Fabrication of Mesh Patterns Using a Selective Laser-Melting Process

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Abstract: The selective laser-melting (SLM) process can be applied to the additive building of complex metal parts using melting metal powder with laser scanning. A metal mesh is a common type of metal screen consisting of parallel rows and intersecting columns. It is widely used in the agricultural, industrial, transportation, and machine protection sectors. This study investigated the fabrication of parts containing a mesh pattern from the SLM of AISI 304 stainless steel powder. The formation of a mesh pattern has a strong potential to increase the functionality and cost-effectiveness of the SLM process. To fabricate a single-layered thin mesh pattern, laser layering has been conducted on a copper base plate. The high thermal conductivity of copper allows heat to pass through it quickly, and prevents the adhesion of a thin laser-melted layer. The effects of the process conditions such as the laser scan speed and scanning path on the size and dimensional accuracy of the fabricated mesh patterns were characterized. As the analysis results indicate, a part with a mesh pattern was successfully obtained, and the application of the proposed method was shown to be feasible with a high degree of reliability.

Keywords: additive manufacturing; selective laser melting; 3D printing; mesh pattern; copper base; Finite element method

1. Introduction

Additive manufacturing (AM) technology has become widely used to fabricate functional metal parts in the automobile, aerospace, and medical device industries owing to its versatile process capacity including a complex geometry, high functionality, and free tool usage. It is advantageous for the fabrication of prototypes and various types of small quantity production because users can easily change the shape of a product using a 3D CAD solid model [1–4].

The selective laser melting (SLM) process is a type of AM process in which a 3D part is built layer by layer by melting metal powder through laser scanning. SLM can be used to build full-density, high-performance, and complex metal parts without the need for dies or tools [5–8]. When compared with other traditional techniques, laser processing typically does not require mechanical tooling and, therefore, exhibits high flexibility [9–15]. A laser beam scans each layer to melt powder particles locally and form a melting pool, which is instantaneously solidified as the laser beam moves away. Therefore, it is critical to optimize parameters that influence the mechanical properties of the part, such as the laser power, scan rate, powder layer thickness, beam spot size, and hatch distance task [16–19].

A metal mesh, widely used in agricultural, industrial, transportation, and machine protection sectors, is a common type of metal screen consisting of parallel rows and intersecting columns [20–23]. A metal mesh can be made using intersecting wires by typically joining them together through welding or weaving. Although similar in appearance and their applications, a perforated mesh sheet and an expanded mesh sheet are not wire mesh types. Figure 1 shows four different types of metal meshes.
weaknesses, and because the formed product is significantly influenced by the manufacturing method, wire through the chosen weave pattern. The wires are then bent toward the reverse position, and the welding methods can be employed, this is usually the most economical. Once a mesh has reached the desired length, it is cut using a shear, resulting in a flat and rigid welded wire mesh sheet.

A woven wire mesh has an array of intersecting wires, similar to a woven cloth. Typically, the wires are woven over and under the perpendicular wires, producing a stable sheet, as shown in Figure 1b. Producing a consistent knitted mesh to exactingly high standards requires a level of technical expertise and experience in the manufacturing and processing of a knitted wire mesh. A woven wire mesh has no welds. Instead, they are fed into a machine similar to a loom, which feeds a straight wire through the chosen weave pattern. The wires are then bent toward the reverse position, and the next straight wire is fed through the pattern. The machine continues this process until the desired dimensions are reached and the completed wire mesh sheet is then cut to the desired size. Wire knitting not only requires the correct machines, cylinder heads, needles, and spools, but also specific knowledge and experience with material science to ensure the performance and quality of the product. As shown in Figure 1c, a perforated mesh sheet is a sheet metal that has been manually or mechanically stamped or punched to create a pattern of holes, slots, or decorative shapes. An expanded mesh sheet is produced in a single piece through the synchronized cutting out and drawing of laminated metal, as shown in Figure 1d. Because this process does not produce any loss of material, the production of an expanded mesh sheet can be important when economics are being considered.

As described above, each manufacturing process is characterized by its own strengths and weaknesses, and because the formed product is significantly influenced by the manufacturing method, a reasonable compromise between process efficiency and product quality is required.

