Comparison of sequential and circular scanning thermal fields and their influence on microstructure of Alnico alloy produced by laser powder bed fusion

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Abstract. Residual stress create deformations and stress in additive structures that lead to geometry deviations of created elements of 3D models and defects as pores and cracks that occur in construction process. Our work rests upon theoretical and experimental approach to the study. The main objective is to compare thermal fields with the microstructure of samples and to establish relationship between laser powder bed fusion (LPBF) modes and the structure of the samples to be created. 3D finite element method (FEM) is used for macroscopic modeling to assess the effect of thermal fields on the microstructure of Alnico alloy. Comparison of the temperature fields with the microstructure of samples made by LPBF showed that the type of scanning (both bidirectional and circular) had a strong influence on the distribution of the thermal fields and, accordingly, on the microstructure of the samples made by LPBF.

1. Introduction

Laser powder bed fusion (LPBF) is a widely used additive manufacturing method for 3D printing of metal structures. LPBF has many advantages over other traditional production methods, such as casting, milling, forging, etc. These include the possibility to manufacture complex structures, low level of material waste, and short production process time [1].

One of the problems of additive manufacturing of metal components is the residual stresses that occur in manufactured samples. Residual stress is defined as a stress that remains in the material in equilibrium state after manufacturing, heating or other changes. Residual stress in additive structures leads to deformations and stress which bring about geometry deviations of created elements of 3D models and defects as pores and cracks that occur during the manufacturing process. Such defects make hard problems in the additive manufacturing of complex parts of uneven cross-section thickness. During manufacture of parts by LPBF the great amount of energy density transmitted by laser generates significant temperature gradients inside the material. This uneven heating causes expansion and contraction that can potentially result in significant residual stress [2].

The residual stress depends directly on temperature distribution during the manufacturing of the part, and the temperature distribution correlates with such parameters of the LPBF process as scanning mode, hatching step, scanning speed, laser power, etc. Different scanning modes lead to a different temperature distribution in the sample, which affects the residual stress and, accordingly, the quality of metal [3, 4]. Thus, by changing the scanning modes, one can reduce the residual stress in the sample.
Numerical simulations can be used to predict the quality of parts made by LPBF. Numerical models especially if they are based on experimental measurements can be used as a simple and inexpensive way to predict characteristics and quality of parts. The LPBF process, however, has difficulties in modeling due to the many phenomena occurring over a large temperature range that varies from room temperature to thousands of degrees.

Currently, different numerical models of LPBF are available. Some of them can only be used to further understand the process [5-7]. Others can be used in an attempt to predict and optimize LPBF process parameters to optimize printing [3, 8, 9].

This paper studies the process of modeling and conducts the experiment to analyze the effect of thermal fields on the microstructure of samples made by LPBF. The main objective of the study is to compare the thermal fields with the microstructure of the sample and establish the relation between the LPBF modes and its structure. 3D finite element method (FEM) for macroscopic modeling is used to assess the influence of the thermal fields on the microstructure of the Alnico alloy with Comsol Multiphysics 5.4 software.

2. Materials and methods

2.1. Numerical simulation. Model formation

Figure 1 shows a LPBF sample model with a laser beam trajectory. The motion of the laser beam filled with bidirectional hatching is analyzed to demonstrate the effect of each pass on temperature dependences and the size of the melt bath.

![Figure 1. Multiple scan model.](image)

The laser beam moves along the cross-section of the created sample with the speed and step of hatching, depending on the specified mode of the LPBF process.

During the sample’s manufacture the metal undergoes numerous cycles of melting and subsequent rapid solidification, which has a direct effect on the microstructural and mechanical properties of the parts that will differ for different LPBF modes.

LPBF is a complex multiphase process therefore several assumptions were made to simplify the model:

- it is assumed that the powder material is a solid medium;
- the laser energy absorption coefficient is constant;
- dynamic processes during melting and evaporation are not taken into account.

