Numerical Simulation of Bridgman Directional Solidification Microstructure of Wide-Chord Aero-Engine Blades: Postprint

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Abstract

A macro-micro mathematical model was established for the directional solidification process of wide-chord blades, with computational results agreeing well with experimental results and the positions and shapes of most grains on the casting surface corresponding one-to-one. The evolution of the temperature field and grain structure under different seeding methods and withdrawal rates was predicted through numerical simulation, and the influence laws of these two factors were studied. By establishing mathematical criteria for mushy zone morphology and grain count, quantitative evaluation of temperature field and microstructure quality was achieved; based on these criteria, the influence mechanism of process parameters on the mushy zone and grains was revealed, thereby enabling quantitative process optimization. The study demonstrates that adopting the seeding method directly below the blade airfoil is conducive to increasing the number of columnar grains, improving grain parallelism, and preventing transverse grain boundary formation, while also allowing higher withdrawal rates to be used while maintaining a flat mushy zone shape, thereby avoiding grain coarsening and improving productivity.

Full Text

Numerical Simulation of Directionally Solidified Microstructure of Wide-Chord Aero Blade by Bridgman Process

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Abstract

Aero turbine blades operate in environments of high temperature and high-pressure combustion gases. Directionally solidified (DS) turbine blades with perfect columnar grains have proven to maintain excellent high-temperature performance under such conditions, indicating that the size and orientation of columnar grains significantly influence the high-temperature properties and performance of turbine blades. However, producing high-quality DS blades is challenging due to the difficulty of obtaining the desired temperature field required for ideal grain morphology. Moreover, the growth of columnar grains in wide-chord hollow guide blades is obstructed by complex camber lines and platforms. How to produce turbine blades with desired microstructures represents a key problem in DS processing. Numerical simulation of the DS process provides an effective approach to investigate grain growth and morphology, thereby enabling process optimization.

This paper establishes a mathematical-physical model for simulating the DS process of wide-chord blades, incorporating nucleation and grain growth modeled by the Cellular Automaton (CA) method with multi-scale dynamic bidirectional coupling technology. General analytical indicators are proposed to quantitatively assess mushy zone morphology and grain structure in blades. Based on simulation results using conventional starter blocks 1, 2, and 3, a new starter block is designed considering numerically controlled machining. Temperature fields and grain structures in DS processes, along with corresponding indicators at different withdrawal rates for all four starter blocks, are numerically predicted to investigate the influence of these technological parameters and determine their mechanisms of action on the DS process. For validation, DS experiments using starter blocks 1, 2, and 3 were conducted.

The numerical and experimental results show good agreement, with similar morphologies including faulty grains. Higher withdrawal rates lead to greater concavity of the mushy zone, though the chilling effect dominates when the contact area between casting and chill plate is sufficiently large. Starter block 3 produces better grain structure than blocks 1 and 2. Starter block 4 yields a larger number of columnar grains and fewer lateral grain boundaries compared to blocks 1-3. Consequently, higher withdrawal rates can be adopted without excessive mushy zone concavity, resulting in parallel columnar grains, finer dendrites, and significantly improved blade productivity. Optimum withdrawal rates are also determined for starter blocks 3 and 4.

KEY WORDS: Aero turbine, Wide-chord blade, Directional solidification, Numerical simulation, Columnar grain

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1. Macro-Micro Mathematical Model for Directional Solidification of Wide-Chord Blades

As shown in Figure 2 [Figure 2: see original paper], after superalloy pouring, the ceramic shell moves downward together with the water-cooled Cu chill plate. During directional solidification, radiation is the dominant heat transfer mechanism. The furnace wall in the heating zone radiatively heats the blade, while intense radiative heat dissipation occurs between the blade assembly and the water-cooled furnace wall in the cooling zone. This creates a vertical temperature gradient in the blade, completing directional solidification. This study develops software based on VC++ to solve the mathematical models for temperature field and grain nucleation/growth.

1.1 Temperature Field

The temperature field control equation is:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + \rho \Delta H \frac{\partial f_s}{\partial t} + Q_{\text{net}}$$

where ρ is density (kg/m^3), c_p is specific heat capacity (J/(kg $\cdot$ K)), T is thermodynamic temperature (K), t is time (s), λ is thermal conductivity (W/(m $\cdot$ K)), ΔH is latent heat of crystallization (J/kg), f_s is solid fraction, and Q_{net} is heat exchange between solid surface elements and the environment (W/m^3).

