OPTIMIZATION OF THE COMPOSITION OF CAST IRON FOR CAST PARTS OPERATING UNDER ABRASIVE FRICTION, ACCORDING TO THE CRITERION OF MAXIMUM WEAR RESISTANCE

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ABSTRACT

The object of research: Titanium-alloyed hypoeutectic iron for mixer blades operating under abrasive friction conditions.

Investigated problem: selection of the optimal titanium content in the alloy according to the criterion of the maximum wear resistance coefficient.

The main scientific results: the content of titanium in cast iron was determined, which provides the maximum wear resistance coefficient with various compositions of the base alloy. It has been established that with the same titanium content, the highest value of the wear resistance coefficient depends on the carbon content and the position of the eutectic point on the Fe-C state diagram. In the studied range, the highest values of the wear resistance coefficient correspond to the average range of variation of these factors. This allows to say that the effect of carbon content and the position of the eutectic point doubly affect wear resistance at the same titanium content, and there is a range of titanium content in which the effect of these factors on the wear resistance value becomes the same.

The area of practical use of the results of the study: the results obtained can be used by designers of industrial enterprises choosing materials for the manufacture of machine parts subject to intense friction due to operating conditions. The wear caused by this friction leads to the failure of the blades, so the designer's task is to choose the one that maximizes the durability of the blades.

Innovative technological product: wear-resistant hypoeutectic cast iron alloyed with titanium for cast parts operating in conditions of intense abrasive friction

The scope of the technological innovative product: mixing plants of various types, mainly used in road construction, construction and agriculture.

1. Introduction

1. 1. The object of research

Hypoeutectic cast iron, alloyed with titanium, for mixer blades operating under conditions of abrasive friction.

1. 2. Problem description

A large number of equipment used in industry, construction and agriculture is designed to carry out the processes of mixing components. As a rule, various types of mixers are used for this, in which the blades are the main part of the mixing unit. They are made of special cast irons with increased wear resistance or alloyed steels. Nevertheless, despite the variety of approaches to the choice of alloys for such parts and the many different grades of alloys used for these purposes, such parts fail due to abrasion and violation of the working profile. A change in the working profile due to wear leads to violations of the technological process, which invariably affects the quality of mixing and, as a result, the finished product. Therefore, the main task is to extend the service life of such parts, which causes the need for scientific and operational research aimed at finding ways to increase their durability.

1. 3. Suggested solution to the problem

The service life of mixer blades under the same operating conditions depends on the quality of the working surface and profile geometry, as well as on the properties of the alloy, which, in turn, depend on its chemical composition.

In [1], the operating conditions were studied when using radial blades inside the chamber, which ensure the distribution of mixing bodies and increase surface flows. This causes the creation of better conditions for the redistribution of material along the mixing axis, which can indirectly inform about the possibility of reducing the load on the rubbing blades.

Mixing conditions affect the resistance of the blades, so the results of modeling during mixing of various media by the discrete element method (DEM) [2, 3], Advanced DEM-CFD [4] or particle imaging velocimetry (PIV) [5] are of interest. In addition, it should be noted analytical methods for constructing blade profiles [6], which make it possible to determine rational parameters and geometric characteristics of the profile, which improve the quality of mixing. Establishing the dynamics of mixed media and assessing its potential effect on friction surfaces are important for studying the processes of abrasion of the working surface, since this allows to analyze wear processes, considering the blade in general as a typical part that works on abrasive friction, regardless of the mixed media.

However, all the above works do not focus on the quality of the working surfaces of the blades and their material. It can be assumed that a violation of the surface quality with an incorrectly selected alloy at the same time under the action of abrasive friction and the combined influence of dynamic loads will lead to a rapid failure of the blades.

When choosing the material for the blades and the technology of its manufacture, it is important to solve the problem of selecting the chemical composition that provides the desired properties. When choosing cast iron as a material, it is alloyed with elements that provide carbide formation processes, for example, vanadium in combination with manganese, chromium, and nickel [7, 8] or titanium and boron [9, 10]. Such elements affect the structure and properties in different ways, depending on the absolute value of the concentrations of elements and their ratios, making it possible to obtain cast irons of different grades, varying these values.

