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Formation of low angle boundaries in Ni-based superalloys

N. D'Souza[a,*], M. Newell[a,b], K. Devendra[a], P.A. Jennings[c], M.G. Ardakani[d], B.A. Shollock[d]

[a] *Precision Casting Facility, P.O. Box 31, Rolls-Royce plc, Derby DE24 8BJ, UK*
[b] *IRC in Materials Processing, The University of Birmingham, Edgbaston, Birmingham B15 2TT, UK*
[c] *Company Research and Development Foundry, P.O. Box 3, Rolls-Royce plc, Filton, Bristol BS34 7QE, UK*
[d] *Department of Materials, Imperial College London, Exhibition Road, London SW7 2BP, UK*

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Abstract

The evolution of misorientation accompanying branching and growth of dendrite stems advancing into an increasingly undercooled liquid at a geometrical discontinuity in cross section (platform of a turbine blade) during solidification of a Ni-base superalloy has been experimentally investigated. The misorientation generated is *cumulative* in nature with a systematic rotation of the principal ⟨0 0 1⟩-crystal axes. It is proposed that the misorientation arises from plastic deformation of the dendrite stems during growth. Low angle boundaries are subsequently produced across impinging dendrite fronts.

Keywords: Cumulative misorientation; Low angle boundary; Dendrite; Plastic bending

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1. Introduction

Turbine blades in single crystal form are routinely cast from Ni-base superalloys. The primary aims of producing single crystals are to: (a) eliminate grain boundaries that limit creep ductility and (b) orient the elastically soft ⟨0 0 1⟩ orientation parallel to the maximum load to minimise cyclic stresses during thermal cycling [1]. The nucleation of stray grains must be avoided during casting of single crystal components, since elements added for grain boundary strengthening are absent. While *nucleation* of geometrically undercooled defects with random misorientation at changes in cross section (e.g. platforms in turbine blades) have been well understood, not much attention has been devoted to the evolution of low/medium angle boundaries within platforms. Using a simple analytical model, Napolitano and Schaefer [2] considered the formation of a low angle boundary to be associated with: (a) initial widening of the primary front; (b) the growth of the split portions; and (c) subsequent impingement of the approaching envelopes at a discontinuity in area. However, they did not address the reason why such a misorientation develops; rather their model tracks the evolution of solid for a given thermal field and specimen geometry and supposes *that every branching event is accompanied by misorientation*; therefore, greater the number of branching events, the larger the misorientation. Newell et al. [3] have attempted to identify the contributions of dendrite *branching* and *growth* in the generation of misorientation under conditions of *directional growth*. In the case of *successive branching* through an elongated spiral or *sustained growth* of a near-axial ⟨0 0 1⟩ orientation in a vertical rod, an upper bound in mean misorientation of 3° was observed. Moreover, the development of misorientation was not monotonic (cumulative). It suggests therefore, that the development of misorientation is not a direct manifestation of branching or growth.

This article describes the generation of misorientation at a geometrical discontinuity in cross section, where dendrite branching and growth occurs during growth of solid. In an earlier study [3] we have reported a detailed microstructural analysis coupled with a thermal model that described the evolution of solid accompanying growth under such non-steady-state conditions. Here, we focus on analysing the crystallographic aspects of misorientation that develop in an attempt to identify a cause for the formation of low/medium angle boundaries.

2. Experimental methods

Turbine blades in single crystal form were directionally solidified using a fully instrumented industrial directional

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[*] Corresponding author. Tel.: +44 1332 244 588; fax: +44 1332 246 933.
E-mail address: Neil.Dsouza@Rolls-Royce.com (N. D'Souza).

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solidification furnace situated at the Precision Casting Facility, Rolls-Royce plc, Derby, UK. A complete description of the furnace and relevant details are available elsewhere [4]. The third generation Ni-base superalloy, CMSX 10N was cast; nominal composition and freezing temperature range are reported elsewhere [5]. The process parameters include an imposed mould withdrawal rate of $5 \times 10^{-5}\,\mathrm{m\,s^{-1}}$ resulting in an average thermal gradient of $3\,\mathrm{K\,mm^{-1}}$ at the solidification front. A detailed thermal analyses using a commercial software package, ProCAST® coupled with a Cellular Automata Finite Element (CA-FÉ) undercooling model [6] was used in an earlier investigation to simulate the evolution of the dendrite envelope within the platform [3].