Austenitic steel 316L was chosen as the material for modeling the process, since austenitic steels are widely used in additive manufacturing and do not have phase transitions up to the melting point which simplifies the modeling. The physical properties of the material are shown in Table 1 and the temperature dependence of the heat capacity of 316L steel is shown in Figure 2.
| Parameter (Designation)                  | Value [Dimension] |
|-----------------------------------------|-------------------|
| Surface absorption coefficient (ε)      | 0.8               |
| Laser energy absorption coefficient (A) | 0.8               |
| Melting point (T_m)                     | 1720 [K]          |
| Evaporation temperature (T_v)           | 3200 [K]          |
| Density (ρ)                             | 7200 [kg/m³]      |
| Thermal conductivity (k)                | 24.9 [W/mK]       |
| Specific heat of melting (L_m)          | 205 [kJ/kg]       |
| Specific heat of evaporation (L_v)      | 6000 [kJ/kg]      |

**Table 1.** Physical properties of 316L steel.

![Figure 2. Heat capacity of 316L steel.](image)

### 2.2. Basic equations

In general, heat transfer can be described by the equation of thermal conductivity:

$$\rho C_p \left( \frac{\partial T}{\partial t} + (\vec{u} \cdot \vec{V}T) \right) = \vec{V} \cdot (k \nabla T)$$

where \( \rho \) is the density of the material, \( C_p \) is the heat capacity, \( T \) is the temperature, \( \vec{u} \) is the velocity vector of the liquid, and \( k \) is the thermal conductivity.

The laser source is represented by a heat source with Gaussian distribution that mathematically can be rendered as:

$$Q_{in} = \frac{2PA}{\pi r^2} \exp \left( -\frac{(x-vt)^2+y^2}{r^2} \right)$$

where \( P \) is the laser power, \( A \) is the laser energy absorption coefficient, \( r \) is the radius of the laser beam, and \( v \) is the speed of the laser beam.

On the upper surface there is a boundary condition of convection that describes the convective heat transfer and is defined as follows:

$$Q_k = \alpha (T_w - T_0)$$

where \( \alpha \) is the heat transfer coefficient, \( T_w \) is the surface temperature, and \( T_0 \) is the ambient temperature.

The boundary condition of convection is defined for all the external surfaces. The radiation boundary condition is set on the upper surface of the model. It describes radiative heat transfer and is defined as follows:

$$Q_s = \sigma \varepsilon (T_w^4 - T_0^4)$$
where \( \sigma \) is the Stefan-Boltzmann constant, \( \varepsilon \) is the surface absorption coefficient, \( T_w \) is the surface temperature, and \( T_0 \) is the ambient temperature.

When the evaporation temperature is reached, a vapor flow appears in the model, which is given by the formula [10]:

\[
Q_{\text{vap}} = L_v (1 - \beta) \sqrt{\frac{M}{2\pi R T_v}} P_{\text{amb}} \exp \left[ \frac{M L_v}{R T_v} \left( 1 - \frac{T_0}{T} \right) \right]
\]

(5)

where \( L_v \) is the specific heat of evaporation, \( \beta \) is the rate of re-condensation, \( R \) is the universal gas constant, \( M \) is the molar mass, \( P_{\text{amb}} \) is the ambient pressure, and \( T_v \) is the boiling point.

Taking into account the formulas (2–4) all input and output heat fluxes on the upper surface can be written as follows:

\[
-k \frac{\partial T}{\partial z} = Q_{\text{in}} - \alpha (T_w - T_0) - \sigma \varepsilon (T_w^4 - T_0^4) - Q_{\text{vap}}
\]

(6)

The melting phase transition is taken into account using the enthalpy method [11]. The specific heat of melting is taken into account in the heat capacity equation.

\[
C_{\text{p}}^{\text{eq}} = C_p + D_m L_m
\]

(7)

where \( C_p \) is the heat capacity as a function of the temperature dependence, \( L_m \) is the specific heat of melting, and \( D_m \) is the Gaussian function normalized around the melting point \( T_m \):

\[
D_i = \frac{\exp \left( \frac{-(T - T_i)^2}{\Delta T^2} \right)}{\sqrt{\pi \Delta T^2}}
\]

(8)

where \( \Delta T \) is the smoothing interval equal to 50 K.

