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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

Ensuring the reliability of the anti-tank hand grenade launcher barrel by diffusion metallization

Speciality: 3328.01 - Special operations technology

Field of science: Technical sciences

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GENERAL CHARACTERISTICS OF THE WORK

The relevance and degree of depelopment of the topic. In modern times, the sustainable development of military-industrial complexes is directly related to the national security and technological sovereignty of countries. In particular, there is a serious need for research based on high-tech solutions in local production to increase the competitiveness of the defense industry of the Republic of Azerbaijan and maintain strategic advantage. Ensuring the reliability and functional sustainability of special-purpose products during their service life is one of the important scientific and technical problems being addressed in this direction.

In this context, the issue of ensuring the reliability of the jet breech, which is the main part of the 40-mm anti-tank grenade launcher (ATG), by diffusion metallization is of particular relevance. Thus, the working surface of the jet breech of the 40-mm ATG is exposed to high temperatures and pressures during firing, and quickly fails due to impact-abrasive, thermoplastic, thermoerosion, thermochemical and mechanical wear, weakening its internal ballistic properties. Currently, high-quality and heat-resistant steels used to ensure the reliability of the jet breech of the 40-mm ATG are not economically viable.

The solution of this problem with efficient and scientifically based technologies, in particular, strengthening and ensuring the reliability of the working surface of reactive etching by vacuum diffusion metallization based on complex coating elements based on chromium and nickel, is expedient both from a technical and economic point of view. With such an approach, the functional indicators of the 40 mm TQ are significantly increased, reliability during operation is ensured, and the application of innovative technologies in domestic production is expanded. All these factors confirm the relevance of the research topic both from a theoretical and practical point of view.

The research was conducted in the "Technology of Special Purpose Products" laboratory of the "Special Technologies and Equipment" department of Azerbaijan Technical University and in the scientific research laboratory of the Institute of Physics, and was tested at the real production enterprise, Iglim EIM LLC.

In the dissertation work, various types of wear mechanisms of the reactive groove part of the 40 mm TQ were modeled, new tribotechnical and structural models were proposed, and the optimization of the diffusion layer thickness and the correlation of coating parameters with functional properties were theoretically and practically substantiated. Based on the experimental results, highly reliable diffusion coatings were obtained, and their microstructural and mechanical properties were studied. The research results were presented at a number of international and local scientific conferences, and were also tested in production.

Thus, we can note that the problem under consideration is very relevant and requires a wide range of scientific research in this direction.

The goals and objectives of the research are to strengthen the inner surface of the jet cutter, which is one of the main functional parts of the 40 mm TGM, using a chromium-nickel-based diffusion metallization method and to develop a technologically efficient method in order to increase the operational reliability and durability of its inner surface.

Achieve this goal, the following research objectives have been set:

1. Analysis and modeling of impact-abrasive, thermoplastic, thermoerosion, thermochemical, and mechanical wear mechanisms encountered by reactive engraving during operation;
2. Development of the scientific basis of the process of coating the inner surface of a reactive cavity using vacuum diffusion metallization methods;
3. Study of changes in coating thickness and linear dimensions during the diffusion process at different regime parameters, and evaluation of the impact of these changes on the functional properties of internal ballistics;

4. Obtaining diffusion layers resistant to wear and temperature effects for reactive etching and studying their microstructural, tribotechnical and physical-mechanical properties;

5. Testing of new coatings obtained as a result of vacuum diffusion metallization - evaluation of reliability parameters through laboratory and bench tests;

6. Evaluation of the results obtained and investigation of application possibilities in production;

7. Preparation of technological instructions for the practical application of the studied method and determination of the feasibility of using this method in restoration and new production processes.

The main points to be defended are:

As a result of the research conducted, the following main provisions are drawn up for the defense.

1. Analysis of justification and methods for eliminating impact-abrasive, thermoplastic, thermoerosion, thermochemical and mechanical wear of the inner surface of a reactive cavity.

2. Development of the theoretical basis for using the vacuum diffusion metallization method to improve the reliability and performance of reactive etching.

3. Development of a new technological process to improve the reliability of reactive etching using the vacuum diffusion metallization method.

4. Metallographic examination of coated parts - study of phase composition and structure.

Object of the research. Anti-tank grenade launcher jet cutting made of special-composition steels of the grades 30ХН2МФА, 38ХХ3МА and 30ХНМФА.

Research methods and reliability of results. The issues raised in the dissertation work were solved on the basis of theoretical and experimental studies conducted in laboratory and production conditions. The research was carried out using modern equipment, devices and measuring instruments, including the application of ultrasound, microwave defectoscopes. Structural analysis, phase composition and metallography of materials were determined using modern devices and equipment . The reliability of the research results is confirmed by processing the experimental results using a computer and comparing the results of other authors.

Scientific novelty of the research.

1. The reasons for the failure of the jet-cutting part of the 40 mm TA were investigated [14];
2. The wear mechanism of the working surface of the jet cutting part of a 40 mm TQ was studied, a new model was proposed, and its topography was investigated [15];
3. The vacuum diffusion metallization method has been theoretically justified and experimentally investigated as an innovative method for ensuring the reliability of the reactive etching part of a 40 mm TGA [12];
4. The regime parameters of the change in the linear size of the reactive etching during diffusion metallization in vacuum were determined and the dependencies between them were determined [12];
5. the diffusion saturation mode, which provides a greater variation of linear dimensions, has been optimized [12];
6. The metallography and structure of parts with increased reliability indicators were studied [9];
7. The tribotechnical and physical-mechanical characteristics of the obtained diffusion coatings were studied [6];
8. A positive opinion was received for 1 patent (AzPatent No. A 2023 0076) on the technological process.

Practical significance and application of the research. The theoretical basis of the research is distinguished by the scientific substantiation of various types of wear processes of jet etching, which is a part of special-purpose weapons. The proposed approach for surface strengthening of the jet etching part of a 40 mm tank destroyer by the method of diffusion metallization in vacuum contributes to the existing knowledge in this field. In the research, a model of wear mechanisms of jet etching was built, functional dependencies between the processes of changing the thickness of the diffusion coating and linear dimensions were determined, and the coating structure and tribological properties were analyzed. This approach allows for the selection of optimal modes of diffusion processes in vacuum on a scientific and practical basis and can serve as a basis for surface strengthening of other similar parts.

The research work has been approved at the Climate EIM production enterprise of the Ministry of Defense Industry of the Republic of Azerbaijan, the National Aerospace Agency and the Scientific Research Institute and has been submitted to enterprises for technological application. In this regard, the dissertation work has not only theoretical, but also practical significance and can be assessed as an important study aimed at the application of innovative approaches in the country's defense industry.

The materials of the research work are recommended for use in the subjects taught at the bachelor's level of the specialty XTB 050106-“Weapon Systems Engineering”, at the specialty 7010006-“Weapon Systems Engineering”, at the master's level of the specialty XTM 060001-“Production Technology of Small Arms, Artillery and Missile Weapons”, at the specialty XTM 060101-“Production Technology of Munitions and Destructive Means” and at the master's level of the specialization XTM 070106 “Production Technology of Special Purpose Drone Aircraft” of the Azerbaijan Technical University.

