The Influence of Laser Powder Bed Fusion (L-PBF) Process Parameters on 3D-Printed Quality and Stress–Strain Behavior of High-Entropy Alloy (HEA) Rod-Lattices

Jianrui Zhang and Bo Li *

School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, China
* Correspondence: libo@ecust.edu.cn

Abstract: Laser powder bed fusion (L-PBF) additive manufacturing technology is suitable for the direct 3D printing of geometrically complex periodic micro-rod-lattices. However, controlling the geometric and performance consistency remains challenging due to manufacturability limitations, non-negligible process defects, and surface roughness, which is inconvenient to measure, affecting the mechanical properties and deformation behavior of the lattice structures. To improve the forming quality of the rod lattices and the consistency of repetitive 3D printing, we theoretically analyzed the causes of the defects and the effects of the L-PBF parameters on the process defects of CoCrFeNiMn high-entropy alloy micro-rods. The forming quality of the micro-rods was evaluated and classified with control experiments, and the surface roughness was measured and analyzed. Randomly protruding metal particles on the surface were mainly caused by the diffusion of laser energy, the incomplete melting of some metal powders, and/or “balling” process-induced defects caused by laser remelting. The tensile mechanical properties of typical L-PBF-printed micro-rods with different geometric characteristics were compared and evaluated. The influence of the geometric characteristics of the defects on the mechanical properties is discussed. The mechanical properties of the L-PBF-printed rod lattices were evaluated by compression experiments. It was found that the properties of different rod lattices have a positive relationship with the relative density.

Keywords: laser powder bed fusion; micro-rod; surface roughness; lattice structures; mechanical properties; additive manufacturing

1. Introduction

Additive manufacturing (AM) is a promising technical means of innovative design, manufacturing, and maintenance of geometrically complex components. Unlike traditional subtractive manufacturing, AM fabricates components in layers based on a 3D model, which can be directly, quickly, and accurately converted into a physical object. This technology offers a high level of flexibility in the design and manufacture of industrial parts, with the potential to spur a new manufacturing revolution. In particular, lightweight components manufactured using metals or alloys can meet certain service requirements according to boundary conditions. Appropriate structural designs, material selection for a high specific strength, and advanced fabrication technologies or processes are all required to achieve this goal.

Laser powder bed fusion (L-PBF), namely, selective laser melting (SLM), as a kind of metal AM technique, is suitable for directly manufacturing geometrically complex, precise, and high-performance metal parts layer by layer. With the assistance of a high-energy laser beam as a heat source, the L-PBF exhibits the advantages of digital forming, nonuse of molds, high forming accuracy, high material utilization rate, and superior mechanical properties of the as-printed parts [1]. L-PBF makes the manufacturing of lightweight components more promising. For instance, using L-PBF AM, Pham et al. [2] additively
manufactured a new lattice structural blade and showed that it was sturdier than the traditional models. As L-PBF AM machines have matured, lattice-type metal structures have been fabricated with relatively high precision. A new lattice structure can be efficiently designed by changing the periodic arrangement of the internal nodes and/or struts, thereby improving the mechanical properties of the overall structure. In addition, an ordered lattice structure can reduce fabrication time and material cost [3]. Accordingly, the fabrication of metallic lattice structures by the L-PBF is a current research focus in the AM study field [4].

L-PBF-printed rod-lattice structures commonly possess non-negligible defects, which affect their mechanical properties and deformation behavior [5]. The failure mechanism of L-PBF-printed rod lattices depends not only on the geometry of the unit cells but also on process-induced defects, including the internal porosity and external surface roughness of the matrix material [6]. Microstructural defects generated during the L-PBF process can also negatively affect the properties of the lattice structures [7]. Of utmost concern is the as-printed surface quality. During the L-PBF process, the upper surface of the part will interact directly with the laser beam, causing almost all of the material particles on it to melt. However, the lower surface of the unsupported structure is in direct contact with the powder bed, causing particles that are not yet molten to adhere to it as the molten pool solidifies [8]. The lower surface area of an unsupported lattice structure is roughly inversely proportional to the inclination angle. For example, an inclined rod with a smaller angle has a larger lower surface area, thereby increasing the possibility of the adhesion of unmelted powder particles and reducing the surface quality. In general, the presence of rough as-printed surfaces reduces the resistance of the lattices to fatigue failure. Nevertheless, an increase in surface roughness is not necessarily disadvantageous for some application scenarios. For example, biomedical performance, e.g., cell attachment on medical implants with rod-lattice structures, can be improved with increased surface roughness [9,10]. Thus, to meet the need for lightweight structural strength, it is necessary to study the causes of defects in the L-PBF process when creating rod lattices and clarify the effects of rod growth angle and laser energy density on the forming in order to optimize the quality.