Direct manufacturing of metal lattice structures is now possible through the use of laser- and electron beam melting (EBM)-based additive manufacturing systems. Fine-structured 3D porous filter elements and porous titanium implants with a channel structure have been built with SLM. Geometrically complex filters with customized shapes and oriented in the through direction were successfully fabricated. The production of porous scaffold structures using additive manufacturing is becoming widespread. There are a number of methods to produce porous components. Of these methods, only additive manufacturing techniques enables the fabrication of anatomically-shaped scaffolds with complex internal architectures, allowing precise control of the

![Figure 1. Four types of metal meshes: (a) welded, (b) woven, (c) perforated, (d) expanded.](image-url)
stiffness [37,38]. EBM process uses an electron beam as the energy source to selectively melt layers of metal powder in vacuum [39]. The electron beam is generated by heating a tungsten filament and accelerating the electron towards the metal powder at the build platform using an accelerated voltage. The electron beam is focused and deflected using electromagnetic coils. Liu et al. [40] reported microstructure, defects and mechanical behavior of porous structures manufactured by EBM. As the peak temperature of EBM is higher than that of SLM, the metallurgical properties of fabricated parts are somewhat different from those of SLM. Although many previous studies using SLM have focused on the manufacturing of porous and lattice-like parts. SLM has demonstrated its potential for manufacturing mesh structure with the desired dimensions.

The formation of a mesh pattern has a strong potential to increase the functionality and cost-effectiveness of the SLM process [41]. In this study, the fabrication of a metal mesh using SLM has been investigated as a fast and easy process with a tailored dimensional accuracy. This is very advantageous for the integrated one-step fabrication of small quantity production of various mesh types because the fabrication of a part with a mesh pattern can be easily achieved using a 3D computer-aided design (CAD) solid model. To fabricate a single-layered thin mesh pattern, laser layering was applied on a copper base plate in this study. The high thermal conductivity of copper allows heat to pass through it quickly, and prevents the adhesion of a thin laser-melted layer. The effects of the process conditions such as the laser scan speed and scanning path on the size and dimensional accuracy of the fabricated mesh patterns were characterized experimentally. In order to optimize processing conditions for the laser layering, the effects of process conditions on line instability of the mesh lines were determined. Based on the above experimental results, a thin cylindrical tube with mesh patterns was fabricated to validate the feasibility of the proposed approach.

2. Material and Process Characterization

Figure 2 shows the morphology of spherical AISI 304 stainless steel powder. Powder particles with an average size of 35 µm or less were used for the SLM experiments. The chemical composition of the powder is shown in Table 1. The parts were built on a copper base plate. The high thermal conductivity of copper allows heat to pass through quickly, and prevents the adhesion of the laser-melted thin layer during the SLM process. Hence, thin laser-melted parts fabricated on a copper plate can be easily detached without the application of any post-separation process.

### Table 1. Chemical composition of AISI 304 stainless steel powder (wt.%).

| Element | Fe  | Cr  | Ni  | Mo  | Mn  | Si |
|---------|-----|-----|-----|-----|-----|----|
| wt. %   | Bal.| 18.00 | 9.00 | 2.25 | 1.00 | 0.20 |
A fiber laser (IPG YLR-200, IPG Photonics Company, Burbach, Germany) irradiation system with a maximum power of 200 W is used. The wavelength of the laser is 1.07 µm, and the laser beam diameter is 0.08 mm at the focal position. A scanner (hurrySCAN®20, SCANLAB, Puchheim, Germany) is used to control the laser scanning. The vertical movement of the cylinder is driven by a motor. Table 2 shows the laser process parameters used in the SLM experiments.

| Table 2. Process parameters used in selective laser melting (SLM). |
|---|---|
| Laser Power (W) | 200 |
| Scan rate (mm/s) | 110 |
| Fill-spacing (mm) | 0.06 |
| Powder layering thickness (mm) | 0.2–0.6 |
| Fabricated shape type | square, circle, rectangle |

Figure 3 schematically shows the single-track SLM process. In a single-track SLM process with a copper base plate, the powder layering thickness is critical in obtaining a sound bead. As shown in Figure 3a, a sufficient sized melted bead is not obtained when the powder layering thickness is 0.2 mm or less. At a low powder-layering thickness, a large amount of heat of the irradiated laser beam is rapidly dissipated from the copper plate and, therefore, a complete melting of the powder becomes hard to achieve at a low powder layering thickness. In contrast, a fully melted bead is obtained when the powder layering thickness is approximately 0.5 mm, as shown in Figure 3b. In this case, an irradiated laser beam with a large amount of heat is used for melting the powder, and the amount of heat loss from the copper plate is relatively small. Owing to the steady melting of the powder and the uniform solidification of the molten pool on the copper base, a sound thin-layered bead with 0.4 mm width has been obtained at this layering thickness. Figure 3c shows a layering thickness of above 0.6 mm, the shape of the bead becomes irregular owing to the free consolidation without the controlled solidification effect of a copper plate. Therefore, single-track SLM experiments were conducted using a laser power of 200 W, a scan rate of 110 mm/s, and a powder layering thickness of 0.5 mm.

