MACHINE BUILDING

МАШИНОБУДУВАННЯ

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ENVIRONMENTALLY FRIENDLY MATERIALS AND TECHNOLOGIES FOR THE PRODUCTION OF CASTINGS FROM ALUMINUM ALLOYS

Т. Лисенко, І. Прокопович, М. Замятін, В. Доценко, М. Тур. **Екологічно чисті матеріали та технології для виробництва виливків із алюмінієвих сплавів.** Стаття присвячена актуальної проблемі розробки та створення екологічно чистих матеріалів та технологій для ливарного виробництва. За останні роки змінилися пріоритети у розвитку матеріалів та технологічних процесів у бік їх сумісності з навколишнім середовищем. На перший план виходять екологічні аспекти виробництва, які визначаються шкідливими викидами в атмосферу, що жорстко регламентується Кіотським протоколом. У ливарному виробництві для отримання виливків в разових формах розроблені і застосовуються різні технології, які можуть бути розділені, виходячи з виду застосовуваної форми і методу її виготовлення. Основний зміст дослідження становить аналіз традиційних ливарних технологій та найперспективнішої технології лиття в низькотемпературні форми (НТФ). Особливістю лиття в НТФ є суттєве збільшення міцності форм, порівняно з литтям у піщано-глинисті форми, а також можливість використання як основного сполучного – воду. Даний метод виготовлення форм покращує структуру, підвищує точність та геометрію виливків, економить формувальні матеріали, і, що особливо важливо, покращує екологію, усуваючи шкідливі викиди в атмосферу ливарних цехів. Однак, спосіб лиття в НТФ має ряд недоліків, пов'язаних з утворенням на поверхні виливків раковин, пір, а також підвищеного пригару. Для усунення даних недоліків пропонується нанесення протипригарних покриттів на поверхню НТФ та стрижнів. Значна увага приділяється розробці та дослідженню протипригарних покриттів, які дозволяють використовувати екологічно чисту технологію лиття в НТФ для виробництва виливків із різних сплавів підвищеної якості. Виділяються і описуються склади покриттів та методика визначення оптимального складу протипригарного покриття, яке можна було б рекомендувати для виробництва алюмінієвих виливків у низькотемпературних ливарних формах. Отримані результати говорять про високий потенціал використання наведеної технології, як засобу підвищення екологічної безпеки ливарного виробництва.

Ключові слова: екологічно чисті матеріали, низькотемпературні форми, протипригарні покриття, ливарне виробництво

T. Lysenko, I. Prokopovich, M. Zamiatin, V. Dotsenko, M. Tur. **Environmentally friendly materials and technologies for the production of castings from aluminum alloys.** The article is devoted to the topical problem of development and creation of environmentally friendly materials and technologies for foundry production. In recent years, priorities have changed in the development of materials and technological processes towards their compatibility with the environment. The environmental aspects of production come to the fore, which are determined by harmful emissions into the atmosphere, which is strictly regulated by the Kyoto Protocol. In the foundry industry to obtain castings in disposable forms, various technologies have been developed and used, which can be separated based on the type of mold used and the method of its manufacture. The main content of the study is the analysis of traditional foundry technologies and the most promising technology of casting in low-temperature forms (NTF). The peculiarity of casting in NTF is a significant increase in the strength of molds, compared with casting in sand-clay molds, as well as the possibility of using water as the main binder. This method of mold making improves the structure, increases the accuracy and geometry of castings, saves molding materials, and, most importantly, improves the environment by eliminating harmful emissions into the atmosphere of foundries. However, the method of casting in NTF has a number of disadvantages associated with the formation on the surface of castings of shells, pores, as well as increased burns. To eliminate these shortcomings, it is proposed to apply non-stick coatings on the surface of NTF and rods. Considerable attention is paid to the development and research of non-stick coatings, which allow the use of environmentally friendly casting technology in NTF for the production of castings from various alloys of high quality. Coating compositions and methods for determining the optimal composition of non-stick coating, which could be recommended for the production of aluminum castings in low-temperature molds, are identified and described. The obtained results indicate a high potential for the use of this technology as a means of improving the environmental safety of foundry production.

Keywords: environmentally friendly materials, low-temperature forms, non-stick coatings, foundry production

Introduction

Problems of environmental safety of production in the 21st century have become global in nature.

