Castings distortion of gas turbine engine parts during solidification and cooling

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Abstract. The paper studies the matters of numeric simulation of the processes of casting, crystallizing and cooling down to room temperature, and addresses the related problem of the stress-strain state of the casting process in manufacturing the cast parts of a gas turbine engine. The influence of the technological parameters of casting onto the development of the deformation defects was evaluated. The works were performed on incorporating predeformation into the burn-out model for compensating temperature deformations during casting, and on production and control of the above casting with predeformation.

1. Introduction

One of the most important tasks in modern production of aviation and industrial gas turbine engines is improving the quality of the manufactured parts and minimizing spoilage in production, while saving the expensive raw materials, energy and labor resources. At UEC-Aviadvigatel Joint Stock Company this task is being solved through development and implementation of elements of digital manufacturing which are capable of optimizing the parameters of each phase of the technological process for obtaining the required parameters of the final product by using virtual modelling and creating “digital twins”.

Cooling of a casting causes changes of its dimensions following the temperature deformations and shrinkage deformations which show as linear shrinkage and bending of the axes of individual elements or distortions. High heat-shrink deformations result in the distortions of the casting mould, and lead to bending the configuration of the casting itself. Thus, for getting an item of the targeted geometry, the probability of deformation should be considered in advance. Combined method of lost-wax casting for gating system and burn-out casting for parts allows to produce burn-out models with predeformation by 3-D printing for achievement of minimal distortion in casting parts after casting process.

Applying the numerical simulation method allows to predict the casting deformation with high accuracy at all the phases of the technological process, to improve the design of the gating system and register its distortions through no real expensive experiments but using the virtual space of the mathematical model [1-2]. The full contact problem of the stress-strain state determination is resolved in the statement “deformed mould – deformed casting”. Studies are carried out in viscoelastoplastic statement using the Perzyna model allowing to account for linear hardening.

The result of the simulation is the possibility to introduce compensatory predeformation into the burn-out model of the casting produced with 3D printing technology. This allows to significantly increase the accuracy of manufacturing and reduce the number of the subsequent machining operations; this is especially important for the thin-walled items of critical duty having complex configurations.
2. Statement of the problem

A casting of the part named “panel” (figure 1) with nominal geometry was manufactured for the purpose of the mathematical model optimization and calibration.

![Burn-out model of the casting.](image1)

**Figure 1.** Burn-out model of the casting.

Non-contact optical 3D scanning revealed deviations of the castings geometry from the nominal geometry. Maximum deformation detected at ingates (bosses) exceeded 8%. Maximum deformation within the casting body was about 5.5% (figure 2).

![Results of 3D laser scanning of the cast part.](image2)

**Figure 2.** Results of 3D laser scanning of the cast part.

Figure 3 shows the model of the gate system for producing a casting of the “panel” and the finite-element approximation of the model, respectively.

![Gate system unit model: (a) CAD model, (b) finite-element approximation of the model.](image3)

**Figure 3.** Gate system unit model: (a) CAD model, (b) finite-element approximation of the model.
3. Mathematical statement of the problem

In the course of the study the full contact problem of the stress-strain state determination is resolved in the statement “deformed mould – deformed casting”. Studies are carried out in viscoelastoplastic statement.

Physical relations are taken as follows:

\[
\sigma = D \cdot \varepsilon + D \cdot \left( \varepsilon^h - \varepsilon^vp - \varepsilon^tr \right)
\]

(1)

where \( D \) is quartic elastic constants tensor.

Geometrical relations look as follows:

\[
\dot{\varepsilon} = \frac{1}{2} \left[ \nabla \pi - (\nabla \pi)^T \right]
\]

(2)

The full deformation is taken as the sum of temperature, elastic, viscoplastic deformation, plus additional contribution made by transformations in solid-liquid state [4-5]:

\[
\varepsilon = \varepsilon^h + \varepsilon^el + \varepsilon^vp + \varepsilon^tr
\]

(3)

The temperature deformation is

\[
\dot{\varepsilon}^h = \alpha (T - T_0)
\]

(4)

where \( \alpha(t) \) is the temperature expansion coefficient. To compute viscoplastic deformation, the Perzyna model is used that allows to consider linear hardening [3]:

\[
\dot{\varepsilon}^vp = \frac{1}{n} \left( \frac{\sigma^*}{\sigma} - 1 \right)^p
\]

(5)

where \( \sigma^* \) is yield stress, \( \sigma_{eq} \) is von Mises equivalent stresses, \( n \) is viscous parameter of the material, and \( p \) is strain rate sensitivity coefficient.

