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Formation of Residual Stresses during Discontinuous Friction Treatment

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Abstract. The tool with grooves on its working surface is used to improve the properties of the strengthened layer. This allows us to reduce the structure's grain size and increase the thickness of the layer and its hardness. Mineral oil and mineral oil with active additives containing polymers are used as a technological medium during friction treatment. It is shown that the technological medium used during the friction treatment affects the nature of the residual stresses' distribution. Thus, when using mineral oil with active additives containing polymers, residual compressive stresses are more significant in magnitude and depth than when treating mineral oil. The nature of the residual stresses diagram depends on the treated surface' shape. After friction treatment of cylindrical surfaces, the highest compressive stresses near the treated surface decreases with depth. And after friction treatment of flat surfaces near the treated surface, the compressive stresses are small. They increase with depth, pass through the maximum, and then decrease to the original values. The technological medium used during friction treatment affects residual stresses in the grains and in the crystal lattice.

Keywords: friction treatment, residual stresses, fatigue, white layer, nanocrystalline structure, technological environment, crystal lattice, grains.

1 Introduction

The current stage of technical development needs increased requirements for the performance of parts. Various parts and assemblies work in friction conditions at high specific loads, temperatures, a wide range of speeds, and exposure to aggressive mediums. Often several factors influence at the same time.

The condition of the surface layer is an essential factor that determines the performance of the product because the destruction of parts begins from its surface. This leads to a decrease in the efficiency and failure of parts due to the processes that take place in the surface layers of parts during operation – friction and wear, plastic deformation, the development of microcracks, and redistribution of residual stresses. The reliability of the parts is directly related to the surface layer's quality and is characterized by geometrical, physical, and mechanical properties. Geometric parameters are determined by the roughness and waviness of the surface and depend on the quality of surface treatment. The properties of materials depend on the chemical composition and structure of the materials. The relationship between the surface layer's quality

characteristics with the parts' performance properties shows that the treated surface must have high hardness, residual compressive stresses, fine structure, etc.

2 Literature Review

Fatigue damage is one of the most common types of metal structures' destruction. Fatigue phenomena occur during the cyclic loading of parts. The material is affected by oscillating stresses and strains, which lead to destruction (failure) due to the accumulation of damage [1]. Fatigue failure is considered the interaction between the metal parts' microstructure, deformations, and mechanical state, especially the surface layer [2]. Avoidance or delay of the parts' damages affected by cyclic loads is an important issue that should be resolved at the design and manufacture of machine parts [1, 2].

Various technological methods improve the quality of surface layers and increase the durability and reliability of machine parts in operation [3–6]. All these technological processes contribute to the formation of high-quality strengthened layers, which slow down the formation and propagation of fatigue cracks. For ensuring appropriate

operating conditions of products and their reliability, it is necessary to study the stresses that occur during the operation of parts, especially in the surface layers [7, 8]. Stresses formed in the parts' surface layers during processing significantly affect the performance properties of parts [9].

The technological processes are required, du to improve parts' performance properties Such methods include processing methods using highly concentrated energy sources [10, 11].

The application of technologies for machine parts' surface strengthening (hardening) by using highly concentrated energy flows leads to the formation the complex temperature-phase transformations in the surface layers of the metal. The surface layer is heated at high speeds to temperatures above the point of phase transformation, and after the removal of the thermal energy source is its subsequent rapid cooling in extreme conditions. As a result, the structure, physical-mechanical and electrochemical characteristics of the metal change in the surface layers significantly affect the machine parts' performance during operation [10, 12].

Residual stresses that occur in the parts' surface layers during their manufacturing process significantly affect their performance during operation. They are among the most critical indicators of the parts' surface layers quality. Thus, the residual compressive stresses in the machine parts' surface layers increase their resistance to fatigue failure, and the tensile, on the contrary – decreases [13, 14]. Knowing the patterns of the 1st kind residual stresses formation can predict and The formation of the someone or other residual stresses plot in the surface layers of the metal depends on the processing conditions, the applied technological medium, the physical and mechanical properties of the processed material.

