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Recommended Citation
Hyer, Holden; Zhou, Le; Liu, qingyang; Wu, Dazhong; Song, Shutao; Bai, Yuanli; McWilliams, Brandon; Cho, Kyu; and Sohn, Yongho, "High Strength WE43 Microlattice Structures Additively Manufactured by Laser Powder Bed Fusion" (2021). Mechanical Engineering Faculty Research and Publications. 305.
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High Strength WE43 Microlattice Structures Additively Manufactured by Laser Powder Bed Fusion

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Abstract
WE43 is a high strength, high creep resistant Mg-alloy containing Y, Nd, and Zr, and has potential for many lightweight structural applications in the automotive, aerospace, and biomedical industries. Additive manufacturing technology such as laser powder bed fusion (LPBF) brings an opportunity to produce complex geometries such as lattice structures. In this study, fabrication, compressive behavior, and fracture modes of 24 different microlattice structures were investigated by varying unit cell type, strut diameter, and number of unit cells. These complex lattice structures were produced by LPBF using the parameter set: laser power = 200 W, scan speed = 1100 mm/sec, slice thickness = 0.04 mm, which was optimized in our previous study to build fully dense (> 99 %) WE43 alloy. Overall, the lattice structures exhibited oscillations in stress, showing many local maxima and minima, with a global maximum in stress at or near 5 % strain. The highest compressive strength, and the corresponding specific strength found in this study were 71.48 MPa and 38.85 MPa·g⁻¹·cm³, respectively, from the cubic fluorite lattice structure with a strut diameter of 0.75 mm and an unit cell number of 10. During compression testing, two different failure modes were observed: 45° shear fracture and crushing. Due to the inherent low ductility of WE43, brittle crushing was predominant after elastic yielding, which resulted in similar strength-density relationships for each lattice type along with similar failure modes.

Keywords
WE43, Lattice structure, Laser powder bed fusion, Additive manufacturing, Compression

1. Introduction
Magnesium (Mg) alloys are used in engineering applications where a high strength to weight ratio is of utmost importance [1], [2], [3]. Mg alloyed with rare earths such as yttrium (Y), ytterbium (Yb), scandium (Sc), neodymium (Nd), and gadolinium (Gd) are known for their high strength (>160 MPa) and high creep resistance [1,3]. With the alloying addition of 4.3 wt.% (Y, Zr) and 4.8 wt.% of other rare earths such as Nd and Gd [4], WE43 is a high strength Mg-alloy with good creep and corrosion resistance with a typical yield strength and density of 172 MPa and 1.84 g/cm³ [1,4]. WE43 is currently used in lightweight structural applications such as missiles, aircraft engines, racing wheels, frames, gear boxes, casings, electronics, helicopters, and automobiles [3,5,6]. In addition, due to its high strength and corrosion resistance, WE43 garnered application interests in lightweight armors and protective helmets for military applications [7,8]. Furthermore, WE43 has been considered for use as a bioresorbable prosthetic implant in the biomedical industry [9,10,11,12,13].

Conventional manufacturing of Mg-alloys through casting and subsequent post-processing techniques (e.g., thermo-mechanical working) remains challenging due to Mg's affinity for oxygen (O) and its high vaporization pressure [14,15,16]. Post-processing techniques such as forging and rolling must be performed under an inert argon (Ar) atmosphere, and at elevated temperatures due to the anisotropic behavior of Mg's hexagonal closed-packed (HCP) crystal structure [14]. To that end, additive manufacturing (AM) can provide a potential route for manufacturing of Mg-alloy component, since AM has demonstrated its ability to produce dense, complex geometries such as lattice structures with little to no post-processing [17,18,19].
Lattice structures are organized, “intended” porous structures with repeating unit cells, adapted from crystal lattice structures such as face-centered cubic (FCC) [17,20,21]. The unit cells are an assembly of strut components (cylindrical rods) that join at nodes. Lattice structures with strut diameters < 1 mm are considered microlattices [17,20]. Through proper design of microlattice structures, i.e., lattice unit cell type, cell size, strut diameter, etc., the open-structure design allows for a production of light and stiff components for loading applications or even for efficient cooling and insulation [17,19,20,22].

Laser powder bed fusion (LPBF) is a common AM technique in which a laser selectively melts regions of a powder bed to build a component through a layer by layer process [18]. LPBF has been widely used to manufacture microlattice structures out of materials such as stainless steel (SS) 316L [23], AlSi10Mg [17,24], and Ti-6Al-4V [[25], [26], [27]]. These alloys are known to behave well with LPBF as they can be processed to build components that are fully dense with no solidification cracks. However, many commercial alloys, such as high strength aluminum (Al) alloy AA7075 [28] or nickel (Ni)-based superalloy CM247 [29], are challenging to produce by LPBF because of solidification cracks and/or excessive porosity. Therefore, exploration into LPBF manufacturing of microlattices has been restricted to alloys that are readily available for LPBF.