The parent material type must also be carefully chosen to obtain mechanically reliable metallic rod-lattice structures. A new alloying strategy has come into vogue in the past fifteen years. In contrast to traditional alloying strategies, high-entropy alloys (HEAs) represent a new view of alloy design based on the principle of configurational entropy of alloy systems, i.e., with the absence of a “dominant element” and the introduction of “chemical disorder” by multi-directional principal component mixing [11,12]. Many HEAs have mechanical properties that are superior to those of conventional alloys, especially in extreme environments. While HEAs have complex compositions, ultra-fast cooling during the L-PBF process prevents the formation of brittle intermetallic compounds (IMCs) compared to conventional alloys. For example, CoCrFeNiMn alloy is typical of a face-centered cubic (FCC) single-phase HEA [13]. Our previous works have demonstrated that L-PBF can easily print CoCrFeNiMn HEA without evident IMCs in its as-printed microstructure. Hence, the present work studies the factors influencing the L-PBF-printed surface roughness of CoCrFeNiMn HEA rod lattices. Accordingly, a roughness prediction model was established to evaluate the as-printed rods, providing a theoretical basis and guidance for our in-depth analysis of the L-PBF-printed rod lattices. In addition, geometry optimization and a comparison of L-PBF-printed rod-lattices are presented in this work.

2. Experimental Method and Material

2.1. L-PBF Experimental Details

The proposed L-PBF equipment (YiBo-3D Co.Ltd., Beijing, China) used in our experiments, including the laser beam system, mechanical motion system, control system, scanning system, material delivery system, and atmosphere protection system, and its parameters, is presented in Table 1. Since the powder is completely melted in the process, it is essential to protect the machined parts from oxidation by allowing no more than 0.2% oxygen in an argon atmosphere throughout the manufacturing process.
2. Experimental Method and Material

2.1. L-PBF Experimental Details

The primary working parameters of the L-PBF platform are presented in Table 1. Since the powder is completely melted in the process, it is necessary to ensure a well-designed atmosphere protection system, material delivery system, and scanning strategy to avoid the risk of unmelting between adjacent tracks. Scanning strategies chosen included interlaced scanning, whereby after each layer has been scanned and the next layer is scanned after a shift, thereby minimizing the risk of unmelting between adjacent tracks.

In this work, the CoCrFeNiMn spherical powder produced by gas atomization was provided by Jiangsu Vilory Advanced Materials Technology Co., Ltd.; its size was $D_{10} = 24.6$ mm, $D_{50} = 36.2$ mm and $D_{90} = 55.8$ mm, respectively. The HEA powder in spherical shape was observed by field emission scanning electron microscopy (Tescan Mira 3 XH, Brno, Czech Republic), as shown in Figure 1. The scanning strategies described in this paper were based on the recommendations presented in [14], and a filling scanning strategy was chosen, i.e., interlaced scanning, whereby after each layer has been scanned and the next layer is scanned after rotating $67^\circ$, by which the risk of unmelting between adjacent tracks is minimized.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
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<tbody>
<tr>
<td>Rated output power/W</td>
<td>$\geq 500$</td>
</tr>
<tr>
<td>Center wavelength/nm</td>
<td>1060–1080</td>
</tr>
<tr>
<td>Output power fluctuation</td>
<td>$\leq 3%$</td>
</tr>
<tr>
<td>Minimum spot diameter/mm</td>
<td>$\leq 0.1$</td>
</tr>
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![Figure 1. SEM of CoCrFeNiMn HEA powder.](image)

2.2. The Tensile Property Test of L-PBF-Printed Micro-Rod

The tensile properties of a single micro-rod were tested by ZQ-990A universal testing machine (Zhiqu Co. Ltd., Shenzhen, China), as shown in Figure 2a. The maximum load of the test machine is 2000 N, and the resolution ratio is 0.01 N. The slippage is a hurdle for micro-rod performance tests. For example, Tsopanos et al. [15] found that the measured modulus of elasticity varies considerably (up to 10 times) during micro-rod tensile tests caused by slippage. Based on the literature [16], a method was adopted to eliminate the slippage between the micro-rod and the chuck of the test machine. As shown in Figure 2b, two splints are manufactured with 1 mm grooves on their surfaces. The L-PBF-printed micro-rod and splints are bonded with a high-strength glue and left to set for at least 24 h at room temperature. During tensile tests, the splints are placed at the chuck of the test machine. The loading rate is 0.1 mm/min. It is challenging to determine the micro-rod diameter. Generally, the micro-rod diameter is directly measured. In that case, the maximum diameter is obtained, which does not consider the micro-rod’s unsmooth surface and non-uniform diameter. Therefore, the average diameter of the micro-rod is used in this work.
3. Results and Discussion

3.1. Analysis of Formability of L-PBF-Printed Cantor HEA Micro-Rod

3.1.1. Manufacturing Quality Assessment of L-PBF-Printed Micro-Rod

The first step of L-PBF is to slice and divide the model based on a certain layer thickness. For a micro-rod with a constant inclination angle, the microscopic slicing and layered manufacturing processes are shown in Figure 3a, which the following equation can calculate:

$$S = H \times cot \theta$$  \hspace{1cm} (1)$$

where \(H\) is the layer thickness of powder spreading, \(\theta\) is the inclination angle, and \(S\) is the theoretical overhanging length between layers.

\[\text{Figure 2. Desktop universal testing machine and micro-rod stress–strain testing parts display: (a) testing machine, (b) testing parts.}\]
where \( H \) is the layer thickness of powder spreading, \( \theta \) is the particle size of the high-entropy powder, the layer thickness is fixed at 45 mm; the inclination angle gradually increases from 0° to 90° in increments of 10°.

