СТРУКТУРОУТВОРЕННЯ. ОПІР РУЙНУВАННЮ ТА ФІЗИКО-МЕХАНІЧНІ ВЛАСТИВОСТІ

STRUCTURE FORMATION. RESISTANCE TO DESTRUCTION AND PHYSICAL-MECHANICAL PROPERTIES

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OPTIMIZATION OF THE CHEMICAL COMPOSITION OF HEAT-RESISTANT CEMENTED STEEL FOR AIRCRAFT BUILDING

Purpose. *Optimization of the chemical composition of heat-resistant cemented steel in order to increase mechanical and operational properties at elevated temperatures - up to 450 ℃. Increasing the resource of aviation gearboxes at high temperatures and increasing the operational properties of hard armor.*

Research methods. *After manufacturing and normalizing samples of heat-resistant cemented steel, the actual content of alloying elements was determined using the following devices: LEGO CS-230 gas analyzer and Spectromax device. Mechanical properties after heat treatment were determined using a special testing machine UME-10TM. Core hardness was determined using a Rockwell hardness tester HRA-1 MIKROTECH.*

Results. *A regression model of the dependence of mechanical properties on the concentration of chemical elements of heat-resistant steel at different temperatures was obtained. Mathematical modeling allowed us to develop an optimal alloying complex taking into account the requirements for the material. The modeling results showed that the greatest influence on the properties of steel is exerted by primary and secondary carbides, which are formed during its smelting, thermal and chemical-thermal treatment. Based on the research, taking into account the requirements of hard armor and aviation gearboxes, an experimental and industrial smelting with rational mechanical properties ($\sigma_в \geq 1200$ MPa, $\delta \geq 10$ %, $\psi \geq 30$ % was produced.*

Scientific novelty. *For the first time, regression models for calculating the parameters of the physical and mechanical properties of heat-resistant cemented steel for dual-purpose aviation equipment were proposed. The obtained regression models allowed developing the chemical composition and properties of steel in accordance with technical requirements.*

Practical value. *The obtained modeling results can be used for a more detailed influence of alloying elements on the properties of steel for the development of new and improvement of existing steel grades, to increase the thermal load and resource of gas turbine engines. The resulting steel can be introduced at aviation enterprises, for example, JSC "Motor Sich" and SE "Ivchenko-Progress", and parts made of this steel can be competitors on the world market.*

Key words: *steel, heat resistance, strength, hardness, optimization, carbides, gear, hard armor, cementation, nitriding, austenite.*

Introduction

The aviation industry is currently developing dynamically, and it is well known that aircraft engines are the heart of any aircraft. They operate in more severe temperature conditions due to the increase in contact, shock, bending, corrosion and temperature loads. In particular, the loads increase while maintaining the size of assemblies and parts. Therefore, the current issue is the creation of new or improvement of existing materials with increased thermal and energy properties.

Analysis of research and publications

The modern development of the aviation industry in Ukraine and abroad directs researchers to the creation and improvement of steels for highly loaded parts. Currently, the following heat-resistant steels are used for the manufacture of highly loaded parts, such as gears of

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aircraft gearboxes and rolling bearings (Table 1): 14ХГСН2МА (ДИ-3А) 13Х3Н3М2ВФБ (ВКС-10) M50NiL 09Х3НМ3ФБч 13Х3НВМ2ФА (ДИ-45)The maximum heat resistance for steels 20Х3МВФ and ВКС - 5 is 250 °С та 350°С, respectively [1]. Steel ВКС-10 shows a good result of heat resistance at 450 °С, and steel ВКС-7 shows a good result after wear tests [2].

Having considered the position of the steel grades from Table 1 on the Schefler-De Long diagram [2] (Fig. 1), we obtain the following result: steel 09Х3НМ3ФБч [4] is located at a greater distance from the A+M region than steels ВКС-5, ВКС-10 and M50NiL. That is, in the cemented layer of steel 09Х3НМ3ФБч, austenite with less stability is formed and, accordingly, metastable austenite is more prone to decomposition. In addition, the solid solution is characterized by greater mobility of the atoms of the embodiment, which causes a shorter period of carbon saturation.

Considering the high temperature load of parts, it is advisable to study the effect of temperature on the change in the properties of steel during operation. Steel 09Х3НМ3ФБч has a multicomponent alloying complex. In view of this, it is necessary to optimize the chemical composition in such a way as to satisfy the requirements of mechanical, economic and operational properties [5]. For this, the static method of experiment planning is used [6–7].

This method is used to solve optimization problems in technical and other branches of science. When planning an experiment, a certain number of input (in this case, 4) and output (in this study, 5) parameters are selected. Since the number of experiments required to obtain a mathematical model reaches 24, i.e. 16, the fractional factorial experiment model was applied. In addition, reducing the number of experiments reduces the cost of the study. Next, the variation interval of each element was selected, an experiment planning matrix was created, and an equation of the dependence of mechanical properties on the concentration of alloying elements was obtained.

