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AUTOMATED DESIGNING OF MANUFACTURABLE HIGH-TEMPERATURE ALLOY COMPOSITION ON NICKEL BASE FOR MANUFACTURE OF ALL-CAST NOZZLE APPARATUSES

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According to the algorithm of a developed comprehensive analytical solution method (CASM), a new cast high-temperature corrosion-resistant nickel alloy ZhS3LS-M has been developed for manufacture of all-cast nozzle appliances. The developed alloy is characterized by the high-temperature strength σ_{40}^{975} = 180–200 MPa at the level of the industrial non-corrosion-resistant alloy VZhL12E as well as technological weldability and corrosion resistance at the level of commercial weldable corrosion-resistant alloy ZhS3LS. 24 Ref., 11 Tables, 1 Figure.

Keywords: *cast high-temperature nickel alloys; performance parameters; CASM-method; regression model; regression equation; service properties, technological weldability*

At present time application of new high-temperature materials and technologies of manufacture of the parts for gas turbine engines (GTE) allows providing a high level of requirements to perspective GTE. Therefore, one of the progressive directions of increase of service characteristics of GTE critical parts is getting the all-cast nozzle appliances (NA) form new cast corrosion-resistant high-temperature nickel alloys (HNA) characterized simultaneously by technological weldability and increased strength characteristics [1–6].

Commercial alloys ZhS3LS and VZhL12E are referred to the most well-known cast HNA widely used for manufacture of all-cast NA of different type. VZhL12E alloy, doped with aluminum in 5.0–5.7 wt.% quantity, in which volume fraction of γ′-phase reaches 58–62 %, has increased thermal stability of structural-phase composition. This provides higher high-temperature strength and better resistance to high-temperature material creep up to 1000 °C in comparison with ZhS3LS alloy, doped with aluminum in 2.4–3.0 wt.% quantity, in which volume fraction of γ′-phase makes only 38–42 %. However, VZhL12E alloy is not characterized by good technological weldability and necessary corrosion resistance that makes its further application not so perspective. The indicated characteristics are typical for commercial alloy ZhS3LS, however, it doesn't have necessary level of strength, that also limits its application for perspective GTE [6–11].

Respectively, designing and implementation into industry of new cast corrosion-resistant HNA differ by technological weldability and increased level of high-temperature strength, is a relevant, competitive and economically profitable direction for manufacture of all-cast nozzle appliances of perspective GTE using a developed express computer designing method replacing low-effective empirical trial and error method.

Problem statement. Welding/surfacing of high-temperature nickel alloys is sufficiently complex process due to presence in them of large quantity of main strengthening γ′-phase — Ni_3Al (more than 60 vol.%). In particular, precipitations of this phase in process of solidification or further heat treatment results in appearance of dispersion hardening cracks [11] in the welds or heat-affected zones.

Aim of the present work is designing employing developed express comprehensive analytical solution method (CASM) [12] of a new cast corrosion-resistant HNA for manufacture of all-cast nozzle appliances (NA) of different types, differ by technological weldability at the level of commercial alloy ZhS3LS and increased strength characteristics at the level of non-weldable and non-corrosion-resistant commercial alloy VZhL12E.

A search of perspective compositions of the developed alloy was carried out according to the algorithm of computer modelling by CASM based on a doping system of commercial cast corrosion-resistant nickel alloy ZhS3LS taken as a prototype. Chemical com-

Table 1. Composition (wt.%) of commercial cast nickel alloys ZhS3L and VZhL12E of average doping level [6. 10]

Alloy grade	C	Cr	Co	Mo	W	Al	Ti	Nb	V	Zr	B	Ni
ZhS3LS	0.09	16.0	5.0	4.0	4.0	2.7	2.7	–	–	0.015	0.015	Base
VZhL12E	0.16	9.25	9.0	3.1	1.4	5.4	4.5	0.75	0.75	0.020	0.015	Base

position of the latter is given in Table 1 together with composition of commercial high-temperature alloy VZhL12E taken as an analogue.

