Technique of increasing the accuracy of GTE parts manufactured by selective laser melting

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Abstract. Among the complex profile components of modern gas turbine engines, special attention is paid to the impellers and its blades, and their surfaces have the most strict requirements for geometric precision. At the present time, additive technologies are becoming increasingly widespread, through which it is possible to obtain complex shape parts in a short time with minimal post-processing. However, the process of selective laser melting (SLM) is accompanied by a constantly changing redistribution of temperature stresses in the fusion zone and in the entire part, which can lead to significant deflections of geometry. The authors propose a technique that allows reducing the drawbacks that occurs during the printing process. The technique is based on the use of computer simulation of the selective laser process for predicting deflections and subsequent pre-correction of the input triangulation model by moving the nodes of its surfaces. Based on the results of the approbation, control and analysis of the batch parts obtained by SLM, an additional algorithm for compensating for discrepancies that exist due to instability of the process was implemented with MATLAB.

1. Introduction

One of main drawbacks in selective laser melting (SLM) technologies is the large thermal deformation that occurs when residual stresses are carried out due to a significant temperature gradient: during crystallization, the upper alloyed layer experiences tensile stresses, the lower ones – compressive stresses. As a consequence – large deflections, especially after the separation of the parts from the platform. Therefore, an important task is to perform the dimensional accuracy compensation of parts manufactured by the SLM method. Active research is being carried out to improve the laser melting process [1, 2]. At present, digital models and optimization methods are actively used in the design and technological preparation of production. In the process of preparing a part for additive production, its structure is transformed into a triangulation mesh (STL format), which also affects both the roughness of the resulting surface [3] and the dimensional accuracy. Current research works are mostly devoted to reducing production costs through topological optimization of the entire structure, the direction of growing and the location of the support system [4-6].

The proposed technique of directed correction of the technological 3D model (master model) consists in calculating the inherited deformations arising from the action of thermal stresses, with subsequent correction of the master model to the values of inverted deformations. Based on the corrected master model, a control program for printing is generated.

The principle of compensating the action of residual stresses [7] by introducing a preliminary correction of the geometry of the part based on the results of the finite element computer aided engineering (CAE) analysis is as follows:

- simulation of the SLM process and post-processing, including heat treatment and cutting operations;
residual stresses are calculated on the basis of thermal analysis during simulation of operations of the technological process;
- deformations and displacements of the geometry caused by the action of residual stresses of the growing part are calculated;
- these offsets connects to the nodes of the master model's STL file are then summed with the opposite sign (inverted) with the coordinates of the nodes of the triangulation surface of the master model.

The developed technology includes the following steps:
- calibration of the model properties of the fused material used on small test samples for the subsequent calculation of the possible displacements occurred from the action of residual stresses when fusing in a specialized CAE system;
- calibration of the CAE system on a small sample that simulates the conditions for growing the full-scale part, in order to minimize the discrepancy function of the material properties specially calculated for this class of parts (identifying and eliminating the systematic discrepancy in determining the material properties for specific growing conditions);
- automated calculation of 3D CAE analysis discrepancy function when performing correction operations of the STL file of the master model in the CAE system by comparing the results of the measurement of the grown sample and the nominal model (revealing the systematic modeling discrepancy and performing the correction operation in the CAE system);
- automated correction of the STL file of the master model of the actual part based on the results of the calculation in the "calibrated" system earlier with the subsequent elimination of the discrepancy in the finite element analysis by the additional displacement of the master model nodes based on the previously calculated 3D discrepancy function.

2. Stages of the developed method of increasing accuracy

2.1. Refining calibration of inherited strains
The purpose of the refining calibration is to eliminate the systematic discrepancy of the material properties for these laser synthesis conditions. Calibrating parameters of material properties is inherit strains - deformations that arise in a crystallized fused layer as a result of influence of tensile stresses from previously synthesized layers.

