MELTING OF RESOURCE-SAVING ALLOYS FOR PRECISION Ni-Mo ALLOYS: OPTIMIZATION OF TECHNICAL AND ECONOMIC INDICATORS

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ABSTRACT

The phase and X-ray structure composition of the initial and target products of Ni-Mo ligature and its melting conditions are determined. The optimal values of the content of charge materials during the smelting of a nickel-molybdenum-containing ligature were determine: scale of the alloy 79NM 4.2 - 28 % wt., shavings of power grinding of metal products 79NM 3.8 - 56.1 % wt., calcite molybdenum concentrate KMo 20.5 - 12.5 % wt., technical nickel oxide 13.0 - 22.0 % wt., cyclone silicon dust 3.4 - 7.9 % wt., metallic manganese MR-1 1.0 - 4.7 % wt., soot TGM-33 1.5 - 4.0 % wt., aluminium AK-8 0.8 - 6.0 % wt.

Regularities of influence of charge parameters on the content of leading elements of ligature and efficiency of smelting of precision alloys with use of ligature are established. According to the specified method, calculations of economic efficiency of Ni and Mo utilization from man-made wastes of different sources of formation are performed. In order to achieve the optimal properties of the target ligature, taking into account the complex effect of the composition of the ingredients of the charge on reducing the cost of redistribution of the ligature smelting used regression analysis.

The developed mathematical model of Ni and Mo burn-up dependences using the ligature on the content of 8 components in the charge for its smelting was tested by the generalized method of least squares on the basis of industrial data. High technical and economic efficiency of use of new alloying and de-oxidizing material at smelting of precision alloys is established.

Keywords: Ni-Mo ligature, precision alloys, man-made wastes, resource conservation, economic efficiency, mathematical modelling, degree of utilization.

INTRODUCTION

Recently, global trends in metallurgical production as in domestic and foreign industries indicate an increase in the rate of special steel production growth comparing to the rate of serial steel production. To ensure stable growth of production and competitiveness of smelting of special steels, it is necessary to develop and implement alternative measures to reduce their cost. One of the promising areas for improving the technical and economic indicators of smelting of special steels is resource and energy saving in the industrial production of metal products [1, 2].

Rational resource conservation is ensured thanks to the implementation of effective economic mechanisms of natural resource management, the use of low-waste and zero-waste technologies, effective systems and means of control over the use and conservation of resources and environmental protection from pollution [3]. Rational use of used energy such as: coke, blast furnace, converter and ferroalloy gases, natural gas energy, heat of hot agglomerate and material resources such as: metal scrap, landfill slag, gas cleaning dust, pickling solutions, carbon dioxide. It is one of the ways to reduce energy and material intensity of the metallurgical industry [4]. First of all, the development and implementation of metallurgical combined processes belongs to the main innovative directions, which allow in the conditions of market relations to ensure the production of high-quality products with high production efficiency [5].

Modern technology improvement of metal and alloys smelting and processing, modernization of production with the use of the latest energy- and resource-saving technologies, advanced innovations, the use of information technologies in particular, encourage expanding views and exploring new production and technological possibilities in metallurgical industry [6].

Thus, one of the most promising directions for improving the efficiency of the metallurgical industry is the secondary use of material resources. The issue of obtaining valuable materials from industrial waste is directly the reasonable direction of current research [7]. In particular, nickel, tungsten, cobalt and molybdenum alloying materials are strategically important in the metallurgy of special steels, including in the production of precision alloys. Their high cost and limited raw material resources constrain the growth of metal production with their content. The target efficiency of its production is not achieved due to the low degree of use of alloying material based on refractory elements, due to insufficiently reliable and tested technologies for the disposal of elements from man-made wastes. This problem is especially relevant in the context of a significant increase in prices for alloying elements.

The accuracy of the chemical composition and purity of precision alloys is ensured by careful selection of charge (source) materials, their melting in zone melting, electron-beam remelting, plasma-arc remelting, and electrolytic deposition. Thus, the issue of obtaining tungsten compounds is covered in several works [8 - 13], and molybdenum achieving in works [14, 15].

This work aims to develop a mathematical model of technical and economic indicators of obtaining nickel-molybdenum-containing precision alloys. To achieve this goal, the following tasks were set:

- to investigate the chemical composition of the initial components of the charge, the composition of the ligature for precision alloys and changes in phase composition during its smelting;
- to reduce the irreversible loss of nickel and molybdenum in the form of sublimation of higher oxide compounds to analyse chemical, phase and X-ray structural transformations during smelting of ligatures in the system of liquid-phase reactions;
- to develop and optimize a mathematical model of technical and economic indicators of ligature production for precision alloys.

