Recent Advances in Single Crystal Solidification Technology for Superalloy Blades: Postprint

Authors: Ma Dexin

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Abstract

This study analyzes the solidification process of complex regions in superalloy blades and proposes a novel concept concerning the three-dimensional growth mechanism and precision guidance of single-crystal microstructures. By presenting a series of innovations, such as thermal conductor seeding technology, parallel heating and cooling directional solidification apparatus, composite control seeding technology with localized cooling and heating applied to different blade regions, and thin-shell descent-ascent method for single-crystal blade manufacturing, this demonstrates new perspectives and initiatives for advancing single-crystal solidification technology in superalloy blades. The introduction of these novel concepts and the implementation of these innovations will facilitate a fundamental transformation from extensive to intensive manufacturing modes for high-precision products such as single-crystal superalloy blades.

Full Text

New Developments in Single Crystal Solidification Technology for Superalloy Turbine Blades

MA Dexin1,2)

1) Material R&D Center, Dongfang Turbine Co., LTD, Deyang 618000

2) State Key Laboratory of Long-Life High Temperature Materials, Deyang 618000

Abstract: Based on analysis of the solidification process in complex regions of superalloy turbine blades, this paper proposes a new concept of three-dimensional growth mechanisms and precise guidance for single crystal (SC) structures. Through a series of new inventions—including the heat conductor (HC) grain selection technique, parallel heating and cooling directional solidification equipment, composite control grain selection technology employing targeted cooling and heating for different blade regions, and thin-shell dipping and heaving methods for manufacturing SC blades—this work demonstrates novel approaches and measures in SC blade production. The introduction of these new concepts and implementations will facilitate a fundamental transformation in the manufacturing of high-precision superalloy SC blades from extensive to intensive processing.

Keywords: superalloy, directional solidification, single crystal, turbine blade

Aircraft engines and ground-based gas turbines are regarded as the "crown jewels" of modern industry and represent important indicators of national comprehensive strength. Among their components, high-temperature turbine blades are the most critical hot-section parts, playing a key role in converting combustion energy into mechanical work. Continuous improvements in gas turbine power output are achieved by increasing turbine inlet temperatures, which requires increasingly advanced blades with higher temperature capability. In addition to high-temperature conditions, hot-section blades operate in extreme environments characterized by high pressure, high loads, high vibration, and severe corrosion, demanding exceptional comprehensive performance. This necessitates the use of special alloy materials (superalloys), special manufacturing processes (precision casting plus directional solidification), and special matrix structures (single crystal structures) to maximally satisfy these requirements. Currently, SC blades are not only installed in all advanced aircraft engines but are also increasingly used in heavy-duty gas turbines.

Early superalloy blades produced by precision casting exhibited equiaxed grain structures, with the matrix cut by randomly oriented grain boundaries that served as weak points under high-temperature operating conditions, severely degrading blade performance. Directionally solidified columnar grain blades eliminated transverse grain boundaries perpendicular to the principal stress axis, substantially improving performance. SC blades further eliminated all grain boundaries, optimizing high-temperature performance.

To date, the conventional Bridgman process has been used worldwide for producing directionally solidified or single crystal superalloy blades. This technique involves lowering the poured mold shell from the furnace hot zone through a radiation baffle into the cold zone. While this solidification technology offers advantages such as simple equipment structure and stable, reliable processes, it suffers from significant drawbacks including extremely low radiative heat transfer efficiency and ineffective thermal isolation between hot and cold zones. For small castings such as aeroengine blades, these issues are not severe, but for heavy gas turbine blades, the large casting size and thick mold shells make heat dissipation particularly difficult, resulting in prolonged and complex solidification processes that are challenging to control effectively. The liquid metal cooling (LMC) method replaces radiative heat transfer with convective heat transfer using liquid cooling, which can increase overall cooling rates but fails to meet the varying solidification condition requirements at different casting locations. Consequently, LMC development has primarily focused on directional solidification rather than single crystal preparation for large blades. Although producing large SC blades using the Bridgman method is extremely difficult with low yield rates, it continues to be used because no better alternative has been found. This paper aims to explore new concepts and measures for SC solidification technology development, seeking breakthroughs in manufacturing technology for SC superalloy blades, particularly large ones.

