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Abstract—The lattice parameter mismatch between the \(\gamma\) and \(\gamma'\) phases (\(\gamma/\gamma'\) misfit) in single crystals of heat-resistant nickel alloys (HRNAs) ZhS32 and VZhM4 was studied by X-ray diffraction at different stages of creep deformation. It was established that, in ZhS32 single crystals, the anisotropy of the form change of the \(\gamma'\)-phase particles during creep is accompanied by an anisotropic change in the \(\gamma/\gamma'\) misfit, whereas, in VZhM4 single crystals, the misfit is almost constant in the directions along and perpendicular to the load direction.

Keywords: structural-phase mismatch, creep of nickel single crystals, relaxation of coherent stresses, size mismatch of lattice parameters of the \(\gamma\) and \(\gamma'\) phases, constrained \(\gamma/\gamma'\) misfit.

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INTRODUCTION

The lattice parameter mismatch between the \(\gamma\) and \(\gamma'\) phases (\(\gamma/\gamma'\) misfit) is one of the most important structural-phase characteristics of heat-resistant nickel alloys (HRNAs). This parameter is closely connected to the degree of concentration-related solid-solution strengthening, along with the creep rate and other high-temperature mechanical properties of single crystals, which ultimately determines the use of these materials under conditions of long-term high-temperature operation.

HRNAs are heterophase \(\gamma/\gamma'\) structures, with the strengthening \(\gamma'\)-phase volume content greater than 60% and a coherent joining of crystal lattices of the \(\gamma'\) phase based on an ordered Ni\(_3\)Al intermetllide with the L1\(_2\) structure and the disordered \(\gamma\) solid solution with the A1 structure.

The authors of [1] showed experimentally that splitting of the (004) matrix reflections in the X-ray diffraction patterns of domestic as-cast and thermally treated HRNA single crystals is caused by elastic distortions which produce coherent joining of lattices of the \(\gamma\) and \(\gamma'\) phases.

Upon long-term thermal annealing, the coherent joining between lattices is ruptured owing to motion of dislocations in the matrix channels promoted by coherent stresses. As a result, interfacial dislocation networks are formed, and the boundaries between the phases become semicoherent [2].

The loss of coherent joining takes place under high-temperature creep as well. In [3], it was shown that the loss of coherence during creep of SRR99 and CMSX-4 alloy single crystals raises the misfit owing to formation of interfacial dislocation networks.

The constrained misfit \(\Delta\) characterizes the degree of coherence of the \(\gamma/\gamma'\) interface. From the constrained misfit value measured in the deformed material, we may judge the stresses induced in phases by plastic creep deformation.

In the present paper, the values of the constrained \(\gamma/\gamma'\) misfit and the relative root-mean-square microdeformation (RMSMD) at different stages of high-temperature creep of HRNA single crystals are studied by X-ray diffraction.

MATERIALS AND METHODS

Single crystals of the ZhS32 and VZhM4 alloys belonging to different generations of HRNAs were taken for the investigations [4]. The chemical composition and technique for synthesis of the studied alloys are reported in earlier paper [1] and in patent [4].

The influence of creep deformation on the constrained \(\gamma/\gamma'\) misfit was studied by X-ray diffraction of longitudinal and transversal sections cut out of the heads and the working parts (\(d = 5\) mm) of the samples (Fig. 1) taken at different stages of creep deformation or after rupture (table). It is suggested that, during creep testing, the stresses in the heads of the samples
are an order of magnitude lower than those in their working parts owing to the difference in diameters. Therefore, the structural changes in the heads indicate mainly the temperature influence, whereas the mutual action of temperature and deformation shows up in the structure of the working parts of the samples. X-ray diffraction studies were carried out using a DRON-4-007 diffractometer in CuKα radiation.

The size mismatch between the lattice parameters (constrained misfit Δ) was calculated by the formula

\[ \Delta = \frac{a_γ - a_γ'}{a_γ}, \]

where \( a_γ \) and \( a_γ' \) are the lattice parameters of the \( γ \) and \( γ' \) phases in the [001] direction.

The technique of simulation and subsequent decomposition of the total profile into phase singlets is described in detail in [1].

The degree of splitting of the \( γ \)-matrix reflection due tetragonal lattice distortions (the degree of tetragonal character), characterized by the distance between the paired lines (004), was estimated by the relation

\[ \delta_m = \frac{a_γ - a_γ'}{a_γ}, \]

where \( a_γ \) and \( a_γ' \) are the lattice parameters for the \{001\} planes of \( γ \) interlayers parallel (P) and perpendicular (N) to the \( γ/γ' \) interface, respectively [5].

The RMSMD value \( \langle E^2 \rangle^{1/2} \) was calculated by the equation

\[ \langle E^2 \rangle^{1/2} = \frac{B}{2\sqrt{2\pi}\tan\theta}, \]

where \( B \) is the physical broadening of the X-ray line [6].

The morphology of particles of the strengthening \( γ' \) phase was investigated by conventional scanning electron microscopy using a JSM-6460LV instrument.

Regimes of creep testing

<table>
<thead>
<tr>
<th>Material</th>
<th>( T ), °C</th>
<th>( σ ), MPa</th>
<th>Creep life ( τ ), h</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>VZhM4*</td>
<td>900</td>
<td>410</td>
<td>830</td>
<td>Ruptured</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td>460</td>
<td>435</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1100</td>
<td>120</td>
<td>1303</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1100</td>
<td>140</td>
<td>680</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1100</td>
<td>160</td>
<td>179</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1100</td>
<td>180</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>ZhS32**</td>
<td>975</td>
<td>310</td>
<td>128</td>
<td>Taken from testing after 38, 64, 77, 89, and 102 h</td>
</tr>
<tr>
<td></td>
<td>1100</td>
<td>160</td>
<td>45.50</td>
<td>Taken from testing after 9, 13, 22, 31, and 36 h</td>
</tr>
</tbody>
</table>

Note: * Fabrication and testing at the All-Russian Scientific Research Institute of Aviation Materials (VIAM). ** Fabrication and testing at the Kazan Motor-Building Production Association (KMPO).