Numerical simulation in additive manufacturing of gas turbine parts

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Abstract. The article describes the development of mathematical models and user environment in the APDL language which are based on the finite element system solver and allow for the SLM physical process numeric modelling with the required accuracy. The main task is to evaluate the final shrinkage and residual strength of the blanks of gas turbine parts for optimizing the technological process of production. The activities on introducing pre-distortions into the part geometry were performed to compensate for thermal deformation during the growth process; the part with pre-distortion was produced and controlled.

1. Introduction
Additive technologies provide for producing parts by sintering one layer after another, thus obtaining parts of complicated topology. From the moment when the additive manufacturing was first introduced, a significant progress has been achieved in understanding the processes, the structure and the properties of the resulting components. However, when a part is produced via selective laser melting (SLM) of the metal powder, a number of problems arise, i.e. distortion of the workpiece, separation of the workpiece from the supporting structures during production, fracture of the workpiece caused by residual stresses in the process of manufacturing and post-treatment. One of the possible solutions of this problem is the computer simulation of the SLM physical process which will allow to forecast the workpiece shrinkage and introduce the relevant compensating corrections, calculate the stresses in supporting structures and reduce their amount, reduce the efforts needed to remove the supporting structures.

Mathematical description of the processes accompanying the selective laser melting is a large-scale cross-disciplinary problem that has to be addressed involving the concepts, laws and methods of heat-and-mass exchange theory, material engineering, metallurgical engineering, thermal mechanics and other sciences. As an element of the modern intellectual digital manufacturing, additive technologies are closely associated with the extensive use of the finite-element computer-based simulation via specialized program complexes which deliver mathematical models of the processes. In the present work, a user environment was developed on the basis of APDL for a set of programs which allow for a high accuracy of numerical forecasting with regard to the generation of the fields of technological and residual stresses and relocations during the selective laser melting of the workpieces.
2. Algorithm Development

For developing the key relations in the SLM physical process, an analysis was performed of the crystallized phase fraction to account for all the specific features of the evolution process. The simulation case was studied when the isotropic material was crystallizing while the body was unevenly cooled. The original state is molten condition described as viscous liquid. At transition between phases, a part of the material crystalizes, with the new structure representing a linear-elastic body model. The system is a two-component mixture of a hard fraction and a liquid fraction, and the volume of each depends on the degree of crystallization. The system which crystalizes out of the molten condition is a two-component mixture of the original product and the final fully crystalized product. The general mathematical problem statement includes equilibrium equations for cases with no mass forces and thermal conductivity; physical and geometrical relationships; an equation for defining the degree of crystallization; initial and boundary conditions.

The task of finding the stress-strain state evolution of the system in the conditions of growing the workpiece using the selective laser melting process, can be split into two tasks to be successively solved: the task of transient conduction and the quasi-steady task of deformable solids where the thermal fields obtained in the 1st phase are used as the volumetric load. With this, it is assumed that the stresses and strains that occur in the system, have no influence on the thermal balance.

For solving both the thermal task and the mechanical task, the elements birth and death method is used for a part of the material which is originally missing in the model and later appears after the next layer of the powder is applied and locally fused. The area occupied by the finished part and the powder at the final phase of growth, is taken as the computation region. Continuous building-up of the metal (operating) structure and the supporting structure is performed discretely at each of the computation sub-steps representing the “birth” of the next sub-area out of the “dead” elements. Thus the boundary thermal conductivity task is solved, with this, the results of the previous sub-step are used as the initial conditions for the next sub-step.

For parts with complex topology, an algorithm of generating a voxel layered grid was created in APDL. The developed and implemented system of simplifying hypotheses allowed to considerably reduce the computational efforts without loss of accuracy.

3. Mathematical Problem Statement

For solving both the thermal task and the mechanical task, the elements birth and death method (Elements Birth and Death in ANSYS) is used for a part of the material which is originally missing in the model and later appears after the next layer of the powder is applied and locally fused. The area occupied by the finished part and the powder at the final build-up phase, is taken as the computation region. Continuous building-up of the metal (operating) structure and the supporting structure is performed discretely at each of the computation sub-step representing the “birth” of the next sub-area out of the “dead” elements. Thus the boundary thermal conductivity task is solved, with this, the results of the previous sub-step are used as the initial conditions for the next sub-step.

At sub-step \( k \) of solving the boundary thermal conductivity task on defining the thermal fields \( T(x,t) \) in region \( V_k \) with boundary \( S_k \), the thermal conductivity equation is given as follows:

\[
\rho(x)c(x,T) \frac{\partial T}{\partial t} = \text{div} \left( \lambda(x,T) \text{grad}(T) \right) + \rho(x) \dot{q}(x,t), \quad x \in V_k, \quad (1)
\]

where \( c(x,T), \lambda(x,T), \rho(x) \) - are respectively thermal capacity, thermal conductivity and density of the non-homogeneously alloyed material, \( \dot{q}(x,t) \) - is the specific capacity of the external heat source.

boundary conditions:

\[
-\lambda(x,T) \text{grad}(T) \cdot n = h(T) \cdot (T - T_{\text{env}}(t)) + \varepsilon \sigma_0(T)^4, \quad x \in S_k, \quad (2)
\]
where the first summand on the right describes the convective heat transfer, and the second summand describes the radiation (Stefan-Boltzmann law); $\varepsilon$ - is the emissivity factor, $\sigma_0$ - is the Stefan-Boltzmann constant, $h(T)$ - is the heat transfer coefficient, $T_c(t)$ - is the ambient temperature, $\mathbf{n}$ - is the outer unit normal to boundary $S$ of the cooled body.

initial conditions:

$$T(x,t_{0,k}) = T_{k-1}(x), \quad x \in V_k,$$

where $T(x,t_{0,k})$ - is the initial thermal distribution for sub-step $k$, $T_{k-1}(x)$ - is the temperature measured at the end of the previous sub-step.

