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**EFFECT OF ION NITRIDING ON DURABILITY  
OF MACHINE PARTS EXPOSED TO JOINT ACTION  
OF BENDING AND FRETTING**

**Summary:** The research was done to carry out a comparative assessment of the durability of samples made of steel 45 in the initial state without chemical heat treatment and after ion nitriding in hydrogen-free media, to determine the effect of technological modes of ion nitriding on fretting fatigue.

Tests were carried out on samples made of steel 45 subjected to ion nitriding in hydrogen-free media under different conditions. The tests were carried out on the standard machine UKI-10M designed for fatigue tests at bending.

At article present results analysis of influence of process-dependent parameters of ion nitriding in hydrogen-free media on fretting fatigue of steel 45 exposed to the joint action of bending stress and contact stress.

Ion nitriding in hydrogen-free saturating media eliminates hydrogen harmful effect on metal and significantly improves the durability of steel 45. The durability of structural elements at fretting-fatigue is seriously affected by process-dependant parameters of ion nitriding and residual compressive stress which can be optimized in terms of maximum durability.

**Key words:** ion nitriding, durability, bending, fretting, fatigue.

## **1. THE RESEARCH TASKS AND URGENCY**

In machinery a lot of machine parts, machineries and industrial machines operate under fretting fatigue conditions. For example, turbine blades, bearers of car wheels, semi-axes of rollers of conveyor traction elements and other structural elements in the cantilever attaching points in nodes are subjected to the joint action of bending stress and contact stress and fail by wear and fatigue. The durability of the parts made of structural low alloy steel does not always meet the usage needs. Therefore, the search for ways to enhance their durability is a topical task of engineering.

At present the methods of chemical heat treatment (nitriding, carburizing, carbonitriding and other methods) are widely used to enhance the durability of structural elements [1, 5]. These methods make it possible to enhance wear resistance and fatigue strength significantly. However, most of the techniques are carried out in hydrogenous media, which causes a decrease in strength and durability of the structural elements because of the adverse effect of hydrogen on the metal is [3, 6]. A promising technique of enhancing the durability of prod-

ucts is ion nitriding in hydrogen-free saturating media (mixtures of nitrogen and argon) [2]. The application of this technique eliminates the harmful effect of hydrogen on the metal and increases its strength characteristics.

The research was done to carry out a comparative assessment of the durability of samples made of steel 45 in the initial state without chemical heat treatment and after ion nitriding in hydrogen-free media, to determine the effect of technological modes of ion nitriding on fretting fatigue, to develop recommendations for enhancing the durability of structural steel operated under fretting and bending conditions.

## 2. THE RESEARCH METHODOLOGY

Tests were carried out on samples made of steel 45 subjected to ion nitriding in hydrogen-free media under different conditions (Table 1). The tests were carried out on the standard machine UKI-10M, designed for fatigue tests at cantilever bending, using a special device (Fig. 1) in which the conical part of the test sample 1 was secured in the check sample 2 with nuts No 5. Certain tightness was caused with a torque indicating wrench in the bevel connection. The check sample 2 was connected with the holder 3 which was secured in the collet attachment of the machine UKI-10M and executed rotary motion. The load device 4 caused bending stress in the sample with the maximum value at the point A and the bending stress caused microdisplacements in the bevel connection. In the process of rotating and impact of Q load the bevel connection of the sample underwent fretting fatigue. The number of load cycles to fracture of the samples was defined as a criterion for evaluating fretting fatigue. The number of cycles to fracture of the non-nitrated sample made of steel 45 was taken as the base number of cycles.

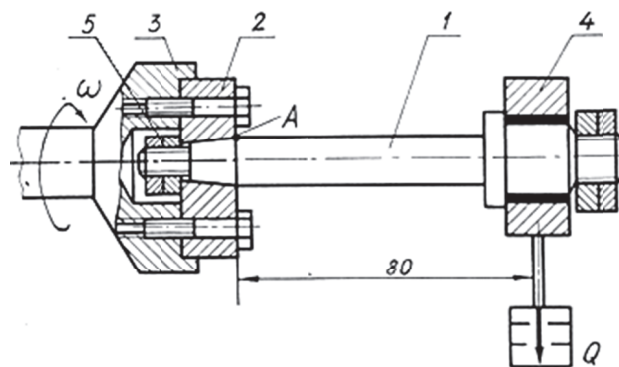


Fig. 1. Fretting fatigue test plot:

1 – sample, 2 – check sample, 3 – holder, 4 – load device, 5 – nut

The tests were carried out in the open, the rotary speed of the sample was  $6000 \text{ min}^{-1}$ , Q load was 392 N, the tightening torque of the sample nut was 25 N·m, and the maximum bending stress was 210 MPa. The sample's jumping

in the site of Q load application was 0.05...0,15 mm and was controlled by the indicator. During the tests the error was estimated according to the procedure described in the work [7] on the basis of the data of preliminary tests of the samples made of steel 45 without nitriding. The relative error in the determination of the durability of the samples did not exceed 10%. The average value of the durability of non-nitrided samples obtained by the tests carried out seven times was  $1.23 \cdot 10^6$  cycles. The properties of the coatings varied at the expense of variation of process-dependent parameters of ion nitriding (the composition of saturating medium – percentage of argon in the mixture with nitrogen, pressure P, temperature T, and the duration of diffusion saturation  $\tau$ ). In order to reduce the number of experiments and improve the reliability of the research results the methods of experimental design (Hartley's second-order design [4]) and statistical processing of results were applied. Four-factor experiment according to Hartley's design provides 20 tests. Therefore, ion nitriding was carried out in 20 operating practices, in the process of which process-dependant parameters varied within the following bounds: T was 480...600°C, p was 80 ... 450 Pa,  $\tau$  was 20 ... 240 min.; content of argon in the mixture with nitrogen was 0 ... 76 vol %.

Mathematical formulation of the process under study according to Hartley's design is expressed by a regression model as quadratic polynomial:

$$\varphi(x) = \beta_0 + \sum_{i=1}^n \beta_i x_i + \sum_{i=1}^n \beta_{ii} x_i^2 + \sum_{i=1}^n \sum_{j=i+1}^n \beta_{ij} x_i x_j \quad (1)$$

where:

$\varphi(x)$  is a response function,  
 $\beta_0, \beta_i, \beta_{ii}, \beta_{ij}$  are coefficients of the regression equation,  
 $x_i, x_j$  are independent variable factors.

For the four-factor experiment of the second order corresponding to our case, the regression equation takes the following form:

$$N = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{44} x_4^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 + \beta_{23} x_2 x_3 + \beta_{34} x_3 x_4, \quad (2)$$

where:

N is durability in cycles at fretting fatigue,  
 $x_1, x_2, x_3, x_4$  are dimensionless coefficients dependent on processing factors of ion nitriding, i.e. on T, p,  $\tau$ , and medium composition.

### 3. THE RESULTS OF THE RESEARCH

The test results (Table 1) show that ion nitriding makes it possible to enhance significantly fatigue resistance of the samples made of steel 45 when they are tested for fretting fatigue. The conditions of ion nitriding have a substantial effect on steel's fatigue resistance which varied from  $1.6 \cdot 10^6$  to  $20 \cdot 10^6$  cycles under the test conditions. Dependences of fatigue resistance on process-

dependant parameters of ion nitriding (Fig. 2) obtained by the processing of the test results are not linear and have an extreme character with explicit maxima for all parameters of the operating procedure. It suggests the possibility of optimization of fretting-fatigue process in terms of durability.

Table 1. Results of fretting-fatigue test of steel 45 according to Hartley's design

nitriding conditions No	Parameters of nitriding conditions				The number of cycles to fracture, $N \cdot 10^6$
	T, °C	P, Pa	$\tau$ , bound/min.	vol. % Ar, in a mixture with nitrogen	
1	570	320	185	57	9.8
2	510	320	185	57	10.1
3	570	160	185	19	4.5
4	510	160	185	19	8.0
5	570	320	75	19	6.5
6	510	320	75	19	8.5
7	570	160	75	57	1.6
8	510	160	75	57	5.1
9	480	240	130	38	8.5
10	600	240	130	38	7.0
11	540	80	130	38	7.5
12	540	400	130	38	20.0
13	540	240	20	38	5.0
14	540	240	240	38	15.0
15	540	240	130	0	12.5
16	540	240	130	76	10.1
17	540	240	130	38	14.5
18	540	240	130	38	15.1
19	540	240	130	38	15.6
20	540	240	130	38	16.0
21	non-nitrided				1.23

Metallurgical and X-ray diffraction studies of samples made of steel 45 show that after ion nitriding the properties of nitrided layers varied depending on the conditions of the operating procedure and were within the following bounds: the thickness of the nitrided layer  $h$  was 50...300 mkm; the microhard-

ness of the surface  $H_{100}$  was 4000..8500 MPa; phase composition varied from the presence of all the three phases ( $\epsilon$ ,  $\gamma'$ ,  $\alpha$ ) in different percentages in the nitride layers on the surface to the predominant presence of  $\alpha$ -phase (internal nitriding zone).

