

REPUBLIC OF AZERBAIJAN

On the rights of the manuscript

ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

**IMPROVING THE STRUCTURE AND PROPERTIES OF
STRUCTURAL STEELS BY SURFACE PLASTIC
DEFORMATION METHOD**

Specialty: 3312.01– Materials technology

Field of science: Technical sciences

Applicant: **Gashang Ramazan Hamzayeva**

BAKU-2025

The work was performed at the Department of “Metallurgy and Materials Technology” of the “Azerbaijan Technical University” PLE.

Scientific supervisor: Doctor of Technology, professor
Arif Tapdig Mammadov

Official opponents: Doctor of technical sciences, professor
Abbas Abdurəhman Guvalov

Doctor of technical sciences, professor
Ugurlu Muhammad Nadirov

Doctor of philosophy in technical,
associate professor
Vurgun Fakhraddin Gahramanov

BFD2.09 One-time dissertation council, established on the basis of the FD2.09 Dissertation Council operating under the Higher Attestation Commission under the President of the Republic of Azerbaijan, “Azerbaijan Technical University” PLE.

Chairman of the Dissertation Council: Doctor of technical sciences, professor

Alakbar Gulahmad Huseynov

Scientific Secretary of the Dissertation Council:

Candidate of technical sciences,
associate professor
Fuzuli Rasul Rasulov

Chairman of the scientific seminar: Honored scientist, doctor
of technical sciences, professor

Rafiq Gurban Huseynov

GENERAL CHARACTERISTICS OF THE WORK

Relevance of the topic and degree of development. The development of science and technology requires the development and application of new techniques and technologies in production, as well as effective methods that enhance the mechanical and operational properties of various steels and alloys. Despite numerous scientific and experimental studies, the issues of increasing the reliability and durability of components, assemblies, machines, and structures generally remain highly relevant.

Considering the operation of various machines, mechanisms, and structures under high-stress conditions, special attention should be paid to the issues of improving the operational properties of their various elements. Increasing the structural strength of machine components made of high-strength steels and alloys is considered a priority. The use of high-strength steel and alloys should ensure the load-bearing capacity of products while reducing their weight.

The complex and demanding requirements of modern mechanical engineering and construction pose serious challenges to scientists in this field.

It is difficult to solve these problems using traditional thermal and thermomechanical methods. Therefore, it is important to explore and develop more effective methods for addressing the challenges ahead. Currently, extensive experience has been accumulated in this field regarding the application of new strengthening methods aimed at increasing the reliability and durability of various components of machines and structures.

It is not always easy to choose the optimal reinforcement method for a given part from the numerous reinforcement methods. Therefore, it is necessary to compare the effectiveness of various methods applied to increase structural strength.

Numerous experimental and theoretical studies conducted by scientists working on the problem of strengthening metals and alloys (D.D.Papshev, M.A.Balter, Y.S.Schneider, R.M.Gurov etc.) show that the most effective method for strengthening parts operating under various loading conditions is surface plastic deformation (SPD).

Hardening processes have a wide range of applications as a final surface treatment method for machine components. The SPD process is carried out by deforming the surface's micro-roughness's without removing chips from the component's surface. As a result, a significant reduction in surface roughness, hardening of the upper layers of the component, and the formation of compressive residual stresses are observed.

The impact property of SPD allows for the full realization of the mechanical and operational properties of high-strength steels. This strengthening method enables the application of steel and alloys for components that have structural and technological stress collectors and operate even under extreme load conditions.

The use of SPD in combination with other reinforcement methods gives good results. Combined reinforcement methods should be considered as an additional resource to improve the performance characteristics of machine parts. The combination of SPD with other reinforcement methods (volumetric plastic deformation + SPD, surface quenching + SPD, chemical thermal treatment + SPD, etc.) makes it possible to use the advantages and capabilities of each of these methods separately and thereby meet various requirements. Compared to the application of each method separately, the application of combined methods results in significantly higher values of static and cyclic strength indicators.

SPD increases the fatigue strength, surface hardness, wear resistance, contact resistance, and corrosion resistance of parts made of structural steel used in machinery and structures, thereby ensuring the longevity and reliable operation of machinery and structures.

Various SPD methods are successfully applied in heavy transport, automotive, agricultural enterprises, and in the mechanical engineering and instrument-making industries.

A review of the existing literature shows that there is no information at all about the application of SPD to structural steels, in other words, research on the strengthening of structural steels by SPD has not been conducted or is at a low level. Therefore, conducting scientific research in this field proves the relevance of the dissertation.

Object and subject of the research. Cylindrical samples with a diameter of 20 *mm* and a length of 150 *mm* made of several construction steels were taken as the object of the research. The mechanical and operational properties of the construction steels (BCТ3СП, 10Г2С1, 15ХГ2СМФР and 12ГН2МФАЮ) studied as a result of surface-plastic deformation of the samples taken as the subject of the research.

The purpose and duties of the research. It consists of studying the effect of surface-plastic deformation processes on the formation of the structure, stress state, and mechanical and operational properties of structural steel.

To achieve this goal, the following issues have been set.

- Investigation of the role of surface-plastic deformation methods (ball rolling and diamond smoothing) in increasing the strength properties of structural steels.
- Justification of an effective method of surface-plastic deformation in order to increase the reliability and durability of metal structures.
- Study of the effect of surface-plastic deformation methods on the geometric parameters (surface roughness) and physical-mechanical properties (residual stresses and embrittlement of the upper layers of the metal) of the structural steels studied.
- Research into improving the performance characteristics of structural steels used in the manufacture of construction structures.

Method of research. The issues raised during the work were resolved on the basis of theoretical and experimental research conducted in laboratory and production conditions. In the process of conducting research to study the effect of SPD on the structure and properties of samples made of accepted construction steels, modern devices and equipment, testing facilities, microscopes, and dynamometric devices specially designed for this purpose were used. The capabilities of computer technologies have been widely applied in conducting research.

The main provisions of the defense.

1. Experimental study of the effect of surface-plastic deformation methods on the quality of the surface layers of components and selection of a rational method for increasing the operational properties of structural steels.

2. Study of the mechanism of influence of the technological process of reinforcement using the selected optimal surface-plastic deformation method on the fatigue strength, wear resistance, corrosion resistance and other mechanical and operational properties of products.

3. Conducting comparative experiments under operating conditions on unreinforced and reinforced components made of structural steel, using the surface plastic deformation method.

4. Research and development of the application of the technological process for strengthening structural steels using the SPD method in production and determination of the economic impact of the proposed technological process.

Accuracy of results. The accuracy of the results obtained has been confirmed by studies conducted using modern equipment, devices, measuring instruments, devices, and supplies.

The scientific innovation of the research. A correlation has been established between the formation of the structure and changes in the properties of steels (BC13CII, 10Г2С1, 12ГН2МФАО, 15ХГ2СМФР), which are widely used in the manufacture of construction metal structures, and the parameters of SPD.

A mathematical model of the dependence of surface hardness and roughness on the main parameters of ball rolling and diamond smoothing processes for the studied steels has been developed. The obtained dependencies made it possible to select rational SPD regimes to ensure the properties of structural steels.