The work aims to study the influence of the technological medium on residual stresses formed during the friction treatment production operation of samples' cylindrical and flat surfaces.

3 Research Methodology

Friction treatment refers to surface strengthening (hardening) methods using highly concentrated energy flows. This flow of energy is created by the friction of the tool disk on the workpiece. At the same time, there is a simultaneous high-speed shear deformation. The heating rate reaches $5.0 \cdot 10^5 - 1.5 \cdot 10^6$ K/s. The surface layers of the metal are heated to temperatures above the point of phase transformation (A_{c3}), cooling occurs at high speeds ($5.0 \cdot 10^5 - 1.5 \cdot 10^6$ K/s) due to heat dissipation into the part [17]. And the nonequilibrium state of the metal is obtained. The carbon content in martensite is much higher than the concentration corresponding to the point of martensitic transformation. The strengthened white layer with a nanocrystalline structure is formed in the machine parts' surface layer [18].

During the friction treatment, the technological medium is fed into the tool and part contact area. Hydrocarbons are mainly used as a technological medium. The technological

medium decomposes into constituent chemical elements (e.g., carbon and hydrogen), which diffuse into the surface strengthened layer.

Friction treatment of sample' cylindrical surfaces was performed on an upgraded lathe, where instead of a tool holder, a particular device with the autonomous drive for rotation of the tool was mounted. Friction treatment of sample' flat surfaces was performed on an upgraded grinding machine, increasing the tool's rotation speed. On both machines, the tool' rotation speed was 70 m/s. A metal disk made of stainless steel is used as a tool. The tool has transverse grooves on the working surface. Mineral oil and mineral oil with active additives containing polymers were used as the technological medium.

Metallographic analysis showed that after friction treatment of samples of Steel C45 (quench hardening and low-temperature tempering) using as a technological medium mineral oil, a surface strengthened (hardened) layer with a nanocrystalline structure with the thickness of 110–130 μm is formed. The microhardness of the strengthened layer was $H_{\mu} = 6.5 - 6.8$ GPa and the hardness of the base metal – $H_{\mu} = 2.1 - 2.3$ GPa. When used mineral oil with active additives containing polymers as a technological medium, the thickness of the strengthened layer increased to 190-220 μm . The microhardness also increased to $H_{\mu} = 8.6$ GPa.

X-ray analysis showed that the grain size of the surface strengthened layer was 20–40 nm near the surface with a smooth transition to the depth to the structure of the base (source) material. The structure of the obtained strengthened surface layer after friction treatment refers to nanocrystalline.

The first kind of residual stresses, which are formed in the surface layers after friction treatment, were determined by changes in the deflection of the sample during layer-by-layer removal of metal from half of the sample during its electrochemical etching. This disrupts the load balance in opposite parts of the sample, and it bends to restore balance. This principle is the basis for measuring the residual stresses of the first kind by this method. Load balance is changed in opposite parts of the sample, and it is bent to restore the balance. This principle is the basis for measuring the first kind of residual stresses by this method.

The obtained deformations determined residual stresses. Residual stresses were determined on the cylindrical samples with a diameter of 20 mm and a length of 150 mm, and on the flat samples with a size of $6 \times 20 \times 150$ mm. Electrochemical etching and measurement of deflections of the samples were performed on a particular device (Fig. 1). The test samples were placed in the bath on special supports, which provided their free deflection during electrochemical etching. The electrolyte must fill the test sample to half its thickness. The electrode was placed under the sample, which corresponded to the shape of the test sample. Strain gauges (FKPA-20-200 type) were glued to the samples on one side. Before the measurement, the strain gauges were calibrated by loading the samples, mounted on two supports, and a calibration curve was constructed. Using electrochemical etching to

remove thin layers sequentially $\delta_1, \delta_2, \dots, \delta_n$ on one side of the sample, and on the opposite side – measured the deformation value using calibration graphs. For ensuring the etching of only one part of the sample, its sides and top were covered by waterproof varnish. Anodic etching was performed at the current density of 5 A/dm² at a constant rate. During etching, the electrolyte was mixed, and the samples were standing without etching before measuring the deformation, as the temperature that occurs at the metal – medium boundary can add errors.

