Article:

Jenkins, S.N.M., Oulton, T.H., Hernandez-Nava, E. et al. (3 more authors) (2019) Anisotropy in the mechanical behavior of Ti6Al4V electron beam melted lattices. Mechanics Research Communications, 100. 103400. ISSN 0093-6413

https://doi.org/10.1016/j.mechrescom.2019.103400

Mechanics Research Communications. Year	Publication Office: **Elsevier UK**
Editor-in-Chief: A. Rosato New Jersey Institute of Technology, Newark, New Jersey, USA Anthony.Rosato@njit.edu	

Anisotropy in the Mechanical Behavior of Ti6Al4V Electron Beam Melted Lattices

Sarah N. M. JENKINS[1], Thomas H. OULTON[1], Everth HERNANDEZ-NAVA[1], Hassan GHADBEIGI[2], Iain TODD[1], R GOODALL[1*]

[1]*Department of Materials Science and Engineering, the University of Sheffield, Sir Robert Hadfield Building, Sheffield, S1 3JD, UK*
[2]*Department of Mechanical Engineering, the University of Sheffield, Sir Frederick Mappin Building, Sheffield, S1 3JD, UK*
*r.goodall@sheffield.ac.uk
Tel.:+44 (0)114 222 5977, Fax: +44 (0)114 222 5943

Abstract

With advances in additive manufacturing methods for metals with defined, complex shapes, the investigation of metallic lattice materials (metals with significant porosity and a regular arrangement of the solid, frequently in the form of thin struts) has become more common. These materials may be highly optimized for particular applications, and can show mechanical behaviors not displayed by other solids; for this reason, they are often used as routes to create mechanical metamaterials. However, thermal history experienced by the material in this novel process affects the microstructure produced, in particular making it highly directional. While understood for dense parts, the behavior in porous materials, where the structure itself can alter the thermal history experienced locally, is more ambiguous. This paper examines the mechanical properties of titanium alloy lattices based on the widely-used diamond structure, fabricated by Electron Beam Melting (EBM). Related forms, distorted to alter the symmetry (from cubic to tetragonal) are tested and compared to more clearly elucidate the anisotropy in their mechanical properties. For the distorted lattices, the elastic modulus along the stretched direction is increased by a factor of over three, and the yield strength is more than doubled. In both lattices the orientation is found to have a much less significant effect than seen for bulk materials, likely to be due to the high proportion of the lattices that are influenced by free surface.

Keywords: Ti6Al4V; lattices; Additive Manufacture; mechanical properties; anisotropy

1. Introduction

Additive Manufacturing (AM) techniques [1, 2], have the ability to create porous metal structures with great control over the form. Such materials may have specific behaviors; the ability to be crushed, to permit fluid transport or to allow an extra level of tailorability (that of the structure) to obtain the desired properties for the material [3]. Complex, highly engineered structures can be made (e.g. [4-6]) and regular lattices can display combinations of mechanical properties and density that are not found in other materials (see e.g. [7] and the review in [8]). This has led to lattice designs being one route explored towards mechanical metamaterials [9].

Metallic metamaterials have a number of potential advantages, particularly mechanically, due to the enhanced strength, ductility and operating temperature over other material classes. Such materials can only be processed by a limited subset of AM techniques, and of these, powder bed methods (where selective areas of sequentially-deposited powder layers are melted to build up the structure) have an advantage for complex structures with fine detail over direct deposition techniques in that the structure does not have to have the same degree of self-support during processing. While different powder bed methods may have different strengths (e.g. laser-based techniques for fine scale structures and surface finish), the Electron Beam Melting (EBM) technique has the significant advantage of reduced processing times.

Whatever the manufacturing technique, analysis of mechanical performance of as-manufactured metal AM parts is vital; the manufacturing method and processing conditions influence the microstructure, potentially in concert with the lattice geometry. For example, the dissipation of heat from the part will affect the solidification and thus the microstructure (in the absence of a post-processing heat treatment); the density and even the structural form of the lattice could influence the pathways available for heat dissipation. Different microstructures have been observed in different areas within the same lattice and correlated to thermal conditions during the AM process [10], and such variations will have potential impact on the overall lattice behavior.