When choosing steel as a material, it is important to ensure high surface properties, in contrast to cast iron, where volume properties are important. This is ensured by nitriding [11] or borating [12] technologies, which provide high surface hardness and a given depth of the diffusion layer.

Based on considerations of cost and metallurgical complexity of manufacture, cast iron is more preferable, the structure of which should provide high resistance to abrasion, for which it should include carbides of elements of varying complexity.

The aim of the study: to determine the chemical composition of cast iron for cast parts operating under conditions of abrasive friction, providing maximum wear resistance.

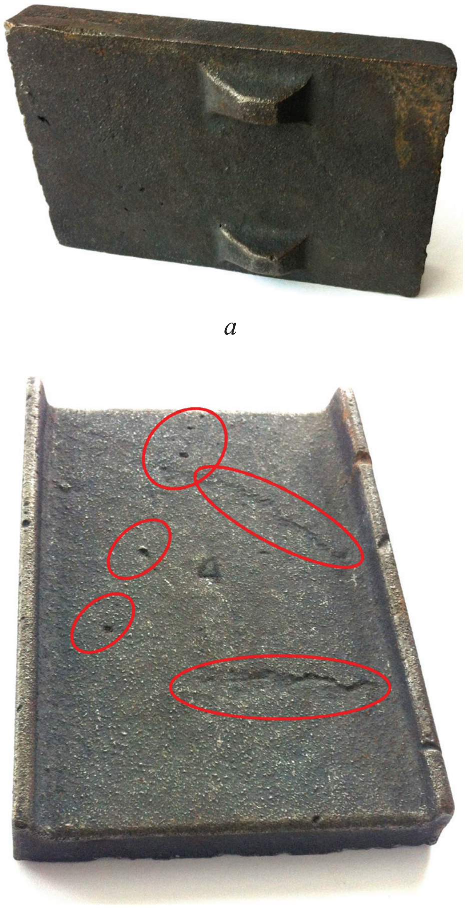
2. Materials and Methods

The research hypothesis was based on the following. Having an adequate mathematical model that describes the dependence of wear resistance on the carbon content in cast iron, the position of the eutectic point on the Fe-C phase diagram and titanium content, as well as data on industrial cast iron melts in the absence of titanium, it is possible to establish its direct effect on wear resistance and determine the optimal amount in the alloy. Thanks to this, it will be possible to obtain an alloy with the highest wear resistance, as well as to determine the most significant factors affecting the resistance of parts subject to abrasive friction. In particular, having adequate dependences of wear resistance on the chemical composition, it is possible to exclude or confirm the influence of the quality of the working surface of parts in contact with mixed media. This is especially important if such surfaces, in addition to friction, are subject to shock dynamic loads, such as the blades of shot blasters (**Fig. 1**).

Therefore, the theoretical-analytical approach to the study is justified. This study was a continuation of the study, the results of which are described in [13]. As initial data for determining the wear of cast iron, determined by the value of the wear coefficient (Kwr, %) in the absence of titanium, the data given in [14] were used, supplemented by the calculation of the position of the eutectic point on the Fe-C state diagram (carbon equivalent):

$$C_{eq} = C(\%) + 0.3\,Si(\%) - 0.03\,Mn(\%). \quad (1)$$

These data are presented in **Table 1.**



a

b

Fig. 1. Shot blast blade: *a* – general view, *b* – working surface with defects

Table 1

Chemical composition and wear factor data for unalloyed cast iron

White cast iron type	Chemical composition of cast iron, %					Wear resistance coefficient *Kwr*, %
	C	Si	Mn	C_{eq}	Ti	
unalloyed	2.17	1.27	0.89	2.52	–	3.38
	2.68	1.3	0.96	3.04	–	5
	3.3	1.28	1.07	3.65	–	4.05