Approbation and application. The main provisions of the dissertation work were discussed and approved at scientific-practical conferences and seminars held in the country and abroad. The main content of the work was published in 15 articles and conference materials. 7 of them are scientific articles (2 in foreign scientific journals indexed in international databases, 5 articles in republican journals included in the list of the AAK), 8 are theses of reports published at international and republican conferences. The published works fully reflect the essence of the dissertation.

1. Ministry of Education of the Republic of Azerbaijan, Azerbaijan Technical University, May 3-5, Baku -2018,

2. Materials of the International Scientific and Technical Conference “Measurement and Quality: Problems and Prospects” of the Ministry of Education of the Republic of Azerbaijan, Azerbaijan Technical University and the Scientific Research Institute of the

Metrological Service of the Russian Federation, November 21-23, Baku -2018,

3. Ministry of Education of the Republic of Azerbaijan, Azerbaijan Technical University, May 6-7, Baku -2021,

4. "Machine-building and Energy: New Concepts and Technologies" International Scientific-practical Conference materials, December 2-3, 2021, AzTU, Baku, Azerbaijan,

5. Program of the technical scientific conference of undergraduate, master and PhD students 29-31 March 2022, Moldova,

6. Republican scientific and technical conference of students and young researchers on the topic "Youth and scientific innovations" dedicated to the 99th anniversary of the birth of the national leader of the Azerbaijani people Heydar Aliyev, May 4-5, 2022, Baku,

7. Discussed in extended seminars of the “Special Technologies and Equipment” department of Azerbaijan Technical University and applied to production at the Climate EIM.

The total volume of the dissertation in characters, indicating the volume of the structural sections of the dissertation separately. The structure of the dissertation work consists of the title page – 404 characters, table of contents – 6369 characters, introduction – 16458 characters, chapter I – 45681 characters, chapter II – 38628 characters, chapter III – 62130 characters, chapter IV – 35303 characters, chapter V – 22957 characters, conclusion – 5039 characters, chapter VI – 35303 characters, list of used literature – 26741 characters, appendices, list of abbreviations and symbols – 31035 characters. The total volume of the dissertation work consists of 158 pages of computer-written text, including 35 images, 26 graphs, 11 tables, and a 152-item bibliography, and 238,387 characters excluding images, tables, graphs, appendices, and the bibliography.

DISSERTATION SUMMARY

The introduction provides information about the relevance and degree of development of the topic, the goals and objectives of the research, the main provisions put forward for defense, the object of the research, the reliability of the research methods and results, the scientific novelty of the research, the practical significance of the research, and the application, approval and application in industry, separately indicating the volume of the structural sections, as well as the total volume of the dissertation.

The first chapter analyzes the structure, working principle and performance of the 40 mm anti-tank guided missile, shows its main design features and uses. Then, the reasons for the failure of the anti-tank guided missile and its current shortcomings are studied.

The chapter also explains the production technology of jet engraving and the technical requirements imposed on it. As a result of the research, it was found that the existing technology does not fully ensure the longevity of the engraving. In this regard, the possibility of increasing the operational durability of jet engraving by the diffusion metallization method is justified.

The technical characteristics, operating conditions and current production technology of the jet rifling, which is one of the main parts of the 40 mm anti-tank grenade launcher (ATG), have been extensively studied. The jet rifling detail is presented as one of the main components that directly affects the reliability and functional efficiency of the weapon system. This is understood as the ability of the grenade launcher to withstand a certain number of shots, and after the process, the working surface of the jet rifling is subjected to wear, in particular, impact-abrasive, thermoplastic, thermoerosion, thermochemical and mechanical-chemical wear, under extreme operating conditions - high pressure, heat and pressure.

It has been shown that the surface quality and workability achieved with chemical coatings within the framework of existing production processes are not sufficient for long-term operation. Therefore, in Chapter I, surface strengthening with chromium-nickel coatings by vacuum vapor-phase diffusion metallization technological process is justified as an alternative and more durable technology.

In connection with the causes of failure of weapons and weapon systems and the improvement of their design, the studies of D.K. Chernov, M.M. Khrushchev, M.A. Babuchev, M.T. Kalashnikov, V.A. Degtyarev, G.S. Shpagin, S.G. Simonov, N.F. Tokarev, I.V. Kragelsky and A.G. Huseynov were referred to. In these studies, the impact-abrasive, thermoplastic, thermoerosion, thermochemical and mechanical-chemical wear properties of reactive gouging, resistance mechanisms related to microhardness were systematically investigated. In addition, the impact-abrasive wear processes were analyzed using data from the fundamental works of D.K. Chernov, which play a unique role in the tribology of weapon parts. NF Tokarev paid special attention to the issues of improving workability.

The scientific works of V.N. Bugaev, K.A. Achkasov, Y.V. Mazaev, V.Z. Sergeev, E.A. Davidenko, B.A. Bogachev, as well as SH Babayev and A.G. Huseynov on ensuring reliability by diffusion metallization were reviewed.

The analysis of the existing scientific literature shows that due to the low wear resistance of the jet cutting part of the 40 mm TGM, they have relatively low operational indicators. Jet cutting parts manufactured in large-scale production quickly fail during operation and cause rejections. The main reason for the failure of the jet cutting part operating in extreme conditions under the pressure of intense gases of gunpowder gases is impact-abrasive, thermoplastic, thermoerosion, thermochemical and mechanical-chemical wear. The extension of the service life of the jet cutting is possible by using coatings with both different and the same strength limits at the junction of the “barrel and sleeve”. The processes occurring in the surface layer after the method of vacuum chromium-nickel diffusion metallization of the working surface of the jet cutting of the 40 mm TGM, as well as the conditions for the controlled formation of a layer with high tribotechnical properties, have not yet been thoroughly studied. This determines the purpose of the research and the main tasks set. Therefore, the development and application of vacuum diffusion metallization based on chromium-nickel plating can be considered one of the most effective directions in terms of increasing the wear resistance of the working surface of reactive etching.

In the second chapter, the theoretical basis for increasing the surface strength of the jet engraving by the vapor-phase diffusion method in vacuum was investigated. For this purpose, first, the critical thermal processes were calculated for the jet engraving part of the 40 mm TQ and the temperature changes of the working surface were scientifically substantiated. Then, the deformation state of the engraving at the critical temperature moment was analyzed, and ways to minimize the maximum temperature of the inner surface to a low limit were shown. In the studies, the effect of gunpowder gases on the erosion of the jet engraving was considered, and the heat transfer coefficient was analyzed.

Let us consider the critical limit state of jet etching, such that the maximum allowable temperature T* for the jet etching material at the contact surface has been reached.

The goal here is to determine the temperature distribution on the inner surface of the jet-carved part. In the coordinate system, we obtain the thermal conductivity equation (6 and 7) in the following sequence.

