Heat-Resistant Steels

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HEAT-RESISTANT EUTECTIC ALLOYS WITH CARBIDE-INTERMETALLIC STRENGTHENING

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Some important characteristics of gas turbine engines (in the first place the thrust and the efficiency) depend on the gas temperature and hence are determined by the service life of the blades. Heat-resistant nickel alloys are used for casting blades that can work at maximum temperatures of 1050 – 1100°C. However, more efficient engines need materials with a higher operating temperature and high-temperature strength. The work concerns the principles of alloying and structure formation of eutectic heat-resistant alloys on a nickel base with carbide and intermetallic strengthening. Their main mechanical properties at high temperatures are analyzed in comparison with the characteristics of high-temperature single-crystal nickel alloys, and the possibility of using them for casting turbine blades of high-temperature gas-turbine engines is considered.

The high-temperature heat resistance of nickel alloys can virtually not be increased further by improving the alloying system. The use of directed crystallization for the production of turbine blades has raised their service characteristics and in particular their long-term strength considerably. In this case the long-term strength is increased by eliminating the inter-grain boundaries that are transverse relative to the acting stresses in the process of creating a single-crystal or columnar structure in castings. It has been established that castings of single crystals with the axial growth orientation <001> from high-temperature nickel alloys with the traditional alloying system have a long-term strength that is virtually the same as that of castings with columnar structure of the same composition, although the heat resistance of single crystals is higher. In order to realize the potentialities of single crystals, high-temperature nickel alloys with special alloying have been developed, that do not contain elements for strengthening grain boundaries (C, B, Zr, Hf), and the concentration of components in the γ- and γ’-phases is close to their maximum solubility in these phases. However, for the best single-crystal alloys such as CMSX-4 [1] elevation of the operating temperature above 1100°C is limited by the high solubility rate of the strengthening γ’-phase.

In this connection eutectic alloys of directed crystallization are of great interest as high-temperature materials for casting turbine blades. Nickel alloys with the structure γ / γ’ – MC (here γ / γ’ is a matrix of nickel γ-solid solution strengthened by γ’-phase based on Ni3Al; MC is filamentary crystals of a monocarbide based on niobium and tantalum) of the VKLS (Russia), COTAC (France), and NITAC (USA) types (Table 1) are the most promising.

The long-term strength at high temperatures in eutectic alloys of directed crystallization is higher than in conventional high-temperature nickel alloys such as ZhS6U, ZhS6UF [7], and MAR-M247 [8]. However, this characteristic in eutectic alloys of directed crystallization should be

### TABLE 1

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Content of elements, %</th>
<th>Density, g/cm³</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>VKLS-10</td>
<td>10.0 7.0 5.6 3.8 1.0 11.0 - 0.45 1.0</td>
<td>8.53</td>
<td>Author's data</td>
</tr>
<tr>
<td>VKLS-20</td>
<td>9.0 4.5 6.2 4.0 1.0 12.5 - 0.40 1.0</td>
<td>8.67</td>
<td>The same</td>
</tr>
<tr>
<td>VKLS-20R</td>
<td>9.0 4.0 6.2 4.0 - 12.0 4.0 0.40 -</td>
<td>8.00</td>
<td>The same</td>
</tr>
<tr>
<td>COTAC-744</td>
<td>10.0 4.0 6.0 3.8 2.0 10.0 - 0.45 -</td>
<td>8.51</td>
<td>[2]</td>
</tr>
<tr>
<td>COTAC-784</td>
<td>10.0 4.0 6.5 4.0 - 4.0 4.0 0.45 -</td>
<td>8.00</td>
<td>The same</td>
</tr>
<tr>
<td>NITAC-13</td>
<td>3.3 4.4 5.4 8.1 3.1 6.2 0.54 5.6</td>
<td>8.69</td>
<td>[4]</td>
</tr>
<tr>
<td>NITAC-3-116A</td>
<td>3.7 1.9 6.5 8.2 - 6.3 0.25 4.0</td>
<td>8.6</td>
<td>[5]</td>
</tr>
<tr>
<td>NITAC-C</td>
<td>3.9 4.0 5.5 11.7 3.0 4.5 6.6 0.45 -</td>
<td>-</td>
<td>[6]</td>
</tr>
</tbody>
</table>

1. All-Russian Institute of Aircraft Materials, Moscow, Russia.

*The remainder is Ni.