Recently, Hyer et al. [30] demonstrated that a nearly fully dense WE43 (> 99 % relative density by volume), with high yield strength (σ_y = 214 to 218 MPa) and tensile strength (σ_T = 250 MPa) [4,30], can be produced by LPBF. Extensive microstructural analysis was carried using optical, scanning electron microscopy and transmission electron microscopy to elucidate the phase constituents of WE43 produced by LPBF, which included α-Mg (hcp) grains with Mg3Nd precipitates and (Y,Zr)2O3 oxide dispersoids [30]. Both Gangireddy et al. [31] and Zumdick et al. [32] also reported that the LPBF can produce WE43 with minimal porosity. These studies suggest that WE43 can be manufactured in microlattice structures with high strength and low density. Such structures have application in structural components or even in use as medical implants such as stints; where enough strength is needed to support the tissue, but the mesh structure would allow for uninterrupted flow of cells and/or other bodily fluids. Even though many studies exist on the LPBF of microlattice structures, few investigators have explored the fabrication microlattice structures manufactured using WE43. Li et al. [33,34] reported the corrosion behavior of WE43 microlattice structures with a cubic diamond unit cell produced by LPBF, however without any mechanical behavior. Qin et al. [35] also produced diamond type microlattice structures by using Zn with a small addition of WE43 (i.e., 100% Zn, Zn-2%WE43, Zn-5%WE43, and Zn-8%WE43), which yielded an ultimate compression strength value of approximately 75 MPa for the Zn-5%WE43. Therefore, this study, for the first time, aimed to examine the fabrication, compressive behavior, and failure modes of WE43 manufactured by LPBF in various types of microlattice structures. Furthermore, structure-property relationships were characterized and compared to that of high strength, low density AlSi10Mg reported in previous work in Yu et al. [17], using the same unit cell types and geometries.

2. Design of lattices
As reported in Table 1 and presented in Fig. 1, 24 different 30 mm x 30 mm x 30 mm microlattice structures were designed for WE43 alloy. Following the work by Yu et al. [17] with AlSi10Mg, six different unit cell types were employed in this study: cubic vertex centroid, cubic diamond, cubic fluorite, tetrahedron octahedral edge, tetrahedron octahedral vertex centroid, and tetrahedron vertex centroid. Fig. 2 shows schematics of unit cells for each lattice type. For the strut geometry, a circular cross-section was used due to its high energy adsorption capacity over a more rectangular cross-section [21]. Furthermore, for each of the six types of microlattice structures, four different combinations varying strut diameter and number of unit cells were designed for each lattice type. The strut diameters (d) and number of unit cells (n) were varied at 0.6 mm and 0.75 mm and at 8 and 10 units per 30 mm in each principle direction (x, y, z), respectively. The theoretical relative density was
taken as the apparent density of the microlattice structures, $\rho$, divided by the density of the base material, $\rho_s$.
The density for WE43 used in this study was 1.84 g/cm$^3$ taken from Magnesium Elektron design data [4].

Table 1. Dimensions and physical properties of microlattice structures.

