Scale Effects in the Structure of Modern Superalloys. Role of Nanoparticles

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Abstract—The structural state of the γ' and γ phases of modern superalloys is considered in detail. A classification of the scale effects in the γ' phase morphology is proposed.

INTRODUCTION

Modern superalloys are two-phase mixtures of the γ' and γ phases. Little attention is paid to the size effects in their structure. However, the problem of superalloy strengthening at different temperatures is closely related to the size effect. The purpose of this study is to consider in detail some versions of the structure of modern superalloys from the point of view of the size effect in the γ' and γ phases. The sizes of γ'-phase particles, shaped as quasi-cuboids or having some other shapes, are analyzed. The sizes of γ-phase interlayers are simultaneously considered.

PHASE COMPOSITION OF MODERN SUPERALLOYS

Let us briefly consider the main phases. γ' phase is an ordered Ni-based fcc solid solution with the $L1_2$ superstructure (Cu_3Au type) [1]. Its amount in different states ranges from 0.7 to 0.85 of the total volume of a material. Morphologically, the main fraction of the γ' phase consists of quasi-cuboids with clear faceting, surrounded by γ-phase interlayers (Fig. 1).

Modern superalloys are characterized by a large volume fraction of the γ' phase in the form of cuboid particles. The general scheme of the complex hierarchical structure of a superalloy is shown in Fig. 2. Generally, the alloy composition may include four structural levels of the γ' phase. They differ in scales and are denoted as γ'_{I}, γ'_{II}, γ'_{III}, and γ'_{IV} in the descending order. Cuboids of the γ'_{II} phase are generally of mesoscopic size. The two-phase mixture ($\gamma + \gamma'_{II}$), having a high cuboid density, is the main phase morphological component of a superalloy. It is stable to temperature and stresses.

SCALE EFFECTS IN THE MORPHOLOGY OF THE γ' PHASE

Figure 2 schematically shows the structure of a superalloy; this scheme is a generalization of the results obtained in a number of investigations. Size classification of the particles of the γ' phase and two-phase $\gamma' + \gamma$ mixtures is given in the table. The $\gamma'_{II} + \gamma$ mixture has the largest volume is a superalloy and forms large extended regions up to 500 μm in size. Real superalloys include some other scale formations of the γ' phase and a mixture of $\gamma' + \gamma$ phases. Primarily, large γ'_{I}-phase particles of dendritic origin can be present. These are isolated irregular particles, elongated in the ⟨001⟩ direc-

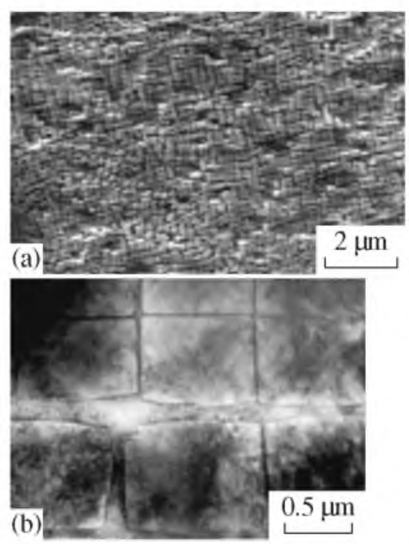

Fig. 1. Typical example of the two-phase structure of a γ' + γ superalloy: (a) SEM and (b) TEM images.

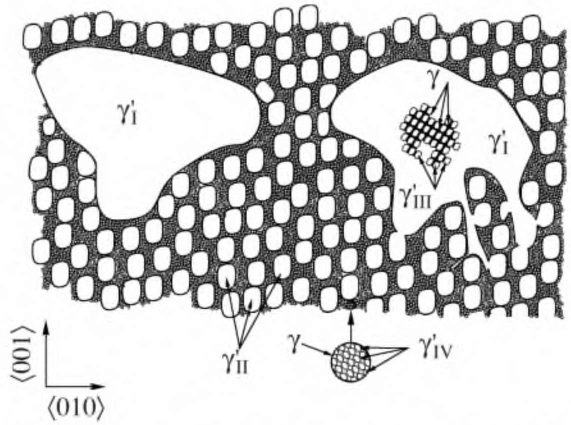

Fig. 2. Schematic image of the morphology of the γ' and γ phases on different scales in a superalloy.