As a result of the research conducted, optimal diamond smoothing regimes applied to strengthen structural steels have been identified. It has been determined that during diamond smoothing, residual austenite is decomposed and transformed into martensite.

Contrary to some opinions in the literature, it has been established that the impact toughness of structural steels after diamond

smoothing is not lower than their toughness after quenching + medium-temperature annealing. In some cases, the impact toughness of polished steels is even 2-3% higher.

According to a number of authors, roughness of parts operating under high loads and shock loads lead to their premature failure as a result of brittle fracture. However, our experimental studies yield opposite results. Tests show that the surface-plastic deformation method, carried out by means of diamond smoothing, has a significant positive effect on the resistance of the material to crack development.

Theoretical and practical significance of the research. The results of computer modeling can be used to optimize SPD processes.

The results of the research work can be used in enterprises producing metal structures and products made of structural steel, as well as in research institutes. Applying the results in production serves to increase the longevity of construction structures and products.

Approval and application. The main content of the dissertation work was published in 16 articles and conference proceedings. 8 of them are scientific articles (2 articles in foreign scientific journals indexed in international databases, 6 articles in republican journals included in the list of the AAK), and 8 are abstracts of reports published at international and republican conferences.

The main provisions of the dissertation work were discussed and approved at scientific-practical conferences and seminars held in the country and abroad.

1. Proceedings of the International Scientific Conference. "International" Trends in Science and Technology" Warsaw, Poland. October 17, 2017.
2. International Scientific Conference of faculty, doctoral students and young researchers dedicated to the 100th anniversary of the Azerbaijan Democratic Republic. Baku, AzUAC, April 26-27, 2018.
3. Republican Scientific-Practical Conference. "Modern problems of using technological machines in construction production", Baku, 2019.

4. 42nd Scientific Conference of Students and Master's Students Dedicated to the 97th Anniversary of the National Leader Heydar Aliyev. Baku, AzUAC, 2020.
5. 42nd Scientific Conference of Students and Master's Students Dedicated to the 97th Anniversary of the National Leader Heydar Aliyev. Baku, AzUAC, 2020.
6. Republican Scientific and Technical Conference dedicated to the 100th anniversary of the National Leader Heydar Aliyev "Prospects for the application of innovative techniques and technologies in production". Baku, December 23, 2023.
7. XII International Scientific and Practical Conference Science and Technology. Collection of theses. Almaty, Kazakhstan June 30, 2024.
8. International scientific-technical conference Modern machine-building systems, technologies and innovations – Voronezh: 06.03.2025.

Name of the organization where the dissertation work was performed: Azerbaijan Technical University, Department of Metallurgy and materials technology.

Personal participation of the author. Conducting experimental research in the dissertation, processing the results obtained, and preparing the materials for publication were mainly carried out by the author. The author's share in the scientific works he co-authored was decisive.

The volume of the structural sections of dissertation separately and the general volume with the sign. The total volume of the dissertation work is 170 pages written in computer text, consisting of 4 chapters, 26 figures, 23 graphs, 14 tables, a list of references with 173 names and appendices.

The structure of the dissertation work is an introduction of 9785, the first chapter of 66287, the second chapter of 46078, the third chapter of 48662, the fourth chapter of 31103, the conclusion of 5217, the list of references of 28184 characters and appendices. The total volume of the dissertation is 207132 characters (excluding the table of contents, graphs, tables, figures and the list of references).

MAIN CONTENT OF THE STUDY

At the entrance justifies the relevance of the subject and characterizes the degree of its elaboration; the purpose and duties of the research, methods are indicated; the main provisions put forward for defense, the scientific innovation of the research; information on its approval and application, the name of the organization where the work was performed, the separate and total volume of structural sections are provided.

In the first chapter presents sufficient material on the production and use of reinforced and high-strength structural steels. Thermal and thermomechanical processing have become effective methods for ensuring the structural strength of these steels in large-scale metal production.

However, the reinforcement methods mentioned above cannot fully ensure the structural strength of the construction steels used in the manufacture of metal structures and products. Therefore, it is necessary to develop an advanced technological process that can provide the required mechanical and operational characteristics of structural steels used in metal structures.

To successfully select an effective strengthening method for improving the mechanical and performance properties of structural steels, it is necessary to analyze and study the operating conditions and requirements of metal products and structures.

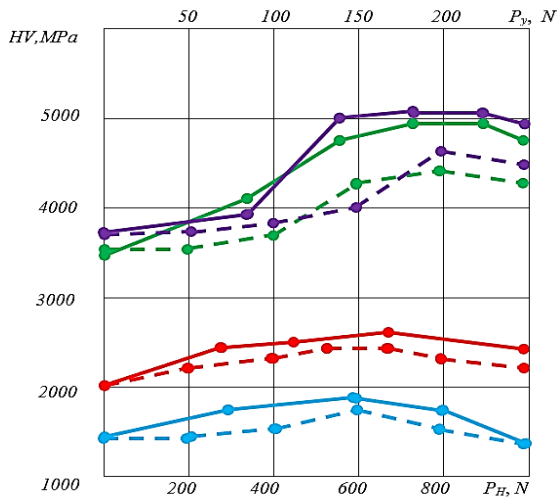
A literature review shows that ball rolling and diamond grinding offer many advantages over other surface plastic deformation (SPD) methods. These operations are simple, require little labor, do not need special equipment or custom design, and are typically performed on universal machines. Additionally, the technological costs are relatively low because there is no need for expensive equipment or complex setups to carry out the grinding and smoothing processes. Both methods can be performed at high speed and with high efficiency.

Thus, the analysis shows that ball rolling and diamond lapping are highly effective methods for increasing the tolerance limit, contact

strength, corrosion resistance, and wear resistance of various materials and reducing surface roughness.

In the second chapter, to study the effect of SPD on the surface hardness of samples made of BCт3cп, 10Г2C1, 15ХГ2СМФР and 12ГН2МФАЮ steels, the first batch of them was subjected to rolling with a ball with a diameter of 5 mm at a speed of 56 m/min after heat treatment. The feed rate was set $S_o=0.12$ mm/cycle, with the number of working passes $i=1$. The second batch of samples from these steels was smoothed using a diamond tip with a radius of $R_{sf}=2$ mm. Processing speed was $V=56$ m/min, the feed rate $S_b=0.06$ mm/cycle, and the number of passes $i=1$ [12]¹.

The results obtained are presented in graph 1.



Graph 1. Dependence of surface hardness on normal force:

■ ■ ■ – roller polishing; — — — – diamond smoothing;

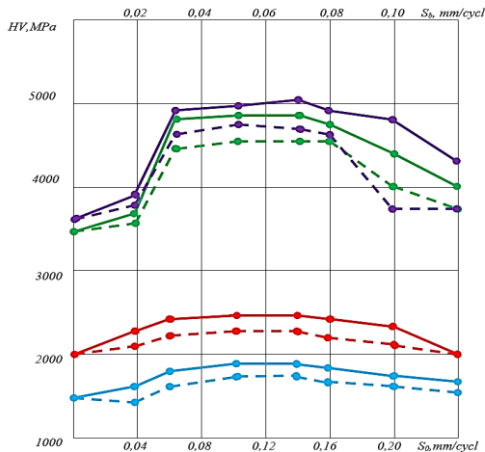
■ – BCт3cп; ■ – 10Г2C1; ■ – 15ХГ2СМФР; ■ – 12ГН2МФАЮ

¹ Hamzayeva, G.R. Mechanical properties of structural steel after diamond burnishing // - Moskva: Russian Engineering Research, -2023. vol 43, №12, -pp.1531-1534.

