Problems of Tribology, *V. 30, No 1/115-2025, 38-44*

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
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DOI: https://doi.org/10.31891/2079-1372-2025-115-1-38-44

Wear resistance of structural steels carbonitrated by the separate method

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Received: 05 Decemberr 2024: Revised 22 January 2025: Accept 28 January 2025

Abstract

The article investigates the influence of technological modes of separate carbonitriding of carbon steels on the thickness and microhardness of the hardened layer. Two hardening variants were investigated: first, carburizing of surfaces was carried out in argon-propane, and then nitriding in argon-nitrogen mixtures and vice versa. As the conducted studies have shown, the variant of the hardening technological process significantly affects the physical and mechanical characteristics of the hardened layer. In all two variants of the technological process, the hardened layer consists of a surface carbonitride zone and a diffusion zone of internal nitriding, but the properties of these zones are different in different variants of the technological process. Thus, when hardening steels according to the first mode, the thickness of the carbonitride zone is maximum, and the internal nitriding zone has a small thickness. This is explained by the fact that the carbonitride layer created on the steel surface at the first stage of processing performs the function of shielding the surface from the penetration of nitrogen ions into the surface layer of the metal. When hardening according to the second mode, the carbonitride zone has a slightly smaller thickness, but a more developed internal nitriding zone. In addition, carbonitriding according to the first mode leads to the formation of carbonitride inclusions in the diffusion zone in the form of a mesh, which significantly reduce the plasticity of the layer and under dynamic loads are centers of microcrack nucleation. It has also been established that a carbonitride ε – phase is formed on the surface of steels, which consists of carbonitrides of the type Fe2(N,C), Fe3(N,C), Fe4(N,C). The carbonitride zone has high hardness, high corrosion resistance, and increased wear resistance. The thickness of the carbonitride zone reaches a thickness of up to 25 microns. Under the carbonitride zone is the internal nitriding zone, which has a large thickness and is the main part of the carbonitrided layer. The internal nitriding zone consists of a nitrogenous solid solution of the base metal, its nitrides and nitrides of alloying elements. The dependences of thickness and microhardness on the technological parameters of carbonitriding of carbon steels obtained in the work: temperature, saturation time, composition of the gas medium, its pressure allow them to be optimized depending on the requirements of further operation.

Keywords: carbon steels, wear resistance, carbonitration, medium pressure, thickness of the hardening layer

Introduction

Machine parts and tools that operate under conditions of intensive wear are widely used in technology. Increasing their service life will significantly reduce operating and repair costs, which will provide a significant economic effect. Known hardening technologies require further processing of parts and tools, require significant energy resources and are in most cases environmentally harmful. The developed technology significantly reduces energy consumption, is environmentally friendly, and allows you to predict the operational properties of the processed parts.

A significant disadvantage of almost all types of chemical-thermal treatment, and especially furnace nitriding, is the need to heat the products to high temperatures and hold them at these temperatures for a long time, which leads to significant energy consumption. In addition, after nitriding, residual tensile stresses are formed in the "coating-base" system, which reduce the performance of the product. Such coatings cannot work in heavily loaded friction units. At high local loads, the nitrided layer is pushed through, since it lies on a soft base, the microhardness of which is significantly lower than the microhardness of the layer itself. This is due to the fact that the technological process of nitriding involves preparatory heat treatment of steel: quenching with high tempering at a temperature of 800-860 K, which coincides with the temperature of furnace nitriding.

There is a known method of strengthening such coatings, which, after the process of furnace nitriding in an ammonia environment at a temperature of 800-860 K with a holding time of 15...20 hours, is subjected to laser treatment, which is performed after nitriding discretely by points with a treatment area of 20-35% of the total area of the steel product, with a power of 105 -108 W/cm2. As a result of such treatment, the microhardness of discrete areas of steel was:20MnCr5G- 6500 MPa, 37Cr4 - 8200 MPa,41CrAlMo7- 8900 MPa [1].

The disadvantage of this method is the duration of the furnace nitriding process (10...15 hours), high energy consumption, explosiveness and environmental hazard of the process, expensive equipment, and its absence on the Ukrainian market.

It is known that the technology of hydrogen-free glow discharge nitriding (GHND) can be used in all industries where there is a need to increase the service life of parts that operate under conditions of intensive wear, cavitation-erosion and corrosive effects of the external environment on them [2, 3].This ensures increased wear resistance [4], surface strength [5], corrosion resistance [6], reliability and durability of the machined parts [7].