The mathematical model on which the numerical calculations of *Kwr* were carried out has the form [13]:

$$y = 12.08145 + 1.917424x_1 - 2.09456x_2 - 0.39929x_3 - 13.2789x_1^2 - 14.3292x_2^2 - \\ -3.20145x_3^2 + 25.76207x_1x_2 + 4.497585x_1x_3 - 5.47818x_2x_3, \qquad (2)$$

where the input variables correspond to those given in **Table 2** and are presented in a normalized k-dimensional space (k=3). The relationship between natural and normalized values is given by the equation

$$x_i^* = x_i I_i + \overline{x_i}, \qquad (3)$$

where x_i^* – the natural value of the i-th independent variable, %, x_i – the normalized value of the i-th independent variable (i=1 for C, i=2 for C_{eq}, i=1 for Ti), $\overline{x_i}$ – the average value of the i-th independent variable, %, I_i – the interval of variation of the values of the i-th independent variable.

Table 2

Input variables and ranges

Normalization parameters	C, %	C_{eq}, %	Ti, %
Lower limit of the interval, %	2.21	2.539	0.28
Upper limit of the interval, %	3.34	3.827	2.94
Average value, %	2.775	3.183	1.61
Variation interval, %	0.565	0.644	1.33

The normalized values of the input variables for the case of obtaining an alloy without alloying with titanium (**Table 1**) are given in **Table 3.**

Table 3

Normalized values of input variables for the case of obtaining an alloy without alloying with titanium

Sample No.	Natural values of input variables		Normalized values of input variables	
	C	C_{eq}	C	C_{eq}
1	2.17	2.52	–1.07	–1.03
2	2.68	3.04	–0.17	–0.22
3	3.3	3.65	0.93	0.73

In its natural form, equation (2) is represented as follows [13]:

$$
\begin{aligned}
Kwr = {} & 12.08145 + 1.917424\frac{C-2.775}{0.565} - 2.09456\frac{C_{eq}-3.183}{0.644} - 0.39929\frac{Ti-1.61}{1.33} - \\
& -13.2789\left(\frac{C-2.775}{0.565}\right)^2 - 14.3292\left(\frac{C_{eq}-3.183}{0.644}\right)^2 - 3.20145\left(\frac{Ti-1.61}{1.33}\right)^2 + \\
& +25.76207\left(\frac{C-2.775}{0.565}\right)\left(\frac{C_{eq}-3.183}{0.644}\right) + 4.497585\left(\frac{C-2.775}{0.565}\right)\left(\frac{Ti-1.61}{1.33}\right) - \\
& -5.47818\left(\frac{C_{eq}-3.183}{0.644}\right)\left(\frac{Ti-1.61}{1.33}\right).
\end{aligned}
\tag{4}
$$

3. Results

The results of Kwr calculations according to the model (2) for the normalized values of the input variables from **Table 3** in the range Ti=[0.28; 2.94] % with a step of 0.665 %, which corresponds in the normalized form to the length of the interval $0.5I_3$, are given in tabular form (**Table 4**).

