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ABSTRACT

The phase composition, mechanical properties, microstructure and crystal structure, and corrosion resistance of alloy EI826 were investigated. The experimental technique followed here is described by F. F. Khimushin (Zharoprochnyye splavy, Metallurgiya, 1964). The microstructure and crystal structure of the alloy were investigated by electron microscopy and x-ray spectroscopy, respectively. The experimental results are summarized in graphs and tables (see Fig. 1). It was found that alloy EI826 possesses all the desired mechanical properties for construction of gas turbine vanes designed for long-term use (15000-20000 hours) at temperatures of 800C. The alloy was suggested by F. F. Khimuskin, D. Ye. Livshits, Ye. F. Trusova, A. V. Ostapenko, and A. A. Fedina; the electron microscope pictures were taken by I. S. Mel'nikova, and the x-ray work was carried out by G. D. Pigrova and S. I. Korkka. The corrosion resistance of the alloy was determined by A. I. Rytvinskiy. Orig. art. has: 10 tables and 5 graphs.

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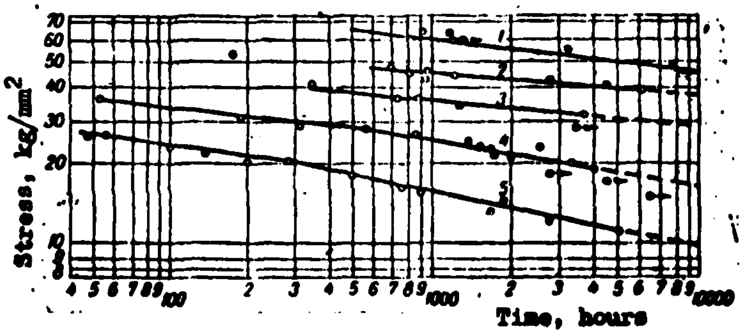
Fig. 1. Long term strength of alloy EI826. 1 - at 650C, 2 - 700C, 3 - 750C, 4 - 800C, 5 - 850C



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ABSTRACT

General principles governing the oxidation processes of 8 nickel alloys suitable for blade material in gas turbine construction were investigated, and an effort was made to correlate the thermal stability of these alloys with their various elements. The following alloys were investigated: EI867, EI827, ZhS6K, EI826, EP99, EI617, EI893, EI869. The tests were performed in air, at 800—1000C for 2000 to 3000 hours. The method of testing and treatment of experimental data was that described by A. I. Rytvinskiy and Yu. D. Red'ko (Trudy TaKTI, vyp. 53, 1965, str. 28—33, 148—156). It was established that: 1) the thermal stability of the nickel alloys is determined by the structure of the scale; 2) at 800—1000C the protective properties of the scale are determined by the spinal phase, and the general level of thermal stability is a function of the chromium and aluminum content in the alloy; 3) at temperatures above 1000C the oxidation rate of the alloys containing molybdenum rises rapidly with formation of a new phase, $NiMoO_4$; 4) the accelerated oxidation of nickel alloys containing molybdenum may also take place at 800—850C when these alloys are in contact with iron oxides. Orig. art. has: 1 table and 5 equations.

TABLE OF CONTENTS

STRUCTURE AND PROPERTIES OF EI826* ALLOY FOR GAS TURBINE BLADES WITH A LONG SERVICE LIFE AT 800°C

Ye. Ye. Levin, Ye. M. Pivnik, et al.

In this report are given results of investigating EI826 alloy applicable to working conditions in long action gas turbines. The aging effect was investigated on the properties of the alloy within a period of [illegible]-10000 hrs at 600-900°C. Durable strength was investigated at 650-850°C and the time till destruction of individual samples up to 10000 hrs. The sensitivity was estimated to stress concentrations under testing conditions on the constant strength of smooth and notched samples of various types. Greater attention has been devoted to the effect of the structural factor on the deformability of the metal. Widely elucidated are the phase characteristics and structural conversions in the alloy. It is shown that EI816 alloy can be recommended in the role of material for blades with a working temperature of 800°C and resource of 15000-20000 hrs with possible overheatings to 850°C and general working duration at this temperature of not more than 5000 hrs.

During the last years in the field of developing alloys for blades of high temperature stages of gas turbines, considerable successes were attained, which allowed one to realize a series manufacture of installations with working temperature of the metal of 700-750°C. But a further riss in temperature to 800-850°C makes the creation of reliable blade materials for turbines with long working resource very complex in connection with the intensification of diffusion processes in the alloys at this temperature level and with the danger of origination of local corrosion defects on the surface of the metal.

To solve this problem, EI826 alloy was investigated, designated

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*The alloy was suggested by F. F. Khimushin, D. Ye. Livshits, Y. E. F. Trusova, A. V. Ostapenko and A. A. Fedina.

for working blades of aviation engines. In Table 1, a trade composition is given of the alloy [1] and the composition of the metal of the investigated melts.

The melts were prepared in 0.5 ton electric induction furnaces and were rolled into rods of Ø 45 mm in conformity with actual technological instructions of industrial manufacture.

One of the important factors, assuring the possibility of considerably increasing the resource of heat resistant alloys, is the increase in their plasticity of brief and long lasting mechanical tests and the preservation of these properties at an acceptable level during the entire working period of the material at a given temperature. On the basis of the experiment of developing blade materials for stationary gas turbines with a resource of 50000-100000 hrs [2], the investigated metal was thermally treated by a regime, including besides harmony, two high temperature intermediate degrees: 1000 and 900 - 1180°C, 6 hrs, quenching in the air; 1000°C, 4 hrs + 900°C, 8 hrs + 850°C, 15 hrs, quenching in the air.

In thermal processing conditions by such a regime, there is attained a uniform distribution of the basic strengthening γ'-phase within the grains of the metal, including areas adjoining to inter-granular boundaries. The dimension of particles of that phase changes relatively little under the effect of long temperature action and action of stresses, and the distance between same ficilitates the occurrence of plastic deformation in the entire volume of the metal and accumulation of same to a relative high level to the moment of disruption of the tested samples. Such a structural state of the metal assures simultaneously with it a high level of lasting strength, resistance to creep and a reduced sensitivity of the alloy to stress concentrations. The advantages of the adopted regime of thermal processing are seen from tables 2 and 3, in which results are given of comparative tests of smelt samples A, B and V.

