DOI:
UDC 621.74

**O. Cherneta**, Ph.D., Associate Professor
**O. Korobochka**, Ph.D., Professor
**V. Kubich**, Ph.D., Associate Professor
Dnipro State Technical University, Kamyanske
National University "Zaporizhzhya Polytechnic", Zaporozhye

# DETERMINATION OF THE OPTIMAL COMPOSITION OF PHYSICO-MECHANICAL CHARACTERISTICS OF MEDIUM-CARBON STEELSFOR CAR PARTS

*The analysis of physical and mechanical characteristics of coverings after the corresponding strengthening processings taking into account structural transformations in surface layers is made. Criteria assessments of technological methods of hardening — nitriding, drilling, borocementation, laser treatment, ion-plasma nitriding, heat treatment, as well as criterion assessments of productivity of technological equipment and economic indicators are defined, borocementation, laser treatment, ion-plasma nitriding, technological processes of hardening.*

***Keywords**: hardening; nitriding; boriding; boron carburizing; laser treatment; ion-plasma nitriding; technological processes for hardening.*

*В роботі проведенідослідження методіввибору оптимальних технологічних процесів зміцнення поверхневого шару деталей.Зроблений аналіз фізико-механічних характеристик покриттів після відповідних зміцнюючи обробокз урахуванням структурних перетвореньв поверхневих шарах. Визначені критеріальні оцінкитехнологічних способів зміцнення — азотування, борування, бороцементації, лазерної обробки, іонно-плазмового азотування, термічної обробки, а також критеріальні оцінки продуктивності технологічного обладнання і економічних показників.*

***Ключові слова**: зміцнення; азотування; борування; бороцементації; лазерної обробки; іонно-плазмовогоазотування; технологічні процесизміцнення.*

## Problem's Formulation

The priority direction of the choice of wear-resistant coatings in mechanical engineering is the optimal choice of technological methods of processing and application of coatings with high physical-mechanical, durable and operational properties. The criterion for assessing the wear-bone coatings is the durability and service life of the contact friction pairs. The efficiency of the final result — the service life of the mechanism — depends on the correct choice of strengthening the surface layer of machine parts. Natural, tribological exams — the process is quite long and expensive. The proposed model using an orthogonal central composite plan of the second order allows with a high degree of probability, where it is possible to set identical parameters of real loads and obtain a mathematical dependence to determine the wear resistance of the tested coatings and structures.

## Analysis of recent research and publications

The choice of performance indicators of technological systems is a decisive and main factor in the system analysis of complexes to strengthen the surface layer and apply wear-resistant coatings of machine-building parts. In accordance with the hierarchical structure of the system for strengthening the surface layer, each stage is characterized by a corresponding indicator of efficiency [1]. The quality of the material is largely determined by its internal structure — the microstructure, which is affected by both the chemical composition and various options for influencing the material. Therefore, the same material, but processed in different ways, has different properties.There are many methods for strengthening the surface of steels [1—3] and traditional methods for studying wear resistance on friction machines. But in real operating conditions there is a lot of unaccounted parameters, which do not allow to fully model the processes occurring in the nodes of mechanisms with intense, alternating loads [4,5]. Therefore, there is a need for each case of interaction of tribological pairs to develop an original model with the specified parameters and actual loads during the test for wear resistance.

## Formulation of the study purpose

On the basis of the analysis of physical and mechanical properties of details of the cars working in extremely heavy operating conditions, to investigate the widespread ways of strengthening of superficial layers of details of average carbon steels, technological ways and variants of combinations of their processing. To achieve this goal it is necessary to: conduct a systematic analysis of working conditions and operation of certain groups of parts operating in extremely difficult conditions; determine the principles of the approach to the choice of materials and technological methods of processing; to study the processes of formation of the microstructure of surface layers on the basis of medium carbon steels, to determine the main criteria for the formation of physical and mechanical properties of the surface layers of parts and the optimal ways of their use. To implement the tasks it is necessary to explore the world developments in the use of materials and technological methods of materials processing. On the basis of the analysis of professional researches and sources to reveal the most attractive directions of realization of the set purposes. To study the condition of the surface layer of parts to choose the maximum possible set of equipment for the study of microstructure (REM 106I), X-ray phase composition (DRON-2M), measurements of microhardness PMT, layer-by-layer analysis of modulus of elasticity, ductility (Micron-Gamma). X-ray phase analysis was performed on an X-ray diffractometer DRON-2 in monochromatized Co-Ka radiation ($\alpha$ = 1.7902A). The identification of the components (phases) was performed by comparing the interplanar distances (d, A) and the relative intensities (Iotn — $I/I_0$) of the experimental curve with the data of the electronic file PCPDFWIN.

