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Weldable corrosion-resistant nickel-based cast superalloy ZHC3LC-M

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Abstract
Feasibility to eliminate the manufacturing defects of the components produced and to obtain the components of complex intricate shapes is topical challenge of practical value in the metallurgical sphere. It promotes the research for the new materials.
This research reports how operative weldability and corrosion-resistance of high-strength nickel-based superalloy are achievable along with high temperature strength preserved as high as σ_{40}^{975} = 180-200 MPa. These characteristics make the two above-mentioned goals possible. In the article we describe how the newly-developed superalloy (ZHC3LC-M) with such characteristics has been designed on the base of high-strength steel of ZHC3LC (Ukrainian steel grade).
Among the practical values of the new superalloy ZHC3LC-M, it also worth mentioning that this superalloy is good to be applied as the alloying material.
The design of the supperalloy was carried out by means of the existing rapid integrated calculation and analytical method. The parameters of the structural stability Nv_{γ}, $\bar{M}d_{\gamma}$, $\bar{M}d_{C}$ and ΔE have also been incorporated in the design technique.
The calculations have been confirmed by the experimental studies with the industrial heats and the research results have been implemented to serve instead of the earlier adopted alloy.
Key words: HIGH-STRENGTH NICKEL-BASED ALLOYS; ALLOYING SYSTEM; PERFORMANCE CRITERIA; OPTIMIZATION, REGRESSION EQUATION; REGRESSION MODEL; THE EXISTING RAPID INTEGRATED CALCULATION AND ANALYTICAL METHOD.

Introduction

One of perspective ways to improve performance characteristics of the critical parts of gas turbine engine is production of all-cast nozzle set for them from new high-strength corrosion-resistant nickel-based cast superalloys (hereinafter referred as superalloy), exhibiting both weldability and enhanced high-strength performance, which is impossible to provide without addressing to the new materials and their production technologies [1-6]. The term of operational weldability for such alloys is regarded as the possibility of eliminating casting defects (cavities, pores, etc.) on the surface of the castings by welding or surfacing.

The Problem to Discuss. This article reports on designing the new cast corrosion-resistant nickel-based cast superalloy, which development has been supported by the application of the existing rapid integrated calculation and analytical method (hereinafter referred as the rapid method) [2]. The superalloy is intended for the production of all-cast nozzle sets. This material is to possess the properties of operative weldability as good as those of the industrially applied nickel-based alloy of ZhC3LC (refer to Table 1) and higher strength characteristics than those of BZhL12E nickel-based alloy.

The search for the promising compositions of the design alloy was carried out according to the computer simulation algorithm of the above-mentioned rapid method and was based on the alloying system of the industrially applied high-strength nickel-based alloys of ZhC3LC and BZhL12E (refer to Table 1).

The chosen basic model of alloying for ZhC3LC (Ni-Co-Cr-Al-Ti-Mo-W-Zr-B-C) has been enlarged with the elements of hafnium (Hf) and tantalum (Ta). This solution has contributed to as follows:

- increase in the volume fraction of the principle strengthening γ'-phase and increase in its thermodynamic stability;
- positive effect on the morphology of the MeC carbide phase, a noticeable suppression of the formation mechanism for $Me_{23}C_6$ carbides (less thermodynamically stable and unfavorable in terms of morphology); this contributes to the increase in the total stock of material plasticity;
- significant increase in the temperature of complete dissolution of the main strengthening γ'-phase, and consequently, the increase in its residual quantity at high temperatures; this contributes to the improvement of the high-temperature strength characteristics, and especially those of the long-term strength.

Table 2 shows the principle parameters observed and applied in the calculation for the multicriteria optimization of the alloy composition being developed.

Analysis Results and Discussion. In order to perform the multicriteria optimization for the composition of the designed alloy, the following requirements have been formulated and the parameters principle for examination of structural stability were chosen for the complex calculation:

– to meet the conditions of structural stability for the following parameters: Π_{SSA}= Cr / [Cr+Mo+W] = = 0.825 ± 0.025; $\overline{N}v_{\gamma} \leq 2.45$, $\overline{M}d_{\gamma} \leq 0.93$, ΔE = = ± 0.04, $\overline{M}d_{C}$ = 0.980 ± 0.008; where and hereafter Π_{SSA} stands for the parameter of the structural stability of the alloy;

– to ensure operative weldability as high as that of the ZhC3LC alloy, taken as a prototype, and the high-temperature strength characteristics close to the values of the BZhL12E alloy, taken as an analog: the controlled amount of the principle strengthening γ'-phase is within 43 < Vγ '20 < 50% wt; the short-term strength is $\sigma_B^{20} \geq 850$ MPa; $\delta^{20} \geq 5.0$% while the long-term strength is $\sigma_{180}^{975} \geq 40$ hours, in accordance to the technical specifications;

– ensuring corrosion-resistant parameters as high as ZhC3LC, taken as a prototype: corrosion resistance $P_{COR} = \sqrt{Cr} \times [Ti / Al] \geq 3.0$.