The phase transformations are considered as follows:

\[
\varepsilon^tr = \frac{\beta}{3} \hat{g}^\sigma
\]

(6)

in which \( \hat{g}^\sigma \) is volume fraction of liquid-solid phase, transforming into a new phase, and \( \beta^t \) is the coefficient of volume expansion associated with the phase transformation.

Balance equation is taken as follows

\[
\nabla \cdot \sigma = 0
\]

(7)

At solid and liquid-solid phases, normal and tangential stresses look as follows:

\[
\begin{cases}
\sigma_s = (\sigma \cdot n)_T \\
\sigma_t = 0
\end{cases}
\]

(8)

The conditions of incomplete cohesion with slippage at the contact interfaces of the casting and the ceramic mould are set as follows [2]:

\[
\begin{bmatrix}
\sigma_t \\
[\sigma_t]
\end{bmatrix} = 0
\]

\[
\begin{bmatrix}
[\sigma_t] = q[\sigma_t]
\end{bmatrix}
\]

(9)

The mould displacements are limited as the mould is fastened in the casting assembly:

\[
\pi_k = 0
\]

(10)
4. Results
Numerical simulation of the cast part production was performed using the ProCAST™ simulation software [6]. The Stress module was additionally used for the strain-stress state evaluation. Thermal fields evolution at pouring is shown in figure 4.

![Thermal fields in metal during pouring: (a) initial phase, (b)-(c) middle phase, (d) end phase.](image)

**Figure 4.** Thermal fields in metal during pouring: (a) initial phase, (b)-(c) middle phase, (d) end phase.
The evolution of the liquid phase boundary progression during crystallization is shown in figure 5. The degree of distortion and the final shape of the cast panel are shown in figure 6. The main reason for distortion is the difference in the thermal expansion coefficients of the Ni-based alloy and of the ceramic mould, along with the relatively low hardness of the main body of the panels as compared to the massive ingates. In the conditions of high-temperature deformations and mechanical resistance of the ceramic
mould material, the localized areas of plastic deformations are formed in the interface zone of bosses and heat-shield panels.

The magnitude of distortion forecasted in numeric simulation process is in good agreement with the measurements results of a real casting shown in figure 1. The scheme of the distortion development is shown in figure 7.

**Figure 6.** Simulation results: (a) distortion of the cast panel, (b) the final distortion (magnification x10).

The magnitude of distortion forecasted in numeric simulation process is in good agreement with the measurements results of a real casting shown in figure 1. The scheme of the distortion development is shown in figure 7.

**Figure 7.** Temperature field °C and deformed state evolution (magnification x5) in the process of cooling down to room temperature, the longitudinal section of part: (a) start of pouring, (b) end of pouring. Time points (c) 0.5 h, (d) 1 h, (e) 2 h, (f) at room temperature.
5. Incorporation of predeformation
Following the results of numerical simulation, predeformation was incorporated into the casting model manually using a CAD system to compensate for the temperature deformations. Figure 8 shows the forecasted magnitude of distortion in the casting with predeformation for compensation, and the shape of the cast panel after cooling, respectively.

![Simulation results after predeformation was incorporated into the part model: (a) cast panel distortion (b) final distortion (magnification x10).](image)

**Figure 8.** Simulation results after predeformation was incorporated into the part model: (a) cast panel distortion (b) final distortion (magnification x10).

A casting with incorporated compensating distortions was manufactured in the production shop of UEC-Aviadvigatel JSC. The results of its 3D optical scanning are given in figure 9. The deformation at bosses was 3%, the deformation within the part body was 1%. Thus, the resulting deformations in the casting were more than 2 times lower.

![Results of 3D laser scanning of the cast panel with incorporated predeformation.](image)

**Figure 9.** Results of 3D laser scanning of the cast panel with incorporated predeformation.

6. Conclusion
Numeric simulation allows to forecast the formation of residual stress fields and displacements in the process of casting. The results of computation are used for subsequent optimization of the technological process parameters in production, and for incorporating preliminary distortions into the geometric model of the part before its manufacture. In the future, it is planned to develop an automated algorithm for CAD-geometry predeformation.

References
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