Therefore, a larger powder layer thickness \( H \), or a smaller inclination angle \( \theta \), causes a greater theoretical overhanging length \( \lambda \). In general, during the actual L-PBF process, the layer thickness generally depends on the particle size of the metal powder. Once the material is determined, the layer thickness remains unchanged, and the preset layer thickness for commercial devices is mainly in the range of 20–50 \( \mu \)m [19]. According to the particle size of the high-entropy powder, the layer thickness is fixed at 45 \( \mu \)m in this work, so the theoretical overhanging length depends mainly on the inclination angle.

When the micro-rods are round struts built at an inclination angle, the overlap length \( \lambda \) and overhanging length \( \phi \) between two adjacent layers are shown in Figure 3b. Specifically, the inclined cylinder is sliced into an ellipse. The short semi-axis \( b \) equals the radius \( r \) of the cylinder, and the long semi-axis \( a \) is related to the inclination angle. The equation is as follows:

\[
a = \frac{d}{2 \sin \theta}
\]

where \( d \) is the cylinder diameter, and the overhanging length \( \phi \) is calculated by the following equation:

\[
\phi = \frac{H}{\tan \theta}
\]

The following equation can obtain the overlap length:

\[
\lambda = 2a - \phi = \frac{d}{\sin \theta} - \frac{t}{\tan \theta}
\]

The size of the overhanging structure is limited by the minimum manufacturing size of the L-PBF, so the minimum diameter of the micro-rod is also limited by manufacturability. Through many experiments, this research analyzes the manufacturability of the micro-rod with different diameters and inclination angles. The diameter increases from 0.3 mm to 1 mm in increments of 0.1 mm; the inclination angle gradually increases from 0° to 90° in increments of 10°.

In this work, the manufactured micro-rods are evaluated and classified according to the forming quality, and Table 2 summarizes the results. It should be noted that some literature has demonstrated that the manufacturability of micro-rods with small inclination

![Figure 3. Schematic diagram of slicing and layered built-up structure by L-PBF: (a) slice of the outer surface of the inclined part; (b) overlapping region of the adjacent molten tracks; (c) layered height of the as-printed micro-rod; (d) the geometric relation between surface roughness, Ra, and the outer surface “steps”.

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angles can be improved by reducing the micro-rod length [20]. The micro-rods’ length is set to more than 10 times the diameter to assess the manufacturability in extreme cases.

### Table 2. Effect of micro-rod diameter and as-built angle on manufacturability: L averages unable to form, M averages a poor forming effect, and H averages a good forming effect.

<table>
<thead>
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<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
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#### 3.1.2. Manufacturing Defects of L-PBF-Printed Micro-Rod

The L-PBFed micro-rod generally has poor quality, and the defects produced in its manufacturing process include the “step effect”, dross formation, and warping [21]. Post-processing, such as sandblasting, is often required after manufacture. However, post-processing is difficult for micro-rods, especially for lattice structures. To improve surface quality, we should analyze and investigate those defects.

1. **“Step effect”**

   In the L-PBF process of round rods, the CAD model of the parts is split into multiple right-angle layers and then built layer by layer to form a three-dimensional part. For any curved or inclined surface, the effect of layer accumulation is called the “step effect”, as shown in Figure 3c. Since the outline of L-PBFed parts is a gradual approximation of the nominal outline of the CAD model, all the L-PBFed parts exhibit the “step effect” [21]. The “step effect” affects the surface quality of L-PBFed parts. As the inclination angle decreases or the layer thickness increases, the “step effect” becomes more evident. The thinner the slice thickness, the smaller the “step” and the smoother the part surface. The slice thickness can be reduced by decreasing the layer thickness, increasing the manufacturing time [22].

   On each oblique surface, the distance between adjacent ridges is compared to h, which is the distance between straight step edges derived from the step triangle of an angled surface, as shown in Figure 3d.

   $$h = \frac{L_t}{\sin(\theta)}$$

   where $L_t$ is the layer thickness and W is the step width.

2. **Layered warping**

   Rapid solidification during the L-PBF process causes several problems, such as thermal, structural, and residual stress [23]. When the internal thermal stress exceeds the material strength, plastic deformation and layered warping will occur.

   The literature [24] argues that the warping in the overhanging structure is mainly caused by the lack of support and infers that it is difficult to avoid the warping phenomenon without adding support. In the forming process, after a single layer of the overhanging structure is scanned, the volume of the melted powder shrinks during the liquid–solid phase transfer, causing the overhanging parts to warp upwards. The temperature difference between the top and bottom of the scanning layer and the uneven thermal conductivity...
cause the upper part of the forming layer to shrink faster than the bottom, resulting in the upward warping of the overhanging layer [25]. Residual stress is also an essential factor affecting the quality of the overhanging structure. L-PBF is a process in which metal powder rapidly melts and instantaneously solidifies under a high-energy laser, likely generating internal residual stress. If unchecked, the residual stress will cause microstructure deformation or microscopic cracks and even macro-defects such as warping or cracking, ultimately affecting the parts’ performance. The existence of residual stress in L-PBFed parts is mainly related to a large temperature gradient during the melting process.

Figure 4b shows the warping effect in the overhanging L-PBF manufacturing process. When warping occurs, the actual inclination angle $\theta'$ between the protruded part of the current layer and the previous layer is greater than the design target. Warping will affect the actual manufacturing layer thickness of the next layer, which will cause severer warping. When the warpage reaches a preset height of the next layer, or even higher than the preset height, the necessary powder is lacking for manufacturing in the region of warping, and the whole part will become increasingly fragile. A laser may repeatedly scan the overhanging surface, or the overhanging part may collide with the powder scraper and detach from the whole part.