EXPERIMENTAL

The initial component chemical charge composition to obtain a ligature for precision alloys is shown in Table 1.

In the production conditions, an active experiment was conducted with the change of parameters in a wide range. The content of elements in the ligature varied within, % wt.: nickel 53.0 - 91.6; molybdenum 2.8 - 18.4; manganese 1.0 - 7.8; silicon 0.3 - 5.6; iron 6.3 - 15.2. The ligature was melted in a 5-ton electric steel melting furnace (ASF-5) with basic lining.

X-ray diffraction phase analysis of the samples was performed on a diffractometer «DRON-8». Fractures of the samples were examined using a REN-106Y raster microscope (Ukraine).

The phase composition of the samples was determined by X-ray diffraction analysis using monochromatic radiation (λ = 0.178897 Å) with a Fe-filter. The measurement was performed at a voltage on the tube $U = 30\ kV$ and current $I = 10\ mA$ X-ray phase analysis was performed using the PDWin 2.0 suite of programs (Russia).

In the research has been used the method of calculating the economic efficiency of the utilization of refractory elements from man-made waste from various sources of formation. In particular, eight factors, components of the initial charge namely, were used during mathematical modelling - $x_1,...,x_8$ when changing twenty compositions of the charge (Table 2).

When processing the estimated data, regression analysis methods were used, in particular, the method of least squares, Fisher's test (F - test), arithmetic mean method, variance (D), coefficient of data determination (R^2) was define using Microsoft Excel 2020. Graphing of the mathematical function (three-dimensional diagram, in particular volumetric surface) was performed using Microsoft Excel 2020.

RESULTS AND DISCUSSION

Investigation of physical and chemical properties of charge and ligature components for Ni-Mo precision alloys

X-ray structural phase analysis of the samples showed that the origina\l scale is represented by compounds Fe_2O_3, Fe_3O_4 and a small part of FeO. Nickel

Table 1. Chemical composition of charge in melting ligature with nickel molybdenum contain.

№	The charge materials, % wt.	The content of elements, % wt.												
		C	Si	Mn	S	P	Ni	Mo	Ti	Cu	O_2	Al	Fe	Impurities
1	Scale of the alloy 79NM,% wt.	≤0.10	0.22-0.55	0.44-1.25	0.018	0.017	63.10	3.15	≤0.15	≤0.20	20.50	-	remain-ders	SiC, FenOm
2	Shavings of force grinding of metal products of an alloy 79NM,% wt.	0.02-0.11	0.41-0.49	0.66-0.88	≤0.41	≤0.31	73.7-76.5	3.30-3.50	≤0.21	0.10-0.17	1.88-3.44	≤0.25	remain-ders	Al_2O_3, SiC, SiO_2, Al_nC_m
3	Calcined molybdenum concentrate brand KMo-2, % wt.	0.12	-	-	0.091	0.008	-	56.73	-	0.77	27.20	-	-	remainders-CaO, FeO,vMgO, Al_2O_3, MnO, SiO_2
4	Technical nickel oxide, % wt.	-	-	-	-	-	75.60	-	-	-	20.62	-	-	CaO, CuO
5	Cyclone silicon dust and/or screening of crystalline silicon, % wt.	-	≥99.9	-	-	-	-	-	-	-	-	-	-	remainders-SiC
6	Metallic manganese MR-1 Manganese metal	0.12-0.17	-	96.10-97.10	0.05	0.04	-	-	-	-	-	-	remain-ders	Al + Ca+ Mg ≤l.0
7	Carbon reducing agent (soot TGM-33)	99.70	-	-	-	-	-	-	-	-	-	-	-	CaC, SiC, MgC
8	Aluminum AK-8	-	0.44	-	-	-	-	-	-	-	-	≥99.00	-	remainders

and molybdenum (cobalt) are present in the form of solid solutions, which have the property of unlimited solubility in iron and form a continuous series based on γ-structures (γ-Fe) [1].

The target product (ligature) consists of γ-Fe and solid solutions of Ni, Co and Mo in γ-Fe and FeNi. These results were obtained by smelting a ligature for alloying Ni-Co precision alloys and utilization of scale for precision alloy 29NK.