## Presenting main material

With the development of modern technologies for processing parts, it is possible to control the physical and mechanical properties and strength characteristics of structural materials. Strengthening of a surface layer of a detail is carried out by various options of processings providing formation in a surface layer of strong and superstrong structures. Using the latest technologies for strengthening steels, it is possible to increase the microhardness of the working surfaces of parts several times ($H_{\mu 50}$ = 2500–13000 *MPa*), at a thickness of 120—200 µm. In the general approach, this is defined as a technological aspect of ensuring the reliability of the friction units due to the impact on the initial wear resistance of parts during their manufacture. Reinforced surface layers of parts, as a rule, work in a lubricating medium, provide the formation of stable adhesive bonds with polyhydric molecules of various oils, such as motor, transmission, etc. And this in turn directly affects the operational aspects of ensuring the wear resistance of materials during friction. Fig. 1 shows a graphical model of the dependence of the hardness of the surface layer of the steel part 45 from the technological strengthening methods of processing [1]. On the graphical model, you can clearly see the dynamics and transformation of the microstructure on which depend the physical and mechanical properties of the working surface of the steel part 45.

It is possible to obtain an exact mathematical dependence for determining the degree of wear on the influence of operational parameters using the method of experimental planning [10], using an orthogonal central composite plan of the second order. The similarity of the nature of wear of different coatings, which proves the possibility of using this mathematical model for the choice of materials and coatings, forecasting with greater certainty of the degree of wear resistance and the service life of this material or coating. {{1 }} Observations of steel parts after various methods of processing and study of microstructures were performed using an electron scanning microscope REM-106I.

Obtain an exact mathematical dependence to determine the degree of wear on the influence of operational parameters is possible using the method of experiment planning [10]. When comparing the graphs of the degree of wear of the test specimens obtained on the basis of calculated data when planning a multifactorial experiment and experimental data of tribological studies models for the choice of materials and coatings, forecasting with greater certainty of the degree of wear resistance and the service life of the material or coating.

Observations of steel parts after various methods of processing and study of microstructures were performed using an electron scanning microscope REM-106I.

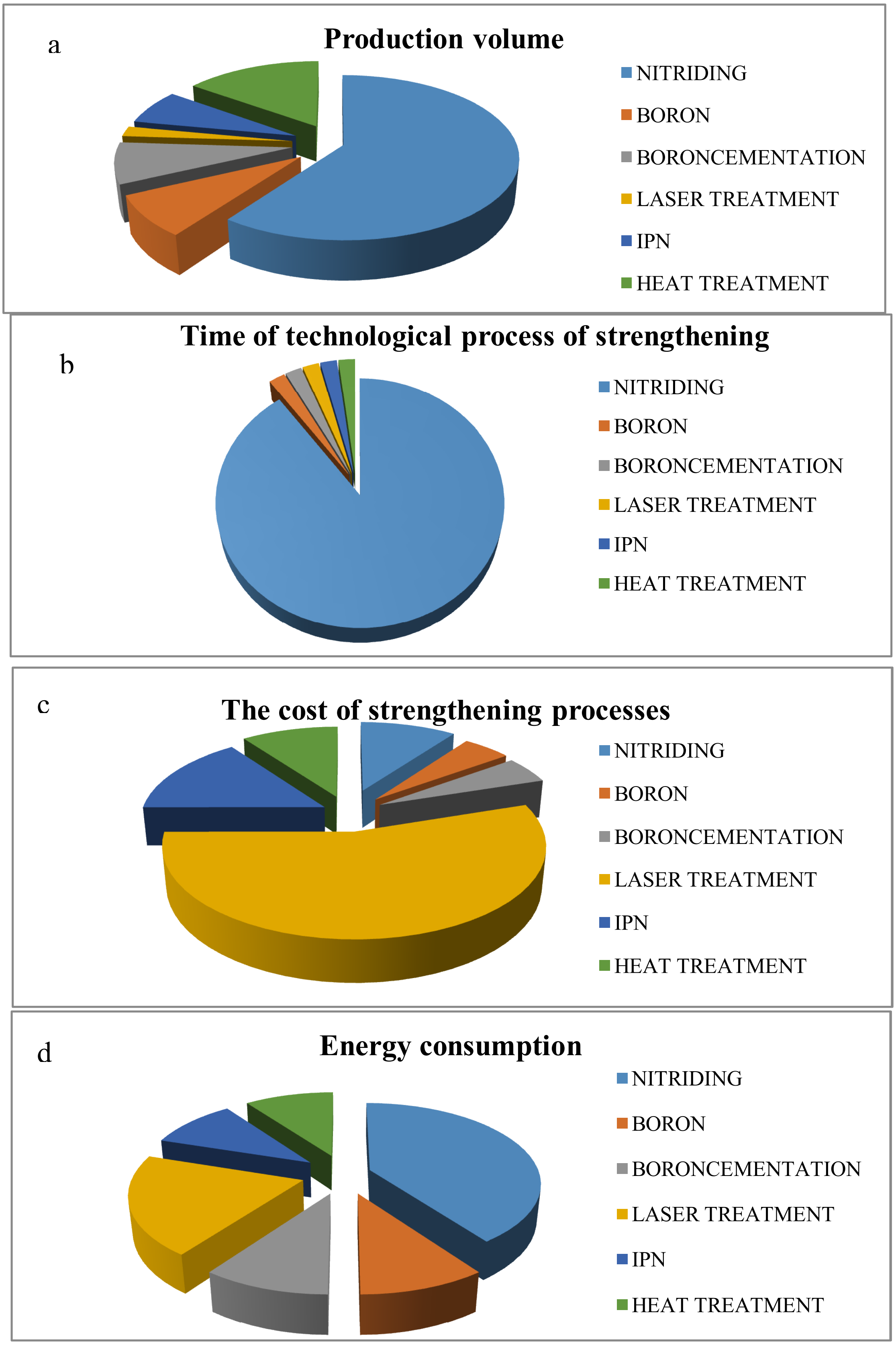

*Fig. 1.* Percentage distribution of material and energy consumption of different processing methods (a, b, c, d)

