Experiment and Simulation of Solidification Process for Directionally Solidified Hollow Blades of Heavy-Duty Gas Turbines Fabricated by Liquid Metal Cooling Method *Postprint

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Abstract

Directionally solidified hollow high-pressure turbine blades for heavy-duty gas turbines were fabricated using high temperature gradient directional solidification-liquid metal cooling (LMC) technology. The temperature field, grain structure, and primary dendrite arm spacing (PDAS) during solidification of hollow directionally solidified blades under LMC directional solidification at different withdrawal rates were calculated using ProCAST finite element simulation software, and the influence of withdrawal rate on defects such as stray grains and freckles was predicted. The results show that the simulation results agree well with the experimental results. With increasing withdrawal rate, both the solidification rate and cooling rate of the blades increase, far exceeding those of the high-rate solidification (HRS) method; the withdrawal rate corresponding to the maximum longitudinal temperature gradient varies among different blade sections, and the longitudinal temperature gradient is an effective metric for evaluating directional solidification processes; LMC-processed gas turbine blades eliminate freckle defects, with PDAS significantly smaller than that of the HRS process.

Full Text

Preamble

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Title

Experimental and Simulation Study of the Solidification Process for Heavy-Duty Gas Turbine Directionally Solidified Hollow Blades Prepared by Liquid Metal Cooling

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Abstract

Directionally solidified hollow high-pressure turbine blades for heavy-duty gas turbines were prepared using high-temperature-gradient directional solidification-liquid metal cooling (LMC) technology. The temperature fields, grain structures, and primary dendrite arm spacing (PDAS) during the solidification of hollow directionally solidified blades at different withdrawal rates under the LMC process were calculated using ProCAST finite element simulation software, and the influence of withdrawal rate on defects such as stray grains and freckles was predicted. The results show good agreement between simulated and experimental results. With increasing withdrawal rate, both the solidification rate and cooling rate of the blades increase, significantly exceeding those of the high rate solidification (HRS) process. The withdrawal rate corresponding to the maximum longitudinal temperature gradient varies at different blade locations, and the longitudinal temperature gradient proves to be an effective method for evaluating directional solidification processes. Blades prepared by the LMC process exhibit eliminated freckle defects, with PDAS substantially smaller than that of the HRS process.

Keywords: liquid metal cooling, directional solidification, industrial gas turbine blade, numerical simulation

Introduction

The gas-steam combined cycle, composed of gas turbines and steam turbines, currently represents the large-scale commercial power generation method with the highest thermal-to-work conversion efficiency achieved by humanity. Developed countries attach great importance to the development of heavy-duty gas turbines and maintain a monopoly position in core technologies. For China, a country with coal as its primary energy resource, developing advanced heavy-duty gas turbines holds urgent practical significance and important strategic importance. To enhance the temperature-bearing capacity of turbine blades, gas turbine blades are widely manufactured using directional solidification technology to produce directionally solidified columnar grain or single crystal blades. Compared with aero-engine blades, industrial gas turbine blades are substantially larger in size and weight, making them prone to casting defects and extremely difficult to manufacture.

Currently, the directional solidification technology widely used in China is the relatively mature high rate solidification (HRS) process. In this method, the mold is placed on a water-cooled chill plate and preheated in a furnace. After pouring molten metal into the mold, the mold is withdrawn from the furnace to achieve directional solidification. Heat is primarily lost through thermal conduction via the water-cooled chill plate and radiation from the casting to the furnace walls. As solidification progresses, heat loss through the chill plate gradually decreases, resulting in reduced temperature gradients. When casting large components, defects such as shrinkage porosity, freckles, low-angle grain boundaries, broken grains, and stray grains readily occur. To control these defects, the withdrawal rate for large blades must generally be maintained at very low levels, which leads to reduced production efficiency, intensified reaction between molten steel and mold shell, and core deformation issues. Therefore, manufacturing large industrial gas turbine directional blades using the HRS method faces significant challenges.

In recent years, foreign researchers have conducted in-depth studies on the preparation of large-scale directional castings using the liquid metal cooling (LMC) method. In the LMC process, the mold is gradually withdrawn into a pool of low-melting-point liquid metal at a constant velocity, with heat transfer dominated by conduction and convection in the liquid metal. The temperature gradient and cooling rate are substantially greater than those in the HRS process, and the temperature gradient remains essentially constant even as mold size increases. Compared with conventional HRS, the LMC process offers significantly improved production efficiency, more uniform material microstructure, and reduced microsegregation.