In the case of utilization of alloying elements from man-made waste of precision alloy 79NM, the initial scale is represented by compounds Fe_2O_3, Fe_3O_4, fragmentary MoO_3 and a solid solution of NiO in iron oxides. In the alloys of the Fe-Ni system, continuous solutions are formed on the basis of the γ-structure, the crystal lattice of which consists of a Fe lattice filled with Ni atoms.

The target product consists of Fe-Ni, γ-Fe and a solid solution of molybdenum in γ-Fe. The final oxygen in the final product is bound in small amounts of FeO and Fe_2O_3. Studies have confirmed the absence of elements and compounds with a high rate of sublimation. This means that for the organization of industrial production of Ni-Mo (Co) ligatures there is no need to create special conditions that prevent irreversible loss of alloying elements in the form of higher oxide compounds of rare metals, which sublimate at relatively low temperatures.

Methods and calculations of economic efficiency of production and use of Ni-Mo ligatures for precision alloys

The unconventional direction of filling the nickel deficit is to use highly concentrated waste from the production of corrosion-resistant materials and precision alloys based on nickel in obtaining nickel ligatures that meet the high requirements of qualitative metallurgic production. These ligatures can be used in the smelting on special nickel-based alloys, as well as alloying impurities of nickel in various fields of its use.

The essence of the new technical solution is to achieve a based-nickel content of 60 - 85 % wt. with the optimal ratio of common active elements (aluminium, titanium, silicon, zirconium, etc.) and some impurities of refractory elements (molybdenum, tungsten, cobalt, etc.).

The tested developments can be implemented at the released smelting facilities of non-ferrous metallurgy without any structural improvements, which opens the prospect of implementing many technological projects without the use of significant capital investments. This should be taken into account, such a typical factors as the form of the presence of elements in the waste, the presence and concentration of associated harmful impurities that reduce the practical value of refractory elements, etc.

The amount of annual economic effect or implementation of a single technical solution for the production and use of new ligature compositions instead of traditionally used metallic nickel and high-purity molybdenum in the production of precision alloys on the base of nickel is determined by the formula:

$$E = \sum_{i=1}^{n} \{(E_{SM_i} + E_{CC_i} + E_{TC_i} + E_{CF_i}) \cdot E_{CF_i}\}, \quad (1)$$

where i is 1, 2, 3, ..., n is the number of options for obtaining and using ligatures that varied the structure of the alloying and active elements; - E_{CMi} the amount of savings of the corresponding costs for charge materials in the production of precision alloys, money. units/t; E_{CRi}- the amount of savings of the corresponding alloying elements and deoxidizers due to the reduction of soot in the following redistributions (cost ratios), money units/t; E_{TCi}- the amount of savings due to the reduction of technological costs (fuel, water, energy, etc.) by reducing the melting temperature and increasing the rate of dissolution of refractory elements in the alloy melt, money. units/t; E_{CFi} - savings (overspending) due to changes in external factors and their impact on increasing the speed of working capital, money. units/t; E_{CFi} - total amount of production alloy using a new type of complex material, t.

The calculation of the amount of charge materials savings for the smelting of the precision alloy was carried out according to the formula [1]:

$$E_{CM_i} = \sum_{j=1}^{m} Q_j \sum_{j=1}^{\beta} \left(X_{01} - X_{ij}\right) \cdot P_j, \quad (2)$$

where j is 1, 2, 3, ..., m is the number of comparable grades of precision alloys; j is 1, 2, 3, ..., β is the number of types of charge materials for melting; Q_j - the volume of production of the j-th brand of precision alloy after the introduction of smelting technology using ligatures, t; X_{01}, X_{ij} is costs of charge materials before and after

Table 2. Variations in the charge composition in the melting of nickel-molybdenum-containing ligatures when factors change $x_1,\ldots,x_8$.