It is known that solid samples made from metal via EBM can display varying mechanical properties depending to some extent on the orientations in which they were built and tested [11-15], as is the case for AM techniques in general [16]. In tests on lattices, the same behavior is often suspected, and has been used for example to explain differences between theory and experiment in the properties of auxetic lattice structures made by EBM [17]. In investigations that specifically explore the effect, Heinl *et al* [18] found that symmetrical lattices were both stronger and stiffer when tested along the build direction. This effect was attributed to the layer-by-layer fabrication, without the precise mechanism being identified. Wauthle *et al* [19] investigated the compressive mechanical properties of diamond structure lattices made by Selective Laser Melting (SLM) in a variety of orientations. They found no significant differences between horizontal and vertical orientations relative to the build direction (although structures rotated by 45° in the build chamber were found to be weaker, due to particular problems of high defect density in the horizontally-built struts that resulted).

It should be noted that the concept of orientation in lattices can cover several different aspects of how the structure is positioned in a larger envelope or component, and how it is fabricated (all AM processes involve sequential deposition, and the final part retains aspects of this in its structure). Other work has explored the effect of changing the orientation of the lattice within a cylindrical sample (where the lattice structure is used to fill the space within the cylinder, rather than being an integral number of unit cells), and found strong effects, but these orientation dependencies can mostly be referred to the design methodology used and the manner in which it fills the sample shape, since build and test directions were identical [20].

In the present research the effect of sample orientation on the build stage is tested in EBM manufactured Ti6Al4V lattices through compression tests of conventional and modified diamond lattices. These lattices are created by taking the conventional diamond structure, based on a repeating unit cell with cubic symmetry (all sides orthogonal, side lengths $a = b = c$), and distorting it in such a way as to reduce this symmetry to that of a tetragonal structure (all sides orthogonal, side lengths $a = b \neq c$). The distortion thus amplifies the difference between the angles at which struts meet the build direction when fabricated in different orientations, encoding a greater response to orientational change in the internal structure. The compression tests give values for the elastic modulus, the 0.02% yield strength and the first peak stress in the compressive stress-stain curve, and thus show the difference in mechanical results produced by the structure distortion and also the effect of build orientation in each case.

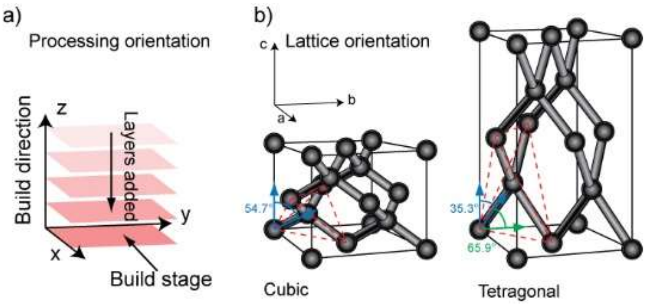

Fig. 1 – Schematic diagram of the lattices used for the cubic and tetragonal lattices. Nodes are exaggerated as spheres for clarity; the build file consisted of struts only.

2. Methods

Key to the understanding of the interaction of structure and mechanical properties in additively manufactured lattice materials is the orientation in both the lattice and the manufacturing process (with each processing operation termed a build). In this paper, orientation in manufacture is described with reference to the build direction (the direction in which the layers are built up), with three orthogonal directions (x, y and z) defined, x and y lying within the plane of the build, and z normal to the plane, i.e. along the build direction (see Fig. 1a). Where reference to the particular lattice structures is required, this is done by describing the different directions in the unit cell, indicated as a, b and c (see Fig. 1b). Lattices were based on a "diamond" lattice (an arrangement where the struts are positioned as the interatomic bonds in the unit cell of diamond) with cylindrical struts, Fig. 1. In order to explore the interaction between lattice structure and orientation and the build direction, the lattice was taken and distorted to alter the symmetry. Both the conventional cubic and tetragonal versions of the lattice were then manufactured. Specification of the tetragonal lattices began with the diamond structure lattice cubic unit cell and doubled the c-axis length, reducing the symmetry from that of the cubic case. The fractional coordinates of the nodes of strut intersections (lattice points) in the new unit cell remain unchanged, but the lengths of the struts and the angles at which they meet at the nodes were altered. For the conventional diamond lattice, (cubic symmetry), the angle between a strut axis and the build direction, z, will be 54.7° whichever lattice direction is aligned with the build direction. For the tetragonal configuration the orientation will affect the angle of the struts to the build direction, which should accentuate orientation effects due to interaction of the processing method and the lattice design. The angle between the struts and the build direction will be 35.3° when the c-axis aligns with z, and 65.9° when perpendicular to it (when z is parallel to a or b). Thus, testing both lattice types built in different orientations will show if there is any anisotropy due to processing, and if the structure of the lattice contributes to this (where the anisotropy would be larger for the tetragonal lattice).

