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Content

Increasing the hardness of low-chromium cast irons by modifying

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Annotation. This research presents the results of practical work on the modification of low-chromium cast irons with boron, barium and magnesium-containing additives. Consider a practical effect of these components on the hardness of wear resistant cast iron with a chromium content of up to 1%.

Key words: grinding media, balls, chromium cast iron, nodular graphite, wear resistance, impact resistance, hardness, steel, alloy, casting, molding, alloying, modification, out-of-furnace treatment, modifier, ligature, magnesium, boron, barium

1. Introduction

Despite the high rate of development of modern world science and technology in many important areas of human life, the problems of increasing the economic efficiency of production processes for the extraction and processing of mineral ore raw materials in the mining and metallurgical industrial sector to this day do not lose their relevance. Economies of many countries of the world, based on the export of natural resources, depend on the effectiveness of solving these issues. This is especially true for many underdeveloped and developing countries, which often have significant reserves of natural resources, but at the same time, due to historical circumstances, a rather low level of development of industrial production.

One of the most important questions in modern engineering is to increase the service life of the wear parts and assemblies of technological equipment, the solution of which depends directly on the technical and economic efficiency of production as a whole.

The solution to this problem, first of all, involves either increasing the special properties of already existing wear-resistant materials for the production of equipment parts or creating fundamentally new compositions and technologies.

There are hundreds of billions of dollars in annual friction and wear losses worldwide. Premature wear of machinery, devices, equipment and tools leads to colossal costs. Wear is one of the main reasons for repairs. In some cases, repair and maintenance costs approximately for various technical products, according to various estimates, 3-10 times more than the cost of their manufacture.

A significant part (about 30%) of the world's energy resources in various forms is spent on friction, 80-90% of the moving parts of machines fail due to wear. At the same time, the efficiency, accuracy, economical efficiency, reliability and durability of the machines decrease, the dynamic and acoustic characteristics deteriorate. [1].

Depending on the operating conditions, a number of specific requirements are imposed on wear-resistant alloys, but the general requirement is, of course, high wear resistance, hardness and strength. It should be emphasized that wear resistance and surface hardness do not always have a direct correlation. For example, steel 40HN2MF after volume quenching and low tempering has a hardness of about 51 HRC, but its wear resistance is lower than that of steel 38HN2MA with a hardness of 43 HRC.

First of all, of course, the wear resistance of the alloy is determined by the type of wear and the operating conditions of the part. According to the type of loads acting on the surface of the material during operation, the types of wear can be divided into 8 main groups [1, 2]: abrasive wear, corrosion-mechanical wear, adhesive wear, fatigue wear, wear during fretting corrosion, erosion wear, cavitation wear and wear when seized. According to GOST 27674-88 "Friction, wear, lubrication. Terms and definitions" wear of machine parts and mechanisms is classified for reasons causing wear: mechanical, corrosion-mechanical, gas-abrasive, etc. In reality, nearly always, the real wear of parts occurs under the complex influence of the listed reasons, i.e. at the same time it can be both, mechanical and hydroabrasive (for example, when pulp or sludge transportation), etc. Therefore, apart from specific types of wear, such as erosion and chemical example, in many cases, machine parts and mechanisms are exposed mainly to mechanical wear with different alternating loads, including shock. In other words, the destruction of the surface in many cases is associated not only with abrasion, but also with the occurrence of cracks, chips and other similar defects under impact.

If we consider the operating conditions of many nodes and parts of metallurgical units (for example, sprockets and couplings of roasting and sintering machines, forging and pressing equipment, shuttle charge distributors, pelletizers, etc.), then all loads in the first approximation can be divided into 2 types: actually abrasive and shock. Meanwhile, most of the measures aimed at improving the quality of wear-resistant materials, as a rule, are associated only with an increase in hardness and wear resistance.

Meanwhile, Charpy's rule [3] unambiguously defines the principles of formation of the structure of a wear-resistant material: a sufficiently strong and plastic matrix with fine and isometric solid inclusions evenly distributed in it.

The purpose of this study is to create a new wear-resistant cast iron alloy with high performance properties based on the Charpy principle. It is clear that in this area was conducted a lot of research, so the creation of the new material will be based on improving the properties of existing analogues.

2. Results and discussion

Today, about 66% of grinding bodies worldwide are produced from steel by cross-helical rolling on ball rolling mills, 13% are steel cylinders ø20-30 mm (cylpebs), and 16% are cast iron balls and cylpebs, 5% - others [4, 5].

Also in publications there is information about other alternative methods for the production of steel grinding balls: bimetallic balls (consisting of a soft and viscous core and a hard shell) [6], hollow forged balls made by liquid stamping of a semi-finished product with plastic deformation at the last stage of forming [4, 5]. However, these developments have not yet been sufficiently studied, and their significance has not yet been practically confirmed.

Magotteaux (Belgium) is the world's leading manufacturer of cast iron grinding bodies, which at 16 factories located around the world produces about 320 thousand tons of high-quality grinding products from high-alloy chromium cast iron costing about $ 1210 per ton [4]. ME Elecmetal (Chile) [7], Shandong Shengye Grinding Ball Co. Ltd. (China), Gerdau Ameristeel (Brazil), Vitkovice (Czech Republic), Scow Metals (South Africa), The Armco Triangle and Moly-Cop (USA) [8], Bragonzi (Italy), Sosiedad Santaana de Boluetta (Spain), etc. can also be referred to large manufacturers of grinding bodies from far abroad.

Among the CIS countries, the market of manufacturers of grinding products is represented by the following companies: Evraz United West Siberian Metallurgical Plant OJSC (Russia), OJSC Nizhniy Tagil Metallurgical Plant (Russia), LLC Zavod Energostil (Ukraine), CJSC Krontif-Center (Sukreml Ironworks) (Russia), PJSC Metallurgical Combine Azovstal (Ukraine).

One of the main manufacturers of steel grinding bodies in Russia - JSC Guryev Metallurgical Plant (the average annual productivity is about 200 thousand tons of manganese steel balls).

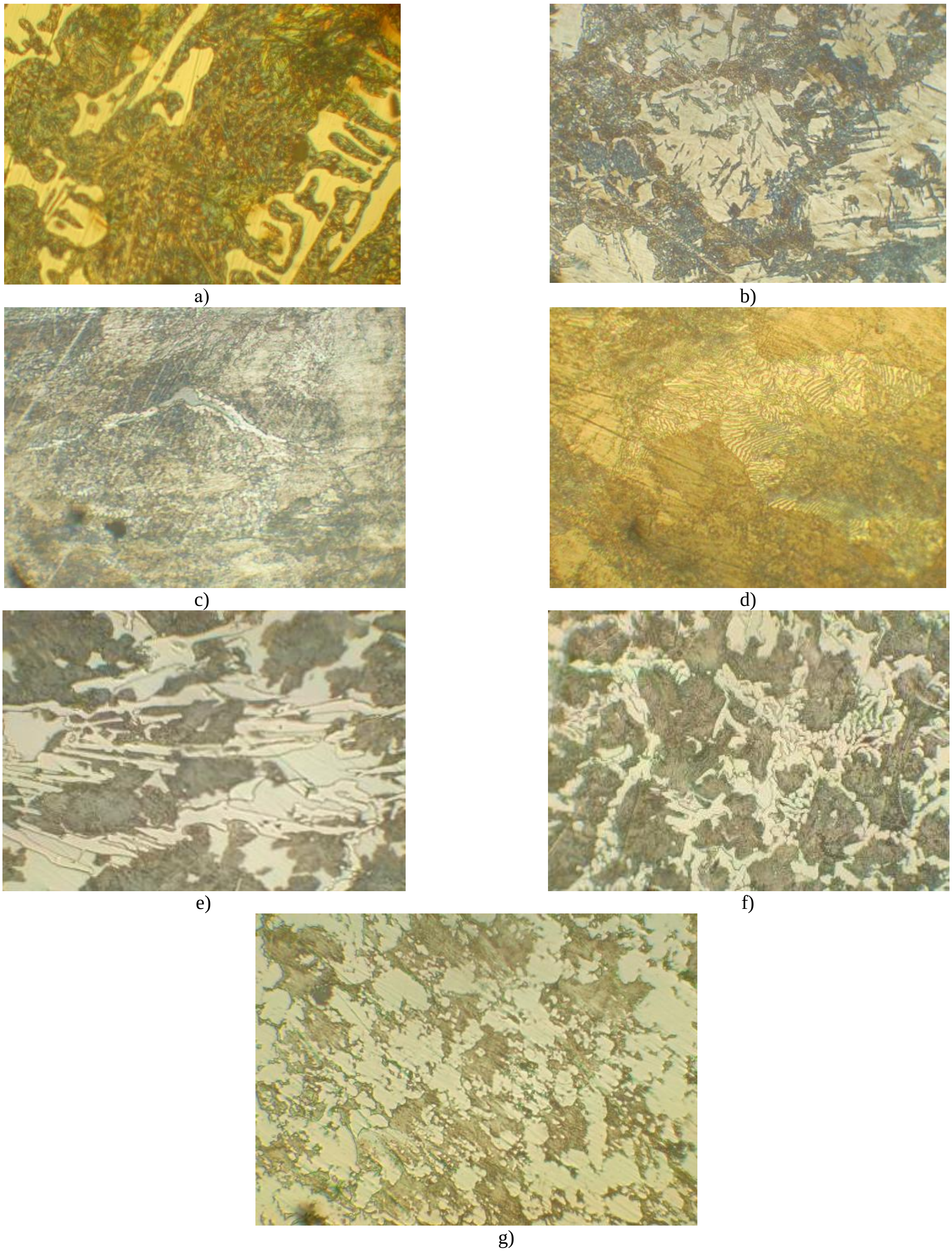
In the Republic of Kazakhstan, steel balls are made in two main ways (table 1):

- by means of cross-helical or cross-wedge rolling (SSGPO JSC - Rudny, Casting LLP, KSP Steel LLP - Pavlodar) in accordance with GOST 7524-2015 "Grinding steel balls for ball mills" of steel grades SHH15, SHH20SG, M76, SH2, SH3, 65G with subsequent heat treatment;
- by casting (QazCarbon - Karaganda Foundry LLP - Karaganda) from low-alloy steels of grades 80GSL, 100HGSL.

Table 1 - Data on manufacturers of grinding balls in the Republic of Kazakhstan

Company - manufacturer	Product type	Alloy grade	GOST	Annual production, thousand tons
QazCarbon - Karaganda Foundry LLP (Karaganda)	Cast grinding balls ø30-100 mm	Chromium special cast iron	RK ST 2310-2013	up to 40,0
		Steel 80GSL	LLP ST 404383730012-004-2010	up to 2,5
KSP Steel LLP (Pavlodar)	Rolled grinding balls ø40-100 mm	Steel 65G	GOST 7524-89, LLP ST 070341015761-010-2012	up to 48,0
Casting LLP (Pavlodar)	Rolled grinding balls ø35-100 mm	Steel SHH15	RK ST 2461-2014	up to 42,0
Vostokmashzavod JSC (Ust-Kamenogorsk)	Cast grinding balls ø80-120 mm	ICHH15G4NT	TU 14-2-882-90	up to 15,0
SSGPO JSC (Rudny)	Rolled grinding balls ø30-100 mm	Steel SH-3		up to 12,0

The main leader in the production of cast iron balls in Kazakhstan is QazCarbon LLP, with a production capacity of about 35-40 thousand tons of low-alloy cast iron balls per year. At this enterprise, the production of cast iron balls ø30-100 mm is carried out by casting low-chromium cast iron (Cr ~ 1.0%) in one-time sandy-clay molds [9]. The microstructure of samples from some alloys for the production of grinding bodies is shown in the figure1.



a) chromium cast iron, Cr~1,0% (42-47 HRC), sandy-clay form;
b) steel 65GL (55-57 HRC), helical rolling method;
c) steel 80GSL (30-35 HRC), sandy-clay form, micro-grinding of the ball surface;
d) steel 80GSL (30-35 HRC), sandy-clay form, micro-grinding to a depth of ½ ball radius;
e) ICHH15G4NT(46-50 HRC), sandy-clay form, micro-grinding of the ball surface;
f) ICHH15G4NT(46-50 HRC), sandy-clay form, micro-grinding to a depth of ½ ball radius;
g) ICHH15G4NT(46-51 HRC), gasified casting, micro-grinding of the ball surface

Fig. 1. – Microstructure of balls made by different technologies from different alloys, ×400

The reasons for the wear of the grinding media can be of different nature. In dry grinding, the grinding media wear mainly as a result of abrasive action. During wet grinding in aggressive (chemically active) aqueous media, abrasive wear is accompanied by corrosive wear, in which the metal is destroyed due to chemical or electrochemical interaction with the medium.

The listed wear factors are objective and cannot be eliminated, because due to the physical reasons of the technological process.

Subjective wear factors are the characteristics of the grinding body itself. Among the factors that significantly affect the premature wear and destruction of grinding balls, two main ones can be distinguished: low impact resistance and low bulk hardness.

Cracking of balls most often happens with balls of large diameters from 80 to 120 mm due to insufficient impact toughness, as well as due to the presence of technological defects, for example, gas, shrinkage or slag cavities (Figure 2), often occurring during casting or deep volume cracks, which can occur during the crystallization period or after quenching, if tempering conditions are not provided to relieve internal stresses in the ball. Also, an increased content of harmful impurities, such as sulfur and phosphorus, can lead to cracks.