In work [8], carbide formation in the surface layers of M50NiL steel under different heat treatment regimes was investigated. In work [9], the influence of different options for the processing regime of heat-resistant steel 09Х3НМ3ФБч was studied. Compared to Chemical-thermal treatment (CTT) and Heat treatment (HT), M50NiL steel has a less complex processing algorithm and a significantly shorter duration in time while maintaining the necessary parameters of the diffusion layer and core.

In work [10], the influence of heat treatment on the surface of cemented steel was analyzed, but there is no experimental confirmation of the obtained data. The influence of the alloying complex W, Mo, Nb, V on the properties of chromium martensitic steel was studied. These elements have a positive effect on the mechanical properties and structure formation during thermal and chemical-thermal treatment [11].

In work [11], the parameters for controlling the saturation of the diffusion layer with carbon were studied. The use of cemented gears has its own characteristics, for example: the distribution, geometric shape and size of carbides, which is presented in the study [12].

One of the important tasks is the development of a surface hardening method. For this purpose, various options were considered in [13]. In [14], steel and hybrid ceramic bearings were compared. Ceramic bearings have better wear resistance, but are very sensitive to tensile and temperature loads.

In [15], the effect of molybdenum on the formation of the σ-phase was shown, and it was found that an increase in Mo content increases the probability of its appearance.

In [16], the effect of vanadium on the properties of steel was studied, and it was found that an increase in the vanadium content refines the grain size and increases the strength and hardness of steel, but at the same time has a negative effect on pearlite hardening.

Research on obtaining the chemical composition of heat-resistant steel is relevant, because it will allow to obtain a rational alloying complex with increased mechanical and operational properties, which will increase the resource of aviation gearboxes.

Objective

Optimization of the chemical composition of heat-resistant cemented steel in order to increase mechanical and operational properties at elevated temperatures - up to 450 °С. Increasing the resource and operation of aviation gearboxes at higher temperatures.

To achieve the goal, it is necessary to solve the following problems:

-to establish the dependence of mechanical properties on the concentration of the alloying elements in steel;

- to develop, based on the obtained regularities, the optimal chemical composition of steel, taking into account modern requirements for steels.

Material and research methods

Laboratory steel castings were carried out in a 60-kilogram induction furnace with a main lining. After the introduction of alloying elements into the ladle, rare earth elements were forcibly added. Then the experimental steels were poured into refractory cylindrical molds with a diameter of 80 mm and rolled on pneumatic hammers in the temperature range of 1000–1100 °С into a square of 15x15 mm.

After that, the samples (Fig. 2) were normalized at a temperature of 850 °С for 1 hour with subsequent cooling in air. The samples were melted in accordance with the Schefler diagram and in such a way that the main alloying elements – carbon, chromium, molybdenum, vanadium, which affect the structure formation and mechanical properties of the core of the studied steels varied.

Optimization of mechanical properties was carried out by the Box-Wilson method. 9 steels with different

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chemical compositions were melted (one variant of the main level and eight variants that form a replica 2^{4-1}. The levels and intervals of variation of factors (concentrations of alloying elements) are given in Table 3.

After manufacturing and normalizing the samples (Fig. 2), the actual content of alloying elements in the experimental steels was determined using the following devices: LEGO CS-230 gas analyzer and Spectromax device. The chemical composition of the experimental samples is given in Table 2.

In order to increase the heat resistance of steels (up to 450 °C), a chemical-thermal treatment (cementation) mode was selected, which ensures their secondary hardening. The samples (for studying the core of steels) were subjected to heat treatment: quenching from a temperature of 1030 °C in industrial oil. After that, 4-times tempering was carried out at a temperature of 530 °C with a holding time of 1 hour each.

Mechanical properties after heat treatment were determined using a special testing machine UME-10TM. The hardness of the core after heat treatment was determined using a Rockwell hardness tester HRA-1 MICROTECH. The alloying elements carbon, chromium, molybdenum and vanadium were selected as input parameters, and the yield strength, relative elongation, relative narrowing, impact strength and hardness were selected as output parameters.

To establish the regularities between the mechanical properties and the concentration of alloying elements and optimize the chemical composition of the studied steel, a regression model was developed using the method of mathematical planning of the experiment, calculations were carried out in the Mathcad 14 package. Replica 2^{4-1} with a generalizing defining contrast X4 = X1X2X3 was implemented (Table 3). After determining the levels and intervals of variation of factors, an experimental planning matrix was constructed (Table 4).

The regression model considers the first-order interactions X1X2, X1X3, X1X4. These interactions correspond to the carbides CCr, CMo, CV, respectively.