The values of characteristics for the alloy developed (refer to Table 2) have been obtained by the multicriteria optimization of the composition alloyed with hafnium and tantalum on the basis of the industrially applied alloy of ZhC3LC, taken as a prototype. The abbreviation ZhC3LC-M in the dedicated picture stands for its modified version. The algorithm of the existing rapid method (refer to Figure 1) was applied for this purpose. The conceptually new approach to the alloying balance for the superalloy is revealed by the following provisions:

– in order to ensure the operability of the designed alloy, it is necessary to balance the overall chemical composition of the alloy: by γ'-forming elements within $\sum_{\gamma'}$ = (Al+Ti+Nb+Ta+Hf) = 8-9% by weight; by the strengthening elements of γ- solid solution $\sum_{\gamma}$ = (Mo+W+Ta+Re+Ru) ≥ 10% wt;

Table 1. Chemical Composition of Cast Nickel-Based Alloys of ZhC3LC and BZhL12E. Average Alloying [2]

Alloy Grade	Average Content of Elements, % wt										
	C	Cr	Co	Mo	W	Al	Ti	Nb	V	Zr	B	Ni
ZhC3LC	0.09	16.0	5.0	4.0	4.0	2.7	2.7	-	-	0.015	0.015	Base
BZhL12E	0.16	9.25	9.0	3.1	1.4	5.4	4.5	0.75	0.75	0.020	0.015	Base

Table 2. Principle Parameters of Structural Stability for Multicriteria Optimization of the Designed Alloy Composition

Controlled Parameters of Structural Stability	Measurement Unit	Value
Stability Parameter, Π_{SSA} = Cr / [Cr+Mo+W]	-	0.825 ± 0.025
Total number of electron vacancies in γ-solid solution, $\bar{N}v_{\gamma}$	-	≤ 2.45
Total number of valence electrons in γ-solid solution, $\bar{M}d_{\gamma}$	-	≤ 0.93
Total number of valence electrons in the alloy, $\bar{M}d_{C}$	-	0.980 ± 0.008
Imbalance of the alloying system, ΔE	-	± 0.04
Substantival composition $\sum_{\gamma}$ = (Mo+W+Ta+Re+Ru)	% wt	≥ 10.0
Substantival composition $\sum_{\gamma'}$ = (Al+Ti+Nb+Ta+Hf)	% wt	$8.0 \leq \sum_{\gamma'} \leq 9.0$
Solidus temperature, t_S	ºC	≥ 1280ºC
Homogenization temperature range, Δt_{HOM}	ºC	≥ 20ºC
Amount of strengthening γ'-phase (20ºC), $V_{\gamma'}^{20}$	% wt	$43 < V_{\gamma'}20 < 50$
Dimensional misfit of lattices γ- and γ'- (misfit), δ	%	0.15 - 0.45
Short-term strength (20ºC), σ_B^{20}	MPa	≥ 850
Relative elongation (20ºC), δ^{20}	%	≥ 5.0
Long-term strength τ_{FAIL}, σ_{180}^{975}	hr	≥ 40
Corrosion-resistance, $P_{COR} = \sqrt{Cr} \times [Ti / Al]$	-	≥ 3.0
Elimination of casting defects in all-cast nozzle set by argon-arc welding method (AAW)	Operative weldability as good as that of ZhC3LC alloy	

– in order to ensure the required level of strength characteristics, it is necessary to increase the value of the misfit factor δ, i.e., an increase in the dimensional discrepancy between the crystal lattice periods of the γ'-phase and the γ-solid solution, which is achieved by introducing the optimal amounts of Hf and Ta into the new alloying system of the alloy being developed;

- the required level of technological and corrosion-resistant characteristics along with an increase in the temperature level of the strength characteristics can be achieved by as follows: 1) the introduction of the optimum amounts of Hf (0.3%) and Ta (2.5%) into the new alloying system along with the decrease in Cr content from 16% wt to 14.5% wt; 2) the increase in the ZhC3LC basic system of alloying with respect to Al (from 2.5% wt to 3.2% wt) and W (from 3.5% wt to 6.2% wt); 3) the decrease in the upper range for Mo (from 4.5% wt to 2.5% wt).