New elements such as hafnium and tantalum were introduced in the selected basic doping system of alloy ZhS3LS (Ni–Co–Cr–Al–Ti–Mo–W–Zr–B–C) for the following reasons:

- tantalum and hafnium promote increase of volume fraction of main γ′-phase and rise of its thermal-dynamic stability;
- have positive effect on morphology of carbide phase of MeC type, at that obviously suppress a mechanism of formation of less thermodynamically stable and unfavorable on morphology carbides of $Me_{23}C_6$ type, that promotes rise of material ductility factor;
- promote significant increase of temperature of complete solution of main strengthening γ′-phase, and, respectively, rise of its residual quantity at high temperatures, that guarantees increase of high-temperature strength characteristics, and, respectively, long-term strength.

Based on mentioned above, the initial conditions for alloy designing in a new system of multicomponent doping Ni–Co–Cr–Al–Ti–Mo–W–Ta–Hf–Zr–B–C were formulated. The main controlled parameters, introduced into computation for multicriterial optimization of composition of developed alloy, are given below.

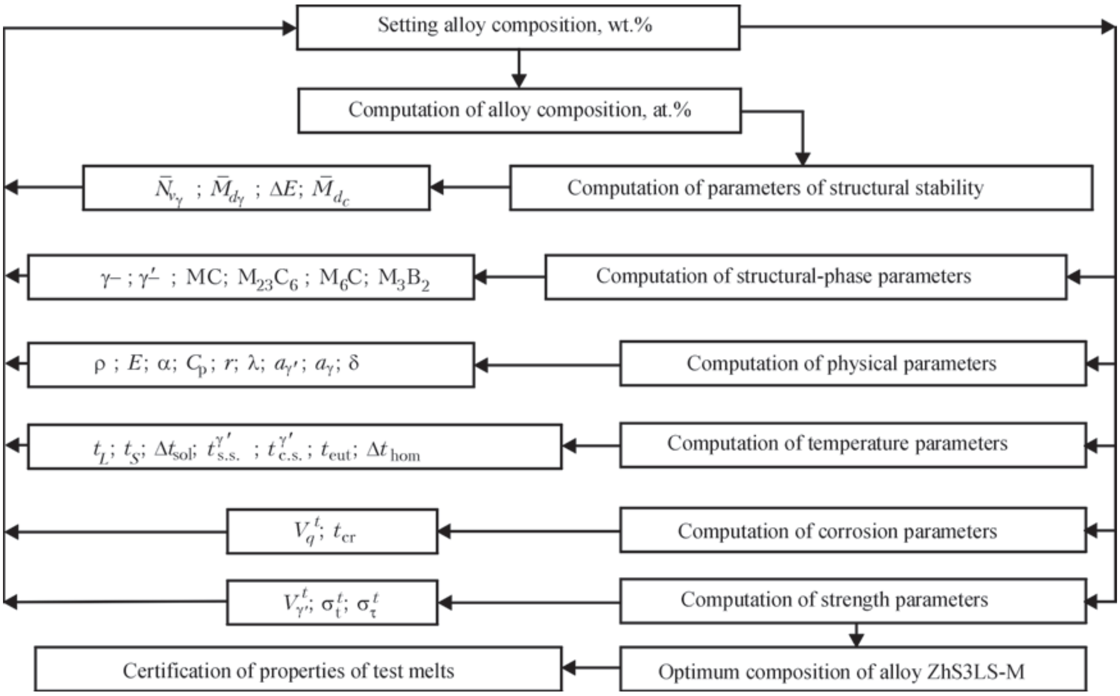
Stability parameter P_{TCP} = % Cr/%[Cr + Mo + W]	0.825±0.025
Total number of electron vacancies in γ-solid solution N_{v_γ}	2.40
Total number of valence electrons in γ-solid solution M_{d_γ}	0.93
Total number of valence electrons in alloy M_{d_C}	0.980±0.008
Parameter of disbalance of doping system ΔE	±0.04
Total content $\sum_\gamma$ = (Mo + W + Ta + Re + Ru), wt.%	≥10.0
Total content $\sum_{\gamma'}$ = (Al + Ti + Nb + Ta + Hf), wt.%	$8.0 < \sum_{\gamma'} < 9.0$
Solidus temperature t_S °C	≥1280
Temperature interval of homogenization Δt_{hom}, °C	≥20
Quantity of strengthening γ′-phase (20 °C) $V^{20}_{\gamma'}$, vol.%	$43 < V^{20}_{\gamma'} < 50$
Dimensional mismatch of γ and γ′-lattices (misfit)	0.15–0.45
Short-term strength limit (20 °C) σ^{20}_t, MPa	≥850
Relative elongation (20 °C) δ^{20}, %.	≥5.0
Long-term strength τ_{fract} σ_{180}^{975}, h	≥40
Corrosion parameter $P_{CR} = \sqrt{}$% Cr % [Ti/Al]	≥3.0
Critical temperature of accelerated HTC, t_{crit}, °C	≥800
Removal of cast defects in all-cast NA by argon-arc welding (AAW) method	Technological weldability at the level of ZhS3LS alloy