Table 4

Results of Kwr numerical simulation

x_0	x_1	x_2	x_3	x_1^2	x_2^2	x_3^2	x_1x_2	x_1x_3	x_2x_3	***Kwr***
1	–1.07	–1.03	–1	1.145	1.061	1	1.102	1.07	1.03	6.5
1	–1.07	–1.03	–0.5	1.145	1.061	0.25	1.102	0.535	0.515	9.2
1	–1.07	–1.03	0	1.145	1.061	0	1.102	0	0	10.2
1	–1.07	–1.03	0.5	1.145	1.061	0.25	1.102	–0.535	–0.515	9.6
1	–1.07	–1.03	1	1.145	1.061	1	1.102	–1.07	–1.03	7.4
1	–0.17	–0.22	–1	0.029	0.048	1	0.037	0.17	0.22	8.9
1	–0.17	–0.22	–0.5	0.029	0.048	0.25	0.037	0.085	0.11	11.3
1	–0.17	–0.22	0	0.029	0.048	0	0.037	0	0	12.1
1	–0.17	–0.22	0.5	0.029	0.048	0.25	0.037	–0.085	–0.11	11.3
1	–0.17	–0.22	1	0.029	0.048	1	0.037	–0.17	–0.22	8.9
1	0.93	0.78	–1	0.865	0.608	1	0.725	–0.93	–0.78	8
1	0.93	0.78	–0.5	0.865	0.608	0.25	0.725	–0.465	–0.39	10.2
1	0.93	0.78	0	0.865	0.608	0	0.725	0	0	10.8
1	0.93	0.78	0.5	0.865	0.608	0.25	0.725	0.465	0.39	9.7
1	0.93	0.78	1	0.865	0.608	1	0.725	0.93	0.78	7

Fig. 2 shows the results of the approximation of the Kwr values obtained by numerical simulation.

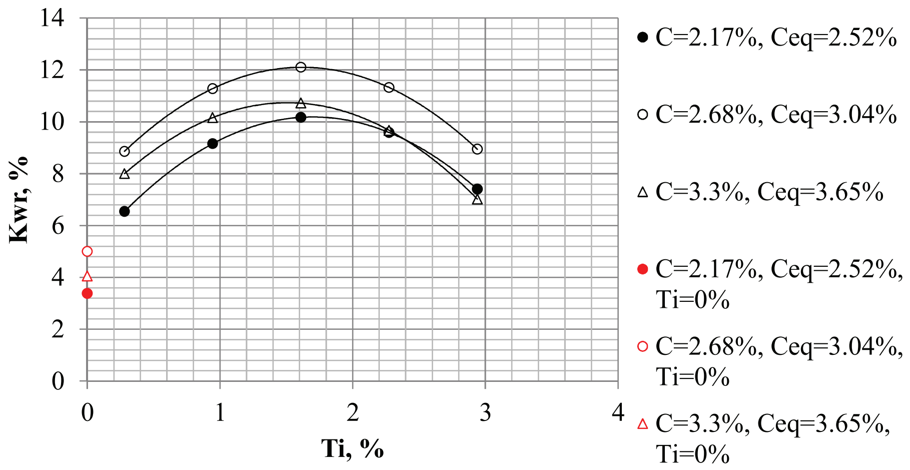


Fig. 2. Results of numerical simulation

From **Fig. 2** it can be seen that the maximum value of the wear coefficient is achieved at an average level of titanium content, regardless of the values of C and C_{eq}. In the variant C=2.17 % and C_{eq}=2.52 % *Kwr*max≈10 %, in the variant C=2.68 % and C_{eq} =3.04 % Kwrmax≈12 %, in the variant C=3.3 % and C_{eq}=3.65 % Kwrmax≈11 %.

Such results make it possible to determine the optimal alloy composition according to the *Kwr*→max criterion: C=2.68 %, C_{eq}=3.04 %, Ti=1.61 %. It provides the wear resistance coefficient *Kwr*max≈12 %.

The optimal value of the carbon equivalent allows to estimate the set of allowable ratios of Si and Mn in the chemical composition, based on equation (1):

$$\mathrm{Si}(\%)=\frac{0.36+0.03\,\mathrm{Mn}(\%)}{0.3}=1.2+0.1\,\mathrm{Mn}(\%). \tag{5}$$

Calculation of the silicon content according to equation (5) at Mn=0.96 % gives the result Si=1.296 %, which practically coincides with the experimental value Si=1.3 % (**Table 1**).