Radiative heat transfer at solid surfaces is calculated using an improved Monte Carlo ray tracing method [7]. The temperature field boundary condition is:

$$Q_{\text{net},u} = \sum_{v=1}^{n} \beta_{u,v} \sigma (T_u^4 - T_v^4) \frac{S_v}{S_u} \varepsilon_u \varepsilon_v$$

where $Q_{\text{net},u}$ is heat flux density between free surface u of shell or chill plate and the environment (W/m^2), S_u and S_v are areas of u and ray v' s environmental subspace (m^2), σ is the Stefan-Boltzmann constant (W/(m^2 $\cdot$ K)), $\beta_{u,v}$ is the improved weight coefficient for ray v, n is the total number of rays emitted from

u, T_u and T_v are temperatures of u and v (K), and ε_u and ε_v are emissivities. Element v may be the hot zone or baffle surface, or another free surface of shell or chill plate. The spatial coordinate Z_u of each element updates in real-time according to withdrawal rate at each time step, with $\beta_{u,v}$ updated every 10 time steps.

1.2.1 Nucleation Model

The Gauss distribution stochastic nucleation model by Rappaz and Gandin [20] is adopted:

$$\frac{dN}{d(\Delta T_t)} = \frac{N_s}{\sqrt{2\pi}\Delta T_\sigma} \exp\left[-\frac{(\Delta T_t - \Delta T_N)^2}{2\Delta T_\sigma^2}\right]$$

where N is nucleation density (m ^{3}), ΔT_t is current thermodynamic undercooling (K), N_s is maximum nucleation density (m ^{3}), ΔT_σ is standard deviation of nucleation undercooling (K), and ΔT_N is mean nucleation undercooling (K). Parameters N_s, ΔT_σ, and ΔT_N are determined empirically based on grain observations in starter blocks.

Thus, grain density $N(\Delta T_t)$ can be expressed as:

$$N(\Delta T_t) = \int_0^{\Delta T_t} \frac{dN}{d(\Delta T')} d(\Delta T')$$

1.2.2 Grain Growth Model

Grain growth follows the approximate KGT model [20]:

$$v_t = \alpha \Delta T^2 + \beta \Delta T^3$$

where v_t is dendrite tip growth rate (m/s), α and β are growth coefficients, and ΔT is undercooling at the dendrite tip front (K).

During solidification, undercooling at the dendrite growth front consists of four components:

$$\Delta T = \Delta T_c + \Delta T_r + \Delta T_k + \Delta T_t$$

where ΔT_c is constitutional undercooling, ΔT_r is curvature undercooling, and ΔT_k is kinetic undercooling (generally much smaller than the other terms).

1.3 Macro-Micro Dynamic Bidirectional Coupling

A dual nested mesh system is employed: macro mesh for temperature field calculation, with each macro mesh subdivided into micro meshes for CA capture calculations of microstructure. Previous CAFE full-blade grain calculations mostly used macro-micro indirect coupling (one-way coupling from macro to micro temperature field interpolation) to save computation [14][19][21]. To more accurately calculate the effect of dendritic latent heat release on the temperature field, this work adopts bidirectional dynamic synchronous coupling.

After each macro time step of temperature field calculation, temperature values are interpolated to micro meshes:

$$T_{i,j,k}^{l,m,n} = T_{i,j,k} + G_i \cdot (l\delta x - a) + G_j \cdot (m\delta y - b) + G_k \cdot (n\delta z - c)$$

where i, j, k are macro element indices in x, y, z directions; l, m, n are micro mesh indices within macro element coordinate system; $T_{i,j,k}^{l,m,n}$ is micro mesh temperature (K); $T_{i,j,k}$ is macro element temperature (K); G_i, G_j, G_k are temperature gradients in x, y, z directions (K/m); $\delta x, \delta y, \delta z$ are micro mesh sizes (m); a, b, c are macro element dimensions. If $l\delta x > a$, G_i uses forward difference, otherwise backward difference; same for G_j and $G_k.

After micro calculation for the time step, enthalpy changes at micro nodes are accumulated to macro nodes:

$$\Delta H_{i,j,k} = \rho \Delta H \sum_{l,m,n} \Delta f_{i,j,k}^{l,m,n} \delta x \delta y \delta z$$

where $\Delta H_{i,j,k}$ is latent heat of solid-liquid phase change in macro element per macro time step (J), and $\Delta f_{i,j,k}^{l,m,n}$ is solid fraction change in micro mesh during macro time step.

