Numeric simulation of aircraft engine parts additive manufacturing process

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Abstract. . This paper presents the results of software (ANSYS software) improvements specific for modeling the physical process of SLM (Selective Laser Melting). Improvement goal was to create a set of mathematical models and user environment (a set of APDL programs) based on the ANSYS finite element analysis system solver, allowing to perform the technological procedure of physical SLM process numerical modeling to the required degree of precision with an estimate of the final distortion and residual stresses of gas turbine engine parts to optimize the manufacturing process.

1 Introduction

Additive Manufacturing enables manufacturing of parts by means of additive layer synthesis and thus getting complex topology parts. From the time AM technologies came into use significant progress has been achieved in understanding the processes, structure and properties of the parts being made. The objective of this work is to generate a set of mathematical models and user environment (APDL program set) based on ANSYS Finite Element Analysis System solver which would allow performing, with the required degree of accuracy, the technological operation of numeric prediction of manufacturing and residual stress fields formation and displacements in the process of Selective Laser Melting of gas turbine engine components blanks for further optimization of manufacturing process parameters.

2 Development

The chosen simulation concept is based on the elements "animation" technique involving natural (unstrained) condition of the built-up part of material at the time it emerges. The area occupied by the finished product and powder at the final building stage is considered as design area. Continuous build-up of the metal (active) and support structure is performed discretely, at each sub-stage of computation corresponding to the "birth" of each next

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subdomain from the "dead" elements, the boundary task of heat transfer is solved, and the result of the previous sub-stage solution serves as initial conditions for the subsequent one.

The verification of the developed numerical algorithms was carried out based on experimental data (Fig. 1). Comparison of analysis results for several discrete analogs of the process with different level of detail is performed. The first group comprises finite element analogs with maximum level of virtual prototype detail. It addresses a full set of the materials participating in the process and the relevant geometrically isolated subareas: metal, powder, baseplate. The finite-element discretization pattern is shown in Fig. 2. In the figure, the red zone indicates the platform area, purple is for powder, green is the area occupied by the metal of the product.
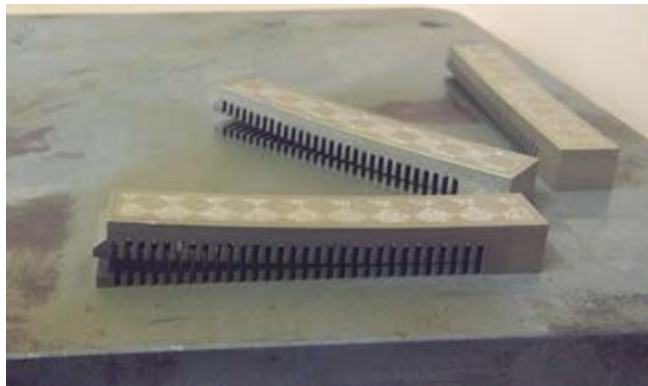

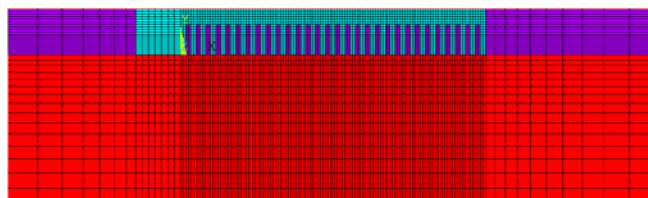**Fig. 1.** Prototypes after Partial Cutting

Fig. 2. Finite Element Model.

The tasks of unsteady heat transfer with moving boundaries and structural quasi-steady flow analysis are addressed successively. Mathematical substantiation of equations for recalculation of heat transfer parameters ensuring initial balance of heat energy is performed while switching to oversimplified spatiotemporal zoning unavoidable in numerical analysis. The comparison of 2D and 3D solutions with experimental data for the full-size test model demonstrated adequacy of assumed hypotheses. The next level of simulation involved averaging of thermomechanical and thermophysical properties of the supporting part of the structure.

