Directional Solidification of Single-Crystal Blades in Industrial Conditions Using the Developed Gas Cooling Casting Method

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The effect of gas cooling on microstructure refinement during the production of single crystal blades by the Developed Gas Cooling Casting (DGCC) method was investigated. Primary dendrite arm spacing (PDAS) reached the highest values in the airfoil and lowest in the blade platform. However, with the Bridgman method, the tendency of PDAS change along the blade was the opposite. When using the DGCC method, the PDAS decreased by about 100 μm in the platform compared to the conventional radiation cooling.

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AN increase in the axial temperature gradient at the solidification front during directional solidification of nickel superalloys, favorably refines the dendritic microstructure by reducing primary dendrite arm spacing (PDAS), thus improving the operating temperature and mechanical properties of the single crystal blades.[1,2] Heat transfer by radiation between the components and the furnace in the Bridgman method strongly limits the effectiveness of mold cooling and thus unfavorably reduces both temperature gradient and dendritic microstructure refinement.[3,4] Therefore, alternative methods of directional solidification such as liquid-metal cooling (LMC),[5,6] gas cooling casting (GCC),[7] downward directional solidification (DWDS)[8,9] and fluidized carbon bed cooling (FCBC)[10] have been developed to improve the quality of the single crystal and the process yield. The efficiency of heat extraction from the mold surface improves mainly by convective cooling using a cooling medium apart from radiation cooling. In the LMC and FCBC method, the mold is immersed into a cooling bath and fluidized bed, respectively.[5,9] While in the GCC and DWDS method, gas is injected onto the mold surface to cool the casting during its movement from the furnace heating zone.[7,8] The continuing development of blade production methods using inert cooling gas shows the high potential of these methods due to the relatively low cost of the process compared to the LMC method and the improved microstructure compared to the Bridgman method.[7,10] Konter *et al*.[7] show the use of inert cooling gas to manufacture large IGT blades, while Wang *et al*.[11] to produce small aero-turbine blade. The improvement of the temperature gradient and the refinement of the dendritic microstructure as well as the effectiveness of the developed methods have been proven.[7,8,11] However, despite the effectiveness of these methods, they probably have very limited application to the manufacture of blades on an industrial scale where several castings are located simultaneously in a complex mold.

The use of a complex mold with many components significantly complicates matching the thermal baffle to the outer contour of the mold.[12] This causes that gas can flow upward between components unfavorably cooling the mold located in the furnace heating chamber. In turn, the relocation of the nozzles downward toward the chill ring can result in a reduction in the thermal effect of the gas stream on the solidification of the mushy zone of the casting. An analysis of published papers shows the high potential of a directional solidification method using a cooling gas.[7–9,11] However, there is no information regarding the application of this method to the production of blades using a complex ceramic mold with multiple components. Therefore, an attempt was made to develop a technology for directional solidification of nickel based superalloy turbine blades on an industrial scale using inert gas to cooling

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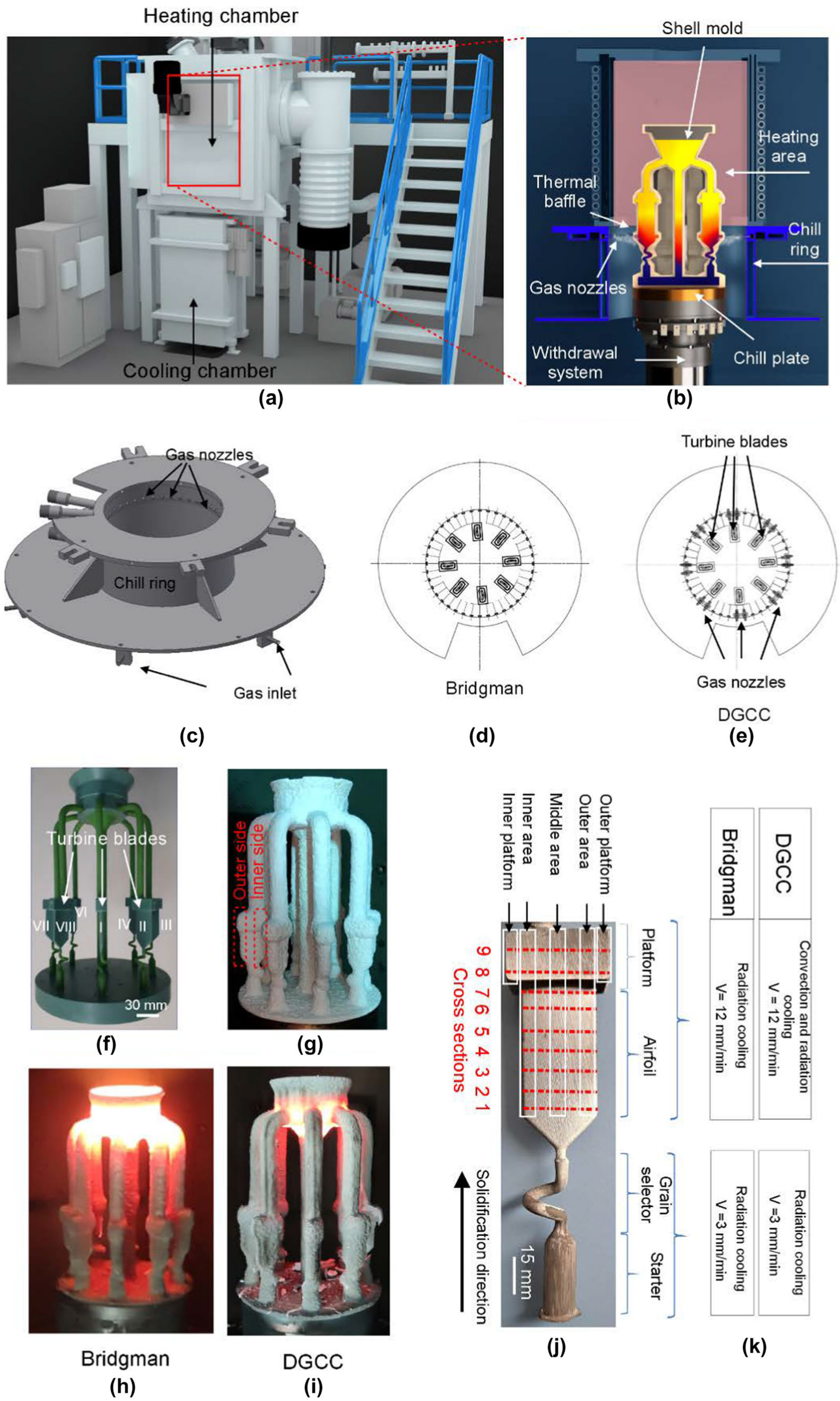
the mold, called Developed Gas Cooling Casting (DGCC) method.[13] In this investigation, cooling of the mold was carried out by inert gas injected at supersonic velocity from multiple nozzles located below the thermal baffle. The used of variable angle nozzles allowed to correctly direct the stream of inert gas on the surface of the complex shaped mold with multiple castings. It was found that the use of gas cooling resulted in a favorable increase in the cooling rate and reduction of PDAS in the platform of the single crystal blade compared to the conventional radiation cooling in the Bridgman method. The achieved preliminary results showed the possibility of applying the Developed Gas Cooling Casting method on an industrial scale to produce high quality single crystal superalloy blade for an aero-engine.