During thermal treatment of the metal by the gradual regime, there is a slight reduction in strength, but plasticity of short and long lasting high temperature tensile tests rises considerably.

The results of testing samples of alloy EI826 in a temperature range of 650-900°C are given in table 4. Strength and plastic properties are at a satisfactory level. Minimum plasticity values during these tests constitute $\delta = 13$ and $\psi = 23\%$, while for high alloyed nickel or nickel-cobalt base alloys at 750-900°C, they do not exceed 5-8%.

Mechanical properties of the alloy at various aging conditions are listed in table 5. With the exception of the first several thousand hours of aging at 700°C, the plasticity of the EI826 alloy is within limits of 12-20% at room temperature testing and 12-17% at high temperatures. The strength of alloy in the process of aging to 700°C inclusively at a duration of up to 10000 hours is preserved at a constant level. At such a level, the strength of the metal is situated at room temperature, aged at 800°C, but the testing of an aging temperature attests to the beginning of weakening, strength drops by 10-30%. A noticeable drop in strength in the aging process is at

Table 1. Chemical Composition of EI826 Alloy

Name	Content of elements %													
	C	Si	Mn	S	P	Cr	Ni	Ti	Al	W	Mo	V	B	Ce
													By calculation	
Trade composition	<0,12	<0,60	<0,50	<0,009	<0,015	$\frac{13}{16}$	Основа	$\frac{1,7}{2,2}$	$\frac{2,4}{2,9}$	$\frac{5}{7}$	$\frac{2,5}{4,0}$	$\frac{0,2}{1,0}$	<0,015	<0,020
Smelt A	0,04	0,33	0,20	0,008	0,006	13,98	Основа	1,98	2,65	6,10	3,81	0,58	0,012	0,010
Smelt B	0,03	0,28	0,16	0,007	0,008	13,80	Основа	1,79	2,78	6,18	3,76	0,51	0,012	0,010
Smelt V	0,05	0,30	0,18	0,007	0,008	13,70	Основа	1,57	2,76	5,77	3,30	—	0,012	0,010

Table 2. Mechanical Properties of EI826 Alloy in Dependence Upon the Thermal Processing Regime (Smelt A).

Thermal processing regime	$\sigma_{0,2}$, кГ/мм²	σ_B, кГ/мм²	δ, %	ψ, %	$a_н$ кГ·м/см²	Testing temperature °C
1180 °C, 6 ч;	60	105	15	16	3,5	20
1000 °C, 4 ч + 900 °C, 8 ч + +850 °C, 15 ч	54	86	20	25	—	750
То же + 750 °C, 500 ч	69	103	11	12	2,3	20
	50	84	19	22	—	750
1210 °C, 2 ч;	74	106	15	15	1,6	20
1050 °C, 4 ч + 850 °C, 16 ч	70	96	7	8	—	750
То же + 750 °C, 500 ч	78	102	8	10	1,4	20
	72	95	14	15	—	750

Table 3. Comparative Tests of Durable Strength at 650°C of Alloy EI826 Samples, Thermally Treated by Various Regime (Smelts B and Б).

Smelt	Thermal processing	Stress kG/mm²	Time till destruction	δ, %	ψ, %
B	1180 °C, 6 ч; 1000 °C, 4 ч + 900 °C, 8 ч + + 850 °C, 15 ч	64	925	1,10	2,5
B		63	1177	4,60	7,6
B		60	>1600	>1,00	Test continues
Б		60	1211	4,00	7,5
Б		55	3233	2,20	5,5
B		53	>2000	—	—
Б		49	7992	2,60	6,3
Б		46	>10 000	—	Test continues
B	1210 °C, 2 ч; 1050 °C, 4 ч + 800 °C, 16 ч	64	552	0,82	—
Б		64	[illegible]	1,80	—
Б		60	897	1,10	—
Б		60	1132	0,50	2,90
Б		49	2436	Brittle destruction	—
Б		46	6720	"	—

850-900°C. Attention is attracted by the fact, that in this case the mechanical properties of the metal in the aging process remain also constant within a period of 3000-10000 hrs.

Table 4. Mechanical Properties of EI826 Alloy at High Temperatures (Smelt Б).

Testing temperature °C	$\sigma_{0,2}$, кГ/мм²	σ_B, кГ/мм²	δ, %	ψ, %
650	50	95	22	28
700	50	95	22	26
800	50	75	15	20
850	50	60	13	23
900	40	50	15	23

After thermal processing by the adopted regime in the structure of the alloy, prevail (as a result of applying high temperature degrees of processing at 1000 and 900°C) relatively large particles of γ-phase.

In the process of cooling from high temperatures and additional annealing, evidently high dispersion particles of γ-phase are also formed, but they are not revealed at microscopic investigations and in this connection they are not taken into consideration when evaluating the average value of γ-phase particles.

A noticeable enlargement of γ-phase particles, as is evident from data in table 6 and Fig. 1, occurs between 5000 and 10000 hrs of aging at 800°C and at much earlier aging stages at 850 and 900°C. The distance between columns of γ-phase particles rises in this case from

Table 5. Mechanical Properties of EI-26 Alloy in Various Aging Conditions (Thermal Processing: 1180°C, 6 hrs; 1000°C, 8 hrs + 850°C, 15 hrs (Smelts A and F).

Aging Conditions		HB, кГ/мм²	$\sigma_{0.2}$, кГ/мм²	σ_B, кГ/мм²	δ, %	ψ, %	$a_н$, кГ·м/см²
Temperature	Exposure hrs						
Testing temperature 20°C							
—	—	280	60	105	15	16	3,5
600	1000	280	70	101	16	17	1,5
600	5000	290	72	100	12	14	1,0
Testing temperature 600°C							
600	1000	—	60	95	17	23	—
600	5000	—	67	103	16	17	—
Testing temperature 20°C							
700	1000	320	71	100	6	6	2,0
700	5000	290	66	100	7	7	2,0
700	10 000	290	67	110	10	8	2,0
Testing temperature 700°C							
700	1000	—	60	105	15	13	3,5
700	5000	—	55	99	14	16	4,0
700	10 000	—	52	94	17	18	4,0
Testing temperature 20°C							
800	1000	270	60	106	17	17	3,5
800	5000	270	58	96	12	10	3,0
800	10 000	250	57	96	15	13	3,0
Testing temperature 800°C							
800	1000	—	49	72	15	19	7,5
800	5000	—	47	67	12	18	6,5
800	10 000	—	44	68	15	17	5,5
Testing temperature 20°C							
850	1000	240	55	99	20	20	3,5
850	5000	230	51	84	14	16	3,0
850	10 000	240	52	77	11	12	7,0
Testing temperature 850°C							
850	1000	—	47	64	15	15	—
850	5000	—	44	63	14	21	—
Testing temperature 20°C							
900	1000	240	53	89	16	20	3,5
900	3000	240	50	86	17	17	3,0
Testing temperature 800°C							
900	1000	—	49	72	10	13	6,5
900	3000	—	46	72	12	14	5,0

0.1-0.2 to 0.3-0.5 μ. This facilitates the deformation process within the grains and leads, in particular, to its accumulation to a level, corresponding to the yield point ($\sigma_{0.2}$) at lower stresses.

