Research on the Defect Formation Mechanism of Shell Mold Cast Gas Turbine Blades

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Abstract: Gas turbines are thermal mechanical devices that utilize gas power to drive rotating shafts, widely used in applications such as power generation, aircraft propulsion, and industrial processes. The current issues with gas turbines include manufacturing defects, turbine blade damage, operational wear during operation, and challenges in detection and maintenance. In this paper, we have analyzed the physical field distribution during the filling and solidification processes and eliminate defects.

Keywords: shell mold casting; numerical simulation; temperature field; defect

1 Introduction

Shell molding is a precision casting process that involves creating a heat-resistant ceramic shell on the surface of a mold, into which molten metal is poured to produce components with complex shapes and precise dimensions. The defects of gas turbine blades were analyzed in slices and the causes of defects were discussed and eliminate the casting defects [1,2].

Smith and Johnson et al. analyzed and optimized the manufacturing process of aerospace engine turbine blades using simulation and experimental methods. They focused on key manufacturing parameters and proposed methods to reduce manufacturing defects [4,5]. Brown et al. predicted and prevented manufacturing defects in gas turbine blade production using computational methods. They proposed strategies for process optimization and parameter control to minimize production issues [6]. Gupta et al. analyzed thermal stresses in turbine blade manufacturing using finite element simulation and proposed effective solutions to mitigate thermal stress risks [7].

2 Experimental procedure

The blade material is a nickel-based superalloy, and the shell material is Mullite, with thermal property parameters selected from a database. Interface heat transfer includes two parts: between the casting and mold shell, and between the mold shell and thermal insulation cotton. The gravity direction is set according to the actual pouring direction. Relevant boundary condition parameters are specified, and the step length exceeds 50,000. The mathematical model of filling and solidification process is as follows：

Continuity equation for compressible fluids [8]：

compressible fluid：

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho w}{\partial z}=0 \quad (1)$$

Incompressible fluid：

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (2)$$

u, v, w - the fraction of velocity in x and z directions; ρ- Density of liquid gold.

Three-dimensional heat transfer model：

$$\rho C\frac{\partial T}{\partial t}=\lambda\left(\frac{\partial^2 T}{\partial^2 x}+\frac{\partial^2 T}{\partial^2 y}+\frac{\partial^2 T}{\partial^2 z}\right)+Q \quad (3)$$

x, y, z - three-dimensional coordinates; ρ- Object density scale, g/w3; Cg specific heat, J/m3; T - Temperature, K; t – time, s and λ-Calorimetric conductivity, W/m • K; Q- Internal heat source, J

3 Result and discussion

Based on the numerical simulation results conducted during the forming process of gas turbine blade castings, the Niyama criterion implemented in ProCAST was utilized to predict shrinkage and porosity within the castings. The simulation outcomes indicate the following observations:

Shrinkage and porosity were observed in the large edge plate region, particularly away from the pouring riser and in the middle area between the two straight runners. In the blade body section near the intake side of the small edge plate, varying degrees of shrinkage and porosity distribution were identified. The resulting shrinkage and porosity distribution closely matched that observed in the actual pouring process.

Analysis of the stress field from the simulation results revealed a higher flow rate of liquid metal at the base of the blade body near the small edge plate during pouring, coupled with a smaller modulus in this region, which consequently favors quicker cooling compared to other areas. As the solid phase fraction reaches a critical value, thermal stress and strain develop, increasing the likelihood of hot cracks in this region. In practical pouring scenarios, hot cracks often originate from grain boundaries. The surface exhibits oxidation and lacks metallic luster, aligning roughly with the location of predicted hot cracks from the simulation results. The temperature field distribution cloud map and defect distribution are shown in the Figures 1(a) and (b) below:

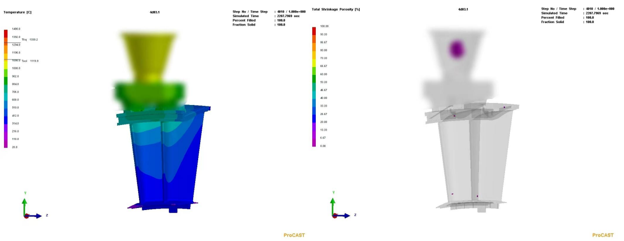

Figure 1 Temperature field distribution cloud map (a) and defect distribution (b)

4 Conclusion

Simulating the filling and solidification processes of castings using ProCAST software involves setting various casting temperatures and process parameters to analyze the filling process, temperature field, and flow field simulation results. This analysis helps determine the appropriate casting temperature and optimize casting process parameters. During the simulation, different casting temperatures and process parameters are tested to observe the flow of molten metal and temperature distribution during the filling process. Analyzing these simulation results, the optimal casting temperature of around 1,490 °C can be found to ensure smooth filling and prevent defects.

Using the HTI module in ProCAST simulation software, predictions were made regarding locations prone to thermal cracking. Through analysis of the flow field and stress field, specific thermal hotspots within the casting were identified, characterized by the highest concentration of thermal stress and strain. These identified areas closely align with actual observations. By optimizing the cooling system, it becomes possible to precisely adjust local temperature distribution, thereby slowing down solidification rates and reducing temperature gradients. These optimizations effectively mitigate the risk of thermal cracking, contributing to improved quality and integrity of the turbine blade castings.

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