Test castings of dummy blades from CMSX-4 nickel superalloy were produced by directional solidification using the standard Bridgman technique and the DGCC method (Figure 1). For this purpose, two wax assemblies that were the basis for making ceramic molds were made [Figures 1(f) and (g)]. The wax assemblies consisted of a chill plate model with a diameter of 250 mm, a gating system, a pouring cup, 8 dummy blades and selectors as well as starters. The blades were positioned in the assembly as shown in Figure 1(f). The assembly was dipped into a ceramic slurry and then sprinkled with alumina particles in a fluidized bed making the first coat of the mold. A second coat was made using mullite. These stages were repeated obtaining 9 coats with an average mold wall thickness of about 7 mm [Figure 1(g)]. Wax was melted from the inside of the mold, which was then preheated at a temperature of 800 °C. The mold thus prepared was mounted on a chill plate inside the cooling chamber of the furnace [Figure 1(b)]. The first process of directional solidification of single-crystal blades was carried out using the DGCC method in a JetCaster® vacuum furnace, with argon gas applied to enhance mold cooling. This furnace consists of a heating and cooling chamber, a mold withdrawal system at a specific velocity, and is equipped with a system of flowing inert gas into the chamber [Figures 1(a) through (c)]. The mold was mounted on a chill plate and moved to the heating chamber of the furnace, where was preheated to 1520 °C using a two-zone induction heating heater with a power of 125 kW. The heated mold was then filled with CMSX-4 molten nickel superalloy at the same temperature and withdrawn at changing velocities from the heating to the cooling area of the furnace. The starter and selector region was withdrawn at a velocity of 3 mm/min while the blade region at 12 mm/min [Figure 1(k)]. The withdrawal velocity was increased gradually in the continuator area (the selector to blade transition area). In this process, a positive temperature gradient at the solidification front of the casting was achieved by the thermal impact of both chill rings and flowing inert gas on the withdrawn ceramic mold. The gas stream was directed at supersonic velocity directly at the mold surface using multiple nozzles [Figures 1(c) and (e)]. These nozzles were located on the perimeter of a water-cooled chill ring with an inner diameter of 300 mm. For this chill ring design, it is possible to install 40 nozzles, with different angles of their inclination with respect to the horizontal plane. However, due to the number of blades and the shape of the mold, two nozzles on each blade were used. Thus, 16 nozzles were mounted, the rest of the free holes in the cooling ring were closed [Figure 1(e)]. The position of these nozzles relative to the location of the castings is shown in Figure 1(e). The volume flow rate of the cooling gas flowing out of the nozzles was 400 Ndm^3/min. In addition, the heating chamber from the cooling chamber was thermally separated by a typical ring shaped graphite thermal baffle with a thickness of 3 mm and an inner diameter of 250 mm, which allowed withdrawal of the mold without collision. The thermal baffle was located directly on the chill ring above the nozzles. The next process of directional solidification of the blades was carried out using the Bridgman method in the same furnace as in the DGCC method, but without inert gas in the chamber [Figure 1(d)]. The working vacuum in the furnace chamber during solidification equaled 1×10^{-3} mbar. The same technological parameters of the process and the same mold design and material as for the DGCC process were used. Thus, the efficiency of the DGCC method compared to the typical Bridgman method was established. The blade castings were knocked out from the mold and then sandblasted [Figures 1(h) through (j)]. The surface of the blades was macro-etched by a chemical reagent to predetermine the quality of the single-crystal macrostructure. Five blades from the mold for each process were then selected to examine the dendritic microstructure. Microstructure evaluation for these blades was carried out in the center region of the blade and platform at cross sections 4 and 9, respectively. In order to better characterize the solidification process, the blade and platform were divided into an inner, middle and outer area as shown in Figure 1(j). In addition, the part of the platform facing the central rod was called the inner platform, while the part that is close to the heaters was named the outer platform.