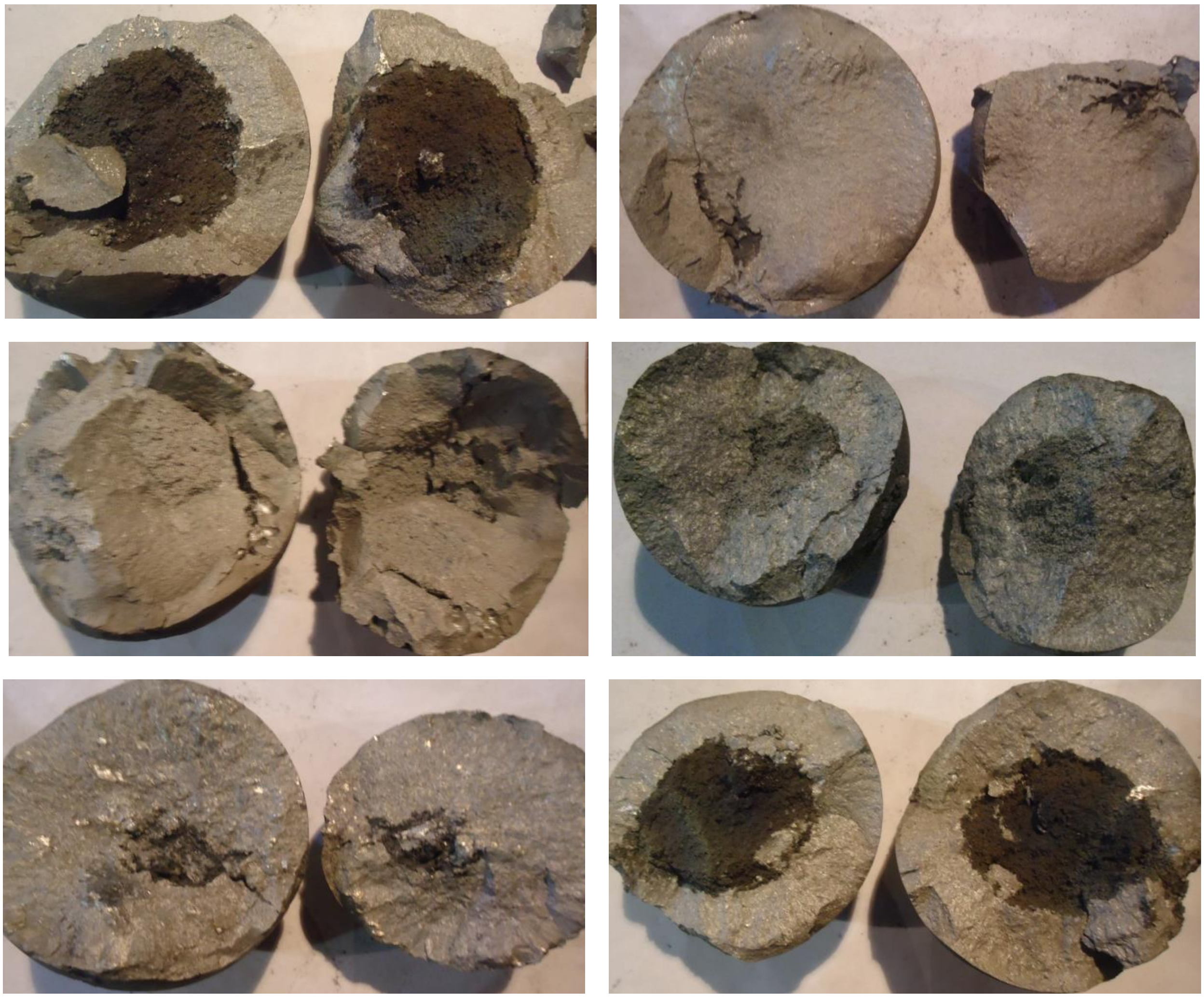


Fig. 2. – Cast iron balls with internal casting defects, after being destroyed on impact copra

If we consider in more detail the causes of the occurrence of shells in cast balls, then the following can be noted [8]:

- high gas content of the molding sand due to excess moisture, which is reduced by chemical or thermal drying of the molds before pouring;

- low gas permeability of the molding sand due to the high clay content or other binding components. It is eliminated by installing additional risers and performing ventilation ducts in the form;

- increased gas saturation of the metal due to the use of dirty and oxidized metal charge. In this case, the liquid metal contains a large amount of free nitrogen, hydrogen and oxygen. This problem is usually solved by in-furnace or in-ladle deoxidation of the liquid melt with aluminum, silicocalcium, ferrosilicon, or their mixtures before casting;

- reduced fluidity of the metal due to a violation of the chemical composition of the metal (deviations in the content of carbon and / or silicon) or low pouring temperature, which prevents the removal of gas bubbles through the gating-feeding system. To ensure a high fluidity of the alloy, it is necessary to ensure a stable content of chemical elements during melting, as well as the required overheating temperature of the metal before tapping from the furnace;

- elevated pouring temperature, which leads to an increase in volumetric shrinkage, at which cavities appear mainly in the central part of the ball. In this case, the surface layers of the ball crystallize as a result of heat exchange with the shape and are fed by liquid metal from the central part of the ball;

- insufficient ball supply during the crystallization period, when shrinkage cavities are localized closer to the metal supply, with the correct calculation of the total cross-sectional area of the elements of the gating-feeding system (feeders, feed lugs and risers). Improvement of the conditions for directional solidification of castings is also achieved by using exothermic products in the form of inserts or coating mixtures.

To prevent defects associated with deviations in the temperature of the alloy, strict temperature control is required during the oxidation and reduction periods of melting, as well as immediately before the release of liquid metal from the furnace and pouring;

- the presence of non-metallic impurities in the body of the casting in the form of slag, molding sand and oxide films. These defects can be eliminated by using filter inserts.

Ball cracks are mainly caused by internal stresses at high cooling rates. This defect can occur during quenching followed by air cooling. To eliminate this problem, tempering is carried out [8].

Steel balls obtained by various methods of severe plastic deformation of metal are also not free from defects (Figure 3).

Fig.3. – Rolled steel balls with external defects

For balls produced at enterprises of the CIS countries, it is relevant to increase the surface hardness with an increase in the depth of the hardened layer. The quality of a rolled ball in accordance with GOST 7524-89 lags behind the world level in terms of surface and volumetric hardness, but no less important is its ability not to crack from impact. If there are internal defects and the thermal hardening mode is not maintained, then the ball quickly splits and then wears out.

According to the technology adopted at the CIS factories for the production of rolled steel balls, immediately after rolling, the products are incompletely quenched in water, followed by self-tempering. In this case, it is impossible to achieve through hardenability, the thickness of the hardened layer (martensite shell) does not exceed 12-15 mm, and the hardness of the ball significantly decreases towards the center. In addition, this technology requires strict temperature control - the overheated product in the mill can crack. [10-12].

The splitting and crumbling of the particles of the balls lead to their uneven wear, while the amount of scrap in the mill increases, which significantly worsens the technological parameters of the grinding process (figure 4).

Fig. 4. – Scrap formed in ball mills as a result of grinding balls

Table 2 - Comparative characteristics of domestically produced ø100 mm cast balls from various wear-resistant alloys

No.	Parameters	Alloy grade			
		Chrome cast iron,Cr~1,0%	St 80 GSL	ICHH15G4NT	
				LGM	PGS
1	Actual ball diameter, mm	103-104	103-106	102-104	103-106
2	Average ball mass, kg	4,75	4,6	4,28	4,52
3	Hardness $HRC_{э}$ on the surface, units	42-47	30-35	46-51	46-50
4	Number of blows before destruction	160-320	200-300	166-536	320-2000

Note: Tests for impact resistance were carried out on a homemade hammer with a striker weight of 30 kg

All this necessitates the search for new alternative solutions to improve the performance properties of castings and parts operating under conditions of severe impact abrasive wear. Despite the fact that there are a lot of technological methods and methods for increasing the impact toughness of castings, improving the wear resistance of metals by alloying, thermal, chemical thermal treatment, varying the cooling conditions of the casting, etc., their use is far from always justified from an economic point of view. This is due to the high consumption of expensive alloying additives, high costs of equipment for thermal/thermochemical treatment, a significant reduction in productivity due to an increase in the duration of the production cycle, etc. Therefore, in light of the above arguments, certain interests are more economical and often less effective ways of improving melt properties such as micro alloying and modifying. At the same time, the in-mold modification method is rightfully considered one of the most effective from the point of view of the assimilation and useful effect of modifying elements on the melt. [13-15].

From the point of view of the ratio of the high modifying effect of the main elements of the additive to its cost, at present, of undoubted interest are studies of the effect on the structure and properties of cast iron of additives containing magnesium, boron and barium, both in combination and separately. This is primarily due to the fact that most of the previously conducted scientific works on the study of the effectiveness of additives containing these elements are devoted to the study of their effect on the structure and properties of high-alloy and complex-alloyed cast irons, as well as steels of the most common grades. [16-21].

An analysis of domestic and foreign scientific literature in this area showed that there are few full-fledged works describing the nature of the effect of magnesium-, boron- and barium-containing modifying additives on the structure and properties of wear-resistant cast iron in the world, and there are few reliable data on the results of treatment with these additives of bleached low-chromium cast irons, today, it is not enough to finally understand this issue. Few information available in this direction, most often, of a more theoretical nature or carries rather contradictory information.

Low-alloy chromium cast iron with a chromium content of up to 1%, which serves as the main most accessible material for the production of cast grinding bodies in the Republic of Kazakhstan, was chosen as the object of this scientific research. As a subject of research, in this case, the influence of modifying additives containing magnesium, boron and barium on the structure and properties of low-chromium cast iron is considered.

As is known, the structure of bleached wear-resistant low-alloy chromium cast irons up to 50% consists of cementite (with a micro hardness of about 950-1000 HV), which determines their increased wear-resistant properties in comparison with gray cast irons. Also, in cast irons of this type, carbon forms carbides with chromium and manganese, the amount of which depends on the content of carbon, chromium and manganese, respectively, in the absence of soft graphite in the structure, which gives them increased wear resistance under conditions of abrasive wear.

The production of a sorbitic, troostite, and martensitic-austenitic metal matrix from pearlite occurs sequentially by increasing the alloying additives Cr, Ni and Mo, which has a positive effect on the wear resistance and hardness of the surface of the castings. In this case, additional processing of cast iron with magnesium, due to the receipt of a spherical shape of graphite, also contributes to a significant increase in strength characteristics. Alloying elements Mn, Mo, Cr, V and Te (in order of increasing influence efficiency), as well as modifying components Mg, Ce and other rare earth metals increase the bleachability of cast iron [22].

The main disadvantages of cast irons of this group are a significant decrease in the wear resistance of the metal over the section of the casting (from the surface to the core), as well as its intractability. [23].

Boron (B) occupies a special place among all other microalloying elements due to the fact that it:

- is introduced in ultra-small quantities, hundreds of times less than other alloying elements;
- in steels it partially replaces more expensive metals (Ni, Cr, Mo, V, etc.), having a positive effect on a wide range of quality characteristics of the metal (strength, plastic, corrosion, etc.), without reducing mechanical characteristics, increasing machinability, fatigue strength and weld ability. Reduces the overall alloying degree of the alloy, improving processability, reduces sensitivity to stress concentrators and the cost of the alloy.

From the results of numerous tests it follows that the introduction of 0.001% boron into steel in terms of the effect on hardenability corresponds to 1.68% of expensive alloying elements of the sum: 1,33% Ni + 0,31% Cr + 0,04% Mo) [21].

Microalloying with boron also refines the microstructure of cast iron, promotes its degassing, and also strengthens the alloy by increasing the microhardness, uniform distribution and grinding of carbide. Over 0.001% promotes carbide formation [19, 23-25].

Barium in the composition of modifiers enhances the formation of graphitization centers and increases the duration of the modifier. Reduces chill tendency and promotes graphite formation.

To solve a set of problems associated with reduced casting properties and the tendency of low-chromium cast irons to form a heterogeneous cast structure during crystallization, which contributes to the formation of many types of casting defects of various nature and also negatively affects the main working properties of the material for casting grinding bodies - wear resistance and ability to resist impact effects, a comprehensive metal treatment is proposed, which consists in microalloying cast iron with ferroboron followed by in-mold modification of the melt with a mixture of ferrosilicon magnesium and ferrosilicobarium.

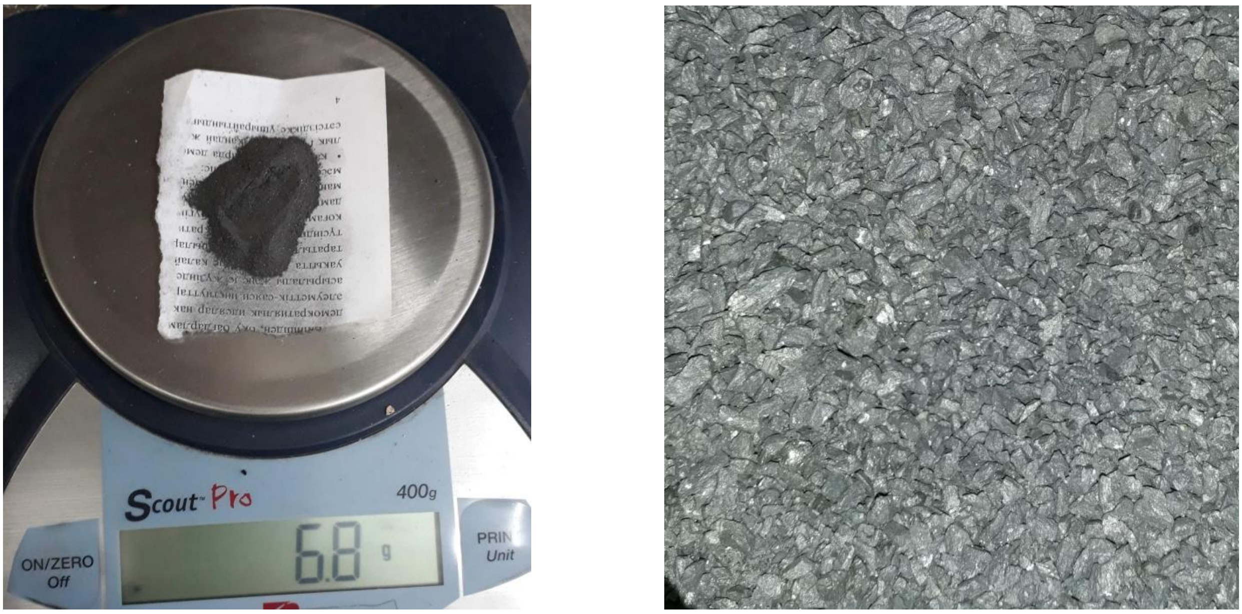
Low-chromium cast iron was adopted as the base alloy for complex processing, which is used as the base alloy for the manufacture of grinding bodies at "QazCarbon" LLP (Karaganda) of the following chemical composition (wt.%): 3,3 C, 0,5 Si, 0,7 Mn, 0,7 Cr, 0,04 S, 0,4 P, rest Fe.

In order to study the effect of each individual modifying component on the properties of low-chromium cast iron, 3 series of melts were carried out with a separate additive in the melt of various amounts of magnesium-, boron- and barium-containing ferro-additives.