1. Solidification Process of Single Crystal Blades

[Figure 1: see original paper] schematically illustrates the formation principles of various microstructures in superalloy turbine blades. In conventional precision casting, after pouring molten alloy into the mold shell, free cooling occurs with heat Q dissipating in all directions, causing nearly simultaneous solidification throughout the casting and resulting in polycrystalline equiaxed structures with random orientations (Fig. 1a). When the mold shell is mounted on a chill plate, raised into the furnace heating zone for preheating above the alloy melting point, and then filled with superheated molten alloy before being withdrawn downward through a heat baffle into the cooling zone, directional cooling and solidification from bottom to top are achieved, forming columnar polycrystalline structures (Fig. 1b). This process and corresponding equipment constitute the so-called Bridgman or high rate solidification (HRS) method. Adding a geometric grain selector structure at the initiation end of directional solidification, such as a helical selector (Fig. 1c), allows only one grain to emerge and extend to the casting top after passing through a narrow, curved channel, forming a single crystal structure. This still belongs to directional solidification but transforms the structure from polycrystalline to single grain. The temperature gradient G in the direction perpendicular to the solidification interface is generally considered the most important parameter for directional and single crystal solidification and must be maximized to avoid constitutional undercooling ahead of the solidification interface, ensuring smooth upward growth of columnar or single crystals at a certain rate.

The key to SC blade manufacturing is avoiding stray grain defects and ensuring complete SC structure integrity. In the blade airfoil section (lower part of Fig. 2a), the simple shape allows the solidification process to be essentially one-dimensional (vertical upward). However, at the platform region, the casting cross-section undergoes sudden large expansion, resulting in a complex three-dimensional growth pattern. Fig. 2a shows the geometry near the platform of a typical blade. Since the platform is inclined, the corners progress from low to high as C, B, and A (with relative heights of 0, 2, and 5 mm, respectively). Corner A is the highest but located near the trailing edge, closest to the airfoil, while other corners are far from it. During directional solidification as the blade descends, platform corners cool sequentially from low to high in the order C-B-A, with undercooled zones forming and expanding outward (Fig. 2b).

The transition region between platform and airfoil exhibits extremely poor heat dissipation conditions, causing the melt to remain superheated for an extended period and forming a nearly closed hot barrier zone (except at point A) that blocks direct lateral SC extension from the airfoil into the adjacent platform. This allows the molten metal at platform corners to continuously cool. If the undercooling in each zone does not exceed the alloy' s nucleation undercooling capability (critical nucleation undercooling), the liquid state is maintained until the highest point A at the hot barrier opening cools below the melting point. Secondary arms of longitudinal dendrites from the airfoil trailing edge then grow laterally into point A, followed by rapid propagation along the platform edge toward point B and then C in a transverse dendritic mode (Fig. 1c). The solidification sequence becomes A-B-C, opposite to the cooling sequence. Vertically, solidification proceeds from the highest point A to the lowest point C, contrary to the overall bottom-to-top solidification direction of the blade. In summary, transverse dendrites in the platform first grow along the coldest outer edges, then expand from the periphery toward the central airfoil region, finally merging with longitudinal dendrites growing from the airfoil. The transition zone between platform and airfoil becomes the hot barrier region due to its poorest heat dissipation, becoming the last area to solidify in the platform plane. During this complex three-dimensional dendritic growth process, the liquid ahead of the solidification interface frequently becomes undercooled with negative temperature gradients, easily generating defects such as stray grains.

The above description of the solidification process in the platform region has been fully confirmed through numerous experiments. For example, Fig. 3 shows the dendritic structure in a transverse section of the platform of an SC hollow blade made from superalloy CMSX-6. The dendritic structure on the section can be divided into three zones: the central longitudinal dendrite zone from the airfoil, the surrounding transverse dendrite zone in the platform, and a transition dendrite zone between them (coinciding with the hot barrier region). Longitudinal dendrites in the airfoil grow vertically, with primary dendrite arms (trunks) oriented in the [001] crystal direction. The approximately horizontal airfoil cross-section shows multiple cross-shaped intersections, revealing the two-dimensional transverse growth of secondary arms of each columnar dendrite, with axes in the [100] and [010] directions. As with most single crystal directional solidification processes, this experiment employed a helical grain selector, which only ensures the [001] orientation (primary orientation) is essentially vertical. However, the transverse crystal orientations ([100] and [010]) are random and uncontrollable.

