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Turbine blades of the single crystal nickel based CMSX-6 superalloy

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ABSTRACT

Purpose: Research and Development Laboratory for Aerospace Materials in Rzeszow University of Technology is the place where production of single crystal nickel base superalloys has been proved technically feasible. This paper presents the method of manufacturing the single crystal superalloys turbine blades and the prospective developments of the enterprise.

Design/methodology/approach: Turbine blades were produced in the vacuum induction melting furnace ALD for investment casting of equiaxed, directionally solidified and single crystal materials. The CMSX-6 nickel based superalloy is used for production of turbine blades.

Findings: The ceramic moulds production process was formulated. All main parameters of single crystal production was accordanted.

Research limitations/implications: EBSD analysis clearly revealed that the casted turbine blades are single crystals and possessed [001] crystal orientation.

Originality/value: The paper gives a general review of the technology of production single crystals turbine blades.

Keywords: Superalloys, Single crystal, Turbine blades, Casting, CMSX-6

1. Introduction

CMSX-6 superalloy was used to produce the single crystal turbine blades. Most of nickel based alloys contain 10-20% Cr, up to 8% Al and Ti, 5-10% Co, and small amounts of B, Zr, and C. Other common additions are Mo, W, Ta, Hf, and Nb. The major phases present in most nickel superalloys are as follows gamma (γ) and gamma prime (γ'). The continuous matrix (called gamma) is an face-centered-cubic (FCC) nickel-based austenitic phase that usually contains a high percentage of solid-solution elements such as Co, Cr, Mo, and W. The primary strengthening phase in nickel-based superalloys is $Ni_3(Al,Ti)$, and is called gamma prime (γ'). It is a coherently precipitating phase with an ordered $L1_2$ (FCC) crystal structure. The close match in matrix lattice parameter (~0-1%) combined with the chemical compatibility allows the γ' to precipitate homogeneously throughout the matrix and have long-time stability. Interestingly, the flow stress of the γ' increases with increasing temperature up to about 650°C. In addition, γ' is quite ductile and thus imparts strength to the matrix without lowering the fracture toughness of the alloy. Aluminum and titanium are the major constituents and are added in amounts and mutual proportions to precipitate a high volume fraction in the matrix. In some modern alloys the volume fraction of the γ' precipitate is around 70%. There are many factors that contribute to the hardening imparted by the γ' and include γ' fault energy, γ' strength, coherency strains, volume fraction of γ', and γ' particle size [1].

The three main advantages of single crystal over the conventionally cast and directionally solidified components are [2]:

a) Elimination of grain boundaries transverse to the principal tensile stress axis has reduced grain boundary cavitations and cracking, resulting in greatly enhanced creep ductility,
b) Elimination of grain boundaries made strengthening elements, such as carbon and hafnium redundant. This has facilitated heat treatment and allowed for the further optimization of the alloy chemistry to increase of the high temperature capability,

c) The preferred <001> crystallographic solidification direction, which coincides with the minimum in Young's modulus and is oriented parallel to the component axis minimizes the thermal stresses developed on engine start-up and shut-down, this has dramatically improved the thermal fatigue resistance of the turbine hot gas path components.

2. Description of the approach, work methodology, materials for research, assumptions, experiments etc.

Make a wax model is the first step in the production of single crystal turbine blade (Fig. 1). A wax model of the casting is prepared by injecting molten wax into a metallic mould – if necessary by allowing wax to set around a ceramic core, which is a replica of the cooling passages required. These are arranged in clusters connected by wax replicas of runners and risers; this enables several blades to be produced in a single casting.