Analysis of the results. This work presents the results of computer designing and experimental investigations of new cast corrosion-resistant nickel alloy designed for manufacture of all-cast NA of TVZ-117 type under conditions of commercial enterprise V.I. Omelchenko ZMZ, having increased strength characteristics and technological weldability. In contrast to more high-temperature commercial alloy VZhL12E, containing 9 wt.% of Cr and does not differ by good corrosion resistance, commercial weldable corrosion-resistant alloy ZhS3LS contains larger quantity of chromium (16 wt.%). In turn, ZhS3LS alloy does not have necessary level of high-temperature strength since quantity of main strengthening γ′-phase makes only 38–42 % that is 20 % lower than in VZhL12E alloy (58–62 %). Therefore, the following requirements were formulated for multicriterial optimization of composition of developed alloy and main controlled parameters, being entered in a complex computation, were selected:

- fulfillment of the conditions of structural stability by parameters: P_{TCP} = % Cr/%(Cr + Mo + W) = = 0.825±0.025;
- $N_{v_\gamma} \le 2.40$; $M_{d_\gamma} \le 0.93$; $\Delta E = \pm 0.04$; $M_{d_C} = 0.980 \pm 0.008$;
- providing technological weldability at the level of ZhS3LS alloy, taken as a prototype, as well as strength characteristics close to the level of commercial cast high-temperature alloy VZhL12E, taken as an analogue: controlled quantity of main strengthening γ′-phase within the limits of $43 < V^{20}_{\gamma'} < 50$ % (on mass): short-term strength $\sigma^{20}_t \ge 850$ MPa; $\delta^{20} \ge 5.0$ % and long-term strength $\sigma^{975}_{180} \ge 40$ h in accordance with OST 1.90126–85;
- providing corrosion resistance at the level of commercial cast corrosion-resistant alloy ZhS3LS, taken as a prototype: corrosion parameter P_{cr} = %(Ti/Al) ≥ 3.0.

Indicated above values of characteristics for developed alloy were obtained of multicriterial optimization of the composition doped with hafnium and tantalum based on commercial alloy ZhS3LS employing an algorithm of developed CASM express-method (Figure). The following approaches can be referred to conceptually new approach in balancing of doped cast HNA:

- in order to provide serviceability of developed alloy it is necessary to balance general chemical composition of the alloy: by γ′-forming elements with-



Algorithm of computer computation of designed alloy ZhS3LS-M on developed CRAM method [12]

in the limits of $\Sigma_{\gamma'}$ = %(Al + Ti + Nb + Ta + Hf) = = 8–9 wt.%; by elements strengthening γ-solid solution Σ_γ = %(Mo + W + Ta + Re + Ru) ≥ 10 wt.%

- in order to provide the required level of strength characteristics it is necessary to increase the value of misfit factor δ due to rise of the size mismatch of periods of crystalline lattices of γ′-phase and γ-solid solution. It can be reached by introduction of the optimum quantity of hafnium and tantalum in a new doping system of the developed alloy. They have positive effect on misfit factor value;
- introduction of the optimum quantity of hafnium (0.3 wt.%) and tantalum (2.5 wt.%) in doping system of the designed alloy at decrease of chromium from 16 to 14.5 % as well as increase of doping lower boundary on aluminum from 2.5 to 3.2 % and on tungsten from 3.5 to 6.2 % in the basic doping system of ZhS3LS alloy as well as decrease of doping upper boundary on molybdenum from 4.5 to 2.5 wt.%. This guarantees necessary level of technological and corrosion characteristics in rise of temperature level of strength characteristics.