Careful observation and analysis of Fig. 3 confirm that dendrite growth from the airfoil enters corner A of the platform at the trailing edge because the hot barrier there is minimal. Subsequent platform solidification can be roughly divided into three stages: First, rapid advancement from point A along the coldest outer edge through point B to point C (indicated by thick arrows on the bottom and left sides of Fig. 3). Due to the high speed, the dendritic structure is very fine, particularly at corners such as B and C, where large liquid undercooling makes dendrites too fine to resolve. Second, transverse expansion from the platform edge toward the center. During this stage, decreasing liquid undercooling leads to progressively coarser dendritic structures. The final stage occurs in the transition zone between platform and airfoil—the hot barrier region formed due to the poorest heat dissipation—where inward-growing transverse dendrites from the periphery merge with slowly expanding longitudinal dendrites from the airfoil.

The above describes the macroscopic solidification sequence in the platform, which is determined by thermal conditions. However, the microscopic dendrite growth direction is primarily determined by crystal orientation. For instance, during the rapid solidification along the platform edge in the first stage, the preferred transverse growth orientations [100] and [010] are randomly oriented and cannot align with the platform edge contour. This causes dendrite arms to grow at certain angles relative to the edge, requiring continuous adjustment. For example, in the solidification process along edge A to B shown in Fig. 3, dendrites mainly grow in the [100] direction because its angle with the edge is less than 45°. However, growth solely along [100] would deviate upward and away from the platform edge, so new dendrite arms immediately form in the opposite [010] direction, growing downward toward the edge. Thus, microscopically, higher-order dendrite arms continuously alternate generation and growth between [100] and [010] orientations, ensuring the macroscopic solidification process always advances along the platform edge.

It should be noted that the blade shown in Fig. 3 uses CMSX-6 alloy, which has an undercooling capability exceeding 40°C. When undercooling of several tens of degrees forms at platform corners without exceeding the alloy' s critical nucleation undercooling, the molten alloy can remain liquid. Single crystal growth extending from the airfoil trailing edge into the platform then stimulates epitaxial single crystal growth in the local melt according to the given orientation, avoiding stray grain formation. Some alloys have very small undercooling capability and are easily exceeded by actual melt undercooling, leading to nucleation and growth of new grains. Fig. 4 shows the macrostructure of a solid blade cross-section made from such an alloy, displaying stray grains in three corner regions of the platform. This occurs because the alloy' s nucleation undercooling capability in the mold shell is very small, measured at only about 9°C. During production, actual undercooling at platform corners often exceeds this critical value, causing nucleation and growth of new grains and forming stray grain defects as shown in Fig. 4.

2. Improvement Measures Under Existing Equipment Conditions

As described above, during SC directional solidification of blades, the transition region between airfoil and platform forms a hot barrier zone due to increased wall thickness and heat content, exacerbated by significantly thicker mold shells and deteriorated heat dissipation conditions. This hot barrier impedes lateral

SC extension from the airfoil into the platform, causing nucleation and growth of stray grains at platform corners. Two measures to avoid stray grain formation at the platform are introduced below: the grain continuator technique and the heat conductor technique.

2.1 Grain Continuator Technique

The grain continuator technique enables single crystals growing from the selector at the bottom to bypass the hot barrier zone and extend into platform corners via added continuators (Fig. 5). This method is relatively simple and practical, requiring only attachment of continuator wax strips during pattern assembly and subsequent removal of corresponding casting sections.