The analysis of the obtained consistent patterns of temperature fields formation in the SLM process served the basis to develop an efficient analytical model of the next level which excludes powder and baseplate zones from consideration. Besides, heat transfer task solution is lacking, and the temperature in the structural task is set according to a special law ensuring minimum loss of accuracy. Fig. 3 shows the residual vertical deflection of the upper face of the samples obtained from the experiment, and its comparison with the design deflection.
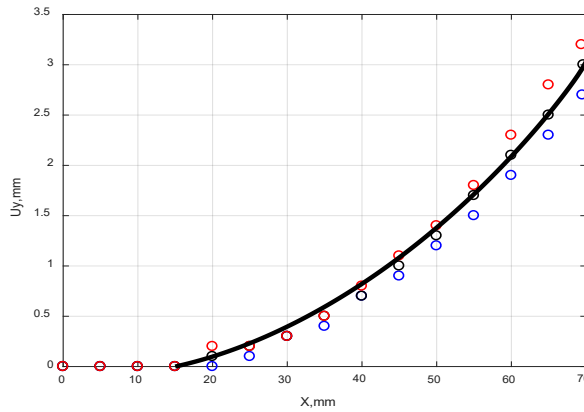
Fig. 3. Residual Vertical Deflection of the Samples Upper Face, mm. Line – estimated (black - full model, red - simplified); dots - experiment: blue marker - Sample 1, black – Sample 2, red – Sample 3.

3 Mathematical statement

The problem of determining the evolution of the system stress-strain state in the conditions of building up by selective laser melting (SLM) may be divided in 2 successive problems: unsteady heat conduction and quasi-steady problem of deformable solids mechanics which uses temperature profiles found at the first stage as volumetric loads. It is assumed that stress and strain arising in the system affect the heat balance.

The temperature and mechanical problems are addressed using the method of 'killing" and further "revivification" (Elements Birth and Death in ANSYS) of part of material initially lacking in the model and then emerging in the process of applying the next powder layer and its local melting. The domain of computation is considered to be the area occupied by the already finished product and powder at the final stage of buildup. Continuous buildup of metal (working) and backup zones is performed discretely at each sub-phase of the computation corresponding to "revivification" of the next subdomain from "dead" elements, the boundary problem of heat conduction is solved, and the result of previous sub-phase solution serves as initial conditions for the next one.

At the kth sub-phase of solving, the statement of the boundary problem of unsteady heat conduction to determine $T(\mathbf{x},t)$ temperature profiles in V_k domain with S_k boundary the heat conductance equation has the following form:

$$\rho(\mathbf{x})c(\mathbf{x},T)\frac{\partial T}{\partial t} = div\big(\lambda(\mathbf{x},T)grad(T)\big) + \rho(\mathbf{x})\dot{q}(\mathbf{x},t) \ \mathbf{x} \in V_k \,, \qquad (1)$$

where $c(\mathbf{x},T)$, $\lambda(\mathbf{x},T)$, $\rho(\mathbf{x})$ - heat capacity, heat conductance and density of the non-uniformly alloyed material respectively, $\dot{q}(\mathbf{x},t)$ - external heat source specific capacity.

Boundary conditions:

$$\lambda(\mathbf{x},T)grad(T)\cdot\mathbf{n} = h(T)\cdot\big(T-T_c(t)\big) + \varepsilon\sigma_0\big(T\big)^4 \qquad\qquad \mathbf{x} \in S_k \,, \qquad (2)$$

where the first summand of the right part describes convective heat transfer, and the second one - radiation (Stefan-Boltzmann law); ε - emissivity, σ_0 - Stefan-Boltzmann constant, $h(T)$ - heat transfer factor, $T_c(t)$ - ambient temperature, $\mathbf{n}$ - external unit normal to S boundary of the cooled solid.

Initial conditions:

$$T(\mathbf{x}, t_{0,k}) = T_{k-1}(\mathbf{x}), \qquad \mathbf{x} \in V_k \,, \tag{3}$$

where $T(\mathbf{x}, t_{0,k})$ - initial temperature distribution for the kth sub-phase, $T_{k-1}(\mathbf{x})$ - temperature determined at the end of the previous one.