The increase in surface hardness during diamond grinding is higher than during ball grinding, and this value is achieved at a lower force. The increase in hardness (420 HV) of samples made of BCТ3cп and 10Г2C1 steels was obtained during diamond grinding at a force of 150-160 N.

As a result of ball rolling, the increase in the surface hardness of these steels was 350 HV, and this value was obtained at a force of 600-700 N. Similar results were obtained for 15ХГ2СМФР and 12ГН2МФАЮ steels. However, the maximum hardness for these steels is obtained at relatively high forces.

The effect of the grinding on the surface hardness of the steels under study during ball rolling and diamond polishing was studied (graph 2). In this case, the force was taken as $P_H = 800\text{ N}$ for rolling, and $P_y = 180\text{ N}$ for polishing [4].



Graph 2. Dependence of surface hardness on feed rate:

■ ■ ■ – roller polishing; ■ ■ ■ – diamond smoothing;
— – BCТ3cп; — – 10Г2C1; — – 15ХГ2СМФР; — – 12ГН2МФАЮ

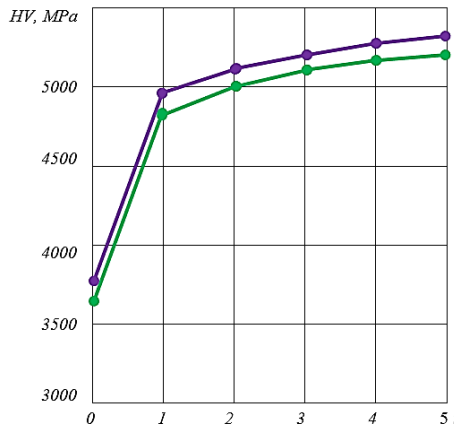
As can be seen from the obtained graphs, the increase in the wear rate of samples made of steels BCТ3cп, 10Г2C1, 15ХГ2СМФР and 12ГН2МФАЮ from 0.06 to 0.16 mm/cycle. during ball rolling and

from 0.03 to 0.07 *mm/cycle*. during diamond grinding practically does not affect the surface hardness.

Since the yield value determines the repetitive load applied to each point on the surface of the processed material, it has a significant impact on the degree of hardening.

Research has shown that when the rate of advance decreases below 0.03 *mm/cycle* during diamond grinding and below 0.06 *mm/cycle* during ball grinding, excessive embrittlement occurs and the surface hardness of the metal decreases slightly, as the number of repetitions of the load on each point increases [4]².

The effect of the number of passes on hardening was studied for 15XГ2СМФР and 12ГН2МФАЮ steels. As can be seen from figure 3, for both steels, hardening (surface hardness) during diamond polishing occurs mainly in the first pass.



Graph 3. Dependence of surface hardness on the number of passes during diamond smoothing:

■ -15XГ2СМФР; ■ -12ГН2МФАЮ

Although increasing the number of passes to five results in a slight increase in surface hardness, it is not recommended, as

² Hamzayeva, G.R., Mammadov, A.T., Aslanov, T.I., On the effect of surface plastic deformation parameters on surface hardness. Scientific Works of ATU (Azerbaijan Technical University), No. 3, Baku: -2018, pp. 27–32.

productivity decreases significantly.

The height of the microroughness resulting from SPD is more strongly influenced by the processing force. The results of experimental studies conducted to determine the effect of rolling and smoothing forces on the average surface roughness (R_a) of samples made from the structural steels under study are presented in the form of graphs. These results are shown in graph 4.

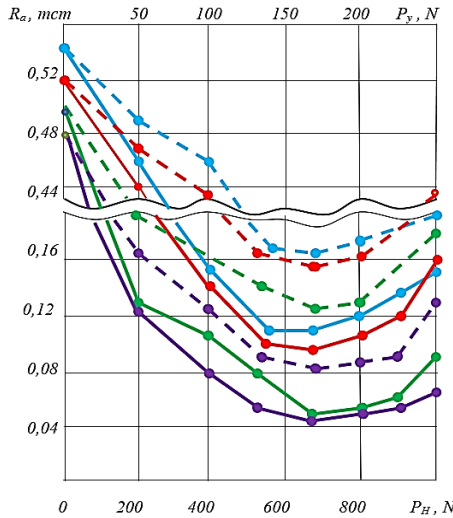


Chart 4. Dependence of average R_a on processing force:

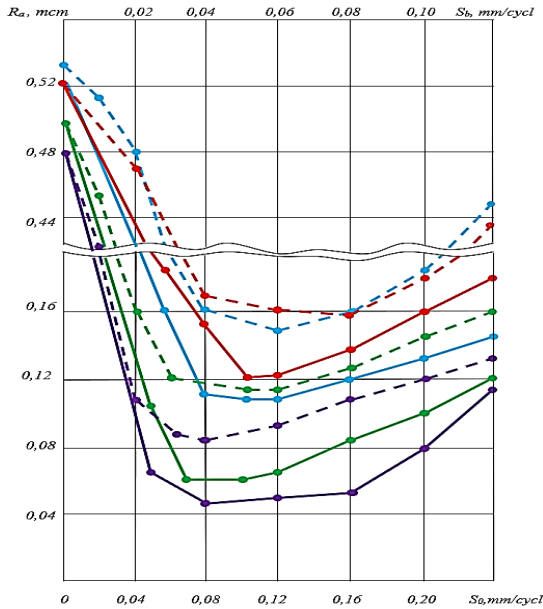
■ ■ ■ – roller polishing; — — — – diamond smoothing;

— — — BCт3cn; — — — -10Г2С1; — — — -15ХГ2СМФР; — — — -12ГН2МФАЮ

The change in the processing force at the first field limit causes a decrease in roughness. Because in this case, the contact of the deforming tool with the processed material occurs at the top of the protrusions of the roughness. After a certain value of the deforming force, despite its increase, the decrease in roughness stops.

Changing the transmission during SPD has a significant impact on the average surface roughness. The dependence of surface roughness on the processing feed rate for samples made of BCт3cn, 10Г2С1, 15ХГ2СМФР, and 12ГН2МФАЮ steels, shown in graph 5, indicates that for all steels, the minimum roughness occurs at feed rates

of 0.06–0.14 mm/cycle during rolling and 0.03–0.07 mm/cycle during smoothing. When the feed rate exceeds these values for either method, surface roughness increases significantly [10]³.



Graph 5. Dependence of Ra on the feed rate:

- - - – roller polishing; — – diamond smoothing;
— – BCт3cn; — – -10Г2С1; — – -15ХГ2СМФР; — – -12ГН2МФАЮ

The fact that the yield value is higher than the indicated value for both reinforcement methods leads to a significant increase in surface roughness.

The results of our experimental studies show that the average numerical inclination of the profile decreases by 3-6 times during ball rolling and by 5-10 times during diamond smoothing.

³ Hamzayeva, G.R. The effect of feed rate and number of passes during diamond burnishing on surface roughness. Problems of Computational Mechanics and Structural Strength, No. 34, -Dnipro: -2022, pp. 16–22.