Note. In addition to the listed elements VKLS-10 alloy contains 0.5% Hf, and NITAC-C alloy contains 0.01% B.
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Fig. 1. Temperature of complete dissolution of the γ'-phase $T_{c,γ'}$ in the γ-solid solution of high-temperature nickel alloys as a function of the content of the alloying elements (the base composition is 0.15% C, 4.5% Cr, 9% Co, 5% Al, 10% W, 0.5% Ti, 0.5% Mo, 0.5% Nb, 0.5% V). Solid lines) elements increasing $T_{c,γ'}$; dashed lines) elements decreasing $T_{c,γ'}$; dot-dash lines) elements that do not affect $T_{c,γ'}$.

even higher in order to make them competitive relative to the new high-temperature nickel alloys with a single-crystal structure.

Eutectic alloys with the $γ'/γ' - MC$ structure are based on the simple eutectic Ni – TaC or Ni – NbC, which is alloyed in accordance with the modern theory of the high-temperature strength of nickel alloys to obtain the requisite mechanical properties. By this theory the solubility of the $γ'$-phase should depend weakly on the temperature. Therefore the temperature of complete dissolution of the $γ'$-phase in the $γ$-solid solution of the melt ($T_{c,γ'}$) should be increased. Figure 1 presents concentration dependences of $T_{c,γ'}$ for a typical high-temperature alloy. These dependences were obtained by statistical processing of experimental data for a large group of alloys whose compositions were varied in correspondence with matrices for planning a full factorial experiment. It can be seen that the alloying elements Al, Ti, Ta, Hf, W, Mo, and Zn in nickel alloys increase $T_{c,γ'}$, whereas Cr, Co, V, and C decrease it, and Nb and Re hardly affect it.

In order to obtain high long-term strength the size difference $Δa_{γ' - γ} = (a_{γ'} - a_γ) / a_γ$ of the crystal lattice constants of $γ$- and $γ'$-phases should be a small positive quantity (~0.2%) that depends weakly on the temperature.

Oriented composite microstructures in preforms of eutectic alloys are formed during directed crystallization under the condition of plane growth of phases, i.e., in the absence of concentration overcooling of the melt ahead of the front of growth of the phase that controls the crystallization. This condition is ensured by a certain ratio of the temperature gradient $G$ in the melt on the front of phase growth created by the heating element of the furnace at the rate $R$ of movement of the front:

$$ G / R > (G / R)_c \approx ΔT / D, \quad (1) $$

where $ΔT = T_L - T_S$; $T_L$ and $T_S$ are the liquidus and the solidus temperatures, $D$ is the effective coefficient of diffusion of atoms in the melt.

Each alloying system for a eutectic alloy is characterized by a critical ratio $(G / R)_c$. In order to obtain an alloy with a unidirectional composite structure condition (1) should be fulfilled in crystallization of the casting. Heat-resistant eutectic alloys with the structure $γ'/γ' - MC$ have high $(G / R)_c \approx 150$ K·h/cm². Therefore, the alloying principles mentioned above should be supplemented by rules allowing for the specific properties of the formation of a composite microstructure during directed crystallization of alloys of the eutectic type. The most important of them is that the smaller the temperature interval $ΔT$ of alloy crystallization the more stable the plane front of growth and hence the greater the pulling rate with which the eutectic composite can be obtained. With an increase in the growth rate the filamentary crystals become thinner and the distance between them decreases, which follows from the well-known relation

$$ λ_m R = A, \quad (2) $$

where $λ$ is the interfilament distance, $m$ and $A$ are constants. For VKLS-20 alloy the experimentally determined values are $m = 2$ and $A = 0.7 \cdot 10^{-6}$ cm³/sec.

An increase in the dispersity of the reinforcing phase increases its contribution to the strengthening of the entire eutectic and makes it possible to improve the mechanical properties of the alloys by accelerated crystallization.

We searched for eutectic alloys with minimum $ΔT$ using data on the effect of alloying elements on the solidus and liquidus temperatures of eutectic alloys. The results of these investigations are presented in Fig. 2.

Hardening of eutectic alloys of the type $γ'/γ' - NbC$ begins with the formation (Fig. 3a) and subsequent growth of basal faceted crystals of monocarbide MC, which then give rise to eutectic grains or colonies that form the composite structure of the casting at a plane growth front (Fig. 3b – d).