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Influence of gibbosity on recrystallization behavior of single crystal blade casting

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A B S T R A C T

Recrystallization (RX) defects formed in the gibbosities induced by platinum chaplet pins were studied by experiments and simulations for single crystal (SX) blade castings. Recrystallization occurs in 39 of the 80 gibbosities and can penetrate more than 250 μm into the SX blade. The RX occurrence ratios for the gibbosities in the upper, middle and lower positions of the blade are 83%, 50%, and 8% respectively, indicating a strong sensitivity of RX to the location height of the gibbosity. The microstructure is SX without the presence of micro misoriented grains in the cross-section of gibbosity of as-cast sample. Secondary carbide particles are found at the interface between the RX and SX grains. A composite image of backscattered electron (BE) and electron backscatter diffraction (EBSD) shows that the migration of the RX interface is hindered by coarse eutectic particles. A thermal elastoplastic model that considers the anisotropic mechanical properties of SX superalloys and is coupled with a finite-element method (FEM) was utilized to predict the deformation behavior during directional solidification. The FEM results reveal that the equivalent plastic strain (PEEQ) tends to concentrate in the gibbosities, and this gives a reasonable and reliable explanation for RX formation.

1. Introduction

Recrystallization (RX) defects can significantly influence the service life of single crystal (SX) turbine blades and vanes in aero-engines. The new grain boundaries introduced by RX decrease the creep rupture resistance of Ni-based SX superalloy blades due to the lack of elements that can strengthen the grain boundaries (Mathur et al., 2017). Plastic strain is usually considered as the main reason for the occurrence of RX in blade castings, and can originate during many processes such as solidification contraction, shell removal and sand blasting (Jo et al., 2003). In addition, the difference in thermal expansion coefficients between superalloys and ceramic moulds is another important reason why plastic strains can be induced during the cooling process. The nucleation of RX grains is usually driven by plastic strain along with the deformation energy stored during the manufacturing process; this type of RX is called static RX (Reyes et al., 2015).

As the shapes of hollow airfoils with cooling channels become progressively more complex, some specific technologies (e.g., chaplets comprising platinum pins) are often used to meet the needs of production (Salkeld et al., 1995; Ning et al., 2013; Jago, 1996). During the directional solidification (DS) process, the core is easily driven to shift by the flowing molten alloy around it; therefore platinum chaplet pins are used to keep them stable. As shown in Fig. 1(a) and (b), 12 chaplets are arranged on either side of a SX hollow blade to fix the core. Fig. 1(c) presents the schematic diagram of Pt chaplet pin and the induced gibbosity. The chaplet extends from the core, across the SX blade, to the inside of ceramic mould, and the gibbosity is formed on the surface of the blade (red dashed line in Fig. 1(c)). This technique can significantly reduce the relevant defects induced by the core, such as core breakthrough and exposure (black circle in Fig. 1(a), the core penetrates the thin-wall of blade airfoil), and the rejection rate caused by these defects decreases from 90% to less than 5%. However, the gibbosity formed in the position of chaplet on the SX blade surface can be hindered by the ceramic mould during DS, thereby leading to the formation of shear stress. This significantly increases the probability of RX, which can decrease the mechanical properties of the SX blade (Ning et al., 2013).

Porter and Ralph (1981) reported that RX nucleation was prone to occur by subgrain coalescence, and the subsequent growth was attributed to strain-induced boundary migration of the grain boundary at which RX nucleated. Zhuo et al. (2015) pointed out that the subgrain boundaries formed in the SX matrix were transformed from the dislocation walls that formed with the migration of dislocations during the annealing process. Mathur et al. (2017) reported another surface nucleation mode, in which the micro-grains of γ' phase in surface eutectics could coarsen during solution heat treatment. Panwisawas et al. (2013) and Li et al. (2015b) proposed isotropic and anisotropic mechanical

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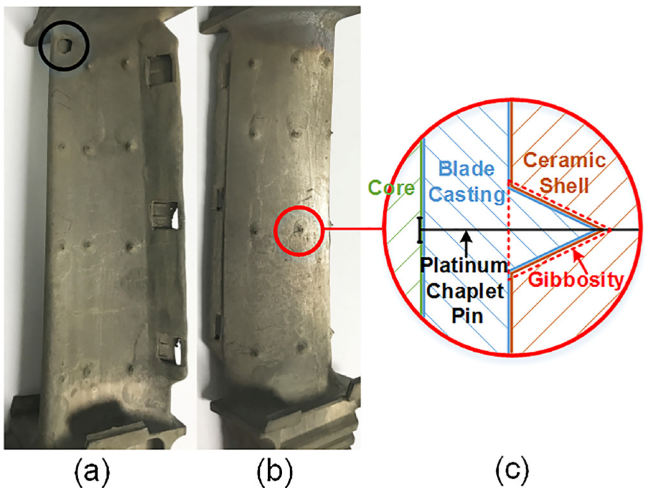

Fig. 1. SX turbine blade with platinum chaplet pins and gibbosities: (a) front and (b) back sides, (c) schematic diagram of a Pt chaplet pin and an induced gibbosity.