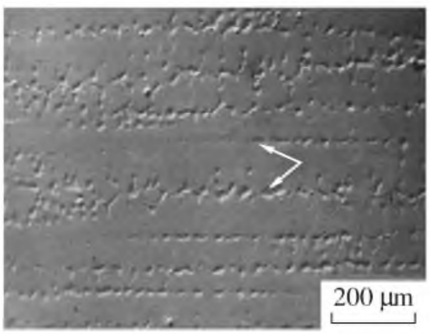

Fig. 3. SEM image of the superalloy structure (arrows indicate the first-level γ'-phase particles).

tion, so that they have a form of a dendritic structure at relatively small magnifications (Figs. 2–4). The interlayers between these particles are filled with a mixture of $\gamma'_{II} + \gamma$ phases. In turn, the space between cuboids of the second-level γ'_{II} phase is filled with interlayers of a fine-grained mixture of $\gamma'_{IV} + \gamma$ phases.

The main morphological component is a two-phase (γ and γ'_{II}) mixture, which is especially clearly seen at large magnifications (Figs. 4b–4d). This mixture contains quasi-cuboid γ'-phase particles. Particle of the γ'_{II} phase are clearly aligned in two directions of the $\langle 001 \rangle$ type.

Scanning electron microscopy (SEM) convincingly reveals the existence of γ'-phase regions of two scale levels in the alloy structure: large (25–90 μm) γ'_{I}-phase particles (the first level) and smaller (2.5–10 μm) γ'_{II}-phase particles (the second level) in the $\gamma'_{II} + \gamma$ mixture. The second-level γ'_{II}-phase particles exhibit coagulation in some directions (Fig. 4d), i.e., form the so-called "raft" structure [2].

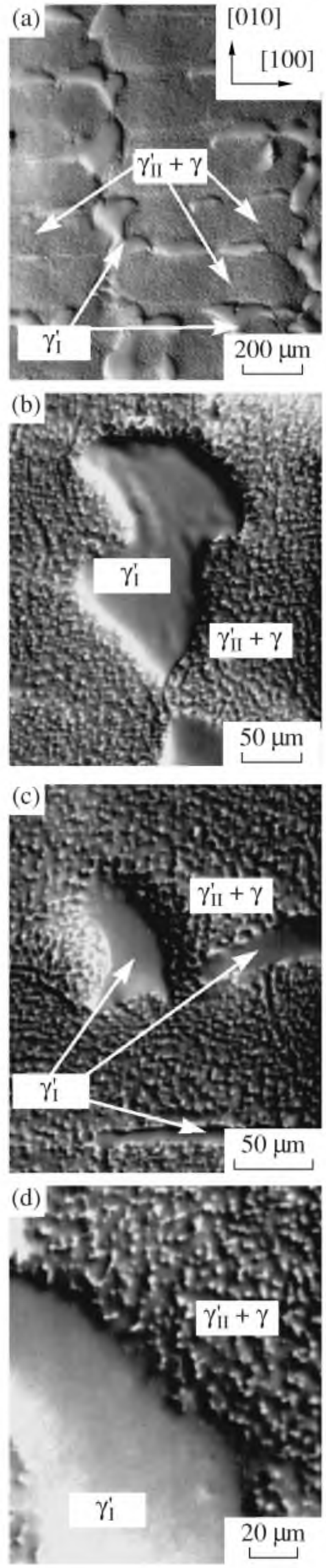

Fig. 4. SEM image of the superalloy structure. Arrows indicate the existing phases.