<table>
<thead>
<tr>
<th>Lattice Type</th>
<th>$d$ (mm)</th>
<th>$n$ (units)</th>
<th>Volume (mm$^3$)</th>
<th>Surface Area (mm$^2$)</th>
<th>Theoretical Relative Density</th>
<th>Strength (MPa)</th>
<th>Specific Strength (MPa·cm$^3$·g$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic Vertex Centroid</td>
<td>0.6</td>
<td>8</td>
<td>2912.80</td>
<td>18701.15</td>
<td>0.108</td>
<td>1.68</td>
<td>0.91</td>
</tr>
<tr>
<td>Cubic Vertex Centroid</td>
<td>0.75</td>
<td>8</td>
<td>4459.81</td>
<td>22131.16</td>
<td>0.165</td>
<td>4.57</td>
<td>2.48</td>
</tr>
<tr>
<td>Cubic Vertex Centroid</td>
<td>0.6</td>
<td>10</td>
<td>4450.18</td>
<td>27530.80</td>
<td>0.165</td>
<td>5.24</td>
<td>2.84</td>
</tr>
<tr>
<td>Cubic Vertex Centroid</td>
<td>0.75</td>
<td>10</td>
<td>6473.72</td>
<td>32011.65</td>
<td>0.240</td>
<td>11.54</td>
<td>6.27</td>
</tr>
<tr>
<td>Cubic Diamond</td>
<td>0.6</td>
<td>8</td>
<td>2925.04</td>
<td>19176.05</td>
<td>0.108</td>
<td>2.42</td>
<td>1.31</td>
</tr>
<tr>
<td>Cubic Diamond</td>
<td>0.75</td>
<td>8</td>
<td>4543.38</td>
<td>22824.39</td>
<td>0.168</td>
<td>6.21</td>
<td>3.37</td>
</tr>
<tr>
<td>Cubic Diamond</td>
<td>0.6</td>
<td>10</td>
<td>4533.44</td>
<td>28361.47</td>
<td>0.168</td>
<td>6.18</td>
<td>3.35</td>
</tr>
<tr>
<td>Cubic Diamond</td>
<td>0.75</td>
<td>10</td>
<td>6922.62</td>
<td>33166.15</td>
<td>0.256</td>
<td>14.7</td>
<td>7.70</td>
</tr>
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<td>Cubic Fluorite</td>
<td>0.6</td>
<td>8</td>
<td>5514.39</td>
<td>32620.26</td>
<td>0.204</td>
<td>9.61</td>
<td>5.22</td>
</tr>
<tr>
<td>Cubic Fluorite</td>
<td>0.75</td>
<td>8</td>
<td>8358.41</td>
<td>36660.35</td>
<td>0.310</td>
<td>21.33</td>
<td>11.50</td>
</tr>
<tr>
<td>Cubic Fluorite</td>
<td>0.6</td>
<td>10</td>
<td>8348.30</td>
<td>45570.46</td>
<td>0.309</td>
<td>24.31</td>
<td>13.20</td>
</tr>
<tr>
<td>Cubic Fluorite</td>
<td>0.75</td>
<td>10</td>
<td>11870.73</td>
<td>49782.95</td>
<td>0.440</td>
<td>71.48</td>
<td>38.85</td>
</tr>
<tr>
<td>Tetrahedron Octahedral Edge</td>
<td>0.6</td>
<td>8</td>
<td>2570.05</td>
<td>16486.08</td>
<td>0.095</td>
<td>1.81</td>
<td>0.98</td>
</tr>
<tr>
<td>Tetrahedron Octahedral Edge</td>
<td>0.75</td>
<td>8</td>
<td>3917.38</td>
<td>19386.41</td>
<td>0.145</td>
<td>3.67</td>
<td>1.99</td>
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<tr>
<td>Tetrahedron Octahedral Edge</td>
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<td>10</td>
<td>3041.98</td>
<td>19178.03</td>
<td>0.113</td>
<td>2.81</td>
<td>1.52</td>
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<tr>
<td>Tetrahedron Octahedral Edge</td>
<td>0.75</td>
<td>10</td>
<td>4711.11</td>
<td>22266.30</td>
<td>0.174</td>
<td>6.81</td>
<td>3.69</td>
</tr>
<tr>
<td>Tetrahedron Octahedral Vertex Centroid</td>
<td>0.6</td>
<td>8</td>
<td>5071.10</td>
<td>29960.61</td>
<td>0.188</td>
<td>11.68</td>
<td>6.35</td>
</tr>
<tr>
<td>Tetrahedron Octahedral Vertex Centroid</td>
<td>0.75</td>
<td>8</td>
<td>4567.23</td>
<td>22104.46</td>
<td>0.169</td>
<td>7.01</td>
<td>3.81</td>
</tr>
<tr>
<td>Tetrahedron Octahedral Vertex Centroid</td>
<td>0.6</td>
<td>10</td>
<td>4477.48</td>
<td>27050.34</td>
<td>0.166</td>
<td>7.01</td>
<td>3.81</td>
</tr>
<tr>
<td>Tetrahedron Octahedral Vertex Centroid</td>
<td>0.75</td>
<td>10</td>
<td>12112.22</td>
<td>46663.28</td>
<td>0.449</td>
<td>48.58</td>
<td>26.4</td>
</tr>
<tr>
<td>Tetrahedron Vertex Centroid</td>
<td>0.6</td>
<td>8</td>
<td>1891.42</td>
<td>12560.16</td>
<td>0.070</td>
<td>0.81</td>
<td>0.44</td>
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<tr>
<td>Tetrahedron Vertex Centroid</td>
<td>0.75</td>
<td>8</td>
<td>2902.00</td>
<td>14924.49</td>
<td>0.11</td>
<td>2.09</td>
<td>1.13</td>
</tr>
<tr>
<td>----------------------------</td>
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</tr>
<tr>
<td>Tetrahedron Vertex Centroid</td>
<td>0.6</td>
<td>10</td>
<td>1662.87</td>
<td>10842.95</td>
<td>0.062</td>
<td>1.14</td>
<td>0.62</td>
</tr>
<tr>
<td>Tetrahedron Vertex Centroid</td>
<td>0.75</td>
<td>10</td>
<td>2526.71</td>
<td>12823.16</td>
<td>0.094</td>
<td>3.08</td>
<td>1.67</td>
</tr>
</tbody>
</table>

Fig. 1. Photographs of the 24 WE43 microlattice structures produced by LPBF and examined in this study.
Fig. 2. Repeating unit cell for (a) cubic vertex centroid, (b) cubic diamond, (c) cubic fluorite, (d) tetrahedron octahedral edge, (e) tetrahedron octahedral vertex centroid, and (f) tetrahedron vertex centroid.