The main technological criteria of processes for strengthening the surface layer are physical and mechanical characteristics of coatings (modulus of elasticity — E (MPa), microhardness Hμ, plasticity coefficient — $K_p$, endurance limit — $\sigma_v$ (MPa), yield strength — $\sigma_t$ (MPa), the coefficient of crack formation KSU (dg / $cm^2$), the coefficient of length increase δ (%), the compression coefficient Ψ (%)). The strength of steels is ensured by a number of strengthening mechanisms: solid-soluble, dislocation, disperse, granite, substrate and pearlitic [2, p. 136]. In steels with hardened to martensite, the values of dislocation and substructural strengthening mechanisms, which depend on the dissolved carbon content, play a significant role. Increasing the strength significantly reduces the ductility, toughness and increases the limit of cold brittleness. For medium carbon ferritic-perlite steels, the carbon content or the amount of perlite in the structure is the main factor in changing the strength and plasticity. As the carbon content increases, the toughness value decreases and the viscosity-brittle temperature increases. The most attractive in terms of properties are medium-carbon and medium-alloy steels (0.3—0.5 % C; $\sigma_{0.2}$ = 700...850 MPa, $\sigma_v$ = 900–1100 MPa). Features of these steels: increased strength properties, low sensitivity to stress concentrators, high endurance and sufficient viscosity. High-strength medium-alloy steels with a content of 0.4 % C provide $\sigma_в$ = 2100 MPa.

Generalization of dimensions in percentage allows you to build a mathematical model that reproduces the composition of physical and mechanical properties for each method of strengthening parts and program the optimal balance of component characteristics. In world practice of strengthening the surface layer of surfaces of parts and practical studies, it is known that with a significant increase in microhardness proportionally decreases plasticity, yield strength, increases the probability of crack formation, etc. The generalized criterion of efficiency of each separate way of strengthening is defined from a parity:

$$D_{0А} = \lambda_1 C_1^*(W_А) + \lambda_А^{'} C_{ПР}^*(А) + \lambda_А^{''} F_{ПР}^*(А) + \lambda_А^{**} Ц_А$$

$$D_{0Б} = \lambda_2 \times C_2^*(W_Б) + \lambda_Б^{'} C_{ПР}^*(Б) + \lambda_Б^{''} F_{ПР}^*(Б) + \lambda_Б^{**} Ц_Б$$

$$D_{0БЦ} = \lambda_3 \times C_3^*(W_{БЦ}) + \lambda_{БЦ}^{'} C_{ПР}^*(БЦ) + \lambda_{БЦ}^{''} F_{ПР}^*(БЦ) + \lambda_{БЦ}^{**} Ц_{БЦ}$$

$$D_{0ЛО} = \lambda_4 \times C_4^*(W_{ЛО}) + \lambda_{ЛО}^{'} C_{ПР}^*(ЛО) + \lambda_{ЛО}^{''} F_{ПР}^*(ЛО) + \lambda_{ЛО}^{**} Ц_{ЛО}$$

$$D_{0ИПА} = \lambda_5 \times C_5^*(W_{ИПА}) + \lambda_{ипа}^{'} C_{ПР}^*(ипа) + \lambda_{ипа}^{''} F_{ПР}^*(ипа) + \lambda_{ипа}^{**} Ц_{ипа}$$

$$D_{0TO} = \lambda_6 \times C_6^*(W_{TO}) + \lambda_{TO}^{'} C_{ПР}^*(TO) + \lambda_{TO}^{''} F_{ПР}^*(TO) + \lambda_{TO}^{**} Ц_{TO},$$

where $C_1$* — criterion estimates of physical and mechanical characteristics of coatings after appropriate hardening treatments, taking into account structural transformations in the surface layers $C_1$ * ($E_1$: H $_{(\mu 1)}$: $K_{n1}$: σ $_{(v1)}$; $\sigma_{t1}$; 〚$KCU_1$: $\delta_1$: $C_1$* ($W_A$); C $*_{PR}$ (A — nitriding, B — drilling, BC — borocementation, LO — laser treatment, IPA — ion-plasma nitriding, TO — heat treatment) — respectively, criterion estimates of productivity of technological equipment depending on the methods of strengthening ; F * $_{PR}$ — criterion estimates of productivity of the used area; S * $_{ek}$ — criterion assessments of economic efficiency; $\lambda_{i\,(1\ldots)}$ — the weight of the efficiency criteria is determined by the formula:

$$\lambda_i = \frac{n_0 - n_н}{n_0},$$

where $n_0$ is the number of analyzed equipment; $n_n$ — the amount of equipment that meets regulatory requirements.