An evaluation of the dendritic microstructure of the fabricated single crystal blades was carried out. An exemplary dendritic microstructure of blades IV and VI produced by the Bridgman and DGCC methods is shown in Figure 2. It was found that a proper and typical dendritic microstructure was obtained in the airfoil and platform of the blades manufactured for both methods. On the cross-section, the arms of the primary, secondary and tertiary orders of dendrites are shown. Well-developed tertiary arms are mainly located in the inner zone of blades produced by various methods [Figures 2(b), (e), (i), (l)]. However, they were rarely observed in the outer region of the platform for the DGCC method [Figure 2(k)]. It was found, different refinement of the dendritic microstructure depending on the thickness of the casting, the directional solidification method, and the location of the analyzed area of the blade. Noticeably, the largest refinement of the dendritic microstructure occurs in the outer part of the blade platform produced by the DGCC method.


Heating chamber
Cooling chamber
(a)
Shell mold
Heating area
Thermal baffle
Chill ring
Gas nozzles
Withdrawal system
Chill plate
(b)
Gas nozzles
Chill ring
Gas inlet
(c)
Bridgman
(d)
Turbine blades
Gas nozzles
DGCC
(e)
Turbine blades
VII VIII VI I IV II III
30 mm
(f)
Outer side
Inner side
(g)
Bridgman
(h)
DGCC
(i)
Outer platform
Outer area
Middle area
Inner area
Inner platform
Platform
Airfoil
9 8 7 6 5 4 3 2 1
Cross sections
Grain selector
Starter
15 mm
Solidification direction
(j)
DGCC
Bridgman
Convection and radiation cooling
V = 12 mm/min
Radiation cooling
V= 12 mm/min
Radiation cooling
V =3 mm/min
Radiation cooling
V =3 mm/min
(k)

◀Fig. 1—Schematic illustration of the JetCaster® vacuum furnace (*a*) and the placement of the gas nozzles in the chill ring (*b*). Design of the chill ring (*c*). Chill ring without nozzles used in the Bridgman method (*d*). The location of the nozzles on the perimeter of the chill ring relative to the position of the blades in the furnace for the DGCC method (*e*). Wax assembly with designated blades (I to VIII) and ceramic mold placed on the chill plate (*f*) and (*g*). Ceramic mold after Bridgman and DGCC process (*h*) and (*i*). Schematic view a cut of the blade and designations of the cross sections (*j*). Cooling conditions and withdrawal velocity of the mold for different areas of the blade (*k*).

In order to better evaluate the directional solidification process, the characterization of the dendritic microstructure was carried out by measuring the primary dendrite arm spacing (PDAS) in different areas of cross sections 4 and 9 of some blades [Figures 3(a) and (b)]. For this purpose, the well-known relation PDAS $= \sqrt{(A/N)}$ was used, where A is the analyzed area, N is the number of dendrite cores on a given area.[2] It was found that PDAS reached different values in the casting depending on the measurement location and the method of directional solidification.

In the first step, the value of PDAS in various blades located on the circumference of the mold was evaluated. This was done to determine the uniformity of solidification conditions in different parts of the mold. Five castings from each mold were taken for this research. Figures 3(a) and (b) show the results of PDAS values in the airfoils and platforms of various blades. A very small change was found in PDAS values between subsequent airfoils located at the circumference of the mold. This was especially true in the inner and middle area of these blades for the DGCC process. For example, in the middle area of the cross section 4 of the airfoil, the largest PDAS value of 366 μm was obtained for blade I, while the smallest value, equal to 355 μm, was found in blade IV. Thus, for these blades produced by the DGCC method, the largest PDAS difference between the middle areas of the airfoils reached a value of only 11 μm. For the Bridgman process, also in the middle area of the blade, the largest

