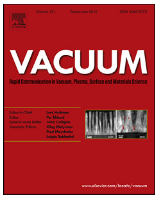
Vacuum 131 (2016) 327–342

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum



Directional solidification of Ni-based superalloy castings: Thermal analysis

D. Szeliga [a], [b], *, K. Kubiak [a], [b], M. Motyka [a], [b], J. Sieniawski [a], [b]

[a] Department of Materials Science, Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Al. Powstancow Warszawy 12, 35-959 Rzeszow, Poland

[b] Research and Development Laboratory for Aerospace Materials, ul. Zwirki i Wigury 4, 35-959 Rzeszow, Poland

ARTICLE INFO

Article history:
Received 23 March 2016
Received in revised form
7 July 2016
Accepted 7 July 2016
Available online 9 July 2016

Keywords:
Solidification parameters
Directional solidification
Ni-based superalloys
Grain structure
Bridgman method
Temperature measurement

ABSTRACT

The method of temperature measurement in directionally solidified (DS) Ni-based CMSX-4 superalloy castings manufactured using withdrawal rates of 3 and 5 mm/min in the Bridgman furnace with graphite heaters, was successfully improved. The numerical simulation of directional solidification process was performed with the use of ProCAST software, for withdrawal rates of 1, 3 and 5 mm/min in order to predict cooling rate, axial and transverse temperature gradients, solidification rate, height of mushy zone, shape of liquidus isotherm and its location relative to thermal baffle along the casting height. The critical distance from chill plate, above which of the steady-state solidification process starts, was established. The liquidus isotherm attained the concave, convex or flat shape, in dependence on withdrawal rate of casting and the distance from chill plate. The relationship between the shape of liquidus isotherm and grain structure was found for castings withdrawn at 1 and 5 mm/min. Grains grew in the direction of the rod axis and that of casting surface for the concave and convex isotherm shape, respectively. The flat shape of liquidus isotherm induced grain growth in the direction which was the most parallel to axis of casting.

1. Introduction

The method of directional solidification of nickel superalloy castings is widely applied to manufacture the aircraft engine hot section components and industrial gas turbines [1]. It is used to produce blade castings with single crystal and columnar grain structure. The ceramic shell mould, which is poured with liquid metal during the directional solidification (DS), is being withdrawn at a specific rate, from the heating to cooling area of the furnace resulting in the movement of solidification front along the casting height [2]. The temperature gradient can be created in castings with different techniques, which consist in the application of directional heat flow in the casting. Such a type of flow is obtained as an effect of withdrawing the casting and intensive cooling of the mould located below the heating part of furnace, in the cooling area [3]. Depending on cooling technique, the Bridgman method, Liquid Metal Cooling (LMC) and, to a lesser extent, Gas Cooling Casting (GCC) have been available at the industrial scale for the last 30 years [4,5]. The techniques have been developed in order to increase the temperature gradient and cooling rate, improve mechanical properties and reduce the production costs of directionally solidified castings [5–7].

The macro- and microstructure of turbine blade castings is formed mainly by controlling the parameters of solidification process such as temperature gradient and solidification rate, which affect the solidification front (planar, cellular or dendritic) of nickel superalloy castings [8]. The temperature distribution and parameters of solidification process change intensively in the lower part of ceramic shell mould and casting [4,9]. It is caused by a strong influence of chill plate. The chill plate plays an important role in the formation of microstructure in the lower part of casting with single crystal and columnar grain structure. The nucleation of equiaxed grains starts after the liquid metal comes into contact with the plate. Primary dendrite arms, which are parallel to the direction of heat flow, are most probable to grow further [10]. Columnar grains form and their quantity diminish with the increase of the distance from the casting base [11]. The directional solidification process is

---

* Corresponding author. Department of Materials Science, Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Al. Powstancow Warszawy 12, 35-959 Rzeszow, Poland.
E-mail address: dszeliga@prz.edu.pl (D. Szeliga).

http://dx.doi.org/10.1016/j.vacuum.2016.07.009

strictly related to heat flow along the casting height. The described mechanism of competitive dendrite growth proceeds in the starter during the manufacture of single crystal castings [12]. The formation of columnar grains depends on size and shape of starter. The amount of grains should be minimal on the height of starter/selector transition [13]. The angle between ⟨100⟩ direction of the grains and symmetry axis of casting should also be as low as possible. Single crystal castings made of nickel superalloy with assumed crystallographic orientation are also manufactured with the use of seed located on the chill plate [14]. Chill plate is responsible for the temperature distribution in the seed and thus affects the selection of its height and solidification process in the melt-back region [15].

The conditions of heat flow stabilize and the value of temperature gradient changes slowly at the distance of approx. 60 mm from the chill plate [4,9]. However, the location of blades in the assembly results in inhomogeneous heat flow on the side which is directed towards the chill rings (external area) and central rod (internal side) [16]. In that way, the shadow effect forms in the casting part on the internal side. It favors the curvature of isotherms between the liquidus and solidus temperatures, which determine the shape of mushy zone. The shape can be concave, flat or convex, depending on the values of transverse and axial temperature gradient [17,18]. Usually it attains the concave shape for standard values of mould withdrawal rate [16,17]. The growth of withdrawal rate leads to the increase of transverse temperature gradient and the change of shape of mushy zone to more concave.

