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Quantitative analysis of withdrawal rate on stray grain formation in the platforms of a Ni-Based single crystal dummy blade

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ABSTRACT

Quantitative analysis of withdrawal rate on stray grain (SG) formation in the platforms of Ni-base single crystal (SX) dummy blades was carried out through experiments and simulations. The results showed that the tendency of SG formation becomes higher with the increase of withdrawal rates from 3 to 12 mm min^{-1}. Considering that SG formation is governed by a competition on the amount of time used for the dendrites branching and the cooling process, the underlying mechanism associated with the influence of withdrawal rate on SG formation was then investigated based on the effect of withdrawal rate on the thermal profile development and the macrostructural evolutions. Finite element simulation indicated that the thermal profile in the platform is wave-shaped, which results in two kinds of SGs formation; one being isolated in small areas in the platform ends, and the other connecting to a large area across the upper and lower edges of the platform.

1. Introduction

The superior mechanical properties of Nickel-base single crystal (SX) turbine blades are attributed to (1) the elimination of grain boundaries and (2) the utilization of the best creep resistant orientation [001] to bear the main stress of the turbine blade [1,2]. The formation of stray grains (SGs) during the directional solidification process, however, introduces high angle boundaries (HABs) that lead to a sharp decrease of the mechanical properties. To suppress such defect occurrence, investigations have been carried out to fully elucidate the underlying mechanism and identify the controlling factors of SG formation. It has been shown that these defect grains usually form around the re-entrant sections, like shrouds and platforms, where the local solidification conditions change. Meyer et al. [3] first illustrated that SG nucleated in a thermal undercooling zone, caused by a macroscopically curved isotherm sweeping through platform extremity, and this was further confirmed by Li et al. [4] through characterizing SG morphologies in multi-scale levels. Bussac et al. [5] described that whether SG will form or not was determined by a competition between the dendritic branching distance and the cooling time of the platform extremity to reach the nucleation temperature. Based on several assumptions and an idealized plane isotherm, they derived a theoretical model to predict the processing window of the SG formation. The results showed that with the increase of withdrawal rates, thermal gradient, grain misorientation, platform length and the decrease of the critical nucleation undercooling, the SG formation increased. Yang et al. [6] and Gao et al. [7] confirmed that increasing the withdrawal rate promoted the SG formation by cellular automaton finite difference (CAFD) and cellular automaton finite element (CAFE) simulations, respectively. Ma [8] designed a set of experiments to measure the nucleation undercooling, so as to deduce the proneness of the SG formation in different alloying systems. Zhang et al. [9] investigated the tendency of SG formation of different generation superalloys through solidifying sets of ingeniously designed castings featuring multi-platforms of different lengths, which could then be treated as the index of the susceptibility of SG formation. Meng et al. [10] paid attention to the effect of platform dimensions on the SG formation, considering that the industry gas turbine blades are large as compared to aero turbine blades, and can readily accommodate the SG defects. Xuan et al. [11,12] investigated the effect of primary orientation of superalloys on SG formation in the platform region and introduced a high magnetic field to suppress its formation.

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Among these factors, withdrawal rate is the parameter that metallurgists can easily adjust to produce SX blade in different conditions. During the directional solidification process, increasing the withdrawal rate is beneficial because, in addition to the enhancement of the production efficiency, the primary dendritic arm spacings (PDASs) decrease [13–16], leading to the alleviation of microsegregation [17], the decrease of the subsequent heat treatment time [18] and the improvement of mechanical properties [19,20]. Unfortunately, with the increase of withdrawal rate, the frequency of SG formation in the platform region is higher [3,5–7,10]. An optimum withdrawal rate is therefore a key to fabricate SX turbine blades without the SG formation. The earlier studies, however, were all based on the idealized planar or the simplified consistently concaved isotherms used to investigate the dependence of SG formation on the withdrawal rate. Due to the abruptly changed configuration of the platform, the local thermal profile in the platform region is rather complex, leading to a much more complicated dendritic branching and SG formation process [21]. Therefore, it is imperative to investigate the SG formation within the consideration of the actual thermal profile evolution.

2. Experiments and simulations

2.1. Experimental process

The composition of Ni-based SX superalloy DD403 was 6.5 Cr, 5.0 Co, 3.8 Mo, 5.2 W, 5.9 Al, 2.1 Ti and the rest is Ni. The liquidus and solidus temperatures were measured by differential thermal analysis (DTA) (Netzsch 409CD, Netzsch, Selb, Germany), as shown in Fig. 1. Approximately 100 mg of the sample was heated in high-purity ZrO_2 crucible at a heating rate of 10 K min^{-1} in a flowing Ar. Samples were heated to 1823K (1550 °C) and then cooled with the same rate to 1473 K (1200 °C). During the experiment, an identical empty ZrO_2 crucible was inserted in the reference cell for calibration. Accuracy has been confirmed by repeating measurements several times. The instrument tolerance was found to be less than ±1 K (±1 °C).

