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Lattice misfit during ageing of a polycrystalline nickel-base superalloy

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Abstract

The temporal evolution of the lattice parameters and lattice misfit of an advanced polycrystalline nickel-base superalloy have been studied in situ during an ageing heat treatment using synchrotron X-ray diffraction. During ageing, the γ and γ' lattice parameters were both observed to decrease, a trend that cannot be attributed to a loss of coherency alone. Phase-extracted γ' replicated this behaviour. Atom probe tomography was used to measure the compositional changes between the start and end of the ageing heat treatment. Using these data, a thermodynamic assessment was made using the software ThermoCalc of the structural change across the interface between γ and γ'. Subsequently, the unconstrained lattice parameters were estimated and were shown to be in good agreement with the X-ray diffraction measurements. Thus, the observed anomalous lattice misfit behaviour was concluded to be dominated by elemental exchange between the γ and γ' phases during ageing.

Keywords: Misfit; Synchrotron radiation; X-ray diffraction (XRD); Nickel alloys; Coarsening

1. Introduction

Nickel-base superalloys are capable of operating under high mechanical loads at elevated temperatures whilst simultaneously providing exceptional resistance to environmental degradation [1]. These alloys derive their strength from an A1, γ matrix with a dispersion of $L1_2$, γ' precipitates. The size and distribution of these precipitates are carefully controlled during processing and subsequent heat treatments to optimize mechanical performance. To minimize changes in precipitate morphology and size, the composition of the γ and γ' are tailored to control and limit their lattice misfit and hence maintain interfacial coherency. In particular, refractory elements, which are added to improve high-temperature properties have a strong influence on the lattice parameters [2,3] and are carefully balanced to provide an appropriate lattice misfit between the two constituent phases. In addition, the cooling rates following heat treatment affect the partitioning of elements between the γ and the different γ' distributions, where present, and must therefore also be carefully considered [4,5].

Modern nickel-base superalloys processed by powder metallurgy for gas turbine disc applications typically have a trimodal γ' distribution. Primary γ' is formed at the grain boundaries, with precipitate diameters between 1 and 5 μm. These precipitates pin grain boundaries, inhibiting boundary migration during subsolvus thermal exposures. In addition, intragranular distributions of secondary and tertiary γ' are present following precipitation during cooling. The size and distribution of these precipitates varies for different alloys, and can be controlled through processing to

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ensure that cutting by strongly coupled dislocations is favoured over cutting by weakly coupled dislocations, thereby maximizing mechanical performance [6–8]. For the nickel-base superalloy RR1000 [9] the size of the secondary γ' is typically 50–350 nm and tertiary γ' is 5–50 nm [10].

Contemporary processes in turbine disc manufacture such as dual microstructure heat treatments (DMHTs) lead to spatial variations in the precipitate distributions across the component. In the DMHT process, the bore of the disc remains at subsolvus temperatures, retaining a trimodal γ' distribution, whilst the rim of the disc is subjected to supersolvus temperatures, creating a bimodal distribution with no primary γ', and allowing grain growth [11,12].

In this study, the temporal evolution of a bimodal γ' distribution produced by rapid cooling from a supersolvus solution heat treatment has been studied using synchrotron X-ray diffraction (XRD) during an ageing heat treatment, thereby allowing the associated variations in the lattice parameters and lattice misfit to be characterized. The influence of compositional changes during ageing have also been considered using atom probe tomography (APT).

2. Experimental

2.1. X-ray diffraction measurements

To characterize the evolution of the lattice misfit during ageing, an in situ experiment was carried out using the ID31 high-resolution powder diffractometer at the European Synchrotron Radiation Facility, France. The setup of the experiment and instrument are shown in Fig. 1a. Samples of the advanced polycrystalline nickel-base superalloy RR1000 were subjected to a 4 h supersolvus heat treatment at 1170 °C followed by an oil quench to obtain a fine bimodal γ' distribution. Such heat treatments have the potential to produce γ' distributions that can maximize the strength of the superalloy [8] and are therefore of great interest. Prior to the solution heat treatment given to the material in this study, the material had been subjected to extrusion and forging from a powder-processed billet followed by a subsolvus heat treatment to provide intergranular primary γ' as well as secondary and tertiary intragranular γ'.