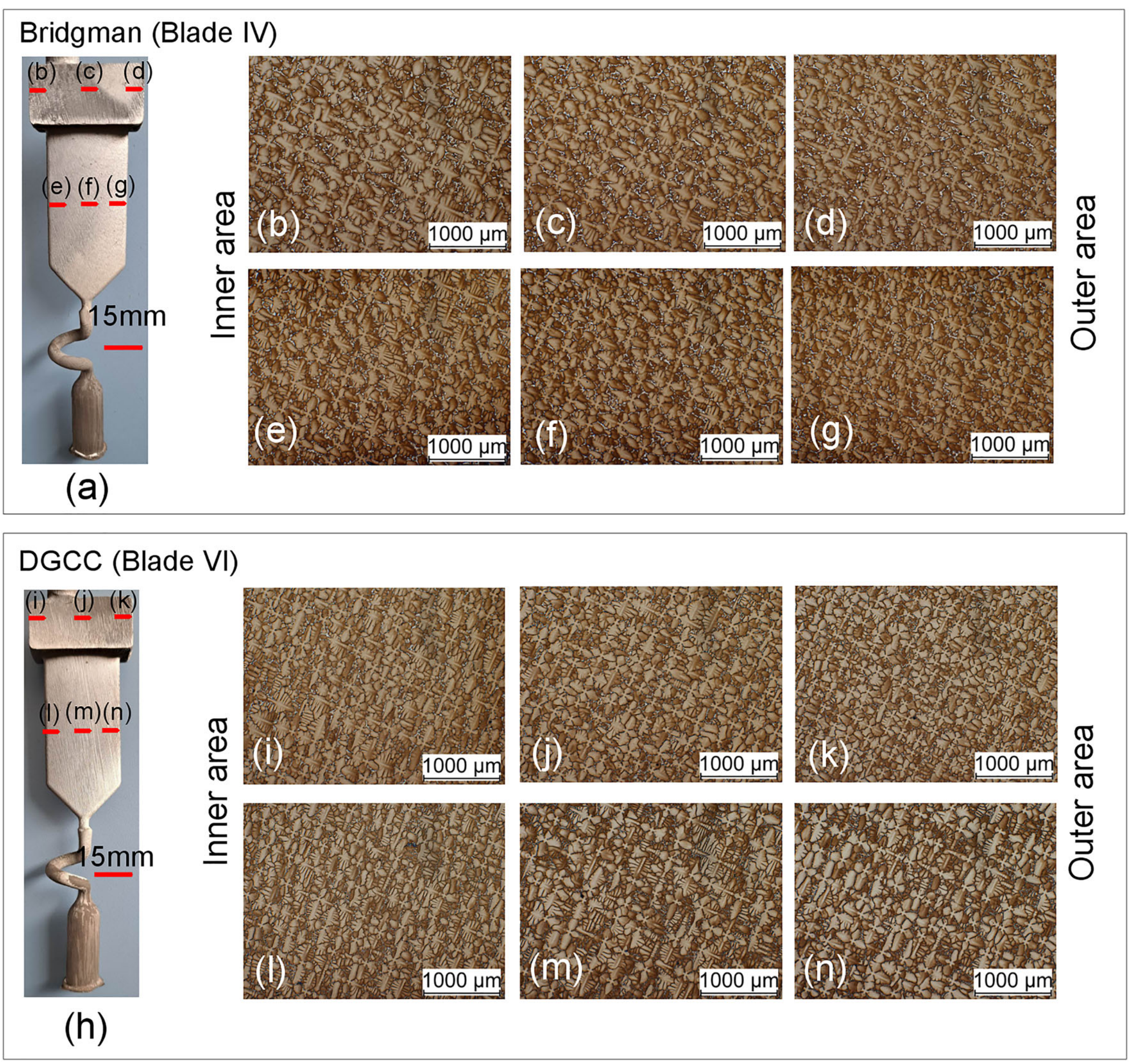


Fig. 2—Macrostructure of the blade surface (*a*) and (*h*) and exemplary dendritic microstructure in the outer, middle and inner areas of the platform and airfoil produced by Bridgman (*b*) through (*g*) and DGCC (*i*) through (*n*) methods.

