

Postprint: Experimental and Simulation Study on Solidification Process of Directionally Solidified Hollow Blades for Heavy-Duty Gas Turbines via Liquid Metal Cooling

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Abstract

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

Full Text

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

In this work, directionally solidified industry gas turbine hollow blades were prepared by high gradient LMC process. Liquid Sn was used as cooling medium. The temperature fields, macrostructures, primary dendrite arm spacing (PDAS) at various withdrawal rates during LMC process have been calculated with ProCAST software. The impact of withdrawal rate on formation of stray grains and freckles was predicted. The calculated results and the experimental observations agreed well. The solidification rates and cooling rates were found to increase with the increase of withdrawal rate. The axial thermal gradient was high and stable during the LMC process. It was found that stray grains would not block the growth of original grains at optimized withdrawal rate. No freckles were observed in the industry gas turbine hollow blades prepared by LMC technique due to the high cooling rate. Though the mean diameters of columnar grains in LMC blades were almost identical to that observed in HRS blades, the PDAS were more than 50% refined in LMC blades than those in HRS blades.

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

Introduction

The gas-steam combined cycle, composed of gas turbines and steam turbines, represents the most thermally efficient large-scale commercial power generation method currently available. Developed countries attach great importance to heavy-duty gas turbine development and maintain a monopoly in core technologies. For China, a nation with coal as its primary energy resource, developing advanced heavy-duty gas turbines holds urgent practical significance and strategic importance [1]. To enhance the temperature capability of turbine blades, directionally solidified (DS) columnar grain or single crystal (SX) blades prepared by directional solidification technology are widely used in gas turbines [2]. Compared with aero-engine blades, gas turbine blades are substantially larger in size and weight, making them prone to casting defects and extremely difficult to manufacture.

The directional solidification technology currently widely used in China is the relatively mature high rate solidification (HRS) process [3-5]. In this method, the mold shell is placed on a water-cooled chill plate and preheated in a heating

furnace. After pouring molten metal into the shell, the shell is withdrawn from the furnace to achieve directional solidification. Heat is primarily lost through conduction via the water-cooled chill plate and radiation from the casting to the furnace. As solidification progresses, heat loss through the chill plate gradually decreases, reducing the temperature gradient. For large castings, defects such as shrinkage porosity, freckles, low-angle grain boundaries, grain interruption, and stray grains readily occur [6-9]. 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 reactions between molten steel and mold shell, and core deformation issues. Consequently, preparing large gas turbine DS blades using the HRS method faces significant challenges [10].

In recent years, extensive research has been conducted abroad on the liquid metal cooling (LMC) method for preparing large DS castings [11,12]. In the LMC process, the mold is gradually withdrawn into a low-melting-point liquid metal bath, 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 as mold size increases. Compared with conventional HRS, the LMC process offers significantly higher production efficiency, more uniform microstructure, and reduced microsegregation [13].

Due to the introduction of low-melting-point liquid metal as a cooling medium in the LMC process, the interaction of process parameters during solidification becomes extremely complex. Numerical simulation can effectively shorten experimental cycles and reduce costs. Regarding the LMC process, Kermanpur et al. [14] established a three-dimensional model using the finite element software ProCAST to calculate temperature distribution during blade directional solidification and predicted grain orientation after solidification using the cellular automaton (CAFE) method. Elliott et al. [15] employed simulation to analyze the influence of solidification parameters on temperature gradient in the LMC process, revealing that the heat transfer coefficient between casting and mold shell is the most sensitive parameter. Research [16] also demonstrated that withdrawal rates in LMC can reach three times those in HRS, with primary dendrite arm spacing refined by approximately 50%. Miller and Pollock [17] investigated various solidification parameters for single-crystal test bars and simulated single-crystal components in the LMC process, showing that LMC can effectively refine dendritic structures and offers clear advantages for producing large single-crystal castings. However, few studies have applied numerical simulation to optimize directional solidification processes for actual large DS hollow blade production.

In this work, the finite element software ProCAST was used to simulate the temperature field during solidification of large DS 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 these simulation results, comparative experiments were conducted, successfully

producing large DS hollow blades for heavy-duty gas turbines.

Experimental and Simulation 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 hot corrosion-resistant superalloy DZ411, with a nominal composition (mass fraction, %) of: Cr 15, Ta 4, Co 11, W 3, Mo 2, Al 4, Ti 5, Ni balance. The solidus and liquidus temperatures of the alloy are 1245°C and 1319°C, respectively. The blades produced in this study were large DS hollow blades for heavy-duty gas turbines, with a blank length of approximately 500 mm and weight of about 20 kg. The blades feature complex internal gas cooling channels, intricate geometry, and significant size variations across different sections, all of which present manufacturing challenges, as shown in Figure 1 [Figure 1: see original paper].