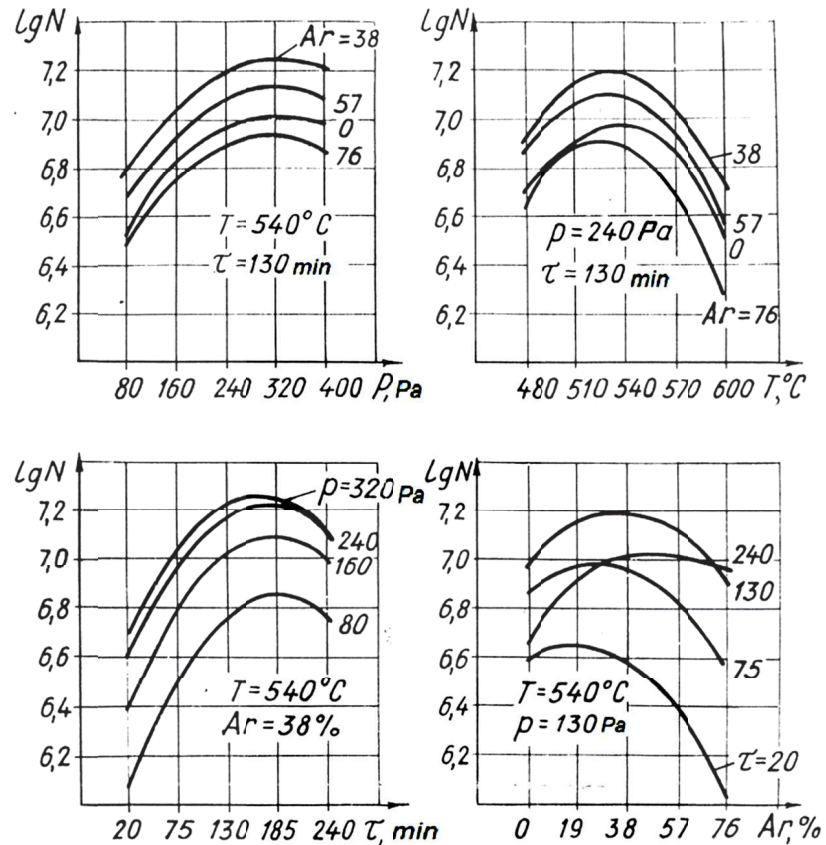


Fig. 2. The effect of ion nitriding conditions on fretting-fatigue of steel 45 (testing in the open at  $\sigma_b = 210$  MPa)

Compressive residual stress occurs in the surface layer of the samples after ion nitriding. Its rate depends on the parameters of the operating procedure and reaches 500 MPa (Fig. 3). The plots (Fig. 3) show that the maximum value of the residual stress occurs on the surface of a diffusion layer in the nitride area and its rate decreases with depth exponentially. The rate of the residual stress can be controlled within wide limits, which is very important for practice. Therefore, the maximum fatigue resistance of nitrided steel at fretting fatigue can be obtained only at the optimal value of the process-dependant parameters of ion nitriding.

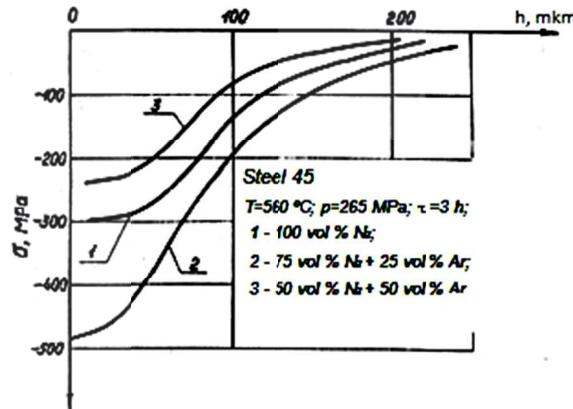


Fig. 3. Distribution of residual stress in steel 45 in the depth of the nitrided layer depending on the process conditions of nitriding

The compressive residual stress changes the tension in bending at critical sections of structural components. Total stress decreases in tensile layers and increases in compressed layers. Taking into consideration the fact that ultimate compressive strength of steel is significantly higher than ultimate tensile strength, we can state that such redistribution of stress is favourable for increasing the bearing capacity and durability of structural components, and the maximum effect is achieved at the optimum value of compressive residual stress.

Optimal compressive residual stress can be defined on the assumption of equality of ultimate tensile strength and ultimate compressive strength at a critical section in bending by the following relation:

$$\sigma_0 = \frac{\sigma_{ut.c}(1 - \chi)}{2\chi} \quad (3)$$

where:

$$\chi = \frac{\sigma_{ut.c}}{\sigma_{uc.c}}$$

is the constant of material,

$\sigma_{ut.c}$  and  $\sigma_{uc.c}$  are the breaking points of coating in tension and compression.

Processing of the results of tests by Hartley's design made it possible to obtain values of the coefficients of regression (Table 2) which defines dependence of steel 45X on process-dependant parameters of ion nitriding.