![Figure 4. Schematic illustration of the cause of surface bulge geometries in an L-PBFed micro-rod: edge warping of the layered built-up structure and unmelted adhesive powder.](image)

In this experiment, warping hardly occurs in the overhanging structure because of the small diameter of the rod. The heat generated during forming can be released quickly and ensure the quality of a product.

3.1.3. Surface Roughness of the L-PBFed Micro-Rod

As shown in Figure 4, the poor surface quality of the micro-rod may be caused by shrinkage of the melted metal, adhesion of unmelted particles, undulating surface, and roughness of micro-rods. Extensive studies have proved that the strength and stiffness of the structure are seriously affected [26]. For commercial equipment, L-PBFed parts usually require post-treatment, such as finishing, polishing, and shot blasting, to ensure better surface quality. However, post-treatment hardly applies to micro-rods, especially lattice structures consisting of micro-rods, so we should study the micro-rod roughness to improve the parts’ quality.
The increase in roughness of L-PBFed micro-rods [25] is mainly attributable to the “step effect” and the existence of particles in the part’s surface [25]. Many incompletely melted particles are adhered to the part surface, as seen in Figure 3. The presence of metal particles on the surface of the micro-rod is attributed to the characteristics of L-PBF. Unsuitable process parameters may cause more particles on the surface, including “balling” and partial particle melting, and metallic balls are easily formed on the part’s surface perpendicular to the growth direction [27]. Specifically, surface tension differences occur in the molten pool at a high thermal gradient between molten materials of different volumes, resulting in Marangoni flow [28]. Small spherical entities formed in the molten pool flow radially outward along the material flow to the surface [29] and finally scattered on the sides of the molten pool [30]. After solidification, irregularity appears along a single scanning track. This process is referred to as “balling” in the literature [25] and is deemed a severe obstacle in the manufacturing process, reducing the part density and increasing the surface roughness. Subsequent laser scanning almost eliminates the balling particles, so the balling particles are only visible at the edges of the final scan.

Moreover, the presence of metal particles is also attributed to the characteristics of micro-rod manufacturing. The particles on the micro-rod surface may be formed by the diffusion of laser energy, incomplete melting of the metal particles at the edges, and laser remelting area, as shown in Figure 4.

1. Diffusion of laser energy

In L-PBF manufacturing, the micro-rod is built on loose powder. Laser radiation on the powder bed brings about a significant temperature difference, and thermal diffusion occurs between the loose powder and the solid material. However, the diffusion energy is not enough to completely melt the particles, which leads to partial adherence of melting particles on the lower surface and at the edge of the layer [9,31]. Figure 4c shows typical metal-particle adherence in a high-magnification SEM photograph, where the particles are nearly spherical and have a size of about 45 μm. By comparison, it can be found that the particles have a similar size and morphology to the original metal particles before L-PBF. This further proves that the particles on the surface are some unmelted particles of raw metal. Figure 5 explains the thermal diffusion process of laser energy in principle.

**Figure 5.** Surface roughness of inclined micro-rods and its primary causes: (a) definition of upper and lower surfaces of the inclined micro-rods; (b) SEM to exhibit a difference in surface roughness morphology between the upper and lower surfaces of the inclined micro-rods; (c) schematic of dross formation; (d) schematic relationship between the unmelted particle adherence and the outer surface morphology of inclined and vertical micro-rods; (e) the laser heat-input energy dissipation causing the powder adjacent to the outer surface not to be completely melted.
2. Incomplete melting of metal powders/particles at the edges

In this work, Figure 5 is drawn to schematically illustrate the reason for unmelted metal particles on the boundary of each layer during L-PBF manufacturing. Some metal particles are partially melted on the boundary of the laser scanning path, and then the unmelted metal particles adhere to the boundary of each new layer.

3. Remelting

To simplify the research work, the parts can be divided into several surfaces—horizontal plane, vertical plane, and inclined plane (upper and lower surfaces)—as shown in Figure 5. To ensure that particle layers can be firmly bonded to each other, the laser melting depth (depth of laser melting through the powder) is generally slightly higher than the layer thickness in the L-PBF process, leading to an overlap between layers. When the laser scans the edges of micro-rod and powder-supported areas, the laser beam will directly penetrate the powder because the thermal conductivity of the powder is less than 1/100 of the solid [32]. As the contact between powder particles is limited and separated by an insulating argon atmosphere, the heat is dissipated slowly. The energy cannot be dissipated. The energy absorbed by the powder is much larger than that absorbed by the solid, resulting in an increase in temperature at the edges of the molten pool and the size of the molten pool. Under gravity and capillary forces, a sizeable molten pool will be formed and extend into the powder layer [32]. The liquid metal leaks into the lower powder area and rolls up at the powder bed, forming a bulge edge during the solidification process [33], resulting in dross formation, as shown in Figure 5. Dross significantly affects the components’ surface quality and dimensional accuracy, which is extremely obvious, especially for micro-rods at a slight inclination angle. The surface quality of the micro-rod at an inclination angle of 30° is shown in Figure 5.