According to the theory of thermal conductivity, the boundary conditions for a hollow-type part will be as follows:

in the contact area:

$$T=T^*$$

in the non-contact area:

$$\lambda \frac{\partial T}{\partial n} - \alpha_1 (T - T_c) = 0 \quad (1)$$

on the outer surface of the carving:

$$\lambda \frac{\partial T}{\partial r} + \alpha_2 (T - T_c) = 0 \quad (2)$$

Here,

$T(r,\theta)$is a function of temperature at the critical thermal state of the groove; λ — thermal conductivity of the groove material; α_1 — is the heat transfer coefficient from the inner cylindrical surface of the groove to the ambient temperature; T_c, α_2 −is the heat transfer coefficient from the outer cylindrical surface of the groove. The thermal conductivity coefficients of the material are assumed to be the same in the axial, circular and radial directions, and do not depend on the coordinates and temperature. In the contact area between the pipe and the shaft, $p(\theta, t)$outside the pressure, the friction force $\tau(\theta, t)$is related to the contact pressure $\tau(\theta, t)$according to the Amon-Thon and Coulomb laws . $\tau(\theta, t) = p(\theta, t)$Friction forces cause heat release in the contact area, however, the total heat amount per unit time is proportional to the friction force, and $\theta$the heat amount of the area at the point will be:

$$Q(\theta, t) = V\tau(\theta, t) = Vfp(\theta, t) \quad (3)$$

where V is the average velocity of the powder particles relative to the jet cavity during the period. Let us divide the heat quantity into two parts: $\theta_1 \leq \theta \leq \theta_2$— the average heat flux Q* over the intervals, equalizing the temperature in the contact area in the cavity with T*; Q*— the similar heat flux.

the cavity to the polar coordinate system $r\theta$ and choose the coordinates L $_0$ and L at the centers of concentric circles with radii R $_0$ and R. Let us consider some realizations of the inner surface of the cavity. Let us imagine the boundary of the inner contour as follows:

$$\rho = R + \delta(\theta), \quad \delta(\theta) = \varepsilon H(\theta) (4)$$

where ε- is a small parameter, $\varepsilon = {}^{R_{max}}/_{R}$-a is equal to $H(\theta)$- a function independent of the small parameter; Rmax is the highest microdefect height of the profile).

Let t = T-Tc be the excess temperature. We find the temperature in the cavity in the form of a decomposition with respect to the small parameter, where we do not take into account the terms of the small parameter X above the first degree.

$$t = t^{(0)} + \varepsilon t^{(1)} + \cdots, \quad (5)$$

Here, $t^{(0)}, t^{(1)}$— are the zero and first approximation temperature functions.

Each approximation corresponds to a differential equation in the theory of heat conduction. $r = \rho^{(\theta)}$To find the values of the temperature components in , we expand the temperature function in series around r=R.

The boundary conditions of the problem in the theory of heat conduction, with first-order small quantities, will be exactly as follows:

For zero approximation

$r = R,\ t^{(0)} = T_0$- In the contact area

$r = R, \lambda \frac{\partial t^{(0)}}{\partial r} - \alpha_1 t^{(0)} = 0$- Outside the contact area

$r = R_0,\ \lambda \frac{\partial t^{(0)}}{\partial r} + \alpha_2 t^{(0)} = 0$- For first approximation

$r = R\,, t^{(1)} = -\frac{\partial t^{(0)}}{\partial r} H(\theta)$- In the contact area

$r = R\,, \lambda \frac{\partial t^{(1)}}{\partial r} - \alpha_1 t^{(1)} = \left[\alpha_1 \frac{\partial t^{(0)}}{\partial r} - \lambda \frac{\partial^2 t^{(0)}}{\partial r^2}\right] H(\theta)$- Outside the contact area

$r = R_0,\ \lambda \frac{\partial t^{(1)}}{\partial r} + \alpha_2 t^{(1)} = 0$-For first approximation

In each approximation, we will use the separation of variables method to solve equation (1) of the heat conduction theory. In each approximation, we will provide the differential equation of the heat conduction theory by giving the temperature distribution in the form $t^{(0)} = \Phi^{(0)}(\theta) V^{(0)}(r)$, where the functions $t^{(1)} = \Phi^{(1)}(\theta) V^{1}(r)$and $\Phi_{(1)}(\theta)$must be periodic for the temperature to be single-valued .$\Phi_{(0)}(\theta)$

Omitting intermediate calculations, we find for zero and first approximation:

$$t^{(0)} = C_{10} + C_{20} lnr + \sum_{k=1}^{\infty} (C_{10}^{(k)} r^k + C_{20}^{(k)} r^{-k}) cosk\theta + \sum_{k=1}^{\infty} (A_{10}^{(k)} r^k + A_{20}^{(k)} r^{-k}) sink\theta \qquad (6)$$

$$t^{(1)} = C_{11} + C_{21} lnr + \sum_{k=1}^{\infty} (C_{11}^{(k)} r^k + C_{21}^{(k)} r^{-k}) cosk\theta + \sum_{k=1}^{\infty} (A_{11}^{(k)} r^k + A_{21}^{(k)} r^{-k}) sink\theta \qquad (7)$$

$C_{10}, C_{20,} C_{10}^{(k)}, C_{20}^{(k)}, A_{10}^{(k)}, A_{10}^{(k)}$, the boundary conditions (1), (2) of the problem were used in the zero approximation to determine the constants.

Similarly, $C_{11}, C_{21,} C_{11}^{(k)}, C_{21}^{(k)}, A_{11}^{(k)}, A_{21}^{(k)}$the boundary conditions (1)–

(7) of the problem were used in the first approximation to determine the constants.

The study found that the high temperature, pressure, and abrasive effects caused by gunpowder gases cause the formation of microcracks on the inner surface of the jet cavity, changes in the structural-phase composition of the material, and, as a result, intensive impact-abrasive, thermoplastic, thermoerosion, thermochemical, and mechanical-chemical wear of the surface.

In the third chapter, the experiments conducted by the author the main goal was to establish theoretical and experimental studies in the right direction to increase the resource and reliability of reactive etching. Experimental studies studied the characteristics of diffusion metallization processes, the conditions for obtaining coatings, their physical and mechanical properties, diffusion ability, corrosion and tribotechnical properties. For this, modern vacuum equipment, metallographic and electron microscopy equipment, X-ray structural analysis systems and microhardness measuring devices were used.

The research work was carried out by the author in the laboratory of “Diffusion metallization and technology of special-purpose products” of Azerbaijan Technical University in a vacuum diffusion device (Fig. 1). The object of the research was a reactive hollow part of a 40 mm TQ made of special-composition steels of the 30XH2MФA, 38XH3MA and 30XHMФA brands. The device was modified on the basis of a prototype of a resistance device with a vacuum chamber of the type СНВ-131/16И4.

Chemical and electrolytic etching were applied to study the structural elements of metals, diffusion zones and coatings. Samples made of 30XH2MФA, 38XH3MA and 30XHMФA steels were subjected to chemical etching in a 4% HNO_3 alcohol solution, and samples were subjected to electrolytic etching in an oxalic acid solution.