3. Experimental methods

3.1. Powder characterization

Gas atomized WE43 powders with a nominal composition of Mg - 4.3 wt.% (Y,Zr) - 4.8 wt.% rare earth (e.g., Gd, Nd) were acquired from Magnesium Elektron with a particle size range of 20 ~ 63 μm. The powders were sampled in accordance with ASTM B215 for sampling packaged powder. Powder particle morphology and cross-section microstructure were analyzed with a field-emission scanning electron microscopy (FE-SEM, Zeiss™ Ultra-55) operated at 20 kV. Compositional analysis was performed with X-ray energy dispersive spectroscopy (XEDS, Thermo-Scientific™ Noran 7) equipped on the FE-SEM. Standardless quantitative compositional analysis was performed utilizing the Thermo-Scientific™ NSSv3.0 software. Powder size distribution was analyzed with a laser powder diffractometer (Beckman Coulter LS™ 13 320).

3.2. LPBF processing of microlattice structures

The microlattice structures were built with a SLM™ 125HL (SLM Solutions Group AG, Lübeck, Germany) LPBF system. The SLM™ 125HL is equipped with a continuous wave Yb fiber laser (wavelength = 1070 nm) with a spot size of approximately 70 μm. All microlattice structures were supported by a thin plate in order to utilize a block support structure underneath that connected the lattice to the build plate. Microlattices were built on an Mg-alloy (AZ31) build plate, which was kept at 100 °C. Ar was employed as the flowing gas in the chamber, keeping the O₂ content below 0.1 %. LPBF processing parameters employed were previously optimized by Hyer et al. [30]: laser power of 200 W, scan speed of 1100 mm/sec, and a slice thickness of 0.04 mm. Due to the size of the struts in the microlattices, a typical stripe hatch pattern was not applied; rather, the laser scan path followed the contour of the strut geometry, as schematically illustrated in Fig. 3, with a separation distance of 0.10 mm between contours. This scan strategy helped to retain the fine resolution of the struts. No re-melting strategies were employed. Once the microlattice structures were removed from the build plate, fine alumina particles (< 100 μm in size) were utilized to grit blast and remove unfused powders on struts of microlattice structures.

Fig. 3. Horizontal slices looking parallel to build direction for (a) cubic diamond and (b) tetrahedron octahedral vertex centroid (lattice combination of $d = 0.6$ mm and $n = 8$ units). Red line contour represents laser scan path with a hatch spacing of 0.1 mm. Lower right insets show superimposed scan path on microlattice cross-section (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).
3.3. Macro and microstructure characterization
The microlattice designs with the lowest relative density (lattice combination of $d = 0.6 \text{ mm}$, $n = 8$ units) from each of the lattice types (cubic vertex centroid, cubic diamond, cubic fluorite, tetrahedron octahedral edge, tetrahedron octahedral vertex centroid, tetrahedron vertex centroid), making a total of six microlattice structures, were chosen for macro and microstructural characterization. Surface morphology of the microlattices were analyzed with optical microscopy (Keyence VHX-900 and Nikon Metaphot). The cross-section of each of the six microlattices was polished with SiC grit paper and diamond paste, with a final finish of 0.05 μm with colloidal silica. The samples were then etched with a 1 vol.% picric acid in distilled water etchant for 40 seconds. The underlying microstructure was analyzed with the FE-SEM operated at 20 kV. Compositional analysis was performed utilizing XEDS equipped on the FE-SEM. Quantitative compositional analysis was performed utilizing the Thermo-Scientific NSSv3.0 software.

3.4. Mechanical testing
The 24 microlattice structures presented in Fig. 1 were compressed with a MTS™ tension-compression instrument with an applied quasi-static strain rate of $7.0 \times 10^{-4} \text{ s}^{-1}$. Compression testing was performed along the build direction for each microlattice. Engineering stress was calculated by dividing the load by the cross-sectional area. Engineering strain was taken from the crosshead displacement of the MTS™ machine. All microlattice structures were compressed to 35 % strain. Positioned perpendicular to the build direction was a digital image correlation (DIC) camera that measured and recorded the local strain deformation and fracture modes. The DIC system consisted of a Tokina AT-X Pro macro 100 mm −f/2.8−d lens with a resolution of 2448 × 2048 and VIC-2D 2009 software by Correlated Solutions, Inc. The capture frequency was 1 Hz.