18 tetragonal lattices and 12 cube samples were made from Ti6Al4V powder using an Arcam AB® A2 machine (commercially available EBM equipment). The Ti6Al4V preheat for 50 µm layers was followed by the standard Arcam Ti6Al4V 50 µm layer net theme, comprised of three contour passes followed by a hatch. All samples were composed of 4 unit cells in each direction to be above the limit found for

Table 1. Mean values (and standard deviation in parentheses) of mechanical properties for cubic and tetragonal lattices, tested for processing in the orientations with c aligned to the build direction, z ($c \parallel z$) and the in-plane direction, x ($c \perp z$). Recall that all tests were performed with compression along the c-axis direction.

Lattice	Orientation	Young's modulus [MPa]	0.02% Yield strength [MPa]	First peak compressive strength [MPa]
Cubic diamond	$c \perp z$	173.7 (15.3)	5.9 (0.8)	6.9 (0.4)
	$c \parallel z$	181.0 (3.5)	5.2 (0.8)	7.1 (0.3)
Tetragonal diamond	$c \perp z$	737.0 (38.3)	12.1 (0.7)	17.0 (0.9)
	$c \parallel z$	713.4 (20.9)	11.7 (0.9)	15.9 (0.7)

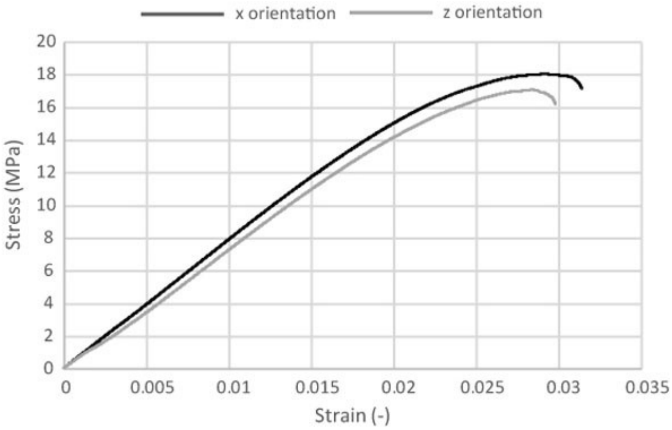

Fig. 2 - Example engineering stress-strain curves produced from compression test data of tetragonal lattices, tested for processing in the orientations with c aligned with x and z.

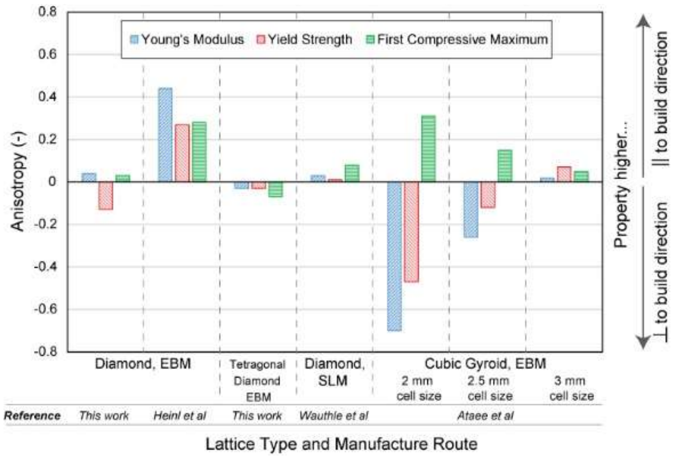

Fig. 3 – Anisotropy indices (Eqn. 1) calculated here for additively manufactured lattices from this work and the literature (Heinl *et al* [18], Wauthle *et al* [19] and Ataee *et al* [22]).

consistent properties in metallic lattices [21], with unit cell size of 6mm, and struts nominally 1mm in diameter.