Table 1 – Chemical composition of heat-resistant steels

Steel grade	Content of alloying elements, wt.%									
	C	Cr	Mn	Si	Ni	Mo	W	V	Nb	REM
14ХГСН2МА (ДИ-3А)	0,11-0,16	1,20-1,60	0,7-1	0,45-0,70	1,60-2,0	0,25-0,40	-	0,03-0,06	-	-
13Х3Н3М2ВФБ (ВКС-10)	0,10-0,15	3,00-3,40	0,3-0,6	0,17-0,37	2,70-3,00	1,90-2,30	0,2-0,5	0,05-0,15	0,05-0,15	-
М50NiL	0,11-0,15	4,00-4,25	0,15-0,35	0,10-0,25	3,20-3,60	4,00-4,50	-	1,13-1,33	-	-
09Х3НМ3ФБч	0,04-0,10	2,00-3,00	0,10-0,80	0,10-0,80	0,50-1,50	1,60-3,00	-	0.20-0,40	0,05-0,030	0,001-0,01
13Х3НВМ2ФА (ДИ-45)	0,10-0,15	0,040-0,80	≤0,6	0,40-0,80	0,80-1,20	1,60-2,10	0,60-0,90	0,15-0,3	-	-

Table 2 – Chemical composition of studied steels

№	Content of alloying elements, wt.%										
	C	Si	Mn	Al	Ni	Cr	Mo	V	Nb	Ce	La
1	0,032	0,8	0,35	0,06	0,96	2,2	1,84	0,45	0,15	0,03	0,01
2	0,06	0,58	0,21	0,09	1,3	1,9	1,71	0,21	0,06	0,002	0,001
3	0,028	0,082	0,14	0,08	1,1	2,85	1,68	0,29	0,13	0,055	0,031
4	0,074	0,092	0,28	0.07	1,2	2,07	2,21	1,21	0,087	0,013	0,0044
5	0,02	0,065	0,1	0,03	1,09	1,99	2,46	0,31	0,22	0,017	0,0045
6	0,05	0,08	0,24	0,1	1,06	2,98	2,29	0,33	0,2	0,054	0,021
7	0,065	0,13	0,26	0,084	1,01	2,89	1,46	1,06	0,37	0,03	0,0094
8	0,028	0,1	5,0	0,07	1,00	2,59	2,61	0,95	0,13	0,012	0,0031

* Contents S, P ≤ 0.25%

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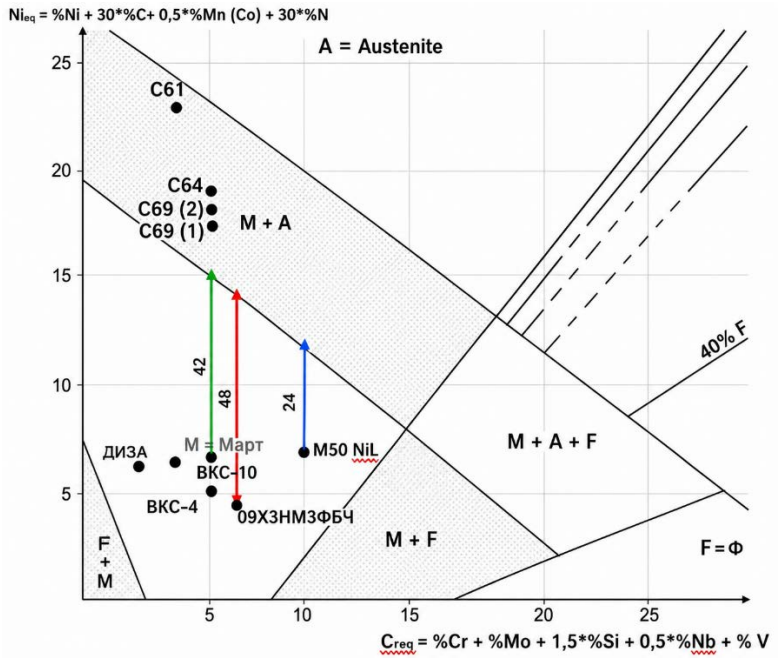


Figure 1. Schefler De Long diagram [1]

