Experimental Thermal and Fluid Science 87 (2017) 149–160

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Investigation of casting–ceramic shell mold interface thermal resistance during solidification process of nickel based superalloy

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ARTICLE INFO

Article history:
Received 19 May 2016
Received in revised form 3 April 2017
Accepted 22 April 2017
Available online 24 April 2017

Keywords:
Interface thermal resistance
Ceramic shell mold
Ni-based superalloys
Numerical simulation
Oxide scale

ABSTRACT

The study of thermal resistance (TR) at the casting-mold interface has been performed to describe the solidification process aimed at the improvement of technology and the reduction of defect quantity of investment castings. The analysis of thermal resistance at casting–mold interface between the solidifying IN 713C nickel superalloy plate casting and ceramic shell mold has been presented. The temperature measurements in the plate casting of IN 713C nickel superalloy and the ceramic shell mold were carried out to determine the casting–mold interface heat transfer coefficient (IHTC) with the use of inverse heat conduction method. The calculations were performed using a ProCAST software. It was found that the casting–mold IHTC (7962 $\text{Wm}^{-2}\,\text{K}^{-1}$) was the highest for the alloy in the liquid state and then it intensively decreased during solidification and cooling followed by its increase close to the end of the solidification process forming another peak on the obtained curve. The formation mechanism of gap between the ceramic mold and Ni based superalloy casting as well as another peak were proposed taking into account the occurrence of mixed oxide scale at the interface. On the basis of numerical simulation, it was found that the IHTC had less influence on cooling rate of casting than the thickness, thermal conductivity and emissivity of the mold for the applied technological parameters of the process.

1. Introduction

Nickel superalloys are widely applied for strongly loaded elements of aircraft engine hot-section components which are particularly exposed to hot corrosion and thermal fatigue [1]. These are mainly the rotor blades and vane rings of both high and low pressure turbines and the elements of combustion chamber. In most cases, they are manufactured by pouring the molten metal into a ceramic shell mold during the investment casting process [2].

The manufacturing process of investment nickel superalloy blade castings is difficult and expensive. Hence, there is a continuous development of numerical methods for the simulation of preheating, pouring the mold and solidification followed with cooling of castings. The application of such software makes possible to assess quickly the correctness of the developed technology. It also reduces the production costs, because it shortens the time needed for the process development and eliminates errors at the initial stage of manufacture [3–5].

The values of thermophysical parameters of the mold and cast material, also the assumed boundary conditions in the applied model, affect the predicted temperature distribution in the casting and the ceramic shell mold during the performed simulation of solidification. The value of casting–mold interface thermal resistance (ITR) is of great significance in terms of heat exchange between the contact surfaces of ceramic shell mold and the casting. The solidification process and the casting shrinkage result in the formation of gap between the casting and ceramic shell mold.

The interface thermal resistance influences the cooling rate and thereby the solidification of castings. Its value depends on conditions of solidification process (vacuum, protective atmosphere, air, pouring and mold temperature), the external pressure of liquid metal, surface roughness of mold and casting, and their emissivity, etc. [6–10]. Therefore it depends on the type of alloy, the material of ceramic shell mold, shape and size of casting and their temperature.

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http://dx.doi.org/10.1016/j.expthermflusci.2017.04.024

The ITR affects also the process of directional solidification of single crystal castings made of nickel superalloys which are manufactured with the Bridgman, LMC (Liquid Metal Cooling) and GCC (Gas Cooling Casting) methods [11–13]. It was also determined that its value affects the cooling rate of the castings manufactured using LMC to a greater extent than of these manufactured with the Bridgman method [14].

The ITR between the casting and mold was the subject of numerous investigations because of its great importance for the process of solidification. The measurements were carried out mostly for iron, copper and aluminum alloys cast into metal and sand molds.

The thermal resistance R is the inverse of the heat transfer coefficient h ($R = 1/h$) of the analysed layer. Hence, the value of thermal resistance at casting–mold interface is often characterized by interface heat transfer coefficient (IHTC). Pouring the molds was usually performed with gravity, vacuum or die casting methods [9]. The casting shape of plates or cylinders were mostly examined in the assumed conditions of unidirectional heat flow [7,8].

There are much fewer reports in the literature on IHTC of elements obtained in the ceramic shell mold with the investment casting technique. O'Mahony and Browne showed the effect of technological parameters and the size of casting on IHTC of the cylinders of Al alloys and ceramic mold during solidification [6]. For example, the average values of IHTC for alloy A319 and A356 were approx. 800 and 350 $\mathrm{Wm^{-2}\,K^{-1}}$, respectively. Zhang et al. [15] presented the results of calculation of IHTC for a more complex shape – turbine blade. They found that the value of IHTC was 12160.4 $\mathrm{Wm^{-2}\,K^{-1}}$ at the start of solidification and then it rapidly decreased to the value of approx. 50 $\mathrm{Wm^{-2}\,K^{-1}}$.