Today, it is extremely important to ensure the maximum possible protection of the environment from industrial facilities that consume a huge amount of natural resources and are powerful sources of pollution.

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The correct direction of industrial development today is an optimal combination of industrial production and clean environment.

Foundry production is one of the most environmentally polluting industries.

There is a huge amount of materials and technologies used in the production of castings. More than 100 special types of casting are used. In addition, each technology requires improvement from the point of view of improving the environmental safety of materials and production.

It should be noted that in recent years, the priorities in the development of materials and technological processes have changed in the direction of their compatibility with the environment. Environmental aspects of production come to the fore, which are determined by harmful emissions into the atmosphere, strictly regulated by the Kyoto Protocol [1].

Analysis of publications and problem statement

It is known that when deciding on the possibility of using a certain technology in the production of castings, they usually use three main criteria, namely, economic efficiency, energy saving and environmental safety.

In the foundry industry, a variety of technologies have been developed and used to produce castings in disposable molds, which can be divided based on the type of mold used and the method of its manufacture.

The traditional method for producing cast products is the method of pouring molten metal into raw or dried molds based on quartz sand with the addition of clay and water to it – sand-clay molds (SCM). It is customary to distinguish between such types of SCM production as “wet molding” and “dry molding”.

For a long time, this casting method, which combines such advantages as simplicity and the absence of scarce materials, was the most common. However, the increasing demands on the quality of cast products have necessitated the development of new technologies that make it possible to obtain products of greater accuracy and with less labor per unit of production.

Since one of the main disadvantages of SCM is considered their low strength, it became necessary to search for new binders that can increase the strength of mixtures based on quartz sand to the required level.

As such a binder, sodium silicate is used, which, to accelerate curing, is treated with such hardeners as carbon dioxide, Fe-Cr slag, etc.

The use of carbon dioxide liquid glass as a hardener (CO_2-process) makes it possible to reduce drastically the duration of the mixture hardening cycle, to ensure high survivability of forms and high versatility of the technological process.

However, the presence of ancillary equipment for carbon dioxide purge creates certain difficulties when used in the production cycle. The process where the curing of sand-liquid-glass mixtures occurs under the influence of a chemical reagent – dicalcium silicate ($2CaO\ SiO_2$) in the form of ferrochrome slag, introduced into the mixture during its preparation, is called the SSM process – a process based on sand-self-hardening mixtures.

The process has found wide application in industry, and it is more advanced technologically than the CO_2 process due to the absence of carbon dioxide equipment. A further development of these processes is a process based on liquid self-hardening mixtures.

Unlike conventional mixtures based on sodium silicate, fluid mixtures practically do not require compaction, which is achieved by adding surfactants to their composition, which form small foam bubbles that reduce friction forces between individual grains of sand. Simultaneously with surfactants, curing additives are introduced into the composition of the mixtures, causing self-hardening of the mixture after it is poured into the mold. However, the high strength of the molds obtained with the use of sodium silicate played a negative role at the final stages of casting production as a result of the absence of thermal degradation of the binder and, as a result, poor knockout. In addition, most of the silicate binders are produced using a two-stage technology. This process is characterized by a high level of emissions of carbon dioxide and carbon monoxide (up to 300 m^3 per 1 ton of glass), sodium oxides, and silica-hazardous silica dust into the atmosphere. And for the neutralization of the resulting alkaline waste, significant economic costs are required. The search for new binders that combine high strength at the stages of the technological cycle prior to pouring and losing it after the casting hardens has led to the use of organic binders that meet all these requirements. Two technologies have received the widest application, namely the production of shell or solid molds from wet mixes “hot boxes“ and the use of dry sands “coldbox” process. However, the use of organic binders, in particular furan resins, has dramatically worsened the environmental situation in foundries due to the release of toxic gases at almost all stages of the technological cycle. The need to neutralize highly toxic hardeners is costly. The ability to obtain castings that are more complex has led to the emergence of new progressive casting methods such as Lost Foam Casting (LFC), Investment Casting and Vacuum molding [2].

Existing varieties of the Lost Foam Casting process differ in the type of molding material and in the methods of hardening the molds. However, in all varieties, the LFC process differs from the others by the presence of a model in the mold during its pouring [2].