With an increase in testing temperature, the interangular displacement rises, and in this connection interangular cracks originate at much earlier deformation stages. At a pure interangular destruction, characteristic for nickel base alloys, this appears to be one of the major causes of reducing the plasticity of the alloy at high temperature tests. At the same time a favorable structure of interangular layer of alloy EI826, in the composition of which prevail large γ'-phase particles, and high plasticity of the die hard γ - solution, assure up to the moment of destruction, a relatively high plasticity level even at high temperature tests.

In EI826 alloy, the γ'-phase corresponds to an $Ni_3(Ti, Al)$ compound. In samples, thermally treated by the adopted regime, are contained about 25% of that phase, further at aging right up to 10000 hrs at 800°C, the amount of γ'-phase changes relatively little, reaching approximately 30%. The rational ratio in aluminum and titanium alloy ($\frac{Al}{Ti}$ = 1.5 ÷ 1.6), of the basic elements determining the amount and dispersion of the strenghtening phase, is assured by the high degree of its stability, which in turn promotes to a considerable degree, the preservation of approximately one and the same level of such an important characteristic, as relative elongation at rupture in various aging conditions (see tables 5 and 6).

Table 6. Dispersion Characteristic of γ'-phase in EI826 Alloy.

Thermo processing regime	d_{cp}, мк	v_{cp}, rate of growth мк/	Elongation at destruction, %	Testing temperature °C
Gradual Aging	—	—	16	650
650 °C, 5000 ч hr	0,241	—	12	20
* Gradual Aging				
750 °C, 1000 ч hr	0,168	13,5·10^{-6}	15	700
750 °C, 3000 ч "	0,195	18·10^{-6}	14	700
750 °C, 5000 ч "	0,231	19·10^{-6}	15	700
750 °C, 10 000 ч "	0,326		17	700
Gradual Aging				
800 °C, 1000 ч	0,325	2,5·10^{-6}	15	800
800 °C, 5000 ч	0,336	18,8·10^{-6}	12	800
800 °C, 10 000 ч "	0,430		15	800
Gradual Aging				
850 °C, 500 ч "	0,318	104·10^{-6}	15	850
850 °C, 1000 ч "	0,370	95·10^{-6}	15	850
850 °C, 3000 ч "	0,560		14	850
Gradual Aging				
900 °C, 3000 ч "	0,635	—	12	800

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* Electron microscope investigation of EI816 alloy with a quantitative evaluation of structural changes in the alloy was made by engineer I. S. Mel'nikova.

Table 7. Phase Composition of Electrolytically Separated Residues from Samples of EI826 Alloy (Thermal Processing: 1180°C, 6 hrs; Quenching in the air + + 1000°C, 4 hrs + 900°C, 8 hrs + 850°C, 15 hrs).

Additional aging condition		**Phase composition**
Temperature °C		
—	—	γ', Y, $Me_{23}C_6$, сл. Me_6C, TiC
700	1000	γ', Y, $Me_{23}C_6$, сл. Me_6C, TiC
700	5000	γ', Y, $Me_{23}C_6$, сл. Me_6C, TiC
700	10 000	γ', Y, $Me_{23}C_6$, Me_6C, TiC
800	1000	γ', Y, $Me_{23}C_6$, сл. Me_6C, TiC
800	5000	γ', Y, $Me_{23}C_6$, Me_6C, TiC
600	10 000	γ', Y, $Me_{23}C_6$, Me_6C, TiC
850	1000	γ', Y, $Me_{23}C_6$, сл. Me_6C, TiC
850	5000	γ', Y, $Me_{23}C_6$, Me_6C, TiC

The growth rate of particles at 750-800 °C with a period of up to 10000 hrs constitutes a total of only $15\text{-}19 \cdot 10^{-6}$ μ hrs. Roentgenographic determination of dimensions of blocks in particles of electrolytically separated γ'-phase has shown, that this value constitutes 400-500 Å and also changes little in the aging process. The presence in titanium and the relatively high chromium content (14-15%) causes formation in thermally processed steel, in addition to γ'-phase, titanium carbide TiC, carbide of type $Me_{23}C_6$ and traces of binary carbide Me_6C of Me^1_n and Me^2_m type. Among electrolytically separated phases, a boride phase is also contained - Y, the amount of which does not change in the aging process. That phase in N. F. Lashko, N. I. Blok and D. E. Livshits' report was decoded as an Me_3B_2 compound, where Me corresponds to Cr, w, Wo elements.

The ratio between the amount of carbides of $Me_{23}C_6$ and Me_6C type, having an identical cubical face centered lattice and close parameters (10.68 and 11.02 dKH) is determined by temperature and aging duration.

In EI826 alloy, the carbide $Me_{23}C_6$, thanks to high chromium content in it, appears to be a highly stable phase, only within 5000-10000 hrs of aging at 700°C or within 4000-5000 hrs at 800 and 850°C, the amount of the carbide phase Me_6, C becomes comparable with the amount of $Me_{23}C_6$ type of carbides. Carbides of type $Me_{23}C_6$ correspond to formula $Me^1_{21}Me^2_2C_6$, where Me^1-Ni, Cr and Me^2-Mo, W, analogous to this binary carbide $Me^1_nMe^2_m$ can be decoded as Me^1-Ni and Me^2-W, Mo, Cr. In the aging process, carbide $Me_{23}C_6$ becomes enriched with Mo and W and changes into a more stable form for these conditions - Me_6C (table 7).