Samples were mechanically tested in compression on a Zwick Roell Z050 test rig with a 50 kN load cell under a displacement-controlled regime, ensuring an initial strain rate of 10^{-3} s^{-1} until the load was seen to consistently fall (identified with the first collapse of a layer in the structure). Displacement was measured with a Zwick Roell VideoXtens video extensometer with a data capture rate of 25 frames per second. In all cases samples were compressed along the c-axis direction, which ever orientation this had in the build.

3. Results and Discussion

Example compressive stress-strain curves of the tested lattices, Fig. 2, and the data extracted, Table 1, show that loading orientation has little effect on the lattice structure performance.

Direct comparison between cubic and tetragonal lattices is not straightforward as the density is altered by the distortion process (average measured porosity of the fabricated lattices was 90.9% and 91.4% for cubic and tetragonal respectively). However, the change in properties with orientation can be compared, assessing anisotropy according to Eqn. 1 with an index derived from the structural properties (P) measured for samples built with the c direction perpendicular ($\perp$) and parallel (ǁ) to z.

$$Anisotropy = \left(\frac{P_{//} - P_{\perp}}{P_{//}} \right) \quad (1)$$

Fig. 3 shows the calculated anisotropy indices obtained from the present research compared with those calculated here for the data given by similar studies in the literature.

The anisotropy is clearly low for most cases in this work, indicating no significant systematic trend for one orientation to produce superior values. Indeed, the tetragonal lattice shows no significant difference to the regular diamond lattice. When the tetragonal samples are made with the c-axis parallel to the build direction, z, the struts are at a low angle to this direction, 35.3°, and a correspondingly high angle to the plane of the layers. This means that deposited material is mostly directly formed on top of previously-melted solid. When the c-axis of the samples is perpendicular to the build direction, the struts are at a high angle to that direction (65.9°), lying closer to the plane of the layers, and more of the deposited material is positioned on top of unmelted powder. This will influence the formation of the strut, extraction of heat and development of the microstructure (the influence of strut angle on strut formation is discussed in detail in Ref. [15]). In comparison, for a regular diamond lattice, the orientation has no effect on this angle, with struts being at 54.7° to the build direction in either orientation. It would therefore be expected that any