The next step in the development of the method was the use of third-generation forms, i.e. forms with physical hardening methods – vacuuming and magnetic field [3].

The use of a ferromagnetic material bound by a magnetic field makes it possible to obtain castings with strength characteristics increased by 20...30 % due to a higher heat storage capacity of the mold material. This feature of magnetic molds makes it possible to significantly reduce the volume of profits on steel casting, and in some cases eliminate them, increasing the yield without compromising the quality of the casting, which for conventional molds is about 75 % [4].

Investment Casting is a method of producing castings in multilayer shell one-piece molds made using lost-wax, burnt-out or soluble disposable models.

The use of highly refractory and heat-resistant materials for the manufacture of shell molds suitable for heating to a temperature exceeding the melting point of the casting alloy, and the possibility of rapid cooling without deformation and destruction, makes it possible effectively use methods of directed crystallization. This makes it possible to obtain high-quality castings with a given structure up to transcrystalline and single-crystal.

Investment Casting makes it possible to produce shaped castings from any alloys with a complex configuration and a wall thickness of up to 1 mm or less, as close as possible in shape and size to the finished part with allowances in the range of 0.2...0.7 mm [5, 6], and in some cases not requiring machining. The high purity of the surface of the shell mold makes it possible to obtain castings with a surface roughness ranging from $R_z = 20$ µm to $R_a = 1.25$ µm. As a result, the labor intensity and cost of manufacturing parts are reduced significantly, the consumption of metal and tools, the need for production space, machine tools and fixtures are reduced.

It should be noted that this is a rather complex process, characterized by high energy consumption, multi-stage and duration. The almost complete impossibility of regeneration of molding materials requires their disposal, which causes significant damage to the environment.

In addition, the use of a large number of raw materials that go through many processing stages increases the number of factors that determine the quality of the resulting casting. In addition, the use of such toxic materials as ethyl silicate, etc., requires additional costs for the purification of gases formed at various stages of the technological cycle.

Vacuum molding (V-process) has recently become quite widespread due to its relatively low price, the absence of scarce materials and the environmental friendliness of production. The dimensions of the castings that can be produced by the V-process are limited only by the overall dimensions of the flasks and the performance of the vacuum pumps used, and the complexity of the configuration of the manufactured castings is limited by the properties of the synthetic films used [7]. The use of this method makes it possible to reduce the consumption of molding materials by 35…40 %, to reduce the labor intensity of operations at all stages of the technological cycle, to increase labor productivity by 2...5 times, to reduce casting defects caused by blockages and cracks, abandon traditional molding equipment, and reduce capital costs and operating costs associated with the preparation and regeneration of sand. In particular, the cost of castings obtained by the V-method is 10…15 % lower than the cost of castings obtained in raw sand-clay molds [7]. However, having undeniable advantages, the method requires the solution of a number of issues related to increased gas porosity and burning. Also significant is the issue of the difficulty of recycling synthetic film and the existing loss of sand, which in one cycle is up to 3 %.

Increasing demands for environmental friendliness of production and a shortage of the main components of molding materials have led to the need to develop new environmentally friendly, resource-saving technologies. A promising direction in this area is the creation of technologies that make it possible to abandon the use of fasteners as such, replacing their action with processes that allow, at the level of physical phenomena, to achieve the strength of the form necessary for the formation of a high-quality casting, in particular, the use of molds based on sand and water, which are hardened by cooling to negative temperatures - low-temperature forms (LTF).

Casting into low-temperature forms (LTF) is one of the most promising areas. A feature of casting in LTF is a significant increase in the strength of molds, compared with casting in sand-clay molds, as well as the possibility of using water as the main binder. This method of making molds improves the structure, improves the accuracy and geometry of castings, saves molding materials, and, most importantly, improves the environment by eliminating harmful emissions into the atmosphere of foundries.

However, the method of casting in LTF has a number of disadvantages associated with the formation of shells, pores on the surface of the castings, as well as increased burn. To eliminate these shortcomings, it is proposed to apply non-stick coatings on the surface of LTF and rods.

With the help of high-quality non-stick coatings, it is possible to significantly increase the surface cleanliness of castings, improve the presentation of castings, improve working conditions at cleaning operations, and reduce the gas saturation of castings metal. A large number of non-stick coatings of sand-clay molds and rods are known, which have found application in casting iron, steel and non-ferrous alloys.