The following variable doping elements were selected as alternating factors for the investigated computed compositions, namely hafnium and tantalum as well as elements included in the composition of basic alloy ZhS3LS, i.e. chromium, tungsten and molybdenum. A range of variation of concentration of investigated doping elements in the selected new doping system Ni–Co–Cr–Al–Ti–Mo–W–Ta–Hf–Zr–B–C was set in the following limits, wt.%: 0–0.5 Hf; 0–3.5 Ta; 4.0–7.5 W; 1.0–4.0 Mo; 3.5–16.0 Cr.

Initially, a computer experiment was used to carry an evaluation of structural stability of the computed compositions in a set range of variation by indicated elements on N_{v_γ}, M_{d_γ}, M_{d_C} and ΔE parameters using traditional methods following known regression equations (RE) [1–4, 6, 7, 13–20] as well as mathematical regression models (RM) in accordance with the algorithm (see Figure) of developed CASM method [12, 21–24].

It is known [1, 2, 14–17] that the value and sign of parameter of doping disbalance ΔE determines a direction of the reactions in γ-solid solution and tendency of high-temperature nickel alloys to precipitation of that or another type of TCP (topologically close-packed) phases. Thus, the alloys with large negative doping disbalance ($\Delta E < -0.04$) have high probability to formation of heterotypical compounds, i.e. carbides of M_6C type, α-phases based on vanadium and molybdenum as well as topologically close-packed phases of σ, μ type. The alloys with large positive doping disbalance ($\Delta E < 0.04$) are susceptible to formation of homeotypic compounds of η-phase type based on Ni_3Ti, Ni_3Nb, Ni_3Ta as well as eutectic (peritectical) phases based on Ni_3Al. If $\Delta E = 0$ than the alloy composition is supposed to be ideally balanced.

Table 2 represents the pilot variants of compositions 1–5 of designed alloy together with compositions of commercial alloys ZhS3LS and VZhL12E of medium doping level. Mixtures of the compositions, which satisfy the conditions: $P_{TCP} = 0.80–0.85$; $N_{v_\gamma} \le$ ≤ 2.40 and $M_{d_\gamma} \le 0.93$; $–0,04 < \Delta E < 0.04$ and $0.972 \le$ $\le M_{d_C} < 0.988$, supposed to be phase stable.

Table 2. Effect of doping elements of basic composition of commercial alloy ZhS3LS on parameters of its structural stability

Composition number	Content of elements, wt.%				Quantity of γ'-phase, vol.%	Misfit, %	Structural stability parameters				
	Hf	Ta	Cr	W/Mo	$V_{\gamma'}^{20}$	δ	P_{TCP}	N_{v_γ}	M_{d_γ}	M_{d_C}	ΔE
ZhS3LS	–	–	16.0	1.00	40.6	0.171	0.8290	2.2141	0.9100	1.0061	0.1372
1	0.1	1.5	15.5	1.83	45.9	0.290	0.8297	2.2597	0.9144	0.9857	0.0289
2	0.2	2.0	15.0	2.40	47.2	0.338	0.8309	2.2593	0.9143	0.9850	0.0250
3	0.3	2.5	14.5	3.25	48.6	0.377	0.8322	2.2566	0.9141	0.9840	0.0200
4	0.4	3.0	14.0	4.67	50.0	0.404	0.8337	2.2510	0.9134	0.9832	0.0156
5	0.5	3.5	13.5	7.50	51.3	0.412	0.8352	2.2489	0.9134	0.9824	0.0111
VZhL12E	–	–	9.25	0.45	60.8	0.151	0.8172	2.2287	0.9114	0.9847	0.0235