When dendrites grow in the mushy zone containing both liquid and solid phases, their strength is still low. Under shrinkage stress and various external forces, inevitable plastic deformation occurs, causing dendrite deviation or twisting and ultimately forming low-angle grain boundaries. Particularly when liquid convection in the mushy zone is severe, dendrites may even fracture, creating freckle defects. Low-angle grain boundaries easily form when dendrite growth branches or converges, or when solidification conditions change. When the temperature gradient decreases, the mushy zone becomes wider, convection more severe, dendrites more slender and weaker, and deviation more pronounced. Due to the complexity of microscopic growth conditions, this dendrite orientation deviation behavior has certain randomness—even under essentially identical macroscopic solidification conditions, the final deviation direction and degree will differ. When using the grain continuator technique, although dendrite bundles originate from the same single crystal, the continuators are completely independent of the airfoil with very different growth conditions. Compared to the relatively vertical orientation and stable solidification conditions in the airfoil, continuators have more inclined orientations, experience more branching and convergence, and encounter unstable solidification conditions, resulting in different crystal orientation deviations from airfoil dendrites. When dendrite bundles from continuators and the airfoil meet in the platform, low-angle grain boundary formation is inevitable (Fig. 5b). Due to the random nature of orientation differences, the visibility of these boundaries varies during metallographic observation.

Additionally, continuators must be removed by machining after pouring. Therefore, this technique cannot be applied to blade regions designated as non-machined surfaces.

2.2 Heat Conductor Technique

Unlike the grain continuator technique that guides single crystals around hot barrier zones, the heat conductor technique invented by the author eliminates hot barrier zones to reduce stray grain defects. As shown in Figs. 6a and 6b, graphite heat conductors are inserted into the transition region between platform and airfoil during ceramic shell mold preparation, with their outer ends exposed outside the shell. Due to graphite' s excellent thermal conductivity and radiation coefficient compared to ceramic, heat at the inner end of the conductor can be rapidly transferred out and radiated to the surroundings during solidification. This significantly reduces or essentially eliminates the hot barrier formed by excessively slow cooling, guiding rapid lateral SC extension from the airfoil into platform corners and preventing excessive undercooling and dwell time that would cause stray grain formation (Fig. 6c). Experimental results on a group of typical blades showed this technique increased SC yield from 38% to 100%. Although slightly more complex than the grain continuator method, this approach produces better SC quality without low-angle grain boundaries formed by dendrite convergence, requires no cutting, and can be applied regardless of whether the corresponding region is a machined surface.

It should be noted that severe non-uniform three-dimensional temperature field distribution exists in directional solidification furnace chambers. Therefore, optimizing the assembly arrangement of blades in the furnace space, combined with other measures, can align solidification sequence with cooling sequence and control SC growth along designed paths to achieve excellent results. For example, Fig. 7 shows a large SC hollow blade for heavy-duty gas turbines weighing 6 kg net. Even for guide vanes with particularly wide platforms where the cross-section differs dramatically from the thin-walled airfoil, strict control of solidification sequence can effectively prevent stray grain formation and successfully produce single crystal components.

3. Invention of New Processes and Equipment

The conventional Bridgman method for producing directionally solidified or SC blades is generally considered to have excessively slow cooling and low temperature gradients, resulting in poor casting quality and long production cycles. For years, researchers have devoted efforts to improving the traditional Bridgman process, with two most notable methods being LMC and gas cooling casting (GCC). These methods replace radiative heat transfer with convective heat transfer using liquid or gas, respectively. Although they increase overall casting cooling rates, they exacerbate non-uniform heat dissipation throughout the casting. For example, platform outer corners, having thinner shells and protruding profiles, already cool faster than the transition region between airfoil and platform, making them prone to stray grains. In stirred liquid or impinging gas, these most protruding platform corners experience the most intense scouring, worsening the excessive cooling problem. Moreover, LMC equipment is complex, expensive, and difficult to operate. Despite decades of development, it has not achieved industrial application. GCC causes furnace temperature drops when cooling gas enters the chamber, resulting in lower temperature gradients. Additionally, side-blown gas flow can cause lateral grain boundaries, degrading blade quality and increasing scrap rates. Consequently, the traditional Bridgman process remains in use worldwide for superalloy directional and SC blade production, with no new breakthroughs in new process applications. The following sections introduce new inventions and concepts by the author for improving SC blade forming processes and equipment.

