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# HIGH-TEMPERATURE AGING NICKEL- AND IRON-BASED ALLOYS

**M.V. Pridantsev (Moscow)**

High-temperature aging nickel- and iron-based alloys came into used in the Soviet Union beginning with 1945 and 1946 in connection with the development of gas-turbine aviation technology.

A great deal of scientific work has been done in recent years. The physicochemical principles of the development of high-temperature aging alloys, the processes of structural changes during aging and the kinetics of the aging of various alloys have been studied. The dependence of the high-temperature strength of the alloys on composition and structure has been investigated. The criteria necessary to provide high heat resistance for aging alloys have been determined. A theory of high-temperature strength has been developed. Special attention has been devoted to a study of the effect of impurities and modifying additives. On this basis various high-temperature alloys and the technological processes of their smelting, hot plastic deformation and thermal treatment have been developed.

Only some of the most important results of the studies in this area are examined in this article.

The study of the principles of alloying alloys based on X20H8C and X15H35 has made it possible to establish the effect on the structure and properties of aging alloys of alloying elements possessing different and variable solubility in a γ-solid solution.

Intensification of the effect of dispersion hardening is achieved by introducing a specific amount of elements possessing comparatively little and variable solubility in a solid nickel-chromium γ-solution and taking direct part in the formation of intermetallic compounds. These elements, first of all, include titanium and aluminum which form during the aging of a supersaturat γ-solid solution strengthening $Ni_3(Ti, Al)$ phases or in the absence of Ti in the alloy, strengthening the $Ni_3Al$ phase. Titanium and aluminum have the most effect on the high-temperature strength of alloys.

The effect of the alloying elements on the high-temperature strength (time to destruction) of an alloy of the X20H8OT type is shown in Fig. 1. The positive effect of Ti, Al, Nb, Mo, W and Co and the negative effect of V, Ta and Be are seen from the graph.

Of the elements possessing comparatively great solubility in a solid-γ-solution, molybdenum has the most favorable effect on the high-temperature strength and plasticity of alloys of the X20H8OT type. Tungsten considerably improves the high-temperature strength of the alloy only when its content is less than 7-8 wt. %. Joint alloying of the alloy with molybdenum and tungsten in a total of up to 10-18 wt. % effectively increases high-temperature strength. At a content of more than 18% Mo or more than 20% W, the high-temperature strength of alloys of the X20H8OT type decreases as a result of the separation of large particles of intermetallic phases rich in molybdenum or tungsten.

The introduction of cobalt into nickel-chromium aging alloys has a positive effect on high-temperature strength, and the margin of plasticity and viscosity.

The high-temperature strength of X20H8OT alloy increases with an increase in the titanium concentration only up to 3.2-3.5%, and with a further increase in its content to 4-4.5% it decreases considerably despite an increase in the quantity of the strengthening phase from ~12 to ~20%. On the basis of a study of the composition and structure of the intermetallic phase, the decrease in the high-temperature strength is explained by precipitation – along with the $Ni_3(Ti, Al)$ phase having a cubic face-centered lattice – of the $Ni_3Ti$ phase with a hexagonal crystalline lattice. The latter is usually present in the form of coarse deposits of lamellar form.

In this respect aluminum exhibits the advantage of forming an $Ni_3Al$ phase with nickel which is similar in structure to the matrix and the amount of aluminum introduced into aging high-temperature alloys is limited only by the permissible (from the viewpoint of service characteristics) amount of the strengthening phase.

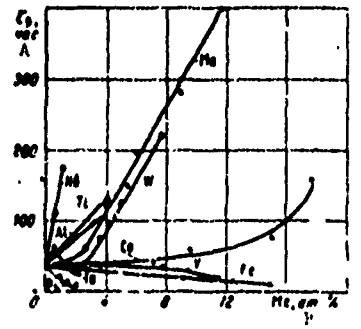

Fig. 1. Effect of various alloying elements on the high-temperature strength of an alloy of the X20H8OT type at 700-800°C. A) Hour; B) at. %.

The increase in the high-temperature strength of an alloy of the X20H8OT on introduction of Mo, W and Co is explained by an increase in the precipitation temperature and the resistance of the dispersed particles of the γ'-phase to coalescence. After aging Mo and W are found in the alloys primarily in a solid solution and retard the diffusion of titanium, chromium and aluminum and increase the activation energy of diffusion at high temperatures, which indicates strengthening of the interatomic bonds in the solid solution and retardation of aging and softening processes.