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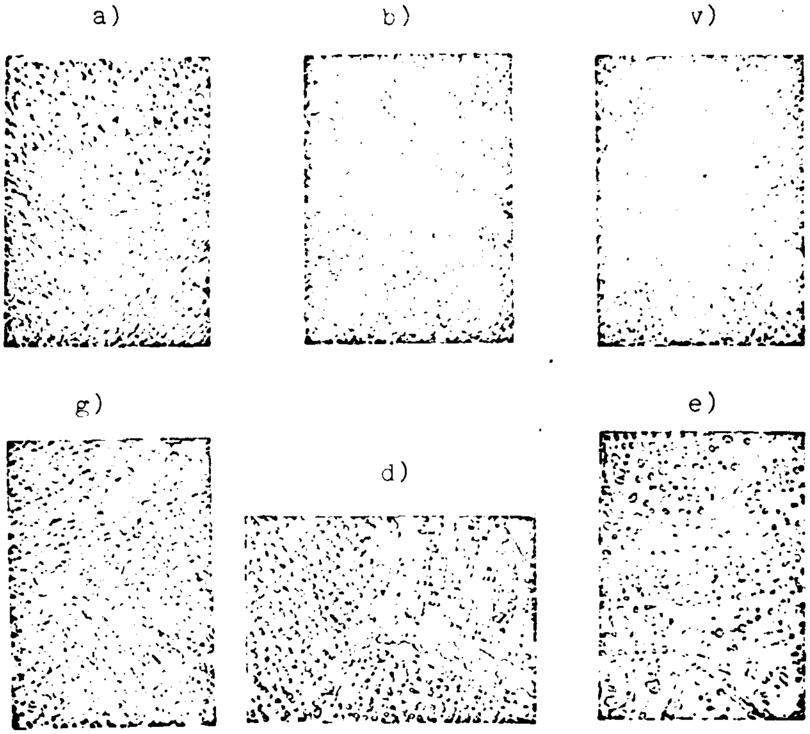

Fig. 1. Microstructure of EI826 alloy (X2000):
a - after thermal processing by the recommended regime and additional aging; b - 600°C, 5000 hrs; v - 700°C, 10000 hrs; g - 800°C, 10000 hrs; d - 850°C, 5000 hrs; e - 900°C, 3000 hrs. Etching by reagent 1 (revealment of interangular and interphasial boundaries) 2 hrs; reagent 2 (used after etching with reagent 1, it colors the carbide phase particles in black color) - 10 g KOH, 10 g potassium ferricyanide, 100 m liters H_2O (reduction at reproduction 1/2).

Metallographic investigations of the alloy in thermally treated state clearly reveal only grain boundaries, along which are situated in dense chains dispersion particles of γ'-phase and carbides. In the process of aging at 600-650°C, there is a noticeable coagulation of carbide particles over the grain boundaries, they acquire in this case an elongated rod-like form. With an increase in aging temperature, the carbide and γ'-phase particles become enlarged, and since this process is more intensive over the grain boundaries, then interangular

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[*] X-ray structural and phase analysis of the EI826 alloys carried out by the Engineers G. P. Pirgova and S. T. Korkka.

layers of the metal, aged at 700-850°C, represent a conglomerate of quite large carbide and γ'-phase particles. The state of grain boundaries, and the strength level of near boundary areas and bodies of the very grains, which change in the aging process at various conditions, determine the nature of the development of cracks, originating at sample tensile tests, and the value of plastic deformation accumulated to the moment of metal destruction.

Evaluation of the deformability of the alloys by the method adopted at the TSKTI, was carried out by determining the plasticity of the metal during tensile testing of the samples at constant rate of deformation at various temperatures [3]. Results of testing the EI826 alloy are given in table 8.

At a deformation rate of 314%/hr, usually applied when tensile testing the samples, with a testing temperature rise to 750°C and over plasticity decreases from 22-23 to 12-16%. When testing at a rate 3.6; 0.8 and 0.08%/hr, the plassicity of the metal remains preserved at an approximately constant and sufficiently high level (9-11%) for the entire temperature range, which attests to the high stability properties of the alloy (Fig. 2, curve 1).

In addition to the data presented in table 9, test results are presented at constant deformation rate of the samples, preliminarily aged at 850 and 900°C for a period of 1000 hrs. Such a treatment of the metal allows one to evaluate the effect on the deformability of the alloy of deep structural changes, which may take place as a result of long lasting exploitation and incidental overheatings of the blades. In addition, the formation over the intergranular boundaries of large particles of carbide and intermetallide phase, allows one during the investigation of the structure of disrupted samples, to establish the effect of these structural components on the origination and development of cracks. A strength reduction by approximately 20% is observed at such tests as a result of aging at 900°C. For the EI826 alloy at a gradual thermal treatment regime, the absence of a clearly expressed effect of change in the deformation rate on the plasticity level is characteristic.

With a rise in testing temperature, the appearance of a rising branch of the plasticity curve is bound with the change in the physical nature of intragranular deformation processes. At approximately 900°C, thanks to the intensification of diffusional processes, the overcoming by dislocations of any kind of hindrances is considerably facilitated. In this connection there is an equilibration of deformations by the grain volume and the work of previously blocked dislocation sources is facilitated. The mentioned circumstances determine the resistance reduction of body grain deformation and reduces localization of deformation to intergranular boundaries. All this leads to a rise in accumulated deformation to the moment of destruction (see Fig. 2, curves 2 and 3).

On microphotos, Fig. 3, a,b is shown, that the origin of cracks takes place on interphasal boundaries, separating carbide particles **from** the intermetallide γ'-phase or die γ'-solid solution. Crack centers have the nature of disconnected pores, originating at various deformation stages of deeply aged samples which develop slowly in

Table 8. Results of Testing the EI826 Alloy at Constant Deformation Rate (Thermal Processing: 1180°C, 6 hrs; 1000°C, 8 hrs + 900°C, 8 hrs + 850°C, 15 hrs).