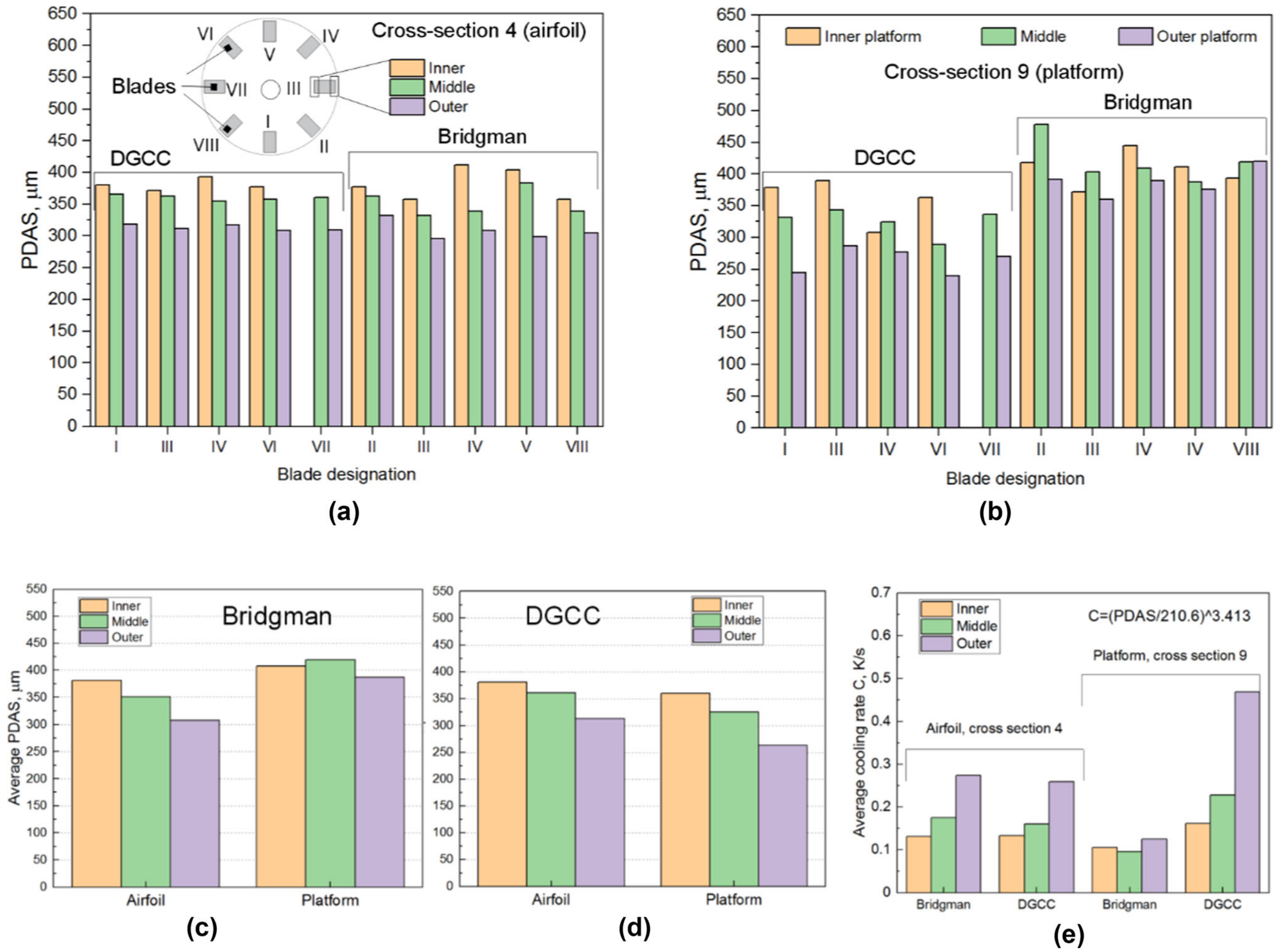


Fig. 3—PDAS in airfoils and a schematic of the castings (I to VIII) location on the circumference of the mold (*a*) as well as PDAS in platforms (*b*) for the different blades produced by the Bridgman and DGCC methods. Average PDAS values for the analyzed blades (*c*) and (*d*). Calculated average cooling rate from the obtained PDAS values (*e*). PDAS and cooling rate were determined in the inner, middle and outer areas of cross sections 4 and 9 located in the airfoil and platform of the blade, respectively.

PDAS difference was 51 μm, which was obtained between blade III and V. However, the change in PDAS values between subsequent platforms of the blades located at the circumference of the mold significantly increased for both the Bridgman and DGCC processes. Based on the analysis of PDAS in the airfoil, it was found that solidification conditions were more identical at the circumference of the mold for the DGCC process compared to the Bridgman process.

Subsequently, the average PDAS value in the outer, middle, and inner areas of the airfoil, as well as the platform, was calculated. This was based on the previously determined PDAS results for the five blades produced by both the Bridgman and DGCC methods [Figures 3(c) and (d)]. It was found that the average PDAS value for the airfoils of the blades (cross section 4), produced by the DGCC method, closely matched those obtained by the Bridgman process [Figures 3(c) and (d)]. However, in the platform PDAS reached a significantly smaller value for the DGCC process compared to the value obtained by the traditional Bridgman method.

The change in PDAS was also observed across the width of the blade cross-section. Generally, PDAS reached the smallest values in the area of the airfoil facing the chill rings while it obtained the largest values in the inner area of the casting, regardless of the production method. The average difference of PDAS between the outer and inner areas of the casting reached a value of approximately 50 μm in both processes. In the platform, the tendency of inhomogeneity of PDAS on the cross section was also visible. The difference in PDAS between the outermost areas of the platform increased significantly, especially for the DGCC process to approximately 100 μm, while for Bridgman it reached only approximately 20 μm. The increase in PDAS inhomogeneity of the upper part of the blade, for the DGCC process, was mainly caused by a significant reduction in the average value of PDAS to approximately 260 μm in the outer platform. In the inner platform of the blade produced by DGCC, smaller values of PDAS of approximately 50 μm were also observed compared to the Bridgman method.

Next, a detailed analysis of the dendritic microstructure along the entire height of the blade was conducted to better explain the reason for the different dendritic microstructure and the large refinement of the microstructure in the platform of the blade produced by the DGCC method (Figure 4). For this purpose, blades IV and VI manufactured by the Bridgman and DGCC processes, respectively, were selected for the research. The microstructure was analyzed on 9 cross sections in the inner, middle and outer areas of the blade. It was found that in the casting produced by the Bridgman method, there was a tendency to increase PDAS along the height of the blade. The smallest PDAS reached in the airfoil, while the largest values were achieved in the platform. The blades, produced by the DGCC method, were characterized by the opposite trend of PDAS change compared to the Bridgman method. For this method, PDAS obtained the largest values in the lower part of the blade, while the smallest in the platform.

Generally, the largest PDAS is observed in the areas with the largest casting thicknesses such as the platform, while the smallest values occur in the airfoil of blade produced by the Bridgman method with typical solidification conditions.[14] The obtained PDAS distribution along the blade produced by the DGCC method does not occur commonly for the Bridgman method. It is well known that PDAS depends on the axial temperature gradient G and the solidification velocity v according to the relation: $\mathrm{PDAS} = K_1 G^{-0.5} v^{-0.25}$ where K_1 is a material constant.[15] Based on this relation, PDAS decreases mainly with increasing temperature gradient or, to a lower extent, with increasing solidification velocity. Solidification velocity and temperature gradient are difficult to measure during directional solidification casting. On the basis of the cooling curve, it is possible obtain the cooling rate C which is related with G and v ($C = Gv$). Therefore, PDAS is often expressed on the cooling rate by the following relation $\mathrm{PDAS} = K_2 C^n$ where K_2 and n are material constants.[16] To better understand the directional solidification process, especially for the DGCC method, cooling rates were calculated based on the known value of PDAS in the specified areas of the blades produced by the two methods [Figure 3(e)]. Using the results in the Reference 17, the material constants of $K_2 = 210.6$ and $n = -0.293$ were assumed for CMSX-4 nickel superalloy. After transforming the above equation, the average cooling rate was calculated from the relation $C = (\mathrm{PDAS}/210.6)^{3.413}$. It was found that the cooling rate on the section 4 of the blade, for the Bridgman method, obtains similar values as in the airfoil of blades produced by the DGCC method. In the area close to the chill rings and heaters, the cooling rate is largest and it decreases in the direction facing the central rod, where the shadow effect occurs, which often appears in the Bridgman process.[18] This was mainly the reason of the inhomogeneous distribution of PDAS over the width of the blade.[19] Typically, both the distribution of the cooling rate and consequently the PDAS is obtained on the cross section of the airfoil of blade despite the use of two different manufacturing methods. This shows that, for the DGCC method the chill rings and eventually the chill plate affect thermally on the middle part of the