Cobalt dissolves in both coexisting phases, in which it replaces part of the nickel, but most of it enters the γ-solid solution. The composition of the γ'-phase in this case corresponds to the formula $(Ni, Co)_3(Ti, Al)$. Cobalt, on entering the solid γ solution, decreases the solubility of Ti and Al, while increasing the quantity of the strengthening phase.

The diffusion constants of Ti and Cr which explain the positive and negative effect of some elements on the high-temperature strength of an alloy are presented in Table 1 for alloys of the X20H80T type, additionally alloyed with Mo, W, V, Ta and Be.

Ti, Al, Nb, Mo, W and B have a similar effect on the high-temperature strength of alloys based on iron. The effect of various elements on the time to destruction of ЭИ 787 alloy (X15H35BTЮ) in which the strengthening phase in the γ'-phase – $(Ni, Fe)_3(Ti, Al)$ is shown in Fig. 2.

TABLE 1

Diffusion Constants of Titanium and Chromium in Alloys of the X20H80T Type Alloyed with Mo, W, V, Ta and Be

| 1 Содержание элемента, вес. % | 2 Коэффициенты диффузии, см²/сек, Ti и Cr при температурах, °C | | | | | | 3 Энергия активации диффузии, ккал/г·атом | |
|---|---|---|---|---|---|---|---|---|
| | 700 | | 800 | | 900 | | | |
| | Ti | Cr | Ti | Cr | Ti | Cr | Ti | Cr |
| — | $9.0\cdot10^{-14}$ | $3.0\cdot10^{-14}$ | $1.6\cdot10^{-11}$ | $7.0\cdot10^{-14}$ | $1.8\cdot10^{-11}$ | $1.0\cdot10^{-11}$ | 60 | 81 |
| 5 Mo | $2.0\cdot10^{-14}$ | $4.0\cdot10^{-14}$ | $1.5\cdot10^{-11}$ | $1.9\cdot10^{-11}$ | $7.0\cdot10^{-11}$ | $4.0\cdot10^{-10}$ | 65 | 77 |
| 5 W | $2.0\cdot10^{-14}$ | $3.0\cdot10^{-14}$ | $1.6\cdot10^{-11}$ | $7.0\cdot10^{-11}$ | $3.0\cdot10^{-11}$ | $9.0\cdot10^{-10}$ | 41 | 64 |
| 15 W | — | — | — | $3.7\cdot10^{-11}$ | — | $6.0\cdot10^{-10}$ | — | 70 |
| 3 V | $2.5\cdot10^{-14}$ | $1.3\cdot10^{-14}$ | $2.0\cdot10^{-14}$ | $1.7\cdot10^{-10}$ | $1.1\cdot10^{-11}$ | $1.4\cdot10^{-10}$ | 42 | 51 |
| 2.6 Ta | — | — | — | $1.8\cdot10^{-11}$ | — | $3.2\cdot10^{-10}$ | — | 57 |
| 6.1 Ta | — | — | — | $1.3\cdot10^{-11}$ | — | $2.6\cdot10^{-11}$ | — | 60 |
| 0.015 Be | — | — | — | — | — | $1.6\cdot10^{-11}$ | — | 47 |

1) Content of element, wt. %; 2) diffusion coefficients, cm²/s, of Ti and Cr at temperatures, °C; 3) activation energy of diffusion, kcal/g-atom.

Unlike alloys based on nickel-chromium, the optimum content of alloying elements in Fe-Ni-Cr-Ti-Al alloys both for those which participate in the formation of the γ'-phase during aging (Ti, Al) and of elements strengthening the solid solution is considerably lower because of the increase in the interatomic bond strength and retardation of diffusion processes (W, Mo). The high iron content in the X15H35 alloy promotes formation, at lower concentration of the indicated elements, of coarse deposits of the surplus phases differing from the principal strengthening phase – the γ'-phase.