Smelt	Testing conditions		$\sigma_{0.2}$, кГ/мм²	σ_B, кГ/мм²	δ, %	ψ, %	Time till destruction
	Temperature °C	Rate %/hr					
A	650	314	51	95	22	28	—
A	700	314	52	95	23	24	—
A	750	314	54	87	15	16	—
A	800	314	57	81	12	21	—
A	850	314	49	61	13	23	—
A	900	314	40	49	16	22	—
A	700	3,6	46	83	10	14	3 h 25 min
A	800	3,6	51	65	9	17	3 h 10 min
A	850	3,6	31	36	6	12	2 h 40 min
A	700	0,8	62	75	9	9	10 h 45 min
B	700	0,8	55	82	10	14	13 h 20 min
A	800	0,8	—	51	9	11	11 h
B	800	0,8	48	50	9	15	10 h
A	850	0,8	—	30	11	16	13 h 40 min
A	900	0,8	20	20	9	16	11 h
B	650	0,08	52	88	11	12	143h 40 min
B	800	0,08	32	39	10	11	114 h

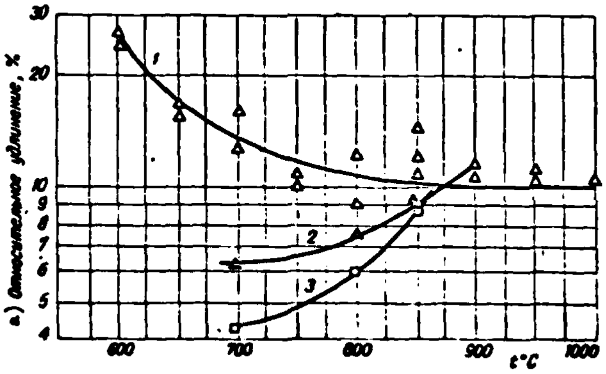

Fig. 2. Change in relative elongation during the rupture of samples from EI826 alloy, tested at various temperatures with constant rate of deformation (0.8%/hr): 1 - after thermal processing by the recommended regime; 2 - after additional aging at 850°C within 1000 hrs; 3 - after additional aging at 900°C within 1000 hrs. a) relative elongation.

Table 9. Results of Testing the Alloy EI826 at Constant Deformation Rate (Thermal Processing: 1180°C, 6 hrs; 1000°C, 4 hrs + 900°C, 8 hrs + 850°C, 15 hrs).

Testing condition		$\sigma_{0,2}$, кГ/мм²	σ_B, кГ/мм²	δ, %	ψ, %	time till destruction
temperature, °C	Rate %/hr					
		Additional aging — 850 °C, 1000 ч				
700	3,6	46	73	10	18	2 h 40 min
800	3,6	39	43	4	11	1 h 50 min
900	3,6	19	27	10	18	3 h 10 min
700	0,8	56	80	6,5	8	7 h 50 min
800	0,8	46	50	8	13	10 h
850	0,8	25	33	9	16	11 h 30 min
900	0,8	16	19	11	17	13 h 40 min
		additional aging — 900 °C, 1000 ч				
700	314	43	78	16	21	—
800	314	44	67	5	10	—
850	314	44	63	8,5	14	—
900	314	31	43	20	30	—
700	3,6	49	60	4,0	10	2 h 40 min
850	3,6	48	54	4,5	7	1 h 45 min
900	3,6	20	25	11,5	16	3 h 15 min
700	0,8	55	69	4	8,5	5 h 10 min
800	0,8	50	55	6	9	7 h 15 min
850	0,8	34	37	9	12	11 h 30 min
900	0,8	—	13	5	12	6 h 15 min

connection with the favorable structure of intergranular layers in the EI826 alloy (presence of large γ'-phase particles, delaying the development of pores). As to the effect of the carbide phase on intergranular strength and plasticity, there are various viewpoints in this problem. On the basis of TSKTI data, the effect of $Me_{23}C_6$ type carbides is considered more favorable: in reports of D. F. Livshits and N. F. Lashko, there is mentioned the positive effect on the heat resistant properties of the alloy of Me_6C type carbides which predominate in intergranular layers after thermal treatment by the regime - 1210°C, 2 hrs, air; 1050°C, 16 hrs, air at a testing duration of up to 2000 hrs.

The persistent strength of EI826 alloy was investigated in a wide temperature range (650-850°C), in many instances the testing duration reached 10000 hrs (table 10). Plasticity of the alloy at 650°C is characterized by a summary relative elongation at destruction, lying within limits of 2.2-4.6% at a test duration ranging from 1200-8000 hrs. Even much higher plasticity values were obtained at a raise in testing temperature to 700-800°C, in these conditions at a test duration within limits of 200-6500 hrs, the summary deformation does not decrease to below 3.0 and for individual tests of greater duration it constitutes 5.5-6.0%. In the role of positive moment, there should be mentioned an extremely weak appearance of a tendency toward reduction of the plasticity of EI826 alloy with a raise in time till destruction. This graphic not reproducible