The uncoupled quasi-steady problem of deformable solids mechanics assuming insignificancy of mass forces contribution has the following form at the kth sub-phase:

Balance equation:

$$div\,\hat{\sigma} = 0 \,, \quad \mathbf{x} \in V_k \,, \tag{4}$$

where $\hat{\sigma}(\mathbf{x}, t)$ - stress tensor.

Cauchy geometrical relationships:

$$\hat{\varepsilon} = \frac{1}{2}\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right), \quad \mathbf{x} \in V_k \,, \tag{5}$$

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

Boundary conditions in displacements:

$$\mathbf{u} = \mathbf{U} \,, \qquad \mathbf{x} \in S_{u,k} \,, \tag{6}$$

and stress

$$\hat{\sigma} \cdot \mathbf{n} = \mathbf{P} \,, \quad \mathbf{x} \in S_{\sigma,k} \,, \tag{7}$$

where S_u, S_σ - parts of the boundary with specified displacements and loads respectively.

Material thermomechanical parameters in the zone of "dead" elements exclude physical non-linearity, and are ideally elastic with degraded values:

$$^4C(\mathbf{x}) \,, \ \mathbf{x} \in V_k^{kil} \ << \ ^4C(\mathbf{x}, T) \,, \ \mathbf{x} \in V_k^{kiv} \tag{8}$$

where ^4C - rank 4 tensor of material elastic constants.

The general system of equations of the deformable solids mechanics boundary problem also includes defining relationships. Viscoelastoplastic behavior of the alloy of which the product is made taking into account the temperature range including the phase change envisages the possibility of using several different physical models of plasticity. The plasticity model with bilinear isotropic hardening and temperature dependence of parameters is taken as the baseline model. Material behavior in the equivalent stress-equivalent strain coordinates is shown in Figure 4.
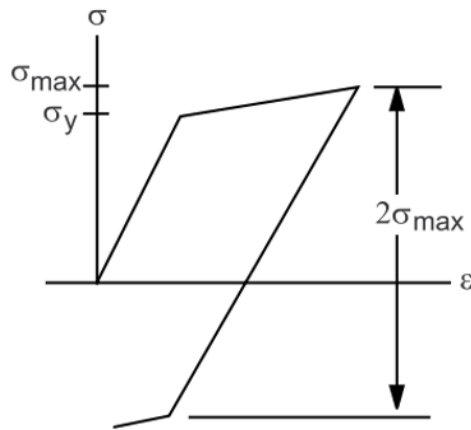
Fig. 4. Diagram $\sigma - \varepsilon$ for bilinear isotropic model BISO

In Figure 4 the σ_y value corresponds to the yield strength

4 Adaptation

For complex topology parts the algorithm of laminated voxel mesh building was developed in APDL. The developed and implemented system of simplification hypotheses enabled significant reduction of computational effort without considerable loss of accuracy. For verification of the developed program suite, simulation of the physical process of the typical aircraft engine part additive manufacturing was performed (Fig. 5). The results of mathematical modeling (Fig. 6) are compared with the real production process data for a given part.
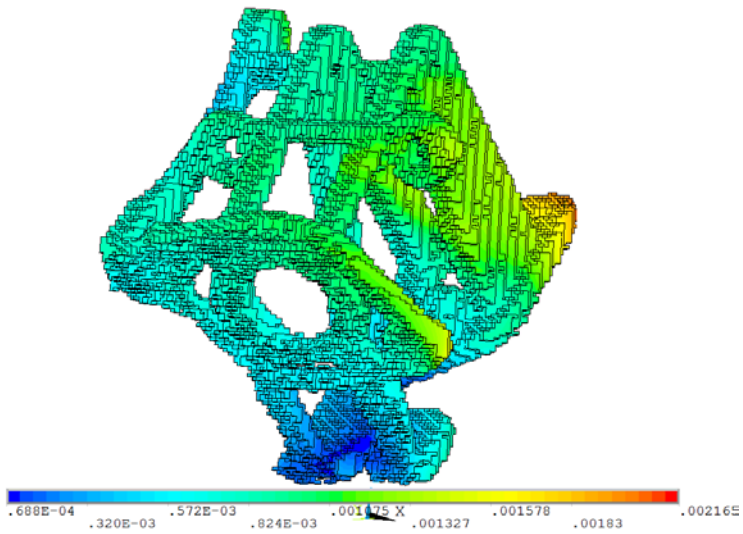