3.1.4. Effects of Laser Parameters on Micro-Rod Forming Quality

The forming quality of the L-PBFed micro-rods of lattice structures is closely related to the scanning speed. The part density may increase with decreasing scanning speed. However, the literature [34] argues that almost-complete densified parts can be manufactured when the scanning speed is reduced to 800 mm/s, and a further decrease in scanning speed will interfere with the efficiency of manufacture. Therefore, the scanning speed gradually increases from 700 mm/s to 1200 mm/s, and the laser power is maintained at 210 W. To consider the effect of laser parameters, the effect of laser energy on micro-rod manufacturing is analyzed. Fifty-five micro-rods were manufactured under eleven different kinds of laser energy, and the detailed process parameters are shown in Table 3.

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameters</th>
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<tbody>
<tr>
<td>1</td>
<td>( v = 1200 \text{ mm/s} ), ( P = 210 \text{ W} ), ( \psi = 51.9 \text{ J/mm}^3 )</td>
<td>2</td>
<td>( v = 1100 \text{ mm/s} ), ( P = 210 \text{ W} ), ( \psi = 56.6 \text{ J/mm}^3 )</td>
</tr>
<tr>
<td>3</td>
<td>( v = 1000 \text{ mm/s} ), ( P = 210 \text{ W} ), ( \psi = 62.2 \text{ J/mm}^3 )</td>
<td>4</td>
<td>( v = 900 \text{ mm/s} ), ( P = 210 \text{ W} ), ( \psi = 69.1 \text{ J/mm}^3 )</td>
</tr>
<tr>
<td>5</td>
<td>( v = 800 \text{ mm/s} ), ( P = 210 \text{ W} ), ( \psi = 77.8 \text{ J/mm}^3 )</td>
<td>6</td>
<td>( v = 700 \text{ mm/s} ), ( P = 210 \text{ W} ), ( \psi = 88.9 \text{ J/mm}^3 )</td>
</tr>
<tr>
<td>7</td>
<td>( v = 1000 \text{ mm/s} ), ( P = 150 \text{ W} ), ( \psi = 44.4 \text{ J/mm}^3 )</td>
<td>8</td>
<td>( v = 1000 \text{ mm/s} ), ( P = 180 \text{ W} ), ( \psi = 53.3 \text{ J/mm}^3 )</td>
</tr>
<tr>
<td>9</td>
<td>( v = 1000 \text{ mm/s} ), ( P = 240 \text{ W} ), ( \psi = 71.1 \text{ J/mm}^3 )</td>
<td>10</td>
<td>( v = 1000 \text{ mm/s} ), ( P = 270 \text{ W} ), ( \psi = 80 \text{ J/mm}^3 )</td>
</tr>
<tr>
<td>11</td>
<td>( v = 1000 \text{ mm/s} ), ( P = 290 \text{ W} ), ( \psi = 85.9 \text{ J/mm}^3 )</td>
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The forming process was observed by a real-time camera system. It was found that severe warping occurs at the 85th layer when the scanning speed is 800 mm/s and at the 101st layer when the scanning speed is 900 mm/s. When scanning exceeds 1000 mm/s, severe warping occurs at the 130th layer. When other process parameters (and the laser power is maintained at 210 W) are the same, warping is more severe at a low scanning speed because of the more significant internal stress. However, the warping degree does not keep decreasing with the increased scanning speed because the laser energy will decrease at excessive scanning speed, and the penetration of the laser beam will become weaker. Therefore, the bonding between adjacent layers is affected, leading to lamination defects.
Figure 6 shows the relationship between micro-rod diameter and laser energy. The results show that micro-rod diameter and laser energy are highly related: the micro-rod diameter significantly increases with increasing laser power. Figure 6 shows SEM images of the micro-rods under four kinds of typical laser energy, and the average diameters of 4 micro-rods are 0.518 (ψ = 69 J/mm²), 0.811 (ψ = 65.2 J/mm²), 0.805 (ψ = 65.2 J/mm²), and 0.754 mm (ψ = 65.2 J/mm²). That is because more powder will be melted at a higher laser energy in the L-PBF process. However, the diameter of the micro-rods manufactured under the same laser energy also obviously changes. That is induced by unstable manufacturing characteristics of L-PBF. Different laser parameters also affect the surface roughness and diameter of the micro-rods. To quantify the relationship between laser energy and micro-rod diameter, experimental data are fitted into the following equation:

\[
d = 0.1306 \cdot \ln(\psi) - 0.2017
\]  

Figure 6. SEM images of the micro-rods using ψ values of 69 J/mm² (a), 65.2 J/mm² (b), 65.2 J/mm² (c), and 65.2 J/mm² (d), respectively, and the relationship between micro-rod diameter and laser energy (e).

3.1.5. Effect of the Inclination Angle on Forming Quality and Performance of Micro-Rod

Micro-rods at different inclination angles with the same diameter (d = 1mm) are designed to verify the effect of inclination angle on the formability, and the angle is reduced from 40° to 10°. The micro-rods are manufactured under the same process parameters, as shown in Figure 7a. Specifically, the quality of the micro-rods becomes significantly worse with decreasing inclination angle. The micro-rod diameter is 1.08 mm at an as-built angle of 40° and increases by 7% to 1.16 mm at an as-built angle of 30° due to the poorer surface quality. As the inclination angle further decreases, the micro-rods have more severe deformation, and a pronounced phenomenon of dross formation is generated at the lower surface.
Figure 7. The profiles (a) and cross-sections (b) of as-printed micro-rods, the relationship between as-built angle and laser energy (c), and the relationship between as-built angle and surface roughness (d).

