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A modelling approach to yield strength optimisation in a nickel-base superalloy

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ABSTRACT

A computational methodology combining models of precipitation and dispersion strengthening with grain growth and grain boundary hardening has been produced to provide a predictive capability of the microstructure and yield strength of nickel-base superalloys subjected to arbitrary thermal cycles. This methodology has been applied to optimise the post-forging heat treatment of the advanced polycrystalline nickel-base superalloy, RR1000, to provide an improved proof stress. The temperature dependent antiphase boundary energies required were obtained using thermodynamic data and temperature dependent lattice parameters obtained via *in situ* synchrotron X-ray diffraction. Optimal yield strength properties between 600 and 700 °C were predicted with precipitates in the range of 34–57 nm. The precipitation modelling software, *PrecipiCalc* was used to optimise the solution and ageing heat treatments to maximise the volume fraction of intragranular γ' precipitates within the target precipitate size range, whilst maintaining a critical minimum volume fraction of primary γ' to give a grain size of 7 μm. The optimal yield strength of the material was predicted following a heat treatment consisting of 4 h at 1105 °C; cooling to ambient at 40 °C s^{-1}, and ageing for 16 h at 798 °C. Tensile testing at 650 °C of samples subjected to this heat treatment showed a 125 MPa increase in yield strength over RR1000 in the conventional microstructural condition. However, this was accompanied by a significant loss of ductility.

1. Introduction

Nickel-base superalloys are an important class of materials, capable of operating under high loads at elevated temperatures whilst maintaining good surface stability with inherent oxidation and hot corrosion resistance (Sims et al., 1987). Their excellent high temperature strength principally arises from a dispersion of $L1_2$, γ' precipitates, with compositions selected to have a low lattice misfit with the A1, γ matrix (Mishima et al., 1985; Brückner et al., 1997). In the polycrystalline nickel-base superalloys used for turbine disc applications, the microstructure typically contains three distinct γ' distributions, denoted as primary, secondary and tertiary γ'. During manufacture of turbine disc components, heat treatments are applied that tailor the size, distribution and morphology of these precipitates to provide mechanical properties suitable for the application.

The primary γ' forms at grain boundaries and serves to inhibit grain boundary migration by Zener pinning. These precipitates typically have diameters of 1–5 μm (Connor, 2009), with their size and volume fraction being controlled via solution

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heat treatments close to the γ' solvus temperature. On cooling from the solution heat treatment temperature, sufficient undercooling of the supersaturated γ matrix allows nucleation of the secondary γ' precipitates, which grow to an extent dependent on the time dependent diffusion fields surrounding each nuclei. With sufficiently high cooling rates, the lower diffusional mobility of atomic species may lead to the formation of channels in the matrix which cannot interact with the diffusional fields of the secondary precipitates (Radis et al., 2009). Upon further cooling, nucleation of a tertiary γ' population may then occur within these channels (Wen et al., 2003). As the size, morphology and distribution of γ' precipitates critically control mechanical properties, the multimodal γ' distributions produced in nickel-base superalloys have been extensively studied using both experimental and modelling methods (Babu et al., 2001; Wen et al., 2003, 2006; Sarosi et al., 2007; Singh et al., 2011). For the nickel-base superalloy, RR1000, the precipitate size distributions (PSDs) of the secondary and tertiary γ' precipitates typically lie in the ranges, 50–350 nm and 5–50 nm, respectively (Connor, 2009).

During the contemporary process of dual microstructure heat treatments (DMHT), the rim of the disc is subjected to supersolvus temperatures, dissolving the primary γ', allowing grain growth and an increased volume fraction of intragranular γ', thereby improving creep properties. Conversely, the bore of the disc is subjected to a subsolvus heat treatment, retaining the primary γ', which inhibits grain growth and preserves the fine grain structure necessary for static strength and good fatigue crack properties (Mitchell et al., 2008; Mourer and Williams, 2004). As each radial location will experience a unique thermal cycle, as illustrated by Fig. 1, prediction of the location specific microstructure and properties is not trivial.