4. Discussion

The analysis of the obtained results (**Table 4** and **Fig. 2**) allows to see an important trend in the influence of titanium on the wear resistance coefficient, as well as to evaluate the influence of the ratios C and C_{eq} on it. Thus, it can be seen that the use of Ti for alloying cast iron with a carbon content close to steels, even in a minimal amount, leads to an increase in the wear resistance coefficient by almost 92 %. Increasing the carbon content from C=2.17 % to C=2.68 % at the minimum level of titanium content leads to an increase in the wear resistance coefficient by 78 %, and an increase in carbon content to the level of C=3.3 % at the minimum level of titanium content leads to an increase in the wear resistance coefficient by 98 % .

Attention is drawn to the fact that if the titanium content exceeds the value that provides *Kwr=Kwr*max, the change in the carbon content and the position of the eutectic point has practically no effect on the trend of change in the value of *Kwr*. This can be seen from the nature of the dependence curves *Kwr=f*(Ti) for C=2.17 %, C_{eq}=2.52 % and C=3.3 %, C_{eq}=3.65 %, which practically coincide. At the same time, an increase in the titanium content leads to a deterioration in wear resistance, and the use of titanium in such quantities can be considered unreasonable both from the point of view of the effect on wear resistance and their economic considerations. Based on this, the direction of further research may be to seek explanations for this fact, at the level of analysis of the structure, processes and mechanisms of its formation.

The limitations of the study are related to the model itself, since it is built on a small sample of data and on an arbitrary planning area, which is actually available based on the available experimental data. An option to increase the accuracy of this model can be the procedure of artificial orthogonalization of the passive experiment data [15]. This would make it possible to obtain more accurate estimates of the coefficients and proceed to the analysis of the response surface [16]. However, the application of this procedure for calculating the values of *Kwr* at the points of the orthogonal plan may face the problem of identifying the ranges of C, C_{eq} and Ti, within which the calculated results will be adequate. In this case, it is necessary to solve the inverse problem – to fix the values of *Kwr* at the levels *Kwr*=*Kwr*min *Kwr*=*Kwr*max and determine the allowable ranges of C, Si, Mn and Ti content in cast iron, and form a new experiment plan on them.

5. Conclusions

Based on the results of numerical simulation, it is shown that the use of titanium in cast iron, the main requirement for which is high wear resistance, can significantly increase the wear resistance coefficient compared to white unalloyed cast iron. Thus, the use of Ti in an amount of 0.28 % provides an increase in the wear resistance coefficient by 78–98 %, depending on the carbon content and the carbon equivalent of cast iron. Alloying the alloy with titanium in an amount of 1.61 % provides the highest possible value of the wear resistance coefficient (*Kwr*max≈12 %). However, a further increase in the titanium content to the level of Ti=2.94 % demonstrates the opposite trend - the value of Kwr will decrease to the value of *Kwr*max≈(7–9) %. Moreover, starting from the value of Ti≈1.61 %, the amount of carbon in the alloy and its carbon equivalent have practically no effect on the nature of the dependence *Kwr*=*f*(Ti). In this case, the numerical values of the wear resistance coefficient at the same titanium content in the alloy practically coincide.

The optimal and recommended chemical composition of cast iron, which provides the maximum wear resistance coefficient, is: C=2.68 %, Ti=1.61 %, and the silicon content as a function of manganese content, described by a linear equation of the form $Si=a_0+a_1Mn$, in which $a_0=1.2$, $a_1=0.1$.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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Data availability

Data will be made available on reasonable request.

References

[1] Golub, G., Myhailovych, Y., Achkevych, O., Chuba, V. (2019). Optimization of angular velocity of drum mixers. Eastern-European Journal of Enterprise Technologies, 3 (7 (99)), 64–72. doi: https://doi.org/10.15587/1729-4061.2019.166944

[2] Hassanpour, A., Tan, H., Bayly, A., Gopalkrishnan, P., Ng, B., Ghadiri, M. (2011). Analysis of particle motion in a paddle mixer using Discrete Element Method (DEM). Powder Technology, 206 (1-2), 189–194. doi: https://doi.org/10.1016/j.powtec.2010.07.025