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2. Mathematical Criteria for Solidification Front Morphology and Grain Count

To quantitatively evaluate temperature field effects on microstructure and compare microstructure quality across different processes, numerical criteria are needed to assess mushy zone shape and columnar grain growth conditions, providing objective basis for process optimization.

2.1 Mushy Zone Width

For quasi-steady directional solidification, primary dendrite arm spacing increases with temperature gradient at the solidification front, which is inversely proportional to mushy zone width. Secondary dendrite arm spacing decreases with local solid-liquid coexistence time, which is proportional to mushy zone width. Therefore, smaller mushy zone width yields finer dendrites.

The average mushy zone width $K_d(t)$ at a given moment is:

$$K_d(t) = \frac{V_m}{S}$$

where V_m is the volume of casting portion enclosed between T_s and T_l isotherms (m^3), T_s and T_l are solidus and liquidus temperatures (K), and S is the projection area of this volume on the xoy plane (m^2).

2.2 Concavity of Solidification Front

From the dendrite growth model, the temperature gradient direction at dendrite tips is the primary factor influencing grain growth direction. Thus, mushy zone curvature determines columnar grain divergence, as shown in Figure 3 [Figure 3: see original paper]. Generally [26], for a given casting size, excessively slow withdrawal rates increase mushy zone convexity, causing V-shaped upward grain divergence, while excessively fast rates increase concavity, causing Λ-shaped downward divergence (anti-divergence) [22]. Optimizing withdrawal rate can minimize mushy zone curvature and improve grain parallelism.

In typical directional solidification, dendrite tips are very close to the T_l isotherm (within 1 mm), so the T_l isotherm can approximate the mushy zone envelope. In calculations, temperature gradients at various points on the T_l isotherm are used to characterize temperature gradients at dendrite tips.

As shown in Figure 4 [Figure 4: see original paper], at a given moment, the T_l isotherm of the casting alloy is a bounded surface Ω (shown in red) with its boundary at the shell-casting interface. Its projection on the xoy plane is Ω' with area S' (m^2). O is the geometric center of Ω; $\mathbf{Z}_O$ is the dimensionless unit vector pointing vertically upward; P is any point on Ω with neighborhood $dx \cdot dy$ (m^2); $\mathbf{G}_P$ is the temperature gradient at point P (K/m), directed along the normal to Ω at P.

The definition of point O satisfies:

$$\int_{\Omega} \mathbf{OP}\, dS = 0$$

The concavity of mushy zone $K_{\text{con}}(t)$ at that moment is:

$$K_{\text{con}}(t) = \frac{1}{S'} \int_{\Omega} (\mathbf{OP} \cdot \mathbf{Z}_O)(\mathbf{G}_P \cdot \mathbf{Z}_O)\, dS$$

$K_{\text{con}} > 0$ indicates a concave T_l isotherm, while $K_{\text{con}} < 0$ indicates convexity. A primary optimization objective is minimizing $|K_{\text{con}}|$.

2.3 Cross-Section Grain Number

Changes in cross-section grain number reflect columnar grain competitive growth and orientation variations. As shown in Figure 5 [Figure 5: see original paper], $K_{NO}(z)$ is defined as the number of grains intersecting a horizontal plane at height z.

2.4 Surface Intercept Grain Number

In production, surface grain inspection is faster than cross-section inspection and has established industrial standards [2]. For thin-walled blades, surface intercept grain number can indirectly reflect cross-section grain number.

In Figure 5, for a horizontal plane at height z' intersecting the casting surface to form intercept line L (a closed curve), the surface intercept grain number is defined as the number of intersection points between L and grain boundaries, denoted as $K_{SNO}(z')$.

Currently, commercial software lacks calculation programs for these four criteria. This work develops a post-processing module based on VC++ to process temperature field and grain calculation results and output criterion values.

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3. Experimental Validation

The casting uses a new intermetallic alloy IC10 [27]. A two-blade assembly with axial symmetry is employed, as shown in Figure 2, with 7 mm shell thickness. Initially, the upper surface of the chill plate aligns with the baffle upper surface. Shell preheat and pouring temperatures are both 1520°C. After pouring, the assembly dwells for 3 minutes before withdrawal begins, with the directional furnace hot zone maintained at 1500°C. Due to top pouring, most molten metal does not flow through the chill plate, and temperature variation during pouring is minimal. Calculations of similar processes [24] show that temperature becomes uniform during the dwell period [28].