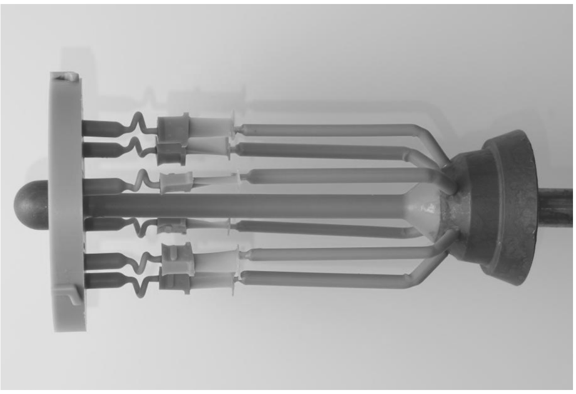

Fig. 1. Wax model of turbine blades

An investment shell is produced by dipping the model into ceramic slurries consisting of binding agents and mixtures of zircon ($ZrSiO_4$), alumina (Al_2O_3) and silica (SiO_2), followed by stuccoing with larger particles of these same materials. This operation is usually repeated three or four times until the shell thickness is adequate. Finally, the mould is baked to build its strength. The first step involves a temperature just sufficient to melt out the wax – usually a steam autoclave is used. Further steps at higher temperatures are employed to fire the ceramic mould (Fig. 2). After preheating and degassing, the mould is ready to receive the molten superalloy, which is poured under vacuum at a temperature of ~1550°C. After solidification is complete, the investment shell is removed and the internal ceramic core leached out by chemical means, using a high-pressure autoclave. It is clear from this description that many steps are required. Fortunately, in most modern foundries considerable amounts of automation have been introduced [2-9].

In Research and Development Laboratory for Aerospace Materials we using Vacuum Induction Melting furnace ALD for investment casting of equiaxed superalloy materials, directionally solidified and single crystal materials for making aircraft engine turbine blades (Fig. 3). This furnace has a conventional Bridgman crystal-growing method. A speed of a few inches per hour is typical – so that the solid/liquid interface progresses gradually along the casting, beginning at its base. This has the effect of producing large, columnar grains which are elongated in the direction of withdrawal, so that transverse grain boundaries are absent [10]. In a variant of this process, the grain boundaries are removed entirely. Most typically, this is achieved by adding a "grain selector" to the very base of the wax mould, typically in the form of a pig-tail-shaped spiral (Fig. 4a).

Fig. 2. Ceramic moulds for production the single crystal turbine blades

Fig. 3. Vacuum induction melting furnace ALD for investment casting of single crystal materials

Since this is not significantly larger in cross-section than the grain size, only a single grain enters the cavity of the casting, which is then monocrystalline form. Alternatively, a seed can be introduced at the base of the casting; provided the processing conditions are chosen such that this is not entirely, growth occurs with an orientation consistent with that of the seed. Figure 4b shows turbine blade after removal of the investment shell, with pig-tail grain selector still in place [11-15].

Figure 5 is schematic illustration of the casting furnace used for the production of single crystal turbine blades. An important recent contribution has come from the alignment of the alloy grain in the single crystal blade, which has allowed the elastic properties of the material to be controlled more closely. These properties in turn control the natural vibration frequencies of the blade.

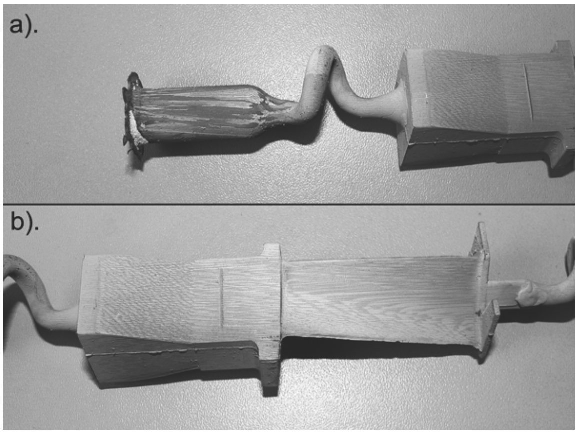

Fig 4. a) Grain selector – pig-tail-shaped spiral, b) turbine blade after removal of the investment shell

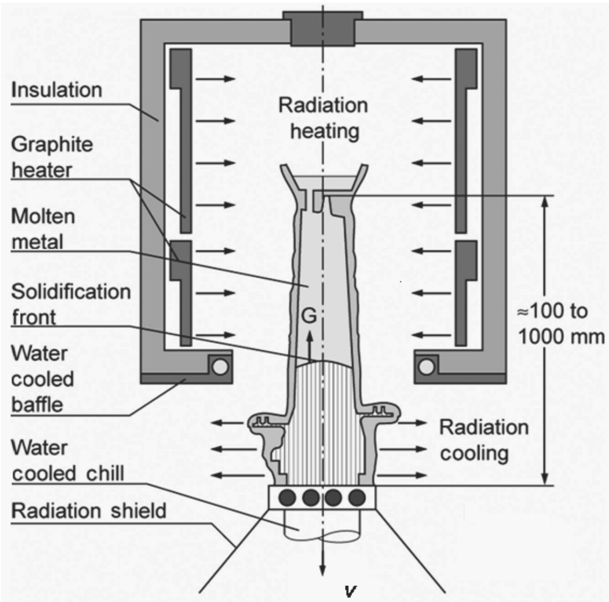

Fig. 5. Schematic illustration of vacuum induction melting furnace ALD, G – temperature gradient, v – velocity of draw out