A dummy turbine blade (Fig. 2(a)) was used to fabricate SXs, using the spiral grain selector technique in a Bridgman furnace (Fig. 2(b)). During the directional solidification, the furnace chamber was first evacuated to a partial pressure of approximately 10^{-2} Pa. The ceramic mold was then preheated to 1823K (1550 °C) by graphite heating elements. Once the ingot was melted, the liquid melt of 1773 K (1500 °C) was poured into the preheated mold cavity and held for 10 min for stabilization. Finally, the ceramic mold was withdrawn out of the furnace at predetermined rates of 3, 4.5, 6, 7.5, 9 and 12 mm min^{-1}.

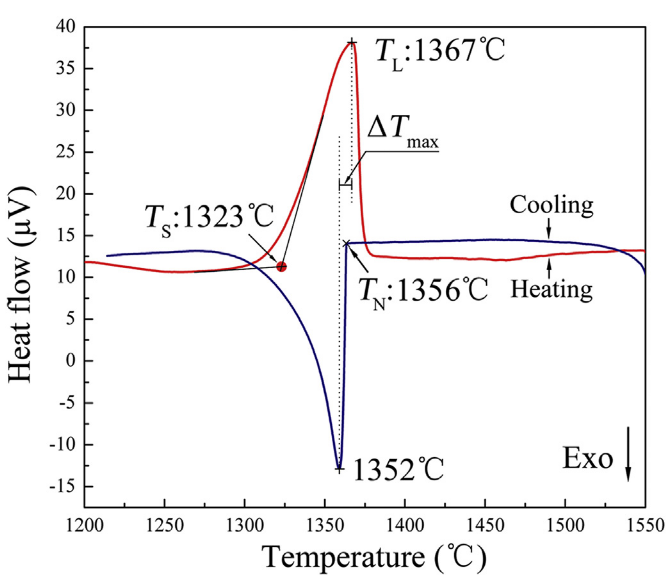

Fig. 1. DTA curves of heating and cooling process of DD403.

Following the casting process, blades were removed from the remnant mold and macroetched for defects inspection. Platforms were subsequently sectioned transversely along the plane 0.5 mm above the platform base and prepared for further defects inspection by submerging them into a macroetching solution of 50% HCl and 50% H_2O_2 for approximately 10 min. The macroetched samples were mounted, ground, polished and etched afterwards for metallographic examination using a solution of 10 mL HNO_3: 20 mL HF:30 mL $C_3H_8O_3$. The dendritic morphologies were observed using an optical microscope (DM-4000M; Leica, Berlin, Germany). EBSD measurements of the crystallographic orientation were performed using a step size of 30 μm under a condition of an accelerating voltage of 20 kV and a probe current of 4 nA in a scanning electron microscope (SEM) (TESCAN VEGA, TESCAN, Czech Republic) equipped with HKL system and Channel 5 analysis software (Oxford instruments, Oxford, UK).

2.2. Simulation details

Thermal profiles of the blades were simulated using ProCAST (CalcomESI, Lausanne-EPFL, Switzerland). Finite element (FE) mesh model of the apparatus and the ceramic shell was established according to the actual measurements (Fig. 2(c)). Considering the computational efficiency, the furnace was constructed into 2D mesh, the dummy blade and the ceramic mold were built into a solid 3D mesh. During the directional solidification, 3D casting mesh was contacted with 2D furnace mesh through thermal radiation performed by a view factors calculation, which was taking account of reflections, obstructions and shadowing effects. The view factors between the ceramic mold and the furnace chamber were continuously updated in every five steps. Thermal simulations initiating at the state after the stabilization of the melt was done; the temperature of casting therefore was set at 1823 K (1550 °C), which is consistent with the temperature of the heating chamber (Fig. 2(c)). During the withdrawal process, the temperature of casting was determined by calculating (1) the radiation heat transfer among mold surface and heating zone/cooling zone; (2) the heat conduction through mold shell; (3) the heat transfer between mold and melt, and (4) the heat conduction in the melt itself using the parameters as illustrated in Fig. 2(c) and Tables 1–3. The thermophysical parameters of DD403 were calculated by JMatPro (Sente Software Ltd., Surrey, United Kingdom). The calculated alloy's liquidus and solidus temperatures (1371 °C and 1324 °C) were not deviated far from the DTA measurement (Fig. 1) (1367 °C and 1323 °C).

Once the temperature profile was calculated, the macrostructure was simulated with the 3D CAFE model in a Post-processing mode: the cells used for temperatures calculation at the finite-element node are interpolated to calculate nucleation and growth of dendritic grains with the CA. The latent heat, released by the phase transformation, is not fed back to the finite-element calculation, which is usually reasonable in the directional solidification. The 3D CAFE model has been explained in detail by Gandin et al. [25,26] and will not be described here. In the present study, heterogeneous nucleation of grains was modeled using a continuous nucleation model [27] (Table 4). Since the internal surface of the mold was not coated with inoculant in the producting process of DS or SX blades, surface nucleation was neglected for the surfaces of the turbine blade. Stray grain formation therefore was modeled by