Batch number	Factor (charge materials)								
	Scale of the alloy 79NM,% wt	Shavings of force grinding of metal products of an alloy 79NM, % wt	Calcined molybdenum concentrate brand KMo-2, % wt	Technical nickel oxide, % wt	Cyclone silicon dust and/or screening of crystalline silicon, % wt	Metallic manganese MR-1, % wt	Carbon reducing agent (soot TGM-33), % wt	Aluminum AK-8, % wt	Reduction of molybdenum burnout using ligature, % wt
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	y
1	4.0	57.2	0.2	13.2	3.0	5.3	1.3	0.6	0.4
2	4.0	57.1	0.2	13.3	3.0	5.2	1.3	0.6	0.5
3	4.0	57.0	0.2	13.2	3.1	5.0	1.3	0.7	0.5
4	4.0	56.9	0.2	13.1	3.1	4.8	1.3	0.7	0.7
5	4.1	56.7	0.3	13.0	3.2	4.7	1.3	0.7	0.6
6	4.2	56.5	0.4	12.9	3.3	4.7	1.4	0.8	0.8
7	4.2	56.1	0.4	12.9	3.4	4.7	1.4	0.8	0.9
8	4.3	55.1	0.5	12.7	3.5	4.5	1.5	0.9	1.1
9	7.3	53.2	1.3	13.9	3.8	4.0	1.9	1.3	1.4
10	8.7	48.9	2.1	14.1	4.1	3.9	2.2	1.8	1.7
11	10.1	45.0	2.4	15.5	4.4	3.8	2.9	2.1	1.8
12	13.0	38.9	3.9	16.3	5.1	3.4	3.1	2.8	2.2
13	15.7	33.3	5.5	17.2	5.9	3.1	3.3	3.6	2.4
14	17.7	28.1	6.4	17.7	6.1	2.7	3.3	3.9	2.4
15	19.0	23.4	7.7	18.8	6.3	2.2	3.4	4.3	2.5
16	22.0	15.5	8.5	19.9	6.6	1.8	3.5	4.8	2.5
17	24.6	9.9	9.9	20.5	7.1	1.3	3.6	5.2	2.5
18	27.0	3.5	11.9	21.7	7.3	1.2	3.7	5.7	2.7
19	27.2	3.6	12.1	21.8	7.4	1.1	3.8	5.7	2.7
20	27.3	3.6	12.2	21.9	7.4	1.0	3.9	5.8	2.6

the introduction of alloy smelting using ligature per 1 ton of alloy, t; P_j is the price of each component of the charge, money units/t.

All other things being equal, the smelting of precision nickel-based alloys doped with rare elements will determine the efficiency of their production and the price and technological features of nickel and other refractory elements. Therefore, at calculation of end-to-end economic benefit it is necessary to consider reserves of increase of economy at a stage of reception of the alloying materials on the basis of the nickel doped with molybdenum and other elements:

$$P_j = (P_j + C_j) \tag{3}$$

$$C_j = \sum_{j=1}^{\mu} C_{oj} \cdot K_1 \cdot K_2, \tag{4}$$

where P_j profit obtained from the production of ligatures on the basis of doped waste, money. units/t; C_j - total cost of production of this ligature, money units/t;

$\sum_{j=1}^{\mu} C_{oj}$ - price of a single standard component of the charge, obtained by available technologies (eg, nickel metal, molybdenum, chromium, etc.), money. units/t; K_1 is a coefficient that takes into account the increase in level of use of each element when introducing them into the melt ligature; K_2 is a coefficient that takes into account the technological advantages of the complex ligature compared to use of each metal element separately (increasing the rate of dissolution in the melt, lowering the melt temperature, etc.) [1].

To analyze the amount of profit in the presence of original and sufficiently reliable technology of smelting ligatures from nickel-based waste doped with refractory elements, it is advisable to take into account non-traditional factors in the formation of itemized cost structure. Then the full cost of smelting the ligature in General can be obtained by the formula:

$$C_j = C_{sp} + C_{rc} + C_o, \tag{5}$$

where C_{sp} is costs under the item «set for production», money units/t; C_{rc} is the redistribution costs, considering the cost of renting fixed assets and ancillary equipment, money. units/t; C_0- overhead, money units/t.

Considering technological factors we get:

$$C_j = \left[\frac{\left(C_{\varepsilon} + C_{\mathfrak{p}} + C_o\right)}{\left(\varsigma \cdot y_{\varsigma}\right) + \left(z_{\hat{a}-\acute{o}} \cdot y_z\right) + \left(L_{\grave{o}-f} \cdot y_L\right)} \right] \cdot K_p \cdot \varpi, \tag{6}$$

where η is the base content of the conductive alloying element in the production waste, wt. %; y_{ς} - the level of assimilation of the leading alloying element by the ligature from wastes; $z_{\hat{a}-\acute{o}}$ - concentration of relevant elements: $\beta = 1, 2, 3, ..., \sigma$ refractory and other useful elements in production waste, wt. %; y_z - the level of assimilation of associated $\beta = 1, 2, 3, ..., \sigma$ elements by ligature from waste; $L_{\grave{o}-f}$ - concentration of active elements (or deoxidizers) in waste and charge components for ligature smelting; y_L - the level of assimilation of active elements (or deoxidizers) in the smelting of the ligature; K_p - coefficient that includes the concentration of harmful or useful impurities that increase or decrease the consumer quality of the ligature; ϖ - the yield of a suitable ligature.