For micro-rods, without adding a support structure, there is a critical angle of manufacturing called the self-supporting angle in the literature [21]. The micro-rod cannot be formed when the inclination angle is smaller than the critical angle.

On the one hand, from only a geometric point of view, as shown in Figure 3, a smaller inclination angle means a larger projected length $S$ between adjacent layers. To guarantee the forming quality, the projected length $S$ must be smaller than the laser beam radius so that most laser energy can be focused on the solid area. Therefore, with the layer thickness $H = 35 \mu m$, the projected length $S$ shall be smaller than the beam diameter $70 \mu m$, and the inclination angle $\theta = 27^\circ$ is the minimum forming angle by theoretical calculation. When the projected length $S = H \cdot \text{ctg} \theta$ is smaller than the beam radius, the inclination angle $\theta \geq 45^\circ$ is a reliable angle for manufacturing micro-rods.

On the other hand, when the laser beam diameter is kept constant, the effects of laser power and scanning speed are comprehensively analyzed based on energy density. Micro-rods are manufactured under the laser parameters shown in Table 3, and the inclination angle gradually increases from $5^\circ$ to $90^\circ$ (at $5^\circ$ intervals). Figure 7 summarizes the relationship between the critical angle and energy density. It can be seen that the critical angle (including the minimum angle and reliable angle) is closely related to the laser energy density, and the critical angle increases with increasing energy input. It should be noted the relationships given in Figure 7 are only instructive for other studies because most of the experimental conditions or machining parameters such as spot diameter, layer thickness, or material, as well as the L-PBF equipment are different from this research.

The changes in the average surface roughness of micro-rod structures with different inclination angles are shown in Figure 7. The average surface roughness tends to decline with increasing inclination angle. As discussed earlier, as the inclination angle increases, the overhanging length becomes smaller, so the step effect is improved, and less powder is bonded.
Three typical as-built angles (30°, 60°, 90°) are selected to evaluate the surface roughness visually. The micro-rod profile is photographed using an optical microscope, as shown in Figure 7. Comparing the upper and lower surfaces, it can be found that the upper surface has significantly better quality because powder bonding and dross formation are more likely on the lower surface. The quality inconsistency between the upper and lower surface presents a challenge in selecting process parameters.

Figure 8a shows the tensile stress–strain curve for a 90° micro-rod manufactured under laser power of 190 W and a scanning speed of 900 mm/s at a displacement rate of 0.1 mm/min. The curves are similar to the tensile curves of the forged samples, but the tensile strength (about 509 MPa) is lower than that of the forged samples. This difference in performance may be caused by microscopic defects in L-PBFed parts and the non-uniformity of macroscopic shape. The elastic modulus is about 73 GPa, only 50% of the forged samples. Young’s modulus significantly differs because the strain in the tensile test is calculated based on the chuck displacement. Micro-rods with inclination angles of 20°, 30°, 40°, 50°, 60°, 70°, and 80° were manufactured under laser power of 190 W and a scanning speed of 900 m/s. The uniaxial tensile properties were tested, and Figure 8b shows the corresponding tensile stress–strain curves. In general, the mechanical properties of the micro-rods gradually decrease with decreasing inclination angles. The tensile response of the micro-rods with angles of 80° and 70° is similar to that of 90°. In contrast, the 40° micro-rod has the worst performance, and the tensile strength is decreased by about 15%. It is worth noting that the performance of the 30° micro-rod is slightly better than that of the 40° micro-rod, probably because the 30° micro-rod has a larger diameter than the 40° micro-rod, as discussed previously, as shown in Figure 6e.

![Figure 8](image_url)

**Figure 8.** Uniaxial tensile test results of micro-rod: (a) 90° micro-rod and (b) micro-rod at inclination angles of 30°, 40°, 50°, 60°, 70°, and 80°.

### 3.2. Lattice Structure Design and Mechanical Behavior Research of Cantor HEA L-PBF Micro-Rod

In previous studies, the most common lattice structures are body-centered cubic unit cell (BCC), face-centered cubic unit cell (FCC), and their derived structures, such as BCCZ (body-centered cubic unit cell with vertical struts) and FCCZ (face-centered cubic unit cell with vertical struts). Moreover, common structures include octagonal lattice and diamond structures, as detailed in Figure 9a [35]. Some lattice structures are selected for analysis in this work, including BCC, FCC, BCCZ, FCCZ, BCCXYZ, and FBCCXYZ, as shown in Figure 9b, where X, Y, and Z indicate that micro-rods are added in the corresponding directions.
This work, including BCC, FCC, BCCZ, FCCZ, BCCXYZ, and FBCCXYZ, as geometric configurations; (a) geometric configurations; (b) macroscopic morphology after L-PBF 3D printing; (c) SEM morphology of an as-printed BCC lattice; (d) SEM and cross-sectional morphology of a typical micro-rod in the BCC lattice structure; (d) SEM morphology of an as-printed BCC lattice.