In each particular case, the inherit strains are functions of not only the properties of the material (metal powder composition), but many specific growth conditions. This is explained by the specificity of the heat stressed state, characteristic for each individual case. In this connection, the calibration of the CAE-analysis system must be carried out on a special sample simulating the conditions for growing the full-scale part. For a radial flow compressor synthesized from titanium powder VT6, such a sample is a sector comprising three adjacent blades (Figure 1).

![Figure 1. Sample for CAE calibration, close to the conditions of growing a final product.](image)
Since we are primarily interested in part areas that are most susceptible to the most influence of inherit deformations, the calibration discrepancy function is calculated for the thinnest elements (the surfaces of the blades).

An important requirement in determining the actual inherit deformations is the principle of non-negative discrepancy values after growing the corrected model, according to which the discrepancy must be deposited in the direction of increasing the allowance i.e. is aligned with the normal to the growing surface.

The purpose of automated calculation of the 3D discrepancy function of the finite element CAE-analysis when performing the correction operations of the STL file of the master model is to minimize the systematic discrepancy caused by imperfections and deviations in the calculation of thermal levers when simulating the laser synthesis of the part in the CAE system.

The algorithm of the proposed method is that at the second iteration:
1) CAE-analysis of laser synthesis is performed at real values of the inherit strains determined at the previous stage;
2) 3D master-model (STL-file) is corrected for the values of the calculated inverted thermal deflections;
3) Sample part is grown (sector with three blades) according to the corrected master model;
4) Measurements of its surfaces are made and deviations from the nominal model are calculated with additional correction of the 3D master-model.

The first 2 stages of the algorithm are performed in Simufact Additive (provided by MSC Software), the detail is grown on a 3D laser machine for metal selective laser melting SLM 280 HL; the measurement analysis was carried out in PC-DMIS (software for DEA Global Performance 07.10.07) and in the calculation module specially developed in the engineering system MATLAB.

The novelty of the proposed technique is the use of author's algorithms and models for additional correction of the master model. As noted above, analysis and compensation of deviations obtained after measurements are made in the MATLAB system.

2.2. The calculation of the deviation values in MATLAB

The coordinates of the measured points and the parameters (vertices, faces) of the master model STL file for building, were loaded into the MATLAB system. Calculation of distances from points to the master-model (deviations during cultivation) is performed.

2.3. Calculation of the discrepancy function of the CAE system

Based on the results of calculation of deviations from the nominal model for the previously corrected master model after CE simulation of the process of its laser synthesis and calculation of deflections from the action of thermal stresses, calculation of the simulation discrepancy function in the CAE-system is performed. In this case, it is convenient for the compressor disk to set the discrepancy function in a pseudocylindrical coordinate system (polar radius, polar angle, coordinate z is fixed for each section).

Basic requirements for the discrepancy function:
- Discrepancy function must be convex due to the considered principle of non-negative discrepancy values (4) obtained in determining the actual inherit strains (see the previous section);
- Discrepancy function should be qualitatively consistent with the physics of the growing process for each specific case, i.e. grow with \( \rho \) and \( z \) growth in relation to the compressor blades.

To determine the modeling discrepancy, a second order function with mixed effects was adopted from the effect of \( \rho \) and \( z \):

\[
V = (a_0 + a_1 \overline{\rho})(1 + b_1 z),
\]

\[
\overline{\rho} = \frac{\rho - \rho_{\text{min}}}{\rho_{\text{max}} - \rho_{\text{min}}}
\]

is the relative radius of the node in the STL file of the master model,
\[ z = \frac{z - z_{\text{min}}}{z_{\text{max}} - z_{\text{min}}} \] is the relative z coordinate.

\[ \rho = \left( (x-x_0)^2 + (y-y_0)^2 \right)^{1/2} \] - is the radius-vector of the node in the projection onto the plane \( z = \text{const.} \) \( x_0, y_0 \) is coordinates of the origin of the coordinate system.