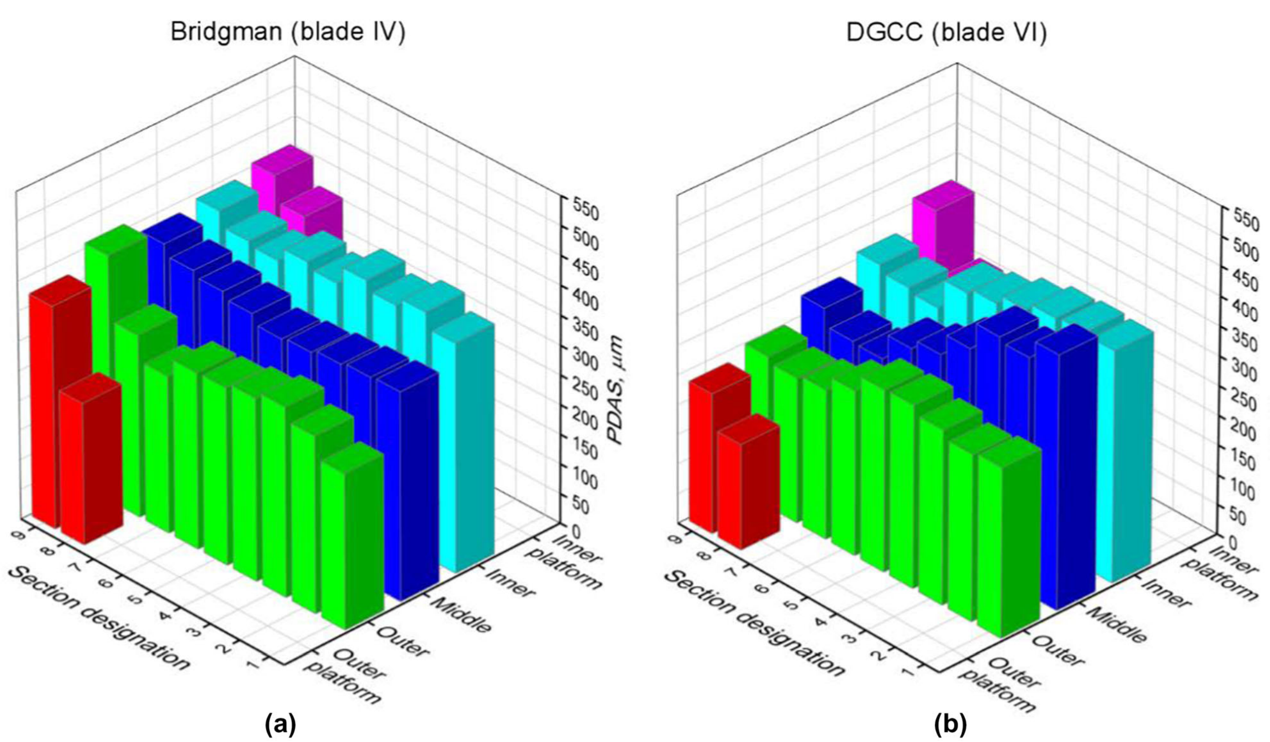


Fig. 4—Distribution of PDAS along the height and across the width of the cross-section of the blade produced by the Bridgman (*a*) and DGCC (*b*) methods.

airfoil (cross-section 4) as in the Bridgman method due to the radiation cooling. The use of cooling gas does not significantly increase both the cooling rate and microstructure refinement in the analyzed middle region of the airfoil. However, the cooling rate of the platform increases significantly relative to values in the airfoil. For the Bridgman method, as expected, the cooling rate reduces, while PDAS increases in the platform. Despite the same designs of the mold and heating chamber as well as the withdrawal velocity used in the Bridgman and DGCC processes, completely different refinement of the dendritic microstructure is observed in the platforms for both processes. This shows that the cooling gas injected by the nozzles into the furnace chamber evidently impacts the cooling of the mold and the directional solidification process of the platform while it has little effect on the solidification of the airfoil for these assumed technological parameters of the process.

According to Liu *et al.*,[20] increase of the casting cross-section should cause a decrease in the temperature gradient at the solidification front and consequently an increase in PDAS for the Bridgman method when radiation cooling occurs. However, for the DGCC method, a reduction in PDAS is observed during thickness increase. Hence, it was assumed that the effect of the shape of the blade and its position in the assembly relative to the gas stream can have a decisive effect on the cooling of the mold surface by the gas. Konter *et al.*[7] reported that increasing the horizontal distance x of the nozzles from the mold surface significantly reduced the convection heat transfer coefficient thus reducing both the temperature gradient and the cooling rate (Figure 5). In the carried out experiments, the width of the airfoil is smaller than the platform. Hence, the horizontal distance of the nozzle from the mold is the largest in the airfoil range, while the smallest in the platform part. Also, the thickness of the platform and thus the lateral surface of the mold assumes a larger size compared to that on the airfoil area. Hence, for the DGCC method, the platform area achieves more favorable thermal conditions for heat extraction from the outer surface of the mold by high velocity gas flow than from the airfoil surface.