Fig. 5. Manufactured Part

Fig. 6. Simulated Distortion

Simulation accuracy inspection was performed by comparing estimated distortion and measurement results from optical CMM for a 3D coordinate measurement. Fig. 7 shows the distortion of manufactured part based on 3D coordinate measurement results and Fig. 8 shows the same geometry comparison for simulation results.
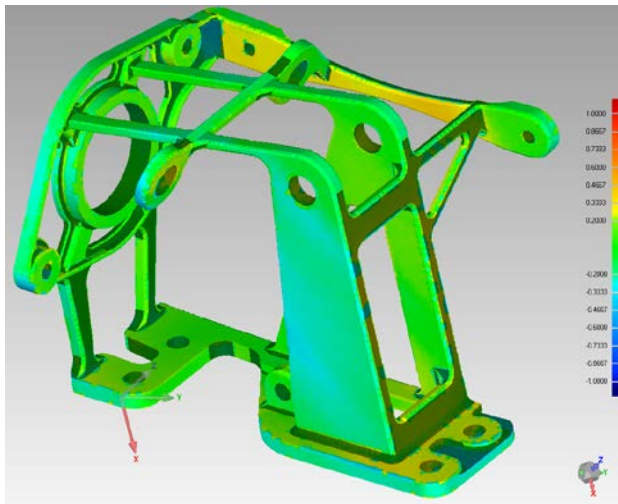

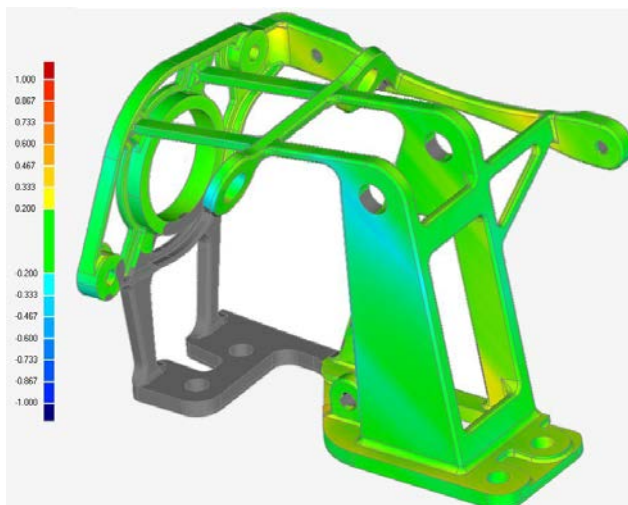
Fig. 7. Real manufactured part geometry control

Fig. 8. Simulation results verification

The maximum absolute deviation of the simulation results against measurements was 0.19 mm.

5 Conclusion

The objective of this work was to generate a set of mathematical models and user environment (APDL program set) based on ANSYS Finite Element Analysis System solver which would allow performing, with the required degree of accuracy, the technological operation of numeric prediction of manufacturing and residual stress fields formation and displacements in the process of Selective Laser Melting of gas turbine engine components blanks for further optimization of manufacturing process parameters. The developed and implemented system of simplification hypotheses enabled significant reduction of computational effort without considerable loss of accuracy. For verification of the developed program suite, simulation of the physical process of the typical aircraft part additive manufacturing was performed. The results of mathematical simulation were matched with this part actual manufacturing process data sourced from UEC-Aviadvigatel. Simulation accuracy was verified by comparing design strain and results of measurement by the optical measurement system for 3D coordinate measurement. The maximum absolute deviation of the simulation results against measurements was 0.19 mm. Thus developed mathematical models and user environment are valid for prediction of distortion in Additive Manufacturing production preparation.

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