In addition, glow discharge nitriding is characterized by the lowest energy consumption among all known processes of this class - 100...130 kWh/t. For comparison, the corresponding indicator for hardening varies within 1250...1450 kWh/t, for annealing - 300...1500 kWh/t, normalizing - 600...1400 kWh/t, cyanidation - 1050...1600 kWh/t, for laser hardening it is 230 kWh/t, gas nitrocarburization - 600 kWh/t, liquid - 800 kWh/t, gas nitriding - 450 kWh/t. Another extremely important advantage of ATP is the practical absence of deformation of products, which eliminates the need for further surface finishing. It is obvious that both of these facts significantly reduce the cost of the processed part [8].

A significant advantage of the proposed technologycompared to domestic and world analogues is the rejection of the use of hydrogen-containing gas media traditionally used in GLOW DISCHARGE NITRIDING - ammonia and a mixture of nitrogen and hydrogen. The presence of hydrogen in the glow discharge stimulates hydrogen embrittlement. Another serious drawback associated with the use of hydrogen-containing media is the environmental hazard of the process [7, 8].

Goal and problem statement

To investigate the influence of technological parameters of separate carbonitriding of carbon steels (temperature, pressure, propane content in the propane-argon mixture, saturation time, sequence of nitriding and carburizing) to find their optimal characteristics that ensure the operational requirements for the hardened surfaces of parts.

Research methodology

The technological parameters of the carbonitriding process in a glow discharge significantly affect the physical and mechanical characteristics, structure, phase composition, and wear resistance of the carbonitride layer, therefore, studying this influence is an important task.

The research was conducted on steel grades: AISI 3415, T8, 37Cr4, 45, 105WC6. The task of the research was to determine the dependence of the characteristics of the carbonitrated layer (depth, hardness, structure, phase and chemical composition) on the main parameters of the technological process (pressure, composition of the saturating medium, temperature and duration of the process). As working gases, mixtures of nitrogen and argon (75% N2 + 25% Ar) and propane C3H8 were used, the saturation temperature varied from 480 ºC to 600 ºC, the pressure of the gas mixture in the process of diffusion saturation was from 80 Pa to 400 Pa, the duration of the process was from 20 min to 240 min.

In the process of research, methods of metallography, X-ray diffraction and chemical analysis were used, as a result of which the following characteristics of the carbonitrated layer were determined: structure and thickness based on microscopes MMP-2P, "Neophot-21"; microhardness using a PMT-3 microhardness tester; phase composition based on an X-ray device DRON-3M.

In order to conduct experiments rationally and obtain reliable information, mathematical methods of planning experiments (first- and second-order plans) and statistical methods of processing experimental results were used.

Studies of the influence of technological parameters of the nitriding process on the operational characteristics of nitrided samples showed that all dependencies are nonlinear. The use of first-order mathematical models to describe these processes is possible only in a narrow range of changes in variable factors, when the function in a given area can be approximated with sufficient accuracy by a straight line. Therefore, when solving the forecasting problem, the method of planning experiments - the Hartley second-order plan - was used to mathematically describe these dependencies and conduct rational research [9]. Hartley plans differ from other second-order plans in their high efficiency. For example, in a four-factor experiment, 25 experiments must be conducted using an orthogonal central-compositional plan, 31 experiments using a uniform rotatable central-compositional plan, and 17 experiments using a Hartley compositional plan. However, processing the results of the experiments requires the use of software.

Studies of the carbonitriding process in a glow discharge were carried out on an experimental setup that provides hardening of both samples and industrial parts with a diameter of up to 400 mm and a length of up to 1000 mm.

Experimental studies of samples for wear resistance were carried out on a universal machine for testing friction materials model 2168UMT. The counterbody material is steel ShKh15 with a base hardness of HRC61; pressure in the contact zone P = 16 MPa; sliding speed v = 0.1 m/s; the controlled parameter is linear wear h, which was determined as a change in the linear size of the sample measured normal to the friction surface as a result of passing a section with a length l. The test was carried out in the dry friction mode, which is typical for many parts of agricultural machinery.