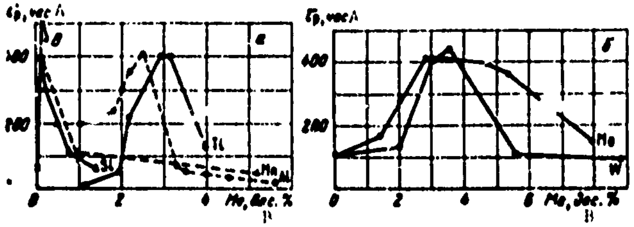

Fig. 2. Effect of various elements on the time to destruction of the ЭИ 787 (X15H35BTЮ) alloy at 750°C and σ = 30 kg/mm². A) Hour; B) wt. %.

TABLE 2

Periods of Crystalline Lattices of γ- and γ'-Phases of High-Temperature Alloys

| 1 Сплав | 2 Количество фазы, вес. % | 3 Периоды решеток a, kX, фаз | | $\Delta a = a_\gamma - a_{\gamma'}$, kX |
|---|---|---|---|---|
| | | γ | γ' | |
| ЭИ 437 Б | 10–12% γ' | 3.561 | 3.581 | −0.020 |
| ЭИ 444 | 11% γ' | 3.573 | 3.584 | −0.011 |
| ЭИ 445 | 14% γ' | 3.582 | 3.582 | ~0 |
| ЭИ 787 | 10–14% γ' | 3.585 | 3.590 | −0.005 |
| ЭИ 857* | 48–50% γ' | 3.578 | 3.576 | +0.002 |

*Foundry alloy; the γ' phase has the composition: $(Ni, Co)_3(Al, Ti)$.

1) Alloy; 2) amount of phase, wt. %; 3) lattice periods *a*, *kX*, of phases.

The physiochemical studies of high-temperature alloys based both on nickel and iron have made it possible to show regularities in the effect of various alloying elements which were taken into account in the development of various high-temperature alloys.

Not only the structure and the composition of the strengthening phases and the role of their structural conformity, but also the effect of various lattice periods of the γ and γ'-phases in aged alloys on the aging process and their high-temperature strength have been established by crystallochemical studies of coexisting phases in high-temperature aging alloys.

Depending on the compositions of the γ- and γ'-phases (which depend on the composition of the alloy), the difference in the periods of their crystalline lattices after aging and even more in the initial period of aging can vary from some negative to some positive value of Δa.

The periods of the crystalline lattices of coexisting γ and γ' phases of five high-temperature alloys after aging are presented in Table 2. In the ЭИ 437Б, ЭИ 444 and ЭИ 787 alloys the periods of the lattices of the γ'-phases are larger than in the coexisting γ-phases, and Δa decreases on the order of the arrangement of the alloys. In the ЭИ 445 alloy the lattice periods of these phases are almost the same, while in the ЭИ 857 alloy the γ'-phase has a smaller lattice period.

From an examination of the dimensional correspondence of coexisting γ and γ'-phases having a similar face-centered cubic lattice in the example of the alloys presented in Table 2, it should be possible to establish a relation between their high-temperature strength and the difference in Δa; however, in this case the different composition of the γ-solid solution and that of the γ'-phase is not taken into account, which determines the interatomic bond and the diffusion constants, nor is the amount of the strengthening phase taken into consideration for all the alloys.

It is interesting to note another explicit quantitative relationship. In high-temperature alloys in which a γ'-phase is precipitated with a crystalline lattice period which is close to or even smaller than that of the solid γ solution (in a hardened or aged alloy state), more intensive breakdown of the supersaturated γ-solid solution is observed during cooling in air after high-temperature heating. Moreover, the resistance of such a γ'-phase to the temperature effect and the length of the aging is higher than in a γ'-phase having a large lattice period in comparison with the γ-solid solution. Such high-temperature alloys after cooling in air, on "hardening" exhibit greater hardness and a considerable amount of the formed γ'-phase.

The development through this factor (dimensional correspondence) of compressive and tensile stresses or the absence of stress fields will naturally have an effect on the high-temperature characteristics of the alloys.

By elimination of the effect of various compositions of the γ-solid solution, it was shown in the work of I.L. Mirkin and O.D. Kancheyev [1] on the example of high-temperature Ni-Cr-Al aging alloys with approximately the same amount of the strengthening γ'-phase ($Ni_3Al$) that alloys in which in an aged state the lattice periods of coexisting γ and γ'-phases are close exhibit great high-temperature strength (Fig. 3).

