Numerical Simulation of Cast Distortion in Gas Turbine Engine Components

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Abstract. In this paper the process of multiple airfoil vanes manufacturing through investment casting is considered. The mathematical model of the full contact problem is built to determine stress strain state in a cast during the process of solidification. Studies are carried out in viscoelastoplastic statement. Numerical simulation of the explored process is implemented with ProCAST software package. The results of simulation are compared with the real production process. By means of computer analysis the optimization of technical process parameters is done in order to eliminate the defect of cast walls thickness variation.

1. Introduction

One of the most important tasks of mathematical modeling of physical processes is comprehensive study of certain aspects of modern engineering industry. The result is creation of cost-effective innovative production technologies which allow not only to save expensive raw materials, energy and labour resources, but also improve the quality of parts manufactured and minimize the rejects.

Among wide range of aviation parts a turbine vane is unrivaled in terms of load degree and purpose criticality. Hence high requirements arise to its metallurgical and strength quality. Design and technological features of hollow vanes have serious effect on gas-dynamic characteristics of an engine. Operating conditions of thin-wall vanes in modern gas turbine engines require their high geometrical precision. That’s why particular attention must be paid to the issues of vanes design and casting.

The process of gas turbine engines vanes manufacturing through investment casting is accompanied by multifactor physical phenomena. The application of mathematical modeling method for processes that accompany parts manufacturing allows to reduce costs since the development of gate system design and temperature-time process parameters is carried out not on real expensive casts, but in virtual space of a mathematical model. Low cost and short terms of carrying out computer experiments, and also big volume and visualization of information received on process progress and quality of a future cast make computer simulation the essential research tool [1].

2. Exploring the technological problem

A vane cast manufactured by investment casting method may differ from a design model in terms of its geometrical characteristics. Cooling of a cast is accompanied by changing of its dimensions due to temperature and structural shrinking deformations which show up in form of linear shrinkage and curvature of individual features axes or shape distortion. High heat-shrinking deformations lead to distortion of a casting mould, a core, to shape distortion of a cast itself. That is why to receive a product with set geometry, one should take into account the possibility of deformation in advance.
Applying predistortions to cast geometry allows to receive a cast matching a design model with set precision. For this purpose it is necessary to know in advance the mechanical behaviour of a cast, a mould, and a ceramic core. A ceramic core forms the internal cavity of a casting; that is why its distortion during tapping and the following solidification may affect the shape of a future cast causing defects in form of walls thickness variation from pressure and suction side along the whole span. Selection of a technological mode for thin-wall vanes casts manufacturing process with minimal distortions of a ceramic core is the essential engineering task.

Let us study the process of hollow vane cluster manufacturing from heat-resistant nickel-base superalloy. The cluster is casted in a special-purpose machine of solidification. Solidification is proceeding in ceramic mould obtained by precise casting. The Ceramic core forms a blade hollow spaces.

Let us consider simulation of stress-strain state (SSS) which appears during manufacturing of hollow vane cluster. In a real production process non-contact optical 3D-scanning revealed casts geometry deviations from design models. Maximum deviations were found on the pressure side of the cast near the internal edge. This deviation and concomitant airfoil walls thickness variation are probably caused by the core distortion during the cluster manufacturing.

It is necessary to carry out the analysis of casting and cast solidification process in order to confirm the hypothesis about core distortion and find a technological mode with minimal distortion. The study was carried out through mathematical modeling. Figure 1 a-c shows the real wax pattern of a cast and pouring gate system, the design model and the discrete model respectively.

![Figure 1. Hollow vanes cluster: a) wax pattern, b) design model, c) finite-element model](image)

Vertical pouring gate system was used with metal supply to radial platform wedge from two sides. Mould heater temperature was 1000°C, tapping time – 5 sec.