The variable alloying elements were assigned to be the variables for the calculated experimental compositions. They were Hf, Ta (newly introduces elements into the base alloy) and Cr, W, Mo (actually have been applied before in ZhC3LC). The range of variation of the concentrations for the alloying elements under study in the new alloying system of Ni-Co-Cr-Al-Ti-Mo-W-Ta-Hf-Zr-BC was set in the following ranges (% wt): Hf (0.0-0.5); Ta (0.0-3.5); W (4.0-7.5); Mo (1.0-4.0); Cr (13.5-16.0). Initially, the computer experiment was directed towards the assessment of the structural stability for the potential composition within the required range of variability by indicated elements according to the characteristics $\bar{N}v_{\gamma}$ [8], $\bar{M}d_{\gamma}$, $\bar{M}d_{C}$ [9] and ΔE [10-14]. Both the traditional methods with the well-known regression equations and the mathematical regressions models were applied in accordance with the algorithm (refer to figure 1) and the existing rapid method.

In Table 3, we write the prototype versions of compositions 1-5 of the alloy to be designed together with the compositions of industrial alloys ZhC3LC and BZhL12E on average. The composite combinations, which meet the requirements of Π_{SSA} = 0.80 – 0.85; $\bar{N}v_{\gamma} \leq 2.45$ and $\bar{M}d_{\gamma} \leq 0.93$; $-0.04 \leq \Delta E \leq +0.04$ and $0.972 \leq \bar{M}d_{C} \leq 0.988$, were considered as phase stable. The calculations of structural stability parameters ($\bar{N}v_{\gamma}$, $\bar{M}d_{\gamma}$, ΔE, $\bar{M}d_{C}$) were carried out with the conversion of chemical compositions for γ-solid solutions and for general compositions into at. %.

Table 3 shows that experimental compositions 1-5 as well as the industrial alloy BZhL12E are in balance with respect to the conditions of alloying imbalance ΔE = ± 0.04. In experimental compositions 1-5, the imbalance value of alloying system ΔE ranges within +0.0111 and +0.0289 meeting the conditions of the balanced alloying.

Further, it should be noted that the value of alloying system imbalance of the basic ZhC3LC taken as a prototype does not suit the conditions of the balanced alloy of chemical composition (ΔE = +0.1372). However, the alloy ZhC3LC exhibits operative weldability as the amount of the basic strengthening γ'-phase corresponds to the condition of ($V_{\gamma'}^{20}$ = = 40.6 < 50%) unlike the other high-strength alloy