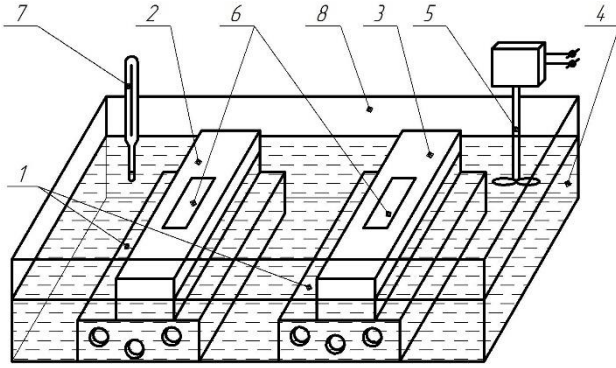


Figure 1 – Scheme of the particular device for determining the first kind residual stresses: 1 – bath; 2 – test sample; 3 – compensating sample; 4 – electrolyte; 5 – mixer; 6 – strain gauges; 7 – thermometer; 8 – bath.

The axial residual stresses that occur in the flat sample after the deformations determined friction treatment according to the formula:

$$\sigma_{rs}(a_i) = \frac{4E}{3l^2} \left[(h-a_i)^2 \frac{df}{da}(a_i) - 4(h-a_i)f(a_i) + 2 \int_0^a f(\xi) d\xi \right] \quad (1)$$

Parabola formulas were used to determine the derivative $\frac{df}{da}(a_i)$. Then,

$$\frac{df}{da}(a_i) = f_{i-1} \left(\frac{-\Delta_{i+1}}{\Delta_i(\Delta_i + \Delta_{i+1})} \right) + f_i \left(\frac{\Delta_{i+1} - \Delta_{i+1}}{\Delta_i \cdot \Delta_{i+1}} \right) + f_{i+1} \left(\frac{\Delta_i}{\Delta_{i+1}(\Delta_i + \Delta_{i+1})} \right) \quad (2)$$

This formula is valid for all values of a_i , eliminate the first and last values.

For the initial value of $i=0$, $a_0=0$, $f_0=0$.

$$\frac{df}{da}(0) = f_1 \left(\frac{\Delta_1 + \Delta_2}{\Delta_1 \cdot \Delta_2} \right) + f_2 \left(\frac{-\Delta_1}{\Delta_2(\Delta_1 + \Delta_2)} \right) \quad (3)$$

For the last removed layer $i=n$:

$$\frac{df}{da}(a_n) = f_{n-2} \left(\frac{\Delta_n}{\Delta_{n-1}(\Delta_{n-1} + \Delta_n)} \right) + f_n \left(\frac{-\Delta_{n-1} + \Delta_n}{\Delta_n \cdot \Delta_{n-1}} \right) + f_n \left(\frac{\Delta_n + (\Delta_{n-1} + \Delta_n)}{\Delta_n(\Delta_{n-1} + \Delta_n)} \right) \quad (4)$$

where E – modulus of elasticity, MPa; l – sample length, m; h – sample height, m; Δ_i – the thickness of the etched layer at the i -th stage, m; f_i – deflection of the sample, m.

When determining the first kind of residual stresses, it was assumed that they are constant along the sample length.

The axial residual stresses were determined by the deformations that occur in the cylindrical sample, according to the formula:

$$\sigma = \frac{E}{\left[\frac{2(r-\delta_i) + \pi y_{ci}}{I_{\delta_i}} \cdot I_{\delta_i} \right]} \frac{d\varepsilon}{d\delta_i} + E \int_0^{\delta_i} A \delta_{(i-1)} \frac{d\varepsilon'_e}{d\delta_{(i-1)}} \cdot d\delta_{(i-1)} \quad (5)$$

where:

$$A \delta_{(i-1)} = \frac{2(r-\delta_{(i-1)}) + \pi y_{c(i-1)}}{I \delta_{(i-1)}} \left(r - \delta_i + y_{c(i-1)} \right) + \frac{\pi}{F \delta_{(i-1)}} ; (6)$$

$$I \delta_{(i-1)} = \frac{2(r-\delta_{(i-1)}) + \pi y_{c(i-1)}}{I \delta_{(i-1)}} \cdot I_{\delta_{(i-1)}} - \frac{\pi}{F \delta_{(i-1)}}$$