3. **Mathematical statement of the problem**
In the course of the study the full contact problem of SSS determination is resolved in the statement “deformed mould – deformed cast – deformed cores”. Studies are carried out in viscoelastoplastic statement.
Full deformation looks as follows:

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

(1)

Hence the following physical relations:

\[ \sigma = 4R \cdot \varepsilon = 4R \cdot \left( \varepsilon - \varepsilon^{el} - \varepsilon^{vp} - \varepsilon^{th} - \varepsilon^{tr} \right) \]  

(2)

where \( 4R \) is quartic elastic constants tensor.

Geometrical relations look as follows:

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

(3)

Balance equation is taken as follows

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

(4)

Temperature deformation:

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

(5)

\( \alpha \) is temperature expansion coefficient, \( I \) is identity tensor.

Liquid-solid phase solildification shrinkage is considered as follows:

\[ \varepsilon^{tr} = \frac{1}{3} g_{tr}(\varepsilon, t) I \]  

(6)

\( g_{tr} \) is volume fraction of liquid-solid phase, transforming into a new phase, and \( \beta_{tr} \) is coefficient of volume shrinkage associated with phase transformation.

Viscoplastic behavior law is taken as follows:

\[ \dot{\varepsilon}^{el} = \frac{3}{2} \varepsilon^{eq} \frac{\sigma^{eq} - \sigma}{\sigma^{eq}} \]  

(7)

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

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

(8)

where \( \sigma^* \) is yield stress, \( \sigma^{eq} \) are von Mises equivalent stresses, \( \mu \) is viscous parameter, \( p \) is strain rate sensitivity coefficient, \( \sigma \) is average stress.

At liquid and solid interface (ls) normal and tangential stresses look as follows:

\[ \sigma_{ls}^I = \sigma_{ls}^S = 0, \quad \sigma_{lsn}^I = \sigma_{lsn}^S \]  

(9)

For contact interfaces of a casting, mould and a core conditions of a contact are set by the following relations (the indices 1 and 2 denote the contact body):

In case of full cohesion and slippage with static friction:

\[ \pi_i = \pi_j \Rightarrow \sigma_{in} = \sigma_{jn}, \quad \sigma_{ir} = \sigma_{jr} \]  

(10)

while \( \pi_i < q \pi_n \)
In case of slippage with sliding friction:

\[ \pi_{in} = \pi_{jn}, \pi_{ij} \neq \pi_{ji} \Rightarrow \sigma_{in} = \sigma_{jn}, \sigma_{ij} = -\sigma_{ji}, \sigma_n < 0, \]  

(11)
while \( |\sigma| = q|\sigma_n| \).

In case of full detachment:

\[ \pi_{in} \neq \pi_{jn} \Rightarrow \sigma_n = \sigma_{\tau} = 0 \]  

(12)

For surface of a mould installed on the bottom of a casting installation the following fastening conditions are true:

\[ u_z = 0, \quad x \in \Gamma_0 \]  

(13)

For free boundaries of a mould, a cast and a ceramic core the following is true:

\[ \sigma \cdot n = 0 \]  

(14)

4. Numerical simulation results

The application task of a real casting process simulation does not have an analytical solution. Thus, we may need to simulate casting process numerically. For several years Aviadvigatel has been using a universal program software named ProCAST for simulating the process of pouring and solidification of gas turbine engine component castings. ProCAST is a system of casting numerical simulation based on FEM method.

Figure 2 shows shape distortion in the cast and cores after solidification, distortion in the cast is increased 20 times, in cores – 50 times.

![Effective Stress [MPa] for Cast SSS after Solidification](image)

**Figure 2.** Results of simulation of the cast SSS after solidification: a) shape distortions in the cast (×20); b) shape distortions in the core (×50)

From Figure 2 the conclusion can be made about significant displacement of a core in the medium part and its influence on final geometrical shape of the cast. Figure 3.a shows core
displacement in the central section of the cast, 5 times increased. Results of the actual cast measurement in respective section using non-contact 3D-scanning are given in Figure 3.b. Results of computer simulation and the cast measurements showed the displacement of the ceramic core towards the pressure side. It caused the effect of cast walls thickness variation.