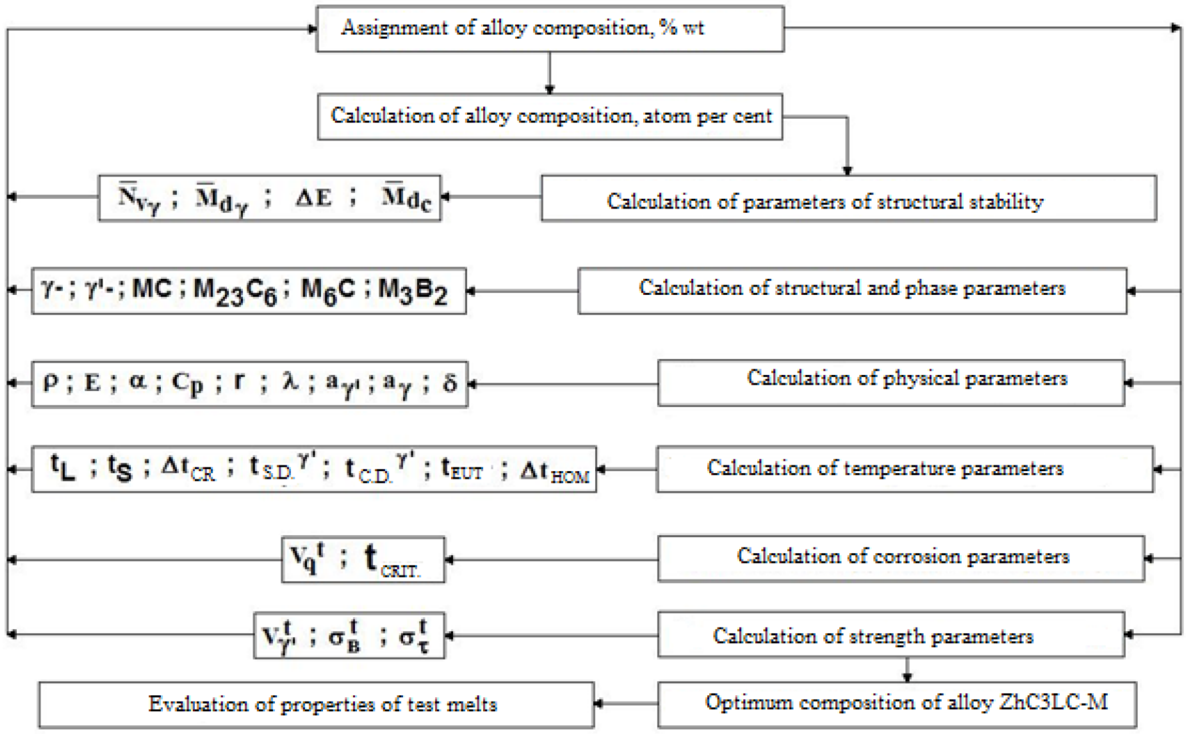

Figure 1. Algorithm for Computer Calculation of the ZhC3LC-M Designed Alloy. Rapid Method

Table 3. Effect of Alloying Elements Variations within the Basic Composition of the Industrial Alloy ZhC3LC on the Parameters of Structural Stability

Composition Number	Elements variation % wt				Quantity, % wt	Misfit, %	Structural Stability Parameters				
	Hf	Ta	Cr	W/Mo	$V_{\gamma'}$ 20	Δ	Π_{SSA}	$\bar{N}v_{\gamma}$	$\bar{M}d_{\gamma}$	$\bar{M}d_{C}$	ΔE
ZhC3LC	-	-	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
BZhL12E	-	-	9.25	0.45	60.8	0.151	0.8172	2.2287	0.9114	0.9847	+0.0235

of BZhL12E ($V\gamma'^{20}$ = 60.8%), which possesses better high-temperature stregnth characteristics but does not exhibit operative weldability. At the same time, the alloy of ZhC3LC does not possess the required level of high-temperature strength performance, since the amount of the basic strengthening γ'-phase does not correspond to the conditions of ($43 < V_{\gamma'}^{20} < 50\%$).

The choice of the optimum composition for the alloy being designed to possess operative weldability to all-cast nozzle applications is supported by the fact that the structural stability is necessary but not a sufficient condition for achieving of the required high temperature strength parameters. The necessary structural and physical factors for this within the temperature of 800ºC -1000 ºC is the value of the volume fraction of γ'-phase, which must be within the controllable range of ($43 < V_{\gamma'}^{20} < 50\%$ wt) and also by misfit-factor, which must be within the limits of ($0.15 \le \delta \le 0.45\%$).

Experimental composition 3 (Table 3) with the assigned designation of the grade ZhC3LC-M was selected for the further experimental studies on the basis of multicriteria optimization of the composition by controlled parameters (refer to Table 2). The experimental studies were carried out on the prototype models with the test and the industrial heats and their given parameters are reported in Table 2. The chemical composition of an optimum alloying level of the designed alloy of ZhC3LC-M is presented in Table 4.

Table 4. Optimized Composition of the Designed Alloy of ZhC3LC-M

ZhC3LC-M	Content of the principle alloying elements, % wt										
	C	Cr	Co	Al	Ti	W	Mo	Ta	Hf	Zr	B	Ni
	0.10	14.5	4.5	3.0	3.0	6.5	2.0	2.5	0.3	0.015	0.015	Basic

The results with the calculated and the experimental values of the designed alloy ZhC3LC-M are presented in Table 5, by the following parameters groups: structural stability [7-11], structural and