3.2.1. Manufacturing Defects of L-PBFed Micro-Rod-Lattice Structure

As mentioned earlier, it is not easy to machine complex lattice structures with traditional manufacturing techniques. With the help of AM technology, especially L-PBF, we can manufacture lattice structures with complex components and lengths. However, L-PBFed parts generally have some inherent geometric defects, especially volume defects. Some experimental studies are conducted to evaluate these geometric defects and explore their effects reasonably.

1. Analysis of geometric defects of the lattice structure

The morphology and microstructure of the lattice structure sample in Figure 9b are characterized by a scanning electron microscope. It can be found that there are many geometric deviations between the manufactured samples and the design, such as metal powder bonded at the micro-rod joints, uneven shape of micro-rod, and over-melting of horizontal micro-rods. It is difficult to extract all the geometric defects of the lattice structures because of the high randomness of geometric defects and many micro-scale defects in the lattice structures [36]. These defects significantly affect the lattice structure’s mechanical properties and failure mechanisms, including porosity, thickness variation, waviness, and dimensional deviations of micro-rods [36]. This research mainly involves three types of geometric defects: thickness variation, waviness, and dimensional deviations of micro-rods. Figure 9d illustrates these common geometric defects. This research focuses on the above defects, intending to study the effects of these defects on the failure mechanisms and mechanical properties of the lattice structures.

- The micro-rod’s waviness: the virtual micro-rod’s centerline deviates from the design and becomes wavy, as shown by the red line in Figure 9d.
- Irregular variation of micro-rod thickness: the cross-section of the virtual micro-rod deforms irregularly along the rod, as shown in blue shading in Figure 9d, and the thickness of the micro-rod varies significantly.
• Dimensional deviation of the micro-rod: compared with the size of the micro-rod along the building direction (BD), the size of the micro-rod in other directions is either larger or smaller. The effect of the inclination angle on the micro-rod size has been discussed. In general, the size of parts perpendicular to the BD is larger than the design value because of over-melting, but smaller in other directions, as shown by the green line in Figure 9d. The effective diameter of the micro-rod perpendicular to the BD is 0.38 mm, which is more significant than the design value (0.35 mm). In comparison, the diameter of the inclined micro-rod is 0.33 mm, smaller than the design value.

2. Extraction and statistics of geometric defects

To extract the surface morphology features of the micro-rods of the lattice structure, geometric defects were extracted according to the process indicated in Figure 9c. The micro-rods were removed from the lattice structure and inlaid into thermosetting resin as the metallographic specimen. The specimen was polished to the middle section of the micro-rod, and then, the micro-rod cross section could be photographed with a light microscope. To evaluate the geometric defects, the design edges are marked by solid blue lines in Figure 9c, and the blue dotted line marks the medium line of the design in Figure 9c. A series of parallel lines with equal spacing are shown as red lines in Figure 9, perpendicular to the micro-rod, and cut by the edges of the actual micro-rod. The center deviation can be obtained by comparing the midpoint of the red line (black point in Figure 9c) with the medium line of design, as shown by the grey line in Figure 9c. The deviation between the actual edge and the design edge was determined by comparing the actual edge line with the design edge line (the left and right deviations are averaged), i.e., the radius deviation, as shown by the green line in Figure 9c. Geometric defects are classified into three categories by their growth direction: (I) micro-rods parallel to the growth direction of the lattice structure (referred to as vertical bars), (II) micro-rods perpendicular to the growth direction of the lattice structure (referred to as horizontal bars), and (III) inclined micro-rods (referred to as inclined bars). This work discusses the BCCXYZ lattice structure (number of cells: $6 \times 6 \times 6$), including a total of 588 vertical bars, 588 horizontal bars, and 1728 inclined bars. To provide reliable data, at least 35 bars (6% horizontal or vertical bars and 2% inclined bars) of each type of micro-rods are randomly selected for probability statistics. To quantitively express these distributions, the average value $a$ and standard deviation $\sigma$ of the radius deviation $r$ and center deviation $c$ are calculated for three micro-rods ($d$ for inclined bars, $h$ for horizontal bars, and $v$ for vertical bars). Three types of geometric defects in Figure 9c can be quantitatively expressed as follows:

- The thickness variation of the micro-rods is expressed as the standard deviation ($\sigma_r$) of the radius.
- The waviness of the micro-rods is expressed as the average center deviation ($a_c$).
- The dimensional change in the micro-rods is expressed by the average radius deviation ($a_r$), where a positive value indicates that the actual size is larger than the design size, while a negative value indicates that the actual size is smaller than the design size.

Taking a micro-rod as an example, its cross section is shown in Figure 10a. The deviations between design and actual manufacturing are statistics, as shown in Figure 10b,c. If $a_r$ is positive, this indicates that the actual radius of this support bar is 9.5% larger than the design value on average, which also confirms that the micro-rod overmelts during the L-PBF process, consistent with the previous conclusion given in Figure 6. In addition, $a_c$ in Figure 10 indicates that the actual medium line of the micro-rod is a deviation by approximately 6.5% from the design medium line.
The compression deformation of the two structures is shown in Figure 11, and it can be found that the FBCXYZ structure has a 45° inclined fracture, while the BCCXYZ structure is collapsed layer by layer.