3.1 Parallel Directional Solidification Furnace

Current universal SC blade manufacturing directional solidification furnaces employ cylindrical heaters that radiate inward to heat annularly arranged mold shells and their contained molten metal (Fig. 8). During blade production, when the shell descends below the heat baffle into the cold zone, heat is dissipated by radiating outward to annular coolers, causing metal solidification. This furnace structure creates severe asymmetry in heating and cooling on both sides of each blade. The outward-facing side of each blade shell (referred to as the "sunny side") directly faces the heater in the heating zone for effective radiative heating and directly faces the cooler in the cooling zone for effective radiative cooling. This creates higher temperature gradients and cooling rates, forming a narrower mushy zone favorable for SC growth. Conversely, the inward-facing side (the "shady side") cannot directly receive radiative heating from the heater, forming a lower-temperature cylindrical shadow zone at the center of the annular shell arrangement. Particularly when the shell descends near the furnace bottom, the shadow zone lacks a heat baffle, accelerating heat loss without effective replenishment from the heater, making the already low shadow zone temperature even lower than the sunny side. After descending into the cooling zone, the shadow zone cannot cool effectively due to facing away from the cooler, becoming a relatively enclosed slow-cooling zone with significantly lower cooling rates and temperature gradients. This results in a concave solidification interface and wide mushy zone with very poor solidification conditions, causing casting defects such as stray grains and freckles to occur primarily on the shadow side of castings—a phenomenon called the shadow effect. It should be noted that as blade dimensions including width increase, the difference in solidification conditions between inner and outer sides worsens due to increased distance, making the shadow effect more severe.

Based on this analysis, the author believes that when using the conventional Bridgman process for superalloy directional or SC blades, the most important issue is not overall cooling improvement but rather the severe non-uniformity in thermal conditions among casting regions, particularly between inner and outer sides—the shadow zone' s inability to effectively receive heat or dissipate it. As described above, the blade' s outer side (sunny side) has excellent heating and cooling conditions in both hot and cold zones, rarely generating casting defects. Eliminating the shadow effect and its associated defects simply requires giving both blade sides sunny-side conditions.

To address this problem, the author invented a new furnace structure (Fig. 9). Compared with current universal directional solidification furnaces (Fig. 8), its heater and cooler are no longer cylindrical but arranged as parallel plates. Fig. 9 shows a double-row configuration of this new furnace, which can be made as a simple single row or increased to three or more rows as needed to improve production efficiency. The heat baffle shape changes from annular to rectangular. Blades in each mold string are no longer arranged annularly but in single rows parallel to the plate-shaped heater and cooler. This makes both sides of each blade sunny sides, receiving symmetric and identical heating and cooling. With the shadow zone eliminated, the shadow effect and its harmful consequences are removed. Preliminary experiments using a single-row prototype furnace reduced stray grain and freckle defects by 80% and 100%, respectively.

In addition to significantly improving furnace thermal uniformity and blade casting quality, the new furnace features a more compact and rational structure. Generally, to increase productivity, furnaces are made as large as possible to cast more blades per batch. In conventional directional solidification furnaces, blades are arranged annularly along the inner side of the heating cylinder. Maintaining blade spacing, the furnace chamber cross-sectional area is proportional to the square of the heating cylinder circumference and thus proportional to the square of blade count. For example, doubling the number of blades per batch requires tripling the furnace chamber cross-sectional area. Moreover, larger heating cylinder diameters create larger shadow zones at the center of annular shells, wasting furnace space and increasing through-area between heating and cooling zones, severely damaging inter-zone insulation and deteriorating directional solidification conditions. This explains why using large furnaces to cast numerous shells seriously degrades casting quality and dramatically increases scrap rates. In contrast, in the new parallel arrangement furnace shown in Fig. 9, the furnace chamber cross-sectional area is proportional to heating plate length—that is, proportional to blade count rather than its square—greatly saving furnace volume. Furthermore, increasing blade count does not worsen insulation between hot and cold zones because the shadow zone at the center of annular shells no longer exists and cannot increase with blade count. This ensures that expanding furnace volume to increase casting quantity does not reduce casting quality, representing another major advantage of the new directional solidification furnace over conventional Bridgman furnaces.