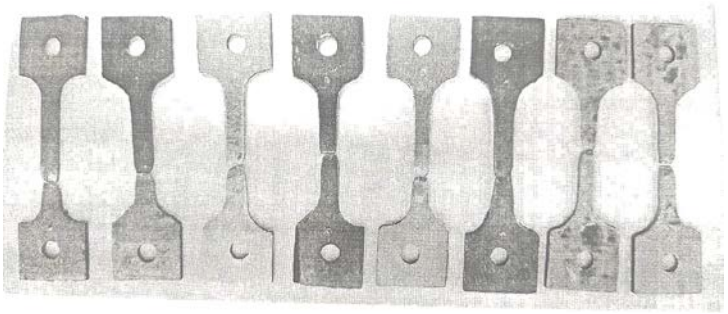


Figure 2. Photo of prototypes

Table 3 – Levels and variation of factors

Model characteristics	Concentration of alloying elements, wt%.			
Levels and intervals	C (X1)	Cr (X2)	Mo (X3)	V (X4)
Upper (+)	0,06	3	2,5	1
Main (0)	0,04	2,5	2	0,6
Lower (-)	0,02	2	1,5	0,2
Variation interval	0,02	0,5	0,5	0,4

Definitive contrast X4=-X1X2X3-

Table 4 – Matrix of planning

X0		X1	X2	X3	X4	X1X2	X1X3	X1X4
+		-	-	-	+	+	+	-
+		+	-	-	-	-	-	-
+		-	+	-	-	-	+	+
+		+	-	+	+	-	+	+
+		-	-	+	-	+	-	+
+		+	+	+	-	+	+	-
+		+	+	-	+	+	-	+
+		-	+	+	+	-	-	-

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Research results

Mathematical modeling allowed us to develop an optimal alloying complex taking into account the requirements for heat-resistant cemented steel for aircraft construction.

The modeling results showed that the greatest influence on the properties of steel is exerted by primary and secondary carbides, which are formed during its smelting, thermal and chemical-thermal treatment. Based on the research, taking into account the requirements of hard armor and aviation gearboxes, an experimental and industrial melt with rational mechanical properties ($\sigma_в \geq 1200$ МПа, $\delta \geq 10$ %, $\psi \geq 30$ %) was produced (Table 5, 6).

The chemical composition and alloying elements have the main influence on improving the studied properties. The main alloying elements that can vary when creating steel are carbon, chromium, vanadium, molybdenum. An increase in the carbon content increases strength and hardness, while at the same time reducing formability and weldability.

The content of C, Mo, V, Cr was selected as input parameters, and the output indicators σ_v, $\sigma_{0.2}$, δ, ψ, HRC, KCU were selected as output indicators. The accuracy of the model for all responses was assessed by comparing the initial data of the theoretical model with experimental data. After obtaining the equations of the dependences of mechanical properties, a search was performed for such values of the content of alloying elements at which the mechanical properties have the highest indicators (Table 7). The linear model was tested for adequacy. The test results are presented in (Table 8). To check the adequacy of the model, a comparison of the tabulated and calculated values of the Fisher criterion was used.

From Table 7 it can be seen that Fp > Fт, in addition, the error reaches 7.58 %. From the above data Table 8 it follows that the obtained theoretical dependence reproduces the experimental data.

Experimental-industrial steel 09Х3НМ3ФБч with the following chemical composition and properties was produced (Table 9).

The results of the regression analysis show that the mechanical properties of steel are most influenced by carbides that are formed during melt crystallization and secondary hardening. Based on previous studies and the results obtained in this work, the following statements are rational:

- the carbon content should be at a level of ≥0.06 mas.%. This is due to the fact that with a decrease in the carbon content, the strength and hardness characteristics of the steel core decrease and the simultaneous complication of steel smelting.

- the chromium content should be in the range of 3.25–3.50 wt.%. This is due to: the lower limit – ensuring the necessary strength characteristics of steel, in particular hardness and impact toughness under conditions of alternating loads. The upper limit is a decrease in the heat resistance of the cemented layer when chromium content increases beyond the specified limit, which is due to the low heat resistance of carbides to coalescence.

- the molybdenum content should be in the range of 2.8–3.2 wt. %. This ensures the formation of the optimal structure and properties of cemented steel under the condition of a given carbon content. When the lower limit is exceeded, the necessary hardenability of the steel, its hardness and heat resistance are not ensured. When the upper limit is exceeded, the deterioration of the mechanical properties of the cemented layer is observed, the σ- phase is formed and, accordingly, the impact toughness indicators decrease.

- the vanadium content should be in the range of 0.25–0.35 wt.%. When the upper limit is exceeded, vanadium reduces the hardenability of the diffusion layer, and when the lower limit is exceeded, the mechanical properties of the steel and heat resistance decrease.