To validate calculations, experiments were conducted for different processes, with grain structures etched using 90% HCl + 10% H O (by volume).

4.1 Optimization of Starter Block Design Based on Numerical Simulation

To overcome the platform' s influence on grains, starter structures are necessary for grain entry into the blade body. Three conventional starter designs exist:

- **Starter 1**: Nucleation only at the lower platform rib, utilizing the component' s own downward extension.

- **Starter 2**: Adds a starter block at one edge of the lower platform based on Starter 1.
- **Starter 3**: Adds a starter block at the middle of the blade lower surface, near the pressure side chord segment.

Starters 1, 2, and 3 are shown in Figures 6(a), (b), and (c) [Figure 6: see original paper]. According to conventional design principles, these three starters facilitate post-casting block removal.

Numerical simulations were performed for all three starter designs at 7 mm/min withdrawal rate, calculating temperature fields and grain structures at each time step. Criterion values were obtained using the aforementioned algorithms to investigate starter effects on temperature field and grains. Experimental validation was conducted for all three designs.

Subsequently, analyzing the influence patterns and shortcomings of conventional designs, a new Starter 4 was proposed, as shown in Figure 6(d) [Figure 6: see original paper].

- **Starter 4**: Extends the entire blade lower surface downward to the chill plate based on Starter 1. This scheme requires specialized molds and post-processing using CNC milling or wire cutting.

Temperature field and grains for Starter 4 at 7 mm/min were simulated.

4.1.1 Mushy Zone Morphology Analysis for Different Starter Designs

Figure 7 [Figure 7: see original paper] shows K_d variation in the blade body for different starters. The horizontal axis represents distance from solidification front to chill surface, with the blade body corresponding to 40-100 mm height. K_d gradually increases as the solidification front moves away from the chill plate because the chill plate' s cooling efficiency per unit area is high, while radiative heat transfer between shell and cooling zone has much lower efficiency per unit area. Thus, the vertical temperature gradient in the mushy zone decreases with increasing distance from the chill plate. Near the upper platform, K_d decreases slightly because the sudden increase in cross-section above the mushy zone increases heat flux required for front advancement, breaking quasi-steady state and reducing cooling rate above the mushy zone, which suddenly increases the vertical temperature gradient within it.

Compared to Starter 1, Starters 2 and 3 have increased contact area between alloy and chill plate, improving cooling efficiency and yielding smaller K_d than Starter 1. Between Starters 2 and 3, Starter 2' s block connects to the blade body through a transverse, thin platform, while Starter 3' s block connects directly, giving Starter 3 higher cooling efficiency and smaller K_d. However, overall K_d differences among Starters 1-3 are not substantial. Starter 4 significantly increases chill plate contact area and connects directly to the blade body, resulting in markedly smaller K_d than the first three designs, which favors finer dendrites.

Figure 8 [Figure 8: see original paper] shows K_{con} variation in the blade body. All four processes exhibit an initial convexity followed by concavity. In casting regions near the shell (surface), heat flow is strongly affected by shell radiation, so solidification front height 主要取决于挡板位置，因而激冷面的传热对铸件心部凝固前沿高度的影响大于对铸件表层的影响。在叶身下半段，亦即凝固前沿离激冷面较近时，铸件心部的凝固前沿推移较快，容易超过表面凝固前沿的高度，造成整个凝固前沿上凸。反之，叶身上半段凝固前沿下凹。对于叶身底端，由于激冷面使得模壳的底端温度较低，铸件表层凝固前沿高度不完全取决于挡板位置，因而底端的上凸程度较小。对于叶身顶端，由于上缘板沿水平向周围突出，糊状区横向周边的上方的冷却速率突然减小，铸件表面凝固前沿推移减慢，因而顶端的下凹程度减小。综上，使得 Kcon 曲线呈 S 形。引晶 1、2、3 的 Kcon 依次略有减小。这是由于叶身与引晶块连接方式和激冷面接触面积的不同，对铸件心部的凝固前沿推移速率的影响强弱也就不同。引晶 1、2、3 的上凸阶段较短，下凹阶段的下凹程度很大，趋势上容易导致晶粒反发散生长。引晶 4 与激冷盘的接触面积大且直接连接叶身，因此引晶 4 的 Kcon 明显小于前 3 种引晶。