Results and discussion. In the tabl. 1 provides a percentage distribution of material and energy consumption of different technological methods of processing and hardening, which were selected from the analysis of individual technological processes and materials of previous studies [3], [4]. In order to objectively assess the nature, impact and relevance of each of the indicators of physical and mechanical properties (each of them has its own dimension), which is characterized by the corresponding physical processes, it is necessary to bring the indicators to a single measurement base. A universal indicator for assessing indicators of different sizes is the percentage. In fig. Fig. 2 shows a graphical diagram of the oscillations of the physical and mechanical properties of steel 45 after different methods of hardening (drilling, nitriding, heat treatment, laser treatment, borocementation, ion-plasma nitriding) [5].

*Table 1.* Percentage distribution of material and energy consumption of different processing methods

| №/№ | Production volume | | Time of technological process of strengthening | | Energy consumption | | The cost of strengthening processes | |
|---|---|---|---|---|---|---|---|---|
| | Q, $m^2$ | % | t, h | % | E,кVт | % | C, грн | % |
| Nitriding | 6 | 60 | 96 | 90 | 625 | 40 | 125000 | 10 |
| Boron | 0.3 | 8 | 8 | 2 | 121 | 10 | 62500 | 5 |
| Borocementation | 0.3 | 8 | 8 | 2 | 121 | 10 | 62500 | 5 |
| Laser treatment | 0.1 | 2 | 1 | 2 | 244 | 20 | 1250000 | 55 |
| IPN ion-plasma nitriding | 0.3 | 7 | 3 | 2 | 121 | 10 | 137500 | 15 |
| Heat treatment | 1.5 | 15 | 8 | 2 | 121 | 10 | 125000 | 10 |

As can be seen from the graph (Fig. 2) at the maximum possible values of microhardness sharply decreases the ductility, coefficients $K_p$, yield strength — $\sigma_t$ (MPa), the coefficient of crack formation KSU (dg/$cm^2$), the coefficient of length δ (%), the compression ratio Ψ (%).

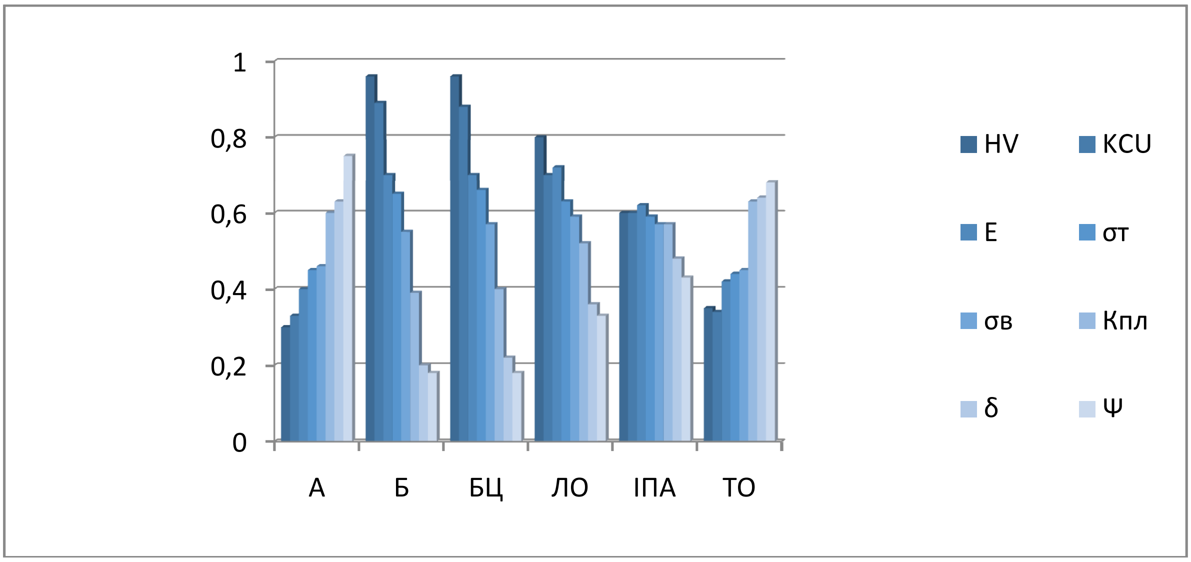

*Fig. 2.* Distribution of physical and mechanical properties at separate ways of strengthening of working surfaces of a detail