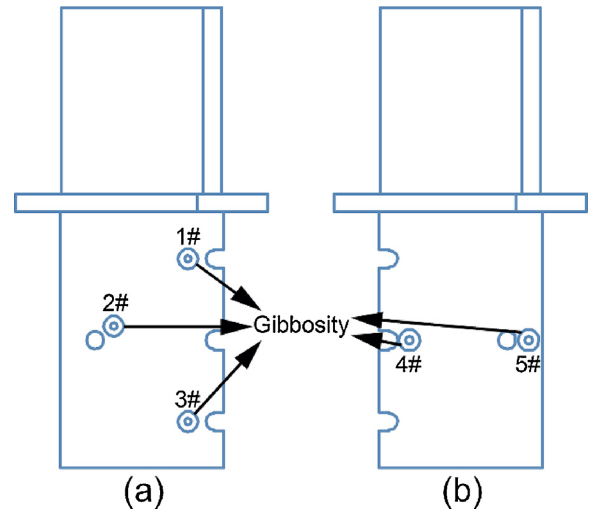

Fig. 2. Positions of Pt chaplet pins and induced gibbosities on the surface of the designed blade casting: (a) front and (b) back sides.

models to simulate the scale of plastic strain accumulated in SX castings during the DS process, respectively. Zambaldi et al. (2007) simulated the RX evolution around the indentation in SX superalloy by combining the cellular automaton method and finite-element method (FEM) based on crystal plasticity theory. Rettberg and Pollock (2014) studied the influence of localized RX on macroscopic creep rates and developed a model for the prediction of RX-accelerated tertiary creep. Jo and Kim (2003) found that the surface RX in the SX CMSX-2 superalloy did not reduce creep rupture life at 982 °C, 240 MPa owing to the strengthening effect of a surface oxide layer. The early initiation of surface cracks on grain boundaries normal to the applied stress implemented harmful effects to the SX specimens, in accordance with the investigation of Zhang et al. (2012). However, the influence of surface gibbosity on RX behavior and the prediction of deformation in the gibbosity of blade casting were seldom reported.

The present research focuses on the investigation of RX behavior in blades with gibbosities on their surfaces. In this regard, a blade casting with several gibbosities on its surface was designed, directionally solidified and heat-treated. The recrystallized gibbosities at various heights were counted and characterized. The nucleation mechanism of the RX grains was discussed. To further study the driving force for nucleation and growth, a thermal elastoplastic model considering the anisotropic mechanical properties of SX superalloys was utilized to predict the deformation behavior of blade castings during DS.

2. Methods

2.1. Experimental procedures

A model of a blade casting with five platinum chaplet pins and gibbosities was designed for a length of 99 mm that approximately equals the length of an aero-engine turbine blade, as shown in Fig. 2. Wax patterns were fabricated by an additive manufacturing technology, and spiral grain selectors were added to the very base of them. Chaplets of platinum wire were inserted into the wax blades, and the gibbosities formed around them. Four wax blade patterns were arranged in one cluster. In this study, three types of mould clusters with angles of 0°, 45° and 90° were fabricated (Fig. 3). The ceramic shells were produced by ceramic slurries and particles. The superalloy used in this study was a second-generation SX superalloy, DD6, whose nominal chemical composition is presented in Table 1. The SX blade castings were prepared in an ALD industrial vacuum Bridgman furnace. The pouring temperature was 1550 °C. After preheating, pouring and heat preservation, the chill, ceramic shell and alloy were withdrawn from the heating zone into a cooling zone through a baffle at the constant rate of 5 mm/min. After casting, the blades were subjected to the standard heat treatment (SHT) consisting of the solution and aging processes (Table 2), which is similar to the process employed in commercial production.

To inspect the surface RX grains, a mixed chemical solution (50% hydrochloric acid and 50% hydrogen peroxide) was used for etching the blade castings. After macro-etching, the macro RX areas can be easily detected on a sample surface by optical inspection. When such a sample is viewed under a directional light source, the RX areas are seen as local chromatic aberrations, with different reflectivities indicating that they differ in crystallographic orientation from the SX matrix. The number of gibbosities (n_a, subscript a denotes gibbosity #a) that are recrystallized at each gibbosity position was counted to calculate the RX occurrence rate at this position ($n_a/12$, 12 is the total number of gibbosities at each gibbosity position). In order to observe the RX microstructure, the gibbosity positions were carefully cut down from the blade casting using electrical discharge machining (EDM) normal to the surface across the gibbosity peak. Subsequently, mechanical grinding and polishing were performed. The as-polished samples were etched using Marble's reagent to enhance the contrast between the precipitate and matrix, then observed by optical microscopy (OM, Zeiss AM10 OM) and scanning electron microscopy (SEM, Merlin FEG-SEM). Composition measurements were performed using energy-dispersive spectroscopy (EDS). The samples for crystal orientation measurements were electrochemically polished, and the images were captured in backscattered electron (BEI) and electron backscatter diffraction (EBSD) mode.

2.2. Mathematical model

In classical theory, plastic strain, as the main driving force, has been widely used to explain the nucleation and growth of RX grains. However, the exact temperature and time at which plastic strain occurs is difficult to measure experimentally. Therefore, it is necessary to use FEM and a constitutive model that considers the anisotropic mechanical behavior of SX superalloys to calculate the equivalent plastic strain (PEEQ) in blade castings during the DS process. Because the elastic and plastic strains are mainly caused by the difference in coefficients of thermal expansion between the castings and the shells/cores during the solidification process, the accuracy of PEEQ is dependent on that of temperature distribution. This distribution is extracted from the simulation results of ProCAST and then imported to Abaqus as a pre-defined temperature field. Both ProCAST and Abaqus are commercially available FEM software packages. To ensure accuracy of the temperature field calculation, experimentally measured temperature/time-