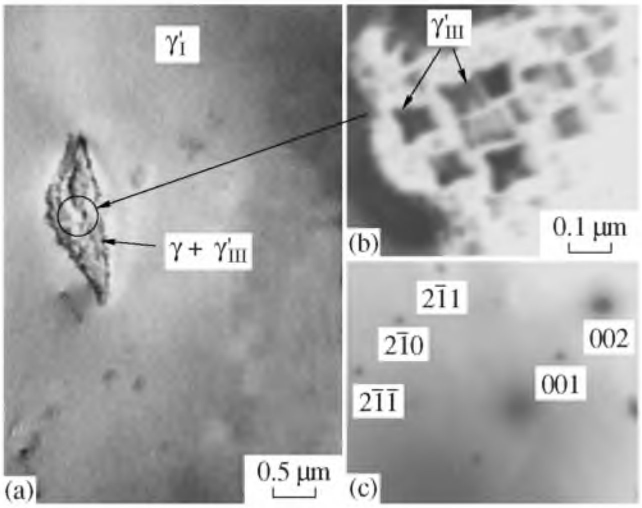

Fig. 5. Complex structure of the first-level $\gamma'_{\rm I}$ -phase particles in a superalloy: (a) bright-field image, a $\gamma'_{\rm I}$ particle consists of a two-phase $\gamma'_{\rm III}$ + γ mixture; (b) dark-field image in the [001] superstructural reflection, arrows indicate $\gamma'_{\rm III}$ particles separated by γ-phase interlayers; and (c) a microdiffraction pattern, containing 001, $2\bar{1}\bar{1}$, $2\bar{1}0$, and $2\bar{1}1$ superstructural reflections.

Investigation of the first-level $\gamma'_{\rm I}$-phase particles, which are similar to single-phase ones in SEM images, has revealed a complex structure of these regions. The $\gamma'_{\rm I}$-phase regions are either homogeneous or inhomogeneous particles (Fig. 5). With a large magnification, one can observe $\gamma'_{\rm I}$-phase particles of two types: (i) single-phase ones ($\gamma'_{\rm I}$) and (ii) particles with inclusions of two-phase ($\gamma'_{\rm III}$ + γ) regions (Fig. 5). The two-phase regions can be formed as a result of decomposition of the $\gamma'_{\rm I}$ phase according to the $\gamma'_{\rm I} \rightarrow \gamma'_{\rm III} + \gamma$ reaction upon superalloy annealing. The volume fraction of these regions is relatively small; their examples are shown in Fig. 5. These regions consist of quasi-cubic $\gamma'_{\rm III}$-phase particles (90–130 nm in size) and γ-phase interlayers with a width of ~10 nm. The bright-field images in Fig. 5 show $\gamma'_{\rm III}$-phase particles separated by γ-phase interlayers. The fine structure of second-level quasi-cuboid particles of the $\gamma'_{\rm II}$ phase and the γ-phase interlayers between them in the $\gamma'_{\rm II} + \gamma$ mixture can also be seen well in the transmission electron microscopy (TEM) images (Fig. 6). The diffraction patterns of the $\gamma'_{\rm II}$ + γ mixture contain superstructural reflections of the γ′ phase. Dislocations are present at the boundaries between the γ′ and γ phases. Detailed TEM analysis of the two-phase $\gamma'_{\rm II}$ + γ mixture showed that the γ-phase