Metallographic studies were performed on an Olympus BX-61 modular microscope, and microstructures were recorded using a DP12 digital camera at magnifications of ×50–×500. In parallel, images were obtained on a “Versa 3D” (FEI Company) scanning electron microscope (SEM) in Z-contrast mode (CBS-detector).

The thickness of the diffusion layers and coatings was measured in 20 sections perpendicular to the boundary, and the relative elongation (K) and area (S) of the melted areas were determined every 5 mm. X-ray dispersive microanalysis (EDS) was performed with an EDAX Trident XM 4 spectrometer in point and line scan modes, and the composition of elements from beryllium to americium was determined with a resolution of 1 μm.

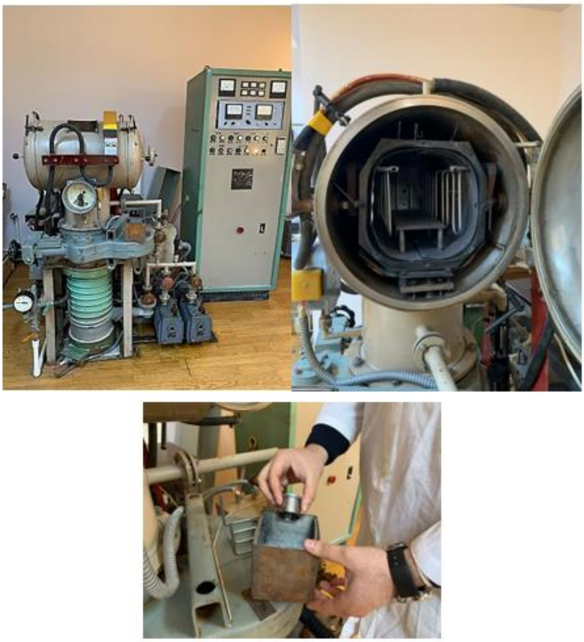


Figure 1. Vacuum diffusion metallization device

X-ray structural analysis was performed on a Bruker D8 ADVANCE ECO diffractometer in Bragg–Brentano geometry with Cu-K α radiation (λ =1.5406 Å), Ni K β -filter and SSD160 detector. When necessary, the layer-by-layer analysis method was applied. The diffusion zone in the diffractograms was more accurately detected by etching in NaOH solution. The study of surface oxide layers was carried out by the sliding beam method with a sliding angle of 0.5°–2°. Phase analysis was performed with the Diffrac.EVA 4.2.1 program.

Surface roughness was evaluated using 253 profilograph-profilometers according to the Ra and Rz parameters in accordance with the GOST 2789-73 standard. At least 6 measurements were made for each sample, and the results were taken as the average value.

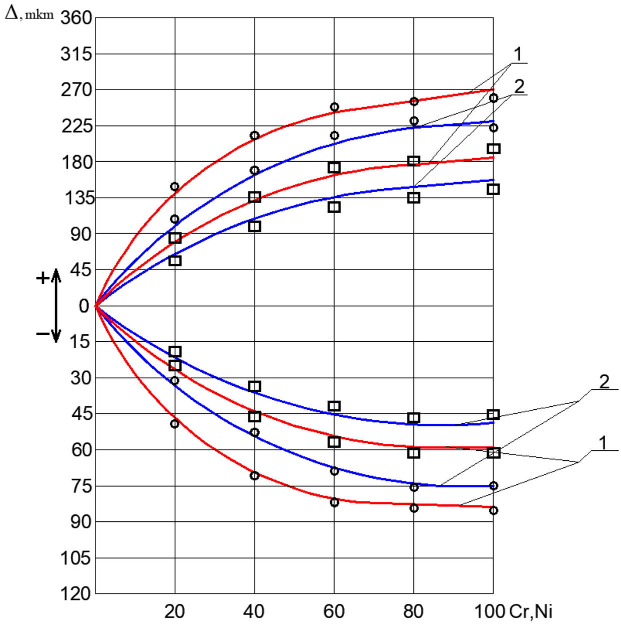
The hardness of the jet-cut part of the 40 mm TQ was measured using the Rockwell and Brinell methods on the TKS-1M device, and the microhardness was measured using the Vickers parameter on the PMT-3M device.

Quality control of chrome-nickel-plated jet etching begins with a visual inspection. The working surface should be light gray, shiny and even. Then the integrity of the diffusion coating is checked by testing in a 20% $CuSO_4$ solution. If, after 2–5 minutes of immersion, a copper precipitate forms on the surface, this indicates damage to the coating.

In conclusion, an experimental research program based on diffusion metallization was developed to improve the reliability of the reactive etching part of the 40 mm TGA. It was envisaged to carry out the process in vacuum, using the vapor phase chromium-nickel plating method using chromium and nickel alloys. The main parameters (temperature, duration, composition) were optimized, and the quality of the coating was evaluated using various test methods.

In the fourth chapter, a study of various types of wear analysis was conducted, taking into account the operating conditions of the jet cutter. Based on the analyses, we can say that the causes of failure of the working surface of the jet cutter are the deformation of the inner surface of the jet cutter as a result of heating, the change in the geometric dimensions of the parts as a result of exposure to impact-abrasive, thermoplastic and mechanical-chemical wear, the formation of residual stress, the decomposition of austenite into separate phases, etc. It was determined that the causes of failure of the working surface of the jet cutter are deformation of the inner surface of the jet cutter as a result of heating, the formation of residual stress, the decomposition of austenite into separate phases, etc. In the worn parts of the working surface of the jet cutter, along with small defects, pits and cracks reaching 250-300 µm in size are observed. During the analysis using analytical methods, it was determined that the average statistical value of the wear of the working surface of the cutter varies between 100-150 µm.

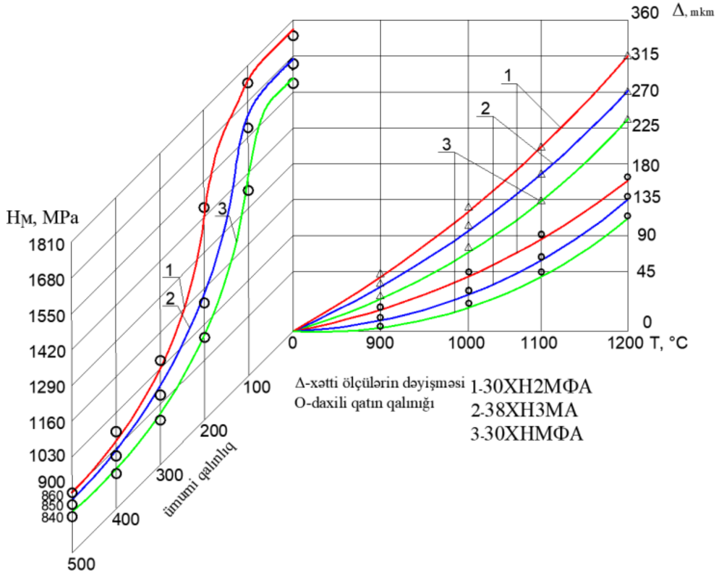
During the study, the reliability and surface hardness of the sample parts were increased by chromium-nickel plating, and the optimal composition of the mixture was experimentally determined. A complex mixture in which both elements were simultaneously deposited in the diffusion coating was applied to the working surface.



