Discussion

Comments on "Long term growth of γ' particles"

In a recent paper, Footner and Richards [1] discuss the coarsening of γ' particles in a number of commercial nickel-base superalloys. Several points worthy of comment are raised by these authors.

It should firstly be appreciated that, despite the title of their work, Footner and Richards describe the coarsening, rather than the growth of γ' particles. The initial ageing treatments given to the various alloys will have produced a microstructure containing a near "equilibrium" volume fraction of γ' (see [2]); changes to the microstructure without significant changes in γ' volume fraction are then described. Developments in γ' morphology, from spherical, to cuboidal, to "degenerate" are reported to occur during this coarsening process. The sizes at which these transitions occur agree quite well with the observations of a similar study, in which the growth of isolated γ' particles was investigated [2]. However, it is inconceivable that, in the present case, the reported morphological transitions are associated with changes in the precipitate/matrix mismatch resulting from a time dependent composition of the matrix, as suggested by Footner and Richards [1]. Particle coarsening, by definition, is not accompanied by a change in precipitate volume fraction; thus the matrix composition must remain essentially constant as ageing proceeds.

The development of γ' morphologies which are described as degenerate is likely to be associated with one (or more) of three processes. Firstly, the minimization of strain energy by the adoption of cubic γ' morphology is only to be expected when the γ/γ' interface is fully coherent. Any loss of coherency as the γ' particle grows will result in a decrease in the relative favourability of $\{100\}$ γ/γ' interfaces, since the effects of elastic anisotropy are diminished. Semi-coherent γ' particles have previously been shown to adopt morphologies with poorly defined facets (e.g. [3]). Secondly, because of the inhomogeneity of the initial γ' distribution, coarsening may lead to the development of irregularly shaped particles simply because of the spatial variation in the availability of γ'-forming solute. Lastly, coalescence of coarsening γ' particles may also result in degenerate precipitate shapes.

The data presented for Nimonic 105 indicate that the development of "degenerate" γ' shapes is less favoured in this alloy than for Nimonics 80A or 90. It has recently been shown that the γ/γ' misfit is very much smaller in Nimonic 105 than in Nimonics 80A or 90 [4]. The less the magnitude of the misfit, the larger the γ' size at which loss of coherency would be expected; the implication, then, is that the development of "degenerate" γ' particles is associated with precipitate coherency loss. The relatively small size at which the spherical–cubic transition occurs in Nimonic 105 in Footner and Richards' paper is somewhat at variance with the results of Ricks *et al.* [2].

The calculation of γ/γ' interfacial energies requires (as Footner and Richards state) detailed knowledge concerning the concentrations and solubilities of solute species within, and near to, growing γ' particles. These data are clearly difficult to obtain with EDS measurements when γ' particles are small and present in high number densities. However, examination of isolated γ' particles of size greater than the foil thickness may allow the relevant information to be obtained, albeit for a somewhat different microstructure. Diffusion fields around growing γ' particles have been measured in Nimonic 80A, and an estimate of γ/γ' interfacial energy obtained [2]. The γ/γ' mismatch, and the symmetry and magnitude of the strain field around γ' particles may all be quantified, with certain restrictions on the microstructure, by convergent beam electron diffraction [4, 5]. Nonetheless, atom-probe field ion microscopy is likely to provide the best quantitative information about solute levels at the γ/γ' interface, as Footner and Richards suggest.

In conclusion, then, whilst the coarsening data of Footner and Richards are undoubtedly useful in understanding the long-term stability of nickel-base superalloys, their interpretation of the morphological changes observed is questionable. In any study of precipitate growth or coarsening, it is essential that the nature of the interphase boundary is characterized, and this information used in any development of a model for the process. It thus seems likely that, in view of a number of studies of similar alloys (e.g. [2, 6, 7]), the morphological sequence described by Footner and Richards may be explained by the gradual increase in local strain energy as the γ' particles coarsen, causing the development of cuboidal precipitates, followed by either coherency loss or impingement which results in a "degenerate" morphology.

References

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Reply to 'Comments on "Long term growth of γ' particles"'

Porter *et al.* [1] make some interesting comments on our recent paper [2], some of which require further clarification. These authors state that in our paper we were discussing a coarsening rather than a growth process. However, the semantic distinction depends on a knowledge of the constancy of the γ' volume fraction. In our experiments precise measurements of volume fractions were not made, due mainly to the large number of samples involved and the techniques adopted. Hence we were unable to comment on the constancy, or otherwise, of the γ' volume fraction or on whether the increase in average size of particles was due to coarsening alone. It was therefore thought prudent to use the more generalized term. However, it is possible in our case, over the extreme times involved, that local compositional changes or repartition of component elements might have occurred, in which case growth (or perhaps re-solution) is the more appropriate term. In this context it should be emphasized that whilst we investigated ageing times up to 15 000 h, the work of Porter *et al.* involved ageing times of only 24 h. Moreover, in the latter work no evidence was presented that equilibrium conditions and constancy of γ' volume fraction and composition had been obtained within the times of heat treatment.

Porter *et al.* state that in any study of precipitate growth or coarsening, it is essential that the nature of the interphase boundary be characterized, and this information used in any development of a model for the process. This is undeniably true, and for this reason we attempted, albeit unsuccessfully, to use a number of analytical techniques at our disposal to obtain such relevant information. As a result of this lack of data we stated "the causes of the changes in γ' morphology during ageing have been discussed, but lack of accurate data with regard to lattice parameters and compositions has prevented firm conclusions".

It was therefore surprising that Porter *et al.* should credit our work with having an unambiguous interpretation stating "their interpretation is questionable . . . it is inconceivable that the morphological transitions are associated with changes in the precipitate/matrix mismatch resulting from a time dependent composition of the matrix". We presented no such conclusion. Instead we discussed a number of possibilities and suggested additional techniques which could be used to resolve the ambiguities of interpretation. Having rejected our tentative suggestions, Porter *et al.* subsequently attempt to interpret our experimental data based on their work on ageing times up to 24 h. However, there must be a considerable question mark on the applicability of such short time data to our long term (15 000 h) study.

Since we made no firm interpretation of our observed morphological changes of spherical to cuboidal, we cannot comment on the suggestion that this was due solely to the degree of mismatch. However, it is interesting to note that the misfit values quoted by Porter *et al.* [3] were measured at room temperature. As noted by these authors the degree of mismatch probably changes at high

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