Table 3. Parameters of structural stability of ZhS3LS-M alloy [21]

Computation method	Structural stability parameters				
	P_{TCP} = = 0.825±0.025	$N_{v_\gamma} \le 2.40$	$M_{d_\gamma} \le 0.93$	$\Delta E = \pm 0.04$	M_{d_C} = = 0.980±0.008
RE	–	2.1945	0.9049	0.0200	0.9692
RM	0.8323	2.2566	0.9141	0.0200	0.9840

Table 4. Values of structural-phase parameters of alloy ZhS3LS-M [24]

Phase type	Phase quantity, vol.%		CALPHAD-method [24]											
			Computed composition of phases at 20 °C, wt.%											
	Experiment	Compu-tation	C	Co	Cr	Al	Ti	Mo	W	Ta	Hf	Zr	B	Ni
γ-	49.3–48.15	48.94	–	7.95	25.3	0.38	0.06	1.4	5.67	0.14	–	–	–	59.1
γ´-	48.5–49.5	48.6	–	1.67	1.88	5.83	6.12	0.13	4.11	5.01	0.62	0.03	–	74.6
MC	0.95–1.05	1.03	10.1	–	0.63	–	25.8	0.49	9.75	37.9	15.1	0.23	–	–
$M_{23}C_6$	1.25–1.30	1.25	5.16	0.77	71.7	–	–	18.1	1.43	–	–	–	–	2.84
M_3B_2	Not found	0.18	–	–	20.7	–	–	69.5	1.65	–	–	–	8.15	–

Table 5. Values of physical parameters of alloy ZhS3LS-M

Alloy ZhS3LS-M	Physical parameters at 20 °C [24]								
	ρ	E	$\alpha \cdot 10^6$	C_p	$r \cdot 10^6$	λ	$a_{\gamma'} \cdot 10^{-4}$	$a_{\gamma'} \cdot 10^{-4}$	δ
Unit	g/cm³	GPa	1/K	J/g·K	Ohm·m	W/m·K	μm	μm	%
CALPHAD	8.47	213.25	11.46	0.42	0.71	10.29	3.589	3.575	0.377

Note. ρ is the specific density; E is the Young's modulus; α is the coefficient of thermal expansion; C_p is the specific heat; r is the specific electric resistance; λ is the heat conduction; $\alpha_{\gamma'}$ is the parameters crystalline lattice of γ′-phase; α_γ is the parameters crystalline lattice of γ-solid solution; δ is the size mismatch of lattice parameters (misfit).

Table 6. Temperature parameters of alloy ZhS3LS-M [12, 22]

Evaluation method	$\sum_\gamma$	t_L	t_S	$\sum_{\gamma'}$	t_{eut}	$t^{\gamma'}_{s.s.}$	$t^{\gamma'}_{c.s.}$	Δt_{cr}	Δt_{hom}	t_{hom}
Computation on RM	11.0	1370	1286	8.8	1243	845	1176	84	67	–
Experiment	–	1355	1290	–	1220	–	1160	65	60	1190

Note. Σ_γ is the total content of elements, strengthening γ-solid solution; $\Sigma_{\gamma'}$ is the total content of elements stabilizing γ′-phase; t_L is the liquidus temperature; t_S is the solidus temperature; t_{eut} is the temperature of local melting of eutectic γ′-phase; $t^{\gamma'}_{s.s.}$, $t^{\gamma'}_{c.s.}$ are the temperatures of start and complete (end) solution of γ′-phase; Δt_{sol} is the interval of alloy solidification; Δt_{hom} is the temperature interval for homogenization; t_{hom} is the optimum temperature for alloy homogenization.

Table 7. Characteristics of ZhS3LS-M alloy corrosion [12, 23]

Evaluation method	V_q^t, g/(m^2·s)					
	$P_{cr} \geq 3{,}0$	$V_q^{800}\cdot 10^3$	$V_q^{850}\cdot 10^3$	$V_q^{900}\cdot 10^3$	$V_q^{950}\cdot 10^3$	t_{cr}, °C
Computation of RM	3.81	0.0483	0.9719	3.5846	6.0234	817
Experiment	–	0.04	0.90	3.50	5.90	820

Computations of parameters of structural stability such as N_{v_γ}, M_{d_γ}, ΔE, M_{d_C} were carried out by means of transfer of compositions of γ-solid solutions and general compositions in at.%.