Graph 1. Diffusion chromium-nickel plating of 30XH2MΦA steel sample on the change in linear dimensions of the part and the effect of the layer thickness, the amount of chromium and nickel in the mixture (T = 1100 ℃; τ = 4 hours):
1- vapor-phase method in vacuum, 2-gas-phase method
O-O chrome; □-□ nickel

It should be noted that the amount of chromium and nickel in the linear dimensions of the parts, other conditions being the same, during vapor-phase chromium-nickel plating, an increase in the amount of chromium in the mixture above 65%, as well as the amount of nickel above 35%, leads to a deterioration in the surface quality of the sample parts. An increase in the amount of nickel does not give a positive result. During vapor-phase chromium-nickel plating, the maximum change in the diffusion layer of the linear dimensions in all parts is obtained when the mixture contains 60% chromium, 35% nickel and 5% NH_4Cl.

The results of the study of diffusion metallization by the vapor phase method are presented in graphs 1 and 2. It is clear from this that the dependence of the increase in the linear dimensions of the coating layer on the deposition temperature obeys the parabolic and hyperbolic law.



Graph 2. Variation of linear dimensions, internal layer thickness, temperature and microhardness as a function of total layer thickness in vapor phase diffusion metallization (τ= 5 hours)

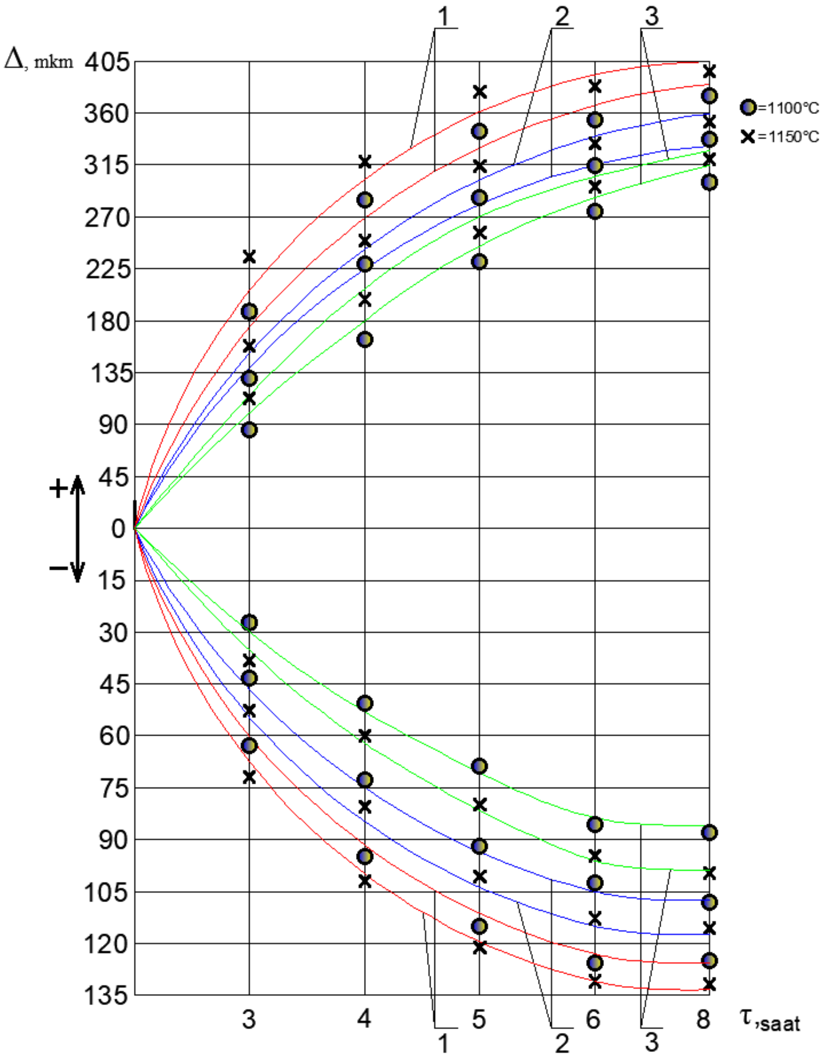
The surface saturated with alloying elements provides indicators of the inner surface of 30-90 μm. The microhardness of the surface is 17000-18000 MPa, which shows that the microhardness of the parts after processing is 2 times higher than that of the coated parts (Figure 2).

Graph 2 shows the linear dimensions of parts and the time-dependent change in the thickness of the coating layer during vacuum vapor-phase chromium-nickel plating. In the samples, the thickness of the coating layer increases intensively for 4, 5 and 6 hours, after which the intensity of the technological process decreases significantly.

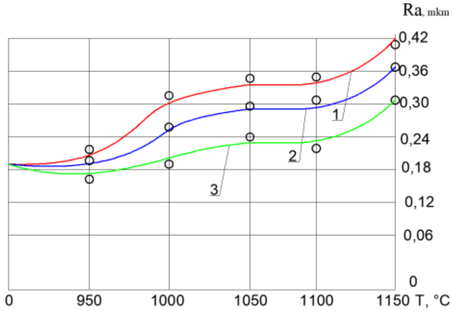
The increase in linear dimensions reached maximum values in 5 hours for steel grades 30ХН2МФА, 38ХН3МА and 30ХНМФА. These values are 315, 270 and 250 micrometers (μm), respectively (graph 2). The thickness of the inner surface increased to 180, 135 and 115 μm, respectively, at the indicated maximum values.

To improve the quality of the coating, vapor-phase diffusion metallization in vacuum was used (Figure 3). The growth and change in linear dimensions and the change in the thickness of the diffusion layer for 30ХН2МФА, 38ХН3МА and 30ХНМФА steels at temperatures of 1100 °C and 1150 °C and for 4.5 and 6 hours are shown in Figure 3. Analysis of Figure 3 shows that it is advisable to carry out the diffusion metallization process in vacuum at a temperature of 1150 °C and for 4 hours. Figure 4 shows the temperature dependence of the surface roughness indicators in the process of vapor-phase diffusion metallization in vacuum.

The vacuum vapor-phase diffusion metallization process was carried out for a period of t=4 hours, and the surface roughness was brought to Ra=0.18 μm as a result of mechanical treatment before the diffusion process. Figure 4 shows the temperature dependence of the roughness of the steels used in the production of the reactive engraving part of the 40 mm TQ in the vacuum vapor-phase diffusion process. It can be seen from the graphs that the roughness changes rapidly for all steels when the temperature is increased to 1150 ^{o}C and is, respectively, Ra=0.18 μm, Ra=0.26 μm and Ra=0.32 μm for the above-mentioned steels.