Due to the introduction of low-melting-point liquid metal as a cooling medium in the LMC process, the interactive effects of process parameters during solidification become extremely complex. Numerical simulation provides an effective means to shorten experimental cycles and reduce costs. For the LMC process, Kermanpur et al. used the finite element software ProCAST to establish a three-dimensional model, calculating temperature distributions during blade directional solidification and predicting grain orientations after solidification using the cellular automaton (CAFE) method. Elliott et al. employed simulation to analyze the influence of solidification parameters on temperature gradients in the LMC process, revealing that the heat transfer coefficient between the casting and mold shell is the most sensitive parameter in LMC. Research has also demonstrated that withdrawal rates in LMC can reach three times those of HRS, with PDAS refined by approximately 50%. Miller and Pollock investigated various solidification parameters during the solidification of single crystal bars and simulated single crystal components under LMC, concluding that LMC effectively refines dendritic structures and offers clear advantages for manufacturing large single crystal castings. However, few studies have applied numerical simulation to optimize directional solidification processes in the actual production of large-scale directionally solidified hollow blades.

This work utilizes the finite element software ProCAST to simulate and calculate the temperature fields during solidification of large-scale directionally solidified hollow blades under the LMC process, predict grain structure evolution, and investigate the effects of withdrawal rate on grain defects, grain size, and primary dendrite arm spacing. Based on simulation results, comparative experiments were conducted, successfully producing large-scale directional hollow blades for heavy-duty gas turbines.

Experimental and Simulation Methods

Experimental Methods

The experimental equipment consisted of a large-scale LMC directional solidification device independently developed by the Institute of Metal Research, using liquid Sn as the cooling medium. The material used was the heat-resistant corrosion superalloy DZ411, with nominal composition (mass fraction, %) of: Cr 15, Ta 4, Co 11, W 3, Mo 2, Al 4, Ti 5, Ni balance. The alloy' s solidus and liquidus temperatures are 1245 °C and 1319 °C, respectively. The blades produced in this study were large-scale directionally solidified hollow blades for heavy-duty gas turbines, with blank lengths of approximately 500 mm, weights of about 20 kg, and complex internal gas cooling channels. The blade geometry is complex with significant dimensional variations across different sections, all of which present manufacturing challenges, as shown in [FIGURE:1].

The manufactured large-scale directionally solidified hollow blades were sectioned and had their cores removed before macroetching to observe macroscopic grain structures. Cross-sections were cut from the blade tip at positions of 10, 30, 60, 100, 160, 200, 240, 300, and 360 mm using wire electrical discharge machining. After metallographic etching, dendritic structures were observed using an Axio Vert.A1 optical microscope (OM). The primary dendrite arm spacing λ_1 was statistically determined using the formula $\lambda_1 = (n\ )^{-1}/^{2}$, where n is the number of dendrites per unit area. The average grain diameter D was calculated using the formula $D = \sqrt{(4s/\pi)}$, where s is the average grain area.

Simulation Methods

Simulations were performed using commercial ProCAST software with boundary conditions from references [18,19]. The three-dimensional meshing of the heavy-duty gas turbine blade is shown in [FIGURE:1a]. The calculations primarily focused on the solid-liquid interface shape, longitudinal temperature gradient, and cooling rate at withdrawal rates of V_1, V_2, V_3, V_4, V_5 ($V_1<V_2<V_3<V_4<V_5$). After optimizing the directional solidification process by comparing these parameters, the primary dendrite arm spacing λ_1 and grain structures were calculated and compared with actual blades. The primary dendrite arm spacing was calculated using the models proposed by Hunt and Kurz and Fisher: $\lambda_1 = A_1G^{-1}/^{2}V^{-1}/^{4}$, where A_1 is a material constant, G is the temperature gradient, and V is the solidification rate. In actual solidification, the solidification rate does not equal the withdrawal rate; therefore, the actual solidification rate rather than the withdrawal rate was used in all calculations.