Table 5 – Mechanical properties of steels of type 05Х3НМ2ФБч after CTT for secondary hardness

Test temperature, °C	Characteristic type	Melting No.							
		1	2	3	4	5	6	7	8
20	$\sigma_в$, MPa	864	941	816	1072	997	1005	957	705
150		819	907	780	1030	874	925	893	640
300		745	884	730	967	780	756	941	601
450		708	835	721	903	652	625	790	598
20	$\sigma_{0,2}$, MPa	823	861	733	1025	920	973	933	664
150		812	787	699	989	927	904	830	580
300		687	837	685	942	730	692	764	562
450		664	789	738	970	631	593	719	564
20	δ,%	7,4	8,2	7,6	7,0	5,7	8,9	6,1	7,1
150		7,5	8,4	7,2	8,5	4,3	7,1	6,9	9,3
300		4,5	7,1	6,4	5,9	6,3	6	6,6	6,1
450		6,1	5,4	6	6,3	5,3	5,2	5,9	6,2
20	Ψ,%	38,7	33	35,3	37,2	37,1	29,5	35,1	44,6
150		30	33,4	24,7	33,6	32	38,8	44,2	45,7
300		32,5	30,3	32	32,8	34,4	26,8	37	44,2
450		28,3	24,4	24,6	32,6	29	23,3	35,8	33,3
20	HRC (core)	38,7	33	35,3	37,2	37,1	29,5	35,1	44,6
20	KCU,J/sm ^{2}	30	33,4	24,7	33,6	32	38,8	44,2	45,7
20	HRC (after nitriding)	32,5	30,3	32	32,8	34,4	26,8	37	44,2

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Table 6 – Equation in coded form

Test temperature, °C	Characteristic type	The resulting equation
20	$\sigma_в$, MPa	1586,3125-12315,625C-242,25Cr-28,25Mo-254,6875V+3612,5CrC+1962,5MoC+5109,375VC
150		1467,25-9481,25C-175,0Cr-102,5Mo-211,25V+1925CrC+3000,0MoC+4468,75VC
300		1108,75+162,5C-82,0Cr-70,0Mo-206,25V-750,0CrC+1150,0MoC+5187,5VC
450		786,875+6912,5C+50,0Cr-110,0Mo-135,625V-3525,0CrC+1025,0MoC+4687,5VC
20	$\sigma_{0,2}$, MPa	1541,375-14481,25C-264,5Cr-30,0Mo-194,375V+4575,0CrC+2200,0MoC+4531,25VC
150		1828,875-20381,25C-334,5Cr-72,0Mo-259,375V+5225CrC+3500MoC+5656,25VC
300		974,5625+2309,375C-46,75Cr-68,25Mo-210,9375V-1912,5CrC+1412,5MoC+5359,375VC
450		778,625+6087,5C+92,0Cr-144,0Mo-196,875V-4425,0CrC+2025,0MoC+5437,5VC
20	δ,%	6,2+25C+1,25Cr-2.05Mo+2,375V-22,5CrC+47,5VoC-81,25VC
150		-5,075+269,375C+4,25Cr-0,9Mo+5,0V-95,0CrC+17,5MoC-84,375VC
300		0,01875+148,4375C+1,375Cr+1,575Mo-1,78125V-26,25CrC-41,25MoC+23,4375VC
450		4,8625+13,125C+0,75Cr-0,5Mo+0,4375V-17,5CrC+10,0MoC+9,375VC
20	Ψ,%	13,80625+410,3125C+4,475Cr+6,125Mo+7,15625V-121,25CrC-113,75MoC-17,1875VC
150		-21,5875+703,125C+2,3Cr+18,55Mo+16.0625V+95CrC-352,5MoC-209,375VC
300		-7,6125+690C+6,8Cr+12,5Mo+5,6875V+-107,5CCCCCCCrC-272,5MoC+37,5VC
450		12,00625+182,1875C-0,075Cr+8,125Mo+1,03125V+18,75CrC-171,25MoC+198,4375VC
20	HRC (core)	69,625-353,125C-9,75Cr-6,25Mo-4,375V+75,0CrC+100,0MoC+109,375VC
20	KCU,J/sm ^{2}	132,21875+120,3125C+8,625Cr-27,625Mo-6,40625V-356,25CrC+506,25MoC-398,4375VC
20	HRC (after nitriding)	69,31875-63,4375C+1,175Cr-2,975Mo-8,78125V-8,75CrC+23,75MoC+164,0625VC

Table 7 – Optimal chemical content of these elements

Test temperature, °C	Characteristic type	Alloying element			
		C	Cr	Mo	V
20	$\sigma_в$, MPa	0,6	2	2,5	1
150		0,6	2	2,5	1
300		0,6	2	1,5	1
450		0,6	2	1,5	1
20	$\sigma_{0,2}$, MPa	0,6	3	2,5	1
150		0,6	2	2,5	1
300		0,6	2	2,5	1
450		0,6	2	2,5	1
20	δ,%	0,2	3	1,5	1
150		0,2	3	1,5	1
300		0,6	2	1,5	0,2
450		0,2	2	2,5	1
20	Ψ,%	0,2	3	1,5	1
150		0,6	3	1,5	1
300		0,2	3	2,5	1
450		0,2	2	2,5	1
20	HRC (core)	0,6	2	1,5	1
20	KCU,J/sm ^{2}	0,6	2	2,5	0,2
20	HRC (after nitriding)	0,6	3	1,5	1