This formula allows to determine the cost of obtaining a complex of alloying and active elements in a nickel-based ligature obtained from highly concentrated wastes, in contrast to the proportional cost of extraction of each element in complex processing of ore or utilization of valuable components from dust, which is captured, [2]:

$$E_{tci} = T_{p1i} - T_{p2i}, \tag{7}$$

where i is $1, 2, 3, ..., n$ - the number of variants of technologies for smelting precision alloys, which differ in the composition of the charge materials, the method of their introduction, technological units for their implementation; T_{p1i}, T_{p2i} are technological costs beyond the production of precision alloys without and with the use of ligatures, according to options, money units/t.

According to these costs, the most reliable are indicators of reduction of technological consumption fuel process (electricity), water, slag-forming impurities and fluxes. This is ensured by the technological advantages of the ligature compared to the individual components of the charge for melting.

Savings by reducing the soot of alloying elements and deoxidizers in smelting can be determined by the formula:

$$E_{CC} = C_1 - C_2 \tag{8}$$

where: C_1, C_2 - the cost of alloying and de-oxidizing elements in the smelting of precision alloys before and after the introduction of the ligature, money units/t. Substituting specific expressions of current factors, in this case we obtain:

$$E_{CC_i} = \left(C_1^{'} \cdot y_\eta^{'} + C_2^{'} \cdot y_z^{'} + C_3^{'} \cdot y_L^{'}\right) - \left(C_1^{''} \cdot y_\eta^{''} + \right.$$
$$\left. + C_2^{''} \cdot y_z^{'} + C_3^{''} \cdot y_L^{''}\right), \quad (9)$$

where: $C_1^{'}$ - the cost of the nickel base in the alloy when using metallic nickel, money units/t; y_η - the level of transformation of nickel into alloy, particle; $C_2^{'}$ - the cost of other alloying elements when using them in metal form, money. units/t; $y_z^{'}$ - the level of assimilation of other alloying elements by precision alloy, the share of units; $C_3^{'}$ - the cost of pure deoxidizers in the smelting of the alloy, money units/t; $y_L^{'}$ - expense coefficients of deoxidizers in smelting the alloy according to the basic technology, t/t; $C_1^{''}$, $C_2^{''}$, $C_3^{''}$ - costs for nickel base, alloying elements and deoxidizers in the case of using a ligature for smelting a precision alloy, money. units/t; $y_\eta^{''}$, $y_z^{''}$, $y_L^{''}$ - the level of use (assimilation) of the nickel base, alloying elements and deoxidizers in the smelting of the alloy from the ligature, respectively. Expected savings due to changes in external impacts can be calculated using factors that take into account the speed of working capital, market prices and other unaccounted reasons. This is possible with a significant amount of end-to-end cost savings (approximately 60 % - 70 %) using a new efficient technology for processing highly concentrated waste into a complex material, which eliminates the use of so expensive material as nickel, molybdenum and other elements. These savings can be calculated by the formula:

$$E_c = C_1 - C_2, \quad (10)$$

where C_1, C_2 - the price of a precision alloy produced using pure elements and a complex ligature obtained on the basis of waste, respectively, money units/t:

$$C_2 = T_0 \cdot K_1 \cdot K_2 \cdot K_3, \quad (11)$$

where: T_0 - the total cost of production and sale of precision alloy obtained using a complex ligature, money units/t; K_1 - coefficient that takes into account the most likely decrease in the wholesale price of precision alloy in market conditions; K_2 - coefficient that takes into account the turnover rate of working capital in terms of direct contractual deliveries; K_3 - coefficient of other unaccounted factors.

The most probable values of the obtained savings were less than 1.0 (in the range of 0.95-0.98).