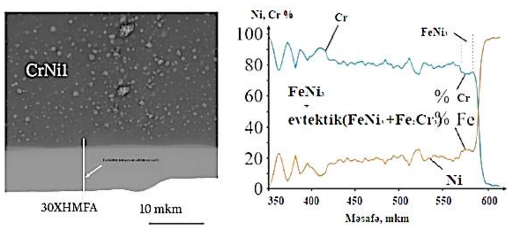
Graph 3. Time dependence graph of changes in linear dimensions of parts and thickness of coating layer in vacuum vapor-phase chromium-nickel plating:
1-(30ХН2МФА), 2-(38ХН3МА), 3-(30ХНМФА)



Graph 4. Temperature dependence of surface roughness in the vapor-phase nanodiffusion process in vacuum:
1-(30XH2MΦA), 2-(38XH3MA), 3-(30XHMΦA)

In the fifth chapter The physicochemical properties of complex diffusion metallization with chromium-nickel plating were studied within the framework of its practical implementation in relation to the application to Cr-Ni multicomponent coatings.

The structure and properties of the interlayer boundary were studied in three different modes of diffusion in chromium-nickel with layers 500-600 mm thick. Analysis of the obtained experimental data allowed us to determine the following. After diffusion neutralization at T=1000 °C, t=4 hours, thin (20-25 μm) local areas form at the interlayer boundary (Fig. 2). The microhardness of the surface does not exceed 40 GPa. A diffusion coating is formed at T=1150 °C, t=5 hours.



a) b)

Figure 2. Image of the layer formed at the interface between layers after vacuum diffusion metallization (a) and the distribution of chemical elements over the thickness (b)

In Figure 3, during diffusion metallization of 30XH2MΦA parts, transition layers of variable thickness (5-80 μm) are formed, the relative elongation is close to 100% and consists of a mixture of Fe(Cr,Ni) + (Fe,Cr,Ni) phases, Fe_3Cr_2, Fe_2Ni_3 inclusions and a quasicrystalline phase $Fe(C_7Ni_2)$. The microstrength of the layers reaches 14-15 GPa.

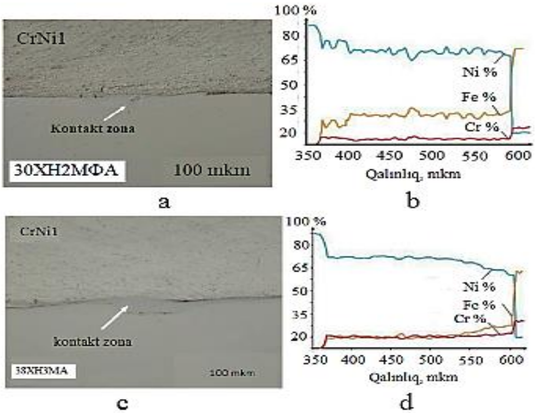


Figure 3. The structure of the transition zone of 30XH2MΦA and 38XH3MA metals (a) after diffusion neutralization in vacuum and the distribution of chemical elements over the thickness

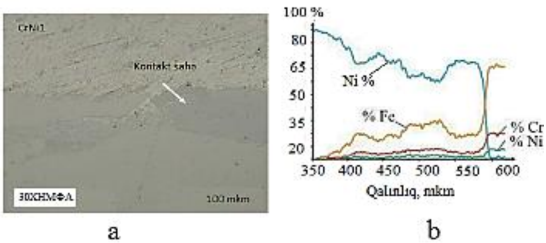


Figure 4. Structure of the transition zone of 30XNMFA metal (a) after diffusion metallization in vacuum and distribution of chemical elements over the thickness

The quantitative results of the experiments are presented in Figure 5, from which it can be seen that the temperature-time dependence of the formation period of intermetallic phase nuclei obeys the exponential law characteristic of mutual concentration diffusion.

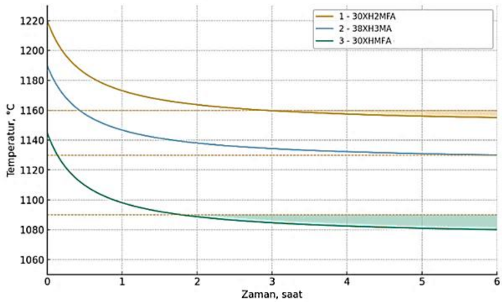


Figure 5. Temperature-time dependence of the formation of intermetallics with steels 1-30XH2MΦA, 2-38XH3MA, 3-30XHMΦA in the CrNi-based complex diffusion metallization method

In the first stage of DZ formation, the formation of the diffusion zone structure begins with the mutual diffusion of contact metals at different speeds.

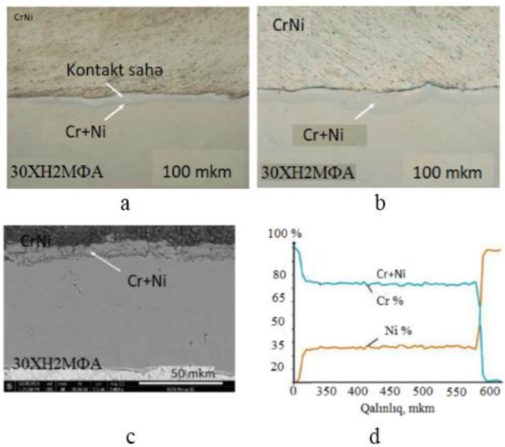


Figure 6. Structural transformation of the interlayer boundary of the metal transition zone and the distribution of chemical elements over the thickness of the DZ after diffusion metallization at 1150 °C for 4 hours (a), 5 hours (b) and 6 hours (c)

In 30XH2MΦA steel (Fig. 7), the presence of carbon does not affect the phase composition of the DZ, but slightly reduces the rate of diffusion interaction with the participation of the solid phase (Fig. 8). At the same time, the morphology of the DZ also changes: as a result of metal-metal fusion, an intermetallic layer of Fe_2Cr_5 is located along the boundary in the form of "fingers", but their size and extension are much smaller than in 38XH3MA steel. On the nickel side, the DZ consists of a two-phase layer of chromium and nickel, the boundary of which is in the form of small "tongues of flame" (Fig. 9). After solid-phase interaction, the microstrength of the Fe_2Cr_5 interlayer is approximately 17-1700 GPa, and the microstrength of the $Ni+FeNi_3$ interlayer is 14-16 GPa.

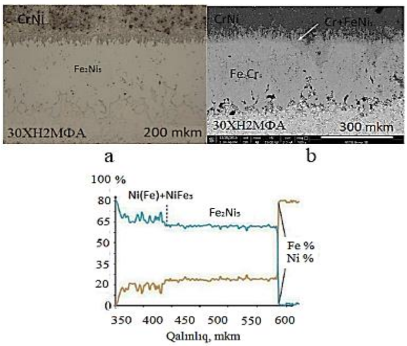


Figure 7. Structure (a), SEM image (b) and distribution of chemical elements according to the interlayer diffusion thickness, T=660 °C, t=3 hours

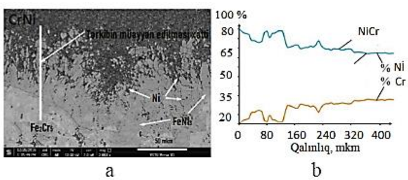


Figure 8. SEM image of the chromium and nickel boundary and distribution of chemical elements in diffusion metallization of 30XHNMFA steel

The nature of the diffusion interaction in the solid-state interaction in the Cr-Ni system is the same as in the 38XHNMFA steel.