For this purpose, in the framework of preliminary laboratory tests for the practical development of the process, the following additives were used:

- carbon ferrochrome grade FH800A, GOST 4757-91, of the following composition (wt.%): 69,06 Cr, 1,46 Si, 2,97 C, 0,05 P, 0,045 S, rest Fe;

- ferroboron of the pilot batch (Figure 5, a), obtained by the carbothermal method in the laboratory "BOR" CMI named after Zh. Abishev, of the following composition (wt.%): 14,63 B, 4,05 Si, 0,78 C, 0,40 Al, 0,011 S, 0,031 P, ~ 80,0 Fe;
- ferrosilicomagnesium grade FSMg9 (Figure 5, b), TU 14-5-134-2005 of the following composition (wt.%): 51,7 Si, 10,2 Mg, 1,2 Al, 0,58 Ca, 0,55 P3M, rest Fe;
- ferrosilicobarium FS60Ba22 composition (wt.%): 56,24 Si, 20,52 Ba, 2,51 Al, 0,014 S, 0,024 P, 18,5 Fe.



a) b)

a) finely ground carbothermal ferroboron;
b) ferrosilicomagnesium grade FSMg9, fraction 1.0-5.0

Fig. 5 – Modifying additives for the treatment of experimental cast iron

Smelting of chromium cast iron was carried out by the remelting method in a laboratory electric resistance furnace Tamman (Figure 6) in alundum crucibles. The mass of cast iron in one heat was 0,4-0,5 kg.

Fig. 6. – Tamman smelting furnace in the process of iron smelting

Metal charge - scrap cast iron balls and ferrochrome (Figure 7) were loaded directly into the crucible.

Fig. 7. – Metallic charge and polystyrene foam models prepared for casting samples

In the first series of experiments, the microalloying of low-chromium cast iron with ferroboron was carried out after complete melting of the charge and holding the melt at a temperature of 1500 ° C for 1 minute by wrapping ferroboron in aluminum foil and lowering it into a crucible on a steel rod. Next, the melt was stirred in a crucible using an alundum tube for 5-7 seconds and poured into a previously prepared evacuated LGM mold (Figure 8) under a pressure of about 0.35 atm. The metal was poured into the mold calmly, the fluidity was high. To provide a vacuum in the mold, a compressor unit of the UK 25-1.6 model was used. The mold was knocked out after a two-minute holding in the mold.

Fig. 8. – Vacuum form, prepared for cast iron casting

In the second series of experiments, melting was carried out in the same way as in the first experiments. Modification with ferrosilicon magnesium was carried out using the in-mold technology by casting according to gasified models. In this case, the modifying charge, consisting of the calculated amount of small crushed FSMg9 particles, was placed directly into the expanded polystyrene model under the riser and poured at a temperature of 1450°C. During pouring, a slight pyroelectric effect was observed the fluidity of the metal was satisfactory. The casting was also knocked out of the mold after holding for 2 minutes.

In the third series of experiments, the modification of cast iron with ferrosilicobarium was carried out in a crucible on a rod at a temperature of 1500°C. The rest of the experimental conditions are the same. When pouring, satisfactory fluidity of cast iron was also noted, pouring proceeds calmly.

From the modified cast iron, cylindrical rods ø25 mm were obtained (Figure 9), which were then cut using an automatic high-speed programmable precision cutting machine MICRACUT 201, Metkon (Turkey) and a manual cutting machine Unitom-2, Struers A / S (Denmark) (Figure 10) for samples about 10 mm high for further hardness measurement.

Fig.9. – Modified cast iron cast rods for making samples

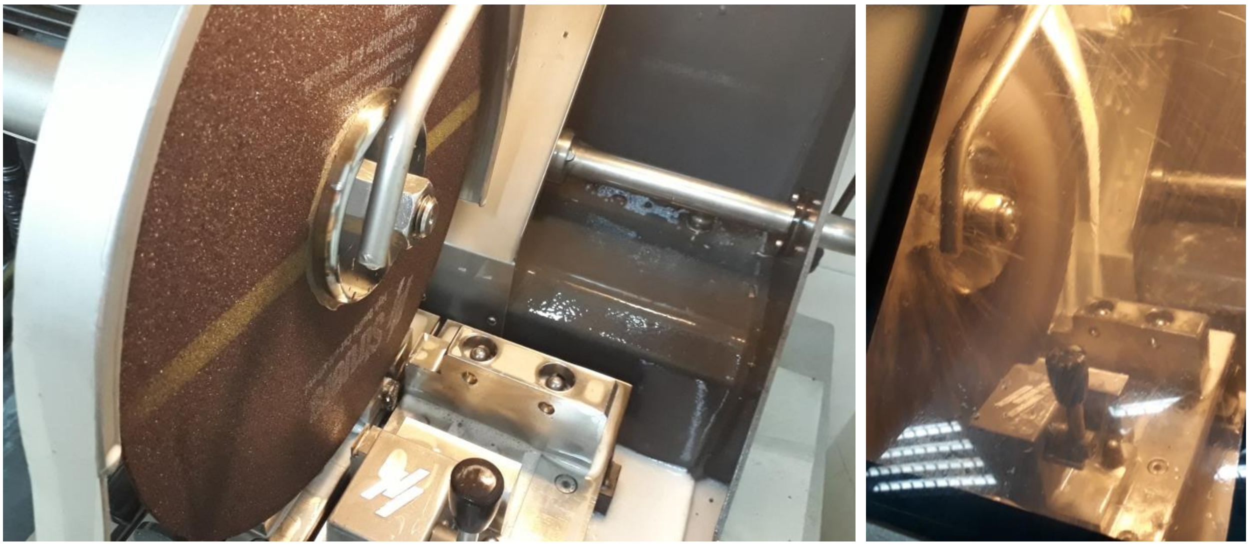


Fig. 10. – Sample preparation process on cutting machine Unitom-2, Struers (Denmark)

The controlled surfaces of the samples were prepared on a LaboPol-5 grinding and polishing machine, Struers A / S (Denmark) using MD-Piano 220 diamond disks.

The hardness of each sample was measured on a Wilson VH1150 hardness tester with a load of 5 kg at four opposite points, at a distance of about 2-3 mm from the surface, as shown in Figure 11, as well as at 2 points in the center.

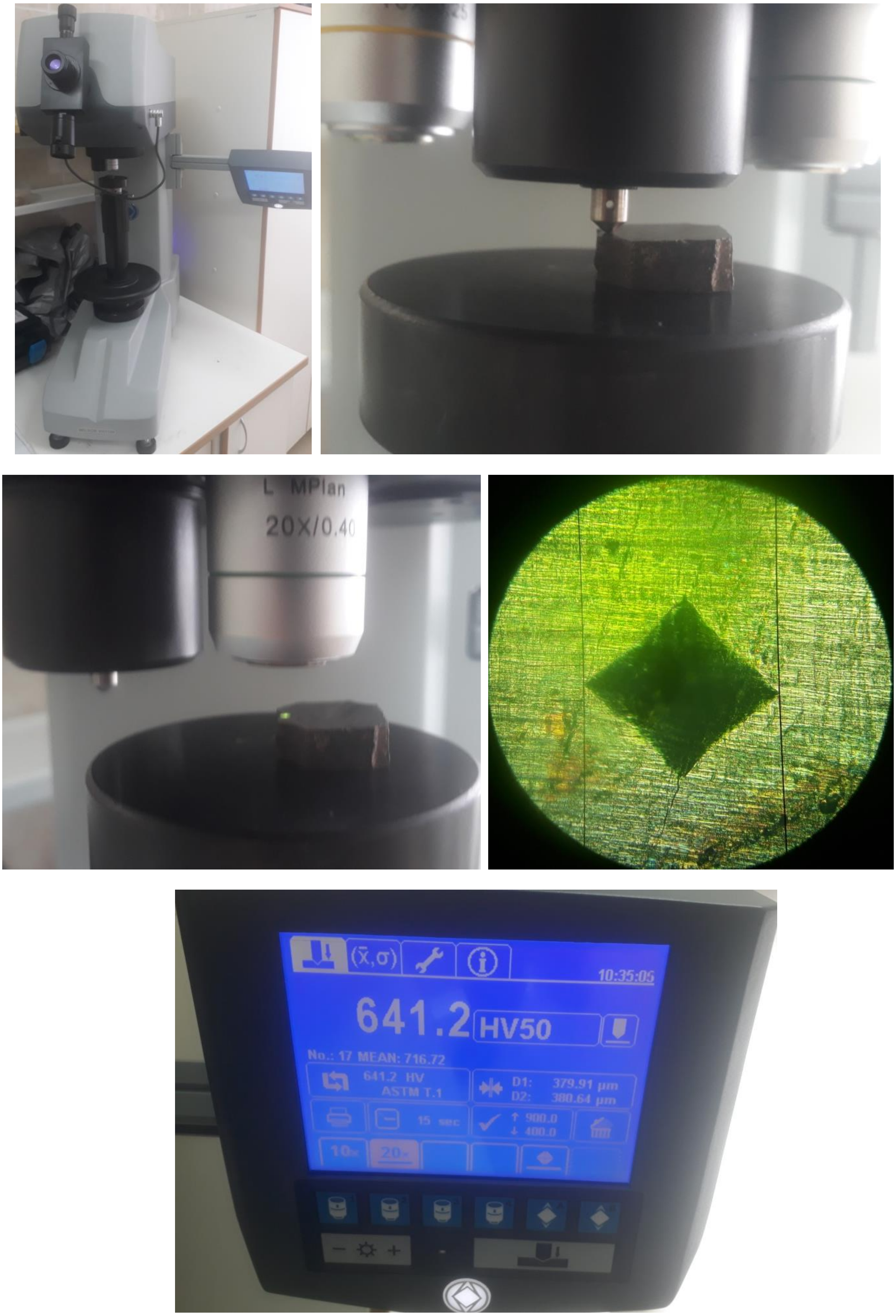


Fig.11 – Hardness measurement on macro Vickers hardness tester Wilson VH1150, BUEHLER (USA)

The results of measuring the hardness at the surface and in the center of the samples are shown in Table 3.

Table 3 – Average values of hardness at the surface and in the center of specimens of low-chromium cast iron modified by FSMg9, FB and FS60Ba22

No.	Type and amount of modifier used	HRC		HV_{50}		ΔHV_{50}, %	
		on the surface	in the center	on the surface	in the center	on the surface	in the center
	Chrome cast iron Cr ≈ 1,0 (basic, no modification)	49,5	48,9	506	497	0	0
1	*Chromium cast irons modified FSMg9*						
1.1	Chrome cast iron Cr ≈ 1,0 + FSMg9, Mg ≈ 0,04 %	45,4	40,9	451	402	-10,9	-19,1
1.2	Chrome cast iron Cr ≈ 1,0 + FSMg9, Mg ≈ 0,06 %	41,2	35,4	405	347	-20	-30,2
2	*Chromium cast irons modified with carbothermal ferroboron*						
2.1	Chrome cast iron Cr ≈ 1,0 + FB, B ≈ 0,006 %	56,6	56,5	628	626	+24,1	+26
2.2	Chrome cast iron Cr ≈ 1,0 + FB, B ≈ 0,02 %	52,5	54,3	553	586	+9,3	+17,9
3	*Chromium cast irons modified FS60Ba22*						
3.1	Chrome cast iron Cr ≈ 1,0 + FSBa, Ba ≈ 0,005 %	57,8	52,6	652	555	+28,8	+11,7
3.2	Chrome cast iron Cr ≈ 1,0 + FSBa, Ba ≈ 0,01 %	58,3	60,5	660	704	+30,4	+41,6

As can be seen from table 3, the highest hardness, about 58 HRC, is possessed by cast irons obtained with the addition of FS60Ba22 in an amount calculated for the residual content of the main modifying element, barium, about 0.01% by weight. Moreover, in these samples, the hardness of the central zone (60 HRC) is slightly higher than the same value at the surface.

Also, a fairly high hardness (56.5 HRC) was obtained in samples of cast iron treated with ferroboron based on the boron content in cast iron ~ 0.006%. This is about 25% higher than the hardness of the base unmodified cast iron with a chromium content of up to 1.0%. It should be noted here that the measured hardness at the surface of the samples and in their central part are practically equal, which may indicate the homogeneity of the structure over the section of the casting.

The hardness of the specimens modified by FSMg9 turned out, in general, lower than in the base alloy. The reason could be the transition of a significant part of magnesium to MgS sulfide due to the increased sulfur content in the initial charge.

3. Conclusion

Based on the data obtained, it can be indirectly assumed that low-chromium cast irons modified with ferroboron, ferrosilicobarium or their mixture will have the highest abrasive wear resistance of those considered.

The use of a magnesium modifier to improve wear-resistant properties requires careful preliminary preparation: desulfurization of cast iron, scrupulous calculation and selection of the gating system during in-mold modification, as well as measures to prevent pyroelectric effect during pouring.

In addition, to obtain a more complete assessment of the wear resistance of the modified cast irons obtained, it is necessary to conduct a laboratory study of cast samples for abrasion resistance in laboratory mills or on special testers for testing abrasion resistance. And to assess the impact resistance, testing of samples on impact copiers is required.

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Features of Selecting Design Parameters and Technological Modes of Combined Machining by Cutting and Surface Plastic Deformation

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Abstract: The article discusses combined machining by cutting and surface plastic deformation (SPD) with rollers, which allows solving the issue of ensuring high productivity for a given quality and low machining cost, however, there are problems in selecting the ratios of geometric parameters of rollers, cutting and deforming elements, as well as matching the machining parameters of two fundamentally different machining methods.

Keywords: surface plastic deformation (SPD), cutting, surface roughness, hardening, modulus of elasticity, deformation, stress, deforming roller.

1. Introduction

The required roughness of the surface when combining cutting and SPD machining PPD is provided by the deforming part of the tool. To determine the design and operational parameters of the rolling tool, the optimal technological modes and the expected quality of the machined surface, it is necessary to use mathematical models that describe the contact zone and its stress state. The most common method currently used to study and to optimize the parameters of the SPD process and the designed tools is the analytical-experimental one. It consists in the analytical determination of some parameters and the appointment of other parameters based on experimental data.