As for frozen molds and cores, no such coatings have been developed. When using the technology of manufacturing castings in LTF with the use of external influence (low pressure) for pouring metal, there is a significant increase in the penetration of metal into the pores of the mold and core, and, consequently, an increase in burn on castings. Therefore, research aimed at the creation and implementation of LTF non-stick coatings and rods is very relevant [8].

The aim of the work

The aim of the work is to study and determine the optimal composition of the non-stick coating, which could be recommended for the production of aluminum castings in low-temperature forms.

The essence and methods of research

Based on the analysis of literature data and the research objectives formulated above, the following six compositions of non-stick coatings have been developed (Table 1).

Table 1

Compositions of non-stick coatings for low-temperature casting forms and cores

Coating marking	Coating components	Composition, % (by mass)
I	Zircon	26…30
	Disthene-sillimanite	53…55
	Bentonite	1…2
	Technical lignosulfonate	4…5
	Sodium Carboxymethylcellulose	7…8
	Water	K required density
II	Graphite amorphous	11…13
	Graphite crystalline	14…15
	$CaCO_3$	18…19
	Bentonite	1…2
	zinc oxide	7…8
	Liquid glass	7…8
	Water	K required density
III	Titanium dioxide	30…32
	Disthene-sillimanite	30…32
	Bentonite	1…2
	Technical lignosulfonate	3…4,5
	Water	K required density
IV	Zircon	23…25
	Disthene-sillimanite	53…55
	Bentonite	1…2
	Furan resin	4…6
	Water	K required density
V	Graphite amorphous	15…16
	Graphite crystalline	10…12
	Talc	20…25
	Bentonite	2…3
	AF binder	4…6
	Water	K required density
VI	Talc	50…52
	Dextrin	8…9
	Graphite	10…12
	Water	29…82

To prepare the non-stick coating, the following method was chosen.

Ceramic balls 3, 30 mm in diameter, were loaded into the drum 1 (Fig. 1), used as grinding media and improving the mixing of the coating components. Then the dry components of the coating were poured. The drum was closed and installed on a ball mill 2. The dry components were mixed for 2 hours. Then distilled water was poured into the drum. The drum was closed and again installed on a ball mill 2. Stirring was carried out for another 30 minutes.

The ratio “dry components – grinding media – water” is taken as 1:2:0.5 by weight. Then the finished suspension was transferred to the mixer, where more water was added to it to achieve the density we needed.

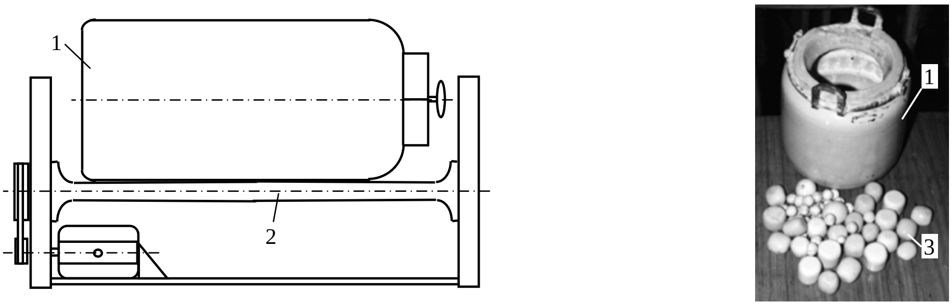


Fig. 1. Ball mill: 1 – drum; 2 – ball mill; 3 – ceramic (alundum) balls

Given in Table 1, non-stick coatings were applied to sandy-clay molds and rods using a spray gun (composition VI (Table 1) – rubbed). After drying at 120–150 °C of the surface layer of the non-stick coating, the painted molds and rods were frozen and poured with AL-5 alloy under low pressure in an experimental setup. According to the above method, the burn-on of the painted mold to the surface of the castings was evaluated.

The data obtained by averaging burn-on values on 3 experimental castings for each of the coatings are given in Table 2.

As follows from Table 2 and the condition of complete absence of burn marks on castings is satisfied by coatings I, III, IV, V (Table 1). When using coatings II and VI, a burn is formed.