δ_i – the thickness of the i -th layer ($i = 1, 2, 3 \dots n$); $l_{\delta_i} = r - y_{ci}$ – the distance from the center of gravity to the lower fiber after removing the layer whose thickness is equal δ_i ; y_{ci} – displacement of the section' center of gravity relative to the axis of the rod after removal of the layer, the thickness of which is equal δ_i :

$$y_{ci} = \frac{4 \left[(r-\delta_i)^3 - r^3 \right]}{3\pi \left[(r-\delta_i)^2 + r^2 \right]} ; \quad (7)$$

I_{δ_i} – the rod' cross-sectional area after removing the layer, the thickness of which is equal δ_i :

$$I_{\delta_i} = \left(\frac{\pi}{8} \right) \left[(r-\delta_i)^4 + r^4 \right]; \quad (8)$$

F_{δ_i} – the rod' cross-sectional area after removing the layer, the thickness of which is equal δ_i :

$$F_{\delta_i} = \left(\frac{\pi}{2} \right) \left[(r-\delta_i)^2 + r^2 \right]. \quad (9)$$

The parabolic approximation method was used to calculate the derivative $\frac{d\varepsilon'_e}{d\delta_i}$ in the equation.

Residual stresses that occur in flat samples were calculated according to the formula:

$$\sigma_{rs}(a_i) = \frac{4E}{3l^2} \left[(h-a_i)^2 \frac{df}{da}(a_i) - 4(h-a_i)f(a_i) + 2 \int_0^a f(\xi) d\xi \right] \quad (10)$$

Parabola formulas were used to determine the derivative $\frac{df}{da}(a_i)$. Then,

$$\frac{df}{da}(a_i) = f_{i-1} \left(\frac{-\Delta_{i+1}}{\Delta_i (\Delta_i + \Delta_{i+1})} \right) + f_i \left(\frac{\Delta_{i+1} - \Delta_{i+1}}{\Delta_i \cdot \Delta_{i+1}} \right) + f_{i+1} \left(\frac{\Delta_i}{\Delta_{i+1} (\Delta_i + \Delta_{i+1})} \right) \quad (11)$$

This formula is valid for all values of a_i , eliminate the first and last values.

For the initial value of $i=0$, $a_0=0$, $f_0=0$.

$$\frac{df}{da}(0) = f_1 \left(\frac{\Delta_1 + \Delta_2}{\Delta_1 \cdot \Delta_2} \right) + f_2 \left(\frac{-\Delta_1}{\Delta_2 (\Delta_1 + \Delta_2)} \right) \quad (12)$$

For the last removed layer $i=n$:

$$\frac{df}{da}(a_n) = f_{n-2} \left(\frac{\Delta_n}{\Delta_{n-1} (\Delta_{n-1} + \Delta_n)} \right) + f_n \left(\frac{-(\Delta_{n-1} + \Delta_n)}{\Delta_i \cdot \Delta_{i+1}} \right) + f_n \left(\frac{\Delta_n + (\Delta_{n-1} + \Delta_n)}{\Delta_n (\Delta_{n-1} + \Delta_n)} \right) \quad (13)$$

where E – modulus of elasticity, MPa; l – sample length, m; h – sample height, m; Δ_i – the thickness of the etched layer at the i -th stage, m; f_i – deflection of the sample, m.