Table 5. Comparative Values of the Alloys Characteristics

Parameters Characteristics	Values of Alloys Characteristics		
	Prototype Alloy ZhC3LC	Designed Alloy ZhC3LC-M	Analogue Alloy BZhL12E
1	2	3	4
Structural stability:			
$\Pi_{SSA} = 0.825 \pm 0.025$	0.8290	0.8323	0.8175
$\overline{Nv}_\gamma \leq 2.45$	2.2141	2.2566	2.2287
$\overline{Md}_\gamma \leq 0.93$	0.9100	0.9141	0.9114
$\overline{Md}_C = 0.980 \pm 0.008$	1.0061	0.9840	0.9847
$\Delta E = \pm 0.04$	+0.1372	+0.0200	+0.0235
Structural and Phase Characteristics:			
$43 < V_{\gamma'} < 50$ % wt	38.0 – 42.0	43.5 – 49.5	58.0 – 64.0
Phisical Properties:			
ρ, g/cm^3	8.33	8.47	7.93
misfit $0.15 \leq \delta \leq 0.45$ %	0.171	0.377	0.151
Temperature Characteristics:			
t_L, °C	1354	1355	1334
$t_S \geq 1280$, °C	1260	1290	1273
Δt_{CR}, °C	94	65	61
$t_{EUT.}$, °C	1188	1220	1229
$t_{I.D.}^{\gamma'}$, °C	835	850	851
$t_{C.D.}^{\gamma'}$, °C	1090	1160	1222
Δt_{HOM}, °C	98	60	7
t_{HOM}, °C	1150º±10º	1190º±10º	without HT
Corrosion-Resistance:			
$P_{COR} \geq 3.0$	4.00	3.81	2.54
$V_q^{800} \times 10^3$, g/m^2·s	0.04	0.04	0.16
$V_q^{850} \times 10^3$, g/m^2·s	0.82	0.90	2.96
$V_q^{900} \times 10^3$, g/m^2·s	3.07	3.50	9.92
$V_q^{950} \times 10^3$, g/m^2·s	5.24	5.90	15.05
$t_{CRITICAL.}$, ºC	~825º	~820º	~770º
Short-Term Strength:			
$\sigma_B^{20} \geq 850$ MPa	740-770	930-975	910-975
σ_B^{800}, MPa	620-650	911-956	880-1000
σ_B^{900}, MPa	520-600	849-854	850-870
σ_B^{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_{1000}^{900}, MPa	-	170-190	180-205
σ_{100}^{1000}, MPa	-	110-130	120-145
σ_{1000}^{1000}, MPa	-	70-80	75-90
$\sigma_{180}^{975} \geq 40$ hours	-	44-68	68-127
Elimination of casting defects in the all-cast nozzle sets by argon-arc welding technique	Exhibits operative weldability	Exhibits operative weldability	Does not exhibit operative weldability

Note for the table designations:
Δt_{CR} – temperature range of the alloy crystallization;
$t_{EUT.}$ – temperature of local fusion for eutecticum (γ+γ′);
$t_{I.D.}^{\gamma'}$ – initiation temperature for the γ'-phase dissolution in the solid solution;
$t_{C.D.}^{\gamma'}$ – temperature of the γ'-phase complete dissolution in the solid solution;
Δt_{HOM} – temperature range for homogenization;
t_{HOM} – optimal temperature for homogenization;
t_L – alloy liquidus temperature;
t_S – alloy solidus temperature.

phase characteristics [1, 7, 15], physical properties [7, 15], temperature characteristics [1, 2, 7], corrosion-resistance [7, 16, 17] and strength characteristics [2]. They are compared with similar characteristics for the industrial alloys ZhC3LC and BZhL12E.

Conclusions

1. In accordance with the algorithm of the rapid integrated calculation and analytical method, a modern high-strength and corrosion-resistant cast superalloy ZhC3LS-M has been designed to possess operative weldability intended for production of the all-cast nozzle sets of the different levels. This superalloy possesses the characteristics of the existing industrially applied alloys but improve the situation by uniting in one metal the properties which the alloys do not have as taken separately: the increased strength at the level of the industrial high-strength alloy BZhL12E along with the corrosion resistance and the operative weldability at the level of the industrial weldable high-strength and corrosion-resistant nickel-based cast alloy ZhC3LC. Note that weldability and the corrosion resistance are not within BZhL12E properties.

2. The newly designed superalloy ZhC3LC-M is industrially tested and introduced into production at JSC "Motor Sich" with the purpose to manufacture the all-cast nozzle sets of TV3-117 type at the different levels instead of widely applied industrial mass production alloy BZhL12E.

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Synopsis of development of wagon materials fatigue failure

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Abstract
The basic part of the rolling stock consists of the freight wagons. However, they are used under heavy conditions (large-tonnage loads, severe atmospheric conditions, aggressive effect of loads, etc.). The load bearing capacity of the wagons should be provided throughout their service life. The main factors affecting the load bearing capacity of wagons are the properties of the corresponding materials and the cross sections shape of the parts. Therefore, the study of fatigue failure of the wagon materials is an important and relevant topic.