Table 2 shows that pilot compositions 1–5 as well as commercial alloy VZhL12E are balanced from point of view of conditions of doping disbalance $\Delta E = \pm\, 0.04$. The value of disbalance of doping system ΔE in the pilot compositions 1–5 is in the limits from 0.0111 to 0.0289 that satisfies the conditions of balanced doping. It should be noted that the value of imbalance of the doping system of basic commercial alloy ZhS3LS, taken as a prototype, does not satisfy the conditions of balanced doping of chemical composition ($\Delta E = 0.1372$). At that ZhS3LS alloy is technologically weldable since quantity of main strengthening γ′-phase corresponds to the condition ($V_{\gamma'}^{20}$ = = 40.6–50 %) in contrast to more high-temperature alloy VZhL12E ($V_{\gamma'}^{20}$ = 60.8 %), which is not characterized by good technological weldability. At the same time ZhS3LS alloy does not have necessary level of high-temperature strength since quantity of main strengthening γ′-phase does not correspond to $43 \leq V_{\gamma'}^{20} \leq 50$ % condition.

Further in accordance with the algorithm of CASM method (see Figure) structural-phase, physical, temperature, corrosion and strength groups of parameters were calculated for the phase-stable compositions 1–4.

In selection of optimum composition of designed alloy for manufacture of all-cast NA, differing by technological weldability, it is shown that structural stability is the necessary, but insufficient condition for getting required indices of high-temperature strength. The necessary structural and physical factors, providing the required level of high-temperature strength in 800–1000 °C temperature interval, are the value of volume fraction of γ′-phase, which should lie in the controlled limits ($43 \leq V_{\gamma'}^{20} \leq 50$ %) on mass as well as misfit-factor, value of which should lie in ($0.15 < < \delta < 0.45$ %) limits.

Pilot composition 3 (see Table 2), with assigned designation of ZhS3LS-M grade, was selected for further experimental investigations taking into account a comparative analysis of received data on groups of computed characteristics for pilot compositions, by means of multicriterial optimization of the composition on controlled parameters.

Experimental investigations were carried out on the pilot specimens of test melts by set parameters in accordance with Table 2.

The optimized composition of designed alloy ZhS3LS-M was the following, wt.%: 0.10 C; 14.5 Cr; 4.5 Co; 3.0 Al; 3.0 Ti; 6.5 W; 2.0 Mo; 2,5 Ta; 0.3 Hf; 0.015 Zr; 0.015 B; Ni — base.

Comparative assessment of a tendency to structural and phase instability of the optimized composition of designed alloy ZhS3LS was carried out using

Table 8. Quantity of γ′-phase in ZhS3LS-M alloy, vol.% [12, 24]

Evaluation method	$V_{\gamma'}^{20}$	$V_{\gamma'}^{800}$	$V_{\gamma'}^{900}$	$V_{\gamma'}^{1000}$
Computation of RM	48.6	47.5	44.6	33.9
Experiment	48.9	–	–	–

Table 9. Characteristics of short-term strength of alloy ZhS3LS-M, MPa [12, 24]

Alloy ZhS3LS-M	σ_t^{20}	σ_t^{800}	σ_t^{900}	σ_t^{1000}	δ^{20}	δ^{800}	δ^{900}	δ^{1000}
Computation of RM	979	835	860	502	–	–	–	–
Experiment	930–975	811–836	849–854	500–563	8.8–13.2	3.8–5.3	2.9–5.9	5.0–11.8

Table 10. Long-term strength limit (100 and 1000 h) of alloy ZhS3LS-M, MPa [12, 24]

Alloy ZhS3LS-M	σ_{100}^{800}	σ_{1000}^{800}	σ_{100}^{900}	σ_{1000}^{900}	σ_{100}^{1000}	σ_{1000}^{1000}
Computation of RM	480	370	280	180	120	70
Experiment	480–500	350–370	280–300	170–190	110–130	70–80