This is associated with the fact that SPD studies cause certain difficulties, since the formation of the surface layer is performed as a result of complex interrelated processes in the deformation zone and adjacent zones, multiple elastic and plastic deformations, changes in strength and plastic properties of the deformable material, friction and thermal processes, changes in the macro- and microstructure, microgeometry of the surface itself and other phenomena.

Controlling the technological factors of rolling that affect the surface roughness, hardening and force interaction with the part: the radial deformation force Py (or a given preload if machining is performed with a rigid tool), feed, the roller diameter, the roller radius, the rolling speed, surface roughness of the part, the number of deforming rollers in the tool, the number of strokes, etc.

The greatest effect on the quality parameters of the SPD part is exerted by the force acting on the treated surface from the side of the deformed element. Determining the functional relationship between the force acting on the tool and the quality parameters of parts is one of the main research tasks in the field of high speed machining.

Various authors offer a number of analytical relationships for calculating the deformation force. Due to the fact that the SPD treatment with rollers in the contact zone develops complex physical and mechanical processes that cannot be accurately estimated, in most cases they resort to experimental studies, on the basis of which the extensive factual material has been accumulated that is reasonable. The selection and the purpose provide rational machining modes that guarantee the required quality and productivity.

2. Research methods

An approximate calculation of the deformation force can be made based on a given work-hardening depth. The simplest and most accurate result is the dependence obtained by S.G. Heifetz [1]:

$$h_H = \sqrt{\frac{P}{2\sigma_m}}, \tag{1.1}$$

It is advisable to apply this dependence for small diameter (5 ... 30 mm) shafts and with relatively low forces on the roller (up to 11 kN). I.V. Kudryavtsev proposed to determine the deformation force corresponding to the maximum endurance limit depending on the diameter of the processed shaft [2]:

$$P = 50 + \frac{D^2}{6}, \tag{1.2}$$

where D is the diameter of the shaft being machined.

Yu.G. Proskuryakov proposes to use as the calculation formula the following dependence [3]:

$$P = \frac{D \cdot b \cdot q^2}{0{,}126 \cdot E \cdot \left(\frac{D}{d} + 1 \right)}, \quad (1.3)$$

where D is the shaft diameter;
b is the width of the roller contact with the part being machined;
q is the largest rolling pressure (approximately);
E is the elasticity modulus;
d is the roller diameter.

The disadvantage of these techniques is the absence of the data of selecting the optimal roller geometry, feed and number of passes. In work [4], V.M. Braslavsky proposes to determine the force when rolling parts with a roller in terms of the optimal value obtained by him for steel 20 corrected for the hardness of the material:

$$P = K_p \cdot P_{20}, \quad (1.4)$$

$$P_{20} = 0{,}324 \cdot \frac{b}{a} \left[\frac{1}{r} + \frac{1}{R} + \frac{b}{a} \left(\frac{2}{D_p} + \frac{2}{D_\partial} \right) \right]^{0,3} \cdot r^{2,3}, \quad (1.5)$$

where KP is the machinability coefficient selected depending on the material hardness of the par being machined, HV;
P20 is the running force for steel 20 with the roller indentation angle in the feed plane 2° 30';
b and a are dimensions of the contact patch;
Dp, r is the diameter and the radius of the roller profile;
Dд, R is the diameter and the radius of the generating part curvature.

The force found in this way will be acceptable in the sense of preventing undulation. The magnitude of the force, in order to avoid peeling of the rolled surface as a result of re-hardening, is recommended by Braslavsky to be limited by the value determined in the formula:

$$P = \frac{5{,}9 HB^{1,15} \frac{b}{a} \varphi^{2,3}}{\left[\frac{1}{r} + \frac{1}{R} + \frac{b}{a} \left(\frac{2}{D_p} + \frac{2}{D_\partial} \right) \right]^2}, \quad (1.6)$$

where HB is the part being machined hardness;
a and b are half-axes of the contact elliptic patch;
φ is the average indentation angle;
Dp, r is the diameter and the radius of the roller profile;
Dд, R is the diameter and the radius of the generating part curvature.

G.M. Azarevich and G.Sh. Bernstein [5] propose to determine the force using the correction coefficients:

$$P = P_0 \cdot k_{\alpha_0} \cdot k_{R_z} \cdot k_R \cdot k_S \cdot k_\sigma \cdot k_d \cdot k_D, \quad (1.7)$$

where kαo is the coefficient accounting the back angle of deformation effect;
k_{Rz} is the coefficient accounting original irregularities;
k_R is the coefficient accounting the roller profile radius;
k_S is the coefficient accounting feed;
k_σ is the coefficient accounting the material hardness;
k_d is the coefficient accounting the roller diameter;
k_D is the coefficient accounting the diameter of the part being machined.

P.G. Alekseyev [6] proposes for determining the deformation force the following formula:

$$P = \frac{7{,}65 \cdot n_H \cdot \sigma_T}{1 + \mu \cdot tg\varphi_н} \cdot \sqrt{\frac{R_q \cdot R_p \cdot R}{R_q \pm R_p}} \cdot \left((\Delta h + \varepsilon) + \sqrt{(\Delta h + \varepsilon) \cdot \varepsilon} \right), \quad (1.8)$$

where Rq is the part radius;
Rp is the roller radius;
R is the roller profile radius;
μ is the Poisson coefficient;
Δh is the reduction value;
σT is the yield limit;
nH is the coefficient accounting strain hardening;
ε is the local elastic deformation;
φн is the average indentation angle.

The dependence obtained by Yu.G. Schneider [7] has the form:

$$P = F_K \cdot q, \quad F_K = 2 \cdot \frac{4}{3} \cdot \frac{S}{R_{исх}} \sqrt{d_\omega} \cdot \sum_{i=2}^{n/2} \left[(R_{исх} - R) - \frac{S_1^2 \cdot (i-1)^2}{d_\varpi} \right]^{\frac{3}{2}}, \quad (1.9)$$

where Fк is the area of the contact patch;
q is the average pressure;
S1 is the original irregularities step;
dω is the ball diameter;
n is a constant characterizing the machined material properties.

Based on the analytical determining of the ratio between the forces acting on the front (plastic) and bach (elastic) zones of the contact area, O.S. Chernenko [8] established the connection between the force applied to the tool, average pressure and deformation in the contact zone:

$$P = 0{,}5 \cdot (1 - e) \cdot F \cdot q, \quad (1.10)$$

where F is the area of the contact hole projection to the plane;
q is the average pressure in the contact plastic zone;
e = Py / Pн.

M.M. Zhassimov in his book [9] gives a rather full review of works in the field of studying the mechanism and regularities of pressure, deformation and stress distribution with SPD and proposes to draw a conclusion of these factors effect on the surface quality with SPD machining. He proposes the method of determining the laws of distribution within a certain period of time before the shape and size of the contact surface. In the solution there is used the method of variable parameters of elasticity without taking into account changing the contact patch shape due to feed and overlapping the traces of the deformed material. Zhassimov describes the contact pressure by the following formula:

$$p(x, y) = \frac{3}{2} \frac{P}{F} \sqrt{1 - \frac{x^2}{a^2} - \frac{y^2}{b^2}} \cdot N_1, \quad (1.11)$$

$$N_1 = \frac{1}{\psi} + \left(1 - \frac{1}{\psi}\right) \cdot \frac{3\lambda + 2\mu}{3(\lambda + \mu)}, \quad (1.12)$$

where P is the deformation force;
F is the contact area;
b and a are the dimensions of the contact patch;
N1 is the coefficient accounting plastic deformations increasing;

ψ is the parameter of plasticity equal to $\psi = 3G\frac{\varepsilon_i}{\sigma_i}$;

G, μ is the elasticity modulus of the 2nd kind;

σ_i , ε_i are the intensities of stresses and deformations;

λ is aspect ratio;

ν is the Poisson coefficient;

E is the elasticity modulus of the 1st kind.

When machining by plastic deformation of a surface, the pressure formed in the contact zone is one of the most important parameters affecting the quality of machining. It is assigned depending on the yield limit of the material being processed using the coupling factor. Depending on the conditions of deformation, this coefficient has the value of 1...10.

Ya.N. Oteni [10], based on theoretical studies of the geometric relationships of the contact zone during machining with rollers of any size, configuration and position in relation to the part, depending on the design and technological machining parameters, as well as theoretical studies of the plastic flow of metal in the deformation zone, gives the dependence of stress states in the contact zone on the movement of points of the deformable surface:

$$\sigma_{н} = \frac{\sigma_m}{m^m} \cdot \varepsilon_y^n \cdot (1 + 1{,}4 \cdot \varepsilon_y^{0,6} + C_y), \qquad (1.13)$$

where ε_y is the part surface deformation,

$\sigma_т$ is the yield limit;

$\sigma_в$ is the strength limit,

C_y is the coefficient of restitution (Cy = 0.3...0.45);

m is calculated by the formula:

$$m = \ln\left|\frac{\sigma_m}{\sigma_в}\right|, \qquad (1.14)$$

Using these formulas, the author obtained the formulas for determining normal Py and tangent Px forces of deformation.

The method proposed by S.N. Olshtyski [11], is the best to take into account the effect of various factors on the deformation force.

$$P_{yp} = \int_0^{L_к}\int_0^{z_{кv}} \sigma_m \cdot f(l) \cdot \sqrt{1 - \left(\frac{z}{z_{кv}}\right)^2}\, dz dl_к, \qquad (1.15)$$

where f(l) is the dominant function dependent on the roller type and the contact zone shape; for a drop-shaped zone it is determined for the incorporation zone and the roller taper by the formulas:

$$f_{кз}(l) = \sqrt{1 - \left(\frac{0{,}5 \cdot L_{к1} - l_{к1}}{0{,}5 \cdot L_{к1}}\right)^2}; \quad f_{кс} = \frac{K \cdot \sigma_м}{h_м} \cdot \left(L_{к2} - l_{к2}\right) \cdot tg\alpha, \qquad (1.16)$$

where Lк is the contact zone length;

K and $\sigma_м$ are the coefficient and the maximum stress which values are to be determined experimentally.

Characteristics of the technological process of hardening and the mechanics of deformation of the surface layer were determined by the method of P.A. Chepy [12]. Its essence is reduced to the preliminary experimental finding of the optimal value of the deformation force under other accepted machining conditions according to the of the parameter M equality to the unit determined by formula (1.17).

$$M = \frac{h_s}{h} \cdot \frac{r + r_2}{r \cdot r_2}, \qquad (1.17)$$

where h_s and h are residual wave height and the roller incorporation depth;
r and r_2 are the radiuses of the deforming roller curvature.

Despite a lot of methods in the production conditions, the force or tension value is determined in the experimental conditions.

In addition to the deformation force, the machining quality, though in a lower degree, is affected by the amount of elastic-plastic loads N that are exerted by the deforming roller and are determined by the formula [13]:

$$N = nK_n^2 z^2 \frac{l}{S}, \qquad (1.18)$$

where Kn is the planetary coefficient;
l is the plastic imprint length;
S is the roller axial feed;
z is the rollers number.

The contact area with SPD with rollers has a significant effect on the deformation process during machining, since specific pressure can vary significantly with the same force but with different contact areas. Consequently, the deformation force can be assigned based on pressure to be provided and the contact area determined by the geometric parameters of the roller, the part and their relative position. In this area, various authors have obtained a number of dependencies: (1.19) [9], (1.20) [11], (1.21) [14]:

$$F_к = \frac{\pi}{4}\sqrt{\frac{R_д R_p}{R_д + R_p}}\left(i^{0,5} + \delta^{0,5}\right)\left[\sqrt{(r - 0,25i)i} + \frac{\delta_y}{4tg\alpha}\right], \qquad (1.19)$$

$$F_K = 2 \cdot \frac{4}{3} \cdot \frac{S}{R_{исх}}\sqrt{d_\varpi} \cdot \sum_{i=2}^{n/2}\left[(R_{исх} - R) - \frac{S_i^2 \cdot (i-1)^2}{d_\varpi}\right]^{\frac{3}{2}}, \qquad (1.20)$$

$$F = 1,05d\sqrt{\frac{2l_{\max} R_p R_д}{R_p + R_д}}\left(1 + 0,35\sqrt{\frac{R_p + R_д}{R_д}}\right), \qquad (1.21)$$

However, when there are proposed the formulas for determining the contact area, it is not clear what geometrical parameters they have.

To determine the parameters of the drop-shaped contact, E.G. Konovalov and V.A. Sidorenko used the following dependences [15]:

$$r_1 = \frac{1}{2} \cdot \sqrt{2 \cdot R_1 \cdot i - i^2}, \quad \beta = \frac{1}{2} \cdot arctg \cdot \frac{\sqrt{2 \cdot R_1 \cdot i - i^2}}{i \cdot ctg\alpha}, \qquad (1.22)$$

where r_1 is the contact radius in the incorporation zone;
R_1 is the radius of rounding;
i is tension;
β is the angle at the roller taper top.

To determine the deformation force according to the law of contact pressure distribution, there is required the equation for the contact contour line. Ya.N. Oteni [11] proposes the following dependence in the form of the contact half-width:

$$z_к = \sqrt{R^2 - \left[\frac{(R \pm r_p) \cdot (R \mp h_к)}{R \pm (r_p \mp h_к)}\right]^2}, \qquad (1.23)$$

where h_k is the upper sign corresponds to the shaft machining, and the lower one to the hole machining;
R is the shaft (hole) radius;
$r_к$ is changing the roller radius and the incorporation depth along the contact length.

The contact area is determined by Ya.N. Oteni on this basis by the formula [11]:

$$S_k = \int_0^{L_k} \sqrt{R^2 - \left[\frac{(R \pm r_p)\cdot(R \mp h_k)}{R \pm (r_p \mp h_k)} \right]^2} dx, \qquad (1.24)$$

The disadvantage of this method is that it does not take into account the self-tightening angle, which is acceptable when machining large shafts. However, given the range of diameters from 10 to 35 mm, such an approximate solution is not completely satisfactory, since it leads to overestimated values of the contact pressure in the calculations. Processing performance is determined by speed parameters, which include the machining speed and feed. The rolling feed is selected either according to the graphs drawn up based on the results of experiments, or according to formulas that take into account only geometric relationships: (1.25), (1.26), (1.27), (1.28):

$$S_p = H(ctg\alpha - ctg\gamma) \qquad (1.25)$$

$$S_{расч} \approx 2{,}87\sqrt{rR_z} \qquad (1.26)$$

$$R = r - \sqrt{r - \left(\frac{S}{r}\right)^2}, \qquad (1.27)$$

$$S_p = 0{,}75R_z(ctg\alpha + ctg\gamma), \qquad (1.28)$$

where Spacч, Sp , S is feed;
Rz, H, R is the irregularities height;
r is the roller profile radius;
γ and α are the front and the back deformation angles.