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Table 8 – Results of linear model testing

Characteristic type	F_{table}	F_{exp}	Average approximation coefficient
$\sigma_B^{20\ °C}$	8,7	7,3	6,364
$\sigma_B^{150\ °C}$	8,7	6,4	6,02
$\sigma_B^{300\ °C}$	8,7	5,7	6,321
$\sigma_B^{450\ °C}$	8,7	6,4	4,94
$\sigma_{0,2}^{20\ °C}$	8,7	8,2	6,638
$\sigma_{0,2}^{150\ °C}$	8,7	4,8	7,391
$\sigma_{0,2}^{300\ °C}$	8,7	5,5	5,921
$\sigma_{0,2}^{450\ °C}$	8,7	7,9	5,788
$\delta^{20\ °C}$	8,7	7,6	5,79
$\delta^{150\ °C}$	8,7	6,2	5,128
$\delta^{300\ °C}$	8,7	2,9	7,58
$\delta^{450\ °C}$	8,7	3,8	3,208
$\Psi^{20\ °C}$	8,7	4,6	3,393
$\Psi^{150\ °C}$	8,7	6,8	4,473
$\psi^{300\ °C}$	8,7	7,4	4,751
$\Psi^{450\ °C}$	8,7	6,7	5,521
HRC $^{20\ °C}$ (core)	8,7	6,3	4,839
KCU $^{20\ °C}$,J/sm ^{2}	8,7	5,6	3,792
HRC $^{20\ °C}$(after nitriding)	8,7	8,1	1,872

Table 9– Optimized steel data

Content of alloying elements by mass,%											
C	Si	Mn	S	P	Ni	Cr	Ti	Mo	V	Nb	Al
0,12	0,27	0,68	0,006	0,017	1,31	2,87	0.01	3.00	0,3	0,28	0,05
Mechanical properties 20 °C											
$\sigma_в$, MPa	$\sigma_{0,2}$, MPa				δ,%			Ψ,%	KCU,J/sm ^{2}		
1274	1202				12			64	22		

Conclusions

The effect of four alloying elements, namely carbon, chromium, molybdenum, and vanadium, on the mechanical properties of heat-resistant steel for aircraft construction has been determined. A linear regression model has been developed to optimize the mechanical properties of heat-resistant cemented steel.

The optimal chemical composition of cemented steel 09Х3НМ3ФБч for aircraft gearboxes and hard armor has been proposed.

References

1. Outokumpu. (n.d.). *Stainless steel grades*. https://www.outokumpu.com/en/products/stainless-steel-types

2. Mishchenko, V. G., Panchenko, O. I., Lyuty, O. P., et al. (2015). *Cemented steel* (Patent No. 108582, Ukraine).

3. Bhatt, A., & Parappagoudar, M. B. (2015). Modeling and analysis of mechanical properties in structural steel–DOE approach. *Archives of Foundry Engineering*, *15*(4), 5–12. https://doi.org/10.1515/afe-2015-0069

4. Li, Y., Chen, T., Ehmsen, S., Gläßner, C., & Aurich, J. C. (2020). A study on impact factors of the energy consumption of the fused deposition modeling process using two-level full factorial experiments. *Procedia CIRP*, *93*, 79–84. https://doi.org/10.1016/j.procir.2020.03.036

5. Diao, Y., Yan, L., & Gao, K. (2021). Improvement of the machine learning-based corrosion rate prediction model through the optimization of input features. *Materials & Design*, *198*, 109326. https://doi.org/10.1016/j.matdes.2020.109326

6. Lian, J.-L., Zheng, L.-J., Wang, F.-F., & Zhang, H. (2018). Evolution of carbides on surface of carburized M50NiL bearing steel. *Journal of Iron and Steel Research International*, *25*(11), 1198–1212. https://doi.org/10.1007/s42243-018-0166-4

7. Mishchenko, V. G., Podoroga, O. S., Mishchenko, V. G., Klochikhin, V. V., & Myloserdov, O. B. (2019). Features of the formation of the structure and properties of steel 09Kh3NM3FBCh during chemical-thermal treatment. *Problems and Prospects of Railway Transport Development*, *4*(82), 92–98.