4. Results
4.1. Powder characterization
Overall composition determined by XEDS for the WE43 powder is reported in Table 2, and is similar to that found in specification from Magnesium Elektron WE43 design data [4] finding that Y, Zr, and Nd were the main alloying elements. Fig.4(a) presents a secondary electron micrograph showing the powder morphology. Overall, the powders were highly spherical with a few satellites, and exhibited good flowability during LPBF by SLM™ 125HL. A cross-sectional backscatter electron micrograph from a representative powder, presented in Fig. 4(b), shows the segregation of heavy atomic number elements such as Y, Zr, and Nd to the inter-dendritic regions (i.e., brighter contrast). The D10, D50, D90, and mean powder size were determined to be 23.9, 40.5, 60.2, and 40.5 μm, respectively, as shown by the powder size distribution in Fig. 4(c).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Relative Density</th>
<th>Composition (wt.%</th>
<th>Mg</th>
<th>Y</th>
<th>Zr</th>
<th>Nd</th>
</tr>
</thead>
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<td>Powder</td>
<td>N.A.</td>
<td>93.50 ± 1.16</td>
<td>4.20 ± 0.84</td>
<td>0.69 ± 0.29</td>
<td>1.61 ± 0.55</td>
<td></td>
</tr>
<tr>
<td>Commercial Spec. [4]</td>
<td>N.A.</td>
<td>Balance</td>
<td>3.7-4.3</td>
<td>0.4 min.</td>
<td>2.2-4.4</td>
<td></td>
</tr>
<tr>
<td>Cubic Vertex Centroid</td>
<td>0.108</td>
<td>92.01 ± 0.70</td>
<td>4.44 ± 0.35</td>
<td>0.45 ± 0.46</td>
<td>3.09 ± 0.49</td>
<td></td>
</tr>
<tr>
<td>Cubic Diamond</td>
<td>0.108</td>
<td>91.45 ± 0.58</td>
<td>4.69 ± 0.30</td>
<td>0.43 ± 0.44</td>
<td>3.41 ± 0.27</td>
<td></td>
</tr>
<tr>
<td>Cubic Fluorite</td>
<td>0.204</td>
<td>91.72 ± 0.59</td>
<td>4.37 ± 0.26</td>
<td>0.34 ± 0.46</td>
<td>3.54 ± 0.31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tetra Octahedral Edge</td>
<td>Tetra Octahedral Vertex Centroid</td>
<td>Tetra Vertex Centroid</td>
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<tr>
<td></td>
<td>91.93 ± 0.58</td>
<td>91.75 ± 0.58</td>
<td>92.49 ± 0.35</td>
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<tr>
<td></td>
<td>4.10 ± 0.23</td>
<td>4.20 ± 0.30</td>
<td>3.69 ± 0.35</td>
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<tr>
<td></td>
<td>0.43 ± 0.44</td>
<td>0.53 ± 0.43</td>
<td>0.32 ± 0.33</td>
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<td></td>
<td>3.53 ± 0.39</td>
<td>3.51 ± 0.27</td>
<td>3.49 ± 0.34</td>
<td></td>
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</tbody>
</table>

*K radiation was employed for Mg and Zr while L radiation was employed for Y and Nd.*

Fig. 4. (a) Secondary electron micrograph of the WE43 powder morphology; (b) backscatter electron micrograph of the cross-sectional WE43 powder microstructure; and (c) WE43 powder size distribution determined from laser diffractometer.

4.2. Surface morphology and microstructure of lattice structures

All microlattice structures used in compression testing were grit blasted to remove loose powders. Fig. 5(a) and (b) present the strut surface of the cubic diamond microlattice structure \((d = 0.6 \text{ mm}, n = 8 \text{ units})\) before grit blasting. Some partially fused and sintered powders covered the surface of the struts. Fig. 5(c) and (d) present the same cubic diamond microlattice structure after grit blasting, which removed most of the fused/sintered powders. Fig. 6 clearly demonstrates the open structure of the six different microlattice structures.
Fig. 5. Optical photographs showing cubic diamond lattice structure \((d = 0.6 \text{ mm}, n = 8 \text{ units})\) (a,b) after LPBF, and (c,d) after grit blasting.

Fig. 6. Optical photographs showing the open-structure of (a) cubic vertex centroid, (b) cubic diamond, (c) cubic fluorite, (d) tetrahedron octahedral edge, (e) tetrahedron octahedral vertex centroid, and tetrahedron vertex centroid (f) microlattice structures. All microlattice structures presented had strut diameter of 0.6 mm and unit cell number of 8 units.

Fig. 7 presents cross-sectional optical and backscatter electron micrographs of the struts in microlattice structures. Formation of melt pool geometry normal to the build direction and elongated laser scan tracks are observed perpendicular to the build direction as shown in Fig. 7(a) and Fig. 7(b), respectively. The melt pool tracks observed in Fig. 7(b) appear as concentric circles due to the scan strategy employed in this study where the laser followed the contour of the strut geometry as depicted in Fig. 3. Pores were observed according to this
concentric scan strategy as presented in Fig. 7(b). Underlying microstructure is similar in all six microlattice types as shown by the backscatter electron micrographs in Fig. 7(c). The microstructure consisted of $\alpha$-Mg matrix (HCP; gray) along with flakes and particles (white). Hyer et al. [30] previously carried out a detailed microstructural analysis, and reported that these white flakes and particles were, respectively, nano-scale $\text{Y}_2\text{O}_3$ dispersoids uniformly dispersed in $\alpha$-Mg and sub-micron $\beta_1$-$\text{Mg}_3\text{Nd}$ precipitates, which are believed to improve the creep resistance and strength of WE43 [36].