Based on the foregoing, we selected coatings of 4 compositions for subsequent studies: I, III, IV and V (Table 1).

After conducting research on non-stick coatings for low-temperature casting molds and cores, the question arose about the optimal composition of the non-stick coating, which could be recommended for the production of aluminum castings in low-temperature casting molds.

Comparative characteristics of non-stick coatings are given in Table 2.

To solve this issue, the method of analysis of hierarchies was chosen.

The Hierarchy Analysis Method (HAM) is one of the decision-making methods in a situation where many criteria are used to evaluate preferences. It was proposed by Professor Thomas Saaty in the 1970s and is one of the most popular methods in its field [9].

Table 2

Comparative characteristics of non-stick coatings

Coating (Table 1)	Coating thermal conductivity coefficient, W/(m °C)	Gas permeability, units		Sedimentation resistance, %	Coating density, kg/m^3	Gas content, m^3/kg
		H_c	H_m			
I	0.178	42	43	14.5	1740	0.00664
II	0.115	243	275	5.5	1200	0.025
III	0.162	56	58	7.9	1610	0.0114
IV	0.198	19	125	9.4	1690	0.00485

Therefore, to solve our problem of choosing the optimal composition of non-stick coatings, LTF used the HAM.

To evaluate preferences, five coating criteria were selected: thermal conductivity coefficient, gas permeability, sedimentation resistance, coating density, gas content of the coating.

When processing the experimental data, a pairwise comparison of the coverage criteria was made. Then we built a normalized matrix for pairwise comparison of the criteria and determined the consistency coefficient for the weights of the criteria. After completing the normalization of the matrix, we calculated the consistency coefficient and checked its value. The purpose of this operation is to ensure consistency in setting preferences in the source table.

A pairwise comparison of coatings was performed for all criteria. One of the options is shown in Table 3 and 4. The last step was to calculate the weighted average scores for each solution (Table 5).

Table 3

Pairwise comparison by gas permeability criterion

Gas permeability				
Coating (Table 1)	I	II	III	IV
I	1.00	0.13	0.33	2
II	8.00	1.00	6.00	10.00
III	3.00	0.17	1.00	5.00
IV	0.50	0.10	0.20	1.00
	12.50	1.39	7.53	18.00

Table 4

Normalized matrix for gas permeability criterion

Normalization for gas permeability criterion						
Coating (Table 1)	I	II	III	IV	average	Measure of matching
I	0.08	0.09	0.04	0.11	0.08	4.02
II	0.64	0.72	0.80	0.56	0.68	4.38
III	0.24	0.12	0.13	0.28	0.19	4.11
IV	0.04	0.07	0.03	0.06	0.05	4.03
					IS	0.07
					IR	0.9
					Coefficient of matching	0.08

Table 5

Decision making model

Index	Criterion	Coating (Table 1)			
		I	II	III	IV
Coefficient thermal conductivity	0.18	0.08	0.68	0.19	0.05
Gas permeability	0.03	0.10	0.67	0.18	0.05
Sedimentation resistance	0.09	0.67	0.04	0.08	0.21
Density	0.35	0.25	0.04	0.08	0.63
Gas production	0.35	0.21	0.05	0.09	0.65
	1.00	1.32	1.48	0.62	1.58

As a result, it was concluded that the optimal non-stick coating. Such a coating is coating IV and coating II. These coatings can be recommended for improving the surface quality of aluminum alloy castings when casting into LTF.

According to the results of the selection of starting materials, the materials that can be used in the developed non-stick coating include:

– refractory filler of non-stick coating – zircon;
– distensillimanite in a ratio of 1 : 2.2 by weight;
– binder – furan resin;
– stabilizer – bentonite.

Optimization of the composition of the developed non-stick coatings was carried out in three components: zircon + distensillimanite, bentonite and furan resin by the method of simplex planning of the experiment according to the plan of G. Scheffe with the construction of simplex lattices for:

- burn – B, gr;
- sedimentation stability – SS, %;
- gas-carrying capacity – GS, m^3/kg;
- gas permeability – GP, units;
- sting resistance – SR, s;
- erosion resistance – ER, %;
- abrasion resistance – AR, kg/mm;
- tensile strength – TS, MPa;
- adhesion forces – AF, MPa;
- density – D, kg/m^3;
- conditional viscosity – CV, s.