The electron back scattered diffraction (EBSD) technique was used to follow the orientation changes accompanying dendrite branching and growth within the platform. The EBSD analysis was conducted on a JEOL 840 scanning electron microscope (SEM) equipped with SINTEF hardware for pattern collection. The patterns were acquired with an accelerating voltage of 20 kV using a beam current of 4 nA. Automated pattern analyses and presentation of data was achieved using *Channel*+ software. Additional details are available elsewhere [7]. Optical microscopy to examine the dendritic structure within the platform was done using an Olympus BX60M optical microscope equipped with a JVC KY-F55B CCD for image capture. Nimonic reagent was used to etch the dendritic structure. Optical

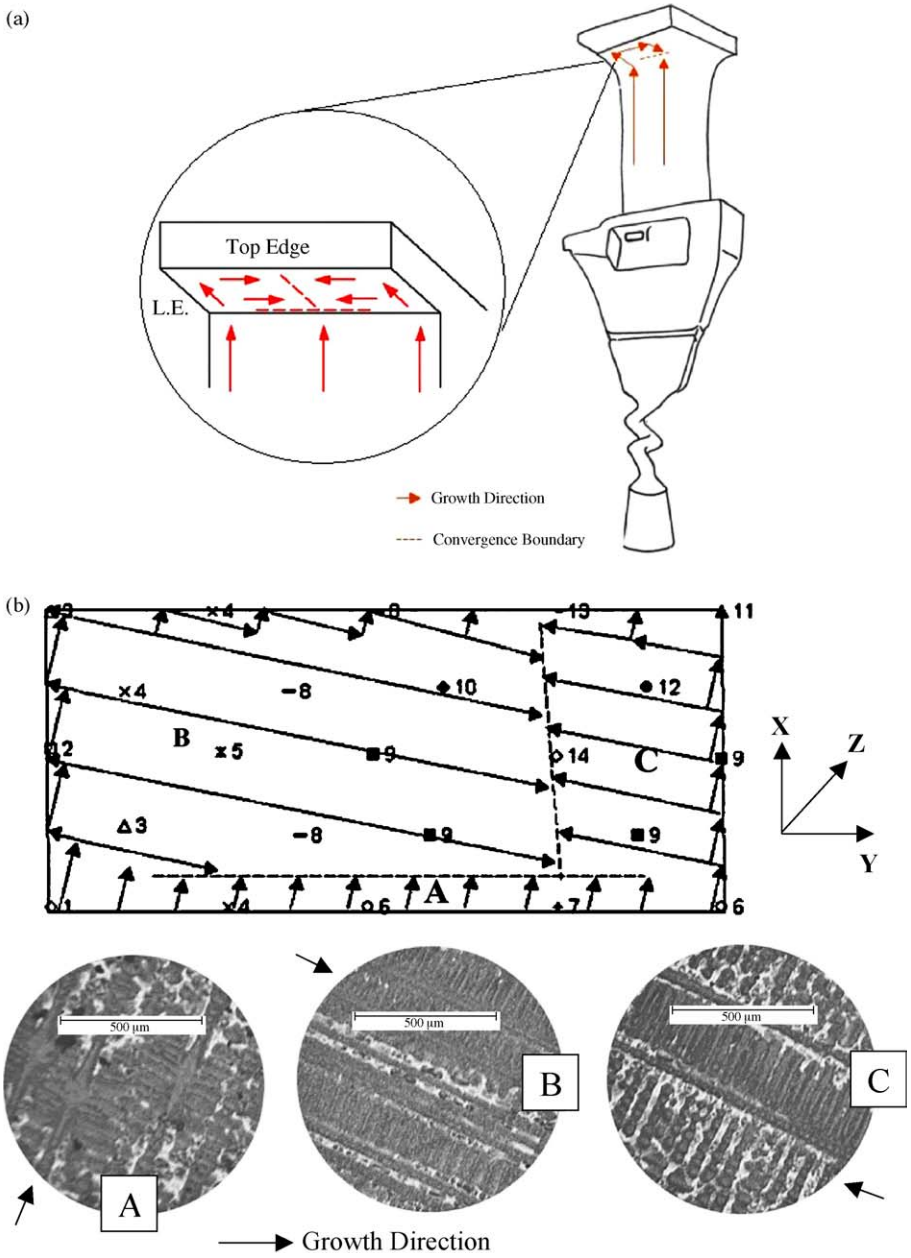

Fig. 1. (a) Schematic diagram showing branching and growth of dendrite envelopes in a turbine blade platform. (b) Evolution of dendrite envelope and microstructure within the platform base in a directionally solidified single crystal turbine blade: schematic diagram showing branching/growth pattern of dendrites within platform; optical micrographs showing dendrite morphology within platform.