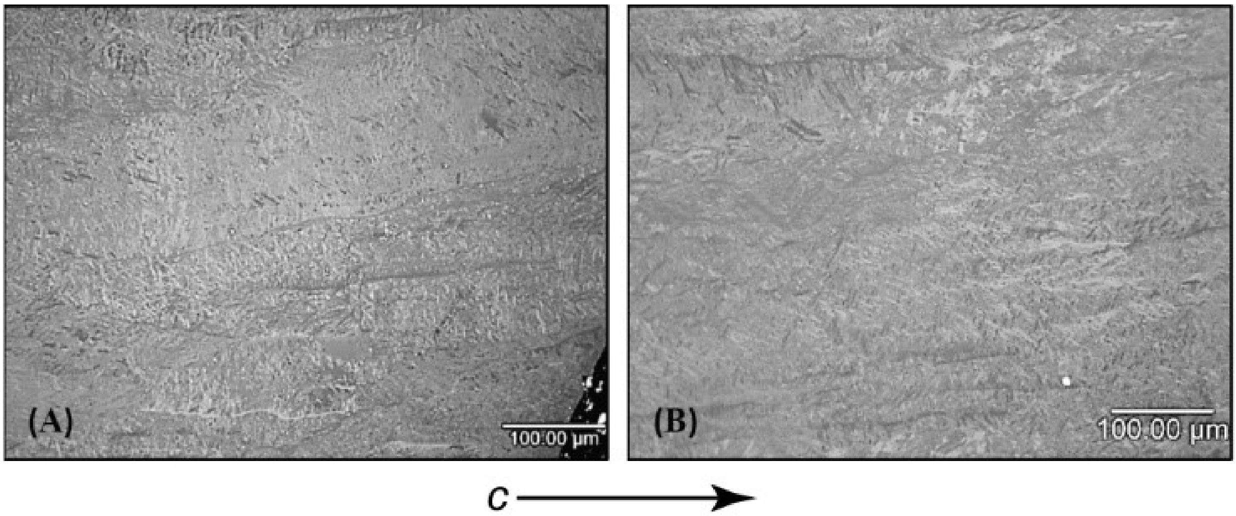

Fig. 4 – Polarized light optical microscope images of a) a Ti6Al4V cubic diamond lattice structure, and b) a dense block produced under the same conditions for comparison. Both show alignment of microstructural features with the build direction, *c* in the figure.

anisotropy arising from the interaction of the characteristics of the processing method with the particular lattice structure would be amplified for the case of the tetragonal lattice. The fact that it is not, and that anisotropy values observed in all lattices tested here are low, shows no significant orientation-based effects in this particular instance.

There is nevertheless inconsistency of findings in this regard for lattice materials, as shown by the literature data included in Fig, 3. The results obtained in this work are in accordance with the results of Wauthle *et al.* [19], obtained for the Selective Laser Melting (SLM) method of manufacture. However, they disagree with the earlier results of Heinl *et al* [18], who used the same EBM technique as applied here, and found significant anisotropy. This could be due to several factors which might lead the different sample sets not to be comparable, such as shrinkage issues in EBM materials [23], different surface finishes which may provide sites for failure initiation [24] or potential differences in processing parameters (a previous version of the processing equipment was used in the Heinl *et al* investigation (Arcam S12), for example). The precise conditions in additive processes have a great effect forming microstructure, such as leading to a strong texture in the growth direction [25]. Another potential reason for variance is indicated by the results of Ataee *et al* [22]. As shown in Fig. 3, the work of Ataee *et al*, on EBM-processed cubic gyroid lattices, finds significant anisotropy (of inverse sign to that of Heinl *et al*) for smaller unit cell sizes, diminishing as the lattice size in increased. Ataee *et al* find that the quality of CAD model reproduction improves with increasing unit cell size (i.e. as the features being processed get larger), with the smaller size ranges showing some distortion. This anisotropy therefore arises from a processing-induced structural anisotropy in the samples; when this is absent (as for their 3mm cell size data) the lattices show isotropic behavior, within experimental error.

Despite the potential sources of disagreement with other studies on lattices, the results obtained in these tests face a greater inconsistency compared to what has been established for dense metallic materials processed by AM methods, where anisotropy in structure and properties in the as-built condition is well known (see [11-13] for examples specific to EBM). Furthermore, the existence of non-uniform microstructure in such lattices has been found previously [10], so some degree of orientation effect would perhaps be expected. The absence of this could be explained by the fact that in a lattice, a much higher proportion of the material is in a position which will be influenced by the surface than in a bulk component.

The surface in EBM-processed Ti6Al4V can show a different microstructure to the rest of the material (a "skin", with a depth of ~0.7-0.8 mm), typically with reduced grain size and weaker texture, due to the different thermal conditions caused by the contour mode of beam motion used for the edges, compared to the hatch used to fill interior spaces, and heterogeneous nucleation of β grains from the surface [26]. In tests on another manufacturing method, Direct Metal Laser Sintering (DMLS) of 316L stainless steel was used to produce single strut members of various thicknesses, inclined at different angles to the build direction [27]. This also showed a skin layer, of reduced depth (~0.15 mm), indicating that this can be highly dependent on material and processing conditions.

Struts here were 1mm in diameter, and optical microscopy showed some directional character to the microstructure, aligned with the build direction, Fig. 4 (these observations are consistent with other similar lattices made by the same method [10]). So while a skin effect may reduce the anisotropy of the microstructure, it is not eliminated. The reason for the absence of an observable effect on the mechanical properties may be due to the mechanical properties of the Ti6Al4V. As titanium and titanium alloy lattice samples tend to show a limited degree of plasticity only, it may be that the behavior of these materials is dominated by brittle, defect-dependent failure, controlled by surface-dependent features, such as the high roughness (as theorized in [24]). A skin effect combined with failure before there is significant plasticity may limit visible effects of microstructure and texture in such materials.