For a better understanding of the effect of the magnitude and sign of the difference in the lattice periods of coexisting phases on the activation energy of the creep process and on prolonged strength, naturally it is necessary to know and to take into account the thermal expansion and lattice periods of the phases at the aging and testing temperatures, which are still not known and must be studied.

The structural changes in different stages of aging, the kinetics of the process, the role of coherence and particle size of the γ'-phase which forms in the strengthening of alloys and the conditions of change in composition and structure of the strengthening phase have been ascertained and established by studies of the aging process in supersaturated γ-solid solutions of various high-temperature alloys on a Ni-Ti, Ni-Cr-Ti, Ni-Cr-Ti-Al, Ni-Cr-Al, Fe-Ni-Cr-Ti and Fe-Ni-Cr-Ti-Al base.

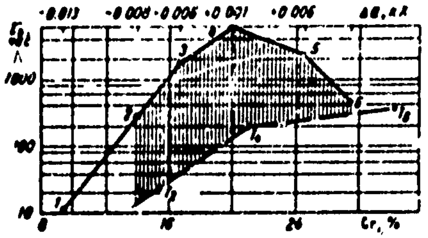

Fig. 3. Comparison of prolonged strength of two-phase (Ni-Cr-Al) alloys 1-6 and the corresponding solid solutions $I_1$-$I_6$ at 700°C and a stress of 15 kg/mm² as a function of the chromium content and the difference in the periods of the γ- and γ'-phases. A) Hour.

In early stages of aging, because of dendritic chemical heterogeneity which remains to a considerable degree in actual deformed alloys, in a supersaturated solid solution, because of the presence of submicroregions enriched with titanium and because of diffusion, a chemical bond develops between the Ni and Ti atoms (or Ni and Al in Ni-Cr-Al alloys).

The data of G.V. Kurdyumov and N.T. Travina [2], who observed an increase in bond strengths from a decrease in the dynamic and static deformations in the crystalline lattice (established from the change in intensity of x-ray interference) after aging of the ЭИ 437 alloy at 500 and 600°C for 4 h, indicate a change in the nature of the bond during the initial stages of aging.

The increase in the quantity and the growth of particles of the γ'-phase coherently connected with the matrix in the case of an increase in the aging temperature (and time) leads to maximum strengthening. In this case the size of the particles of the γ'-phase is about 120-140 Å at which they present the maximum obstruction to the movement of dislocations.

In further rise in the aging temperature and growth of the particles, coherence is impaired and coalescence of the γ'-phase and softening of the alloy is observed. This is the picture of the aging process in high-temperature alloys which is illustrated in Fig. 4 by a change in the specific electrical resistance, hardness and amount of the strengthening phase as a function of the aging temperature using ЭИ 437 and ЭИ 445 alloys as an example.

The role of dendritic liquation in the creation in supersaturated γ-solid solution of regions with a specific degree of long-range and short-range order of arrangement for the Ti, Al and Ni atoms is quite clear, based on known diagrams of binary or sections of triple and more complex systems and the laws of the crystallization of melts, as well as experimental data from determination of the degree of dendritic liquation of certain elements in high-temperature alloys.

Data [3] on the dentritic liquation of titanium in high-temperature ЭИ 437, ЭИ 444 and ЭИ 445 alloys determined in an electronic microprobe of the Kameka Company are presented in Table 3. We see that the maximum degree of liquation defined as the ratio of the maximum titanium content in the interaxial segments to its minimum content in the axes of the dendrites is considerable not only in case but also in deformed (97%) alloys.

These data indicate the considerable chemical heterogeniety of supersaturated solid solutions which actually, considering the local nature of the electronic microprobe, will be even greater, that is, with an even higher titanium content in the submicroregions.

The processes of the structural changes during the aging of supersaturated solid solutions in Fe-Ni-Cr-Ti alloys are analogous to those described for high-temperature aging Ni-Cr-Ti alloys. The difference in the aging processes in alloys based on iron and nickel consists only in the precipitation kinetics of the γ'-phase and its chemical composition. In high-temperature strength, for example, ЭИ 787 alloy not only is not inferior to, but even somewhat superior to ЭИ 437Б alloy based on nickel. In this connection it should be noted that it is doubtful whether it is possible to accept as correct the opinion concerning the considerable role of the *K*-state (observed in alloy X20H80) and its contribution to the strengthening of the high-temperature alloys ЭИ 437 and others expressed in previously published articles.