Without the proofs, we count that due to the convexity of the discrepancy function, the resulting discrepancy in the displacement of the nodes of the STL file during the correction is decomposed along the coordinates as follows:

\[ V = \mathbf{v}, n_i = \mathbf{V} \frac{V_i}{\sqrt{(V_i)^2 + (V_j)^2 + (V_k)^2}}, \quad i = x, y, z, \]  

(2)

\( n \) is the vector of the direction cosines of the normal to the discrepancy surface.

Taking into account (1), the values of the partial derivatives from \( \mathbf{V} \) for calculating the displacement of the nodes of the STL file with additional correction can be written as:

\[
\begin{align*}
V_x &= -a_i \left( 1 + b_i \frac{z - z_{\text{min}}}{z_{\text{max}} - z_{\text{min}}} \right) \frac{1}{\left( (x-x_0)^2 + (y-y_0)^2 \right)^{1/2}} (x-x_0)(\rho_{\text{max}} - \rho_{\text{min}}) \\
V_y &= -a_i \left( 1 + b_i \frac{z - z_{\text{min}}}{z_{\text{max}} - z_{\text{min}}} \right) \frac{1}{\left( (x-x_0)^2 + (y-y_0)^2 \right)^{1/2}} (y-y_0)(\rho_{\text{max}} - \rho_{\text{min}}) \\
V_z &= a_0 + a_i \frac{\left( (x-x_0)^2 + (y-y_0)^2 \right)^{1/2} - \rho_{\text{min}}}{\rho_{\text{max}} - \rho_{\text{min}}}
\end{align*}
\]

(3)

2.4. Algorithm for classifying facets of a triangulation surface

To compensate for the discrepancies in the CAE analysis of laser synthesis, it is necessary to isolate the facets belonging only to the surfaces of the back and trough, and for which the discrepancy function is determined. Brief description the stages of the algorithm developed for the particular case of the facet classification (filtration) follows [8-10].

The input parameters of the algorithm are: \( V_{g \times 3} \) (the matrix of the coordinates of the vertices of the mesh of the STL model); \( F_{m \times 3} \) (a matrix of combinations of vertices of three that form facets of surfaces); \( N_{m \times 3} \) (the matrix of the coordinates of the normal facets), \( \mathbf{p} \) (the coordinate vector of the point on the surface whose facets it is necessary to select), \( \mathbf{t} \) (the normal at the point), \( \alpha \) (allowing for the angle to find the corresponding facets).

It is necessary to search for a facet which the point \( p \) belongs to (the point of intersection of the ray and the facet).

It is necessary to search for all facets which the normal vector differs from the \( \mathbf{t} \) normal vector by not more than \( \alpha \) value (the scalar product of normal vectors is used to check the angles).

Of all the found facets which are suitable in the direction of the normal, it is necessary to choose the vertices connected with the first one and between each other by common peaks.

2.5. Filtering the boundaries of the correction function

To satisfy the integrity preservation conditions when the nodes of the resulting corrected model are shifted, the 3D correction function takes the following form:
\[ V_i = V_t, \quad i = x, y, z \]  \tag{4}

where \( t \) is the frame filter for \( m \) corrected nodes with coordinates \( q_m = (x_m, y_m, z_m) \):

\[
t_m = \begin{cases} 
    p_m = [0...1], \overline{q}_m \in [0, a] \cup [a, 1] \\
    1, \overline{q}_m \in [a, ar]
\end{cases} 
\]

where \( \overline{q}_m \) are the relative coordinates of shifted nodes.

The function of the \( p_m \) filter is Gaussian function:

\[
p_m = e^{-\alpha(q_m - \overline{q}_m)^2}; \alpha = ar, n \gg 1 
\]

\[ \tag{6} \]

3. Results

The estimation of the deviations received as a result of building was carried out. The standard software of CMM allows visualizing the pattern of deviations in individual sections. Figure 2 shows the results of measurements of geometry in the first and third sections of the middle blade.