4. Conclusions

The impact of build orientation on the mechanical properties of Additively Manufactured (Electron Beam Melting) titanium lattices with the diamond structure under compression has been investigated by the manufacture of related specimens, distorted to alter the symmetry. Compression tests have revealed the elastic modulus, 0.02% yield strength and first peak compressive strength of the structures, showing that the distortion increases the modulus along the stretched direction by a factor of more than three, and doubles the yield strength. Furthermore, comparison of the results of samples made in different orientations, via the calculation of the anisotropy in these properties, shows that build orientation does not contribute to the mechanical properties in the same way that AM solid structures are affected. This is somewhat at variance with some other studies of lattices in the literature, though it agrees with others. The effect observed here may stem from a higher proportion of the material being influenced by the surface (roughness, cracks, or a skin effect on microstructure) in a lattice. Indeed, lattice materials would appear to be a good way of studying the effects of the differences caused by the surface in Additively Manufactured processes of all types.

Acknowledgements

SNMJ would like to acknowledge The EPSRC Centre for Doctoral Training in Advanced Metallic Systems [project EP/G036950], and GKN Aerospace, for providing her studentship. RG would like to acknowledge a Fellowship supported by the Royal Academy of Engineering under the *RAEng/Leverhulme Trust Senior Research Fellowships* scheme. The authors would like to acknowledge the EPSRC Future Manufacturing Hub in Manufacture using Advanced Powder Processes (MAPP)(EP/P006566/1) for access to processing equipment.

References

[1] L. Murr, S. Gaytan, D. Ramirez, E. Martinez, J. Hernandez, K. Amato, P. Shindo, F. Medina, R. Wicker, Metal Fabrication by Additive Manufacturing Using Laser and Electron Beam Melting Technologies, Journal of Materials Science & Technology 28(1) (2012) 1-14.

[2] W.E. Frazier, Metal Additive Manufacturing: A Review, Journal of Materials Engineering and Performance 23(6) (2014) 1917-1928.

[3] R. Goodall, A. Mortensen, Porous Metals, in: D. Laughlin, K. Hono (Eds.), Physical Metallurgy, 5th Edition, Elsevier, Amsterdam, Netherlands, 2014, pp. 2399-2595.

[4] A. Amendola, E. Hernández-Nava, R. Goodall, I. Todd, R.E. Skelton, F. Fraternali, On the additive manufacturing, post-tensioning and testing of bi-material tensegrity structures, Composite Structures 131 (2015) 66-71.

[5] A. Amendola, C.J. Smith, R. Goodall, F. Auricchio, L. Feo, G. Benzoni, F. Fraternali, Experimental response of additively manufactured metallic pentamode materials confined between stiffening plates, Composite Structures 142 (2016) 254-262.

[6] M. Dumas, P. Terriault, V. Brailovski, Modelling and characterization of a porosity graded lattice structure for additively manufactured biomaterials, Materials & Design 121 (2017) 383-392.

[7] N.A. Fleck, V.S. Deshpande, M.F. Ashby, Micro-architectured materials: past, present and future, Proc. Roy. Soc. A 466 (2010) 2495-2516.

[8] T.A. Schaedler, W.B. Carter, Architected Cellular Materials, Annual Review of Materials Research 46 (2016) 187-210.

[9] J.B. Berger, H.N.G. Wadley, R.M. McMeeking, Mechanical metamaterials at the theoretical limit of isotropic elastic stiffness, Nature (2017).

[10] E. Hernandez-Nava, C.J. Smith, F. Derguti, S. Tammas-Williams, F. Leonard, P.J. Withers, I. Todd, R. Goodall, The effect of defects on the mechanical response of Ti-6Al-4V cubic lattice structures fabricated by electron beam melting, Acta Materialia, 108 (2016) 279-292.

[11] N. Hrabe, T. Quinn, Effects of processing on microstructure and mechanical properties of a titanium alloy (Ti–6Al–4V) fabricated using electron beam melting (EBM), Part 2: Energy input, orientation, and location, Mat. Sci. Eng. A 573 (2013) 271-277.