For medium carbon ferritic-pearlite steels, the carbon content or the amount of perlite in the structure is the main factor in changing the strength and ductility. As the carbon content increases, the toughness decreases and the viscosity-brittle temperature increases. The most attractive in terms of properties are medium-carbon and medium-alloy steels (0.3–0.5 % C; $\sigma_{0.2}$ = 700…850 MPa, $\sigma_v$ = 900–1100 MPa). Features of these steels: increased strength properties, low sensitivity to stress concentrators, high endurance and sufficient viscosity. High-strength medium-alloy steels with a content of 0.4 % C provide $\sigma_в$ = 2100 MPa. Indicators of physical and mechanical properties have their own dimension and are characterized by appropriate physical processes. There was a need to bring the indicators to a single base of measurement and evaluation. A universal indicator for assessing different indicators is the percentage. Thus, the measurements, for example, boron coatings, microhardness on the surface of the reinforced part to the core, will range from the maximum to the nominal value, which can be assumed, respectively — $N_{max}$ — 100%, $N_{ser}$ — 80%, $N_{min}$ — 60 %, at the actual state of measurement — $H_{\mu max} = 16000$ MPa; $H_{\mu ser} = 12000$ MPa; $N_{\mu min} = 8000$ MPa. We also use similar assumptions for other indicators (E (MPa), $K_p$, $\sigma_v$ (MPa), $\sigma_t$ (MPa), KSU (dg / cm$^2$), δ (%), Ψ (%)).

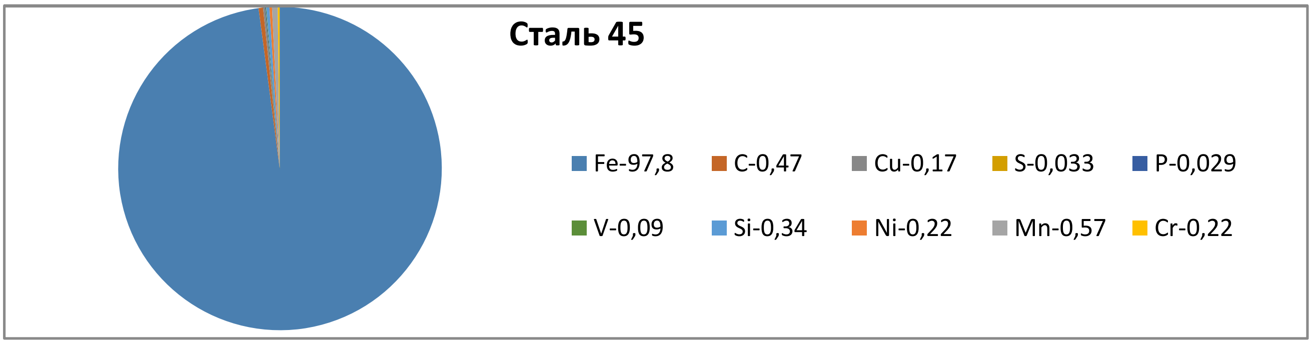

*Fig. 3*. Chemical composition of elements in steel 45 after reduction

Graphic diagram of fluctuations of physical and mechanical properties of steel 45 after various methods of hardening, heat treatment, nitriding, IPA, microwave, laser treatment (LT), boron, harrowing + LO) is given in fig. 4. At the maximum possible values of microhardness, the plasticity decreases sharply, the coefficients Kp, the yield strength — $\sigma_t$ (MPa), the coefficient of cracking KSU (dg/cm$^2$), the coefficient of length increase δ (%), the compression coefficient Ψ (%) . The red line shows the dynamics of changes in microhardness depending on the methods and technologies of hardening. At the maximum possible values of microhardness, ductility decreases sharply, coefficients Kp, yield strength — $\sigma_t$ (MPa), crack formation coefficient KSU (j / cm$^2$), length increase coefficient δ (%), compression coefficient Ψ (%)). Ultra-high microhardness (plane B-D) during drilling, borocementation on the one hand provide high surface properties for wear resistance, but at the same time significantly reduce the plasticity, durability, cracking and provoke the destruction of surface layers due to high stresses and especially the structure of the surface layer. Dotted black lines highlight the field (A, B, D, C) of the most attractive optimal values of the group of physical and mechanical parameters that provide the surface layer with a balance of strength and performance properties. This field, highlighted by dotted black lines, is basic in the choice of technologies and methods of strengthening and is taken as the zero level (Fig. 4). All emissions from this field cause risks of destruction of the surface layer.In fig. 5 shows the values of microhardness indices depending on the degree of penetration of the indenter into the depth of the impression (Micron-Gamma device) [9—10] and characteristics of coatings, total costs of the technological process, equipment and economic indicators that take into account the end result — wear resistance of coatings and the total cost of obtaining them.

For comparison, selected both classic, traditional methods of hardening, and the latest technologies with using laser drilling, nitriding, borocementation, IPA and microwave technologies.

According to the set of generalized criteria of efficiency of each of the given methods of strengthening the general schedule of criteria of efficiency of the corresponding methods of strengthening is constructed. Therefore at a choice of technologies and ways reinforcement must clearly understand the operating conditions of the part, the full range of loads on the surface layer. From the analysis of physical and mechanical properties of the strengthened coverings most widespread and developed in world practice it is possible to define basic values of indicators of wear resistance, durability, microhardness, plasticity for modern coverings which can be received by means of various technologies (fig. 6).