Composition of the six different LPBF microlattice types measured by XEDS is presented in Table 2. The main alloying elements for WE43 in all six microlattices types were Y, Zr, and Nd. Overall, the sum of the concentration of alloying elements (Y+Zr+Nd) did not vary significantly between the different microlattice types and was consistent with the nominal composition of WE43, which includes 7 to 8 wt.% alloying elements in Mg [4]. Also, there was no systematic variation in WE43 composition as a function of relative density as per on lattice structure design.

4.3. Mechanical behavior under compression

Engineering stress-strain plots from the compression tests of all 24 microlattice structures are presented in Fig. 8. Majority of the stress-strain curves have saw-tooth appearance with multiple local stress maxima and minima. The multiple oscillations can be attributed to multiple events of deformation and cracking. The compressive strength of each of the microlattice structures, taken as the global maximum compressive strength measured, is reported in Table 1. The maximum strength was observed near $\sim 5$ % strain for all the microlattice structures. The maximum compressive strength achieved among all the lattice structures was 71.48 MPa for the cubic fluorite structure with a strut diameter of 0.75 mm and 10 unit cells per 30 mm, which had the second largest relative density ($\rho/\rho_s = 0.44$). Of the four different lattice combinations produced for each lattice type, the highest strengths were observed for those with the largest strut diameter and the larger unit cell number of 0.75 mm and 10 units, respectively, which corresponded to the highest relative density within each lattice structure type. Fig. 9 presents maximum compressive strength recorded for each lattice type as a
function of relative density. Overall, the compressive strength increased with an increase in relative density. However, the compressive strength variation as a function of lattice type did not appear to be significant.

Fig. 8. Engineering stress-strain curves for (a) cubic vertex centroid, (b) cubic diamond, (c) cubic fluorite, (d) tetrahedron octahedral edge, (e) tetrahedron octahedral vertex centroid, and (f) tetrahedron vertex centroid microlattice structures tested in compression. Lattice combinations, e.g., strut diameter (d) and number of unit cells (n) are distinguished in plot legends.
Fig. 9. Compressive strength as a function of relative density for the microlattice structures examined in this study.

Fig. 10 shows DIC images with superimposed color mapping corresponding to the local displacement/distortion for six selected microlattice structures (i.e., d = 0.6 mm and 8 units). Four images were chosen for each lattice type: (1) at 2% strain before initial fracture, (2) at 5% strain at or close to initial fracture, (3) at 10% strain after initial fracture, and (4) at 30% near the end of the compression test. Fig. 10 demonstrates that the local displacement/distortion increased with an increase in strain for all structures. Unfortunately, the color mapping could not be correlated at higher strain when the local displacement/distortion was too high.
Even though compressive strength variation as a function of lattice type was not significant, the failure modes were different between lattice types. Two dominating failure modes were observed: 45° shear fracture and crushing. The 45° shear fracture was the most common failure mode, which was observed primarily in the cubic vertex centroid, cubic fluorite, tetrahedron octahedral edge, and tetrahedron vertex centroid lattice types. The majority of the stress-strain curves for lattices that failed by 45° shear fracture show multiple stress maxima which correspond to repeated build-up of stress followed by a 45° shear fracture. This behavior is presented in Fig. 11(a) by local displacement mapping. On the other hand, tetrahedron octahedral vertex centroid only gave one maximum stress peak before reaching a plateau of constant stress as presented in Fig. 8(e). This crushing failure presented in Fig. 11(b) occurred by continuous local failure of the lattice structure. The cubic diamond lattice type also exhibited crushing failure at low relative density (e.g., \(d = 0.6\) mm, and \(n = 8\) units). The tetrahedron vertex centroid displayed a clear sign of an initial 45° shear fracture, but exhibited crushing failure tendencies as shown in Fig. 11(c) as the stress drops to a relatively constant magnitude.
5. Discussion

For lattice structures, there are two general compression response behaviors: bending dominated and stretch dominated [20–22,37,38]. Bending dominated behavior occurs when a stress maximum is achieved followed by a drop in stress to a constant, plateau until densification of the lattice starts near maximum strain [20–22]. Stretch dominated behavior is observed when continuous strain results in an oscillation of high and low stresses until densification near maximum strain [20–22]. Typically, bending dominated behavior is favored since a continual failure mechanism keeps the total stress constant. A sudden drop in load in the lattice structure due to oscillatory stress may cause consecutive and immediate failure of the lattice structure under high loads. However, the oscillatory behavior, which is observed in stretch dominated lattices, may prove useful for applications where energy adsorption and energy dissipation is desired.