Results and Discussion

The shapes of the solidus/liquidus (S/L) interface at the same blade position and their positional relationship with the Sn liquid surface at different withdrawal rates are shown in [FIGURE:2]. At withdrawal rate V_1, the blade profile geometry has minimal influence on the solidification interface. As the withdrawal rate increases (V_3), the solidification interface gradually moves downward with increasing curvature, which is unfavorable for grain structure growth. At withdrawal rate V_4, severe curvature of the S/L interface occurs throughout the blade solidification process, leading to convergent grain growth with large deviations of grain preferential orientation from the withdrawal direction. The interface shape is significantly influenced by the blade profile, with the highest position at the trailing edge where wall thickness is minimal and the lowest position at the maximum wall thickness region (maximum blade curvature). Due to the significantly greater wall thickness at the blade root (dovetail) compared to the airfoil, when the withdrawal rate is high and the solidification interface reaches the dovetail region, the mushy zone widens markedly, the temperature gradient decreases significantly, and the entire interface lies below the Sn liquid surface, which is highly detrimental to directional structure growth and prone to stray grain nucleation.

Since LMC technology replaces the thermal radiation in the later stages of the HRS process with thermal conduction from liquid tin, the temperature gradient and cooling rate are substantially increased. However, during the production of large-scale blades, improper withdrawal rates can easily cause solidification interface curvature and generate lateral temperature gradients (G). In this case, the temperature gradient G consists primarily of lateral temperature gradient G and axial temperature gradient G . The temperature gradient angle = arctan(G /G) is defined, as schematically shown in [FIGURE:3]. Since lateral temperature gradients are unfavorable for directional columnar grain growth, directional solidification processes cannot be formulated based solely on the magnitude of temperature gradient G. Examining both G and provides a more accurate quantitative optimization of LMC process parameters. This work primarily investigated the effect of withdrawal rate on G and determined the withdrawal rates yielding maximum longitudinal temperature gradients at different positions. Miller’ s research also demonstrated that solidification interface curvature angle and longitudinal temperature gradient provide better metrics for evaluating process parameter quality.

The longitudinal temperature gradient distributions in the blade at different withdrawal rates are shown in [FIGURE:4]. Under the LMC process, the average temperature gradient for large-scale blades is 60 °C/cm, higher than the average temperature gradient of 20 °C/cm reported in literature for similar thickness castings under HRS. The figure also reveals that as withdrawal rate decreases, the variation pattern of longitudinal temperature gradient differs across blade locations. At the leading and trailing edges where wall thickness is minimal, the temperature gradient decreases with reduced withdrawal rate, dropping from over 100 °C/cm to approximately 65 °C/cm. In contrast, the temperature gradient in the mid-section of the airfoil first increases then decreases.

The variation of longitudinal temperature gradient at the surface of cross-sections along the blade centerline with withdrawal rate is shown in [FIGURE:5]. Due to blade geometry effects, the withdrawal rate corresponding to maximum longitudinal temperature gradient varies by location. As withdrawal rate increases, the longitudinal temperature gradient initially increases then decreases, indicating an optimal withdrawal rate exists for achieving maximum longitudinal temperature gradient.

The calculated solidification rates at different blade positions and withdrawal rates are shown in

. Solidification rates increase with withdrawal rate at all blade locations. At low withdrawal rates (V_1), the solidification rate approximates the withdrawal rate, with minimal change in S/L interface position during solidification. As withdrawal rate increases, the solidification rate gradually deviates from the withdrawal rate. Cross-sections at 240 mm and 360 mm are located in the dovetail region with large wall thickness, where the solidification interface lies below the Sn liquid surface, preventing higher solidification rates even with increased withdrawal rate.

Since the LMC process uses liquid metal Sn as the cooling medium, heat from the casting is continuously removed through thermal conduction by the liquid tin during directional solidification. As shown in [FIGURE:7], cooling rate decreases with reduced withdrawal rate. Throughout the entire withdrawal rate