The decisive influence on the cooling rate of the melt and the temperature gradient can mainly have the position of the jet centerline with regard to the position of the mushy zone in the casting. Depending on the casting shape, the solidification front and mushy zone are located at different vertical distance L from the nozzles (DGCC) or cooling bath (LMC). Miller and Pollock[3] reported that the largest axial temperature gradient for the LMC method was obtained when almost the entire mushy zone was immersed in a cooling bath. For these conditions, heat extraction along the height of the mushy zone is realized by convective cooling while the mold region located above the solidification front is cooled by less efficient radiation cooling. For the Bridgman method, the largest cooling rate is achieved at the interface of the chill plate and the casting base. It decreases with increasing distance of the moving mushy zone from the chill plate. For this distance greater than approximately 25 mm, heat flow by conduction in the direction of the chill plate is small, while it mainly occurs in the lateral direction as a result of radiation cooling of the mold.[21] Based on the widely obtained results for the LMC and Bridgman methods, a similar assumption can

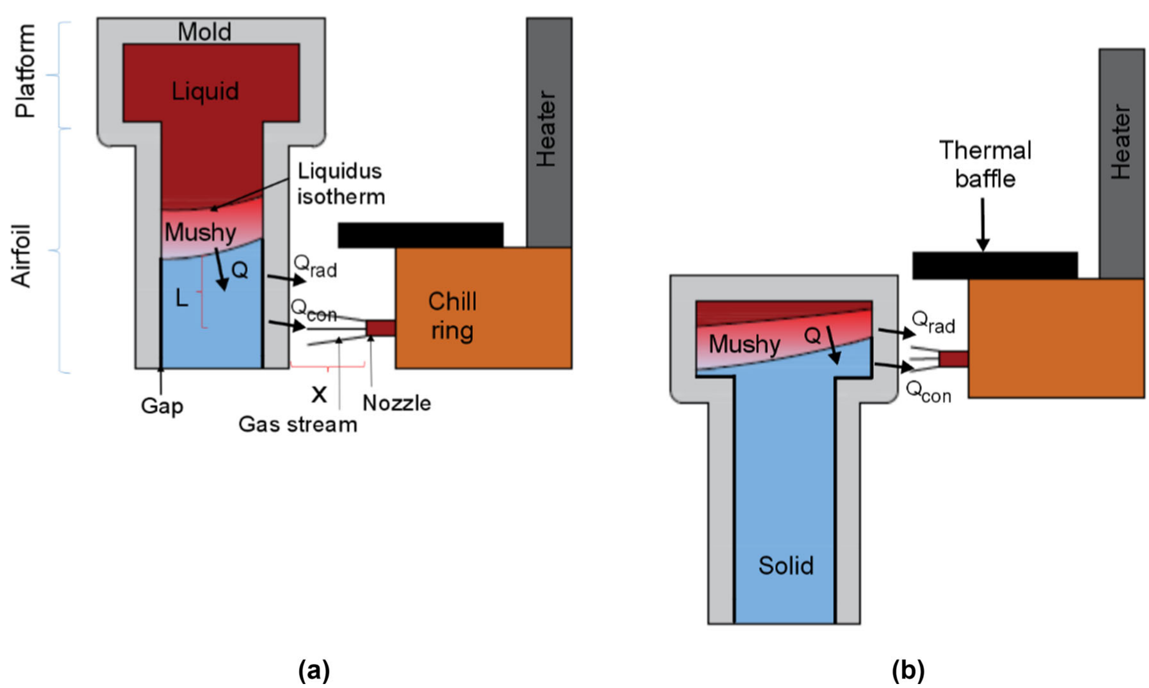


Fig. 5—Schematic illustration of the proposed mechanism of directional solidification of airfoil (*a*) and platform (*b*) blade produced by DGCC method, where: L is vertical distance of mushy zone from position of the jet centerline, x is horizontal distance of mold from gas nozzles, Q is heat flow by conduction, Q_{con} and Q_{rad} are convection and radiation heat extraction from the surface mold to the cooling area of furnace.

also be made for the DGCC method where the vertical distance of the cooling gas stream from the mushy zone position should be as small as possible.

Based on the obtained results, a mechanism of directional solidification of single crystal blade produced by DGCC was proposed. Figure 5 shows a schematic view of the blade with the position of the mushy zone relative to the gas nozzles for different solidification stages. Analysis of both the dendritic microstructure and the cooling rate shows the low effectiveness of the cooling of the airfoil by the gas stream. It was assumed that during solidification of the airfoil, the mushy zone is located above the position of the nozzles [Figure 5(a)]. The jet centreline mainly cools the area of the mold below the solidus temperature. For this case, the distance from the bottom of the mushy zone to the area of impact of the gas jet on the mold (position of the nozzles) determines the path of heat flow Q by conduction, mainly in the axial direction of the casting. The heat then flows mainly in a radial direction from the casting through the mold to its surroundings at the height of the nozzle position. The heat flow decreases with increasing distance from the bottom of the mushy zone to the level of the nozzle position. Therefore, the thermal effect of the gas jet on the formation of the microstructure can be limited if the mushy zone is located at too large a vertical distance from the nozzles. A significant increase in the cross-section of the platform relative to the airfoil disturbs the heat flow in the axial direction [Figure 5(b)]. In order to maintain directional solidification, the velocity of solidification decreases and the liquidus isotherm becomes curved as a result of also lateral heat flow in the platform. As a consequence, the mushy zone in the casting moves downwards towards the cooling area of the furnace. The most favorable cooling conditions in terms of microstructure refinement were obtained for this solidification stage. The mushy zone in the casting is located at the level of the nozzle position. In this case, the cooling gas extracts heat from the mold whose internal surface has direct contact with the mushy zone. At the interface of the mushy zone and the inner surface of the mold, the thermal resistance of the forming gap is significantly smaller than in the area of the completely solidified casting. At simultaneously, the thermal resistance of the casting area located below the mushy zone decreases, due to the reduction of the heat flow path length in the axial direction. The horizontal distance of the nozzles from the mold surface also decreases. Hence, this can result in an increase in the extraction of heat from the mold surface by the gas. Consequently, the temperature gradient increases and PDAS decreases in the platform.