Maxwell [38] defined the stiffness of lattice structures and proposed a criterion for compression failure modes of cellular/lattice structures. A simple algebraic expression defined the Maxwell number, M as:

\[ M = s - 3e + 6 \]
where \( s \) is the number of struts and \( e \) is the number of nodes or joints where struts intersect. When \( M < 0 \), the lattice is considered under-stiff because there are not enough struts for moments to transfer to nodes. Therefore, a lattice that is under-stiff will exhibit bending dominated behavior. If \( M = 0 \), the lattice is “perfectly” stiff since there are the correct number of struts to transfer bending moments to the nodes. In other words, when \( M = 0 \), the cellular structure has the highest structural efficiency. For lattices where \( M > 0 \), the lattice is over-stiff with too many struts. Over-stiff lattices may defeat the purpose of designing and choosing lattice structures. Over-stiff lattices do not require bending moments to shift to the nodes, as they are usually strong and resilient. For perfectly stiff and over-stiff lattices, stretch dominated behavior would be favored. Under Maxwell's criterion, only the common polyhedrons, tetrahedron, and octahedron would have the Maxwell number to be 0. Other polyhedrons such as dodecahedron and icosahedron, which are more complex, are either under-stiff or over-stiff [39]. Therefore, in this study, design of lattice types based on tetrahedron and octahedron were selected.

The number of struts, nodes, and calculated \( M \) for the lattice types examined in the study are reported in Table 3. For five of the lattice types, \( M < 0 \), and so, the bending dominated behavior would be expected. Only the tetrahedron octahedral edge lattice type had an \( M = 0 \). Accordingly, as presented in Fig. 8(e), the tetrahedron octahedron vertex centroid exhibited the most consistent bending dominated behavior among all lattice types with little oscillation in the stress. As shown by Fig. 8(a) and 8(d), respectively, the cubic vertex centroid and tetrahedron octahedral edge lattice types exhibited the most oscillation in stress indicative of more stretch dominated behavior.

<table>
<thead>
<tr>
<th>Lattice Type</th>
<th>Number of Struts per Unit Cell (s)</th>
<th>Number of Nodes per Unit Cell (e)</th>
<th>Maxwell Number, M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic Vertex Centroid</td>
<td>8</td>
<td>9</td>
<td>-13</td>
</tr>
<tr>
<td>Cubic Diamond</td>
<td>16</td>
<td>14</td>
<td>-20</td>
</tr>
<tr>
<td>Cubic Fluorite</td>
<td>32</td>
<td>22</td>
<td>-28</td>
</tr>
<tr>
<td>Tetrahedron Octahedral Edge</td>
<td>6</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Tetrahedron Octahedral Vertex Centroid</td>
<td>28</td>
<td>21</td>
<td>-29</td>
</tr>
<tr>
<td>Tetrahedron Vertex Centroid</td>
<td>4</td>
<td>5</td>
<td>-5</td>
</tr>
</tbody>
</table>

From Gibson-Ashby model [22,40] for compression behavior, dominated either by stretching or bending, the relative strength can be estimated as the compressive strength of the microlattice structures over the compressive strength of the base material (\( \sigma_s \)), taken as 417 MPa for LPBF processed WE43 [30] as:

\[
\frac{\sigma}{\sigma_s} = C \left( \frac{\rho}{\rho_s} \right)^m
\]

where \( C \) is a constant that can range between 0.1 and 1.0. For bending and stretch dominated behaviors, constant \( m \) equals to 1.5 and 1, respectively. Relative strength of WE43 microlattice structures was examined as a function of relative density as presented in Fig. 12(a). In previous work, Yu et al. [17], examined the same lattice types built with AlSi10Mg alloy and suggested that the behavior of the tetrahedron octahedral edge lattice types followed a power law of a higher order power (\( m = 3.88 \)). Therefore, simple power laws were fitted to each of the lattice types as shown in Fig. 12(a). All lattice types except for tetrahedron octahedral vertex centroid, exhibited a higher order power law dependence (\( m > 2 \)). Fig. 12(b) presents relative strength of all
microlattice structures along with various limits of relative strength based on Eq. (2) with varying values of constants $C$ and $m$. The compressive behavior of the microlattice structures examined closely follows more bending-dominated behavior (i.e., when $m = 1.5$), but can be better fitted with constant $m = 2$. However, a constant, plateau stress would be expected when compression behavior is bending dominated, which was only significantly observed for the tetrahedron octahedral vertex centroid and moderately observed in the cubic diamond and tetrahedron vertex centroid lattice structures.

Under bending dominated behavior, the struts in the unit cells would bend plastically, allowing for a continuous elastic/plastic response until the struts rupture. Upon collapse, the stress would remain relatively constant until densification of the lattice. If a material is brittle and the lattice is expected to be bending dominated, brittle fracture will be observed after the initial elastic response. As described by Gibson and Ashby [22,40], the brittle response can display continual oscillation in stress in the stress-strain curves. If the lattice type exhibits crushing failure modes, the stress-strain curve would show a low amplitude oscillation, whereas a higher amplitude oscillation would be observed for lattice types that undergo 45° shear fractures during compression. The elongation/total strain of WE43 is low (< 7% in tension), due to the anisotropic HCP crystal structure of Mg [4,14,30]. Therefore, with minimal ductility, brittle fracture is likely to occur after elastic yielding in the WE43 microlattice structures, which would cause little difference in fracture modes between lattice types.