Taking into account the insignificance of the mass forces contribution on sub-step $k$, the unlinked quasi-static boundary thermoelasticity task of mechanics of deformable solids is given as follows:

equilibrium equations:

$$\text{div } \hat{\sigma} = 0, \quad x \in V_k,$$

where $\hat{\sigma}(x,t)$ - is the stress tensor;

Cauchy geometrical relations:

$$\hat{\varepsilon} = \frac{1}{2}(\nabla \mathbf{u} + (\nabla \mathbf{u})^T), \quad x \in V_k,$$

where $\mathbf{u}(x,t)$ - is the displacement vector, $\hat{\varepsilon}(x,t)$ - is the total deformation tensor.

boundary conditions at displacements:

$$\mathbf{u} = U, \quad x \in S_{u,k},$$

and at stresses

$$\hat{\sigma} \cdot \mathbf{n} = P, \quad x \in S_{\sigma,k},$$

where $S_{u,k}$, $S_{\sigma,k}$ - are the parts of the boundary with the specified displacements and loads, respectively.

The material thermomechanical parameters in the region of the “dead” elements exclude physical non-linearity and are perfectly elastic with degraded values:

$$^4\hat{C}(x), \quad x \in V_k^{\text{kill}} \ll ^4\hat{C}(x,T), \quad x \in V_k^{\text{div}},$$

where $^4\hat{C}$ - is the forth-rank tensor of elastic constants of the material.

The general system of equations of deformable solids mechanics also includes the key relations. Visco-elastic-plastic behavior of the alloy from which the workpiece is produced, with the account for the temperature range including the phase transition, provides an opportunity to use several different physical plasticity models. A plasticity model with bilinear isotropic hardening (BISO) and temperature dependence of the parameters, was taken as a baseline model. The material behavior in the equivalent strain - equivalent stress coordinates is shown in Fig. 1 (the value of $\sigma_y$ corresponds to the yield point).

![Figure 1. $\sigma - \varepsilon$ diagram for bilinear isotropic (BISO) model.](image-url)
4. Applied Use
For verification of the developed program package for simulating the SLM process, a computation was performed for a gas turbine engine part made of high-temperature material. The selected part model is presented in Figure 2.

![Image](https://example.com/image1.png)

**Figure 2.** Geometrical model of a gas turbine engine part

Figure 3 shows a 3D design for producing the selected part and its supporting structure using SLM. The finite-element model of this design is shown in Figure 4. The results of building a finite-element voxel discrete model are shown in Figure 5.

![Image](https://example.com/image2.png)

**Figure 3.** 3D design

**Figure 4.** Finite element model

**Figure 5.** Voxel grid.

The results of interpolation of the received distribution field of the residual dislocations vector length onto the surface grid of the virtual part prototype are shown in Figure 6.
The part of interest was made of high-temperature material using SLM at UEC-Aviadvigatel Joint Stock Company. Figure 7 shows the part with its supporting structure before it was cut off the plate. Figure 8 shows the produced part after the supporting structure was removed.

The simulation accuracy was controlled via comparing the expected deformations and the results of measuring by the optical metrological system for 3D measurement of the coordinates of the part produced. The comparison of the simulation results with the real manufactured part are given in Figures 9 and 10. The maximum absolute deviation of the simulation results from the results of manufacture is 0.19 mm.
Figure 9. The results of the optical control of the part manufacture before pre-distortions were introduced

Figure 10. The results of numerical simulation before pre-distortions were introduced

Subsequent to the results of the numerical computation, the actions were performed on introducing pre-distortions into the part geometry to compensate for thermal deformations in the process of growth. A part with pre-distortions was also manufactured at UEC-Aviadvigatel JSC and underwent an optical control procedure. The comparison of the simulation results with the really manufactured part after pre-distortions were introduced is shown in Figures 9-10.

Figure 11. The results of the optical control of the part manufacture after pre-distortions were introduced

Figure 12. The results of numerical simulation after pre-distortions were introduced

After the pre-distortions were introduced into the model prior to manufacturing, the mean deviation of the grown workpiece from the master part reduced by 27% and the absolute deviation reached 0.24 mm.

5. Conclusion
In the present work, a user environment was developed on the basis of APDL which allows for a numerical simulation of the gas turbine engine parts manufacturing using SLM process. The demonstrated set of mathematical models makes it possible to forecast the formation of the fields of residual technological stresses and dislocations in the part growing process. The results of numerical simulation are used for the subsequent optimization of the production process technological parameters,
and for having an opportunity to introduce pre-distortion into the geometrical model of the part prior to growing.

The actions were performed on introducing pre-distortions into the geometry of a real part to compensate for thermal deformations in the process of manufacturing using SLM, the part with pre-distortions was manufactured and optically controlled. The efficiency was demonstrated of applying the numerical simulation method for reducing the shrinkage of the part produced using selective laser melting.

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