4.1.2 Grain Structure Analysis for Different Starter Designs

Figure 9 [Figure 9: see original paper] shows calculated and experimental grain structures for Starter 1 at 7 mm/min. Both simulation and experiment show that grains in the starter block undergo competitive growth to form roughly vertical columnar grains, then grow transversely through the lower platform, with only a small fraction entering the blade body to form excessively wide grains. On the pressure side, two grains exceed 30% of chord width (marked I), occupying nearly the entire 30 mm width from leading edge to pressure side and 45 mm to suction side. The suction side near trailing edge has relatively more grains due to proximity to the starter block, with slightly narrower grain width than the leading edge (marked II). The lower pressure side near leading edge shows obvious fragmented grains with transverse grain boundaries (marked III). Overall grains show slight anti-divergence tendency, creating large triangular 露头晶 on the suction side (marked IV).

Figure 10 [Figure 10: see original paper] shows results for Starter 2 at 7 mm/min, showing improvement over Starter 1. Both simulation and experiment show increased grain number entering the pressure side and reduced grain width, though grains near leading edge remain wider than near trailing edge. Both pressure and suction sides near trailing edge show a few narrow fragmented grains (marked I). Large triangular grains appear on suction side near leading edge (marked II) but connect to upper/lower platforms without being fragmented. Fragmented grains with transverse boundaries on lower pressure side near leading edge are greatly reduced (marked III). Overall grains show slight anti-divergence tendency.

Figure 11 [Figure 11: see original paper] shows results for Starter 3 at 7 mm/min, showing further improvement. Both simulation and experiment show increased grains entering the blade body because grains from the starter block can grow directly into the blade rather than through the platform, avoiding orientation deviation and grain coarsening at the platform. Grain width differences between leading and trailing edges on both pressure and suction sides are minimal. Large triangular grains disappear from suction side, while 1-2 forked narrow grains appear in the middle (marked I) with slightly wider grains on both sides. Multiple branched dendritic grains appear on lower pressure side near both edges (marked II). Overall grains show anti-divergence tendency. Branched grains interfere with surface intercept grain number statistics because one grain corresponds to multiple segments, not reflecting true growth conditions. Therefore, production should minimize branched grains.

Calculated typical grain shapes and positions for the three conventional starters match experiments, validating the model. Figure 12 [Figure 12: see original paper] shows simulated grain structures for Starter 4 at 7 mm/min. Grain numbers on both pressure and suction sides increase substantially, with greatly reduced grain width. Width differences between leading and trailing edges are minimal on both sides. A few narrow 露头晶 appear on lower blade sections without obvious transverse boundaries. Individual triangular 露头晶 appear on suction side near trailing edge. No branched grains appear. Reduced mushy zone concavity yields generally vertical, parallel grains with essentially no divergence tendency.

Figure 13 [Figure 13: see original paper] shows K_{NO} variation for different starters. Grain number decreases with solidification front advancement, with K_{NO} increasing sequentially from Starter 1 to 3. Starter 4 shows significantly higher grain numbers than the first three. The rapid K_{NO} decrease at the blade bottom indicates more fragmented grains, but as previously noted, these are narrow 露头晶 with few transverse boundaries.

Figure 14 [Figure 14: see original paper] shows K_{SNO} variation. K_{SNO} increases sequentially from Starter 1 to 3. For Starters 1 and 2, K_{SNO} variation matches K_{NO}, while for Starter 3, K_{SNO} first decreases then increases in the lower blade, fluctuating around a plateau before decreasing again in the upper blade. This mainly results from interference by branched grains in the lower blade —one branched grain corresponds to multiple segments in K_{SNO} calculation, artificially elevating the value. Starter 4 shows higher K_{SNO} than the first three starters without the K_{SNO} rebound caused by branched grains.

The three conventional starter simulations match experiments, validating the model and parameters. The results show that increasing casting-chill plate contact area reduces mushy zone width and concavity, increases grain number entering cross-sections, and reduces fragmented and excessively wide grains.

This study finds that among the four starter designs, Starters 3 and 4 are superior. Starter 3 still exhibits grain anti-divergence, which can be addressed through withdrawal rate optimization.