A method to improve the refinement of the dendritic microstructure over the whole range of the blade has been proposed. The results presented for conducted experiments suggest that the position of the mushy zone relative to the nozzles can be crucial for improving the effectiveness of mold and casting cooling. In the DGCC industrial process, the position of the mushy zone in the casting can be controlled mainly by changing the angle of the nozzles, the withdrawal velocity of the mold, the temperature of the heaters, or the volume flow rate of the cooling gas flowing out of the nozzles. In order to reduce the path of heat flow through the casting, the gas flow can be directed toward the region of the mushy zone by increasing the angle of inclination of the nozzles. The increase in the temperature of the heaters will cause the mushy zone to move downward in the casting toward the cooling area and nozzles.[18,21] A similar result can be achieved by increasing the mold withdrawal velocity.[18,21] Increasing the volume flow rate of the gas should favorably improve the heat removal from the mold surface simultaneously moving the solidification front upward toward the heater.[7] However, the excessive increase in gas flow with simultaneous direction of the jet towards the solidification front, additionally driven by the upward convective flow of gas inside the heaters, can cause unfavorable cooling of the part of the mold located in the heating area. Consequently, this then leads to a reduction in the temperature gradient at the solidification front. Therefore, in order to maintain a high effectiveness of heat extraction from the mold with simultaneous reduction of upward gas flow between the blades, it may be necessary to improve the thermal separation of the cooling chamber from the heating chamber of the furnace. The matching of the thermal baffle opening to the mold may also have affected the PDAS in the airfoil of the blade made by the DGCC method presented in this article (Figure 5). In this experiment, during the airfoil solidification, the gap between the thermal baffle and the mold was larger than the gap for the platform solidification stage (Figure 5). Therefore, the gas cooling effectiveness of the airfoil area may also have been lower than the platform. The use of a horizontal thermal baffle with an opening contour better matched to the shape of the cross-section of the mold should significantly reduce the upward flow of gas between the blades and provide better control of the curvature of the solidification front. Furthermore, this modification of the process results in a stabilization of the position of the solidification front (vertical distance L) relative to the thermal baffle[17] and the nozzles, along the height of the blade, which may be crucial in the DGCC process. The proposed modification of the DGCC process can improve the refinement of the dendritic microstructure also in the airfoil of the blade.

Directional solidification of blade castings, produced by the DGCC method, requires control of a significant number of technological parameters. This can make this technique more complex compared to the Bridgman method. In the DGCC method, apart from typical technological parameters such as mold withdrawal velocity and heater temperature, the volume flow rate and jet angle of the gas injected by nozzles into the furnace chamber must be precisely controlled. This is necessary to achieve the required mold cooling by convection. Another challenge can be the selection of the number of nozzles and their placement in the chill ring at an appropriate distance from the solidification front and from the mold. Additionally, the previously established optimal technological parameters of the process may require adjustment when a new blade shape is produced. However, this is also the case in the Bridgman process. The need to control a large number of parameters in the directional solidification process by the DGCC method can undoubtedly pose a problem in the initial stage of selecting the conditions for manufacturing single crystal blades, especially given the limited information on this process presented in the literature. However, the appropriate selection of directional solidification parameters can enhance the quality of the single crystal blade while simultaneously increasing the mold withdrawal velocity compared to the Bridgman method.

The complexity of directional solidification process of single crystal blades using the DGCC method on an industrial scale requires conducting further experiments as well as numerical simulations of gas and heat flow in the furnace chamber and mold, respectively, the results of which will be published in the following papers.

In summary, the effect of injected gas at supersonic velocity into the furnace chamber on the effectiveness of mold cooling and microstructure refinement during the production of Ni-based superalloy single crystal blades by the DGCC method under industrial conditions was investigated in this paper. The cooling of the mold surface by the gas jet resulted in a change in the directional solidification conditions of the blade castings compared to the Bridgman method. The blade produced by the DGCC method features a different tendency of change in PDAS along the height of the single crystal. For this method, the PDAS has the highest values in the lower part of the blade, while it obtains the lowest values in the platform. In addition, blades produced by the DGCC method, obtain PDAS approximately 100 μm smaller in the platform and similar values in the airfoil compared to blades produced by the Bridgman method.

According to the proposed mechanism of controlling directional solidification with the use of gas, the change in PDAS along the height of the blade depends mainly on the position of the mushy zone relative to the level of the position of the gas nozzles. When the mushy zone is at the same level as the nozzles, the gas extracts heat from the surface of the mold area being in direct contact with the mushy zone, improving the cooling rate of the casting and the temperature gradient, thus reducing PDAS.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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