3.2 Composite Control Grain Selection Technique (Targeted Cooling + Targeted Heating)

As previously described, single crystal solidification of turbine blades with complex geometries, particularly large heavy gas turbine blades, is a complex three-dimensional growth process requiring rational design and control of SC growth paths throughout the blade. Different casting regions require different cooling conditions. Some regions, such as the airfoil-platform transition zone, need early and rapid cooling, while others, such as platform corners, need delayed and slower cooling to create an ideal solidification sequence enabling SC growth to extend smoothly to every blade region. However, reality is often the opposite, necessitating artificial intervention.

Taking Fig. 10 as an example, a hot barrier forms in the airfoil-platform transition zone, hindering transverse SC extension into the platform. Therefore, forced cooling is required at this location, such as targeted spraying or contact conduction cooling using Ga-In molten metal. Ga-In alloy has a very low melting point and is liquid at room temperature, making it an excellent cooling medium. However, due to its relatively high cost, it cannot be used in the aforementioned LMC process, which requires hundreds of kilograms or even tons of cooling metal liquid to form a bath, necessitating cheaper Sn or Al melted and maintained in a molten state. This requires special heating and insulation devices, complicating the process. In contrast, the amount of metal liquid needed for targeted spraying or contact cooling in this process is very small, allowing convenient use of Ga-In alloy without significant cost increase.

During directional solidification, casting heat dissipation is controlled by two stages: heat transfer through the poorly conductive mold shell to its outer surface, and heat dissipation from the outer surface to the surroundings. In the airfoil-platform transition zone where the mold shell is thickest with large thermal resistance, internal heat transfer becomes the controlling factor. Forced cooling of only the outer mold surface would be ineffective. As previously described, the heat conductor technique enables rapid heat transfer from the casting through highly conductive graphite, significantly enhancing local cooling. Combined with forced cooling measures such as targeted spraying or contact cooling to dissipate heat faster from the outer surface, optimal targeted cooling effects can be achieved.

Platform outer corner regions have thin mold shells and good radiation conditions, causing excessively fast heat dissipation that leads to melt undercooling and stray grain formation. To prevent premature and rapid cooling of platform corners, the author experimented with locally thickening mold shells and wrapping ceramic fiber, but these insulation measures proved ineffective due to the small heat content of thin platform corners. Attempts were also made to insert graphite into the upper mold surface to import heat for insulation, but this could not prevent rapid downward heat dissipation and associated undercooling at platform corners. Laser heating offers unique advantages: it is an efficient and controllable heat source that heats from below, precisely targeting the platform lower edge where heat dissipation is fastest and undercooling greatest. This maintains the region in a superheated state, preventing premature solidification and stray grain formation. Moreover, dynamic adjustment of heating power and area can control three-dimensional directional movement of the liquid-solid interface while maintaining positive local temperature gradients at the liquid-solid front, achieving alignment between cooling direction and solidification direction to precisely guide SC growth to every casting endpoint according to design.

Even in the airfoil region with relatively uniform cross-section, where overall solidification is primarily vertical, solidification conditions vary significantly at different points. At trailing and leading edges, particularly the former, casting and mold wall thicknesses are small with rapid heat dissipation, while at the mid-airfoil, mold and casting walls are several to ten times thicker, cooling much more slowly and causing significant delay in interface advancement. This results in an upward-curving solidification interface at both airfoil edges and downward curvature at the thick central region, creating lateral temperature gradients and solidification processes. Implementing targeted forced cooling at the thick central airfoil region and targeted heating at both edges, especially the leading edge, helps establish a flat solidification interface and achieve unidirectional vertical solidification in the airfoil region. Therefore, the composite control technique of targeted cooling and heating can be applied at any stage of blade solidification to establish optimal conditions for SC growth in corresponding regions.

The above describes the principles and implementation concepts of composite control technology. The next step involves laboratory and industrial experiments, with the ultimate goal of achieving a fundamental transformation in SC blade solidification process control from macroscopic to microscopic, one-dimensional to three-dimensional, and extensive to intensive precision.