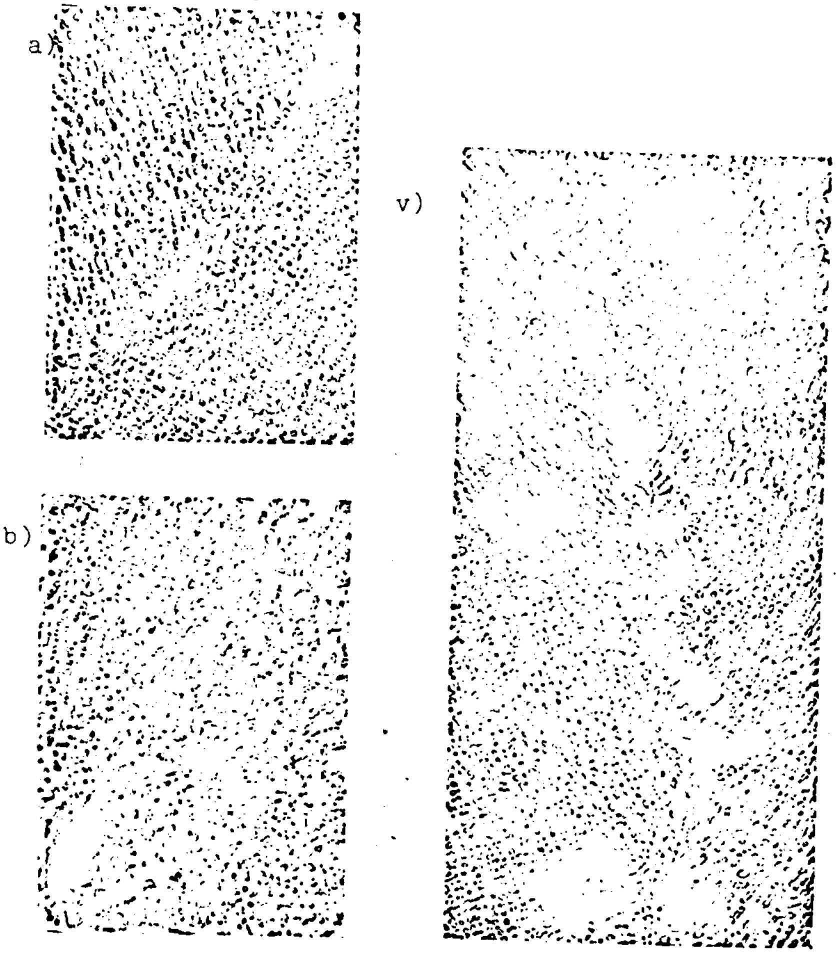

Fig. 3. Microstructure of samples (at the rupture point) destroyed during tests: a - preliminary aged at 850°C, 1000 hrs, rate of deformation 3.6%/hr, testing temperature 800°C; δ = 4.0%; b - preliminary aged at 900°C, 1000 hrs, rate at deformation 0.8%/hr, testing temperature 800°C, δ = 6%; v - tested for durable strength at 850°C, σ = 11 kg/mm^2, time till destruction 5000 hrs, δ = 2.50% (X2000), etching with reagent 1, see Fig. 1 (reduction at reproduction 3/4.

tendency appears more clearly at a test temperature of 850°C. In samples of smelt A, this is expressed in a reduction in summary deformation from 7 to 2.5% at an extension in time till destruction from 100 to 5000 hrs, in samples of smelting B from 5.7 to 4.0% respectively, at changes in test duration from 1800 to 2800 hrs. In spite of testing a greater number of samples (more than 90 pieces) of a metal of three industrial smelts, there is a slight dispersion in data even at such a high temperature, as 850°C.

The lasting strength tesd results are given on a logarithmic graph (Fig. 4) and in table 10. Evaluation of sensitivity to stress concentrations was made by testing with constant rate of deformation of samples with spiral notching and testing the durable strength of samples with annular and spiral notches.

The sample with spiral notch represents a bar of cylindrical form Ø 8 mm at a calculated length of 80 mm. The double spiral notch has a depth of 0.75 ,,. pitch 12.7 mm and a rounding radius of 0.15 mm. The angle at the peak of the notch equals 60°. The coefficient of concentration in case of a spiral notch $k_t^{sr} = 3.7$. The sample with annular notch has a calculated length of 25 mm. The rounding radius at the bottom of the notch is 0.22 mm, depth of notch 1 mm. The notch angle is also 60°. For this sample, the concentration coefficient $k_t = 3.8$.

Results of testing at constant rate of 0.8%/hr, carried out at 600-850°C, are shown in Fig. 5. Maximum sensitivity to concentration is observed at 600-700°C, relative elongation in these testing conditions decreases from 9-10 to 1.5-1.7%. The stress concentration coefficient constitutes 0.5 for 650°C and 0.8 fpr 750-850°C.

At all test temperatures the durable strength of samples with annular notch, actually suppressing deformation of creep in the zone of notch action, thermally treated by the recommended regime, is higher than the durable strength of smooth samples.

In this case, when in the zone of perturbation action of the notch a considerable creep deformation may take place, as it does take place at a spiral notch, the sensitivity to the notch appears in a reduction of limits of durable strength by approximately 20% and in reduction of plasticity at a relatively low testing temperature (650°C). This circumstance should be considered during the construction and preparation of details from the investigated alloy.

An interesting microstructure, obtained during the investigation of the sample, destroyed within 5000 hrs when testing for durable strength at 850°C and stress $\sigma = 11$ kg/mm^2 (see Fig. 3, v). The structure of the intergranular layer represents a typical picture for EI826 alloy - chains of carbide, divided either in larger sections of the dispersion γ'-phase with particles, close in dimensions and form to intragranular formations of that phase, or in large particles of the very same phase, having an improper form. At the initial destruction stage, disconnected pores are formed. The development of fusion of same at the indicated structure of intergranular layers occurs sufficiently slowly and assures the accumulation of a relatively great summary deformation, which appears to be a highly important reliability characteristic of the blade material.

Investigation of corrosion resistance of alloy EI826 has shown, that by general oxidizability it belongs to highly cinder resistant materials (depth of corrosive destruction after 10000 hrs at 800-1000°C constitutes 0.007-0.145 mm). It should be mentioned, that the chromium content in EI826 alloy (about 14-15%) and the favorable

Table 10. Results of Strength Duration Testing of EI826 Alloy (Thermal Treatment: 1160°C, 6 hrs, air; 1000°C, 4 hrs + 900°C, 8 hrs + 850°C, 15 hrs, air).

Melt	Stress σ, кГ/мм²	Destruction		
		Time, hrs	δ_p, %	ψ_p, %
1	2	3	4	5
		Testing temperature	650° C	
Б	60	1211	4,0	7,4
Б	55	3233	2,2	5,5
Б	49	7292	2,6	6,3
Б	46	10000	Test continues	
В	63	1177	4,6	7,8
В	53	2000	Test continues	
		Testin temperature	700° C	
А	54	178	5,5	7,8
А	48	693	3,8	6,4
А	46	967	4,7	7,8
А	44	1225	3,0	5,6
А	43	951	4,3	4,0
А	42	2828	4,7	5,9
А	40	4400	3,7	6,1
А	38	6199	3,8	4,4
		Testing temperature	750° C	
Б	36	739	6,0	10,2
Б	34	1227	5,9	7,6
Б	30	3670	4,5	9,3
Б	28	3500	1,9	Test continues
В	40	357	7,9	10,9
В	36	870	5,8	8,8
		Testing temperature	800° C	
А	36	54	3,8	9,0
А	30	188	7,1	10,0
А	28	322	5,0	7,8
А	27	564	3,6	6,9
А	26	873	4,0	9,8
А	25	1377	4,4	8,1
А	24	1550	4,1	7,3
А	23	1692	5,2	10,0
А	22	1701	3,7	7,1