4.2 Withdrawal Rate Optimization Based on Numerical Simulation

As previously noted, for Starters 1-3, starter design has limited effect on K_d and K_{con} but significantly affects grain number and width. Their K_{con} values are generally large, indicating grain anti-divergence tendency, suggesting withdrawal rate reduction. Production experience shows that withdrawal rate differences must exceed 2 mm/min to significantly affect grains when other parameters are fixed. Therefore, this work uses rate intervals of at least 2 mm/min.

For Starter 3, temperature fields and microstructures were calculated at 3, 5, and 7 mm/min. To validate accuracy, an experiment was conducted for Starter 3 at 5 mm/min.

4.2.1 Mushy Zone Morphology Analysis at Different Withdrawal Rates

Figure 15 [Figure 15: see original paper] shows K_d variation for Starter 3 at three rates. In the lower blade, withdrawal rate has minimal effect on K_d, with curves nearly overlapping for the same starter. When the solidification front is near the chill plate, the chill plate’ s heat dissipation efficiency dominates the temperature gradient in the mushy zone, and shell temperature is strongly affected by the chill plate, weakening the baffle position’ s influence. Thus, baffle position changes during withdrawal have minimal impact on mushy zone temperature gradient. In the lower blade, K_d depends mainly on casting-chill plate contact area. In the upper blade, K_d increases slightly with withdrawal rate.

Figure 16 [Figure 16: see original paper] shows K_{con} variation for Starter 3 at three rates. K_{con} at the blade bottom shows similar parameter dependence as K_d, being minimally affected by withdrawal rate. Starting about 12 mm from the lower platform, K_{con} increases significantly with withdrawal rate, with the effect growing continuously. For the same starter, lower withdrawal rates reduce overall concavity, extend the convex stage, and shorten the concave stage.

4.2.2 Grain Structure Analysis at Different Withdrawal Rates

Figure 17 [Figure 17: see original paper] shows calculated and experimental grain structures for Starter 3 at 5 mm/min. Both simulation and experiment show that grain number and width entering the blade body are similar to those at 7 mm/min. Wide grains (marked I) and triangular grains (marked II) appear on the suction side near leading edge, but widths do not exceed 30% of chord length. Branched grains decrease in the middle suction side and lower pressure side near leading edge. Most importantly, overall anti-divergence tendency is reduced compared to 7 mm/min, particularly improving grain parallelism on the pressure side.

Figure 18 [Figure 18: see original paper] shows simulated grain structures for

Starter 3 at 3 mm/min. Simulation shows similar grain number and width as at 7 mm/min, with inverted triangular grains on suction side (marked I) and multiple branched dendritic grains on pressure side near leading edge. Overall grains show divergence tendency.

Figure 19 [Figure 19: see original paper] shows K_{NO} variation for Starter 3 at three rates. Grain number decreases with solidification front advancement, with withdrawal rate having minimal effect on K_{NO}.

Figure 20 [Figure 20: see original paper] shows K_{SNO} variation for Starter 3 at three rates. K_{SNO} increases with withdrawal rate. For Starter 3, K_{SNO} shows obvious rebound about 10 mm from the lower platform across all rates.

The K_{SNO} rebound indicates Starter 3 readily forms branched grains, with formation tendency weakly affected by withdrawal rate. Three-dimensional grain analysis reveals two grain sources in the blade: grains entering the lower platform from the rib starter block then growing transversely into the blade; and grains from the pressure-side starter block entering the blade directly through longitudinal competitive growth. When transverse and longitudinal grain groups converge in the blade, both roughly along preferred orientations compete for growth space. Combined with complex blade surface interference, this sometimes causes alternating spatial occupation between two grains, splitting one into multiple branches.

Starter 1 only has rib nucleation; Starter 2’ s added block grains must first enter the platform to compete transversely with rib grains before entering the blade; Starter 4’ s full-chord block grains dominate through longitudinal competitive growth, preventing platform transverse grains from entering the blade. Thus, Starters 1, 2, and 4 rarely experience transverse-longitudinal grain competition in the lower blade, making branched grains unlikely. Experiments only observed branched grains in Starter 3 blades.

The study found withdrawal rate significantly affects K_d and K_{con} but minimally affects cross-section grain number and width. Starters 1 and 2 have poor grain numbers and widths, so withdrawal rate optimization was not pursued for them.

Starter 3 simulations indicate its optimal withdrawal rate is 5 mm/min, with the only drawback being unavoidable branched grains.