Presentation of research materials

To find the optimal amount of propane in the saturating medium and the pressure in the discharge chamber, a number of technological modes of hardening of AISI 3415, 105WC6 and 37Cr4 steels were carried out. Technological parameters of the process of forming a carbide layer in a glow discharge: process temperature T = 580 °C, hardening duration τ = 240 min, the pressure in the chamber varied from 67 Pa to 333 Pa, the propane content in the saturating medium in a volume fraction from 3% to 15% (hereinafter, the abbreviated notation of the composition of the gas mixture will be used in the text, for example, 15% C3H8).

In the process of studying samples of AISI 3415, 105WC6 and 37Cr4 steels, the dependences of the surface microhardness of the carbide layer on the technological parameters of the hardening process - pressure in the discharge chamber and propane content were obtained. Data on the microhardness of hardened steels are given in Table 1. The dependences of microhardness on the parameters of carbonitriding are shown in Figures 1 and 2.

Table 1

Microhardness of AISI 3415, 105WC6 and 37Cr4 steels hardened in a glow discharge in a carbon environment

Mode	Technological parameters of the mode				Microhardness H100, MPa					
	p, Pa	% C3H8	I, A	U, B	AISI 3415		105WC6		37Cr4	
					To	After	To	After	To	After
1	333	9.0	6.8	315	2420	6500	3000	4350	2970	4700
2	266	9.0	6.7	380	2700	7300	3150	4800	3000	5500
3	200	9.0	5.6	410	2850	6800	2550	5300	2860	4750
4	133	9.0	4.6	550	2450	5650	2800	4500	2600	3800
5	67	9.0	3.6	970	2650	5000	3000	3750	2800	3600
6	266	15.0	6.6	360	2600	5500	3050	3900	2930	4100
7	266	12.0	6.5	400	2800	6700	3080	4550	2700	5150
8	266	9.0	6.7	380	2750	7300	3050	4800	2950	5500
9	266	6.0	6.1	450	2800	6250	3180	4280	3050	5000
10	266	3.0	6.3	420	2700	5500	3000	3500	2950	3600

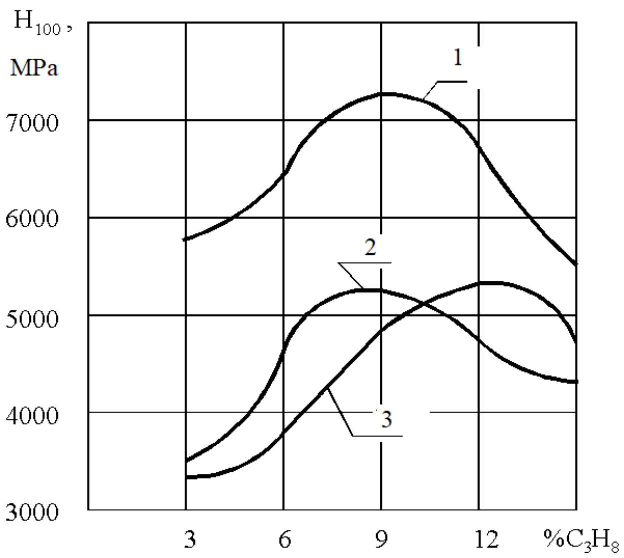

Fig. 1. Dependence of the microhardness of the carbide layer on the propane content in the saturating medium: 1- AISI 3415; 2- Steel 37Cr4; 3- Steel 105WC6

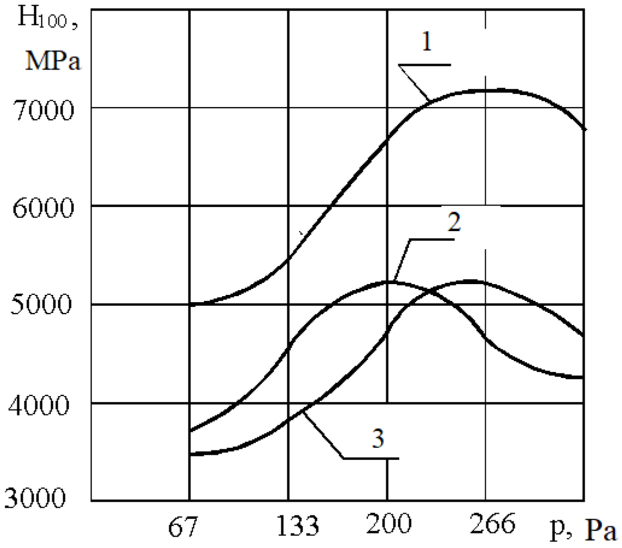

Fig. 2. Dependence of the microhardness of the carbide layer on the pressure in the discharge chamber: 1- AISI 3415; 2- Steel 37Cr4; 3- Steel 105WC6