Table 10 continued

1	2	3	4	5
A	21	2064	3,7	8,4
A	20	3448	5,0	10,5
A	19	4118	3,2	6,3
B	23	2556	6,4	10,9
B	17	5800	1,6	Test continues
B	15	6400	0,6	Test continues
Testing temperature 850° C				
A	28	22,5	5,8	11,4
A	26	56	4,4	8,3
A	26	48,5	7,6	11,4
A	24	102,5	6,9	12,9
A	22	135,0	5,7	6,7
A	20	200	2,4	8,4
A	20	283	3,5	6,1
A	18	509	3,8	11,1
A	16	760	2,8	5,2
A	15	896	4,4	8,3
A	13	1642	2,5	4,0
A	11	5050	2,5	—
B	14	1842	5,7	10,9
B	12	2796	3,9	9,5

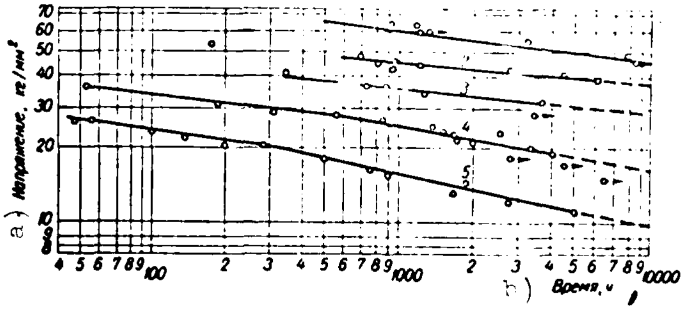

Fig. 4. Durable strength of EI826 alloy:
1 - at 650°C; 2 - at 700°C; 3 - at 750°C; 4) at 800°C;
5 - at 850°C. a) stress, kg/mm; b) time, hours.

chromium and aluminum ratio (2.5% Al) allow one to consider a successful application of the alloy for work at 800°C with brief overheatings to 850°C without local damages*.

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* Evaluation of corrosion stability of the EI826 alloy was made by Engr. A. I. Rytvinskiy.

Conclusions

1. The analysis of experimental data, attesting about the high constancy of the deformability level of the alloy at a temperature of 800-850°C, as well as the continuing durable strength tests, offer bases of recommending this alloy in the role of a meterial for blades with a working temperature of 800°C and resource of 15000-20000 hrs, and at 850°C within a period of 5000 hrs.

2. Comparative tests of alloy EI826 samples from several industrial melts with various thermal treatment, allow one to recommend the following regime: 1180°C, 6 hours; cooling in the air; 1000°C, 4 hrs, cooling with the furnace to 900°C, 8 hrs, cooling with furnace to 850°C, 12 hours, cooling in air.

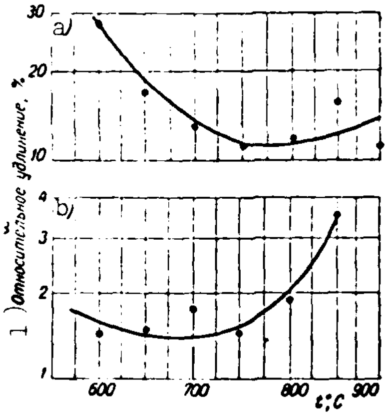

Fig. 5. Change in plasticity of alloy EI826 when testing constant deformation rate (0.8%/hr): a - smooth samples, b - samples with spiral notch; 1) relative elongation.

3. After realizing the mentioned alloy treatment, the alloy possesses a high stability of properties in conditions of long lasting thermal action and preserves a highly satisfactory deformability when testing at constant rate of deformation in a wide range of its values and when testing for lasting strength in a temperature range of 650-850°C.

4. When creating structural elements from alloy EI826, the results of the above carried out investigations should be considered, including sensitivity to stress concentrations, evaluated by various methods.

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PHASE COMPOSITION OF CLINKERS AND HEAT RESISTANCE OF NICKEL BASE ALLOYS

A. I. Rytvinskiy and G. D. Pigrova

Gas engine installations acquire a greater circulation not only in transport machine construction, but also in stationary power engineering. The development of the GTU (gas turbine installations) is on the way of increasing their power, and on the way of increasing their efficiency, basically on account of raising the working gas temperature. Works are already being conducted on the creation of stationary installations with a gas temperature at turbine input of up to 1000-1200°C. It is perfectly evident, that the immediate problem of a stationary power engineering gas turbine construction is the obtainment of alloys, capable of maintaining such high temperatures at a time resource, applicable for this type of turbines.

For the development and adoption by industry of each new alloy, very great time and media losses are required. Therefore, the effort is natural of a more detailed examination of already adopted by industry, highly heat resistant alloys, applied at the present time for nonstationary GTU, for the purpose of explaining the temperature limit of their application in the role of blade materials at a time resource, applicable for station GTU.

One of the necessary stages of such an investigation appears to be the establishment of general rules of oxidation of the selected alloys, allowing one to make an extrapolation by temperature and time.

To the investigation of heat resistance of technical nickel base alloys, there was devoted a greater number of reports in our native and foreign literature, but efforts to generalize data, obtained by various authors, are connected with greater difficulties, included in the fact, that first of all, in a majority of instances the composition of the investigated alloys differs considerably from technical alloys, presently used in native nonstationary gas turbine construction; secondly, the given data were obtained as a result of comparative brief tests [1-8].

The purpose of this report was to determine general oxidation rules of eight nickel bas alloys, presently used in the role of these materials in transportation gas turbine construction, as well as efforts to find a relationship between the heat resistance of these alloys and the basic alloying elements included in their composition. The following nickel base alloys were investigated: Types EI867, EI827, ZhS6K, EI826, EP99, EI617, EI893, EI869.

The tests were carried out in open air at a range of temperatures of 800-1000°. The testing duration constituted 2000-3000 hrs. The testing method and processing of experimental data have been thoroughly described in our previous reports [7].

Together with the study of oxidation kinetics of the selected alloys, we also investigate phase and chemical composition of the clinkers forming on them. The obtained results are given in table 1. These results enabled one to establish the following general oxidation rules of highly heat resistance alloys of nickel base.

Table 1. Results of Testing the Investigated Alloys.