4 Results

Studies have shown that the applied technological medium significantly affects the nature of the 1st kind residual stresses redistribution during friction treatment. Thus, when strengthening (hardening) the samples' flat surfaces of Steel C45 (quench hardening and low-temperature tempering), there are residual compressive stresses (Fig. 2). When using mineral oil with active additives containing polymers, they extend to a greater depth and are more significant in magnitude than the stresses obtained during strengthening with mineral oil. Their value is small near the surface, but with increasing depth, the stresses increase, pass through the maximum and decrease. The same pattern is observed in the strengthening samples of Steel CT80 after quench hardening and low or high-temperature tempering (Fig. 3). The highest stresses occur on the samples after quench hardening and low-temperature tempering, slightly less after friction treatment of the samples after quench hardening and high-temperature tempering. Notably, the residual stress magnitude is influenced by the structural state of the source metal, but the nature of their distribution is almost the same.

During friction treatment using the mineral oil with active additives containing polymers as the technological medium, it is destroyed, and hydrogen is intensively evolved as a component of hydrocarbons and polymers. Hydrogen plasticizes the metal's surface layer, the shear and impact deformations extend to greater depths than when strengthened by using mineral oil as the technological medium. Therefore, the residual stress increases in magnitude and depth.

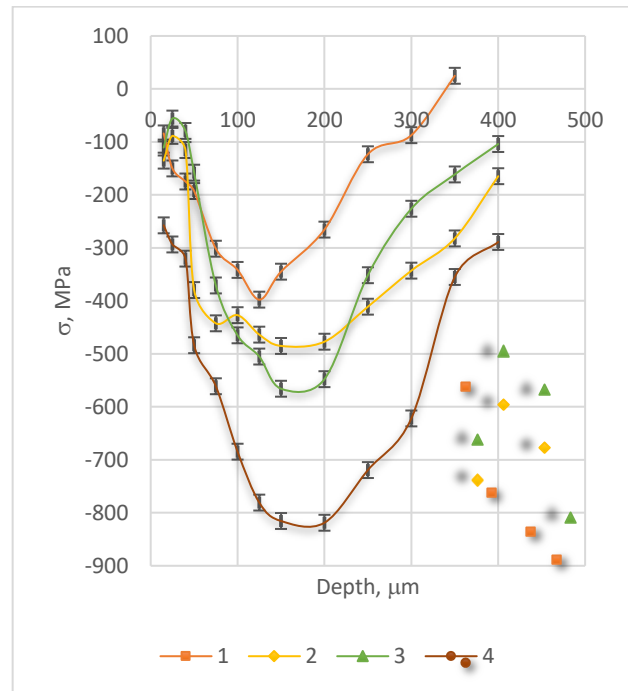


Figure 2 – The first kind of residual stresses obtained on Steel C45 (quench hardening and high-temperature tempering – 1, 2), (quench hardening and low-temperature tempering – 3, 4) after friction treatment: 1, 3 – with mineral oil; 2, 4 – with mineral oil with active additives containing polymers

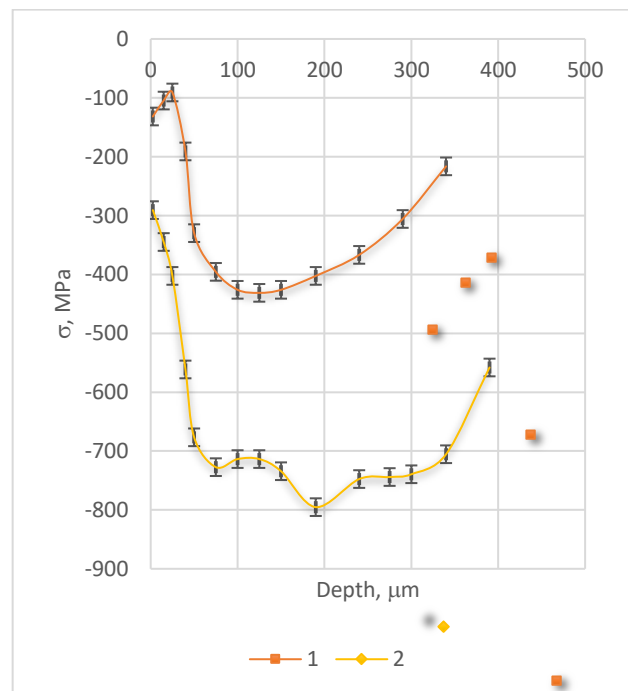


Figure 3 – The first kind of residual stresses obtained on Steel CT80 (quench hardening and low-temperature tempering) after friction treatment: 1 – with mineral oil; 2 – with mineral oil with active additives containing polymers