When cutting, the feed speed should be selected based on the following considerations. It is known that the surface cleanliness increases by 4...5 classes with SPD with tapered rollers [16]. Therefore, after correcting the value of the final roughness obtained after rolling, it is necessary to set approximately the roughness after cutting, and then along it and the feed during cutting. In this case, it is necessary to take into account the number of cutting and deforming elements in the tool design based on the relationship [17]:

$$s_p z_p n_p = s_д z_д n_д, \qquad (1.29)$$

where sp and sд is the feed per one cutting and deforming element, mm/f and mm/l;
zp and zд is the number of cutting and deforming elements on the combined tool;
np and nд the number of rotations per minute of cutting and deforming element around the tool axis.

The calculated feed for a prismatic cutter with the radius cutting edge can be determined by the formula [11]:

$$s_p = 2\sqrt{2h_p r}, \qquad (1.30)$$

where h_p is the height of micro-combs obtained after cutting;
r is the radius of the cutter cutting edge.

In case of using rotational cutters the feed can be calculated from the dependences:

$$R_{zpрас} = R_p - \frac{\sqrt{4R_p^2 Cos^2\lambda - s_z^2}}{2Cos\lambda}, \qquad (1.31)$$

$$R_z^m = \frac{s_z^2 Sin\beta}{4dCos^2\omega}, \quad (1.32)$$

where Rzрасч and Rzт are calculated heights of micro-irregularities;
Rp and d are the cutter radius and diameter;
λ, β and ω are the angles of the cutter setting relative to the part being machined.

For rotation cutting, the standards of determining the cutting conditions have not yet been sufficiently developed but there are, for example, experimental dependences obtained for certain steels. For example, for steel 2X13 they have form (1.35) [37], and for steel 35 (1.38) [18].

$$P_x = 97\frac{t^{0,37}s^{0,51}}{V^{0,43}}, \quad (1.33)$$

$$P_y = 1000\frac{t^{0,65}s^{0,51}}{V^{0,3}}, \quad (1.34)$$

$$P_z = 1100\frac{t^{0,95}s^{0,41}}{V^{0,38}}, \quad (1.35)$$

$$P_x = 780...805\frac{t^{0,29}s^{0,42}}{V^{0,41}}, \quad (1.36)$$

$$P_y = 920...945\frac{t^{0,51}s^{0,21}}{V^{0,41}}, \quad (1.37)$$

$$P_z = 960...985\frac{t^{0,83}s^{0,37}}{V^{0,49}}, \quad (1.38)$$

To determine the height of microroughness in the case of pressure maintenance, a number of authors obtained dependences connecting the feed rates, the radius of the roller curvature, the initial height of the roughness, specific pressure, the profile radius of the roller, and elastic deformation. So, for example, D.D. Papshev [13] proposed the following dependence for determining the height of microroughness:

$$R_Z = \frac{S_0^2}{8 \cdot R} \cdot \left(1 - \frac{k-1}{k}\right) \cdot k_\xi \cdot k_p, \quad (1.39)$$

where k is the coefficient characterizing the material radius increasing;
kξ is the coefficient accounting the material plastic properties;
kp is the coefficient accounting pressure on the contact area.

In the calculation formula proposed by V.M. Braslavski [4], the Rz value is associated with the feed value and the deforming element curvature:

$$R_Z = R_{pr} - \frac{\sqrt{4 \cdot R_{pr}^2 - S_0^2}}{2}, \quad (1.40)$$

where Rz is the microroughness height;
Rpr is the roller curvature radius;
So is feed.

An important role in selecting feed belongs to the back angle α, that is recommended, for achieving stable surface cleanliness (up to Ra=0.16 μm), especially for thin-wall and unequally rigid parts, to be set within the range of 0°36'…1° [17].

3. Conclusions

The dimensions of the deforming roller are recommended by a lot of authors as a small diameter, since this allows reducing the deformation force. However, their smallest dimensions are limited by the condition that the roller does not slip in the contact areas with the support cone and the part (with the part diameter of 4...50 mm the roller diameter is at least 5 mm) [2]. According to numerous studies, the rate of deformation has no significant effect on the roughness of the machined surface. The limitation consists in the capabilities of the technological equipment used, as well as in the increased heating and wear of the deforming tool. The value of the rolling speed is assigned according to experimental tests no more than 200...300 m/min.

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Theoretical aspects of corrosion and thermal destruction of metallic materials

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Abstract. A huge amount of work has been devoted to metal corrosion, but despite this, work in the field of the theory of corrosion continues to grow with an increase in the variety of structural metallic materials used in various areas of industrial production. In the most general case, metal corrosion can be represented as the nucleation and growth of a new phase (oxidized metal). It is this approach that we used in this work when discussing the theoretical aspects of metal corrosion, on the basis of which a method for determining thermoelastic stresses in a coating was proposed; a statistical model for the formation of frustron clusters has been developed; formulas are obtained for calculating the equilibrium number of frustrons in a cluster and for a qualitative analysis of the rate of destruction of metal and coatings under deformation and thermal effects.

Keywords: Corrosion, growth of a new phase, Markov processes, statistical model.

1. Introduction

The destruction of metals during the supply of thermal energy is accompanied by the accumulation of thermoelastic stresses, leading to an increase in the density of dislocations, various defects (dilatons, frustrons, etc.).

Most naturally occurring mechanical systems with the free movement of scatter ordered kinetic energy of its motion and make it a random thermal motion of molecules. Such systems are usually called dissipative systems. Sometimes the flow of energy supplied to the system can reach such intensity that the old dissipation mechanism can no longer cope with it. The system is threatened with destruction. Then it can make an internal restructuring of its elements in such a way that the process of energy dissipation would go more intensively. Such internal rearrangement occurs during phase transitions in the bulk of metals and alloys [1], at grain boundaries [2], on the surface [3]. Based on the theory of phase transitions, an attempt was made to combine various mechanisms of destruction processes [4]. The monograph [5] proposes a different mechanism for the destruction of solids, which is not associated with the presence of defects in their initial state.

In all cases of the transition of various systems to a new stable state, a parameter is clearly distinguished. Exceeding the critical value of this parameter leads to the formation of dissipative structures and the inclusion of a new mechanism of energy dissipation of the system [6]. Dislocation concentration is a parameter that controls the behavior of metallic materials under heating and load. Plastic deformation begins at the moment when there are so many dislocations that the distance between them decreases to a critical value, below which they begin to actively interact with each other.

The problem of thermoelasticity in a quasi-static formulation, when the inertial terms in the equations of motion and the connecting term in the heat conduction equation are not taken into account, is of greatest practical importance. The dynamic effects due to unsteady heating and heat fluxes resulting from deformation are so small that the corresponding terms in the equations can be discarded, and the system of equations decomposes into the usual equation of unsteady heat conduction and equations describing the problem of thermoelastic stresses at a given temperature field.

The theory of thermoelasticity of thin plates, and in our case of coatings, like the corresponding isothermal theory, is based on the hypothesis of invariability of a normal element and on the assumption of a two-dimensional stress state, similar to a plane stress state. The most complete issues of thermoelasticity of thin plates are presented in the work [7].

2. Markov processes and kinetics of formation of new phase nuclei

A critical nucleus of a new phase is formed sequentially in a series of random acts of attachment and detachment of atoms (molecules) from each other. Therefore, nucleation is a random process in time and space. This determines the probabilistic nature of the parameters which describe the kinetics of nucleation during crystal growth or corrosion [8].

A quantitative description of a random process is given by its distribution function, which satisfies the kinetic equation. In general, the kinetic equation is a complex integro-differential equation that cannot be solved. However, if we consider a random process as a Markov, then the kinetic equation transforms into a differential equation, which has a simpler form [9].

In the particular case of the Poisson process of death and reproduction with a finite number of states, a system of differential equations is obtained:

$$\begin{cases} dp_0(t)/dt = -\lambda_0 p_0(t)\mu_1 p_1(t), \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ dp_к(t)/dt = \lambda_{к-1} p_{к-1} - (\lambda_к + \mu_к) p_к(t) + \mu_{к+1}\, p_{к+1}(t) \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ dp_n(t)/dt = \lambda_{n-1} p_{n-1}(t). \end{cases}, \quad (1)$$

Here λ_0 – probability of system transition from state E_0 to E_1 and etc.; μ_1 - the probability of transition from state E_1 to E_0 and etc. The probability of transition from E_n to E_{n-1} relies on zero $(\mu_n = 0)$, that is, the state E_n for such a system is absorbing; $p_i(t)$ - the probability of finding the system in a state E_i. The system of equations (1) is the system of Kolmogorov equations [10]. The general solution is so cumbersome that it does not allow analysis even by numerical methods.

The above example shows that most researchers follow the path of solving diffusion-type equations, the mathematical theory of which has been developed quite fully and which describe the process of random (Brownian) walks, as well as the theory of reliability, order statistics, mass service and a number of others.

The main kinetic equations following from the Kolmogorov differential equations for random Markov processes include the Smoluchowski-Chapman and Fokker-Planck equations. In the case of a multidimensional state vector, the Fokker-Planck equation has the form [11]:

$$\frac{\partial f}{\partial t} = -\sum_j \frac{\partial}{\partial q_j}\left[K_j f\right] + \frac{1}{2}\sum_{j,к} Q_{jк} \frac{\partial^2}{\partial q_j \partial q_к} f \cdot \quad (2)$$

It is possible to obtain an explicit solution to equation (2) only in special cases, for example, if the quantity K is linear in the q variables and the quantity Q_{jk} does not depend on q.Equation (2) plays an important role in the nonstationary theory of neutron moderation [86], but its linearization leads to the fact that its solution is reduced to finding the corresponding Green's function for various boundary conditions.

To solve stochastic differential equations of diffusion type, which also include equations (1) and (2), several approaches have been developed, of which it is necessary to note the approaches of Itô and Stratonovich. Solving the Langevin-type stochastic equations written for the Markov process $y(t)$, one can find the corresponding unsteady or stationary moments and correlators, simultaneous or multi-time stochastic Ito equations:

$$\dot{y}_\alpha = f_\alpha(y) + \sum_S \sigma_\alpha^{(s)}(y)\xi^{(s)}(t), \quad (3)$$

where $\xi^{(s)}(t)$ - time-delta-correlated random functions have the disadvantage that the expressions of the type $\sigma(y)\xi(t)$ included in it cannot be treated according to the usual rules suitable for smooth functions for various calculations. This circumstance is inconvenient from a practical point of view. The usual transformation rules can be applied to the stochastic Stratonovich equation:

$$\dot{y}_\alpha = q_\alpha(y) + \sum_S q_\alpha^{(s)}(y)\xi^{(s)}(t), \quad (4)$$

written in the symmetrized sense. In this case, equation (4) is understood as follows: first, we write it down for the δ_ε -correlated approximation of the processes $\xi^{(s)}(t)$, and then in this equation we pass to the limit $\varepsilon \to 0$, which gives us the equation(3).

Note that both approaches have not yet found their implementation in the theory of the nucleation of a new phase and, in particular, in the theory of corrosion. For example, in [12] it is said that "the study of the formation of a new phase led to the creation of a general method for describing the kinetics of a first-order phase transition, in which the growth of a macroscopic nucleus of a stable phase is usually reduced to solving the one-dimensional Fokker-Planck equation.

From the above, we note the following:

- the formal probabilistic nature of the description of the new phase process as a random Markov stationary or non-stationary Poisson process requires a more rigorous justification, since a number of assumptions (absence of aftereffect, ordinariness, etc.) do not follow from the physical picture of the corrosion phenomenon;

- since it is not the distribution functions themselves, but their moments and correlators, that are experimentally observable (as in the quantum theory), it is advisable to analyze the statistical regularities of the initial stage of corrosion using the approach [13].

3. Fractals and the diffusion-constrained aggregation model

Evaluation of the durability of equipment in corrosive environments actually boils down to determining the corrosion rate of the metal from which it is made, and calculating the service life by dividing the margin of wall thickness by the corrosion rate. This approach allows you to correctly predict the life of the equipment in case of uniform (general, continuous) corrosion of its elements. However, uniform corrosion is observed in about 30% of all cases of equipment failure, and the concept of uniform is conditional, since in real conditions unevenness always exists.

More than 20 years ago, researchers were attracted by the irreversible combining of particles into clusters - a task similar to the one we noted above. It became clear that it is clustering that is one of the ways for fractals to appear in irreversible processes.

Witten and Sander proposed a model of this kind - the diffusion-limited aggregation (DLA) model, which has become the subject of intensive research. The model is very simple: particles making a random walk as a result of accretion (attachment) form a cluster, arriving one at a time from a distance and joining either a point clustering center or previously accreted particles. Intensive computer studies have shown that as a result of this process, complex branched fractals are formed. In [13], three dynamic modes are identified: 1) a mode close to equilibrium; 2) formation of structures and 3) chaotic regime. In this case, the diffusion of latent heat released during oxidation is identified with the motion of randomly wandering particles to the cluster. The most famous experimental example of DLA is the electrolytic deposition of metals on a small electrode. The average crystallite growth is described using a stationary diffusion equation for the ion density $U(\vec{r},\ t)$ with absorbing boundary conditions:

$$\nabla U(\vec{r}, t) = 0\,. \tag{5}$$

supplemented by growth conditions at the border

$$\vec{v}_n \sim n\nabla U/S\,, \tag{6}$$

where $\vec{V}_n$ - normal growth rate of a particle at the boundary.

Using the value $\vec{V}_n$, given by relation (14), it was possible to show by numerical simulation that the above process is equivalent to DLA. Later Sander proposed a continuous DLA. Instead of equations (5) - (7), it was proposed to formulate the problem in terms of the motion of the interface, fed by randomly wandering particles, and to rewrite the equations in the form:

$$\begin{gathered} \nabla^2 U = 0\,. \\ \vec{v}_n = -n\nabla U\,|\,S/4\pi\,. \\ U(R_0) = 0\,, \end{gathered} \tag{7}$$

At a large distance R_0 the U field is maintained equal to zero; within the area bounded by the interface, it is equal to one; æ(X_s) means the curvature of the interface at the point X_s; $\vec{V}_n$ - normal speed of the interface.