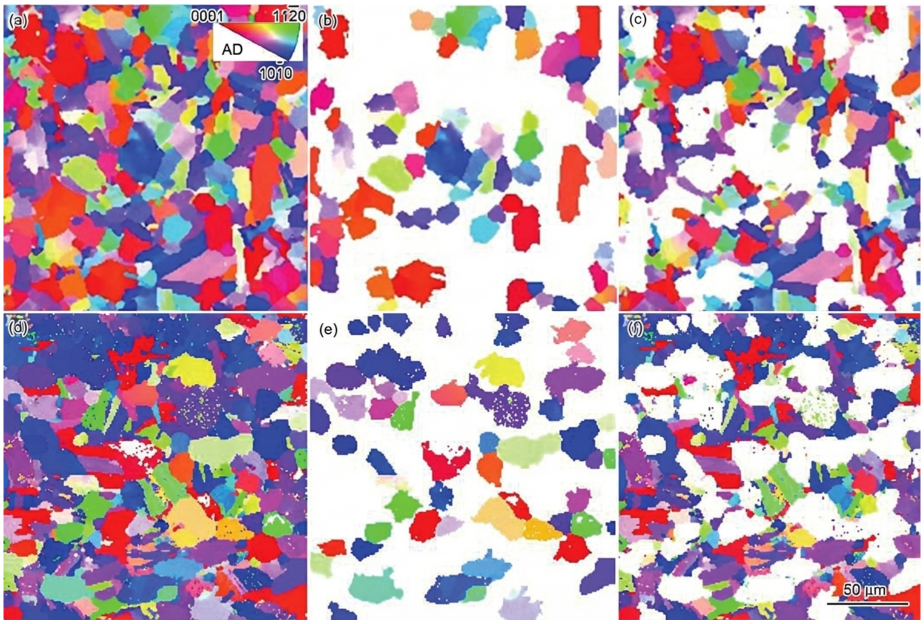

Figure 1: Figure 6

range, cooling rates under LMC are 0.11-2.00 °C/s, significantly higher than the 0.05-0.10 °C/s reported for HRS process castings of similar size. Higher cooling rates are achieved at the leading and trailing edges due to smaller wall thickness.

Heavy-duty gas turbine blades exhibit large cross-sectional area changes at the platform. Calculations revealed that stray grains readily nucleate at these platform transitions. At withdrawal rate V_4, numerous new grain nucleations occurred at the blade platform, which gradually grew during subsequent solidification, even blocking the growth of original grains and causing broken grain defects in the blade root region. As withdrawal rate decreased (V_2), the number of newly nucleated grains gradually reduced, and their subsequent growth did not obstruct the continuation of original grain growth toward the dovetail, as shown in [FIGURE:8].

Through the above numerical simulations, directional solidification process parameters for heavy-duty gas turbine blades can be comprehensively optimized to obtain high-quality large-scale directionally solidified blades. The simulated grain structure after process optimization and the experimentally produced blade are shown in [FIGURE:9]. The directionally solidified blade exhibits straight grain growth with uniform grain size. The grain width is comparable to typical heavy-duty gas turbine blades produced by HRS, and simulation results agree well with experimental results.

Based on the calculated longitudinal temperature gradients and solidification rates, the primary dendrite arm spacing of the heavy-duty gas turbine blade was calculated, with results shown in [FIGURE:10]. Both simulated and experimental PDAS data indicate that under LMC, primary dendrite arm spacing ranges from 180–300 m, significantly smaller than the 380–550 m PDAS of heavy-duty gas turbine blades prepared by HRS. Additionally, due to the substantially increased cooling rate in LMC, defects such as freckles are eliminated. Pollock and Murphy’ s research indicates that unstable convection in the liquid phase ahead of the solid-liquid interface is the primary cause of freckles, which form when cooling rates are below 0.1 °C/s. Increasing cooling rate reduces or eliminates freckles. Calculations show that under LMC, by selecting appropriate withdrawal rates, cooling rates can still reach 0.4 °C/s even in the thickest dovetail and extension regions, effectively preventing freckle formation. No freckle defects were observed in experimentally produced heavy-duty gas turbine blades using optimized process parameters, consistent with simulation results. In contrast, numerous freckles were observed in the extension regions of HRS-processed heavy-duty gas turbine blades, as shown in [FIGURE:11].

Currently, heavy-duty gas turbine directionally solidified hollow turbine blades produced using LMC technology have successfully passed the designed 500-cycle super-service-condition thermal shock testing, representing the first such achievement in China and establishing a solid foundation for the independent development of heavy-duty gas turbine blades in China.

Conclusions

1. By calculating temperature distributions, longitudinal temperature gradients, and cooling rates during solidification of heavy-duty gas turbine blades at different withdrawal rates, the withdrawal rates corresponding to maximum longitudinal temperature gradients were determined. The maximum longitudinal temperature gradient provides an effective method for evaluating directional solidification parameters.
2. Through optimized process parameters, the influence of stray grains on grain growth continuity was avoided.
3. The simulated grain structures and primary dendrite arm spacing after solidification show good agreement with experimental results.
4. This numerical model provides an effective means for optimizing directional solidification processes for large-scale complex-shaped blades.
5. Heavy-duty gas turbine directionally solidified hollow blades were successfully produced using LMC technology, refining dendritic structures and eliminating defects such as freckles.

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