Type of Alloy	Rate of Oxidation Constant, r^2/m^4 · hrs					Parameter of Forming Spinel
	800° C	850° C	900° C	950° C	1000° C	
EI ЭИ867	0,013	0,028	0,048	0,095	—	$a = 8,13\,kX$
ЭИ827	0,012	0,029	0,049	0,105	—	$a = 8,13\,kX$
ZhS ЖС6К	—	0,043	0,095	0,214	0,320	$a = 8,15\,kX$
ЭИ826	0,022	0,053	0,120	—	0,480	$a = 8,20\,kX$
ЭИ893	0,059	0,200	—	0,920	3,300	$a = 8,29\,kX$
ЭИ869	0,152	0,545	2,080	—	20,000	$a = 8,36\,kX$

1. At temperatures less than 1000°C, the prevalent phase of the clinker appears to be spinel $(Ni,Co)O \cdot (Al,Cr)_2O_3$. In addition to the spinel, small amounts of nickel oxide NiO are present, also chromium oxide Cr_2O_3.

2. At temperatures above 1000°C, a three-layered structure is observed of the clinker. In this case, the basic phase of the external layer appears to be NiO, on the middle layer - spinel $(Ni,Co)O \cdot (Al,Cr_2O_3$, and in the internal layer adjoining the alloy, in addition to spinel, there is in noticeable amounts the $NiMoO_4$ phase.

3. The content of chromium and aluminum in the clinker exceeds their content in the alloy by approximately 1.2 and 1.5 times correspondingly, whereby their greatest amount is contained in the internal clinker layers.

4. The total content of nickel and cobalt in the clinker corresponds approximately to their content in the alloy.

5. Tungsten converts in the clinker in a very small amount.

Its content in the clinker constitutes approximately 20-30% from the content in the alloy. The amount of molybdenum in the clinker, forming at a temperature below 1000°C, is approximately the same. With a rise in temperature the molybdenum content in the clinker rises sharply.

In this way, for the investigated alloys there is observed a clear selective oxidation of chromium and aluminum. In conformity with the structure and composition of the clinker for heat resistant alloys, two oxidation cases should be distinguished.

1. Oxidation of alloys at temperatures up to 1000°C

As is evident from the data, given in table 1, the rate of oxidation constants rise from alloy EI827 to alloy EI869. In this case, the parameter of the forming spinel also rises $(Ni,Co)O \cdot (Al,Cr)_2O_3$. Since at these temperatures spinel appears to be the prevalent phase on the clinker, it should be anticipated, that the protective properties of the clinker are determined by the structure and composition of the spinel. The spinel phase in the clinker - is a solid solution of oxides $(Ni,Co)O \cdot Cr_2O_3$ and $(Ni,Co)O \cdot Al_2O_3$. The parameter of the spinel lattice is determined by the concentration of these oxides. It was found that the parameter of spinel is in a regular relationship with the chromium and aluminum content in the alloy, which increases with the rise in chromium to aluminum ratio. In such a regular relationship, with the composition of the alloy are values A and Q in the expression of oxidation rate constant:

$$\lg K = \lg A - \frac{Q}{2,3RT}, \qquad (1)$$

where K - rate of oxidation constant, $g^2/m^4 \cdot$ hrs;
A - constant;
Q - activation energy of oxidation process, cal/mol.

For A and Q were obtained equations, expressing their relationship with the composition of the alloy:

$$\lg A = 3,70 + 1,22\, m \qquad (2)$$

and

$$Q = 28\,000 + 5100\, m, \qquad (3)$$

where $m = \frac{\%\ \text{at Cr}}{\%\ \text{at Al}}$ (in the alloy).

The rate of oxidation constant can be expressed as a function of temperature and composition of the alloy

$$\lg K = 3,70 - \frac{6120}{T} + \left(1,22 - \frac{1115}{T}\right) m. \qquad (4)$$

Calculation of rate of oxidation constant for the investigated alloys, given in formula (4), gives a satisfactory coincidence with experimentally found values.

In this way, the general heat resistance level of nickel base alloys, alloyed with chromium (10-20%) and aluminum (1-3%), is determined by the magnitude ratios of these elements. In this case, maximum heat resistance is possessed by alloys, in which the $\frac{Cr}{Al}$ ratio < 3.

[illegible]. Oxidation of alloys at temperatures above 1000 °C.

The alloys investigated by us, with the exception of EI869, contain molybdenum as a basic strengthening element. As was shown above, as well as in report [3], its role at temperatures up to 1000 °C in the oxidation of alloys, is insignificant. In the internal layer of the clinker, formation is possible of $NiMoO_4$ phase on account of reaction of the molybdenum with nickel oxide by reaction

$$4\ NiO + Mo \rightarrow NiMoO_4 + 3Ni.$$

In addition as was shown in report [8], during the oxidation of nickel-molybdenum alloys, the outer layer of the alloy becomes enriched in molybdenum dioxide MoO_2.

The rapid growth of the clinker at a temperature above 1000 °C, leads to the origination of defects in the structure and disruption in the solidity of the clinker, which promotes oxidation of the MoO_2 clinker into MoO_3, on account of facilitated approach of oxygen to the surface of the alloy, enriched with MoO_2. MoO_3, possessing a high vapor elasticity, is partially sublimated, disturbing the layer of the clinker, enters partially partially into reaction with nickel oxide NiO, forming the $NiMoO_4$ phase. As a result, the oxide layer suffers a total loss in its protective properties, and the very oxidation process is so fast, that it derived in literature the name of "catastrophic" destruction [9].

We have previously shown [7], that this characteristic for alloys, containing molybdenum, the type of corrosive destruction is observed for nickel base alloys also at temperatures of the order of 800-850 °C, when tjese alloys come in contact with ferric oxide. The role of the latter in the initiation of accelerated destruction is included evidently, in the fact that in the outer clinker layer brittle spinel is formed, capable of spontaneous cracking. The mechanism of further destruction remains the very same, as during the oxidation of alloys at temperatures above 1000 °C.

The characteristic feature of accelerated destruction and the evidence of nonsuitability of the alloys for long lasting exploitation, appears to be the presence in the clinker of noticeable amounts of $NiMoO_4$ phase.

Conclusions

1. Heat resistance of nickel base alloys is determined by the structure of the clinker.

2. At temperatures of 800-1000 °C, the protective properties of the clinker are determined by the spinel phase and the total level of heat resistance depends upon the chromium and aluminum content in the alloy.

3. At temperatures above 1000°C, the rate of oxidation of nickel base alloys containing molybdenum, rises sharply on account of the appearance of the $NiMoO_4$ phase.

4. Accelerated oxidation of nickel base alloys, containing molybdenum, may take place at temperatures of 800-850°C when these alloys come in contact with ferric oxides.

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