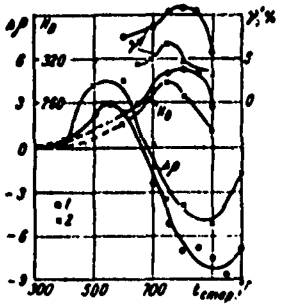

Fig. 4. Change in specific electrical resistance Δρ, hardness $H_B$ and in the quantity of the strengthening γ' phase as function of aging temperature for the alloys: A-ЭИ 445 (1) and ЭИ 437 (2).

TABLE 3

Dendritic Liquation of Titanium in High-Temperature Alloys in Cast and Forged (Deforamtion 97%) States

| 1<br>Сплав | 2<br>Содержание в сплаве вес. % | | | | | | 3<br>Состояние сплава | 4<br>Содержание Ti вес. % в осях (I) и в междуосных участках (II) | | 5<br>Степень ликвации |
|---|---|---|---|---|---|---|---|---|---|---|
| | C | Cr | Ti | Al | [illegible] | W | | I | II | |
| ЭИ 437 | 0.02 | 19.80 | 2.73 | 0.76 | — | — | 6 Литой | 1.7–2.4 | 4.1–5.5 | 3.25 |
| | | | | | | | 7 Кованый | 2.1–2.0 | 4.9–5.3 | 2.50 |
| ЭИ 444 | 0.03 | 20.00 | 3.00 | 1.17 | 5.10 | — | 6 Литой | 2.0–2.9 | 5.4–7.0 | 3.50 |
| | | | | | | | 7 Кованый | 2.1–2.6 | 4.3–4.7 | 2.20 |
| ЭИ 445 | 0.03 | 16.60 | 2.45 | 0.93 | 5.05 | 4.55 | 6 Литой | 1.5–1.8 | 5.3–6.1 | 4.00 |
| | | | | | | | 7 Кованый | 1.8–2.2 | 4.6–5.0 | 2.80 |

1) Alloy; 2) content in alloy, wt. %; 3) state of alloy; 4) Ti content, wt. %, in axes (I) and in interaxial segments (II); 5) degree of liquation; 6) cast; 7) forged.

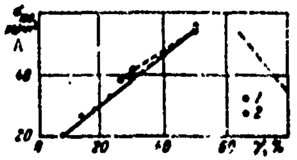

Fig. 5. Relations between quantity of strengthening phase γ and the 100 h limit of prolonged strength at 800°C for alloys based on nickel. 1) $Ni_3(Ti, Al)$; 2) $Ni_3Al$. A) kg/mm².

The $Ni_3(Ti, Al)$ phase with a face-centered cubic lattice is relatively stable only when its aluminum content is sufficient (the Ti:Al ratio in the alloy must be no more than 2.5); otherwise the γ'-phase can be partially converted into the η-phase of $Ni_3Ti$ with a hexagonal lattice with an increase in the aging temperature and an increase in the duration of aging.

For example, in ЭИ 437Б alloy containing 2.8% Ti and 0.98% Al, after aging at 800°C for 300, 600 and 1000 h, in addition to the $Ni_3(Ti, Al)$ phase, the $Ni_3Ti$ phase was present with lattice periods of $a$ = 5.10, $c$ = 8.31 kX, $c/a$ = 1.63; their phase is precipitated in the form of plates which are clearly visible in a number of high-temperature alloys under a light microscope. The main process in the conversion of the γ'-phase into a phase with a hexagonal lattice is the diffusion migration of the Ti atoms and the withdrawal of Al atoms. The $Ni_3(Ti, Al)$ phase in comparison with the $Ni_3Ti$ phase has a shortage of titanium because of the aluminum which at a specific content creates stability of the γ'-phase and hampers the formation of the η-phase from it, in the case of prolonged heating.

In the high-temperature ЭИ 787 alloy a lamellar phase of the

(Ni, Fe)$_3$(Ti, Al) type is observed after aging at 800 and 850°C for 6000 and 750 h, respectively; the lamellar phase does not differ in structure from the γ'-phase, but has an increased iron content (9-10%) and a larger lattice period: $a$ = 3.60 kX.

The appearance of the γ" lamellar phase does not noticeably decrease plasticity and ductility at normal temperature, nor plasticity with prolonged fracture at 750°C and somewhat decreases the high-temperature strength.