The nature of the change in residual stresses obtained on cylindrical samples is different from the change in residual stresses obtained after the strengthening of flat samples (Fig. 4). Thus, after friction treatment of samples made of Steel C45 (quench hardening and low-temperature tempering), using the mineral oil with active additives containing polymers as the technological medium, the residual stresses are most significant near the treated surface. With increasing depth, the stresses decrease. The depth of compression stresses is greater than the thickness of the strengthened layer. Compression stresses are observed near the surface, which then turns into tensile stresses. This transition is located outside the white layer on the base metal. After treatment using mineral oil as a process medium, the residual stresses are smaller in value and depth than after treatment with mineral oil with active additives containing polymers, but the nature of the stress distribution is similar.

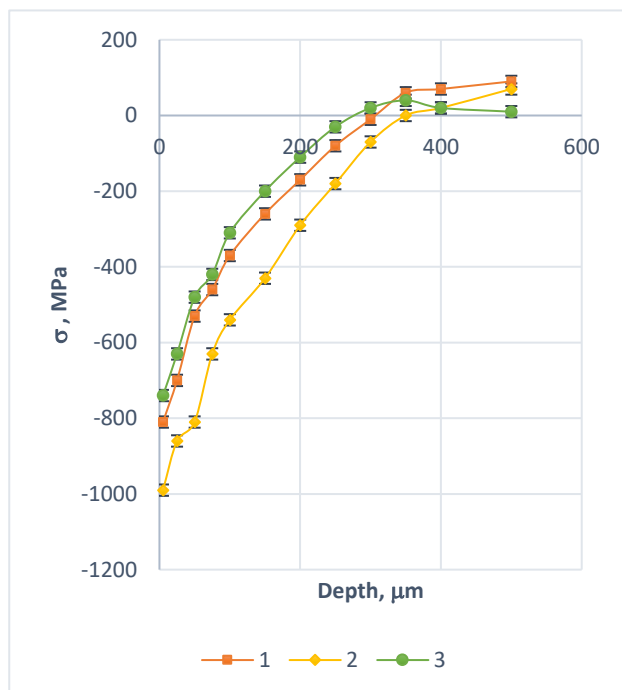


Figure 4 –The first kind of residual stresses obtained on Steel C45 (quench hardening and low-temperature tempering) after friction treatment: 1 – with mineral oil; 2 – with mineral oil with active additives containing polymers; 3 – with mineral oil and stand of 1,5 years.

For determining the effect of the stand on the change in residual stresses, the strengthened samples were stand in the laboratory for 1.5 years. After research, it was found that the stand leads to a slight change in residual stresses, the nature of their distribution is preserved. This allows us to conclude about the high stability of the stress state of the strengthened white layers with a nanocrystalline structure.

The 1st kind of residual stresses obtained on flat surfaces are significantly different from the stresses formed after the frictional treatment of cylindrical surfaces. On the samples' cylindrical surfaces near the treated surface, maximum compressive stresses are

formed, which decrease with depth. After frictional treatment of the samples' flat surfaces, the nature of the stress distribution is different. Near the treated surface, the value of residual stresses is small. With increasing depth, they increase, pass through the maximum, and gradually decrease. The geometric parameters of flat and cylindrical surfaces affect the nature of the 1st kind of residual stresses distribution during frictional treatment.