The cutoff shape corresponds to the problem of viscous fingers, but its suitability within the DLA model is questionable, since the boundary condition in the numerical modeling based on DOA includes only cutoff at a small distance corresponding to the particle size. But some kind of circumcision is necessary - otherwise non-physical conditions will arise. It is difficult to solve equations (3.8) by direct methods. However, it was later shown that a more efficient solution can be achieved by passing to the integro-differential equation:

$$1 + (4\pi)^{-1}\int dX_{S'}\, æ(X_{S'})\partial G(X_S, X_{S'})/\partial n' = \int dX_{S'} G(X_S, X_{S'})\vartheta(X_{S'})\,, \tag{8}$$

where $G(x, y)$ – Green's function for the two-dimensional Laplace equation. The integral on the left-hand side of equation (8) is the potential of the double layer of the quantity – æ/4π which creates a jump in the field from 1 to 1-æ(Xs at the interface. Solving (8) numerically, one can obtain fractal structures.

in recent years, in theoretical terms, there have been no significant changes in the DLA. We now note the following circumstances: the DOA model does not go beyond the framework of the theory of Markov processes, which we talked about above, especially since Markov branching processes, in principle, describe complex branching structures; DLA equations (5) - (8) are inapplicable to the initial stage of aggregation due to uncertainty in determining the surface of "one" or "two" particles, etc. and its curvature, as well as because of the "strong" nonstationarity of the initial aggregation process; there are serious objections to the boundary conditions that do not follow directly from the physical picture of the phenomenon.

Thus, fractal models, including DLA, are not very suitable for describing the initial stage of corrosion. However, they are very useful for modeling many subsequent stages of metal corrosion.

4. Statistical model of corrosion stain formation

The most common case of metal corrosion is its interaction with oxygen molecules. Obviously, this interaction begins with "weak" areas of the metal surface or with its defects. We will present a model of the formation of a corrosion spot from the standpoint of statistical physics.

Consider a metal surface with a number of defects m. Let the distance between defects be the same and equal to R. We describe around each defect 0 a circle with radius R. Let the density of the number of particles in this circle be n_0, then the probability $W_0(r)$ that the nearest oxygen particle will fall at a distance r from particle 0 can be easily obtained on the basis of statistical physics and is equal to:

$$W_0(r) = \pi n_0 r^2 \exp[-\pi n_0 r^2]. \tag{9}$$

The probability of finding N_0 oxygen particles in the zone of defect 0 with radius r is, obviously,

$$W_{N_0}(r) = \prod_{k=1}^{N_0} W_k(r) = (\pi n_0)^{N_0} r^{2N_0} \exp[-\pi N_0 n_0 r^2]. \tag{10}$$

On the other hand, we define the probability (3.11) as the ratio of the number of particles N_0 in the defect zone to the total number of particles in the selected circle - Q_0:

$$p_0 = \frac{N_0}{Q_0} = (\pi n_0)^{N_0} r^{2N_0} \exp[-\pi n_0 r^2]. \tag{11}$$

For a system of m defects, we have:

$$\begin{aligned}
p_0 &= (\pi n_0)^{N_0} r^{2N_0} \exp[-\pi N_0 n_0 r^2] = \frac{N_0}{Q_0},\\
p_1 &= (\pi n_1)^{N_1} r^{2N_1} \exp[-\pi N_1 n_1 r^2] = \frac{N_1}{Q_1},\\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\
p_m &= (\pi n_m)^{N_m} r^{2N_m} \exp[-\pi N_m n_m r^2] = \frac{N_m}{Q_m}.
\end{aligned} \tag{12}$$

For the entire metal with the number of defects 0,1,2,,,m we have:

$$P = \prod_{i=0}^{m} p_i = \prod_{i=0}^{m} (\pi n_i)^{N_i} r^{2N_i} \exp[-\pi N_i n_i r^2] = \frac{\prod_{i=0}^{m} N_i}{\prod_{i=0}^{m} Q_i}. \tag{13}$$

The system of equations (13) and (14) is a system of transcendental equations, which can be solved only by approximate or numerical methods.

In this regard, it is possible to make a numerical estimate based on the real situation and equation 1 of the system (13):

$$\ln N_0 - \ln Q_0 = N_0 \ln(\pi n_0) + 2N_0 \ln r - \pi N_0 n_0 r^2.$$

The corresponding estimate gives that the first term on the left side of the equation and the first two terms on the right side are negligible. As a result, we get:

$$N_0 = \frac{\ln Q_0}{\pi n_0 r^2}. \tag{14}$$

Taking into account that $\pi r^2=S$ - areas of the corrosion spot and n_0N_0=const, from (3.15) we have:

$$S = \cos t \cdot \ln Q \tag{15}$$

The last expression shows the logarithmic dependence of the area of the corrosion spot on the "defectiveness" of the metal surface.

5. Statistical model of brittle fracture carriers clustering

Consider a crystal with the number of frustrons m. Let the distance between frustrons be the same and equal to R. We describe around each frustron 0 a sphere of radius R. Let the density of the number of frustrons in this sphere be n_0, then the probability $W_0(r)$ that the nearest frustron is at a distance r from frustron 0 can be easily obtained from classical statistical physics and is equal to:

$$W_0(r) = 4\pi n_0 r^3 \exp[-4\pi n_0 r^3 / 3]. \tag{16}$$

The probability of finding N_0 frustrons in the frustron zone 0 of radius r is obviously,

$$W_{N_0}(r) = \prod_{k=1}^{N_0} W_k(r) = (4\pi n_0)^{N_0} r^{3N_0} \exp[-4\pi N_0 n_0 r^3 / 3]. \tag{17}$$

On the other hand, we define probability (17) as the ratio of the number of frustrons N_0 in the frustron zone to the total number of frustrons in the selected sphere - $Q_0 = 4/3\ \pi n_0 R^3$:

$$p_0 = \frac{N_0}{Q_0} = (4\pi n_0)^{N_0} r^{3N_0} \exp[-4\pi n_0 r^3 / 3]. \tag{18}$$

Carrying out further calculations, we obtain:

$$N_0 = \left(\frac{1}{c} \cdot \frac{\ln n_0}{n_0} \cdot \frac{G^0}{kT} \right)^{1/2}. \tag{19}$$

Formula (19) corresponds to the equilibrium value of the number of frustrons in the cluster. Let us estimate the number of frustons in a cluster for a KCl crystal: $G^0 \approx 410$ kJ / mol; $c \approx 0{,}001$; $\ln n_0/n_0 \approx 0{,}02$; $k=1{,}38 \cdot 10^{-23}$, T=300 K. Then $N_0 \approx 60$ alkali metal atoms. The value obtained by us correlates with the number of atoms N_0 in a cluster during homogeneous cluster formation in melts of various metal.

The resulting formula (19) describes the entire region of the deformed state of a solid, including the fracture process.

6. Conclusions

Based on the analysis of the current state of the theory of fracture, corrosion, thermal and deformation loading of metals and coatings, as well as on the basis of the proposed models, the following conclusions can be drawn:

- in the most general case, metal corrosion can be represented as the nucleation and growth of a new phase (oxidized metal). It is this approach that we used in this work when discussing the theoretical aspects of metal corrosion;
- the formal probabilistic nature of the description of the new phase process as a random Markov stationary or non-stationary Poisson process requires a more rigorous justification, since a number of assumptions (absence of aftereffect, ordinariness, etc.) do not follow from the physical picture of the corrosion phenomenon;
- since it is not the distribution functions themselves that are experimentally observable (as in the quantum theory), but their moments and correlators, it is advisable to analyze the statistical regularities of the initial stage of corrosion using the approach of Stratonovich R.L.;
- fractal models, including DLA, are not very suitable for describing the initial stage of corrosion. However, they are very useful for modeling many subsequent stages of metal corrosion;
- on the basis of a statistical approach to the formation of a corrosion spot, an expression is obtained that shows the logarithmic dependence of the area of a corrosion spot on the "defectiveness" of the metal or coating surface;

- based on nonequilibrium quantum statistical thermodynamics, a formula is obtained for the response function of a system of defects (corrosion centers) to an external field;
- the fragile fracture mechanism is provided by clustering frustrons into the supercritical fracture center. In viscous materials, where the opposite condition is realized, fracture proceeds according to the dilaton mechanism inherent in inhomogeneous materials, where the presence of stress concentrators leads to the ultimate strength, the value of which is much lower than the theoretical limit;
- the theory of thermoelasticity of thin plates, and in our case of coatings, like the corresponding isothermal theory, is based on the hypothesis of the invariability of a normal element and on the assumption of a two-dimensional stress state, similar to a plane stress state;
- a method for determining thermoelastic stresses in a coating based on experimental values of microhardness measured along and across the sample is proposed;
- a statistical model of the formation of clusters of frustrons is proposed and a formula for the equilibrium number of frustrons in a cluster is obtained;
- the kinetics of clustering of brittle fracture carriers is considered and a formula is obtained that describes the entire region of the deformed state of a solid, including the fracture process;
- a formula was obtained that is suitable for qualitative analysis and prediction of the rate of destruction of metal and coatings under deformation and thermal effects.

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Analyzing Reliability Problems of High-speed Metal-cutting Machine Tools at Machine-building Enterprises

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Abstract. At present the development of machine-tool building is characterized by high rates of growth in the output of products achieved as a result of specialization of production and a high level of its automation. In recent years, there have taken place serious qualitative changes caused by the replacement of outdated designs that are characterized by low weight and a higher degree of wear resistance of the materials used. In the periodical literature, a large number of articles have been published in which the results of studying individual parts of high-speed machines are presented. In most cases, the available research results from one manufacturer cannot be used to analyze machines from another manufacturer. In addition, studying the work of one part is considered in isolation from its interaction with other parts. It should also be noted that various issues of reliability of mechanisms are considered with different depth and completeness. All this makes it difficult to synthesize highly reliable designs of machine tool mechanisms at the stage of experimental debugging and adjustment in production.

Keywords: machine tool reliability, theory of reliability, assessment of reliability indicators.

1. Introduction

Features and trends in the development of updated designs of high-speed machine tools are fully determined by the requirements to the types of activities for which these machines were developed; these requirements are reduced to ensuring maximum productivity with the minimum cost of work performed and low repair costs.

The development of machine-tool building is characterized by high rates of growth in the output of products achieved as a result of specialization of production and a high level of its automation. In recent years, there have taken place serious qualitative changes caused by the replacement of outdated structures that are characterized by a low weight and a higher degree of wear resistance of the materials used.

Improving machine tools, in particular their design, increasing speed, improving the quality of manufacture and the use of more durable and wear-resistant materials remain the main trend of the development.

However, increasing the level of forcing, negatively affects reliability of the machines. To ensure reliability, it is necessary to improve designs by increasing strength and wear resistance of the main parts and interfaces. This problem can be successfully solved only on the basis of deep studying the actual operating conditions of the machine tools main elements, loads, real characteristics of the materials used, etc.

In a fully mastered and manufactured design of the machine, reliability should be determined only by natural wear and tear of the main interfaces. Breakdowns of parts within the motor resource due to wear of the main fits should not take place.

The main task of ensuring reliability of equipment in the manufacturing process should be considered the output of products with reliability indicators that meet the requirements of design normative and technical documentation. Such indicators of their operational properties as wear resistance, strength, corrosion resistance, and some others should be considered as criteria of their working state [1].

2. Results and discussion

In the periodical literature, a large number of articles have been published in which the results of studying individual parts of high-speed machines are presented. In most cases, the available research results from one manufacturer cannot be used to analyze machines from another manufacturer. In addition, studying the work of one part is considered in isolation from its interaction with other parts. It should also be noted that various issues of reliability of mechanisms are considered with different depth and completeness. All this makes it difficult to synthesize highly reliable designs of machine tool mechanisms at the stage of experimental debugging and adjustment in production.

The reliability characteristics can be most fully and objectively determined as a result of experimental testing, which makes it possible to assess the effect of all external conditions and acting loads. In this case, the following sources of information are used (Fig. 1).

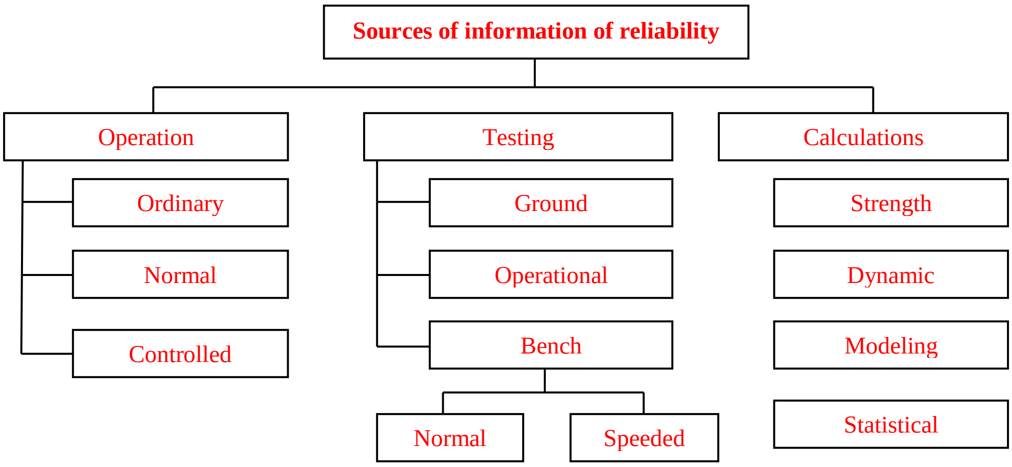

Fig. 1. – Sources of data for determining the information of reliability

In the general case, methods of statistical processing of information of random variables (sudden failures are determined by random unfavorable combinations of several factors) can be divided into separate groups.

The first group of methods includes the simplest calculations of the average values of the operating time between any events, if the total operating time of all controlled items and the number of events under consideration (failures, repairs, maintenance measures, etc.) for the period of observations are known [2].

The second group includes methods of calculating the average value of any measurable feature x, if the values of this feature are known for several observed objects. In this case, the assessment of reliability and accuracy of calculating the average value should be obtained for making a decision on the possibility of extending the obtained result to any object of the type under consideration.