The profilogram shows that there is a significant difference between the roughness of the polished sample and the roughness of the smoothed samples (figure 1). On the other hand, with increasing diamond smoothing force, the height and shape of the roughness change in a positive direction (the height decreases, the support area increases).

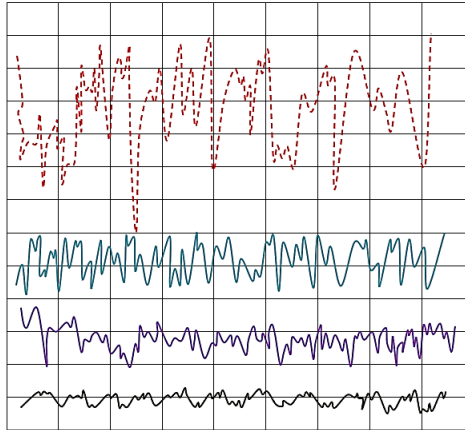


Figure 1. Surface profilograms of samples made of 15XГ2CMΦP steel:

vertical magnification x 60000, horizontal magnification x 200

- ■ ■ – polishing;
- – diamond smoothing ($P_{сж} = 50\text{ N}$);
- – diamond smoothing ($P_{сж} = 130\text{ N}$);
- – diamond smoothing ($P_{сж} = 150\text{ N}$).

Testing the mechanical properties of polished and diamond-polished samples of BCТ3cп and 10Г2C1 steels with varying surface hardness showed that diamond smoothing has almost no effect on their tensile and yield strength, with an increase of only about 1%. In contrast, diamond smoothing improves the tensile and yield strength of 15XГ2CMΦP and 12ГH2MΦAЮ steels by 6–10% compared to polishing alone [5]⁴.

⁴ Hamzayeva, G.R., & Aslanov, T.I. On the effect of surface plastic deformation on the mechanical properties of structural steel. Scientific-Practical Conference on Modern Problems of the Use of Technological Machines in Construction Production, Baku: -2019, pp. 22–25.

The main factor affecting the structural state of the upper layers of the metal during diamond polishing is the plastic deformation that occurs during solidification. Plastic deformation occurs by sliding along planes in certain areas of the crystals. As a result, large crystals are crushed and the structure of the upper layers becomes fine-grained (*textured*).

The microstructure of the upper layers of the studied 15XГ2CMΦP steel before and after strengthening by diamond smoothing is shown in figure 2. Following diamond smoothing, traces of plastic deformation are clearly visible in the upper layers of the metal. As a result of this process, the martensite needles become finer and are elongated in the direction of deformation [8]⁵.

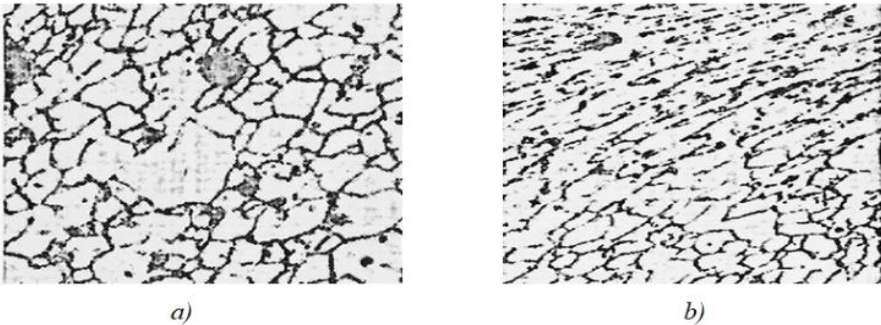
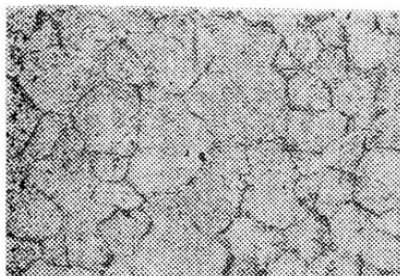


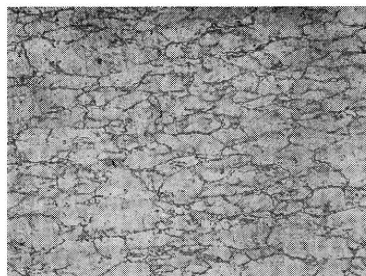
Figure 2. Microstructure of the top layer of 15XГ2CMΦP steel ($\times 800$) before (a) and after (b) diamond smoothing

A comparison of the microstructures after polishing and diamond smoothing for the other steels studied is presented in figures 3-5.

⁵ Hamzayeva, G.R. Structural-phase transformations during diamond burnishing. Scientific Works of AUAC (Azerbaijan University of Architecture and Construction), No. 2, Baku: -2022, pp. 92–96.



a)



b)

Figure 3. Microstructure of the top layer of 12ГН2МФАЮ steel ($\times 800$) before (a) and after (b) diamond smoothing

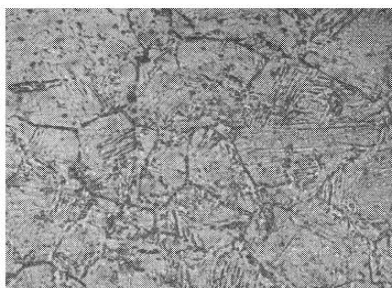


a)



b)

Figure 4. Microstructure of the top layer of 10Г2С1 steel ($\times 800$) before (a) and after (b) diamond smoothing



a)



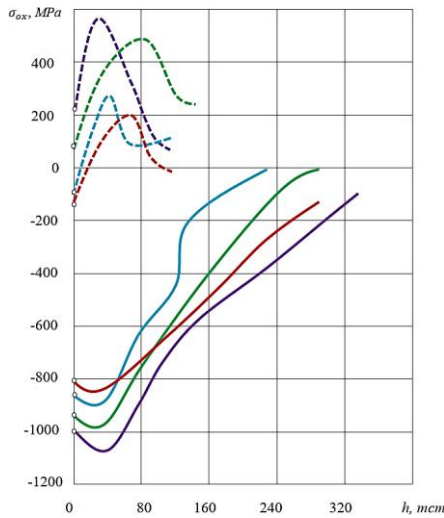
b)

Figure 5. Microstructure of the top layer of ВСТ3сп steel ($\times 800$) before (a) and after (b) diamond smoothing

In the third chapter, when studying tangential and axial residual stresses in steel, two types of samples were used: a ring with an outer diameter of 20 mm, an inner diameter of 14 mm, and a thickness of ≤ 0.4 mm (the ring is cut from the middle of the cylindrical sample); and a plate with a width of 5 mm and a thickness of 3 mm.

Axial stresses in the samples were determined by removing stress-affected layers from semi-cylindrical specimens. In this case, a 2ПКБ-30-200 strain gauge was used. The removal was carried out through electrochemical etching in an electrolyte bath with the following composition: orthophosphoric acid – 60%, sulfuric acid – 15%, chromic anhydride – 10%, and water – 15%. The electrolyte temperature was maintained at 30 °C.

Graph 6 presents comparative plots of axial residual stresses in the upper layers of the studied steels after polishing and diamond smoothing.