3.3 Thin Shell Dipping and Heaving Method Combined with Composite Grain Selection Technique

While the aforementioned composite control grain selection technique combining targeted cooling and heating creates favorable conditions for controlling three-dimensional solidification of large SC blades, its effectiveness is limited by inherent drawbacks of existing Bridgman directional solidification processes and equipment. First, ceramic shells for large blades are very thick with large thermal resistance, particularly at the airfoil-platform transition, significantly reducing the effectiveness of targeted forced cooling. Although combining with the heat conductor method is possible, this increases process complexity and is not applicable to all blade regions. Second, blade outer contour dimensions vary greatly along the height direction, while the heat baffle has a fixed inner profile, causing large variations in gap between them during directional solidification and sometimes creating nearly open states that produce poor and variable solidification conditions, greatly increasing the difficulty of precisely controlling blade solidification.

To solve the problems of excessively low heat transfer efficiency and ineffective thermal isolation between heating and cooling zones in the Bridgman directional solidification process, the author invented the thin-shell dipping and heaving (D&H) process, with principles shown in Fig. 11. The shell mold is first lowered through a flexible insulation layer into an alloy melt bath in a crucible, with molten metal filling the shell from below. The inlet is sealed with a plug of the same alloy to prevent insulation material entry. The filled mold is then pulled upward to achieve top-down SC directional solidification. Cooling of the emerged mold by inert gas blowing enhances heat dissipation, further increasing casting cooling rate and temperature gradient at the solidification front. Single crystal structures can be produced using either the seed crystal method shown in Fig. 11 or geometric selectors such as necked or helical designs, as shown in Figs. 12 and 13.

Compared with conventional Bridgman processes, this new technology offers many advantages, the most important being: (1) Since internal and external liquid pressures cancel each other, the shell has no risk of rupture and can be made very thin. Actual shell thickness is only about 1 mm, far less than the approximately 6 mm average thickness required by conventional processes. This not only reduces shell manufacturing costs but, more importantly, significantly decreases shell thermal resistance, greatly improving casting heat dissipation capability and solidification process controllability. (2) Above the melt bath is a floating flexible insulation layer that provides seamless, tight coverage during mold movement, reducing heat loss and dramatically increasing temperature gradient at the solidification interface. The insulation material can be hollow ceramic microspheres, but liquid slag is preferable due to better fluidity and its purifying effect on the alloy melt. (3) The mold receives conductive heating from the melt in the hot zone and convective cooling from gas in the cold zone, providing significantly higher heat transfer efficiency than radiative heat transfer in conventional Bridgman processes. (4) In conventional Bridgman directional solidification, dendrites grow upward, and solute segregation creates a density inversion (heavier above, lighter below) in the mushy zone liquid, triggering strong convection and freckle defect formation. In the new process, dendrites grow downward, creating a stable density distribution (lighter above, heavier below) that prevents convection, eliminating the root cause of freckle defects and solving a major quality control problem for large superalloy SC blades.

Fig. 12a shows an experiment manufacturing an Al alloy SC blade in air atmosphere to verify process feasibility. Fig. 12b shows a blade during shell removal, with the residual shell cross-section revealing very thin walls resembling eggshells. Fig. 12c displays the blade’ s macroscopic and microscopic SC structure, showing very fine dendritic structures. Measured temperature gradients during solidification were about an order of magnitude higher than in conventional Bridgman processes, demonstrating significant improvement in solidification conditions.

Manufacturing superalloy SC blades using the D&H method requires vacuum conditions. Fig. 14a shows a schematic of the corresponding setup in a modified vacuum furnace, while Figs. 14b and 14c show surface and cross-sectional views of a small SC blade made from alloy CMSX-4. Due to excellent solidification conditions, very fine dendritic structures were also obtained. These experimental results prove the new process feasibility, and future work will gradually expand to medium and large blade production experiments.