### 3.2.2. Mechanical Properties of L-PBFed Micro-Rod-Lattice Structure

The lattice structure is tested under quasi-static uniaxial compression conditions to evaluate its mechanical properties. Figure 11 shows the engineering compressive stress–strain curves for different lattice structures under considerable strain. When the load is applied, the initial curve is nonlinear and concave downwards, similar to the result in the literature [37], probably because slight deformation of the samples occurs in the cutting process, resulting in an uneven surface. In the elastic area, the curves show better linearity than the metal foam structure, and the local yielding of the lattice structure is not apparent, probably because the lattice structure is a typical hierarchical structure. In contrast, the pore size of the metal foam structure is randomly distributed. The yield performance of the lattice structure is stronger under low to medium stress load.

The Z-direction support significantly affects the curve in the transition area from the elastic to the plastic area. For example, the entire curve is relatively smooth without sharp yield points in the BCC lattice, and the stress increase is limited, although with a further increase in strain, called a stress plateau. For structures with Z-directional supports, there is an apparent initial stress peak at the beginning of the curve, which is related to the plastic bending of the Z-directional support bar. After the failure of the Z-directional support bar, the overall structure becomes unsteady, and the stress oscillates when the strain subsequently increases. In this research, the initial peak stress is taken as the yield point, while for structures without Z-directional support bars, the stress corresponding to 5% strain is set as the yield stress of the structure.

Most structures exhibit high initial strength, but the strength significantly decreases after the first collapse. In general, compared with structures with lower relative density, the stress of the structures with a relatively high density significantly decreases. In contrast, the strength of the BCC structure does not significantly decrease, similar to the results observed in the literature [38]. The load applied on the micro-rods of the BCC structure is mainly a bending load, resulting in the gradual collapse of the whole structure. For other structures, by contrast, a tensile and compressive load is mainly applied on the micro-rods, resulting in the sudden collapse of the whole structure. By comparing with FBCXYZ and BCCXYZ, it can be found that the initial strength of the two structures has little difference (about 11%), while there is a significant gap in the range of strength decrease (about 21%). The compression deformation of the two structures is shown in Figure 11, and it can be found that the FBCXYZ structure has a 45° inclined fracture, while the BCCXYZ structure is collapsed layer by layer.

![Figure 10](image_url)
Ashby et al. have investigated the metal foam model and believe that the relative Young’s modulus, compressive strength, and relative density are closely related [39]:

\[
\frac{E}{E_S} = C \times \left( \frac{\rho}{\rho_S} \right)^n \tag{7}
\]

\[
\frac{\sigma}{\sigma_S} = C \times \left( \frac{\rho}{\rho_S} \right)^n \tag{8}
\]

where C and n are constants, and the s subscript represents the properties of the base material. Gibson [40] proves that the above equations estimate the mechanical properties of similar structures. Figure 12 shows the ratio of relative Young’s modulus (\(E/E_S\), where \(E\) is the elastic modulus of 2% strain), relative compressive strength (\(\sigma/\sigma_S\)), and relative density (\(\rho/\rho_S\)) of different structures. It can be found that, similar to the open-cell foam structure, the mechanical properties of the lattice structures present a positive powder relationship with the relative density. In addition, the modulus is proportional to 1 and 2 times the relative density, and the strength is proportional to 1 and 1.5 times the relative density.
Figure 12. Relationship between relative modulus, compressive strength, and relative density of the lattice structures: (a) the relative Young’s modulus, (b) the relative modulus of 2% strain, and (c) the relative compressive strength.

Conclusions

The L-PBF is effective in directly and rapidly fabricating geometrically complex, precise, and high-performance metal lattice parts. The path exhibits the advantages of digital.
4. Conclusions

The L-PBF is effective in directly and rapidly fabricating geometrically complex, precise, and high-performance metal lattice parts. The path exhibits the advantages of digital forming, the nonuse of molds, the relatively high forming accuracy, the high material utilization rate, and good mechanical properties of the as-printed lattice parts. The L-PBF makes the manufacturing of lightweight components more promising. This work analyzed the causes of common manufacturing defects of L-PBFed micro-rods and rod lattices. The effect of L-PBF processing parameters on formability was also discussed. Then, the mechanical property experiments were carried out on L-PBFed micro-rods and rod-lattices. The results are as follows:

1. The manufactured micro-rods are evaluated and classified according to the forming quality. In the actual L-PBF process, manufacture defects such as “step effect”, dross formation, warping, and metal particles on the surface are likely to occur for micro-rods, which are mainly caused by the diffusion of laser energy, incomplete melting of some metal particles at edges, and laser remelting.

2. With the increased laser power, the micro-rod diameter increases significantly, and the experimental data were fitted. There is a critical angle for micro-rod manufacturing. Manufacturing defects are apparent when the inclination angle is less than the critical angle. The average surface roughness tends to decline with increasing inclination angle. A reliable angle is closely related to the laser energy density and increases with increasing energy input.

3. The causes of common manufacturing defects of the rod-lattice structure were analyzed, including irregular variations in the support bars’ thickness, waviness, and dimensional deviations. By giving statistics on the defects of different micro-rods in the lattice structure, the results show that different micro-rods significantly vary in forming quality, and horizontal bars have more geometric severe defects.

4. The mechanical properties of the rod-lattice structure were evaluated by compression experiments, finding that the mechanical properties of different lattice structures present a positive power relationship with the relative density. The modulus is proportional to the relative density between 1 and 2 times, and the strength is proportional to the relative density between 1 and 1.5 times.

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