According to the proposed method of calculating the economic efficiency of refractory elements from man-made waste of precision alloys performed transformations and preliminary calculations according to formulas (1)-(11), and the final calculations are performed as follows: calculation of the volume of smelted precision alloy brand 79NM:

$$70.6 \cdot \frac{1000}{180} = 392.22t.$$

The amount of 70.6 tons and alloy chemical composition certification for alloying and de-oxidation HM-1 in the industrial production of alloy brand 79NM, the nickel savings was measured as follows:

$$\frac{70.6}{100} \cdot 86.5 = 61.07t,$$

where: 70.6 is the weight of the used alloy brand NM-1, t; 100 - base content of the conductive element, wt. %; 86.5 - the average value of the nickel content in the alloy brand NM-1, wt. %.

Similarly to the calculations of nickel savings savings on molybdenum were:

$$\frac{70.6}{100} \cdot 2.45 = 1.73t.$$

Cost savings by reducing the cost of alloying elements per 1 ton of precision alloy 79NM (compared with the use of standard ferroalloys and alloying materials):

$$E_1 = (n_1 - n_2) \cdot \eta_1 \cdot P_1 + (m_1 - m_2) \cdot \eta_2 \cdot P_2,$$
$$E_1 = (792.5 - 636.8) \cdot 0.98 \cdot 15.999 + (39.5 -$$
$$- 35.1) \cdot 0.97 \cdot 22.5 = 2537.47 \ \$US/t,$$

where: n_1, n_2- the cost of nickel in the smelting of the alloy 79NM using standard electrolytic nickel and an additional additive of the alloy NM-1, respectively, kg/t of alloy; m_1, m_2 - molybdenum consumption during smelting of 79NM alloy using standard ferromolybdenum and additional additive of NM-1 alloy, respectively, kg/t of alloy; η_1, η_2- the degree of absorption of nickel and molybdenum, respectively, according to the proposed technical solution using the alloy NM-1,

$US units; - price per 1 kg of nickel and molybdenum, respectively, as of 25.03.2020 on the London Metal Exchange (LME), $US.

Savings when using 1 ton of alloy for alloying and deoxidation brand HM-1:

$$E_2 = E_1 \cdot \frac{1000}{180},$$

$$E_2 = 2537.47 \cdot \frac{1000}{180} = 14097 \ \$US,$$

Total cost savings when using 70.6 tons of alloy for alloying and deoxidation brand HM-1:

$$E = (E_2 - C_1 - C_2) \cdot 70.6,$$

$$E = (14097 - 8672.13 - 2124.28) \cdot 70.6 =$$

$$= 233.03 \ \textit{thousand} \ \$US,$$

where: C_1 - the cost of collecting components of the charge, smelting and casting of the alloy, grinding and transportation per 1 ton of alloy brand NM-1, USD USA; C_2- the cost of research, support of regulatory and technical documentation for testing and production of industrial batches, in terms of 1 ton of alloy brand HM-1, the $ US.

The total amount of expenditures for research on scientific substantiation, development of alloy smelting technology for alloying and deoxidation and its use in the smelting of nickel-molybdenum-containing precision alloys amounted to 150 thousand $ US.

Complex doping with simultaneous utilization of metallurgical waste is achieved because the charge includes metal powder and oxide material content of alloying elements, precision alloy amount, ore concentrates and technically pure oxides of target elements, carbon reducing agent, metallic manganese and alumina.

To achieve the optimal properties of the target product, we must take into account the complex effect of the charge composition on reducing the cost of redistribution of the smelting alloy for alloying and deoxidation of the alloy. Regression analysis was used [16 - 18].

The generalized method of least squares on the basis of experimental and experimental data has created a mathematical model of the dependences of molybdenum burn reduction using ligature (factor y) from the content of 8 components in the charge for its smelting (factors $x_1,\ldots,x_8$).

Iron powder brand PZH-1 causes the presence of multicollinearity in these models and leads to inefficient estimates of the least squares method. Comparison of individual correlation coefficients showed that this component is less significant in these models, so the impact of this component is not taken into account. The investigated factors are presented in Table 2.

The obtained nonlinear mathematical model has been calculated by the form:

At the same time, the sum of squared deviations (dispersion D) is 14.525, and the coefficient of determination R^2 is 0.99. The estimated Fisher test (F) calculated for the model is 425, which is well above the critical value $F = 2.7$ taken for the 5 % significance level.

$$y = -5{,}99 + 14{,}95\ln x_1 - 5{,}7\ln x_2 - 14{,}48\sqrt{x_3} -$$

$$-17{,}40\ln x_4 + 33{,}73\sqrt{x_5} + 6{,}68 \cdot x_6 + 0{,}01x_7^3 - 5{,}06 \cdot x_8. \tag{12}$$

The obtained calculated data were presented in the form of a three-dimensional diagram with fixed values of the factors: $x_1 = 15.4$, $x_2 = 32.2545$, $x_3=5.4636$, $x_4=17.1182$, $x_5=5.4727$, $x_6=2.9$, $x_7=2.9454$, $x_8=3.3091$ (Fig. 1 - 4). These indicators are selected as the average values of the presented data.