The developed non-stick coating was considered optimized if it corresponded to the set of properties given in Table 6.

The composition was optimized using the following components (%, by mass): zircon, distensillimanite (designation “O”), bentonite (designation “B”), AF-binder (designation “C”).

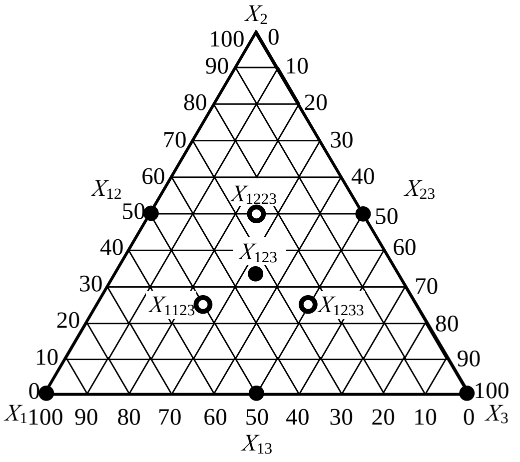


Fig. 2. Scheme of experiments according to the plan of G. Scheffe

Table 6

The maximum permissible values of parameters adopted for optimization

Parameter	B, gr	SS, %	GC, m^3/kg	GP, units	SR, s	ER, %;	AR, kg/mm	TS, MPa	AF, MPa	D, kg/m^3	CV, s
Value	≤0	≤10	≤5	≥90	≤92	≤1	≥1	≥4500	≥500	≤1800	≤4

To construct a simplex lattice according to the simplex-lattice plan of G. Scheffe [10, 11] (a second-order model with a central point), the scheme shown in Fig. 2 was used.

The codes of the coatings under study in accordance with the scheme presented in Fig. 2, their elementary composition and response function codes are given in Table 7, 8, 9.

Table 7

Code designation of coatings

Coating	Symbol	Composition					
		in natural scale (%, by mass)			in coded scale		
		O	B	C	X_1	X_2	X_3
I	X_1	100	0	0	1	0	0
II	X_2	0	100	0	0	1	0
III	X_3	0	0	100	0	0	1
IV	X_{12}	50	50	0	1/2	1/2	0
V	X_{13}	50	0	50	1/2	0	1/2
VI	X_{23}	0	50	50	0	1/2	1/2
VII	X_{123}	33.333	33.333	33.333	1/3	1/3	1/3

Table 8

Elementary composition of coatings

Coating	Symbol	The content of the material in the alloy, % (by weight)		
		Zircon, distensillimanite	Bentonite	AF binder
I	X_1	85	1	2
II	X_2	70	5	2
III	X_3	70	1	8
IV	X_{12}	78	1	8
V	X_{13}	78	5	2
VI	X_{23}	85	3	5
VII	X_{123}	78	2	5

Table 9

Response function codes

Response function	Code
burnt	Y_1
Sedimentation stability	Y_2
Gas generating capacity	Y_3
Gas permeability	Y_4
Squeeze resistance	Y_5
erosion resistance	Y_6
Abrasion resistance	Y_7
Tensile strength	Y_8
Adhesion strength	Y_9
Density	Y_{10}
Nominal viscosity	Y_{11}

Since the implementation of G. Scheffe's plan involves the construction of an incomplete cube model in a triple system:

$$Y=\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_{12}x_1x_2+\beta_{13}x_1x_3+\beta_{23}x_2x_3+\beta_{123}x_1x_2x_3, \qquad (1)$$

where Y is a material property;

β – regression coefficient;

x is the amount of material in the coating,

then the regression coefficients in formula (1) were calculated by the formulas:

$$\beta_1=\xi_1,\ \beta_{ij}=4\xi_{ij}–2\xi_i–2\xi_j,\beta_{123}=27\xi_{123}–1\cdot(\xi_{12}+\xi_{13}+\xi_{23})+\cdot(\xi_1+\xi_2+\xi_3),$$

where ξ_i , ξ_j, ξ_{123} are the results of experiments at points of simplex lattices.

The results of experimental studies of the properties of materials and alloys listed in Table 9 are given in Table 10, and the results of calculating the regression coefficients are given in Table 11.