Table 2. Values of the regression coefficients

$\beta_0$	$\beta_1$	$\beta_2$	$\beta_3$	$\beta_4$	$\beta_{11}$	$\beta_{22}$	$\beta_{33}$
7.14	-0.786	1.278	1.434	-0.278	-2.466	-1.26	-2.16
$\beta_{44}$	$\beta_{12}$	$\beta_{13}$	$\beta_{14}$	$\beta_{23}$	$\beta_{24}$	$\beta_{34}$	-
-1.482	1.872	1.068	-0.451	-0.418	-0.169	1.254	-

The analysis of the regression equation makes it possible to define the optimal nitriding conditions for steel 45 which for the experimental conditions are the following:  $T = 540^{\circ}\text{C}$ ;  $p = 320 \text{ Pa}$ ;  $\tau = 150 \text{ min.}$ ; the medium is 62 vol %  $\text{N}_2 + 38 \text{ vol}\% \text{Ar}$  (Fig. 4). Under the given nitriding conditions the thickness of the nitrated layer was  $h = 250 \text{ mkm}$ , the surface microhardness was  $H_{100} = 7150 \text{ MPa}$ , the maximum residual stress was 240 MPa and the phase structure of the surface layer was 20%  $\epsilon + 55\% \gamma' + 25\% \alpha$ . Figure 4 shows the graphs of dependence of the durability of samples made of steel 45 at fretting-fatigue on process-dependant parameters of ion nitriding under the optimal conditions of diffusion saturation.

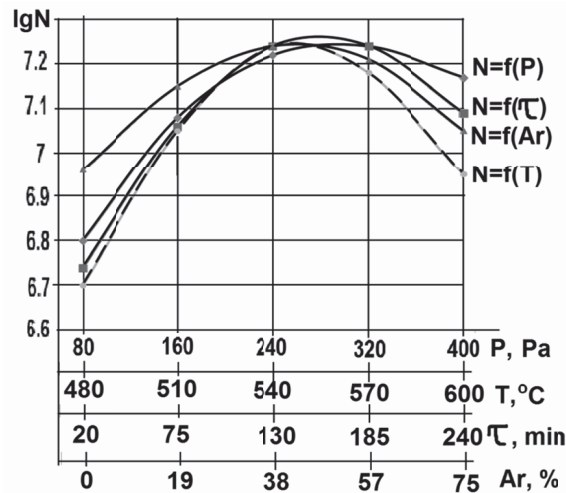


Fig. 4. Dependence of the durability of nitrated steel 45 samples tested for fretting-fatigue on process-dependant parameters of ion nitriding under the optimal conditions of diffusion saturation ( $T = 540^{\circ}\text{C}$ ;  $p = 320 \text{ Pa}$ ;  $\tau = 150 \text{ min.}$ ; medium is 62 vol%  $\text{N}_2 + 38 \text{ vol}\% \text{Ar}$ )

#### 4. CONCLUSIONS AND RECOMMENDATIONS

1. Ion nitriding in hydrogen-free saturating media eliminates hydrogen harmful effect on metal and significantly improves the durability of steel 45 in the process of testing for fretting fatigue.
2. The durability of structural elements at fretting-fatigue is seriously affected by process-dependant parameters of ion nitriding and residual compressive stress which can be optimized in terms of maximum durability.
3. To enhance the durability of machine parts made of structural steel and exposed to joint effect of bending stress and contact stress at fretting it is recommended to apply ion nitriding in hydrogen-free media (mixtures of nitrogen and argon) under the optimal conditions at the optimum values of compressive residual stress.

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## WPLYW AZOTOWANIA JONOWEGO NA TRWAŁOŚĆ CZĘŚCI MASZYN NARAŻONYCH NA ZGINANIE I FRETTING

**Streszczenie:** Przeprowadzono badania porównawcze trwałości próbek wykonanych ze stali 45, w stanie początkowym bez obróbki cieplno-chemicznej oraz po azotowaniu jonowym w atmosferze wolnej od wodoru, w celu określenia wpływu sposobów technologicznych azotowania jonowego na zmęczenie przez fretting. Testy przeprowadzono na standardowej maszynie UKI-10M przeznaczonej do badań zmęczeniowych ze zginaniem. W pracy przedstawiono wyniki analiz wpływu parametrów procesu azotowania jonowego na zmęczenie przez fretting próbek ze stali 45 narażonych na działanie naprężeń zginających i naprężeń kontaktowych. Azotowanie jonowe w atmosferze bezwodorowej eliminuje szkodliwy wpływ wodoru na powierzchnię metalu i znacznie poprawia trwałość stali 45.

**Słowa kluczowe:** azotowanie jonowe, trwałość, zmęczenie, fretting