Graph 6. Distribution of axial residual stresses in the upper layers of the metal:

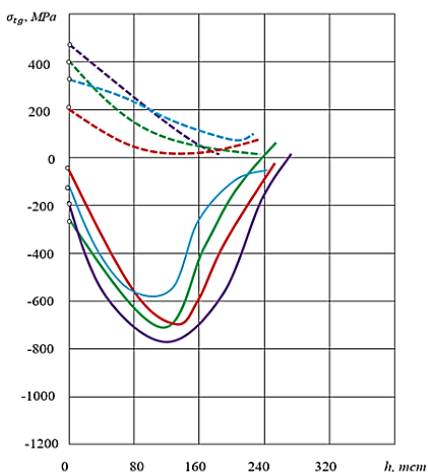
■■■ – after polishing; ■■■ – after smoothing;
 ■ – BCт3cп; ■ – 10Г2C1; ■ – 15ХГ2СМФР; ■ – 12ГН2МФАЮ

As shown by the curves, axial compressive residual stresses of 100-120 MPa are formed on the surface of BCт3cп and 10Г2C1 steel

samples after polishing. At a depth of 10-20 *mcm* from the surface, these compressive stresses transition into tensile stresses reaching approximately 200 *MPa*. In contrast, only tensile residual stresses are observed on the surface of 15XГ2СМФР and 12ГН2МФАЮ steels following polishing [14]⁶.

Unlike polishing, the diamond smoothing process induces compressive residual stresses in the upper layers of 15XГ2СМФР and 12ГН2МФАЮ steel samples. After smoothing, axial compressive stress reaches values of 800-1100 *MPa*. These stresses have a beneficial effect on the operational performance of the components.

According to our experiments, the nature and value of the surface distribution of tangential residual stresses determined in ring-shaped samples made of ВСТ3СН, 10Г2С1, 15XГ2СМФР and 12ГН2МФАЮ steels before and after diamond polishing are shown in graph 7.



Graph 7. Distribution of tangential residual stresses on the surface:

■ ■ ■ – after polishing; — — — — after smoothing;
 ■ — ВСТ3СН; ■ — 10Г2С1; ■ — 15XГ2СМФР; ■ — 12ГН2МФАЮ

⁶ Hamzaeva, G.R. Residual stresses in surface plastic deformation. XII International Scientific-Practical Conference "Science and Technologies" – Book of Abstracts, Almaty: -2024, June 30, pp. 23–24.

As shown in the graphs, tensile residual stresses appear in the upper layers of the polished samples, negatively affecting the as shown in the graphs, tensile residual stresses appear in the upper layers of the polished samples, negatively affecting the material's operational properties. The magnitude of these stresses' ranges from 250 to 500 MPa. After diamond smoothing, these tensile stresses are converted into compressive stresses.

Impact viscosity characterizes a material's resistance to rupture under dynamic loading conditions. Impact toughness is determined by testing specimens in a Charpy impact tester, where stress concentrators (notches) are introduced. The experiment was conducted on samples with a square cross-section of 10×10 mm and a length of 55 mm in accordance with ГОСТ 9454-78. The results of the impact toughness tests are given in table 1.

Table 1
Impact viscosity of diamond-finished samples

Steel grade	Processing type	Impact viscosity KCU^{+20} , Mc/m^2
BCт3cp	Quenching, annealing 300°C + polishing	0.68
	Quenching, annealing 300°C + polishing + smoothing	0.71
10Г2С1	Quenching, annealing 300 °C + polishing	0.62
	Quenching, annealing 300°C + polishing + smoothing	0.66
15ХГ2СМФР	Quenching, annealing 300°C + polishing	0.55
	Quenching, annealing 300°C + polishing + smoothing	0.53
12ГХ2МФАЮ	Quenching, annealing 300°C + polishing	0.88
	Quenching, annealing 300°C + polishing + smoothing	0.85

The results obtained show that the toughness of diamond-polished steels is practically the same as the impact toughness of polished steels.

To fully characterize the viscosity of metals, dispersion viscosity tests must be conducted. Dispersion viscosity is a material property that describes its resistance to dispersion process. The dispersion of viscosity of a material is determined through specialized testing methods.

Table 2

Effect of diamond smoothing on dispersion viscosity and dispersion work of structural steels

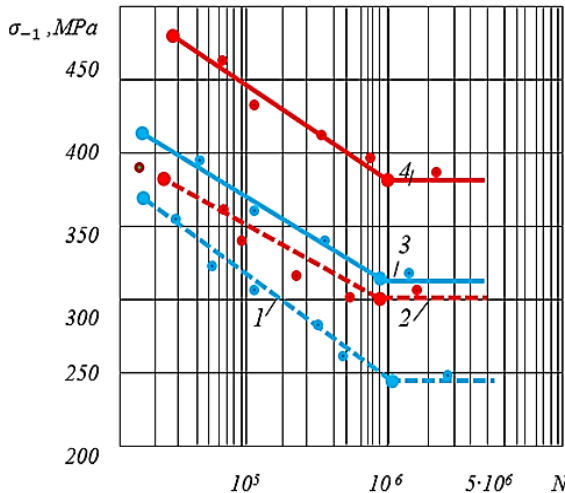
Steel grade	Processing type	Dispersion viscosity K_{1C} , $MPa \cdot m^{1/2}$	Destructive load P_T , N	Dissolution work A_T , C
BCr3cp	Quenching, annealing 300 °C + polishing	71-76	5887	18.5
	Quenching, annealing 300°C + polishing + smoothing	92-96	7580	26.6
10Г2С1	Quenching, annealing 300 °C + polishing	105-108	8548	52.5
	Quenching, annealing 300°C + polishing + smoothing	130-133	10564	71.0
15XГ2СМФР	Quenching, annealing 300°C + polishing	140-152	12096	51.0
	Quenching, annealing 300°C + polishing + smoothing	218-223	17740	98.4
12ГН2МФАЮ	Quenching, annealing 300°C + polishing	167-171	13630	62.8
	Quenching, annealing 300°C + polishing + smoothing	250-254	20322	112.7

When testing cracked specimens to comprehensively assess the resistance of steel to brittle fracture, it is necessary to analyze not only the values of A_T and K_{1C} , but also the maximum value of the destructive load (P_T). The amount of P_T depends significantly on the material's yield strength and carbon content. Thus, an increase in the

yield strength to a value of $\sigma_{0,2} \leq 1600 \text{ MPa}$ leads to an increase in the destructive load. Since the yield strength of the studied structural steels is up to 1000 MPa , the value of P_T also increases with an increase of $\sigma_{0,2}$ (table 2).

To evaluate the effectiveness of diamond smoothing on the endurance limit of structural steels, fatigue tests were conducted using an МУИ-6000 rotational bending machine. The loading was $5 \cdot 10^6$ cycles during the symmetrical cycle. Samples with a diameter of 12 mm and a length of 226 mm were prepared according to ГОСТ 25.503–79.

Based on the results of the fatigue tests, fatigue curves were constructed for the steels under investigation (see graphs 8 and 9).