Unlike the location specific solution heat treatment experienced during DMHT processing, ageing heat treatments are typically performed under isothermal conditions. This cannot compensate for any variations in secondary and tertiary γ' PSDs that arise as a consequence of the location specific thermal cycles experienced prior to ageing. The isothermal heat treatment conditions selected will therefore be a compromise between the range of properties required across the disc rather than optimised to meet the needs of a specific location. In principle, it may be possible to develop location specific ageing heat treatments to optimise the PSDs and hence the properties across the disc. However, determination of the conditions required using experimental techniques is quite impractical, with each radial location requiring a unique heat treatment. It is therefore desirable to be able to accurately predict the precipitation behaviour for an arbitrary thermal cycle and, using this, tailor a heat treatment for target precipitate sizes and subsequent properties.

In a study by Jackson and Reed (1999), the size of the secondary γ' in the nickel-base superalloy U720Li was found to be strongly dependent on the cooling rate from the solution heat treatment. In addition, only coarsening of the tertiary γ' was observed during ageing, with the secondary γ' remaining largely unchanged. Tensile testing of samples following various heat treatments showed an approximately parabolic relationship between the proof stress and ageing time, with peak yield strength properties being achieved with a precipitate size close to the transition from strong to weak dislocation coupling.

A later study by Kozar et al. (2009) assessed the strengthening mechanisms in the polycrystalline nickel-base superalloy, IN100. Their investigation also incorporated models of weak and strong dislocation coupling, similar to the study by Jackson and Reed (1999). Modifications of note included the assumption that all dislocations have mixed character and that precipitate sizes are described by distributions, rather than a mean radius alone. This is particularly important when the distribution extends across the transition from weak to strong dislocation coupling. In addition, the effects of temperature on pair coupling was also incorporated by the addition of thermally activated deformation, as described by Kocks et al. (1975).

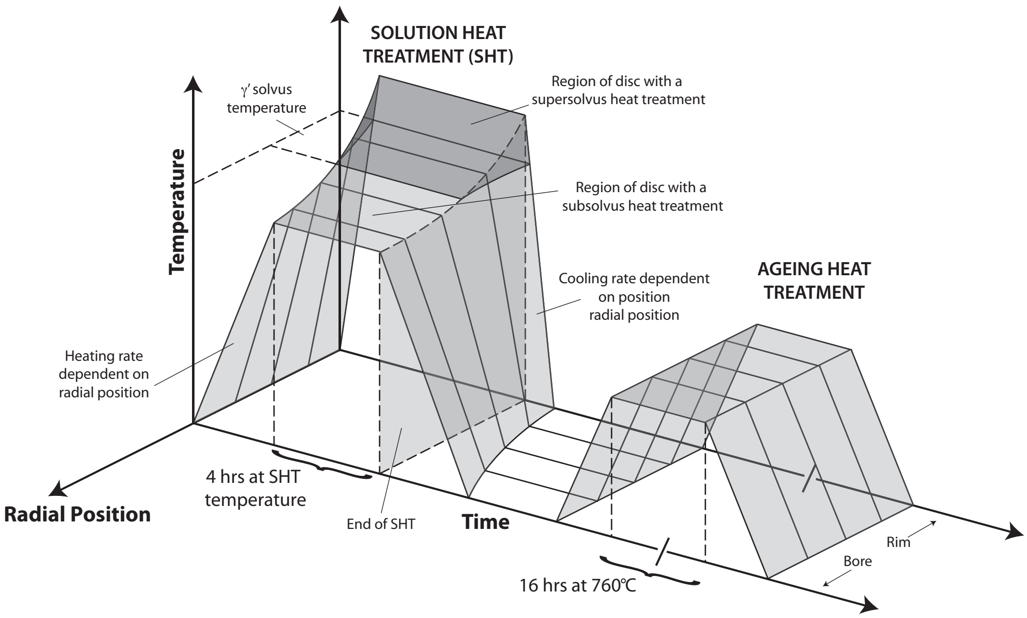

Fig. 1. Schematic illustration of the post-forging heat treatments experienced by a turbine disc during dual microstructure heat treatments.