![Figure 2. Visualization of measurements results for first cross-section (a) and third cross-section (b).](image1)

The calculation models of the discrepancy function are shown in the figure 3a for the surface of compressor blades disk (the degree of reliability of the model is 77%) and in the figure 3b, for the surface of pressure side (the degree of reliability of the model is 69%). The statistical indices of the calculation of the coefficients of the discrepancy model (5) for the back and pressure side, respectively, are presented in Table 1.

![Figure 3. The error function for correcting the STL file.](image2)
The results of measuring the geometric deviations of the manufactured experimental part show that the scale correction of all points of the STL model by a constant coefficient inversely to the predicted deformations does not sufficiently reduce the deviations obtained. Therefore, it is necessary to correct the displacement of the nodes of the input triangulation mesh by the amount of the systematic discrepancy, by comparing the observed displacements of the predicted and measured coordinates of the mesh nodes.

**Table 1.** Statistical indices for calculating the coefficients of the error model for blade front and rear surfaces.

|           | Most probable value | Standard deviation | Student’s t-test | P-value | Lower boundary | Upper boundary |
|-----------|---------------------|--------------------|------------------|---------|----------------|----------------|
| \( a_{bc} \) | 0.100945            | 0.014468           | 6.976944         | 0.00    | 0.072313       | 0.129578       |
| \( a_{1c} \) | 0.123820            | 0.020387           | 6.073549         | 0.00    | 0.083475       | 0.164165       |
| \( b_{x} \) | 3.438871            | 0.482276           | 7.130508         | 0.00    | 2.484461       | 4.393280       |
| \( a_{bc} \) | 0.174000            | 0.012432           | 13.99653         | 0.00    | 0.149390       | 0.198610       |
| \( a_{1c} \) | 0.456336            | 0.027046           | 16.87278         | 0.00    | 0.402796       | 0.509876       |
| \( b_{x} \) | 1.386937            | 0.100848           | 13.75279         | 0.00    | 1.187299       | 1.586575       |

During elimination the discrepancies associated with the displacement of the nodes of the master file's STL file from dependencies (1) - (3), it is necessary to adhere to the principle of selectivity of node selection. Since the discrepancy function (3) was calculated for the blade (separately for the back and pressure side), then when correcting the coordinates of the nodes, it is required to do the following:

- to shift only those nodes for which its own discrepancy calculation function is defined.
- to connect the corrected areas of the STL-model with the rest of the regions, small transitional correction areas should be defined, in which the node displacements smoothly change from zero and at the interfaces to a value \( t \) on a small margin from the boundary.

The results of applying the filtering of the boundaries of the correction function are shown in the figures 4 and 5.

**Figure 4.** Function for filtering shift values on the edges.

**Figure 5.** The result of applying the Gaussian function for edge filtering.

### 4. Conclusions

As a result of the research, a technology was developed and tested, including algorithms and techniques, as well as adjust licensed and proprietary software to achieve dimensional accuracy when growing details by laser synthesis of metal powder compositions.

The dimensional accuracy of details of complex geometry such as blade, blink is achieved through the use of directional correction of the original 3D master model in the STL format used for synthesis.
Correction is aimed at reducing distortion caused by large thermal deformations with SLS. Based on the corrected master model, a control program for the SLM-printer is generated.

Preliminary correction of the geometry of the model is made on the basis of finite element analysis after calibration of the calculated CAE-module with the help of special growing samples. The final correction is automated by selectively shifting the facet assemblies of the previously corrected master model in the STL format using a special algorithm. The developed methodology and algorithms allow minimizing the systematic discrepancy that arises in the calculation of distortions. The systematic discrepancy includes the following components: 1) the discrepancy in determining the inherit deformation, depending on the properties of the material and the specific growing conditions; 2) the discrepancy in the calculation algorithms (the discrepancy in the finite element analysis).

At the same time, when growing test work pieces in the form of sectors of a centrifugal compressor, significant values of the random discrepancy were found, which constitutes a significant part of the total discrepancy (up to 40%). In the future, we can say that in order to reduce the random component of discrepancy, it is necessary to observe strictly unified conditions for the technological process of manufacturing parts.

5. References

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