Only a few papers reported the IHTC investigation of ceramic mold and nickel superalloy casting [16,17]. Those castings were produced in vacuum in the range of solidification temperatures 1473–1673 K. The results of IHTC determination during the solidification of single crystal blade casting of nickel superalloy in contact with the mold and chill plate were discussed in paper [16]. A large decrease in the value of IHTC at the beginning of solidification followed by its stabilization at approx. IHTC = 210 $\mathrm{Wm^{-2}\,K^{-1}}$ and then at IHTC = 1520 $\mathrm{Wm^{-2}\,K^{-1}}$ after the formation of the gap for the interface casting-mold and casting-chill plate, respectively was observed. A similar change of IHTC value between the single crystal casting of nickel superalloy DD6 and the mold was reported in paper [17]. The IHTC values of 1000 $\mathrm{Wm^{-2}\,K^{-1}}$ and IHTC = 500 $\mathrm{Wm^{-2}\,K^{-1}}$ were determined on the basis of temperature measurements above liquidus and below the solidus, respectively using a numerical method of commercial ProCAST software. The values of IHTC between the plate casting of nickel superalloy IN738LC and the ceramic mold for different values of technological parameters were delivered in paper [18]. It was established that the average values of IHTC during solidification of casting depended on mold temperature, thickness and temperature of pouring the mold and was contained in the range of 250 $\mathrm{Wm^{-2}\,K^{-1}}$ up to 560 $\mathrm{Wm^{-2}\,K^{-1}}$. Overfelt and Sahai confirmed in [19] a great influence of shape of nickel superalloy IN718 casting on IHTC value. For the cylindrical casting (the mold heated to 1018 K), the IHTC values were approx. 200 and 100 $\mathrm{Wm^{-2}\,K^{-1}}$ for temperature 1573 K and 1103 K, respectively, while the plate shape was characterized by 5000 and 100 $\mathrm{Wm^{-2}\,K^{-1}}$ for temperature 1673 K and 1373 K, respectively.

The analysis of literature data showed a small number of reports on IHTC of nickel superalloy castings produced in ceramic molds with the investment casting method. Hence, the determination of the accurate IHTC value is still vitally required for the numerical simulation of nickel superalloy solidification process.

It was assumed that fixing the interface heat transfer coefficient value would make the numerical simulation of solidification process and the manufacture of the nickel superalloy castings with equiaxed grains more efficient. Therefore, in the paper an attempt was made to develop the method of establishing the true value of the coefficient and its influence on the solidification kinetics of nickel superalloy casting.

2. Methodology

2.1. The experimental

The experiment was performed to determine the thermal resistance between the mold and casting of IN 713C nickel based superalloys. Plate models (50 × 40 × 5 mm) and gating system elements (sprue or runner) were designed in order to realize the assumed research objectives (Fig. 1a). Models of two plate castings were combined with the gating system into the model assembly. The gating system consisted of pouring cup, sprue and runner for the supply and the distribution of molten metal in the mold cavity. The size and geometry of the model assembly and plate casting elements were designed taking into account the geometry of furnace heater, the manufacturing technology of ceramic shell mold and castings, the temperature distribution and the heat flow in the casting.

The wax assembly was a base to manufacture the multilayer ceramic shell mold (Fig. 1b). The first ceramic layer (prime coat), approx. 1.2 mm thick, was formed on a corundum matrix. The remaining layers were made of mullite. The molds were dried and the wax was successively melted out in the autoclave at proper temperature and pressure. The remaining wax was removed during the initial preheating of the mold. The average thickness of ceramic shell mold layer was about 10 mm.

The temperature measurement was carried out in the middle region of the plate casting and in the layer of ceramic shell mold. The B type thermocouples (PtRh30 – PtRh6) with the diameter of 0.2 mm were mounted (Fig. 1b and Fig. 2a). The junctions of thermocouples were located parallel to the surface of plate casting behind the 1st, 5th and the 9th layer of ceramic shell mold (Fig. 1b). The distance between thermocouple junctions and the inner surface of ceramic mold was of 1.2, 5.5 and 10 mm (Fig. 2a).

The temperature measurement was also carried out near the surface of the ceramic mold and in the cooling chamber using ther-

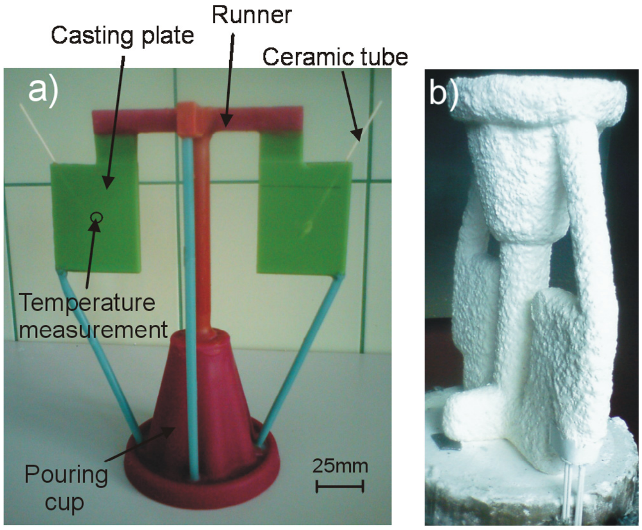

Fig. 1. Wax assembly with schematically marked area of temperature measurement (a) and the ceramic shell mold placed in the furnace with mounted thermocouples (b).