The high-temperature strength of alloys is associated not only with the nature, dispersion and quantity of the strengthening phase. High-temperature strength of an alloy as a function of the amount of the strengthening γ'-phase of the Ni$_3$(Ti, Al) and Ni$_3$Al type is shown in Fig. 5. As seen, the limit of the prolonged strength in 100 h at a temperature of 800°C for alloys based on nickel chromium with a strengthening phase different in composition increases almost in proportion to its content in the alloy.

However, this relationship will evidently be retained only up to a specific phase quantity, above which, as a result of considerable sensitivity to brittle fracture, the long-term strength will be sharply decreased.

The considerable role of the granule bounaries in high-temperature alloys based on nickel and iron which, after aging, show a greatly strengthened γ-solid solution has been established by numerous investigations. In such high-temperature aging alloys a primarily intergranule nature of creep with slippage of the granules is observed because of the lower strength of the granule borders. The formation and development of cracks and fracture occurs only along the granule borders at a relatively low prolonged plasticity and at a residual elongation on the order of 1-5%.

In this connection, low-melting impurities having some solubility in liquid, absence of solubility in a solid alloy and a high boiling point have a considerable effect on the high-temperature strength of such alloys. The presence of low-melting impurities increases the negative properties of the granule borders, as places with the most imperfect crystalline lattice.

As shown, the strengthening of the granule boundaries and a considerable increase in the high-temperature strength of alloys can be achieved not only by an increase in their freedom from harmful impurities, but also by using small additions of chemically active alkaline earth and rare-earth metals, boron and others.

The results of scientific work in this direction can be illustrated by the graphs of Fig. 6$a$, in which the dependence of time to destruction of a high-temperature alloy of the X20H80T type on the amount of Pb, Sb and S and additions of Ce, La, Ba, Ca and Zr is shown, and Fig. 6$b$ [4] in which the effect of Ce, La, Nd and Pr on the time to destruction of ЭИ 437 alloy at 700°C and 36 kg/mm$^2$ is shown.

Such effect of indicated modifying additives, usually remaining in the solid metal in very small quantities, must be explained by an increase in the intergranule strength as a result of subsequent processes.

The chemically active additives have a refining effect during smelting of the alloy, and binding the harmful impurities (S, Pb, Bi, Sb, Sn) present in the metal into high-melting compounds, as a result of which part of the impurities and oxides is removed from the metal into the slag, while the rest remains in the solid metal, being located either inside the granules or along the boundaries in the form of high-melting and safe compounds.

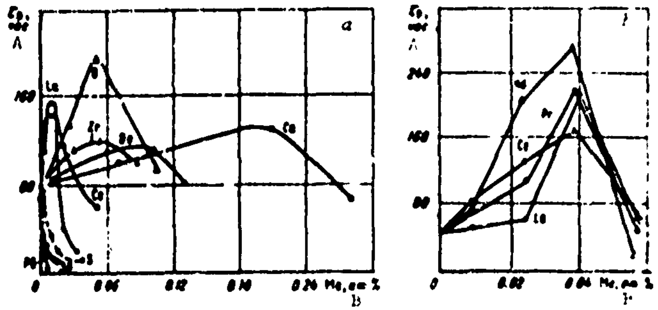

Fig. 6. Time to destruction of high-temperature alloys depending on the amount (by calculation) of various additives. $a$) XH80T alloy, 700-800°C; $b$) ЭИ 437 alloy at 700°C and 36 kg/mm$^2$. A) Hour; B) at. %.

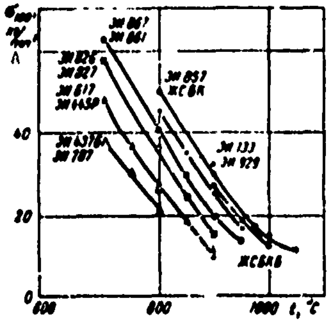

Fig. 7. Limits of prolonged strength of alloys during 100 h at various temperatures. A) kg/mm$^2$.

Boron evidently directly strengthens the boundaries of the granules through the formation of high-melting borides.

In addition, alkalin earth, rare earth and certain other metals increase the resistance of the surface oxide film of high-temperature alloys and the boundaries of their granules to diffusion penetration of oxygen during tests and service, thus protecting the surface layers from damage and more rapid destruction.