The as-prepared large DS hollow blades were sectioned and had their cores removed before undergoing macro-etching to observe the macroscopic grain structure. 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 (l_1) was measured using the following formula:

$$l_1 = n^{-1/2}$$

where n is the number of dendrites per unit area. The mean grain diameter D was calculated using:

$$D = \sqrt{s}$$

where s is the average grain area.

The simulations were performed using the commercial software ProCAST with boundary conditions from references [18,19]. The three-dimensional mesh of the heavy-duty gas turbine blade is shown in Figure 1a [Figure 1: see original paper]. Calculations primarily focused on the solid-liquid interface shape, longitudinal temperature gradient, and cooling rate at withdrawal rates of V1, V2, V3, V4, and V5 ($V1 < V2 < V3 < V4 < V5$). After optimizing the directional solidification process by comparing these parameters, the primary dendrite arm spacing (l_1) and grain structure were calculated and compared with actual blades. The primary dendrite arm spacing was calculated using the models proposed by Hunt [20] and Kurz and Fisher [21]:

$$l_1 = A_1 G^{-1/2} V^{-1/4}$$

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 was used rather than the withdrawal rate.

Results and Discussion

Solid-Liquid Interface Morphology

The shape of the solid-liquid (S/L) interface at identical blade positions and its positional relationship with the Sn liquid surface at different withdrawal rates are shown in Figure 2 [Figure 2: see original paper]. At withdrawal rate V1, the blade geometry has minimal influence on the solidification interface. As the withdrawal rate increases (V3), the solidification interface gradually shifts downward with increasing curvature, which is detrimental to blade grain structure growth. At withdrawal rate V4, severe interface curvature occurs throughout the solidification process, leading to convergent grain growth and significant deviation of grain preferential orientation from the withdrawal direction. The interface shape is strongly influenced by blade geometry: at the thin-walled trailing edge, the interface is highest, while at the thickest section (maximum blade curvature), the interface is lowest. Since the blade root (dovetail) has significantly thicker walls than the airfoil, when the withdrawal rate is high and the solidification interface reaches the root region, the mushy zone widens considerably, the temperature gradient drops markedly, and the entire interface lies below the Sn liquid surface. This condition is highly unfavorable for directional grain growth and prone to stray grain nucleation.

Temperature Gradient Analysis

The LMC technology employs thermal conduction through liquid tin instead of the thermal radiation used in the later stages of HRS, substantially increasing temperature gradient and cooling rate. However, during production of large blades, improper withdrawal rates can easily cause solidification interface curvature, generating a lateral temperature gradient (GL). In this case, the total temperature gradient G consists primarily of lateral temperature gradient GL and axial temperature gradient GA, with the temperature gradient angle defined as $q = \arctan(G_L/G_A)$, as schematically shown in Figure 3 [Figure 3: see original paper]. Since lateral temperature gradients are detrimental to directional columnar grain growth, process parameters cannot be determined based solely on the magnitude of G. Examining both GA and q enables more accurate quantitative optimization of LMC process parameters. This work primarily investigated the effect of withdrawal rate on GA and calculated the withdrawal rates yielding maximum longitudinal temperature gradients at different positions. Miller's research [22] also demonstrated that solidification interface curvature angle and longitudinal temperature gradient provide better metrics for evaluating process parameter quality.

The distribution of longitudinal temperature gradient in the blade at different withdrawal rates is shown in Figure 4 [Figure 4: see original paper]. The results indicate that the average temperature gradient for large blades under LMC is $60^{\circ}\text{C}/\text{cm}$, significantly higher than the $20^{\circ}\text{C}/\text{cm}$ reported for similar thickness castings in HRS [23]. Additionally, the figure reveals that as withdrawal rate decreases, the variation pattern of longitudinal temperature gradient differs across blade sections. At the thin-walled leading and trailing edges, temperature gradient decreases with reducing withdrawal rate, dropping from over $100^{\circ}\text{C}/\text{cm}$ to approximately $65^{\circ}\text{C}/\text{cm}$. In contrast, the mid-section of the airfoil exhibits an initial increase followed by a decrease in temperature gradient.

The variation of longitudinal temperature gradient at the surface of cross-sections at different heights along the blade centerline with withdrawal rate is presented in Figure 5 [Figure 5: see original paper]. Due to blade geometry and size effects, the withdrawal rate required to achieve maximum longitudinal temperature gradient varies by position. As withdrawal rate increases, the longitudinal temperature gradient initially rises then declines, indicating an optimal withdrawal rate exists for obtaining the maximum gradient.