The third, most complicated group includes methods of finding the probability distribution of random variables, which is necessary to estimate the mean time to failure if only a part of the products failed during the observation period, as well as to calculate the gamma-percentage resources or the probability of reaching the limit state.

From the practical point of view, the assessment of the reliability indicators of any type of machine tools is always made according to the finite limited sample, therefore, the resulting value of the indicator is a random value, the more deviating from the general value, the smaller the sample size. In this regard, it is necessary to indicate the confidence limits for the found value of the reliability indicator.

Observations carried out in various branches of the domestic mechanical engineering have shown that universal machine tools operate 60-75 % of the time with the power of up to 0.5 of the rated power and only 1-10 % of the time with the rated power or permissible overload. Later foreign studies show similar results. The weighted average values of the calculated relative powers of the machine tools are recommended: for lathes 0.4-0.48; for boring and milling machines 0.35-0.45. The lower values correspond to the use of the traditional set of tools (carbide and high-speed steel), the upper values correspond to the use in finishing and semi-finishing operations of mineral-ceramic, and in rough operations the use of hard-alloy tools with coatings [2, 3].

CNC machines have higher average and maximum load ratings than general purpose machines. Thus, the level of use of lathes with CNC for machining in a chuck is 20-25 % higher in torque, for machining in centers is higher in power by 20 % and in rotation frequency by 30-40 % [4].

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The third, most complicated group includes methods of finding the probability distribution of random variables, which is needed to estimate the mean time to failure if only a part of the products failed during the observation period, as well as to calculate the gamma-percentage resources or the probability of reaching the limit state.

For each number *x* in the range of variation of a continuous random variable *X*, by which in specific cases the corresponding indicator should be understood (mean time between failures, wear rate, engine power, etc.), there is a certain probability P(X < x) that that X does not exceed x. This dependence F(x)=P(X<x) is called the distribution function or the probability function of the random variable X.

The F(x) function is a non-decreasing function (monotonically increasing for continuous processes and stepwise increasing for discrete processes). Within the limits of the random variable X, it changes from 0 to 1.

The derivative of the distribution function for the current variable is called the distribution density:

$$\mathrm{f(x)} = \frac{dF(x)}{dx} \ . \tag{1}$$

It characterizes the repetition rate of a given value of a random variable. In reliability problems, it is widely used as the probability density [3].

In some cases, it is enough to characterize the distribution of a random variable with some numerical values: mathematical expectation (mean value), mode and median characterizing the position of the centers of the random variables grouping along the numerical axis, variance, standard deviation, coefficient of variation, characterizing the scattering of a random quantity. In reliability theory, the probability of failure-free operation is usually determined using quantiles of the normalized normal distribution.

Reliability indicators include: the probability of no-failure operation, the mean time to failure, the failure rate, the mean number of failures, the mean time between failures, the characteristic and parameter of the failure flow. These indicators in the theory of reliability can only take positive values.

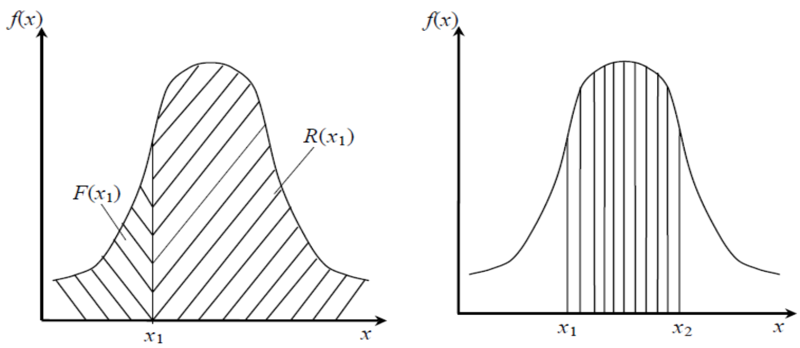
When considering failures as random events, such characteristics as the distribution density (probability density) f(x) of failures, the integral function (probability) F(x) of the failure distribution, the probability of failure-free operation (decay curve) R(x). The f(x) and F(x) functions are related by dependence (1).

When the operating time X does not exceed the required $\boldsymbol{x_1}$, the probability of a failure is found using the distribution density, i.e.

$$P(X \le x_1) = \int_0^{x_1} f(z)dz, \tag{2}$$

where z is the integration variable.

The probability of a failure for the operating time X that is lower than the required x_1 can be determined as the area under the curve f(x) to the left of the value x_i (Fig. 2, a).



a b

Fig. 1. – Graphic interpretation of the reliability indicators: a – probability of failure-free operation R(x_1) and failure F(x_1); b – probability P(x_1 < X < x_2) that the failure takes place within the interval from x_1 to x_2

The probability of failure-free operation R(x), i.e. the value opposite to F(x), can be found using the distribution density. Since R(x_1) + F(x_1) = 1 (a product can be in the only of two states: failure or worability), then:

$$R(x_1) = P(X > x_1) = 1 - F(x_1) = \int_{x_1}^{\infty} f(z)dz.$$

The probability of failure-free operation is eqaul to the area under the f(x) curve to the right of x_1, i.e. in this case the operating time X before the failuure will be larger that the required x_1.

The probability that a random value X lies between x_1 and x_2 (Fig. 2, b), is equal:

$$P(x_1 \le X \le x_2) = F(x_2) - F(x_1) = \int_0^{x_2} f(z)dz - \int_0^{x_1} f(z)dz. \tag{3}$$

The mean operating time before the failure is:

$$x_{av} = \int_0^\infty z f(z) dz. \quad (4)$$

Observations during testing or operation are carried out according to a special plan. This is necessary to assess the products reliability. There can be two cases: a statistical model of an object with its laws of distribution of a random variable is known; the statistical model is unknown.

In the latter case, it is necessary to determine directly the numerical values (point estimates) of the reliability indicators: average (operating time before failure, resource, service life, shelf life, recovery time); gamma percent (resource, service life, storage life); probability of failure-free operation, failure rate [4].

Another problem often occurs when the statistical model is known, but it is necessary to find the characteristics of the system reliability, that is, the characteristics of the operating time to failure distribution and other random quantities that determine the product reliability, for example, the distribution density f (x) and others.The data for determining the distribution are usually observed values of the random variable grouped by frequency of occurrence, that is, the empirical distribution density. When processing the constructed histogram, one passes from the empirical distribution to one or another statistical model and selects one or another distribution.

It is used to determine the reliability indicators during normal operation, that is, in the period after the end of the running-in of the product and before the significant manifestation of gradual failures. At this stage, failures do not yet appear, and product reliability is characterized by sudden failures. The exponential distribution is convenient for describing non-systemic failures, since it is assumed that events (failures) occur independent on one another. It can often be successfully applied when each failed element is immediately replaced with an efficient one [4].

The exponential distribution is one-parameter, that is, it depends on one parameter *X(X> 0),* the failure rate for non-recoverable products or the parameter of the failure flow for recoverable ones [4]. For non-recoverable products, primary failures are considered, for recoverable products primary and secondary ones.

In contrast to the calculation of the reliability indicators, when predicting them, the probabilistic problem is solved, while the probability of the machine being in a certain state is estimated depending on the possible operating modes and operating conditions. The quality of the forecast depends to a large extent on the source of information of reliability of individual elements and the processes of their loss of performance.

For forecasting in the general case, various methods are used that include modeling, analytical dependences, statistical information, expert assessments, etc.

When predicting reliability, the following tasks are usually solved:

1) predicting the behavior of a specific machine sample under fixed operating conditions;

2) predicting reliability of a specific sample with randomly varying operating modes within certain limits;

3) predicting the behavior of the entire general population of these machines operating under random operating conditions.

The last task is the most important, since only by the behavior of the general population can a reasonable assessment of the type of machine, design or technological solution be given.

Let's suppose that according to the delivered batch of machines N_0, manufactured by the manufacturer plant, it is precisely known about n_0 failures. Moreover, every n_i failure occurred in the interval $(t_i' - t_i'')$. To determine the needed parameters at a particular plant, there is a sample of operating hours for a certain period of time. Knowing these parameters, it is possible to derive the law of distribution of the working time of all machines mounted at the enterprise, manufactured by a certain company, for the required period of time [4].

To determinnne this law, let's suppose that the working time of the machine tools is desctibed by the Weibull distribution with the given parameters τ_0 and μ, from which there can be defined the number of machines from the barch N_0 that has worked its resource t (5):

$$N_t = N_0 exp\left[-(\frac{t}{\tau_0})^\mu\right]. \quad (5)$$

Let us take for the assumption that the number of failures or breakdowns of the considered batch of machines at a given enterprise is approximated in time by the Weibull law with the given parameters t_0 and m. Knowing this, the number of failures or breakdowns in the time interval will be obtained from the following expression (6):

$$n_t = n_0\left[e^{-(\frac{t-\Delta t}{t_0})^m} - e^{-(\frac{t}{t_0})^m}\right]. \quad (6)$$

It follows that the ratio of the failure number in a unit of time Δt to the number of working machines at a certain moment of time is called the failure or breakdown rate (7):

$$\lambda_t = \frac{n_t}{N_t \Delta t}. \quad (7)$$

Taking into account the above-said, the expression can be presented in the following form (8):

$$\lambda_t = \frac{n_0}{N_0} e^{(\frac{t}{t_0})^m} \left[\frac{e^{-(\frac{t-\Delta t}{t_0})^m} - e^{-(\frac{t}{t_0})^m}}{\Delta t} \right]. \quad (8)$$

To simplify the expression, let's use the limit $\Delta t \rightarrow 0$ (9):

$$\lambda(t) = \frac{n_0}{N_0} \frac{m}{t_0} (\frac{t}{t_0})^{m-1} exp \left[(\frac{t}{\tau_0})^{\mu} - (\frac{t}{\tau_0})^m \right]. \quad (9)$$

For often cases under the condition that $\mu = m = 1$ there can be used the following expression (10):

$$\lambda(t) = \frac{n_0}{N_0 \bar{\bar{t^*}}} exp \left[\left(\frac{1}{\bar{\tau}} - \frac{1}{\bar{\bar{t^*}}} \right) t \right] \quad (10)$$

where $\overline{t'}$ is the machine working time in hours within a certain period of time;

$\overline{t^*}$ is the conventional average working time before the failure of the machine elements for which failures are most often registered.

3. Conclusions

The complexity of solving the problem of predicting the behavior of the general population depends on the source data for determining reliability. The most common cases are as follows:

1) there are the data of the general population behavior in some operating conditions; forecasting is needed in connection with the expected change in operating conditions;

2) there is provided the information of the specific sample of the device behavior; forecasting evaluates the behavior of the general population in these conditions;

3) there are the data of operating conditions and physical prerequisites for failures; as a result of forecasting the behavior of the general population at the design stage, an assessment of the structure is given in terms of its reliability.

The first case is usually associated with intensification of the machine operation without significant changes in its design. The accuracy of predicting reliability of an object in prospective operating conditions is determined by the accuracy with which the statistical characteristics of the loading indicators $g_i(t)$, $g_2(t)$, $g_s(t)$, are predicted, as well as the accuracy of the mathematical model of the output parameter in the new predicted area.

Since extrapolation of previously obtained mathematical models outside the known region Q is usually illegal, it is necessary to carry out additional experiments on natural or model objects.

The second case occurs when there is a prototype of a new product that has passed fairly complete operational tests. Based on the results of these tests, the failure rate is estimated in various operating modes, and according to the available statistical characteristics of the load indicators, parametric reliability of the given sample during its operation in real conditions is determined. To predict the behavior of the general population, the most significant factors must be identified that cause technological instability and accordingly, dispersion of the output parameter.

Each of the technological factors, in accordance with the permissible deviations of dimensions, material properties and other characteristics, must be given a statistical description. So, manufacturing errors of parts are, as a rule, distributed within the tolerance A according to the normal law, it is usually considered that there is a standard deviation. In case of sudden failures, using the analytical relationship of the output parameter with technological factors, one of the known techniques (linearization method or Monte Carlo method) can predict the distribution of the output parameter for the entire general population followed by an assessment of reliability in terms of P_n or $P(T)$ [3].

The most difficult and least accurate predicted reliability at the design stage is in the third case, when, based on general considerations or analysis of the prototype operation, the scheme of the object loss of operability and physical prerequisites leading to failure are preliminarily estimated. The reliability indicators for such analytical prediction are usually used to compare the effectiveness of various design options. The calculation of reliability in forecasting is based on the models discussed above that describe sudden, sudden-gradual and gradual failures.

The scope of use of analytical dependences is often narrowed due to the arbitrary distribution laws of the loading indicators and nonlinearity of the relationship between the output parameter and wear. This leads to the widespread use of statistical modeling in forecasting problems.

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Methods and models for the formation of a system for organizing group production at machine-building enterprises

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Abstract. This article highlights the problem of the need to modernize and redesign the production organization system, adapted to the modern conditions of an innovative economy and a dynamic environment for creating competitive production. The stages of preparing an enterprise for redesign are described. Comparison of organizational design processes of domestic and foreign manufactures is given.

Keywords: organization of production, design features, forms of organization of production.

1. Introduction

The fall in production in the 1990s, the financial crisis and the interruption of economic ties for several years made the problem of modernizing machine-building production irrelevant. Some revival after 1998 also did not require additional investments in industrial production: the average age of equipment in mechanical engineering was 10-15 years, the economic situation allowed to manufacture products under conditions of 5-7% of production capacity and ignoring consumer requests for modification products and adaptation to market requirements. However, at present, the change in the situation in the industrial and manufacturing sector is due to a number of reasons:

- the equipment is on the verge of running out of resource;
- the need to develop and put into production numerous modifications of manufactured products and new products is obvious;
- there is a problem of selection of qualified engineering and technical personnel as a result of the aging production staff;
- the modern level of communications allows to find manufacturers of components on terms that are much more profitable than your own production.

In the current conditions, the need for modernization and redesign of production comes to the fore. However, a significant part of the theoretical, methodological and practical base in the field of engineering production is limited to the period 1955-1985 of the XX century and reveals the design issues of large industrial giants with maximum productivity and a closed cycle. It is obvious that designing a new production according to the old principles will make it uncompetitive in an innovative economy and a dynamic environment. Modern publications, in turn, provide answers only to local questions. There is no comprehensive methodology for the design of industrial production, linking together all the design factors characteristic of modern conditions.