Table 11. Comparative values of alloy characteristics

Characteristics of parameters by groups	Values of alloy characteristics		
	Alloy-prototype ZhS3LS	Designed alloy ZhS3LS-M	Alloy-analogue VZhL12E
Parameters of structural stability			
$P_{TCP} = 0.825 \pm 0.025$	0.8290	0.8323	0.8175
$N_{v_\gamma} \le 2.40$	2.2141	2.2566	2.2287
$M_{d_\gamma} \le 0.93$	0.9100	0.9141	0.9114
$M_{d_C} = 0.980 \pm 0.008$	0.1372	0.0200	0.0235
$\Delta E = \pm 0.04$	0.1372	0.0200	0.0235
Structural-phase parameters			
$43 \le V_{\gamma'} \le 50$, vol.%	38.0–42.0	43.5–49.5	58.0–62.0
Physical parameters			
ρ, g/cm^3	8.33	8.47	7.93
misfit $0.15 \le \delta \le 0.45$ %	0.171	0.377	0.151
Temperature characteristics			
t_L, °C	1354	1355	1334
$t_{Sol} \le 1280$, °C	1260	1290	1273
Δt_{cr}, °C	94	65	61
$t_{eut.}$, °C	1188	1220	1229
$t^{\gamma'}_{s.s.}$, °C	835	850	851
$t^{\gamma'}_{c.s.}$, °C	1090	1160	1222
Δt_{hom}, °C	98	60	7
T_{hom}, °C	1150±10	1190±10	Withou HT
Corrosion resistance parameters			
$P_{CR} \cdot 3.0$	4.00	3.81	2.53
$V_q^{800} \cdot 10^3$, g/(m$^2 \cdot$s)	0.04	0.05	0.16
$V_q^{850} \cdot 10^3$, g/(m$^2 \cdot$s)	0.82	0.97	2.98
$V_q^{900} \cdot 10^3$, g/(m$^2 \cdot$s)	3.07	3.58	9.97
$V_q^{950} \cdot 10^3$, g/(m$^2 \cdot$s)	5.24	5.92	15.12
t_{cr}, °C	825	820	770
Mechanical parameters			
Short-term strength:			
$\sigma_t^{20} \ge 850$ MPa	740–70	930–975	910–975
σ_t^{800}, MPa	620–650	911–956	880–1000
σ_t^{900}, MPa	520–600	849–854	850–870
σ_t^{1000}, MPa	–	500–563	500–580
Long-term strength:			
σ_{100}^{800}, MPa	380–400	480–500	480–530
σ_{1000}^{800}, MPa	–	350–370	370–420
σ_{100}^{900}, MPa	180–200	280–300	270–305
σ_{100}^{900}, MPa	–	170–90	180–205
σ_{100}^{1000}, MPa	–	110–130	120–145
σ_{1000}^{1000}, MPa	–	70–80	75–90
$\sigma_{260}^{975} \ge 40$ h	–	44–68	68–127
Elimination of cast defects in all-cast NA by AAW method	Differs by technological weldability	Differs by technological weldability	Not characterized by technological weldability

traditional computation methods PHACOMP (N_v) [7, 11], New PHACOMP (M_d) [13], ΔE-method [14–17] with their known regression equations (RE) as well as received mathematical regression models (RM) [12, 21–24] (Table 3).

Computations using CALPHAD method [25] on structural-phase and physical parameters [24, 26] were carried out based on criteria (parameters) of serviceability of cast HNA, grounded on works [12, 21–24]. Tables 4 and 5 represent the computed values of structural-phase and physical parameters for designed alloy ZhS3LS-M of the optimum doping level.

Table 6 represents the computed and experimental values, which were received by a method of differential thermal analysis (DTA) on VDTA-8M unit in helium at constant heating rate (cooling) being equal 80 °C/min. Thermally inert specimen of pure tungsten (W-reference) was used as a reference. Calibration technology on temperatures of melting of pure metals allowed getting well reproducible results independent on heating rate.