As has been established, because of the high chemical stability of the rare-earth metals, their addition to austenite steel alloyed with nitrogen leads to severe contamination by thermodynamically stable nitride inclusions and to a decrease in the plasticity characteristics at high temperatures; therefore it is not advisable to introduce them into alloys containing nitrogen.

The technological process for smelting high-temperature alloys with observance of the necessary degree of purity from admixtures of Pb, Sb, Sn, Bi, S and others and with the obligatory addition of a small amount of boron and rare-earth metals before discharge of the metal has been established on the basis of studies which were carried out on the basis of studies which were carried out on the effect of low-melting admixtures and modifying additions.

In recent years, vacuum-arc and electric-slag remeltings which make it possible to obtain ingots of a higher quality in terms of microstructure have been used on an ever increasing scale for smelting high-temperature alloys.

In connection with the necessity of obtaining larger ingots of high-temperature alloys in which extra-axial (mottled) liquation was observed, research was undertaken for the purpose of studying the nature of this defect and the conditions of its elimination. As a result it was established that an increase in the capacity of the arc and a remelting rate above a certain value (kg/min) have an effect on the formation of extra-axial liquation in ingots from vacuum-arc wleding. The use of a direct-current solenoid during vacuum-arc remelting leads to strongly developed liquation nonuniformity owing to rotation of the liquid-metal bath and separation of the liquid and solid phases during crystallization. An alternating current solenoid showed more favorable results.

Vacuum-arc remelting of high-temperature alloys in a copper water-cooled crystallizer under optimum electrical conditions makes it possible to obtain ingots without extra-axial liquation nonuniformity.

As a result of the extensive scientific research work of institutes and plants in the last 20 years, great success has been achieved in the area of physicochemical, crystallochemical and technology research on high-temperature alloys. A large number of aging alloys with a high level of prolonged strength at working temperatures up to 1030-1050°C has been developed.

As an example, the limits of the prolonged strength of some aging high-temperature alloys in 100 h are shown in Fig. 7.

In conclusion, we should dwell in some detail on the principal directions of future research in highly heat-stable aging alloys.

1. In the area of physicochemical research on the effect of alloying elements on the structure and properties of alloys of the systems Ni-Cr and Ni-Co-Cr, additions of Zr and Nb in a wider concentration range as well as the effect of such metals as rhenium which have still not been studied in the indicated systems should be studied.

2. It is advisable to study the properties of alloys to increase the working temperatures of heat-stable alloys based on Cr-Ni and Cr-Co and also the effect of additional alloying with elements forming intermetallic compounds with similar lattices and it is also necessary to conduct research on the development of composition high-temperature alloys strengthened with thermodynamically stable oxides and other compounds.

3. Special attention should be devoted to a study of the vulnerability and reaction of surface layers of alloys with the working medium and to a search for methods of protecting against a change in chemical composition and oxidation on the boundaries of the granules. The use of calorizing is recommended for these purposes.

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| 7 | стар. = star. = stareniye = aging |

## DATA HANDLING PAGE

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ABSTRACT

(U) Alloys of this kind began to be investigated in 1945-1946 in view of their applications to the development of aviation gas-turbine engineering. In this connection, the article surveys the principal results of the pertinent R&D work. Thus research into the effect of treatment with alloy elements on high-temperature alloys of the Kh20N80 and Kh15N35 types has made it possible to elucidate the effect of alloy elements displaying varying and variable solubility. High-temperature strength of these alloys is greatly affected by readily fusible impurities which enhance the adverse properties of grain boundaries. This can be offset and the grain boundaries can be toughened not only by using purer alloys but also by adding small amounts of chemically active alkali-earth, rare-earth metals, boron, etc. The vacuum arc and electroslag melting methods have recently been employed on an increasingly broader scale in the production of high-temperature alloys. The principal orientation of further research into high-temperature aging in alloys are: 1) studies of the effect of a broad range of concentrations of Zr and Nb on the structure and properties of alloys of the Ni-Cr and Ni-Co-Cr systems, as well as the effect of metals such as Re which have not yet been investigated with respect to these systems; 2) studies of the effect of treatment with alloy elements which form intermetallic compounds having lattices of the same type on the properties of Cr-Ni and Cr-Co alloys. Orig. art. has: 7 fig., 3 tables.

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