Analysis of the dependencies presented in (Fig. 1 - 4), makes it possible to determine the optimal values of the factors $x_1,\ldots,x_8$ (min and max) (Table 3).

High technical and economic efficiency of use of

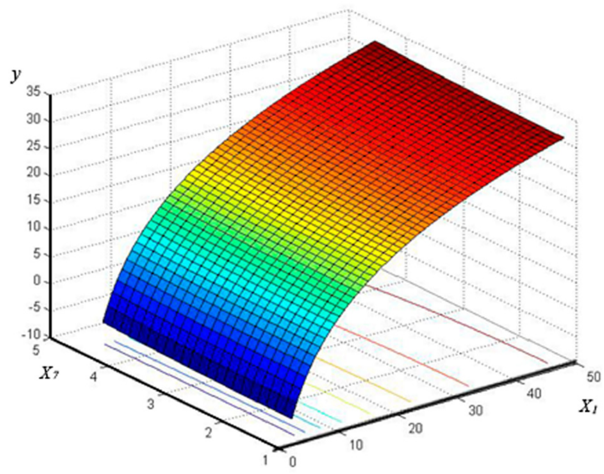

Fig.1. Dependence of the reduction of molybdenum burnout using a ligature (factor y) on the content of 79NM alloy slag (factor x_1) and carbon reducing agent (factor x_7), wt. %.

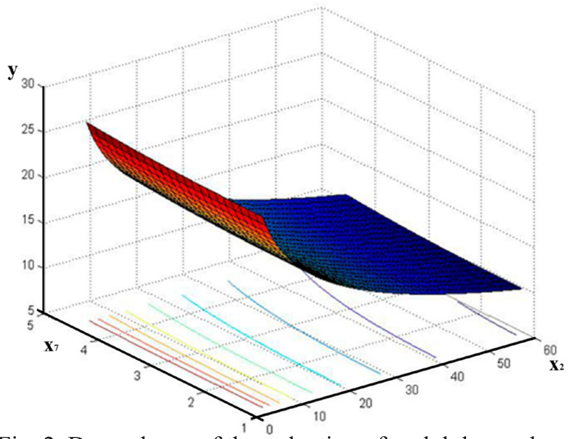

Fig. 2. Dependence of the reduction of molybdenum burning using a ligature (factor y) on the content in the charge of shavings of power grinding of metal products of the 79NM alloy (factor x_2) and carbon reducing agent (factor x_7), wt. %.

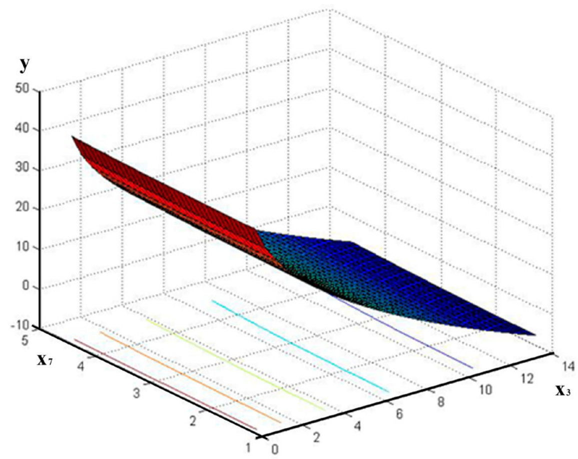

Fig. 3. Dependence of the reduction of molybdenum burnout using a ligature (factor y) on the content in the charge of fired molybdenum concentrate brand KMo-2 (factor x_3) and carbon reducing agent (factor x_7), wt. %.