[12] L. Portolés, O. Jordá, L. Jordá, A. Uriondo, M. Esperon-Miguez, S. Perinpanayagam, A qualification procedure to manufacture and repair aerospace parts with electron beam melting, Journal of Manufacturing Systems 41 (2016) 65-75.

[13] H. Galarraga, D.A. Lados, R.R. Dehoff, M.M. Kirka, P. Nandwana, Effects of the microstructure and porosity on properties of Ti-6Al-4VELI alloy fabricated by electron beam melting (EBM), Additive Manufacturing 10 (2016) 47-57.

[14] X. Zhao, S. Li, M. Zhang, Y. Liu, T.B. Sercombe, S. Wang, Y. Hao, R. Yang, L.E. Murr, Comparison of the microstructures and mechanical properties of Ti–6Al–4V fabricated by selective laser melting and electron beam melting, Materials & Design 95 (2016) 21-31.

[15] O. Cansizoglu, O. Harrysson, D. Cormier, H. West, T. Mahale, Properties of Ti–6Al–4V non-stochastic lattice structures fabricated via electron beam melting, Materials Science and Engineering A 492 (2008) 468-474.

[16] L. Hitzler, M. Merkel, W. Hall, A. Ochsner, A Review of Metal Fabricated with Laser- and Powder-Bed Based Additive Manufacturing Techniques: Process, Nomenclature, Materials, Achievable Properties, and its Utilization in the Medical Sector, Adv. Eng. Mater. 20 (2018) 1700658.

[17] F. Warmuth, F. Osmanlic, L. Adler, M.A. Lodes, C. Körner, Fabrication and characterisation of a fully auxetic 3D lattice structure via selective electron beam melting, Smart Mater. Struct. 26 (2017) 025013.

[18] P. Heinl, L. Muller, C. Korner, R.F. Singer, F.A. Muller, Cellular Ti–6Al–4V structures with interconnected macro porosity for bone implants fabricated by selective electron beam melting, Acta Biomaterialia 4 (2008) 1536-1544.

[19] R. Wauthle, B. Vrancken, B. Beynaerts, K. Jorissen, J. Schrooten, J.-P. Kruth, J.V. Humbeeck, Effects of build orientation and heat treatment on the microstructure and mechanical properties of selective laser melted Ti6Al4V lattice structures, Additive Manufacturing 5 (2015) 77-84.

[20] V. Weißmann, R. Bader, H. Hansmann, N. Laufer, Influence of the structural orientation on the mechanical properties of selective laser melted Ti6Al4V open-porous scaffolds, Materials & Design 95 (2016) 188-197.

[21] S.J.N. Morrish, M. Pedersen, K.F.W. Wong, I. Todd, R. Goodall, Size effects in compression in Electron Beam Melted Ti6Al4V diamond structure lattices, Materials Letters 190 (2017) 138-142.

[22] A. Ataee, Y. Li, D. Fraser, G. Song, C. Wen, Anisotropic Ti-6Al-4V gyroid scaffolds manufactured by electron beam melting (EBM) for bone implant applications, Materials & Design 137 (2018) 345-354.

[23] C. Körner, E. Attar, P. Heinl, Mesoscopic simulation of selective beam melting process, Journal of Materials Processing Technology 211 (2011) 978-987.

[24] E. Hernandez-Nava, C.J. Smith, F. Derguti, S. Tammas-Williams, F. Leonard, P.J. Withers, I. Todd, R. Goodall, The effect of density and feature size on mechanical properties of isostructural metallic foams produced by additive manufacturing, Acta Mater. 85 (2015) 387-395.

[25] A.A. Antonysamy, Microstructure, Texture and Mechanical Property Evolution during Additive Manufacturing of Ti6Al4V Alloy for Aerospace Applications, Univeristy of Manchester, PhD Thesis, 2012.

[26] A.A. Antonysamy, J. Meyer, P.B. Prangnell, Effect of build geometry on the β-grain structure and texture in additive manufacture of Ti6Al-4V by selective electron beam melting, Materials Characterization 84 (2013) 153-168.

[27] A. Leicht, U. Klement, E. Hryha, Effect of build geometry on the microstructural development of 316L parts produced by additive manufacturing, Materials Characterization 143 (2018) 137–143.