**Figure 3.** Displacement of the ceramic core towards the pressure side of the airfoil a) – predicted by numerical simulation (mm \times 5); b) – received at the actual cast measurement, mm

To eliminate the casting defect in form of walls thickness variation it was decided to carry out a number of numerical experiments on simulation of hollow vanes cluster manufacturing process with different technological parameters and to select optimal ones.

### 5. Optimization of technological parameters

In the numerical study of the multiple airfoil vane manufacturing process maximal core displacement towards the pressure side was 0.35 mm.

It was decided to explore the influence of melt tapping on the core displacement, according to the studies undertaken in [6]. It was suggested to reduce tapping time from 5 to 3 seconds. The rest of production parameters remained unchanged.

Computer simulation results showed that maximum distortion of the core was 0.3 mm, which is 0.05 mm less than maximum distortion found in production process simulation at alloy tapping in 5 seconds. Thus, the increase of melt feed rate is rational for reduction of cast distortion.

Next suggestion was to increase the mould heater temperature during mould preheating. Two technological modes were suggested: mould heater heating up to 1100°C and up to 1200°C. Tapping time was 3 seconds.

For mould temperature 1100°C maximum core distortion was 0.23 mm. At heating up to 1200°C the distortion did not exceed 0.14 mm. Results of the numerical experiments carried out are given in Table 1.

| Number of numerical experiment | Alloy tapping time | Mould temperature | Maximum displacement |
|-------------------------------|--------------------|--------------------|----------------------|
| 1                             | 5 s                | 1000 C             | 0.35 mm              |
| 2                             | 3 s                | 1000 C             | 0.30 mm              |
| 3                             | 3 s                | 1100 C             | 0.23 mm              |
| 4                             | 3 s                | 1200 C             | 0.14 mm              |
Figure 4 shows cores distortions fifty times increased for the experiments carried out. One can see that distortions in the fourth numerical experiment are minimal.

Cast distortion equal to 0.14 mm falls within the tolerance during measurement of cast dimensions deviations from geometrical model. Thus, for the production process the technological mode was recommended with melt supply in 3 seconds and mould preheating in the mould heater up to 1200°C.
Comparison of a casting model and resultant blade using three-dimensional scanning indicates how obtained results are essential. Results of the vane clusters measurement in respective section using non-contact 3D-scanning are given in Figure 5. Figure 5.a shows result of cluster measurement produced by regular technology. Average casting distortion is about 0.58 mm. Figure 5.b shows result of cluster measurement produced by optimized production conditions. Average casting distortion is 0.19 mm. Thus application of this technology for the hollow vane cluster manufacturing allowed reducing distortion of cores more than three times.

Figure 5. Displacement of the ceramic cores received at the actual casts measurement a) – fore regular technology b) – fore optimized production conditions

So, solution of the stress-strain evaluation task enables to determine temperature and time parameters with which deformation will be minimal. This helps to deal with such defects as variations of wall thickness in hollow airfoils.
6. Conclusions

Mathematical modeling of hollow vanes cluster manufacturing process was carried out. The problem included the processes of casting, crystallization and calculation of the cast SSS during solidification.

Deviations of the deformed grid from initial cast geometry were compared with the real cast distortion, found by non-contact optical 3D-scanning. High level of correlation of distortions received by numerical simulation with real cast distortions was noted.

After the cast measurements, wall thickness variation was found, caused by the displacement of the core towards pressure side. This data confirmed the results of mathematic modeling.

A number of numerical experiments was carried out to select technological parameters of multiple airfoil vane manufacturing process in order to reduce the displacement of the core towards pressure side.

As a result of the numerical study, it was suggested to change alloy tapping time and the heated mould temperature, which allowed to reduce distortion of cores more than three times and to bring airfoil thickness variation on pressure and suction side into the tolerance zone.

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