2. Results and discussion

According to the established organization of production of the concept of organizational design, this process includes four stages:

- Pre-project preparation - development of a general concept for the organization of production, a comprehensive survey of the design object.
- Technical design - development of the main provisions of the production organization system and the principles of its functioning.
- Detailed design - development of a complex of working documentation, including structural diagrams, organizational and planning calculations, as well as software.
- Implementation - provision of training and psychological training of personnel, introduction of new instructions and regulations, restructuring of the production and management structure.

The analysis of the works of foreign authors made it possible to single out the six stages of the process of organizational design of production in the USA, Germany and Japan, combined into four blocks of design work, corresponding to the Russian structure of the design process:

1 stage: Goal setting.
2 stage: Preliminary design.
3 stage: Draft design:
- perfect design;
- real design.

4 stage: Detailed design.
5 stage. Development of an executive project.
6 stage. Project realization.

Despite the obvious structural repeatability of domestic and Western approaches to organizational design, they are conceptually different in content. Preliminary design is carried out with the involvement of consumers and is characterized by the establishment of the initial production base (input values), consumer requirements (output values), identification of the main problem areas in the process of virtual transformation of input values into outputs and a preliminary feasibility study.

Draft design involves the implementation of the principle of variance: at the same time, independent approaches to design solutions are being developed, key factors are developed that determine the preference of various options and the project is selected that is most preferable in a specific production environment.

The next stage - detailed design - requires a lot of money and time to bring the selected design option to a state ready for project implementation. Consequently, between the third and fourth stages, a point of no return should be determined, characterizing the point in time after which any intervention in the design process or changes will entail significant costs and an increase in the design time [1].

The development of an executive project is characterized by the transformation of the master project into master plans, schedules, applications and other project documentation, reflecting the implementation of the project in industrial operation, broken down by timing and performers. Project realization includes training of personnel, monitoring of realization, trial operation of the project, launching into production and adjustment.

The presented content of design works meets the basic requirements for the concept of organizational design in modern conditions:

- consistency in the organization of project works;
- flexibility and variability of project solutions;
- consumer participation in design;
- the ability to combine project work;
- transparency of information, material and financial flows in the project process.

The main features of designing a system for organizing group production based on a six-stage model are as follows:

1. Goal setting. Goal planning is the process of developing a framework for making informed decisions during designing. Goal setting in the design of group production is based on the fundamental choice of the type of project work based on a specific production situation (Table 1).

Table 1 - Design goals of a system for organizing group production at an industrial enterprise

Type of project work	Distinctive features	Designing goals
1	2	3
1. Designing a group production for a newly created industrial enterprise	- long preparatory period; - a large amount of preparatory work; - enlarged forecasts of the production program, the required number of equipment, personnel, etc.; - a high degree of freedom in the design process, an unlimited number of design options.	Formation of a comprehensive project of a system for organizing group production in the context of a new enterprise construction.
2. Design of group production in the context of revitalization of an industrial enterprise	- use of the production capacity of a non-operating enterprise for the organization of group production of industrial products - revitalization; - a large amount of preparatory work; - restructuring of production facilities, reconfiguration of production units; - aggregated forecasts of key production indicators; - relatively high degree of freedom in the development of design solutions, limited only by the scope of the location of production units.	Formation of an integrated project of a system for organizing group production of new products on the basis of the revitalized enterprise.
3. Designing group production in the context of re-profiling	- using the production capacity of an existing industrial enterprise for the purpose of organizing group production of new types of products - re-profiling; - reduced amount of preparatory work; - restructuring of production facilities, reconfiguration of production units; - the forecast of the main production indicators is due to the production potential of an industrial enterprise; - normal degree of freedom in developing design solutions, limited by the capabilities and deficiencies of the enterprise.	Formation of a project for a system of organizing group production of new products in the context of re-profiling.
4. Design of group production of industrial products of an operating industrial enterprise (reengineering)	- modernization of the existing production system based on the introduction of group production; - shortest preparatory period; - relatively accurate forecasts of key performance indicators; - continuous adjustment of the production complex under the influence of the market, process and product innovations to ensure the high competitiveness of the enterprise; - low degree of freedom in making design decisions due to the scope of the production system, the peculiarities of the	Formation of a project for a system for organizing group production to improve the efficiency of industrial production

	placement of non-mobile equipment, the terms of long-term contracts with external contractors.	

As can be seen from Table 1, at the stage of goal-setting, depending on the type of design work, the characteristics of a complex project change significantly. With a decrease in the volume of design work, their complexity increases due to the limitation of the variability of design solutions and the degree of detail and accuracy of forecasts increases.

After establishing the main design goal, a fundamental approach to its implementation should be determined, i.e. level of organization of group production. Making a managerial decision on the choice of the appropriate type of system for organizing group production should be based on ensuring a balance between the capabilities / deficiencies of the production system, due to the strategic factors of the enterprise's development, and the design goals. In our opinion, the main strategic factors in the development of an enterprise that influence the decision to organize group production can be consolidated into the following areas:

- economic development of the enterprise;
- technical and technological development of the enterprise;
- innovative development of the enterprise;
- social development of the enterprise;
- structural development of the enterprise;
- balance of flexibility and stability of the enterprise.

The choice of the level of organization of group production is influenced by a large number of factors, which makes the issue of making a managerial decision on the type of system for organizing group production extremely laborious. The choice of the type of system for organizing group production ends with the determination of the permissible costs and the framework of financing, as well as the justification of investment sources and the establishment of project terms [2].

Thus, at the stage of goal-setting, a mock-up of the organizational project of the group production organization system is developed, including the following basic provisions:

- description of the project and justification of the need to implement group production;
- selection of the type of design work and formulation of the design goal;
- identification of opportunities / deficiencies, production system and identification of problem areas for the design of a system for organizing group production;
- project management program development.

The resulting document is the basis for starting preliminary design of the group production organization system and launching design work.

When designing a group production at LLP Maker - KLMZ, the type of design work will be reengineering.

2. Preliminary design.

Preliminary design is the process of forming a structured data array - a design base - required for making a decision to start design and conducting further design calculations.

In our opinion, the main tool that allows you to most effectively solve the problem of collecting and analyzing the required data is the analysis of production potential, since it allows you to solve the following main tasks:

- preparation of initial data for designing a system for organizing group production by determining quantitative indicators;
- analysis of the values of the obtained indicators for their compliance with the reference values;
- studying of the results of the analysis of the data obtained in order to identify "bottlenecks" and areas that are vulnerable from organizational, technical, operational and economic points of view.

In our opinion, for the presentation, analysis and formalization of data, it is advisable to use special methods: functional-cost analysis, product-quantitative analysis, and others.

The results of preliminary design should be used to develop a general concept of the production organization system. In our opinion, in the process of developing a concept, it is necessary to set logistical goals related to the procurement, production, marketing and disposal of waste. At the same time, special attention should be paid to such principles of logistics that have a direct impact on the configuration and organizational decisions of the production system, and purposefully put them into the project.

The resulting document contains concise design results that are relevant for making a decision to start direct design, and is an intermediate link between the analysis of opportunities (at the stage of goal setting) and the feasibility study (at the stage of preliminary design).

3. Draft design of a group production organization system.

At the stage of preliminary design, the main provisions of the system for organizing group production are developed. It should be noted that a distinctive feature of this stage in modern conditions is the development of a system for organizing group production in two directions: perfect design and real design [3].

Perfect design is characterized by the development of basic design solutions in the field of production organization based on the most optimistic forecast and, according to the six-step design model, consists of the following steps:

3.1. Determination of the functions of the group production organization system. At this stage, the most optimistic design solutions for functional subsystems of group production are being developed.

The maximum value at this stage has the design subsystem organization of production processes, including the design of group technology.

3.2. Determination of dimensional parameters. At this stage, the quantitative values of the need for space, raw materials, materials, equipment and personnel are determined based on the considerations of effectively ensuring the implementation of the above functions of organizing group production.

The obtained dimensional values are the basis for the feasibility study of the project for the organization of group production and the determination of the real volume of investments.

3.3. Structuring. This stage represents the implementation of the main design idea and includes the determination of the form of production organization, the basic principles of production organization and the development of an ideal layout. Structural design can be carried out with varying degrees of generalization, which is due to a differentiated view of the design level of the production system. The main characteristic of the ideal design is the choice of the form of organization of group production, due to the specific principles of spatial placement of workplaces and equipment within the autonomous production areas and their linking to the technological route of the material flow. A critical review of domestic and translated literature in the field of industrial design made it possible to single out two main forms of organization of production that correspond to the principles of organizing group production:

- production island (PI) - Russian approach;
- (Integrated Subject-specialized Areas of Production ISAP or Integrierte gegenstandsspezialisierte Fertigungsabschnitte IGFA (German) — foreign approach.

PI is a form of group production organization that allows processing groups of parts with an organizationally concentrated placement of the necessary equipment in the form of an independent production site. PI has the following characteristic features:

- formation of groups of parts from structurally / technologically similar families;
- space-concentrated placement of the necessary workplaces (5-20), more focused on the technological process of the main group of parts - a reference group technological process;
- ensuring flexible use of staff within group work;
- integration into the general range of indirect production tasks: preparation and maintenance of the workplace, tool management, quality control and operational management of production, thereby achieving greater autonomy and flexibility of the production process;
- free configuration of logistics processes - rejection of system-based instructions and the transition to situational management of logistics;
- application of the principles of organizing group production for assembly and warehouse activities.

3.4. Configuration. This stage is a spatial and functional integration of an ideal project in a specific production system, or real design. The result of the design work should be a ready-made scientifically grounded design decision regarding the real form of organization of group production and the principles of its integration into the production system of an industrial enterprise.

3.5. Feasibility study of the project for the organization of group production. The feasibility study of the project completes the preliminary design and is the basis for making a decision to continue the design work - the beginning of detailed design. In our opinion, it is precisely the transition from preliminary design to detailed design that should be the “point of no return” that determines the moment of rejection of any changes to the initial design, since changes made to the executive design developed at the detailed design stage can entail significant costs of time, labor and financial resources.

4. Detailed design. This stage of the six-step organizational design model is aimed at ensuring the maximum level of elaboration of design solutions for preliminary design, indicating that the project is ready for implementation.

The result of detailed design is a set of project documentation based on the results of work in the selected areas: precise planning diagrams, technological process maps, job descriptions, lists of needs, private plans, etc. The above documentation together forms the "executive version" of the design solution. However, in order to implement the received executive version, it is necessary to determine the terms of implementation, performers, draw up orders for the release of areas, construction and installation work, in other words, it is necessary to develop an executive project.

5. Development of an executive project of a group production organization system. The content of this design stage is characterized by the following areas of project activities:

- selection, differentiation and docking of complex tasks and work order packages;
- drawing up a work plan and timetables for its implementation to ensure coordination of the design of the group production organization system;
- distribution of powers and responsibilities.

The maximum detailing of the executive project of the group production organization system, in our opinion, will allow avoiding shortcomings, mistakes and disruptions in the process of implementing the developed project.

6. Realization. This stage is the final one in the six-stage design model and includes the construction / reconfiguration of structures, installation of equipment, installation work, as well as the implementation of work packages set in the executive project.

Separately, attention should be paid to personnel training, the introduction of group methods of work organization, the development of appropriate incentive systems and labor. It should be borne in mind that the implementation of a design solution, as a rule, is accompanied by significant failures and deviations. Therefore, it is necessary to exercise direct control of the project in terms of costs, timing, quality in order to ensure effective regulation of the implementation of the executive project.

Within the framework of the Industry 4.0 program, LLP Maker - KLMZ underwent a multi-purpose modernization, including: financial issues; expansion of the range to 7 thousand types of parts; expanding the diversification of the client base; increasing the share of import substitution from 10% to 30% with access to the international market; 3 times increase in productivity achieved by a complete renovation of the production line. New equipment allows replacing several technological operations on old equipment, as well as expanding the parameters of processed parts (for example, trolley axles and mining equipment shafts).

The implementation of the principles of organizing group production at machine-building enterprises highlighted in this work provides a reduction in the time spent on equipment changeover, a decrease in the duration of the production cycle, a reduction in the size of the machine park, etc. Consequently, in the process of designing production systems for organizing serial production of products, it is advisable to use group forms of organizing production in the microstructuring of departments. [3].

The principles of organizing group production make it possible to implement several basic options for microstructuring at a machine-building enterprise by identifying several levels of grouping objects in the production system (Table 2).

Table 2 – Grouping levels in microstructuring the group production organization system

The principles of organizing group production	Classification of principles by grouping object
1. Constructive and technological unification.	Grouping parts
2. Organizational and successive normalization and regulation.	
3. The cellular arrangement of equipment.	Grouping equipment
4. Autonomy of production units.	
5. Grouping workers.	Grouping workers
6. Joint responsibility for the development of the system.	
7. Modular principle of building a production structure.	Grouping units
8. Grouping plots by product.	

Focus on the main stages of microstructuring the system of organizing group production on the example of LLP Maker - KLMZ.

1. In the production structure of the enterprise, a specialized unit should be created - a group for organizing group production - for the implementation of the following activities:

– development of a long-term plan and technical specifications for the organization of group production in specific production conditions at the stage of preparation of group production (engineering training);

– general management of the activities of all interested technical services at the stage of implementation of group production (management activities);

– monitoring the activities of production units at the stage of group production operation (collection and statistical processing of analytical data);

– development, implementation and adjustment of a long-term plan for the improvement and development of group production with detailing by years, quarters and months (engineering and analytical work).

Thus, based on the structure and volume of activities, the group should include:

– group leader - a manager with higher education, specialist in the field of organization and management of production (1 person);

– engineers - specialists with higher engineering and economic education, with production experience (2 people);

– analysts - specialists with higher education who have experience in planning and economic work and skills of a computer operator (1C: Enterprise) (2 people).

Practice shows that the highest level of responsibility and authority of this structural entity can be achieved by including it in the production structure as an independent entity with subordination directly to the head of production LLP Maker - KLMZ.

3. Conclusions

The proposed for use six-step design model of the group production organization system meets the current level of development of industrial design science and allows you to form a largely detailed scientifically grounded project of the system, containing not only the basic provisions for microstructuring and spatial configuration of group production, but also a certain variability of design solutions, basic principles of their implementation and proposals for the integration of logistics processes. In our opinion, the practical use of the main provisions of the proposed system will make it possible to qualitatively develop and rationally apply the most effective principles for organizing group production.

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