A complex of comparative experimental investigations was carried out on pilot specimens of test melts from designed alloy ZhS3LS-M in comparison with the similar specimens of commercial alloys ZhS3LS and VZhL12E. The pilot specimens of designed alloy ZhS3LS-M were received using vacuum-induction melting on unit of UPPF-3M type by series technology.

Computation investigations of (high temperature corrosion) HTC-resistance were carried out for composition of designed alloy ZhS3LS-M (Table 4) in synthetic ash at testing temperatures 800, 850, 900 and 950 °C on the basis of 100 h following received mathematical RM for given group of parameters [12, 23]. Experimental investigations of HTC-resistance of the specimens of test melt of alloy ZhS3LS-M were carried out in synthetic ash at testing temperatures 800, 850, 900 and 950 °C in comparison with alloys ZhS3LS and VZhL12E using method developed by Nikitin V.I. (I.I. Polsunov CBTI), which is widely applied in the field [8–10]. The experiments at all temperatures were carried out during 100 h. Resistance of specimens of pilot compositions to HTC was evaluated on average corrosion rate V_q^t g/(m^2·s). Table 7 represents the computed and experimental values of corrosion parameters of designed alloy ZhS3LS-M.

Mechanical tests for short-term and long-term strength were carried out on the standard cylinder specimens from developed alloy ZhS3LS-M using standard procedures. Short-term strength tests were performed at 20, 800, 900 and 1000 °C temperatures on tensile-testing machines UME-10TM and GSM-20 (GOST 1497–61, GOST 9651–73 and GOST 1497–84). Long-term strength tests were carried out at 800, 900, 975 and 1000 °C temperature on AIMA-5-2 and ZTZ 3/3 machines (GOST 10145–81). Quantity of γ'-phase in ZhS3LS-M alloy is presented in Table 8.

Tables 9 and 10 show the computed and experimental values of limits of short-term and long-term strength of the specimens of test melts of designed alloy ZhS3LS-M at different temperatures.

Table 11 gives the comparative results of computed and experimental values of characteristics of designed alloy ZhS3LS-M on groups of parameters, namely structural stability, structural-phase, physical, temperature, corrosion and strength characteristics in comparison with the values of similar characteristics of commercial alloys ZhS3LS and VZhL12E.

It is determined as a result of multicriterial optimization of composition based on computation and experimental investigations of set design conditions that developed alloy ZhS3LS-M provides necessary level of required parameters and characteristics. The balanced composition with indicated doping limits contains the optimum quantity of tantalum — 2.5±0.3 wt.%; lower content of chromium — 14.5±0.3 wt.%, molybdenum — 2.0±0.5 wt.% and higher content of tungsten — 6.5±0.3 wt.% than in commercial alloy ZhS3LS, taken as a prototype; lower content of aluminum — 3.3±0.3 wt.% than in VZhL12E alloy, taken as an analogue.

5 melts from developed alloy ZhS3LS-M of total mass 500 kg were certified by strength characteristics under production conditions of JSC «Motor Sich». The pilot all-cast nozzle apparatus SA TVZ-117 were manufactured by serial technology under production conditions of V.I. Omelchenko ZMBP enterprise. Technological process of elimination of the cast defects by AAW method was modernized. Pilot SA TVZ-117 was installed on technological engine, where it has worked for a period of service life with a positive result and is working up to the moment in order to increase specified service life.

Conclusions

1. Multicriterial optimization of composition on algorithm of developed CASM method allowed designing a new cast weldable corrosion-resistant alloy ZhS3LS-M for manufacture of all-cast NA of different types a varying by increased strength characteristics at the level of high-temperature non-weldable and non-corrosion-resistant alloy VZhL12E as well as characterizing with corrosion resistance and technological weldability at the level of commercial cast weldable corrosion-resistant nickel alloy ZhS3LS.

2. New developed alloy ZhS3LS-M is implemented in commercial production of JSC «Motor Sich» for manufacture of all-cast nozzle apparatus of TVZ-117

type of different stages instead of widely used commercial alloys ZhS3LS and VZhL12E.

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