Previous studies of the influence of the propane content in the medium and the pressure in the discharge chamber have shown that for all the studied steels there are optimal values of the propane content in the saturating medium (from 9% to 12%) and the pressure in the discharge chamber (from 266 Pa to 300 Pa), at which the surface microhardness will be maximum. With an increase in the propane content in the saturating medium, the surface of the samples is covered with soot, which complicates the penetration of saturating gases into the metal surface and the formation of a hardened layer.

The influence of the technological process of carbonitriding on the physical-mechanical and tribological characteristics of AISI 3415, 105WC6 and 37Cr4 steels are researched. Hardening was carried out using two variants of the technological process:

1. Carbon saturation (τ = 120 min, medium – 88% Ar + 12% C_3H_8) + nitrogen saturation (τ = 120 min, medium – 25% Ar + 75% N_2).
2. Nitrogen saturation (τ = 120 min, environment – 25% Ar + 75% N_2) + carbon saturation (τ = 120 min, environment – 88% Ar + 12% C_3H_8).

The process temperature and pressure in the discharge chamber in all two variants of the hardening process remained unchanged. The results of studies of the surface microhardness, the thickness of the hardened layer and the thickness of the carbonitride zone of the hardened steels are given in Table 2. The microstructures of steels for different variants of hardening processes are shown in Fig. 3. As the conducted researches showed, the variant of technological process of hardening significantly influences physical and mechanical characteristics of the hardened layer. In all two variants of technological process the hardened layer consists of a surface carbonitride zone and a diffusion zone of internal nitriding, but the properties of these zones at different variants of technological process are different. Thus, at hardening of steels according to the first mode.

Table 2

Characteristics of carbonitrided layer of steels, hardened in glow discharge depending on the variant of technological process

Mode	Parameters strengthening	Steel grade	Microhardness H100, MPa		Layer thickness, μm	Carbonitrided zone, μm
			to	after		
1	τ = 120 min, 88% Ar + 12% C_3H_8 τ = 120 min, 25% Ar + 75% N_2 T = 580 °C, p = 266 Pa	AISI 3415 105WC6 37Cr4	2700 3000 2950	7800 7200 7350	48 45 40	20 13 25
2	τ = 120 min, 25% Ar + 75% N_2 τ = 120 min, 88% Ar + 12% C_3H_8 T = 580 °C, p = 266 Pa	AISI 3415 105WC6 37Cr4	2800 3180 3050	8200 7240 7900	100 65 80	15 12 20

τ = 120 min, environment (88% Ar + 12% C3H8); τ = 120 min, environment (25% Ar + 75% N2), T = 580 °C, p = 266 Pa) the thickness of the carbonitride zone is maximum, and the internal nitriding zone has a small thickness. This is explained by the fact that the carbonitride layer created on the steel surface at the first stage of processing performs the function of shielding the surface from the penetration of nitrogen ions into the surface layer of the metal (Fig. 3a, 4a, 5a).

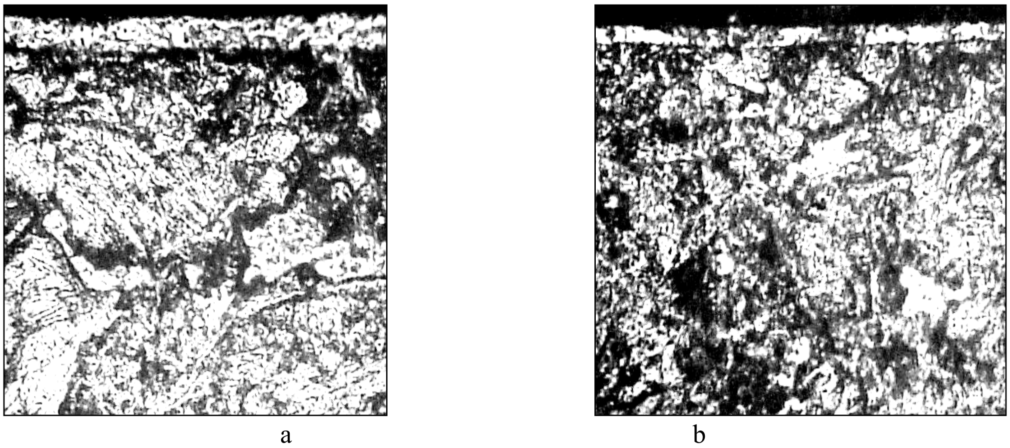
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Fig. 3. Microstructure of AISI 3415 steel: a – mode 1, b – mode 2