The boundary of the DZ with the sample is in the form of small "tongues of flame" with small fragments separated in the nickel matrix, while on the steel side it has a smooth boundary without "fingers" characteristic of the $Cr_3 Ni_2$ intermetallic compound (Fig. 9, a, c). Unlike the DZ formed by the solid-state diffusion regime, no H-(Cr,Fe,Al) metastable inclusions were detected on the nickel side, while the phase composition of the interlayer on the steel side remained unchanged and consisted of the Fe_2Cr_5 intermetallic compound with Cr_2Ni_7 and $(Cr,Fe)_5Al_8$ inclusions (Fig. 9, d).

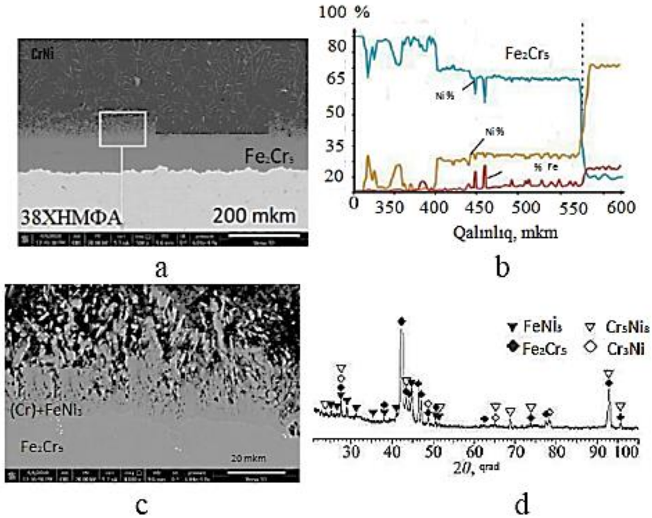
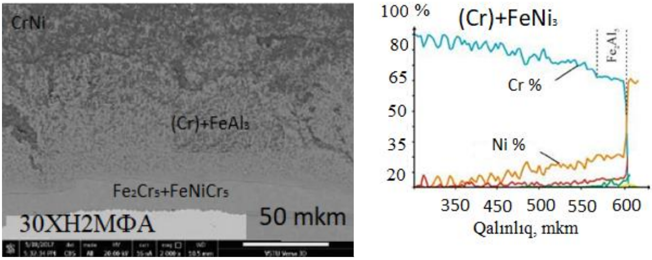


Figure 9. SEM image of vacuum diffusion metallization, 30XH2MΦA steel (c), distribution of chemical elements over its thickness (b) and diffractogram (d), T=1150 °C, t=5 hours

The effect of diffusion neutralization by vacuum chromium-nickel plating on the structure and phase composition of coatings of the Fe-Cr-Ni system - After diffusion metallization at 1100 °C in coatings of the (Fe-Cr-Ni) system, the austenitic structural base of steel grade 30XH2MΦA causes a number of differences in the course of diffusion processes. After a 5-hour storage period, the concentration of Fe in the surface layer of the coating decreased to 37%, and its thickness was 400 μm (Fig. 13).



a b

Figure 10. SEM image of M at the interlayer boundary of the 30XH2MΦA compound (a) and the distribution of chemical elements over its thickness (b), T=1150 °C, t=5 hours

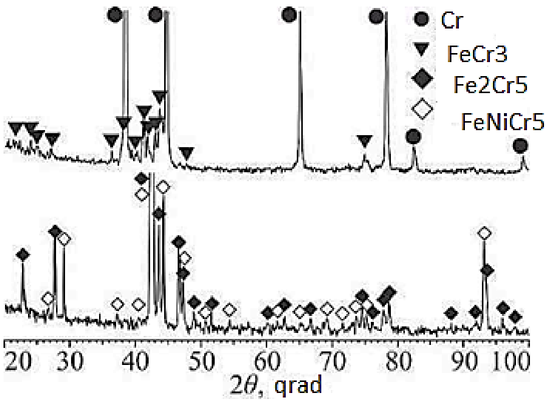
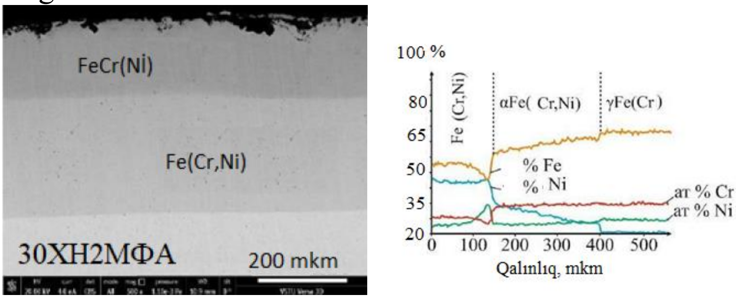


Figure 11. Diffraction pattern of M at the boundary of 30XH2MΦA steel , T=1150 °C, t=5 hours

Analysis of the SEM image (Fig. 11, a) showed that the coating has a layered structure. Based on the data of X-ray structure and energy dispersive analysis (Fig. 11, b), it was determined that the upper layer consists of a solid solution based on the Fe(Cr,Ni) intermetallic compound (thickness 150 μm), while the lower layer is a solid solution of αFe(Fe,Cr,Ni) (thickness 250 μm), and the Ni content gradually decreases towards the 30XH2MΦA steel. The sharp increase in the Ni concentration (up to 35%) observed in the distribution of chemical elements is due to the formation of the β-phase at the boundary of the coating layers (Fig. 13, point I). This phase corresponds to an unconfined solid solution based on the FeNi and CrNi intermetallic compounds and creates favorable conditions for the saturation of this area with Ni. The microstrength of the coating gradually decreases from 18 GPa to 16 GPa throughout its thickness, while the microstrength of the steel base is at 9.4-8.6 GPa.



a b

Figure 12. SEM image of the structure of the diffusion coating after diffusion chromium-nickel plating on 30XH2MФA steel, 1100 °C, 5 hours (a) and the distribution of chemical elements over its thickness (b)

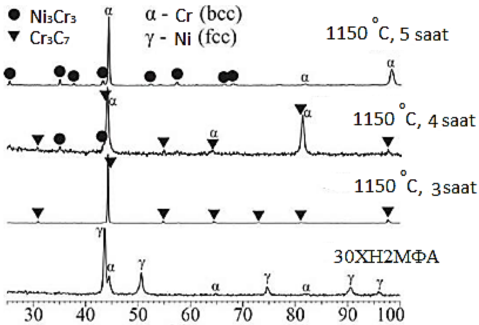


Figure 13. Diffractograms taken from the surface of 30XH2MФA steel (a) and diffusion chromium-nickel coating, T=1100 °C, t=5 hours