Table 10

Results of experimental studies

Coating	Response function									
	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8	Y_9	Y_{10}
	B,gr	SS, %	GC, м^3/kg	GP, units	SR,s	ER, %	AR, kg/mm	TS, MPa	AF, MPa	D, kg/m^3
I	0	9	3	100	94	1.1	0.85	4150	410	2000
II	0.03	12	3	70	93	1.1	0.8	4250	420	1950
III	0	9	7	100	94	0.8	1.5	4600	600	1750
IV	0	9	7	100	93	0.9	1.4	4550	590	1760
V	0.02	12	3	70	94	1.2	0.8	4200	450	1950
VI	0.01	11	5	80	93	1	0.9	4400	490	1900
VII	0	10	5	90	92	1	1	4500	500	1800

Table 11

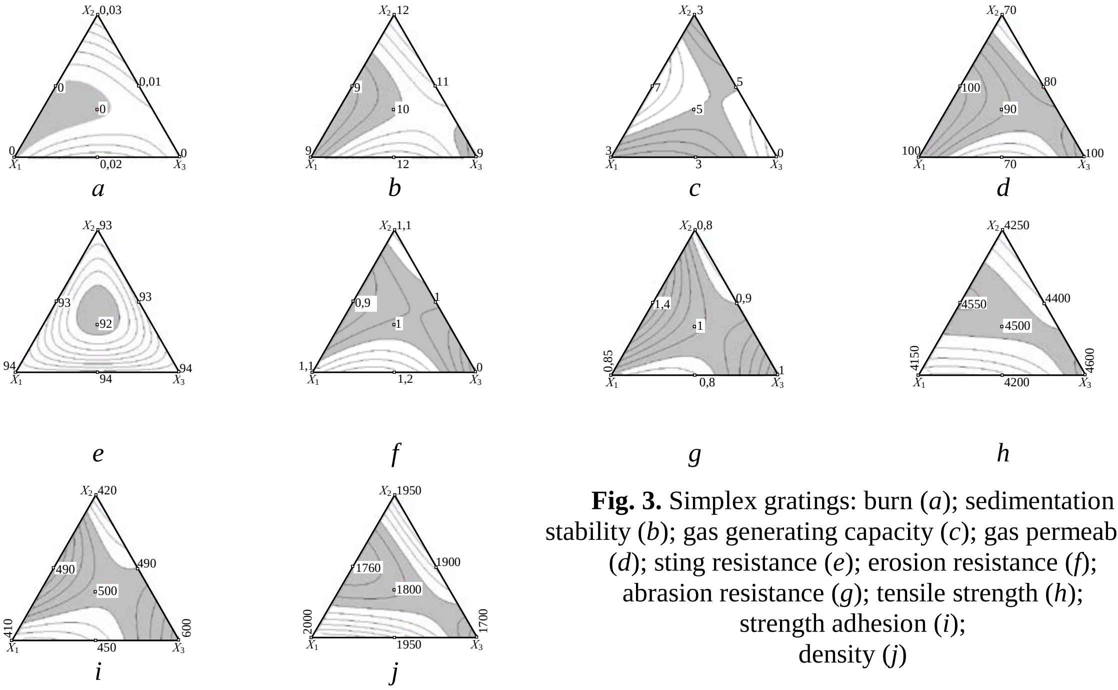
Regression coefficients

β	Regression coefficients									
	B, gr	SS, %	GC, м^3/kg	GP, units	SR, s	ER, %	AR, kg/mm	TS, MPa	AF, MPa	D, kg/m^3
β_1	0	9	3	100	94	1.1	0.85	4150	410	2000
β_2	0.03	12	3	70	93	1.1	0.8	4250	420	1950
β_3	0	9	7	100	94	0.8	1.5	4600	600	1750
β_{12}	–0.06	–6	16	60	–2	–0.8	2.3	1400	700	–860
β_{13}	0.08	12	–8	–120	0	1	–1.5	–700	–220	300
β_{23}	–0.02	2	0	–20	–2	0.2	–1	–100	–80	200
β_{123}	–0.45	–204	–84	–1380	–1719	–19.2	–19.65	–75300	–9150	–35820

The adequacy of the obtained mathematical models was checked by the results of three control experiments, which in Fig. 2 codes were assigned – x_{1123}, x_{1223}, x_{1233}, by comparing the experimental and calculated values for each of the obtained mathematical models. In addition, the adequacy of mathematical models was checked by comparing the tabular and empirical values of the t-criterion for each of the points indicated in Fig. 2.