### 2.3. Numerical methods

FEM is the most commonly used numerical approach to analyze the temperature profile and the size of the melt bath during melting and solidification of materials. Models are made with Comsol Multiphysics 5.4 commercial software using "Heat Transfer" module. The grid elements have a triangular shape. Since most of the processes occur on the upper surface of the model where the laser’s radiation interacts with the substance, the grid elements located in this area are minimal in size. The transition from the high mesh sampling (on the upper surface of the model) to the low one is smooth to improve the convergence of the solution. On the upper surface of the sample, the maximum length of the element (a distance between farthest nodes) is 25 microns. With the use of a smaller grid the results changed by less than 1 %. Such size of the grid elements was chosen as optimal because it provides the maximum accuracy at the lowest calculation speed.

In this paper the various modes of sample scanning are investigated: 1) bidirectional; 2) circular shading with increasing radius from the center; 3) circular shading with decreasing radius to the center. The model parameters for the different scan modes are shown in Table 2.

![Figure 3](image-url)

**Figure 3.** Scanning modes: (a) bidirectional; (b) circular from the center; (c) circular to the center.
Table 2. Model parameters for different scan modes.

| №  | Power, W | Speed, mm/s | Line hatch, μm | Sample size, mm | Mode                     |
|----|----------|-------------|----------------|-----------------|--------------------------|
| 1  | 190      | 800         | 95             | L=5; W=2; H=1   | bidirectional            |
| 2  | 190      | 800         | 75             | R=1; H=0,8      | circular from the center |
| 3  | 190      | 500         | 75             | R=1; H=0,8      | circular to the center   |

2.4. LPBF and examination of structure and properties of the samples

Alnico alloy metal powder was manufactured by Hermiga 75/VI. The target fraction of less than 80 μm, which was used for LPBF, was sifted out of the resulting powder.

The samples for the microstructure examination were made by LPBF on the Russian SLM Factory unit with an ytterbium fiber laser in a protective argon atmosphere. Cylindrical samples with a diameter of 10 mm and a height of 20 mm were manufactured. With the laser power of 190 W the scanning speed varied in the range of 500-800 mm/s.

Structural studies were carried out on metallographic sections prepared in vertical and horizontal planes relative to the direction of the sample construction using Tescan Vega 3 electron microscope.

3. Results and discussion

3.1. Modeling

The obtained model makes it possible to get the distribution of temperatures at any time within the entire LPBF process in the whole volume of the sample. In order to study the nature of the temperature distribution in various scan modes, the temperature distributions for all the examined models after LPBF were analyzed (Figure 4). It was found out that the temperature gradient was relatively high near the melt bath and the nature of the scan mode has little effect on the size of the melt bath.

The nature of the scan mode has a strong effect on the temperature distribution. Figure 4 illustrates that different scan modes greatly affect the temperature distribution in the sample. The circular to the center scan mode brings about an approximate temperature distribution of diagonal symmetry. As compared with the other scan modes, it has a more concentrated distribution of the heat front. The circular from the center scan mode brings about an approximate temperature distribution of diagonal symmetry.

It is known that stress is higher in the lengthwise direction of laser beam than in the transversal because of the uneven compression during cooling [12-14]. In the bidirectional scan mode when laser moves only in two directions, the stress is higher in the lengthwise direction than in the transversal that may produce cracks in the sample. When the laser’s lengthwise movement changes for the circular one, the circular scan mode leads to less residual stress.
The temperature dependences for different laser passes in scan modes 1-3 were analyzed. The temperature distributions in cross-section \( x = 2.5 \, \text{mm} \) (Figure 4a) and \( y = 0 \, \text{mm} \) (Figure 4b, c) are plotted for the moments of time when laser crosses the cross-section plane.

![Temperature distributions](image)

**Figure 5.** The distribution of temperatures in cross section: (a) bidirectional scan mode where \( x \) is 2.5 mm; (b) circular from the center mode where \( y \) is 0 mm; (c) circular to the center mode where \( y \) is 0 mm for the moments of time when laser crosses the cross-section plane.

Figure 5 shows that in the bidirectional scan mode the heating occurs asymmetrically in cross-section. When one side of the sample is heated, the other one remains in balance. The circular from the center mode leads to a symmetrical and evenly temperature distribution (there is less difference between max and min surface temperatures in the scanning area). Since the laser starts moving from the smaller circles, it is not enough time for the sample to be cooled down to the initial temperature in one pass. Accordingly, temperature difference between various points in the fusion area is less than in the circular to the center mode.

