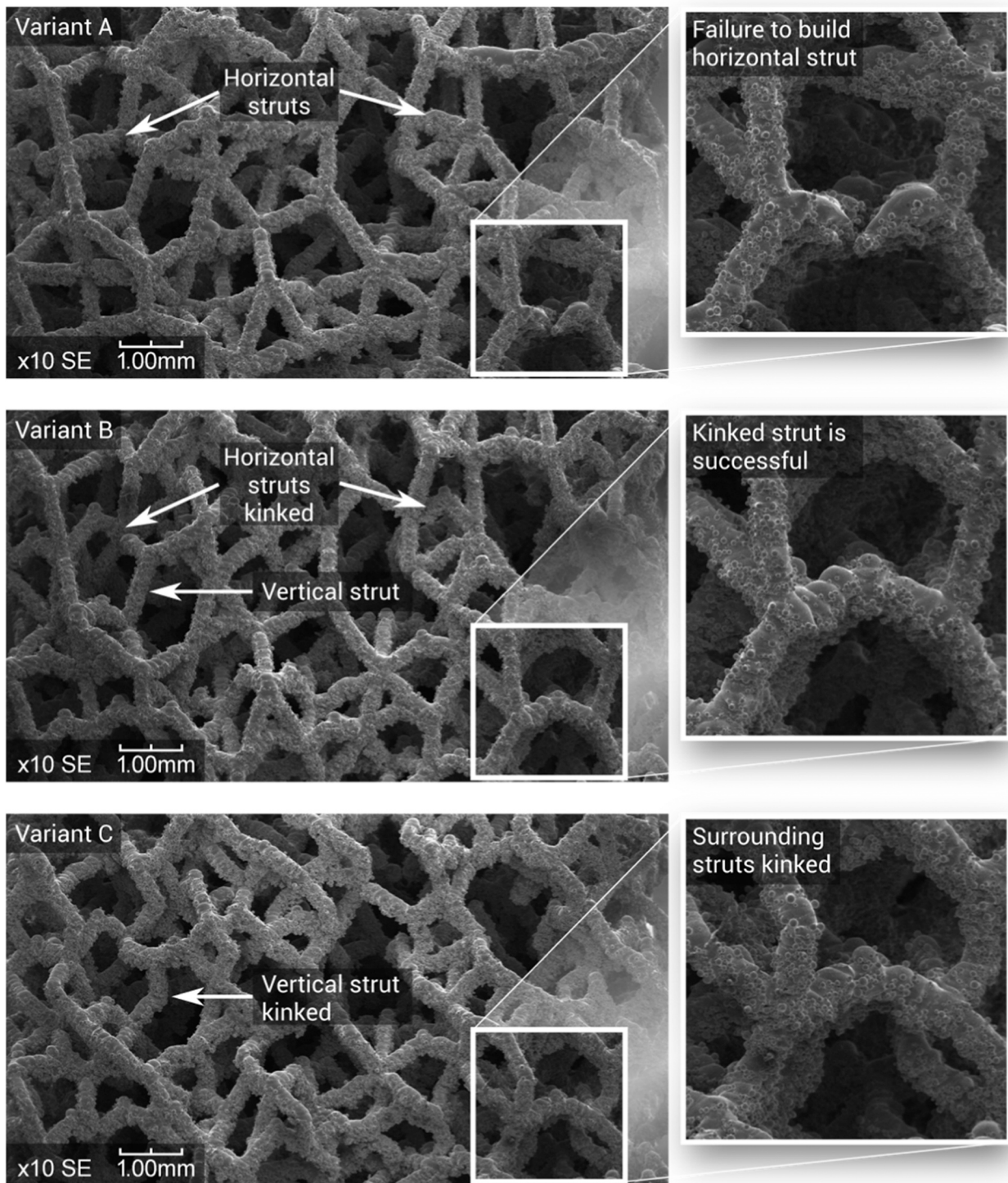


Fig. 8. SEM images of the same location on a Ti6Al4V specimen '0' structure for each variant A, B and C.

necessary to evaluate the robustness of the structure against manufacturing method. Some parameters have been fixed for this study, which may have a key role in the mechanical behaviour. The effect of the value chosen for the critical angle of 25° has not been explored. Further work would explore how the mechanical isotropy changes with variation in that angle. The structures have also been tested at one density only. Testing at higher densities would allow a relationship with strength and modulus to be established, and whether this fits the Gibson-Ashby model for porous materials. FEA models could also be used to see how kinking the beams affects whether the structures are more stretch or

bending dominated in their behaviour [43].

5. Conclusion

The modified stochastic structure presented here has the potential to be used as a base structure for stiffness-controlled components, either for light-weighted components that need a uniform stiffness in all directions or in AM biomaterials that replace trabecular bone. Overcoming PBF manufacturing limitations that cause anisotropy in stochastic structures reduces the dependence of the lattice performance on build direction,

especially compared to some unit cell based lattices. This has the benefit of allowing a greater range of orientations that the lattice could take within a component. This increases the options for arranging components on a build platform as different orientations would be possible, reducing the space required and providing flexibility in build layout.

Funding

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC), (grant Nos EP/R042721/1, EP/N006267/1), National Institute for Health Research (grant No NIHR300013) and the Wellcome Trust (208858/Z/17/Z). We also thank Renishaw plc for their financial and technical support.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is currently being moderated by Mendeley Data: <https://dx.doi.org/10.17632/sx426rr8k4.1>.

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