Deformations and casting defects depending on the gating system for gas turbine engine castings

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Abstract. The article covers researching the processes of pouring, crystallizing and cooling to room temperature, while simultaneously solving the related task of the stress-strain behaviour of the casting process in course of the heat-protective panels manufacture. 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”.

The operating conditions of parts in gas turbine engines demand high strength properties and geometric accuracy. 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 mold, 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.

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 [3].

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
The computation of pouring, crystallizing and cooling to room temperature with simultaneous solving of the related task of the stress-strain behaviour of the casting process in course of the heat-protective panels manufacture was performed for three variants of the collector cross-sections: a standard size (option 1), a cross-section reduced by 10% (option 2), a cross-section reduced by 10% (option 3). The geometric models of gating systems are shown in Fig. 1. The finite element approximation of block models with heat-protective panels is shown in Fig. 2.

Figure 1. Geometric models of computed options.

Figure 2. Finite-element models of computed options.
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:

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

(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]:

$$\dot{\varepsilon} = \dot{\varepsilon}^th + \dot{\varepsilon}^el + \dot{\varepsilon}^vp + \dot{\varepsilon}^tr$$

(3)

where the temperature deformation is as:

$$\dot{\varepsilon}^th = \alpha(T - T_0)$$

(4)

$$\alpha(t)$$ - is the temperature expansion coefficient.

To compute viscoplastic deformation, Perzyna model is used that allows to consider linear hardening:

$$\dot{\varepsilon}^vp = \frac{1}{n} \left( \frac{\sigma_{eq}}{\sigma^*} - 1 \right)^p$$

(5)

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

The phase transformations are considered as follows:

$$\dot{\varepsilon}^tr = \frac{\beta_r}{3} \dot{\varepsilon}_{tr}$$

(6)

$$\dot{\varepsilon}_{tr}$$ - is volume fraction of liquid-solid phase, transforming into a new phase, and $$\beta_r$$ - is 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:

$$\sigma_n = ((\sigma) \cdot \pi)n$$

$$\sigma_t = 0$$

(8)

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

$$\begin{cases}
\left[ \sigma_t \right] = 0 \\
\left[ \sigma_n \right] = q \left[ \sigma_n \right]
\end{cases}$$

(9)

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

$$\pi_s = 0$$

(10)

To predict shrinkage defects in the form of shrinkage porosity, the model is supplemented by the mass conservation law for the melt being crystallized, written as follows:

$$\nabla \cdot \left( \rho l \frac{K}{\mu l} \left( \nabla p_l - \rho l g \right) \right) + \rho l \frac{\partial g}{\partial t} = \frac{\partial \left( \rho l \right)}{\partial t}$$

(11)
where $\rho_l$ – is the density of the liquid melt, $p_l$ – is the pressure influencing the front of liquidus, $\mu$ – is the viscosity, $K$ – is the permeability of the dendritic frame, $\langle \rho_1 \rangle$ – is the averaged density, $g_p$ – is the pore content proportion.

The following is true at the contact boundary between the melt being crystallized and the environment:

$$p_l(x) = p_{ext} + \rho_l g(z_{ext} - z),$$

where $z_{ext}$ – is the free surface coordinate influenced by pressure $p_{ext}$, $z$ – is the corresponding coordinate of the liquidus isotherm.

In the case with a closed liquid pocket, when there is no pouring anymore, a macro-pore is formed in the area with minimal pressure; and the following equality is true at the assumed boundary between the phases $\Gamma_c$:

$$p_l = p_c,$$

where $p_c$ – is the cavitation pressure in the melt.

In the case with a partially closed metal pocket, when the area being crystallized is still being poured in with melt, the pressure at the assumed boundary between the phases $\Gamma_c$ can be represented as the sum of

$$p_l(x) = p_{lz_0} + \rho_l g(z_0 - z),$$

where $p_{lz_0}$ – is the pressure applied to the boundary of the pocket with coordinate $z_0$.

4. Numerical Simulation Results

For each geometry option, the evolution of the stress-strain state during crystallizing and subsequent cooling to room temperature is similar.

The main reason for the formation of the “shrinkage cavity” – is the difference in the coefficients of linear temperature expansion of the alloy and the ceramic mould, together with the relatively low stiffness of the main body of the panels as compared to that of the massive gates. Under conditions of high-temperature deformations and mechanical resistance of the ceramic mould material, an area of localized plastic deformation is formed in the zone of the gates (bosses) interfacing the heat-protective panels.

The scheme of the shrinkage cavity formation as exemplified in computed option 3 is shown in Fig. 3. The shrinkage cavities and the final shape of the heat-protective panels for option 3 is shown in Fig. 4.

As the size of the collector cross-section decreases, the size of the shrinkage cavity decreases in direct proportion almost linearly. The size of deformations in the casting is shown in table 1.

The minimum values of deformations and shrinkage cavities from the options involved are demonstrated in computed option 3 having the minimum collector cross section.

It is worth noting that along with the cross section size, the depth value of the shrinkage cavities can be influenced by the following parameters: gate cross section diameter, cooling rate of the casting, holding time under vacuum inside the semipermanent mould, thickness of the ceramic mould, ceramic mould material (strength of the mould).
Table 1. Deformation size, %

|                          | Option 1. | Option 2. | Option 3. |
|--------------------------|-----------|-----------|-----------|
| At the gates (bosses)    | 11.6      | 10.1      | 8.2       |
| Maximum within the body  | 8.1       | 6.7       | 5.5       |
| of the casting           |           |           |           |

Figure 3. Simulation results after predeformation was incorporated into the part model: a - cast panel distortion (mm) b - final distortion (magnification x10).

Figure 4. Deformed state evolution in the process of cooling down to room temperature (magnification x5), °C: a - start of pouring, b - end of pouring, c - time point 0.5 h., d - time point 1 h., e - time point 2 h., f - room temperature.
The analysis of the distribution of the shrinkage defects probability in the body of castings (Fig. 5) shows that the collector cross-section size does not significantly affect the distribution and size of porosity.

**Figure 5.** Prediction of porosity in a heat-protective panels

5. Incorporation of predeformation
Since option 3 showed the minimum values of the shrinkage cavities, further studies were carried out for it. Following the results of numerical simulation, predeformation was incorporated into the casting model to compensate for the temperature deformations [8].

Figure 6 shows the forecasted magnitude of distortion in the casting with predeformation for compensation, and the shape of the cast panel after cooling, respectively.

**Figure 6.** Simulation results after predeformation was incorporated into the part model: a - cast panel distortion (mm) b - final distortion (magnification x10).

Non-contact 3D laser scanning revealed deviations in the geometry of castings from the nominal one for the original model, and for the model with pre-deformations. For the original model, the maximum deformation detected on the gates (bosses) was more than 8 %. In the body of the casting, the maximum amount of deformation was about 5.5 %. After incorporating predeformations, the amount of deformation on the bosses was 3 %, and in the body of the part 1 %. Thus, the deformations in the casting were reduced by more than half (Fig. 7).
6. Conclusion

The size of the collector cross section does not significantly affect the probability of occurrence and distribution of shrinkage defects in the body of panel castings. However, it affects the warping depth of the casting. The minimum values of deformations and shrinkage cavities of the proposed options provide the design option with the smallest cross-section size of the collector.

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.

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