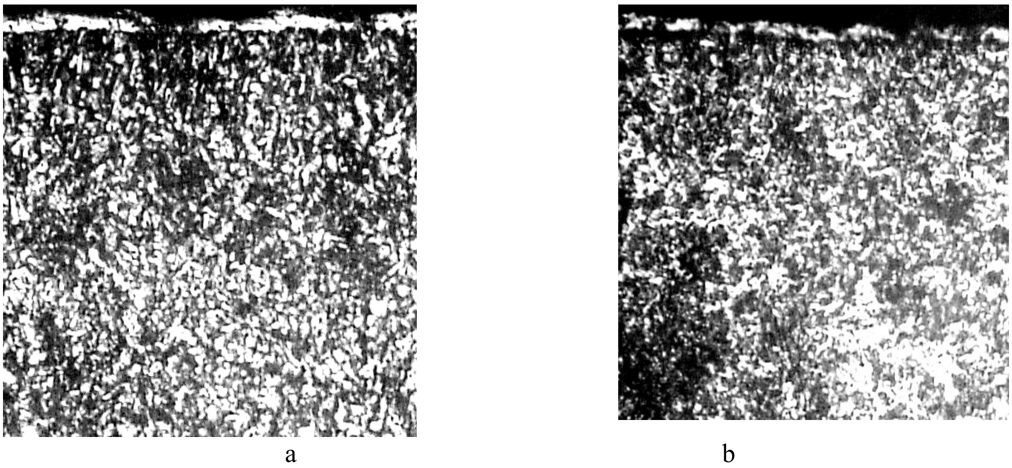
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Fig. 4. Microstructure of 37Cr4 steel: a – mode 1, b – mode 2

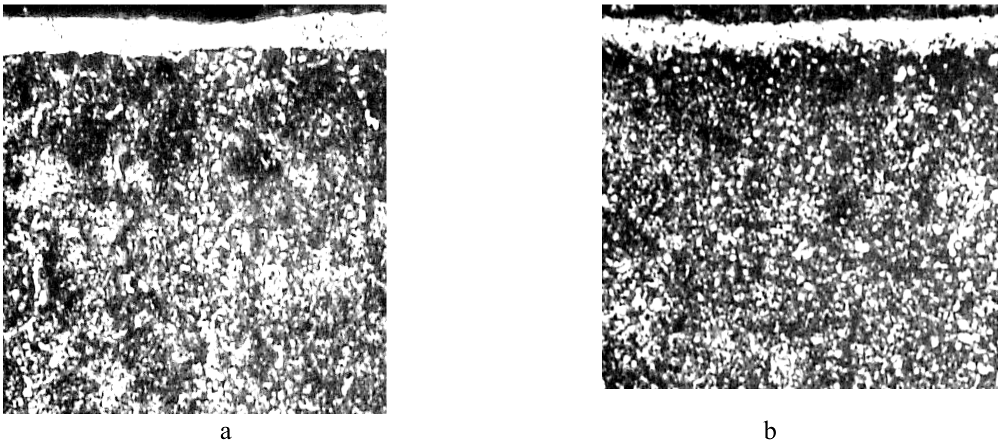
a b

Fig. 5. Microstructure of 105WC6 steel: a – mode 1, b – mode 2

When hardening in the second mode τ = 120 min, environment (25% Ar + 75% N2); τ = 120 min, environment (88% Ar + 12% C3H8), T = 580 °C, p = 266 Pa) the carbonitride zone has a slightly smaller thickness, but a more developed zone of internal nitriding (Fig. 3b, 4b, 5b).

Carbonitriding in the first mode leads to the formation of carbonitride inclusions in the diffusion zone in the form of a mesh, which significantly reduce the plasticity of the layer and, under dynamic loads, become centers of microcrack nucleation.