It has been established that the transverse temperature gradient influences the growth of dendrites in directionally solidified castings [19]. Therefore, the shape of liquidus isotherm affects the direction of solidification of columnar grains, relative to the symmetry axis of casting. The concave shape of liquidus isotherm strengthens the tendency of columnar grains to grow towards the middle of casting [20]. However, the convex shape induces the grains to grow towards the external part of casting. The castings which solidify with flat shape of liquidus isotherm have the highest mechanical properties. However, it is difficult to preserve the shape along the blade height, especially in large, complex castings [21]. The experimental determination of liquidus isotherm shape along the height and width of casting is difficult on the basis of temperature measurements, which are possible only in some parts of casting. Therefore, this shape is usually established by means of numerical simulation.

The presented literature data indicate that the manufacture process of high quality, directionally solidified castings of nickel superalloys requires the exact determination of conditions of solidification along the casting height, as well as in the area of chill plate influence. Hence, the experimental and predicted temperature values in the casting have been established, followed by the parameters of directional solidification process such as cooling rate, axial and transverse temperature gradient, solidification rate, shape of liquidus isotherm, height of mushy zone and location of liquidus isotherm in regard to thermal baffle.

2. Methodology

2.1. Numerical simulation

The numerical simulations of temperature distribution and directional solidification process were carried out with the use of ProCAST software. Three-dimensional geometric models were manufactured for the purposes of numerical simulation. The design of device for the production of castings with the Bridgman method was a basis for the development of geometric models of the heating area. It consisted of two heaters with the diameter of 300 mm and thermal insulation plates (Fig. 1c). Chill rings of 250 mm diameter were located beneath the heating area. The model of assembly was placed inside the heating area. The assembly consisted of eight models of rod castings ($\varphi 12.5 \times 243$ mm), gating system, pouring cup and chill plate (Fig. 1b). The predicted temperature distribution was determined along the rod symmetry axis, at heights $z_1 - 8$, $z_2 - 13$, $z_3 - 21$, $z_4 - 39$, $z_5 - 58$, $z_6 - 78$, $z_7 - 102$ and $z_8 - 122$ mm from its base (Fig. 1a).

In the developed model of heating area, the model of thermal baffle was taken into account in order to reduce heat losses and to increase the temperature gradient in the casting. The graphite radiation baffle was a ring with internal diameter 220 mm and thickness 2.5 mm. It was located on the plate of thermal insulation of the heating area. All the described models were placed inside the three-dimensional ambience which depicted the internal surface of heating and cooling area of furnace (Fig. 1d).

The symmetry of geometrical models allowed dividing them into four equal parts in order to reduce time of both, their preparation and numerical calculations. The finite elements mesh was generated on the pouring cup, gating system, castings and models of mould ambience (Fig. 1b,c). Then, of 10 mm layer of mould was

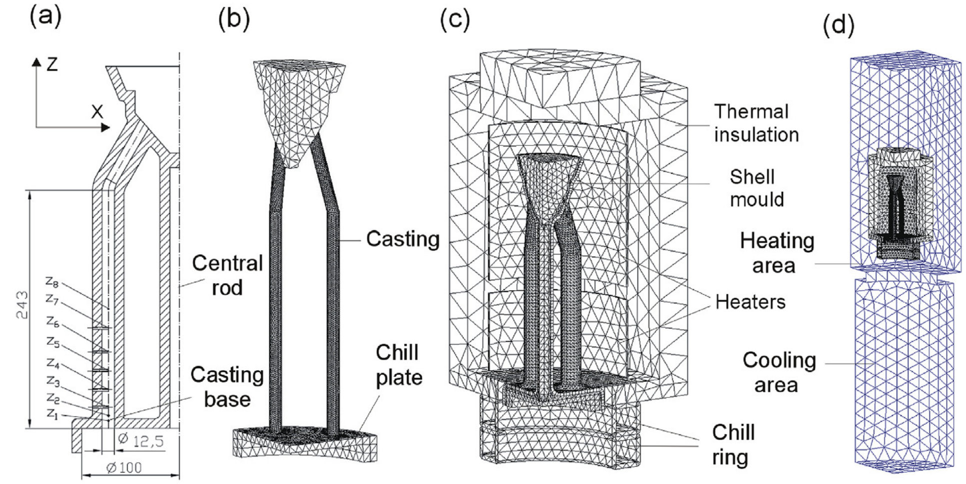


Fig. 1. The location of measurement points of temperature along height of the casting (a), the finite elements mesh of model assemble (b), heating chamber (c), inner surface of the melting (heating) and the cooling area of furnace (d). $z_1 - z_8$ – simulation, $z_3 - z_7$ – measurement.