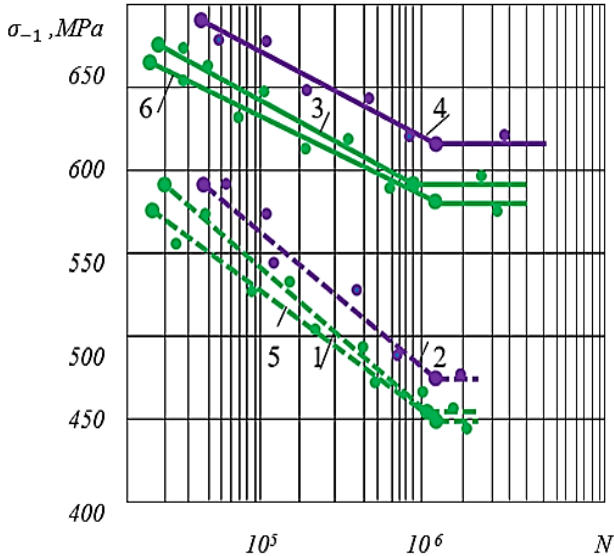


Graph 8. —BCт3cп вѧ —10Г2C1 dependence of the endurance limit of structural steels on the number of loading cycles:
 1,2 – after polishing; 3,4 – after smoothing

A comparison of test results for polished and diamond-smoothed samples of BCт3cп and 10Г2C1 steels demonstrates the high effectiveness of the diamond smoothing process (see graph 8). As can be seen, the yield strength of samples made of unreinforced (polished) BCт3cп steel was 245 MPa , but after diamond polishing it was

314MPa, while the yield strength of samples made of 10Г2С1 steel increased from 300 MPa to 370 MPa [9]⁷.

Similar results were observed for the 15ХГ2СМФ and 12ГН2МФАЮ steels, with their toughness increasing by 30-33% after diamond smoothing (see graph 9).



Graph 9. Dependence of the endurance limit of

— 15ХГ2СМФ (1,3,5,6.) and — 12ГН2МФАЮ (2,4)
steels on the number of loading cycles:

1,2,5—after polishing; 3,4,6—after smoothing.

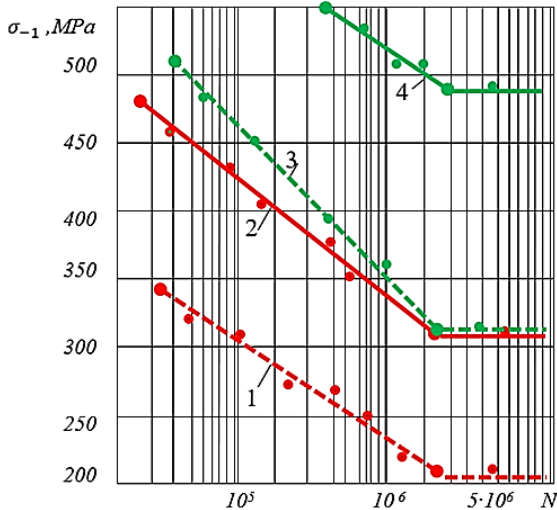
1-4—experimental curves; 5,6—statistical curves

Experimental studies have shown that diamond honing increases the fatigue strength of all structural steels studied by an average of 23-33%.

⁷ Hamzayeva, G.R. Improving the performance properties of structural steels by surface hardening methods. Scientific Works of ATU (Azerbaijan Technical University), No. 1, Baku: -2022, pp. 27–32.

In order to evaluate the effectiveness of diamond smoothing, a comparative test was conducted on the fatigue fracture resistance of structural steels in the presence of stress collectors.

The tests were conducted on specimens with a diameter of 10 mm, made of 15XГ2CMΦP and 10Г2C1 steels (grap 10).



Graph 10. Fatigue curves of specimens with stress concentrators:

— 10Г2C1; **—** 15XГ2CMΦP;

1,3 – after polishing; 2,4 – after smoothing

Groove is placed on the samples to create tension assemblies. The edges of the inner part of the groove are rounded with a radius of 1 mm. The inner surface of the grooves was polished and smoothed until the roughness $Ra=0.25...0.40$ mcm was obtained. After heating to 200°C, the grooves were pressed and seated onto the specimen.

The results of the test experiments (see graph 8) show that the fatigue strength of polished specimens with stress concentrators is significantly lower (47-50%) than that of polished specimens without stress concentrators (compare the curves in Graphs 8, 9, and 10). After diamond smoothing, the fatigue strength increased and even exceeded the endurance limit of the specimens polished without grooves.

Thus, experimental studies have shown that diamond smoothing increases the endurance limit of stress concentrators in 10Г2С1 and 15ХГ2СМФР steels by 48-55% compared to conventional polishing.

Comparative experiments were conducted to study the effect of the diamond smoothing process on the corrosion resistance of ВСТ3СП, 10Г2С1, 15ХГ2СМФР, and 12ГН2МФАЮ steels under seawater and humid atmospheric conditions [2]⁸.

The results of the studies conducted in seawater environment are presented in table 3.

Table 3

Corrosion of steels studied in seawater environment

Processing type	Weight loss of the specimen due to corrosion over a 6-month period, g			
	ВСТ3СП	10Г2С1	15ХГ2СМФР	12ГН2МФАЮ
Quenching + annealing 300°C + polishing	13.5	13.1	10.7	11.0
Quenching + annealing 300°C + polishing + smoothing	12.5	12.0	9.5	9.9

Corrosion tests conducted on specimens of various structural steels in seawater have shown that surface strengthening through polishing and diamond smoothing positively affects the corrosion resistance of these steels. The corrosion loss of the diamond-smoothed specimens made of ВСТ3СП steel, stored in natural seawater for 6 months, was 7% lower than that of the polished specimens. Additionally, the corrosion resistance of 10Г2С, 15ХГ2СМФР, and 12ГН2МФАЮ steels increased by 9-11% after smoothing compared to polishing (see Table).

⁸ Hamzayeva, G.R. & Aslanov, T.I. The effect of diamond burnishing on stress concentration sensitivity and corrosion resistance. Scientific Works of AUAC, Azerbaijan University of Architecture and Construction, No.1, Baku: -2017, pp. 52–56.

The positive effect of the microrelief produced by diamond smoothing on all the steel specimens studied in a humid atmosphere is clearly evident. The surface of polished specimens stored in a humid chamber for three months developed numerous dark-colored dots and spots. In contrast, no such spots were observed on the surface of the diamond-smoothed specimens (only a few faint spots were visible on the surface of some samples). This once again demonstrates the increased resistance of these steels to atmospheric corrosion, attributed to the significant reduction in surface roughness achieved through diamond smoothing.

Comparative experimental studies were conducted to determine the effect of diamond smoothing on contact resistance. The tests were performed on specialized specimens made of 15XГ2СМФР and 12ГН2МФАЮ steels using an МКВ-КМ type machine, under contact stress conditions of 5000-5500 *MPa*.

The results of the contact resistance tests for the specimens are presented in table 4 blown [1]⁹.

The highest contact resistance for both studied steels was observed in specimens smoothed with a force of 70 *N*. Increasing the smoothing force to 220 *N* not only fails to increase durability but also leads to a decrease in it. However, when the smoothing force was 70 *N*, the contact resistance of specimens made from 15XГ2СМФР and 12ГН2МФАЮ steels was, on average, 2.3 to 2.5 times higher than that of the polished specimens.