Based on the foregoing, the circular from the center mode seems optimal. The temperature distribution characteristic in this mode looks more even than that in the other scan modes.

3.2. **Structural examination of the samples made by LPBF**

The samples were made for compliance inspection of numerical simulation results of LPBF and examination of the actually obtained microstructure.

Figure 6 shows the microstructure of the samples that were obtained by bidirectional shading (Mode 1, Table 2), which is commonly applied for LPBF in most cases.
Cracks are settled in accordance with the cylindrical shape of the sample. A belt of small cracks is detected on a lateral forming surface of the cylinder in its near-surface layer of about 100 μm (presumably, it is due to the laser beam action in contour scanning). Further on with distance growth from the forming surface of the cylinder, large cracks turn into a smaller grid. In the vertical plane of the sample (Figure 6b) elongated clusters formed by a grid of cracks can be detected.

An experiment with two types of ring scanning was carried out based on the data obtained upon the investigation of the structure of the samples in order to minimize the thermal stress that occurs during the sample’s construction. The cross section of the cylindrical sample was scanned by laser beam in each powder layer from the generatrix to the center and back with a scanning step of 75 μm, a speed of 800 and 500 mm/s, and a power of 190 W (Modes 2, 3 and Table 2). This experiment enabled us to evaluate the scanning strategy effect on the thermal stress in the sample made by LPBF that led to the formation of cracks. The samples’ structure is shown in Figures 7 and 8.
The structure of the samples obtained in Modes 2 and 3 (Figures 7 and 8) is specified by the absence of cracks in the sample’s volume, with just a grid of cracks settled radially in the depth of about 300 μm from the surface, and a large number of pores distributed over the sample’s volume.

The samples (Modes 2 and 3) were created in such a way to have a scanning trajectory of the laser beam coincided in each layer that could lead to the formation of a large number of pores. The following modes were selected to investigate the structure of the samples (Modes 2 and 3) with the ring scanning: double scanning with a step of 76 μm and 38 μm was used for the sample given in Figure 9; triple scanning with a step of 75 μm, 50 μm and 25 μm was used for the sample given in Figure 10. The laser power was always 190 W. Thus, each powder layer is subjected to a double or triple scan with a beam path displacement by half width of the track in the first mode, by 2/3 in the second, and by 1/3 in the third mode. These LPBF modes mean to reduce porosity of the sample as compared to Modes 2 and 3. The structure of the obtained batch of the pilot samples is shown in Figures 9 and 10.

![Figure 9](image1.png)  ![Figure 10](image2.png)

**Figure 9.** Microstructure of the sample with double ring scanning (190 W, 500 mm/s, step is 75 μm and 40 μm) from the center in two planes: (a) horizontal and (b) vertical.

**Figure 10.** Microstructure of the sample with triple ring scanning (190 W, 500 mm/s, step is 75 μm and 40 μm) from the center in two planes: (a) horizontal and (b) vertical.

Repeated remelting of the metal in one layer added to the thermal stress of a higher level (in comparison with the samples 2 and 3), which led to a grid of radial cracks within the entire sample. The excessive overheating and formation of rough surface have resulted in the uneven deposition of powder layer and hence to the formation of pores.

4. Results and discussion
Numerical modelling was the basis to study the distribution of temperature fields in LPBF cylindrical samples in various scan modes, such as bidirectional, circular from the center, and circular to the center. The experiment enabled us to know how the scanning strategy of LPBF affects the thermal stress that generates within the sample and leads to the formation of cracks.
The comparison of the temperature fields with the microstructure of the samples made by LPBF showed that the type of scanning (both bidirectional and circular) had a strong influence on the distribution of the thermal fields and, accordingly, on the microstructure of the samples made by LPBF.

The structure of the samples manufactured by circular scanning was specified by the absence of cracks in the sample’s volume. Scanning increase in one layer does not lead to porosity decrease and structure improvement, quite the contrary; it brings about an increase in thermal stress in the sample and the formation of typical radial cracks.

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