The change in chemical composition caused the structure to transition to a two-phase region (Fig. 14). This is confirmed by the two-phase structure observed in the SEM image taken at a magnification of ×60000. The surface microhardness of the coating decreased to 17-18 GPa, while the microhardness of the steel was 14-15 GPa. Structure of the coating of 38XH3MA steel and distribution of chemical elements over the thickness, T=1150 °C, t=5 hours

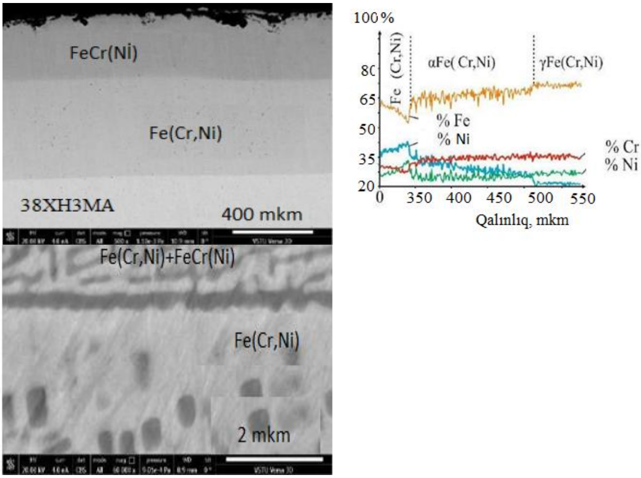


Figure 14. SEM image of the structure of the diffusion coating and the distribution of chemical elements over the thickness, T=1150 °C, t=5 hours

The sixth chapter presents the results of a comprehensive study on the tribological and corrosion resistance of vacuum vapor-phase diffusion chromium-nickel coatings applied to the surface of 40 mm TQ jet engraving parts. The goal is to extend the service life of jet engraving by determining the wear and corrosion resistance of the coatings in friction pairs with various materials.

Tribotechnical properties were measured on a friction machine of the brand II-5018, according to the “disk-pad” scheme, under a pressure of 2.7 MPa and a speed of 1.3 m/s, in an environment lubricated with diesel oil with quartz abrasive. The wear of rollers and pads of chromium and chromium-nickel coated steel (30XH2MФA, 38XH3MA and 30XHMФA) was evaluated both by mass loss and by changes in the friction coefficient.

The results obtained show that: Carbide coatings showed high performance when rubbing against cast iron. Wear with titanated pads was 20 mg, and with chrome-plated pads - 24 mg. The coefficient of friction is 0.17 and 0.18, respectively. Chrome-nickel-plated pads work more stably with cast iron and steel than titanated ones and show less wear. The lowest coefficient of friction was recorded as 0.11.

Diffusion coatings were tested under severe hydrothermal conditions — in water at a temperature of 380 °C, under a pressure of 18 MPa, and in steam heated to 1150 °C. The results show that Ni additions, especially when used in combination with chromium, prevent the formation of Fe oxides on the metal surface and significantly reduce mass loss. A thin and passive protective layer is formed in the structure of chromium-nickel-plated coatings, which limits the spread of the corrosion process. In aggressive environments such as KCl, chromium diffusion coatings are highly corroded, but the presence of Ni slows down this process.

CONCLUSIONS

1. According to the technological requirements of the manufacturer, the service life of the jet-carrying part of the 40 mm TQ has a resource of 8000-10000 shots. However, during operation, the resource of shots is 5000 shots. This means that the reserve factor decreases by 1.6-2 times [1].

2. The main reason for the failure of a jet engraving part operating in extreme conditions under the pressure of gunpowder gases is impact-abrasive, thermoplastic, thermoerosion, thermochemical and mechanical-chemical wear. It is possible to extend the service life and ensure the reliability of the jet engraving by applying a coating of vacuum diffusion metallization to the working surface at the junction of the "barrel and sleeve" to ensure microhardness and reliability [2].

3. The maximum temperature limits resulting from thermal effects on the working surface of the reactive engraving were modeled. It was proven that an increase in the critical temperature leads to the formation of plastic deformations and cracks on the surface [3].

4. The theoretical basis of local deformations occurring under the influence of mechanical stresses formed on the surface of the jet cavity at the critical temperature moment has been studied. As a result, it has been determined that thermal shocks are mostly confined to the surface layer and do not spread to the core [4,5].

5. The dissertation investigated the mechanism of formation of the layer obtained on the working surface of the jet engraving of a 40 mm TQ and ways to increase its thickness. It was shown that the change in the linear dimensions of the working parts of the jet engraving occurs mainly depending on the diffusion metallization modes. The conducted studies made it possible to determine the effect of the diffusion metallization mode on the linear dimensions, microstructure, phase composition and other physical and mechanical properties of the working surface of the jet engraving [6].

6. the diffusion metallization reinforcement were determined. It was found that the thickness and microhardness of the reinforced layer formed during the diffusion metallization reinforcement process

are sufficient to meet the normal operating requirements of the precessional part with increased surface strength [7].

7. Optimal diffusion regimes in surface reinforcement and the main technological parameters affecting the formation of the enrichment layer have been determined. The thickness of the reinforced layer and surface hardness obtained as a result of the proposed diffusion regimes fully ensure the technological reliability of the reactive carving of the 40 mm TQ [8,9].

8. The increase in the duration of diffusion metallization at the interlayer boundary of the 30ХН2МФА, 38ХНМФА and 30ХНМФА steels used in the study leads to the transformation of its structure in the Fe-Cr-Ni system from the Ni+$FeCr_3$ eutectic mixture to the Fe_2Ni_5 +$FeCr_3$ intermetallic mixture. The formation of $(Cr,Fe)_5$ intermetallic inclusions in the composition of the intermediate layer during nickel deposition reduces the hardness of the diffusion zone from 16 GPa to 15 GPa, while co-deposition with chromium and nickel increases the hardness to 17-18 Gpa [10,11].

9. In the studied range, the carbon content in the steel does not significantly affect the growth rate of the diffusion zone during vacuum diffusion metallization. The deposition of the base material with chromium and nickel increases its growth rate, but this increase has optimal values when using base components with a content of 65% Cr and 35% Ni [12,13].

10. Based on X-ray and metallographic analyses, it was found that the main reinforcing phase of the diffusion layer is chromium carbide –Cr_7C_3 . After the carbide layer on the upper surface, there are transitional and decarburized layers. The material and the core of the layer do not contain residual austenite in the area after the carbide layer (sensitivity of the method – 5%). The structure of the core is troostosorbite [14].

11. Tribotechnical properties of 40 mm TQ jet groove parts after diffusion metallization were studied on the II-5018 friction machine. The results of the experiments show that the workability of surface-strengthened parts increased by 2-3 times compared to serial parts [15].

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The author's personal participation in published works

In works [5, 7, 8, 13, 14], the plaintiff formulated the problem, conducted theoretical research, and conducted experimental studies.

Works [1, 2, 3, 4, 6, 11, 12, 15] were performed by the authors at an equal level.

Works [9, 10] were performed independently by the author.

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