When smoothing with a force of 220 *N*, the durability of the samples is reduced by 1.5 times compared to the sample smoothed with a force of 70 *N*.

⁹ Hamzayeva, G.R. On the effect of diamond burnishing on contact fatigue strength. Conference International Trends in Science and Technology, Vol. 1, Warsaw: -2017, p. 18.

Table 4

Results of the contact resistance tolerance test

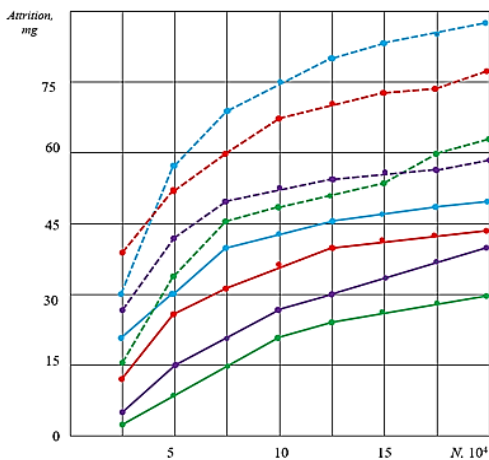
Steel grade	Processing type	Contact resistance, $\times 10^6$ cycle	Increased contact resistance of smoothed specimens compared to polished ones (%)	
15XГ2СМФР	Polishing	2.5	100	
	Smoothing P_y, N	50	4.8	192
		70	6.3	252
		100	5.6	224
		140	5.2	208
		180	4.7	188
		220	4.1	164
12ГН2МФАЮ	Polishing	3.4	100	
	Smoothing P_y, N	50	8.0	235
		70	9.0	242
		140	7.3	215
		220	5.8	172

Wear tests were conducted in a laboratory setting to assess the effectiveness of diamond smoothing in enhancing the wear resistance of friction surfaces. The objective of the tests was to compare the wear resistance of polished and smoothed specimens [11]¹⁰.

The wear curves of specimens made from ВСТ3СП, 10Г2С1, 15XГ2СМФР, and 12ГР2МФАЮ structural steels, as a function of the test duration, are shown in graph 11.

As seen from the curves, diamond smoothing increases the wear resistance of all tested steels by an average of 3.5 times during the initial periods (hardening phase) compared to polishing.

¹⁰ Aslanov, T.I., & Hamzayeva, G.R. (2023). Strengthening of part surface by burnishing. Proceedings of the Scientific-Technical Conference "Prospects for the Application of Innovative Equipment and Technologies in Production", Baku, pp. 25–28.



Grap 11. The wear curves █ – BCТ3сп; █ – 10Г2С1;
█ – 15ХГ2СМФР; █ – 12ГН2МФАЮ *of steels after*
polishing (▣▣▣) and smoothing (▬▬▬)

As shown in the curves (see graph), up to 25,000 cycles (approximately at the end of the break-in period), unreinforced (polished) specimens of BCТ3сп and 10Г2С1 steels experienced an average wear of 36 mg per hour, while specimens of 15ХГ2СМФР and 12ГН2МФАЮ steels showed an average wear of 22 mg. During this period, specimens strengthened by diamond smoothing experienced an average wear of 16 mg and 5 mg, respectively. In other words, diamond smoothing reduces wear intensity by 2-3 times [13]¹¹.

In the fourth chapter, recommendations are provided for selecting the optimal modes of the diamond smoothing process. A diamond smoothing technology is developed for preparing friction parts of construction machinery, the technical and economic efficiency of applying the research results in production is substantiated, and potential areas for the application of the research results are identified.

¹¹ Hamzayeva, G.R. Aslanov, T.İ. Impact of surface and plastic deformation to deterioration // Engineering Mechanics Scientific and Technical Journal, -Bakı: - 2024. №1, -pp. 34-38.

GENERAL RESULTS

1. It has been established that the main requirements for structural steels used in various construction structures, installations, road construction machinery and equipment are their high structural strength. The main characteristics determining the application of structural steels are their strength, plasticity, impact toughness, fatigue strength, corrosion resistance, weldability, the value and distribution of residual stresses in the material, as well as their type.

2. Research shows that traditional strengthening thermal, thermomechanical, chemical-thermal processing methods of steel and alloys, and others, do not fully restore the reliability and longevity of metal structures. Therefore, there is a need to develop and apply more advanced and effective methods to enhance the structural strength of steels used in various metal structures.

3. It has been determined that surface-plastic deformation methods, which have recently gained widespread use as strengthening techniques, are also suitable for structural steels. Studies have shown that ball rolling and diamond smoothing are particularly effective methods of surface-plastic deformation for these steels. One of the primary objectives of this research is to select the optimal reinforcement method and its corresponding regimes.

4. A mathematical relationship has been established between the key parameters of surface-plastic deformation (processing force and longitudinal yield) and the hardness and roughness of the surface of the studied steels. This mathematical relationship aids in selecting the optimal processing modes to achieve the desired properties of structural steels.

5. As a result of the experimental studies, it was determined that surface-plastic deformation significantly increases the surface hardness of the studied steels. Specifically, the surface hardness of BCт3cп and 10Г2C1 steels increases by 18-24% after ball rolling and by 22-32% after diamond smoothing. The hardness of 15ХГ2СМФР and 12ГН2МФАЮ steels increases by 24-29% after ball rolling and by 36-37% after diamond smoothing.

6. The results of the studies show that surface-plastic deformation leads to a significant reduction in the surface roughness of all the studied steels. As a result of ball rolling, the surface roughness decreases from $Ra = 0.48-0.60 \text{ mcm}$ to $Ra = 0.08-0.16 \text{ mcm}$, while after diamond smoothing, it decreases to $Ra = 0.05-0.12 \text{ mcm}$. Experimental tests determined that diamond smoothing is a more effective, and thus simpler and more economically efficient, method for strengthening structural steels compared to ball rolling. Based on the theoretical and experimental studies conducted, the optimal modes for the diamond smoothing process were established to enhance the mechanical and operational characteristics of the studied structural steels.

7. After polishing, tensile stresses are formed in the upper layers of the metal, which negatively affect its operational properties. However, after diamond smoothing, these stresses are transformed into compressive stresses of $600-1000 \text{ MPa}$, which positively influence the material properties. As shown by the results of tensile tests, diamond smoothing has little effect on the strength and yield strength of BCТ3cп and 10Г2C1 steels (with an increase of approximately 1%). However, diamond smoothing increases the strength and yield strength of 15XГ2CMФP and 12ГH2MΦAЮ steels by 6-10% compared to polishing. The plasticity characteristics (δ , φ) of all the studied steels decrease by 5-12% after smoothing compared to polishing.

8. Experimental tests have shown that the impact toughness of structural steels after diamond smoothing is at least equal to that of these steels after tempering and medium-temperature annealing. In some cases, the impact toughness of smoothed samples is even slightly higher (by up to 2-3%). Additionally, the tests revealed that diamond smoothing significantly enhances resistance to crack development, with the dispersion viscosity increasing by 25-45% for the studied steels.