The results of experimental studies of the microhardness and thickness of the carbonitrided layer of AISI 3415, 105WC6 steels, 45, 37Cr4 and U8 steels for 20 modes according to the Hartley plan were obtained in the work and the dependences of the change in the microhardness H100 of the samples on the depth h of the carbonitrided layer at different technological modes were constructed. From these dependences it follows that when carbonitriding in a glow discharge, as a rule, the highest hardness is obtained on the surface of the part. The latter is explained by the fact that a carbonitride ε − phase is formed on the surface of the part, which consists of carbonitrides of the type Fe2(N,C), Fe3(N,C), Fe4(N,C). The carbonitride zone has high hardness, high corrosion resistance, and increased wear resistance. The thickness of the carbonitride zone reaches a thickness of up to 25 μm. Below the carbonitride zone is the internal nitriding zone, which has a large thickness and is the main part of the carbonitrided layer. The internal nitriding zone consists of a nitrogenous solid solution of the base metal, its nitrides and nitrides of alloying elements.

The dependences of thickness and microhardness on the technological parameters of carbonitriding of carbon steels obtained in the work: temperature, saturation time, composition of the gas medium, its pressure allow them to be optimized depending on the requirements of further operation. Thus, previously conducted studies on the wear resistance during dry friction of carbonitrided steel 45 by the developed method showed that to achieve 100 μm of wear, a friction path of 560 km is required, and for the traditional method, 410 km. That is, we have an increase in wear resistance by 1.36 times. It should be noted that with an increase in the content of carbon (steel U8) and alloying elements (steels 37Cr4, AISI 3415, 105WC6) the effect of increasing wear resistance also increases. The developed method of carbonitriding of carbon steels is protected by a patent of Ukraine [10].

Conclusions

Thus, carbonitriding in a glow discharge allows you to change the structure of the hardened layer by changing the technological parameters of the saturation process and, as a result, change its operational properties. Thus, the increase in wear resistance during dry friction of carbonitrided steel 45 by the developed method increases by 1.36 times compared to the known method.

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Стечишин М.С., Диха О.В., Здоренко Д.В., Олександренко Є.Г. Зносостійкість карбоазотованих роздільним способом конструкційних сталей

У статті досліджено вплив технологічних режимів роздільного карбоазотування вуглецевих сталей на товщину та мікротвердість зміценого шару. При цьому досліджувалося два варіанта зміцнення: спочатку проводилося навуглецьовування поверхонь в аргоно-пропановій, а далі азотування в аргоно-азотній сумішах і навпаки. Як показали проведені досдідження, варіант технологічного процесу зміцнення значно впливає на фізико−механічні характеристики зміцненого шару. У всіх двох варіантах технологічного процесу зміцнений шар складається із поверхневої карбонітридної зони та дифузійної зони внутрішнього азотування, але властивості цих зон при різних варіантах технологічного процесу різні. Так, при зміцненні сталей по першому режиму товщина карбонітридної зони максимальна, а зона внутрішнього азотування має невелику товщину. Це пояснюється тим, що створений на поверхні сталі карбонітридний шар на першому етапі обробки виконує функцію екранування поверхні від проникнення в поверхневий шар металу іонів азоту. При зміцненні по другому карбонітридна зона має дещо меншу товщину, але більш розвинену зону внутрішнього азотування. Крім того, карбоазотування за першим режимом приводить до утворення в дифузійній зоні карбонітридних включень у вигляді сітки, які значно знижують пластичність шару і при динамічних навантаженнях являються центрами зародження мікротріщин. Встановлено також, що на поверхні сталей утворюється карбонітридна ε − фаза, яка складається із карбонітридів типу $Fe_2(N,C)$, $Fe_3(N,C)$, $Fe_4(N,C)$. Карбонітридна зона має велику твердість, високу корозійну стійкість, підвищений опір зносу. Товщина карбонітридної зони досягає товщини до 25 мкм. Під карбонітридною зоною розташована зона внутрішнього азотування, яка має велику товщину і є основною частиною карбоазотованого шару. Зона внутрішнього азотування складається із азотистого твердого розчину основного металу, його нітридів та нітридів легуючих елементів. Отримані в роботі залежності товщини та мікротвердості від технологічних параметрів карбоазотування вуглецевих сталей: температури, часу насичення, складу газового середовища, його тиску дозволяють їх оптимізувати залежно від вимог подальшої експлуатації. Розроблений спосіб карбоазотування вуглецевих сталей захищено патентом.

Ключьові слова: вуглецеві сталі, зносотійкість, карбоазотувння, тиск середовища, товщина шару зміцнення