At 7 mm/min, Starter 4 shows superior grain number and width compared to the first three starters, with distinctly different K_d and K_{con}. Therefore, Starter 4’ s withdrawal rate effects, particularly whether 5 mm/min is optimal, require investigation. Moreover, Starter 4 grains show no anti-divergence tendency, with $K_{\text{con}} < 0$ covering nearly 2/3 of blade height, so further rate increases would not improve grains. Thus, Starter 4 at 5 mm/min was simulated and compared with 7 mm/min.

Figure 15 shows Starter 4’ s rate effects are similar to Starter 3, but starter design influence exceeds withdrawal rate influence–Starter 4’ s K_d at maximum rate remains smaller than Starter 3’ s at minimum rate.

Figure 16 shows Starter 4's rate effects are similar to Starter 3. Due to increased chill contact area, Starter 4' s concavity is significantly lower than Starter 3' s. Starter 4' s K_{con} curve at 7 mm/min is similar to Starter 3' s at 5 mm/min, but the former' s absolute values are smaller in most stages—meaning its convexity is less convex and concavity less concave, with smaller variation amplitude and closer to planar. Since 5 mm/min is optimal for Starter 3, 7 mm/min may be optimal for Starter 4.

Figure 21 [Figure 21: see original paper] shows simulated grain structures for Starter 4 at 5 mm/min. Simulation shows fewer pressure side grains than at 7 mm/min, fewer 露头晶 in the lower blade, but one fragmented grain on leading edge. Two branched grains appear in middle suction side. Overall grains show slight divergence tendency, particularly severe inclination on suction side near trailing edge. Thus, Starter 4 at 5 mm/min produces inferior grain structure compared to 7 mm/min.

Figures 19 and 20 show Starter 4' s K_{NO} and K_{SNO} at both rates significantly exceed Starter 3' s, with more grains at 7 mm/min than 5 mm/min.

Starter 4 simulations indicate its optimal withdrawal rate is 7 mm/min, with all evaluation metrics superior or comparable to Starter 3 at its optimal 5 mm/min, while avoiding Starter 3' s branched grains.

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4.3 Comprehensive Comparison of Different Processes

Comprehensive analysis of all results shows Starters 1 and 2 at 7 mm/min have poor mushy zone width, grain width, and grain number, with obvious transverse boundaries from fragmented grains. The study demonstrates most starter designs can achieve good grain parallelism through withdrawal rate adjustment, but rates have limited effect on other metrics. Therefore, Starters 1 and 2 would not be optimized at other rates.

Studies of Starters 3 and 4 show their optimal rates are 5 and 7 mm/min respectively, both producing superior structures to Starters 1 and 2.

Thus, Starters 1 and 2 should be abandoned. If high-precision machining costs are acceptable, Starter 4 at 7 mm/min should be selected for optimal microstructure and highest casting efficiency; otherwise, Starter 3 at 5 mm/min should be chosen for relatively good microstructure.

* * *

5. Conclusions

1) A macro-micro multiscale mathematical model for directional solidification of wide-chord aero blades was established. Based on independently developed software, temperature fields and grain evolution were simulated for

different processes. Calculated results agree well with experiments, with most grain positions and shapes on casting surfaces matching one-to-one.

2) Mathematical evaluation criteria were established, enabling quantitative comparison of mushy zone width, solidification front curvature, and grain numbers across different processes. The influence 规律 of process parameters on mushy zone and grain structure were obtained.

3) When starter block-chill plate contact area changes little, starter design mainly affects grain number and width, while withdrawal rate mainly affects mushy zone width and solidification front curvature. Increasing withdrawal rate increases concavity tendency and extends the concave stage, slightly increasing mushy zone width, and vice versa.

4) When casting-chill plate heat conduction area increases, the mushy zone narrows and convexity tendency increases. This area' s effect is more pronounced when the solidification front is near the chill plate, weakening withdrawal rate effects.

5) Based on numerical simulation and criteria, grain structure evolution mechanisms under different starter designs and withdrawal rates were studied. Among the three conventional starters, pressure-side nucleation (Starter 3) was found optimal, with its best withdrawal rate determined.

6) Based on simulation predictions and microstructure formation theory, a new full-chord starter method was proposed and its withdrawal rate optimized, yielding castings with finer dendrites, more parallel grains, more columnar grains, and further improved productivity.

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