8. Ooi, S., & Bhadeshia, H. K. D. H. (2012). Duplex hardening of steels for aeroengine bearings. *ISIJ International*, *52*(11), 1927–1934. https://doi.org/10.2355/isijinternational.52.1927

9. Ren, S. Y., Wang, C. Q., Zhang, W., & Li, Y. (2020). The heat treatment effect on the surface

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DOI 10.15588/1607-6885-2026-3-1

characteristics of 9310 steel gear. *IOP Conference Series: Materials Science and Engineering*, *770*(1), 012111. https://doi.org/10.1088/1757-899X/770/1/012111

10. Michaud, P., Delagnes, D., Lamesle, P., Mathon, M.-H., & Levaillant, C. (2007). The effect of the addition of alloying elements on carbide precipitation and mechanical properties in 5% chromium martensitic steels. *Acta Materialia*, *55*(14), 4877–4889. https://doi.org/10.1016/j.actamat.2007.05.004

11. Mishchenko, V. G., Meniailo, O., Bagriichuk, O., & Bulakh, O. (2016). Parameters control of 09Cr3NiMo3VNbr carburizing steel diffusion layer in the process of thermochemical treatment. *Materials Science and Technology Conference and Exhibition 2016*, *1*, 159–166.

12. Klecka, M. A., Subhash, G., & Arakere, N. K. (2013). Microstructure-property relationships in M50-NiL and P675 case-hardened bearing steels. *Tribology Transactions*, *56*(6), 1046–1059. https://doi.org/10.1080/10402004.2013.818393

13. Gloeckner, P., & Ebert, F.-J. (2010). Micro-sliding in high-speed aircraft engine ball bearings. *Tribology Transactions*, *53*(3), 369–375. https://doi.org/10.1080/10402000903312364

14. Cento, P., & Dareing, D. W. (1999). Ceramic materials in hybrid ball bearings. *Tribology Transactions*, *42*(4), 707–714. https://doi.org/10.1080/10402009908982273

15. Yamada, K., Osuki, T., Ogawa, K., Holmes, B., Sotoudeh, K., & Dong, H. (2023). Effects of Mo and Cu contents on sigma phase precipitation in 25Cr-5Ni-Mo-Cu-1Mn-0.18N duplex stainless steel. *ISIJ International*, *63*(1), 143–149. https://doi.org/10.2355/isijinternational.ISIJINT-2022-361

16. Wang, P., Li, Z., Lin, G., Zhou, S., Yang, C., & Yong, Q. (2018). Influence of vanadium on the microstructure and mechanical properties of medium-carbon steels for wheels. *Metals*, *8*(12), 978. https://doi.org/10.3390/met8120978

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ОПТИМІЗАЦІЯ ХІМІЧНОГО СКЛАДУ ТЕПЛОСТІЙКОЇ ЦЕМЕНТОВАНОЇ СТАЛІ ДЛЯ АВІАБУДУВАННЯ

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Мета роботи. *Оптимізація хімічного складу теплостійкої цементованої сталі з метою підвищення механічних та експлуатаційних властивостей при підвищених температурах – до 450 °С. Збільшення ресурсу авіаційних редукторів при високих температурах та підвищення експлуатаційних властивостей твердої броні.*

Методи дослідження. *Після виготовлення та нормалізації зразків теплостійкої цементованої сталі було визначено фактичний вміст легувальних елементів за допомогою приладів: газоаналізатора LEGO CS-230 та приладу Spectromax. Механічні властивості після термічного оброблення визначали з використанням спеціальної випробувальної машини УМЕ-10ТМ. Твердість серцевини визначали за допомогою приладу твердомір Роквелла HRA-1 МИКРОТЕХ.*

Отримані результати. *Отримано регресійну модель залежності механічних властивостей від концентрації хімічних елементів теплостійкої сталі при різних температурах. Математичне моделювання дозволило розробити оптимальний легувальний комплекс із врахуванням вимог, які висуваються до матеріалу. Результати моделювання показали, що найбільший вплив на властивості сталі мають первинні та вторинні карбіди, які утворюються в процесі її виплавляння, термічного та хіміко-термічного оброблення. На основі дослідження з урахуванням вимог твердої броні та авіаційних редукторів виготовлено дослідно-промислову плавку з раціональними механічними властивостями ($\sigma_в \geq 1200$ МПа, $\delta \geq 10$ %, $\psi \geq 30$ %).*

Наукова новизна. *Вперше запропоновано регресійні моделі розрахунку параметрів фізико-механічних властивостей теплостійкої цементованої сталі для авіаційної техніки подвійного призначення. Отримані регресійні моделі дозволили розробити хімічний склад та властивості сталі у відповідності до технічних вимог.*

Практична цінність. *Отримані результати моделювання можуть бути використані для більш*

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детального впливу легувальних елементів на властивості сталі при розробленні нових та вдосконаленні існуючих марок сталей, для підвищення теплоенергетичного навантаження та ресурсу газотурбінних двигунів. Отриману сталь може бути впроваджено на авіаційних підприємствах, наприклад АТ «Мотор Січ» та ДП «Івченко-Прогрес», а деталі виготовлені з даної сталі можуть бути конкурентами на світовому ринку.