**Figure 3.** Single-track beads fabricated at powder layering thickness of (a) 0.2 and (b) 0.5 mm (c) 0.6 mm.
Figure 4 shows a schematic of the multi-track SLM process. Figure 5 shows cross-sectional views of beads obtained under various laser heat input conditions. At a laser power of 100 W, an unstable irregular bead is obtained owing to insufficient heat input and heat dissipation through the copper plate, as shown in Figure 5a,b shows a bead obtained at a laser power of 150 W. An unstable irregular bead still occurs owing to insufficient heat input and heat dissipation through the copper plate. A sound fully melted bead is obtained at a laser power of 200 W, as shown in Figure 5c. In this case, an irradiated laser beam with a large amount of heat is used for melting the powder, and a uniform solidification of the molten pool on the copper base steadily occurs. Because a thin layered bead with good dimensional accuracy can be obtained under these processing conditions, a laser power of 200 W, scan rate of 110 mm/s, and powder layering thickness of 0.5 mm are used for fabrication of the thin mesh part. The fill spacing of the scan path is set to 0.06 mm, and the Ar gas flow of the shielding chamber is maintained at a rate of 10 L/min.

![Schematic drawing of multi-track SLM](image.png)

**Figure 4.** Schematic drawing of multi-track SLM with various amounts of laser energy heat input.

![Cross-section views of beads](image.png)

**Figure 5.** Cross-section of the multiple parts obtained using various amounts of laser heat input (laser scan rate of 110 mm/s, powder layering thickness of 0.5 mm), with a laser power of (a) 100 W for low laser heat input, (b) 150 W for medium laser heat input, and (c) 200 W for higher laser heat input.

### 3. Finite Element Analysis

To evaluate the residual stress and transient temperature distributions according to scan track in the SLM process, finite element (FE) simulation has been conducted. The commercial finite element analysis code, ABAQUS™, was used in this study. Figure 6 shows two different scan tracks, one is a straight scan track and another is a circular scan track. The solution processes of the finite element analysis involved two main steps. In the first step, a transient thermal analysis was carried out to generate the temperature history of the entire workpiece. In the second step, a mechanical analysis was conducted to calculate the residual stress and the load in this step is the temperature field file...
generated in the previous step. The temperature history of all nodes generated in the thermal analysis was imported as a predefined field into the mechanical analysis.

The powder bed was modeled with a dimension of $2.5 \times 2.5 \times 0.5$ mm. Element type was an 8-noded heat transfer brick element (DC3D8) of $60 \times 60 \times 60$ μm as shown in Figure 7. Total number of elements was 14,112 and total number of nodes was 16,641. To represent a moving heat source, heat flux was applied on the top surface of powder bed by using the DFLUX user subroutine in ABAQUS and the USDFLD user subroutine was used to consider the temperature dependent properties of powder and solid.

In transient thermal analysis, the laser beam heat source was modeled as a Gaussian distribution heat flux on the powder bed surface, which is represented as Equation (1). The user subroutine DFLUX in ABAQUS was used to model the motion of the heat source according to a different scan track.

$$I(r) = \frac{fAP}{\pi r_0^2} \exp\left(-\frac{r^2}{r_0^2}\right)$$

(1)

where $I$ is the laser intensity, $f$ is the distribution factor, $A$ is the energy absorption coefficient, $p$ is the power of the heat source, $r_0$ is the radius of the heat source, and $r$ is the radial distance of any point from the axis of the heat source. The laser power absorptivity is 0.4 [42]. A combined surface
film condition \((hk)\) was applied as a film boundary condition to account for convection and radiation on all external surface. The combined surface coefficient is \(hk = 2.4 \times 10^{-3} \varepsilon T^{1.61}\), where \(\varepsilon\) is 0.85 emissivity [43]. The thermo-capillary phenomenon in a molten pool was considered by modifying the thermal conductivity by a factor of 2.5. As the density increases, the Young’s modulus of material also increases. For an accurate FE analysis, the temperature dependent density and Young’s modulus of the material need to be used [44]. The relevant temperature dependent thermal and mechanical properties for AISI 304 are obtained from literature [42], and Poisson’s ratio of 0.3 was used. The powder bed was considered as a mixture of solid and gas phase thus the density and conductivity of powder were considered as Equations (2) and (3) [45].