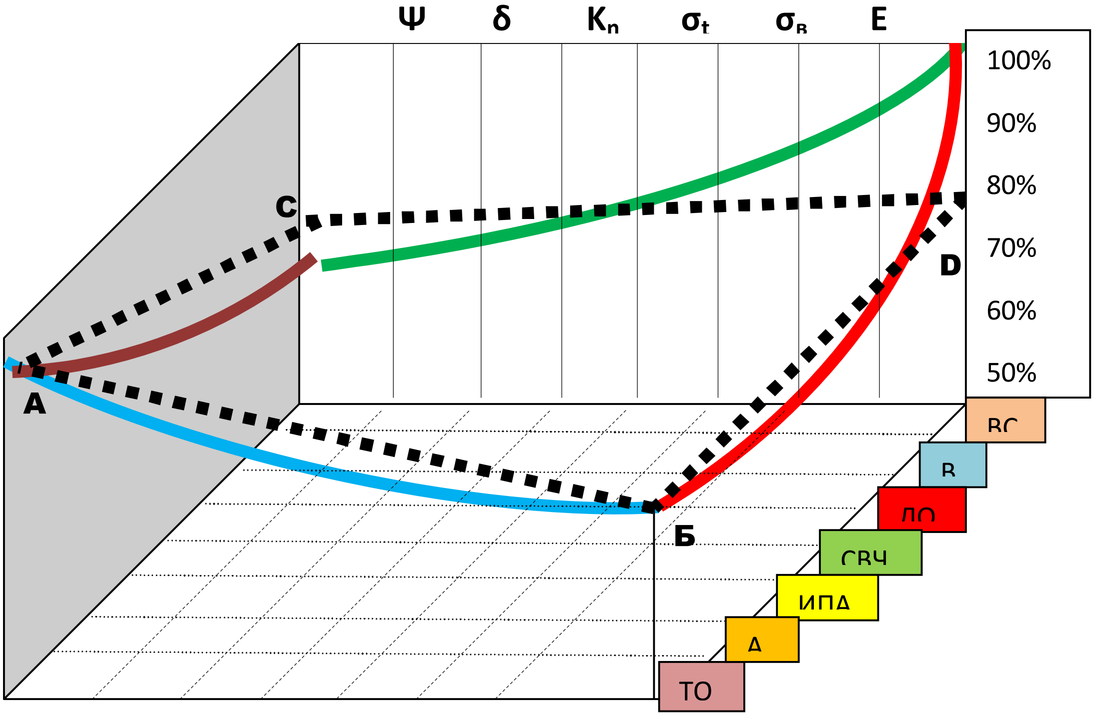

*Fig. 4.* Spatial diagram of changes in the physical and mechanical properties of the surface layer of steel parts 45 depending on different methods and technologies of hardening

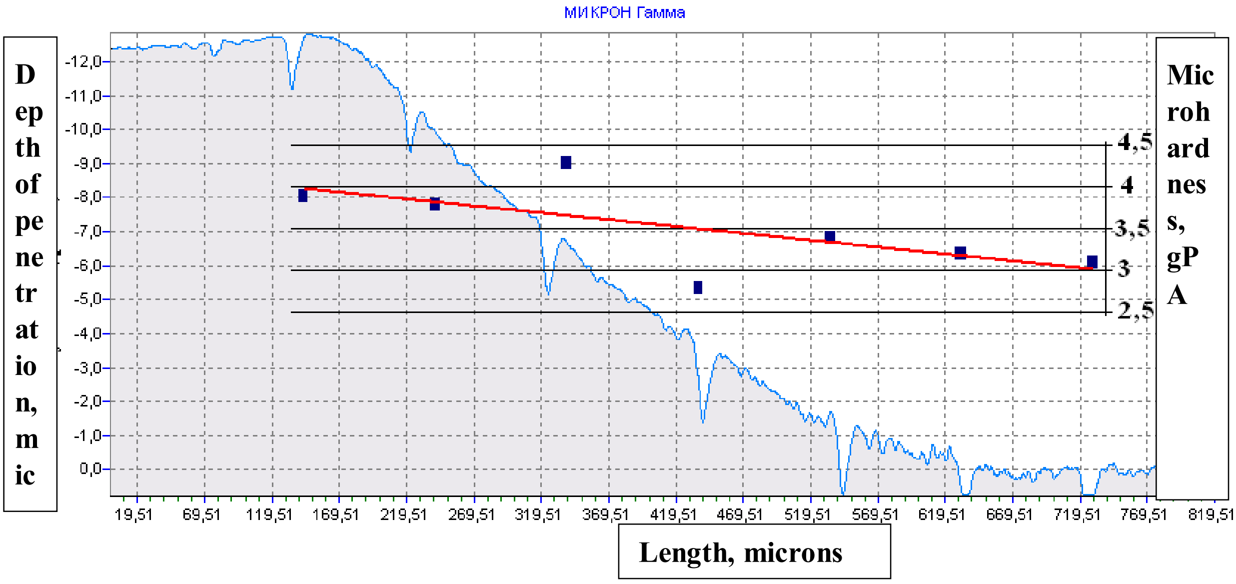

*Fig. 5.* The values of microhardness depending on the degree of penetration of the indenter into the depth of the impression (Micron-Gamma device)

## Conclusions

The technique of definition of optimum ways and technologies of strengthening of a top layer of details from steel 45 on criterion indicators of efficiency is developed. The basic values of the basic indicators, which make D — zero level and are necessarily necessary for the strengthened surfaces at the corresponding technologies are defined.