Because the difference between the experimental and calculated values for each of the obtained mathematical models at points x_{1123}, x_{1223} and x_{1233} does not exceed 3.4 % and in all cases $t_{\text{exp}} < t_{\text{tabl}}$, the hypothesis of the adequacy of the obtained mathematical models at a 5 % level significance has been accepted.

Using the obtained mathematical models, we built the corresponding dependencies, which are presented in the form of simplex lattices in Fig. 3.



a *b* *c* *d*

e *f* *g* *h*

i *j*

Fig. 3. Simplex gratings: burn (*a*); sedimentation stability (*b*); gas generating capacity (*c*); gas permeability (*d*); sting resistance (*e*); erosion resistance (*f*); abrasion resistance (*g*); tensile strength (*h*); strength adhesion (*i*); density (*j*)

The field of optimal contents of starting materials in the non-stick coatings being developed was obtained by shading on simplex gratings fields with an acceptable parameter level and then superimposing the obtained images on one grating.

The result of combining simplex lattices is shown in Fig. 4, where the field of optimal contents of the tested materials is placed in the concentration grid and highlighted in black. The key of the simplex lattice is shown in Fig. 5.

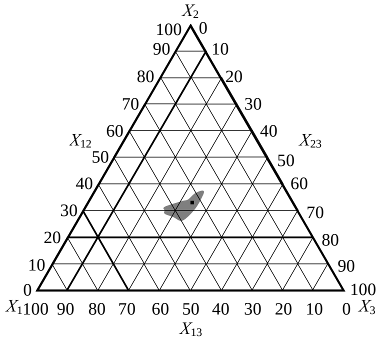


Fig. 4. Optimal area obtained as a result of overlaying images of simplex gratings (gray area)

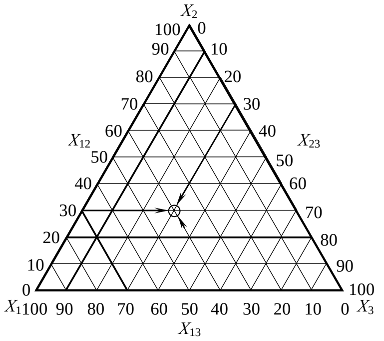


Fig. 5. Key of the simplex lattice

Conclusions

In accordance with the data in Table 8, the optimal content of materials in the developed non-stick coatings is (% by weight): zircon – 23...25; distensillimanite – 53...55; bentonite – 1…2; AF-binder – 4...6.

The technology for producing castings in the LTF was considered using the example of manufacturing a casting “body” from an aluminum alloy D16 GOST 4784-97.

As a method of cooling the mold, the previously described method of placing a cooled model in a painted mold cavity was used.

The mold was made from a molding sand consisting of 95 % 3K02A sand and 5 % water.

The assembled mold was installed in a designed low pressure casting machine.

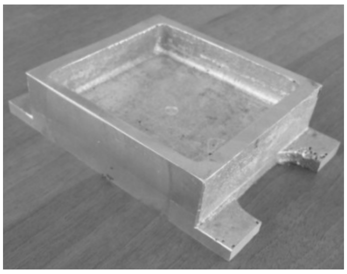


Fig. 6. Casting “body”,
alloy D16 (Д16) GOST 4784-97

Fig. 7. Casting “cover”,
cast iron SCh (СЧ20) GOST 1412-85

Fig. 8. Casting “anemostat”,
alloy AK5M2 (АК5М2) GOST 1583-93

Fig. 9. Casting “watch case”,
alloy BrO6TsC2H (БрО6Ц6С2Х) GOST 614-97

The temperature of the metal at the time of pouring was maintained at 730...740°C, the temperature of the LTF was –40...–50 °C.

After cooling, the casting was removed from the flask. Because of the sand being completely softened, the work at the knockout stage was minimal.

The surface quality is satisfactory – shells, gas defects, blockages, etc. were absent.

This technology can be used to produce castings from various iron-carbon and non-ferrous alloys (Fig. 6, 7, 8, 9).

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