In our previous work, Yu et al. [17] reported on the compression behavior of the same 24 lattice structures built with AlSi10Mg alloy. The tetrahedron octahedral edge lattice type exhibited a higher order strength-density relationship ($m = 3.88$) that is potentially associated with elastic/plastic buckling behavior rather than crushing. Crushing behavior was observed in tetrahedron octahedral vertex centroid and tetrahedron vertex centroid lattice types, which demonstrated low order ($m < 1$) strength-density relation. For WE43, five of the six lattice
types exhibited a higher order power law with $m > 2$, suggesting that elastic/plastic buckling should be observed. However, the minimal ductility lead to brittle failure before any plastic response, e.g., buckling, could occur.

The highest specific strength determined for WE43 microlattice structure was 38.85 MPa·g⁻¹·cm⁻¹ using the cubic fluorite with the combination of $d = 0.75$ mm and $n = 10$ units. This value is higher than those reported for lattice structures with a relative density less than 0.5 processed with SS316L at 2.18 MPa·g⁻¹·cm⁻¹ [23], NiTi at 25.65 MPa·g⁻¹·cm⁻¹ [41], and Ti-6Al-4V at < 35 MPa·g⁻¹·cm⁻¹ [25], but lower than AlSi10Mg at 83.1 MPa·g⁻¹·cm⁻¹ for the cubic fluorite with the combination of $d = 0.75$ mm and $n = 10$ units [17]. The compressive strength and specific strength ($\sigma/\rho_s$) of WE43 microlattices as a function of apparent density ($\rho$) are shown in Fig. 13(a) and 13(b), respectively, for the microlattice structures built with WE43 and Al10SiMg [17]. The maximum compression strength and density of bulk AlSi10Mg was taken as 460 MPa [42] and 2.67 g/cm³ [43], respectively. Overall, the AlSi10Mg microlattice structures had a higher compressive strength and a higher specific strength. However, the scatter for AlSi10Mg is larger as indicated in Fig. 13(a). In comparison, the scatter for WE43 is smaller in general and is highly linear. This difference in the scatter is most likely due to the ductility difference between AlSi10Mg, which can compress up to 25% strain before fracture [42], and LPBF WE43, which can compress only up to 9.5% strain at fracture [30]. The brittle behavior of WE43 could be the reason for the highly linear relationship between compressive strength and relative density regardless of lattice type. However, even with the minimal ductility in WE43, the WE43 lattices still exhibited good strength and the ability to continually re-load without complete failure after the maximum compressive strength was reached. Therefore, these WE43 lattices would still have good promise for use in structural applications including load-bearing biomedical applications.
Fig. 13. Apparent density ($\rho$) vs. (a) compression strength and (b) specific strength ($\sigma/\rho_s$) for WE43 and AlSi10Mg [17] microlattice structures.

6. Conclusions
Fabrication of 24 WE43 microlattice structures was carried out to examine their compression behavior and failure modes. Key findings of this investigation included:

1. Consecutive melt pools were observed in both the macro and microstructures within struts of microlattices, consistent with the LPBF process.
2. The highest compressive strength and the corresponding specific strength determined was 71.48 MPa and 38.85 MPa·g$^{-1}$·cm$^3$, respectively. This strength was found for the cubic fluorite with lattice combination of $d = 0.75$ mm and $n = 10$ units. The specific strength reported is higher than that of SS316L or NiTi, but slightly lower than AlSi10Mg.
3. Two main failure modes were observed from the compression testing of the WE43 microlattice structures: (1) 45° shear fracturing and (2) repeated crushing. Lattice combinations of the cubic diamond and tetrahedron octahedral vertex centroid lattice types were found to exhibit the most crushing behavior based on DIC image capturing, whereas 45° shear fracturing was mainly observed in the tetrahedron octahedral edge lattices. The 45° shear fracturing was consistent with the oscillation in stress, and the repeated crushing was consistent with low constant stress with minimal oscillations.
4. Except for the tetrahedron octahedral vertex centroid lattice type, all other lattice structures exhibited higher order ($m > 2$) strength-density relationship, which corresponds more to the elastic/plastic buckling. However, the low ductility of the WE43 most likely lead to brittle failure. Furthermore, the brittle behavior was most likely the limiting factor for the simple relationship between relative density and relative strength regardless of lattice type.

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.

Acknowledgments
This research was sponsored by the DEVCOM Army Research Laboratory under a cooperate agreement contract, W911NF1720172. The views, opinions and conclusions made in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the DEVCOM Army Research Laboratory or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein. The authors would like to thank Ms. Stacy Meyerowich of Keyence Corporation of America for access to the VHX-900 digital microscope.

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