9. Fatigue strength tests showed that diamond smoothing significantly increased the endurance limit of all the steels studied. The endurance limit of BCТ3cп steel increased from 245 MPa to 314 MPa, while the endurance limit of 10Г2C1 steel increased from 300 MPa to

370 MPa. The experiments also demonstrated the effectiveness of diamond smoothing under stress concentrator conditions. The fatigue strength of samples with stress concentrators increased by 48-55% compared to polished samples after smoothing.

10. Experimental studies have shown that diamond smoothing is effective as a finishing treatment for steels operating in various aggressive environments. Corrosion tests of samples made from various structural steels, immersed in natural seawater for 6 months, demonstrate that smoothing increases corrosion resistance by 8-11% compared to polishing.

11. The conducted studies show that after 200,000 cycles, the wear of polished samples made from ВСт3сп, 10Г2С1, 15ХГ2СМФР, and 12ГН2МФАЮ steels was 88, 77, 62, and 59 mg, respectively. In contrast, the wear of samples strengthened by diamond smoothing was 50, 44, 30, and 40 mg, respectively. It is important to note that diamond smoothing significantly increases wear resistance, particularly during the hardening period, with resistance being, on average, 3.5 times higher.

12. After cold pressing the received sleeve-type workpiece (50% iron ore - ПЖ2М3 + 50% cast iron ore), porosity of 15-18% is formed both in the volume and on the surface. Quenching at 800-850°C fully restores the plasticity of the workpiece, and after ball rolling, the surface porosity is reduced to approximately 5%. Following diamond smoothing, the porosity decreases further to 2%.

LIST OF PUBLISHED SCIENTIFIC WORKS ON THE TOPIC OF THE DISSERTATION

1. Гамзаева, Г.Р. О влиянии алмазного выглаживания на контактную выносливость // Conference International Trends In Science and Technology, -Варшава: -2017. Vol 1, -с.18.
2. Гамзаева, Г.Р., Асланов, Т.И. Влияние алмазного выглаживания на чувствительность к концентрации напряжений и на коррозионную стойкость // -Баку: Вестник АЗАСУ, - 2017. №1, -с. 52–56.
3. Hənzəyeva, Q.R., Məmmədov, A.T., Aslanov, T.İ. Səthi-plastiki deformasiya üsulu ilə möhkəmləndirmənin tədqiqat metodikası // Azərbaycan Xalq Cümhuriyyətinin yaranmasının 100 illiyinə həsr olunmuş Beynəlxalq Elmi Konfransın materialları, - Bakı: - 2018, - s. 296-299.
4. Hənzəyeva, Q.R., Məmmədov, A.T. Aslanov, T.İ. Səthi-plastiki deformasiya parametrlərinin səthin bərkliyinə təsiri haqqında // AzTU Elmi Əsərləri, -Bakı: -2018. №3, -s. 27-32.
5. Hənzəyeva, Q.R., Aslanov, T.İ. Səthi-plastiki deformasiyanın inşaat poladının mexaniki xassələrinə təsiri haqqında // Tikinti istehsalatında texnoloji məşinlərin istifadəsinin müasir problemləri mövzusunda Elmi-Praktiki Konfrans, Bakı: -2019, -s. 22-25.
6. Hənzəyeva, Q.R., Qasımov, E.V. Vibrohamaralama və almazla hamarlaşmanın texnologiyasının əsasları // Ümumilli Lider Heydər Əliyevin anadan olmasının 97-ci ildönümünə həsr olunmuş tələbə və magistrantların 42-ci Elmi Konfransının materialları, Bakı: -2020, -s.135-136.
7. Hənzəyeva, Q.R., Qasımov, E.V. Kürəciklə diyirləmənin inşaat poladının möhkəmlənməsinə təsiri // Ümumilli Lider Heydər Əliyevin anadan olmasının 97-ci ildönümünə həsr olunmuş tələbə və magistrantların 42-ci Elmi Konfransının materialları, Bakı: -2020, -s.136-138.
8. Hənzəyeva, Q.R. Almazla hamarlaşma zamanı struktur-faza çevrilmələri // - Bakı: AzMİU Elmi əsərləri, -2022. №2, -s.92-96.

9. Həmzəyeva, Q.R., Səthi möhkəmləndirmə üsulu ilə inşaət poladlarının istismar xassələrinin artırılması // -Bakı: AzTU Elmi Əsərləri, -2022. №1, -s.27-32.
10. Гамзаева, Г.Р. Влияние подачи и числа проходов при алмазном выглаживании на шероховатость // - Дніпро: Проблеми обчислювальної механіки і міцності конструкцій, -2022. №34, -с.16-22.
11. Həmzəyeva, Q.R., Aslanov, T.İ. Hissənin səthinin hamarlama ilə möhkəmləndirilməsi // İstehsalatda innovativ texnika və texnologiyaların tətbiqi perspektivləri, Elmi-texniki konfransın materialları, Bakı: 2023, -s.25-28.
12. Hamzayeva, G.R. Mechanical properties of structural steel after diamond burnishing // - Moskva: Russian Engineering Research, -2023. vol 43, №12, -pp.1531-1534.
13. Hamzayeva, G.R. Aslanov, T.İ. Impact of surface and plastic deformation to deterioration // Engineering Mechanics Scientific and Technical Journal, -Bakı: -2024. №1, -pp. 34-38.
14. Гамзаева, Г.Р. Остаточные напряжения при поверхностном пластическом деформировании // XII Международная Научно-Практическая Конференция. Science And Technologies. Сборник тезисов, -Алматы: -30 июн, -2024, -с.23-24.
15. Гамзаева, Г.Р. Разработка математической модели алмазного выглаживания рабочей поверхности деталей из строительных сталей //Международная научно-техническая конференция Современные машиностроительные системы, технологии и инновации – Воронеж: 06.03.2025. -ст.72-77.
16. Hamzayeva G.R., Aslanov, T.İ., Sultanova, K.İ. Influence of the number of passes on the surface quality of drilling rig chain components // Engineering Mechanics Scientific and Technical Journal, -Bakı: -2025. №4, -pp. 6-8.

Personal participation of the author in published works

The works numbered [1, 8, 9, 10, 11, 14, 15] were performed independently by the applicant.

Works [3, 4] were written as a result of joint discussions between the authors and the recommendations of the scientific supervisor to master the theoretical aspects of the problem.

In works [2, 5, 6, 7, 12, 13, 16], the author formulated the research questions, conducted theoretical and experimental studies, processed the results, and made recommendations. The remaining parts of the work were carried out by the authors equally.

A handwritten signature in blue ink, appearing to be 'H. P. ...', is centered on the page. The signature is fluid and cursive, with a large initial 'H' and a smaller 'P' following it.

The defense of the dissertation will be held on *29 September 2025* at *12:00* at the meeting of the Oni-time Dissertation Council BFD 2.09, established on the basis of the Dissertation Council FD 2.09 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at the PLE "Azerbaijan Technical University"

Address: AZ1073, Baku, H.Javid Avenue, 25.

Dissertation is accessible at the "Azerbaijan Technical University" PLE Library

Electronic versions of the abstract is available on the official website (www.aztu.edu.az) of the Azerbaijan Technical University PLE.

Abstract was sent to the required addresses on *" 30 " Jule 2025.*

Signed for print: 01.07.2025

Paper format: A5

Volume: 39983

Number of hard copies: 100