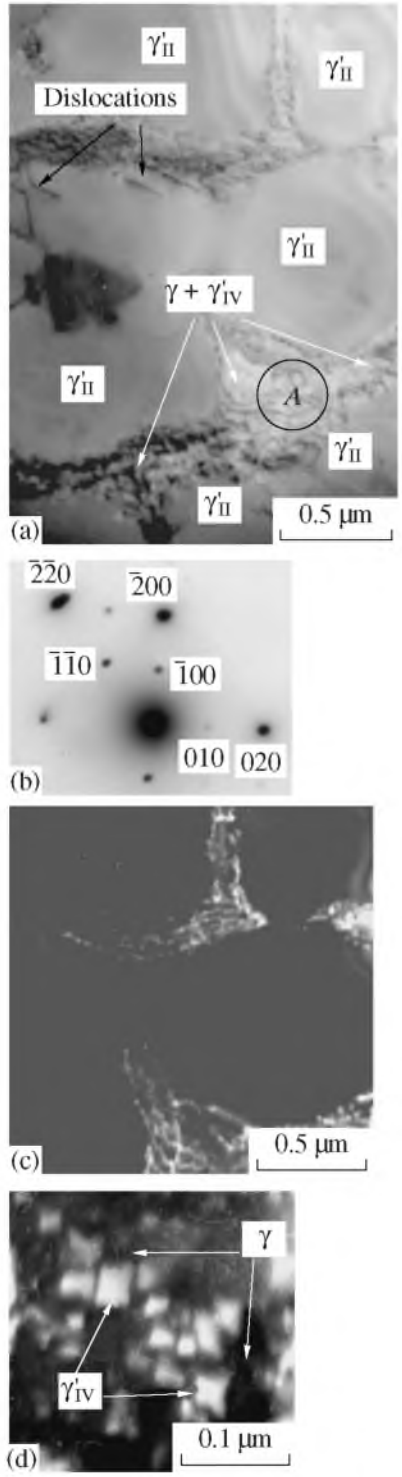

Fig. 6. TEM image of the superalloy structure: (a) bright-field image of $\gamma'_{\rm II}$ particles, white and black arrows show, respectively, the regions of the two-phase $\gamma + \gamma'_{\rm IV}$ mixture and dislocations; (b) a microdiffraction pattern corresponding to this foil region and containing $\bar{1}\bar{1}0$, $\bar{1}00$, and 010 superstructural reflections; (c) a dark-field image in the main 020 reflection; and (d) a dark-field image of the region *A* in the 010 superstructural reflection; white arrows indicate the phases in the two-phase $\gamma + \gamma'_{\rm IV}$ mixture.

Morphological structure parameters of the γ' and γ phases

Number of a structural level	Structural level	Structural elements	Size scale of γ'-phase particles
I	Main superalloy structure	$\gamma'_{II} + \gamma$ regions	150–500 μm
II	Residues of dendritic formations	γ'_{I} particles	25–90 μm
III	Mesolevel	γ'_{II} particles	2.5–10 μm
		$\gamma'_{III} + \gamma$ regions	0.45–1.0 μm
IV	Microlevel	$\gamma'_{IV} + \gamma$ interlayers	250–700 nm
V	Nanolevel	γ'_{III} particles	90–130 nm
		γ'_{IV} particles	30–80 nm
		γ-phase interlayers in the $\gamma'_{III} + \gamma$ mixture	10 nm
		γ-phase interlayers in the $\gamma'_{IV} + \gamma$ mixture	2–5 nm

interlayers in this mixture also have a complex structure (Fig. 6). They contain small quasi-cubic γ'_{IV} -phase particles, which are not observed in SEM images. Their identification with the use of bright- and dark-field (in the [010] superstructural reflection) images is shown in Figs. 6b and 6d. Small (30–80 nm) γ'-phase particles are classified here as the fourth-level γ'_{IV} particles of the γ' phase. The γ-phase interlayers between γ'_{IV} particles have thicknesses from 2 to 5 nm. Actually, γ'_{IV} and γ'_{III} particles are nanoscale ones [3].

CONCLUSIONS

γ'_{II} and γ'_{IV} particles are especially important in the formation of alloy properties. γ'_{II} particles form the main strengthening phase. Nanoscale γ'_{IV} particles fill channels of the γ phase between γ'_{II} cuboids. Thus, they form a new mechanism of superalloy strengthening. The width of the γ-phase interlayers, retained in this case, is such that dislocations cannot be generated and pass through them [3]. A paradoxical fact has been revealed: segregated γ'_{IV} nanoparticles strengthen a superalloy under creep conditions at high temperatures. This phenomenon should be used to increase the resource and improve the operation parameters of superalloys.

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