\[
\rho_{\text{powder}} = \rho_{\text{bulk}} \times (1 - \varnothing) \\
k_{\text{powder}} = k_{\text{bulk}} \times (1 - \varnothing)
\]

where \(\varnothing\) is the porosity of the powder and is assumed as 0.4 [42].

Figure 8 shows the transient temperature distributions for both straight and circular scan tracks. The color was set as grey if the temperature is higher than the melting point (1733 K); therefore, the gray region represents the molten pool area.

The temperature gradient at the front of the moving laser is larger than that in the rear side which be attributed to the fact that the molten pool has greater conductivity than the untreated powder bed in front of the laser. This sharp thermal gradient can induce high residual stress and result in distortion and cracks during the SLM process. Therefore, the residual stress was investigated for two different scan tracks. Von-Mises stress was measured along the measuring path as shown in Figure 9. Position A and B represent both ends of the laser scanning region. Distribution of Von-Mises stress for straight and circular scan tracks were illustrated in Figure 9. Distribution of residual stress shows that the region of start and final of scan track has higher residual stress. Maximum Von-Mises stress is 160 MPa for straight scan track and 166 MPa for circular scan track. Average of residual stresses within the laser scanning area is 156 MPa for a straight scan track and 159 MPa for a circular scan track. This result indicates a straight scan track reduces the residual stress; therefore, a straight scan track was used in manufacturing mesh part in this study.
Figure 9. Von-Mises stress for two different scan tracks; (a) straight track, (b) circular track.

4. Selective Laser Melting (SLM) of Thin Mesh Patterns

Figure 10 shows the three mesh types fabricated in this study. Mesh patterns with dimensions of 20 × 20 × 0.4 mm were built using the SLM process on a copper plate. The line spacing of the meshes was 0.82, 0.82, and 2 mm for square, circular, and rectangular shapes, respectively.

Figure 10. Computer-aided design (CAD) models of different mesh types: (a) square, (b) circular, and (c) rectangular holes.

The layer was made of AISI 304 stainless steel powder on a copper plate. To see the effect of copper plate, the molten-pool temperatures for AISI 304 stainless steel and copper base plates are compared by FE simulations. Figure 11 shows the molten-pool temperatures obtained for the two different base plates. As the thermal conductivities of the base plates differed, the geometries and temperatures of the molten pools also changed. When using the AISI 304 stainless-steel base plate, the temperature of the plate surface is above the liquidus temperature, and the molten pool is expected to adhere to the base plate, due to local fusion. In the case of the copper base plate, the rapid heat dissipation due to the enhanced thermal conduction can reduce the possibility of local adhesion. However, the overall molten-pool area obtained for the AISI 304 stainless-steel base plate is larger than that of the copper base plate, due to the reduced heat dissipation.
For the validation purpose, the multi-track bead shapes obtained from experiments for the two different base plates are shown in Figure 12. When using the AISI 304 stainless-steel base plate, the molten pool adheres to the base plate due to the local fusion. In the case of the copper base plate, no adhesions are observed along the boundary due to the rapid heat dissipation due to the enhanced thermal conduction. The overall layer height obtained for the AISI 304 stainless-steel base plate is 100–150 µm larger than that of the copper base plate, due to the reduced heat dissipation.

Figure 13 shows a schematic drawing of the mesh fabrication method applied. As obtained by the FE simulations described in Section 3, straight scan track has been applied in the SLM process. After completing the irradiation, the fabricated mesh part is detached from the copper plate.
Figure 14 shows images of SLM-fabricated mesh parts having square, circular and rectangular holes with a size of 20 × 20 mm. As the figure shows, sound mesh parts with the target dimensions are quickly obtained through a single continuous irradiation.