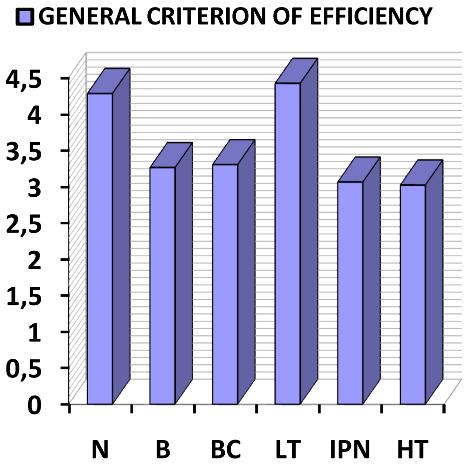

*Fig. 6.* Graph of efficiency criteria of the corresponding methods of strengthening

## References

[1] Suslov A.G., Gulyaev Yu.V., Dalsky A.M. (1995) Kachestvo mashin. [Qualitis of machines. Reference book]. M. Machinostroenie. T2. [in Russian].

[2] Francynuk I.V. Francynuk L.I. (2004) Albom mikrostryktur chugynov, staley, tsvetnih metalov i ih splavovAlbum Microstructures ofsteel, colorful metal catches and their allies. M: ICC "Academagnig". [in Russian].

[3] Grigoriyanz A.G., Shiganov I.N., Misurov A.I. (2006) Tehnologichrskie protsesy lazernoy obrabotkyTechnological processes of laser care: Textbook.Features for knobs / Ed.AG Grigoryanza. M.: Izd-MgTU IM. N.E. Bauman. [in Russian].

[4] Devoyno O.G. (2001) Tehnologiya formirovaniya iznosostoykih pokritiy lazernoy obrabotkoy Technology of the formation of wear surfaces bylaser treatment, Minsk: UP "Technology". [in Belarus].

[5] Cherneta O.G., Sukholin V.I., Voloshchuk R.G., Gubarev S.V. (2018) Osoblivosty struktyri vidnovlenogo poverhnevogo shary stali 45 pislya zmitsnennya lazernim boryvannyam. [Features of the structure of the reconstructed surface layer of steel 45 after strengthening laser borrowing].*Collection of scientific works "Perspective Technologies and Devices"* M. Lutsk, NTU, (13). 170–175. [in Ukrainian].

[6] Cherneta O.G., Korobochka O.M.Sasov O.O., Kubich V.I. (2020) Vibir tehnologichnyh metodiv zmitsnennya detaley mashinobudivnogo kompleksy. [Choice of technological methods for strengthening parts of machine-building complex] *1 International scientific and practical conference "Achievemens and Prospects of Modern Scientific Research"*. 6-7 December, Buenos Aires, Argentina.175–182. [in Ukrainian].

[7] Cherneta O.G., Sasov O.O., Soshenko S.V. (2020) Doslydzshennya fiziko-mehanichnyh vlastivostey staly 45 pislya riznyh sposobiv zmitsnennya. [Research physical and mechanical properties of steel 45 after different ways of strengthening]. *V International Scientific and Practical Conference "Study of Modern Problems of Civilization"* Oslo, Norway, 19-23 October. 486–490. [ in Ukrainian].

[8] Cherneta O.G., Kubich V.I.,Korobochka O.M. (2020). Rozrobka metodiv vubory optymalnyh tehnologichnyh protsesiv zmitsnennya poverhnevogo shary detaley. [Development of methods for choosing optimal technological processes of strengtheningsurface layer of details] *2 International scientific and practical conference «EUROPEAN Scientific Discussions»* December 26-28 Rome, Italy. 211–217. [in Ukrainian].

[9] Ignatovich S.R., Zakyev I.M. (2011) Universalniy mikro nano indentor. Universal micro nano is indentometer "Micron-Gamma". Factory laboratory. T. 77, No. 1 [in Ukrainian].

[10] ISO/FDIS 14577-1: (2002); Metallic Materials – *Instrumented Indentation Test for Hardness and Materials Parameters*. Part 1: Test Method – Geneva: ISO CENTRAL SECRETARIAT. [in Ukrainian].

## ВИЗНАЧЕННЯ ОПТИМАЛЬНОГО СКЛАДУ ФІЗИКО-МЕХАНІЧНИХ ХАРАКТЕРИСТИК СЕРЕДНЬОВУГЛЕВІДОВОЇ СТАЛІДЛЯ АВТОМОБІЛЕЙ

**Чернета О.Г., Коробочка О.М., Кубіч В.І.**

### Реферат

Були проведені дослідження методів вибору оптимальних технологічних процесів для зміцнення поверхневого шару деталей. Наведено аналіз фізико-механічних характеристик покриттів після відповідних видів зміцнення з урахуванням структурних змін у поверхневих шарах. Вказано критеріальні оцінки технологічних методів зміцнення — азотування, бордування, бороцементації, лазерної обробки, іонно-плазмове азотування, термічна обробка, а також отримані критеріальні оцінки продуктивності технологічного обладнання та економічні показники.