Ключові слова: *сталь, теплостійкість, міцність, твердість, оптимізація, карбіди, шестерня, тверда броня, цементація, азотування, аустеніт.*

Список літератури

1. Stainless steel grades [Електронний ресурс] // Outokumpu products. Режим доступу: https://www.outokumpu.com/en/stainless-steel/grades/Pages/default.aspx (дата звернення: 25.08.2026).

2. Цементована сталь : пат. 108582 Україна : МПК C22C 38/44 / В. Г. Міщенко, О. І. Панченко, О. П. Лютий [та ін.]. № 108582 ; заявл. 12.05.2014 ; опубл. 12.05.2015, Бюл. № 9.

3. Bhatt A., Parappagoudar M. B. Modeling and Analysis of Mechanical Properties in Structural Steel-DOE Approach // Archives of Foundry Engineering. 2015. Vol. 15, № 4. P. 5–12. DOI: https://doi.org/10.1515/afe-2015-0069.

4. Li Y., Chen T., Ehmsen S., Gläßner C., Aurich J. C. A study on impact factors of the energy consumption of the fused deposition modeling process using two-level full factorial experiments // Procedia CIRP. 2020. Vol. 93. P. 79–84. DOI: https://doi.org/10.1016/j.procir.2020.03.036.

5. Diao Y., Yan L., Gao K. Improvement of the machine learning-based corrosion rate prediction model through the optimization of input features // Materials & Design. 2021. Vol. 198. 109326. DOI: https://doi.org/10.1016/j.matdes.2020.109326.

6. Long J., Zhang K., Zhu M.-L., Xuan F.-Z. Evolution of carbides on surface of carburized M50NiL bearing steel // Journal of Iron and Steel Research International. 2018. Vol. 25, № 11. P. 1198–1211. DOI: https://doi.org/10.1007/s42243-018-0166-4.

7. Клочихін В. В., Милосердов О. Б., Подорога О. С., Міщенко В. Г. Особливості формування структури та властивостей сталі 09Х3НМ3ФБЧ під час хіміко-термічного оброблення // Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту. 2019. № 4 (82). С. 92–98. DOI: https://doi.org/10.15802/stp2019/172412.

8. Ooi S., Bhadeshia H. K. D. H. Duplex Hardening of Steels for Aeroengine Bearings // ISIJ International. 2012. Vol. 52, № 11. P. 1927–1934. DOI: https://doi.org/10.2355/isijinternational.52.1927.

9. Ren S. Y., Wang C. Q., Zhang W., Li Y. The heat treatment effect on the surface characteristics of 9310 steel gear // IOP Conference Series: Materials Science and Engineering. 2020. Vol. 770, № 1. 012111. DOI: https://doi.org/10.1088/1757-899X/770/1/012111.

10. Michaud P., Delagnes D., Lamesle P., Mathon M.-H., Levaillant C. The effect of the addition of alloying elements on carbide precipitation and mechanical properties in 5% chromium martensitic steels // Acta Materialia. 2007. Vol. 55, № 14. P. 4877–4889. DOI: https://doi.org/10.1016/j.actamat.2007.05.004.

11. Mishchenko V. G., Meniailo O. I., Bagriichuk O. S., Bulakh O. I. Parameters control of 09Cr3NiMo3VNbr carburizing steel diffusion layer in the process of thermochemical treatment // Materials Science and Technology Conference and Exhibition 2016, MS&T'16. 2016. Vol. 2. P. 159–166.

12. Klecka M. A., Subhash G., Arakere N. K. Microstructure-Property Relationships in M50-NiL and P675 Case-Hardened Bearing Steels // Tribology Transactions. 2013. Vol. 56, № 3. P. 1046–1059.

13. Gloeckner P., Ebert F. Micro-Sliding in High-Speed Aircraft Engine Ball Bearings // Tribology Transactions. 2010. Vol. 53, № 3. P. 369–375.

14. Cento P., Dareing D. W. Ceramic Materials in Hybrid Ball Bearings // Tribology Transactions. 1999. Vol. 42, № 4. P. 707–714. DOI: https://doi.org/10.1080/10402009908982273.

15. Yamada K., Osuki T., Ogawa K., Holmes B., Sotoudeh K., Dong H. Effects of Mo and Cu Contents on Sigma Phase Precipitation in 25Cr-5Ni-Mo-Cu-1Mn-0.18N Duplex Stainless Steel // ISIJ International. 2023. Vol. 63, № 1. P. 143–149. DOI: https://doi.org/10.2355/isijinternational.ISIJINT-2022-361.

16. Wang P., Li Z., Lin G., Zhou S., Yang C., Yong Q. Influence of Vanadium on the Microstructure and Mechanical Properties of Medium-Carbon Steels for Wheels // Metals. 2018. Vol. 8, № 12. 978. DOI: https://doi.org/10.3390/met8120978.

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