![Image of mesh parts](image)

**Figure 14.** Mesh parts fabricated using SLM: (a) square, (b) circular, and (c) rectangular holes.

Figure 15 shows an optical microscope image of the mesh part obtained. The bead has a continuous and dense appearance. According to the optical microscope image obtained at 500× magnification, the microstructure consists of a γ-austenite matrix with δ-ferrite having a dendrite size of about 20 μm. During the solidification of austenitic stainless steel, such as AISI 304 stainless steel, the first phase to solidify as the temperature drops below the point of peritectic transformation is δ-ferrite [46]. Hence, δ-ferrite tends to transform into austenite (γ) during cooling. The phase transformation from δ-ferrite into γ-austenite depends on the diffusion mechanism through a solid phase. The time available for the transformation δ → γ to occur and complete itself decreases with the increase in cooling rate. Compared with that of the substrate, the δ-ferrite content of the laser melted layer increases dramatically owing to the higher cooling rate. As the cooling rate significantly increases from the heat dissipation of the copper plate, a considerable amount of δ-ferrite is observed at room temperature. The presence of δ-ferrite in a γ-austenite matrix in laser processed AISI 304 stainless steel is known to improve both the corrosion resistance and the mechanical properties [47,48].

![Image of optical microscope](image)

**Figure 15.** Optical microstructure of the mesh part.

5. Fabrication of Part with Mesh Pattern

For validation, a part with a mesh pattern was fabricated. The dimensions of a cylindrical tube with a mesh pattern are shown in Figure 16. As the monolithic cylindrical mesh made of AISI 304 stainless steel has strong application potential for filters and fluid-permeable components, spherical AISI 304 stainless steel powder with an average size of 35 μm or less was used in fabricating both the mesh pattern and the cylindrical tube.
To obtain the targeted shape, a thin-walled cylindrical tube was first fabricated using the SLM process. Figure 17 shows a schematic of the fabrication sequence of a thin-walled cylindrical tube. As shown in the figure, the cross-hatching technique was used in this study. The full pattern of subsequent layers was rotated 90° to reduce an uneven, rib-shaped structure, which can be observed on a laser-melted horizontal surface without a rotation applied. The powder layering thickness was 0.09 mm and the gas flow rate was 10 L/min.

Figure 18 shows a schematic of the fabrication method for a cylindrical tube with a mesh pattern. Spherical AISI 304 stainless steel powder with an average size of 35 μm or less was used in fabricating both the mesh pattern and the cylindrical tube. As shown above, a cylindrical hollow tube is first fabricated using the SLM process. A straight scan track simulated by the FE simulations has been applied in the SLM process. To fabricate a mesh pattern on the cylindrical tube, a cylindrical copper base that fits in terms of the height and inner diameter is inserted into the hollow tube. The diameter of copper plate is machined to be 7.95 mm slightly smaller than the inner diameter of the cylindrical tube, 8 mm. Next, a feeding and layering of the powder on the top surfaces of the cylindrical tube and copper base are applied. The cylindrical copper base is fitted into the inner wall of the tube so as to fabricate detachable thin mesh patterns. After laser irradiation is conducted based on the CAD
data of the mesh shape, the cylindrical copper base is removed from mesh by shooting compressed air. A cylindrical tube with a mesh pattern is then obtained.

Figure 18. Schematic of mesh-tube fabrication method.

Figure 19 shows a fabricated cylindrical tube with a mesh pattern. As shown in this study, various types and sizes of meshes can be quickly and easily fabricated on hollow cylindrical parts by single continuous irradiation. The rough surface of the SLM part can be improved significantly by laser remelting. A remelting process that irradiates again the surface of the part obtained from SLM provides enhanced roundness with a smooth surface. Yasa et al. [49] also suggested laser-surface remelting as a potential method for improving the surface quality during the laser-melting process.

Figure 19. Mesh tube fabricated using SLM; (a) Step 2, (b) Step 5, (c) fabricated mesh tube.
6. Conclusions

The fabrication of mesh patterns using an additive selective laser-melting process was investigated in this study. The effects of the process conditions such as laser heat input, scan speed, and powder-layering thickness on the dimensional accuracy of a fabricated mesh pattern were characterized through single- and multi-track SLM experiments. Based on a parametric analysis of the SLM experiments, a hollow cylindrical tube with a mesh pattern was successfully fabricated on a copper base plate. The high thermal conductivity of copper enhances the stable deposition of the bead and prevents adhesion of the thin laser melted layer. The fabrication of a metal mesh using SLM on a copper base plate was advantageous for the integrated one-step small quantity production of various mesh types, and the proposed method was shown to be feasible with a high degree of reliability.

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