Solidification and Cooling Rates

The calculated solidification rates at different blade positions for various withdrawal rates are shown in Figure 6 [Figure 6: see original paper]. Solidification rate increases with withdrawal rate at all blade positions. At very low withdrawal rates (V1), the solidification rate nearly equals the withdrawal rate, and the S/L interface position changes minimally during solidification. As withdrawal rate increases, the solidification rate progressively deviates from the withdrawal rate. The cross-sections at 240 and 360 mm are located in the thick-walled root region where the solidification interface lies below the Sn liquid surface, preventing higher solidification rates even with increased withdrawal rate.

Since the LMC process employs liquid Sn as the cooling medium, heat from the casting is continuously extracted through thermal conduction by the liquid Sn during directional solidification. Figure 7 [Figure 7: see original paper] shows that cooling rate decreases with reduced withdrawal rate. Across the entire withdrawal rate range, cooling rates in LMC range from 0.11 to $2.00^{\circ}\text{C}/\text{s}$, substantially higher than the 0.05 - $0.10^{\circ}\text{C}/\text{s}$ reported for similarly sized castings in HRS [24]. Higher cooling rates are achieved at the leading and trailing edges due to their thinner walls.

Defect Formation and Process Optimization

Heavy-duty gas turbine blades feature significant cross-sectional area changes at the platform, where simulations revealed that stray grains readily nucleate. At withdrawal rate V4, numerous new grains nucleated at the blade platform. During subsequent solidification, these grains grew and eventually blocked the

growth of original grains, causing grain interruption defects in the root region. As withdrawal rate decreased (V2), the number of newly nucleated grains gradually reduced, and their growth no longer obstructed the original grains from extending into the root, as shown in Figure 8 [Figure 8: see original paper].

The numerical simulations enabled comprehensive optimization of directional solidification process parameters for heavy-duty gas turbine blades to obtain high-quality large DS castings. The simulated grain structure and experimentally produced blade after process optimization are shown in Figure 9 [Figure 9: see original paper]. The DS blade exhibits straight grain growth with uniform grain size, and the grain width is comparable to that of typical heavy-duty gas turbine blades produced by HRS [24]. Simulation and experimental results show good agreement.

Based on the calculated longitudinal temperature gradient and solidification rate, the primary dendrite arm spacing of the heavy-duty gas turbine blades was determined, with results shown in Figure 10 [Figure 10: see original paper]. Both simulated and experimental PDAS data indicate that under LMC, PDAS ranges from 180 to 300 μm , significantly smaller than the 380-550 μm reported for HRS-processed heavy-duty gas turbine blades [24]. Additionally, the substantially increased cooling rate in LMC eliminates freckle defects. Pollock and Murphy [25] demonstrated that unstable convection in the liquid ahead of the S/L interface is the primary cause of freckles, with defects forming when cooling rates fall below $0.1^\circ\text{C}/\text{s}$ and being reduced or eliminated by higher cooling rates. Calculations show that under LMC, by selecting appropriate withdrawal rates, cooling rates can reach $0.4^\circ\text{C}/\text{s}$ even in the thickest root and extension sections, effectively preventing freckle formation. No freckle defects were observed in the experimentally produced heavy-duty gas turbine blades using the optimized parameters, consistent with simulation results. In contrast, numerous freckles were observed in the extension sections of HRS-processed blades, as shown in Figure 11 [Figure 11: see original paper].

The heavy-duty gas turbine DS hollow turbine blades produced using the LMC process have successfully passed the designed 500-cycle thermal shock test under super-service conditions, marking the first such achievement domestically and establishing a solid foundation for China's independent development of heavy-duty gas turbine blades.

Conclusions

- (1) By calculating temperature parameters including temperature distribution, longitudinal temperature gradient, and cooling rate during solidification of heavy-duty gas turbine blades at different withdrawal rates, the withdrawal rate corresponding to the maximum longitudinal temperature gradient was identified. The maximum longitudinal temperature gradient

provides an effective metric for evaluating directional solidification parameters.

- (2) Process parameter optimization prevented stray grains from affecting the continuity of grain growth.
- (3) The solidified grain structure and primary dendrite arm spacing were calculated, with simulation results agreeing well with experimental observations.
- (4) This numerical model provides an effective tool for optimizing directional solidification processes for large, complex-shaped blades.
- (5) Heavy-duty gas turbine DS hollow blades were successfully produced using the LMC process, which refined the dendritic structure and eliminated defects such as freckles.

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