[3] Gao, W., Liu, L., Liao, Z., Chen, S., Zang, M., Tan, Y. (2019). Discrete element analysis of the particle mixing performance in a ribbon mixer with a double U-shaped vessel. Granular Matter, 21 (1). doi: https://doi.org/10.1007/s10035-018-0864-4

[4] Li, S., Kajiwara, S., Sakai, M. (2021). Numerical investigation on the mixing mechanism in a cross-torus paddle mixer using the DEM-CFD method. Powder Technology, 377, 89–102. doi: https://doi.org/10.1016/j.powtec.2020.08.085

[5] Bohl, D., Mehta, A., Santitissadeekorn, N., Bollt, E. (2011). Characterization of Mixing in a Simple Paddle Mixer Using Experimentally Derived Velocity Fields. Journal of Fluids Engineering, 133 (6). doi: https://doi.org/10.1115/1.4004086

[6] Zaselskiy, V., Shved, S., Shepelenko, M., Suslo, N. (2020). Modeling the horizontal movement of bulk material in the system “conveyor – rotary mixer.” E3S Web of Conferences, 166, 06008. doi: https://doi.org/10.1051/e3sconf/202016606008

[7] Frolova, L., Barsuk, A., Nikolaiev, D. (2022). Revealing the significance of the influence of vanadium on the mechanical properties of cast iron for castings for machine-building purpose. Technology Audit and Production Reserves, 4 (1 (66)), 6–10. doi: https://doi.org/10.15587/2706-5448.2022.263428

[8] Demin, D. A. (1998). Change in cast iron's chemical composition in inoculation with a Si-V-Mn master alloy. Litejnoe Proizvodstvo, 6, 35.

[9] Kontorov, B. M., Kunin, N. M. (1960). Iznosostoykie belye chuguny, legirovany borom i titanom. Liteynoe proizvodstvo, 4.

[10] Emelyushin, A. N. (2000). Vliyanie titana i bora na iznosostoykost' chuguna prednaznachennogo dlya mehanicheskoy obrabotki nemetallicheskih materialov instrumenta iz hromistyh chugunov. Izvestiya vysshih uchebnyh zavedeniy. Chernaya metallurgiya, 2, 28–29.

[11] Mohanad, M. K., Kostyk, V., Domin, D., Kostyk, K. (2016). Modeling of the case depth and surface hardness of steel during ion nitriding. Eastern-European Journal of Enterprise Technologies, 2 (5 (80)), 45–49. doi: https://doi.org/10.15587/1729-4061.2016.65454

[12] Kostik, K. O. (2015). Development of the high-speed boriding technology of alloy steel. Eastern-European Journal of Enterprise Technologies, 6 (11 (78)), 8–15. doi: https://doi.org/10.15587/1729-4061.2015.55015

[13] Kharchenko, S., Barsuk, A., Karimova, N., Nanka, A., Pelypenko, Y., Shevtsov, V., Morozov, I., Morozov, V. (2021). Mathematical model of the mechanical properties of Ti-alloyed hypoeutectic cast iron for mixer blades. EUREKA: Physics and Engineering, 3, 99–110. doi: https://doi.org/10.21303/2461-4262.2021.001830

[14] Vasenko, Iu. A. (2012). Technology for improved wear iron. Technology Audit and Production Reserves, 1 (1 (3)), 17–21. doi: https://doi.org/10.15587/2312-8372.2012.4870

[15] Domin, D. (2013). Artificial orthogonalization in searching of optimal control of technological processes under uncertainty conditions. Eastern-European Journal of Enterprise Technologies, 5 (9 (65)), 45–53. doi: https://doi.org/10.15587/1729-4061.2013.18452

[16] Demin, D. (2017). Strength analysis of lamellar graphite cast iron in the «carbon (C) – carbon equivalent (Ceq)» factor space in the range of C = (3,425-3,563) % and Ceq = (4,214-4,372) %. Technology Audit and Production Reserves, 1 (1 (33)), 24–32. doi: https://doi.org/10.15587/2312-8372.2017.93178