The thin-shell D&H method solves several fundamental problems in conventional directional solidification processes: excessively low radiative heat transfer efficiency, overly thick shells with large thermal resistance, and ineffective thermal isolation between hot and cold zones. When manufacturing SC blades, the mold emerges from superheated alloy melt through a slag cover layer into the cooling zone, experiencing ideal heating, insulation, and cooling processes that provide excellent and stable solidification conditions, laying a good foundation for further three-dimensional precise guidance of SC growth in large blades. Due to the new process characteristics, the operating space is more open, making it easier to apply targeted cooling and heating for composite grain selection (Fig. 13). Particularly at the platform, targeted cooling of hot barrier regions can be conveniently performed using liquid or gaseous Ar or He through dripping or spraying. Used Ar or He can remain in the cold zone as protective gas, unlike in GCC where it enters the furnace chamber causing hot zone temperature drops or other adverse effects. Platform corners can also be easily heated from above with lasers to prevent excessively fast cooling and premature solidification that cause stray grains. With thin and uniform shell walls, both forced cooling and heating produce rapid response and obvious effects, enabling more effective and precise control of the solidification process. In summary, this thin-shell D&H method combined with composite control technology essentially eliminates all disadvantages of conventional Bridgman directional solidification processes and equipment, potentially becoming the optimal process for manufacturing large SC blades. Further research and development are needed to achieve industrial application as soon as possible.

When discussing directional solidification principles earlier, the Bridgman process feature of heat baffle application was mentioned. The gap between the baffle and mold shell should be minimized to effectively separate heating and cooling zones, creating the largest possible temperature drop between zones while forcing heat from the hot zone to transfer vertically downward only through the casting itself, creating high temperature gradients and a flat solidification interface. However, even for simple cylindrical castings, a perfectly flat solidification interface is difficult to achieve. If furnace temperature is high, alloy melting point is low, mold shell is thick, and casting withdrawal rate is fast, the solidification interface positions below the baffle, becoming concave due to side cooling. Conversely, the interface moves above the baffle, becoming convex due to side heating. For complex real castings such as turbine blades, heat transfer and solidification are not unidirectional. In the airfoil region with relatively uniform cross-section, solidification is primarily vertical with lateral components, forming longitudinal dendritic structures. In the platform region, solidification is primarily lateral, forming transverse dendritic structures, as shown in Figs. 2 and 3.

During Bridgman solidification, the airfoil-platform transition zone generally solidifies below the baffle due to poor heat dissipation conditions. When applying composite control grain selection technology (Fig. 10) with forced cooling measures such as targeted spraying, no interference from the baffle occurs, similar to typical LMC and GCC processes. Laser heating of platform corner lower edges is performed from below or obliquely below, and even if the platform has not yet descended below the baffle, the fixed baffle inner profile is larger than the maximum mold shell outer profile, so it does not block the laser beam.

When applying the thin-shell D&H process (Fig. 13), since the mold contacts the flexible insulation layer without gaps, effective heat dissipation and solidification only occur after the casting emerges from the insulation layer. Therefore, forced cooling and heating are generally performed above the insulation layer without interference. Even if the platform has not yet emerged, indirect heating or cooling of corresponding platform regions below can be achieved by targeted heating or cooling of the insulation layer. In summary, whether under conventional Bridgman or new thin-shell D&H conditions, applying composite methods of targeted spraying and targeted laser heating for precise SC growth control is not hindered by fixed heat baffles or flexible insulation layers.

Conclusions

1) Analysis of solidification processes in complex SC blade regions reveals the cause of opposite solidification and cooling sequences in platform areas, breaking through traditional one-dimensional directional solidification concepts. A new concept of three-dimensional growth mechanisms and precise guidance for SC structures is proposed, with a series of corresponding new technologies invented and their effectiveness and feasibility explored.
2) The heat conductor grain selection method eliminates hot barriers in the airfoil-platform transition zone, guiding rapid transverse SC extension into the platform and preventing stray grains at outer corners. Rectangular parallel heaters and coolers replace conventional cylindrical directional solidification furnaces, enabling symmetric heating and cooling on both sides of linearly arranged molds and eliminating shadow effects and associated defects.
3) Composite control through targeted cooling and heating of different regions in large blades precisely guides SC growth along designed directions and paths. Applying composite control technology in the thin-shell D&H method enables more precise control of SC growth in blades. The introduction of these new concepts and inventions will facilitate a fundamental transformation in manufacturing high-precision superalloy SC blades from extensive to intensive processing.

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