3. Description of achieved results

The preferred grown direction for nickel and its alloys, in common with all known FCC alloys, is <001>. Thus turbine blade airfoils have a <001> direction aligned along, or close to, the axis of the casting. The dendrites grow at a rate which is largely controlled by solute diffusion, since the solid phase grows from the liquid with a very different composition from it, thus the local dendrite tip undercooling, scales monotonically with the velocity (v) of the dendrite, measured along the temperature gradient (G). It follows that dendrites which are misaligned by an angle Θ with respect to perfectly aligned ones must grow at a greater undercooling and hence at the rear of the grown front (Fig. 6).

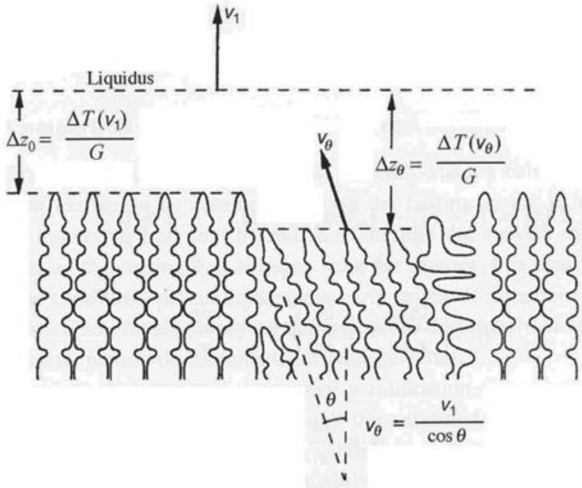

Fig. 6. Illustration of the competitive grain growth process, in which misaligned dendrites are suppressed by the secondary arms of well aligned ones [2]

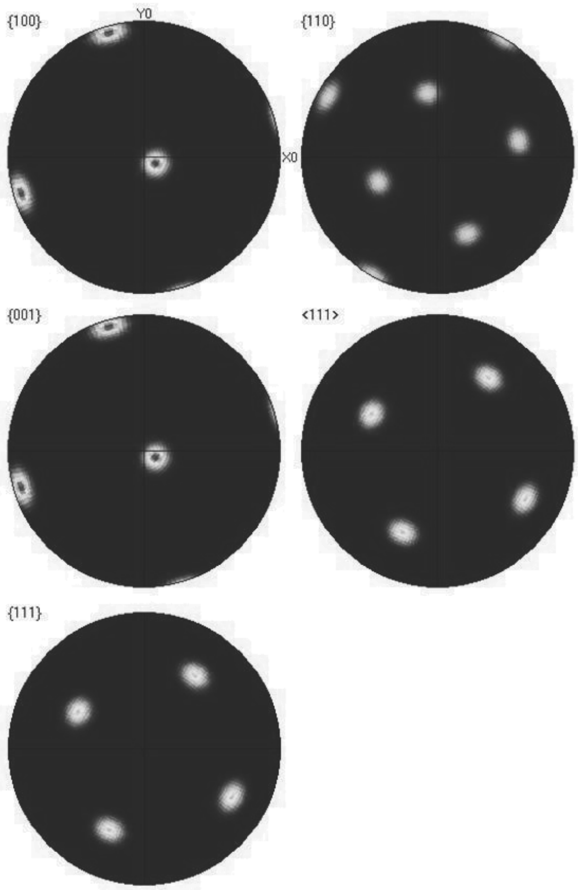

Fig. 7. EBSD pole figures corresponding to the various orientation map

Figure 7 shows an EBSD orientation maps for CMSX-6 superalloy. <001> is a prefer crystal orientation for CMSX-6 and Fig. 7 shows this orientation.

Fig. 8. The microstructure of CMSX-6 single crystal turbine blade (center area of the turbine blade)

4. Conclusions

The laboratory tests show that, the technology of production single crystals is completely elaborated. Single crystal turbine blades have a adequate microstructure (Fig. 8) for CMSX-6 superalloy and [001] crystal orientation (Fig. 7). The remark was paid in the work to the critical stages of the process of the production of ceramic forms and single crystal turbine blades with CMSX-6.

At present in Research and Development Laboratory for Aerospace Materials in Rzeszow University of Technology are led experimental works with settlement of the correct conditions of the process of the production of the forms and casting single crystal turbine blades with alloys CMSX-4, CMSX-10 and PWA 1426.

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