Міцність сталей забезпечується низкою зміцнюючих механізмів: твердорозчинні, дислокаційні, дисперсні, гранітні, субструктурні та перлітні. У сталях, загартованих до мартенситу, значення дислокаційних та субструктурних механізмів зміцнення, які залежать від вмісту розчиненого вуглецю. Збільшення міцності значно зменшує пластичність, в'язкість і збільшує межу крихкості. Для середньовуглецевихферитно-перлітних сталей вміст вуглецю або кількість перліту в структурі є головним фактором зміни міцності та пластичності. Зі збільшенням вмісту вуглецю ударна в'язкість зменшується, а крихкість зростає. Найбільш привабливими за властивостями є середньовуглецеві та середньолеговані сталі (0,3—0,5% С; $\sigma_{0,2}$ = 700..850 МПа , $\sigma_v$ = 900—1100 МПа). Особливості цих сталей - підвищені міцнісні властивості, низька чутливість до концентраторів напруги, висока витривалість та достатня в'язкість. Високоміцні середньолеговані сталі із вмістом 0,4% С забезпечують $\sigma_в$ = 2100 МПа. При максимально можливих значеннях мікротвердості пластичність різко зменшується, коефіцієнти $K_p$, межа текучості — $\sigma_t$ (МПа), коефіцієнт утворення тріщин KSU (дж/см$^2$), коефіцієнт збільшення довжини δ (%), коефіцієнт стиснення Ψ (%). Червона лінія показує динаміку змін мікротвердості в залежності від методів і технологій зміцнення. При максимально можливих значеннях мікротвердості різко зменшується пластичність, коефіцієнти $K_p$, межа текучості - $\sigma_t$ (МПа), коефіцієнт утворення тріщин KSU (дж/см$^2$) ), коефіцієнт збільшення довжини δ (%), коефіцієнт стиснення Ψ (%).

З аналізу фізико-механічних властивостей посилених покриттів найпоширенішої та найрозвиненішої у світовій практиці можна визначити основні значення показників зносостійкості, довговічності, мікротвердості, пластичності для сучасних покриттів, які можна отримати за допомогою різних технологій. Розроблена методика визначення оптимальних способів і технологій зміцнення поверхневого шару деталей зі сталі 45 за критеріальними показниками ефективності. Визначено основні значення основних показників, що складають рівень $D_0$, що обов'язково необхідні для зміцнених поверхонь за відповідними технологіями.

### Література

1. Суслов А.Г., Гуляев Ю.В., Дальский А.М. и др. Качество машин. Справочник. Т2 М. Машиностроение: 1995. 430 с.
2. Франценюк И.В., Франценюк Л.И. Альбом микроструктур чугуна, стали, цветных металлов и их сплавов. М:ИКЦ «Академкнига», 2004. 136с.
3. Григорьянц А.Г., Шиганов И.Н., Мисюров А.И. Технологические процессы лазерной обработки: Учеб. Пособие для вузов / Под ред. А.Г. Григорьянца. М.: Изд-во МГТУ им. Н.Э. Баумана, 2006. 293 с.
4. Девойно О.Г. Технология формирования износостойких поверхностей лазерным легированием:Минск: УП «Технология», 2001. 180 с.

5. Чернета О.Г., Сухомлін В.І., Волощук Р.Г., Губарєв С.В. Особливості структури відновленого поверхневого шару сталі 45 після зміцнення лазерним боруванням. Збірник наукових праць «Перспективні технології та прилади» // м. Луцьк, грудень 2018 р. Луцьк: Луцький НТУ, 2018. Випуск 13. С. 170–175.
6. Чернета О.Г., Коробочка О.М. Сасов О.О., Кубіч В.І. Вибір технологічних методів зміцнення деталей машинобудівного комплексу. *1 Міжнародна науково-практична конференція «Achievemens and prospects of modern scientific research»*. 6-7 декабря, Буенос Айрес, Аргентина 2020. Р.175–182.
7. Чернета О.Г., Сасов О.О., Сошенко С.В. Дослідження фізико-механічних властивостей сталі 45 після різних способів зміцнення. *V Міжнародна науково-практична конференція «Study of modern problems of civilization» Oslo, NORWAY*, 19-23 October, 2020. Р. 486–490.
8. Чернета О.Г., Кубіч В.І., Коробочка О.М. Розробка методів вибору оптимальних технологічних процесів зміцнення поверхневого шару деталей. *2 Міжнародна науково-практична конференція «European scientific discussions»* 26-28 грудня РИМ, Италія, 2020. Р. 211–217.
9. Ігнатович С.Р., Закиев И.М. Универсальный микро нано-индентометр «Micron-Gamma». Заводская лаборатория: Т. 77, № 1. 2011. 67 с.
10. ISO/FDIS 14577-1: 2002; Metallic materials – Instrumented indentation test for hardness and materials parameters. Part 1: Test method – Geneva: ISO Central Secretariat, 2002.