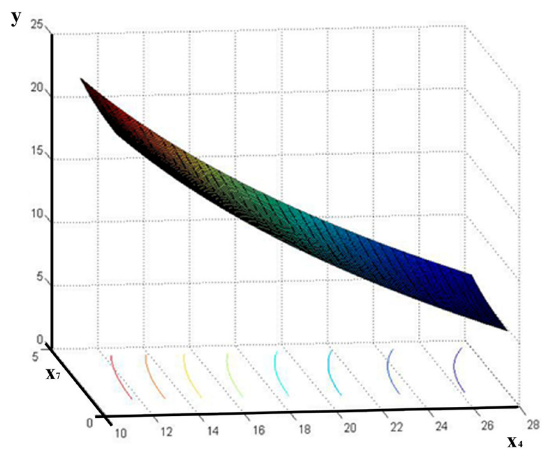

Fig. 4. Dependence of the reduction of molybdenum burnout using a ligature (factor y) on the content in the charge of technical nickel oxide (factor x_4) and carbon reducing agent (factor x_7), wt. %.

Table 3. Optimal values of charge materials (factors $x_1,\dots,x_8$) melting of a nickel-molybdenum ligature.

Limits of optimal value	Factor (charge materials)							
	Scale of the alloy 79NM, % wt	Shavings of force grinding of metal products of an alloy 79NM, % wt	Calcined molybdenum concentrate brand KMo-2, % wt	Technical nickel oxide, % wt	Cyclone silicon dust and/or screening of crystalline silicon, % wt	Metallic manganese MR-1, % wt	Carbon reducing agent (soot TGM-33), % wt	Aluminum AK-8, % wt
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
Min	4.2	3.8	0.5	13.0	3.4	1.0	1.5	0.8
Max	28.0	56.1	12.5	22.0	7.9	4.7	4.0	6.0

new alloying material at smelting of precision alloys are achieved by:
1) the increased degree of utilization of refractory alloying elements from man-made wastes and use of cheaper ore materials containing oxide compounds of metals, the boundaries of the main steel making furnace unit;
2) reduced molybdenum carbon in the smelting of the precision alloy by 0.5 - 2.7 % due to some excess de-oxidizing potential with increasing residual aluminium and silicon in the ligature;
3) reduced dissolution time of molybdenum in the ligature melt due to increased thermal conductivity of the charge ingredients and intensification of redox processes of ligature smelting, including the formation of an additional reducing phase of CO during the use of carbon reducing agent.

CONCLUSIONS

The method of calculation of economic efficiency of utilization of refractory elements from man-made wastes from various sources of formation is improved. High specific efficiency of utilization of rare alloying elements by smelting of reduction-refining Ni-Mo ligature for precision alloys is confirmed.

The constructed mathematical model allowed establishing and investigating the optimal areas of technological indicators and cost coefficients, which revealed the possibility of improving the quality of nickel molybdenum-containing ligatures in relation to precision alloys with the most favourable content of alloying elements and increasing the degree of assimilation of alloying elements using reduced secondary raw materials.

The optimal values of the content of charge materials during the smelting of a nickel-molybdenum-containing ligature were determined, wt. %: scale alloy 79NM is from 4.2 to 28.0, shavings of power grinding of metal products of alloy 79NM is from 3.8 to 56.1, calcined molybdenum concentrate brand KMo-2 is from 0.5 to 12.5, technical nickel oxide is from 13.0 to 22.0, cyclonic silicon dust and/or screening of crystalline silicon is from 3.4 to 7.9, manganese metal brand MR-1is from 1.0 to 4.7, carbon reducing agent (carbon black TGM-33) is from 1.5 to 4.0, aluminium brand AK-8 is from 0.8 to 6.0.

Testing of the proposed technical and economic solution for obtaining nickel-molybdenum-containing precision alloys revealed the following advantages over the prototype:

- the degree of utilization of alloying elements from man-made waste and the use of cheap ore materials containing oxide compounds of metals has been increased due to the removal of reduction and de-oxidation processes in the smelting of precision alloys outside the furnace unit;
- reduced molybdenum burnout during smelting of precision alloy from 2.9 - 3.2 % to 1.1 - 2.7 % due to excess de-oxidation potential with increasing residual aluminium and silicon content in the ligature;
- reduced costs of standard ferro alloys and metal alloying materials from ore concentrates and the degree of their utilization from man-made waste;
- the cost of redistribution of ligature smelting from 79NM alloy was reduced by 5 - 27 % due to fuller use of ore concentrates and increasing the degree of utilization of high-value elements from man-made waste.

The obtained data allowed to be optimized parameters of cost coefficients. The significant saving of expensive alloying elements in the melting of precision alloys together with the investigated ligature, confirm innovative feasibility of production by use of a new alloying material.

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