A scanning electron microscopy (SEM) image of this material is shown in Fig. 2(a). Cylindrical specimens, 1.25 mm in diameter and with a height of 2.5 mm, were cut from these samples using electrodischarge machining. Any surface oxide was removed by manual abrasion with 800 grit SiC paper. The specimens were placed into borosilicate glass capillaries, with a narrower capillary butting up to the sample, holding it in place and affixed to the sample

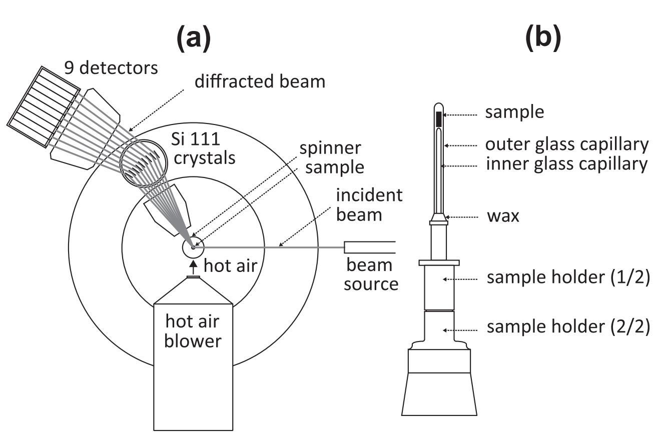

Fig. 1. Schematic illustrations of (a) the ID31 diffractometer and (b) a standard ID31 sample holder assembly.

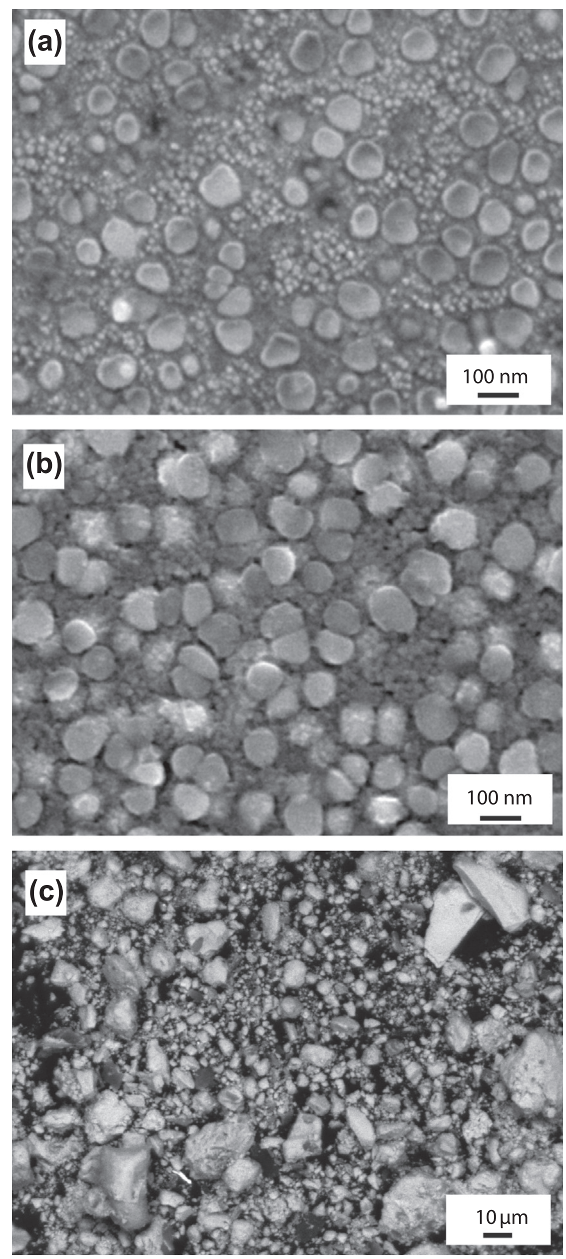

Fig. 2. Microstructure of RR1000 at (a) $t = 0$ and (b) after $t = 16$ h at 760 °C; (c) phase-extracted γ' precipitates.