Frictional treatment refers to methods of obtaining strengthened surface layers with a nanocrystalline structure. Nanocrystallization consists of creating a large number of defects and the demarcation boundary in the surface layer, which are needed for the transition to a structure with nanometric crystal sizes. The necessary conditions for forming the nanocrystalline layer are the provision of high temperatures and stresses in the contact zone. During friction treatment, by using the tool with a discontinuous working surface in the contact area of the tool and part occur the thermoplastic deformation of the treated surface and with heating above the point of phase transformations, cycling of temperatures with high-speed cooling, also shock loads form the nanocrystalline structure. The rate of heating and cooling is 10^3 - 10^4 times higher than with ordinary quench hardening.

During normal quench hardening, a non-equilibrium state of the metal and the corresponding structure are formed, and during high-speed cooling, the time for the formation of such structures and phases is insufficient. As a result, a state is formed, and the individual phases do not have time to separate from the solid solution, or this separation has not yet been finished. At a high cooling rate of the heated iron is fixed γ -phase, carbon does not have time to stand out in the form of cementite formations and remains in solution or partially passes into the tetrahedral pores of Fe_α , and as a result, the martensite is forming. The carbon content in martensite is much higher than the concentration corresponding to the point of martensitic transformation.

The interaction of grains with each other forms residual micro stresses. The action of external load forms unequal deformation of neighboring grains due to their arbitrary orientation and anisotropy.

The study of the technological medium influence during friction treatment on the value of residual micro stresses that occur in grains and crystal lattices was performed on samples made of Steel C45 (quench hardening and low-temperature tempering). Residual micro stresses between grains or crystallites occur due to differences in the microstructure of the material, the presence of different phases or components that have different coefficients of thermal expansion between the phases. Residual microstresses in the metal' crystal lattices are determined by coherence at the demarcation boundary, the presence of various dislocations, lattices defects, dissolved atoms, etc., which cause deformation and stress.

During the friction treatment, the grains of the surface' layer structures sharply decrease to nano-size near the treated surface. With the depth of the layer, the grain size increases to the size of the main structure. The use of different technological mediums during friction treatment

causes various micro distortions in the white layer. Thus, in the white layer obtained on Steel C45 (quench hardening and low-temperature tempering), the most considerable micro distortions occur during friction treatment using a technological medium mineral oil with active additives containing polymers (Fig. 5). After treatment with mineral oil, the stresses are slightly lower. When strengthened using mineral oil, the micro stresses are not much smaller in magnitude than when strengthened using mineral oil with active additives containing polymers but uniform in depth. At depths greater than 100 μm , they begin to decrease towards the initial. Their most considerable value is observed near the surface, at a depth of more than 60 μm . They are close to the initial.

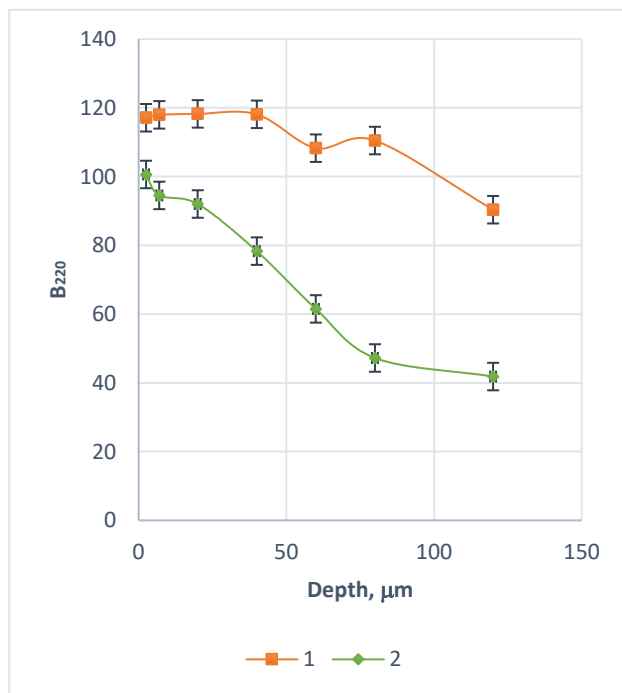


Figure 5 – Changing the width of the diffraction line (220) on Steel C45 (quench hardening and low-temperature tempering) after friction treatment: 1 – with mineral oil; 2 – with mineral oil with active additives containing polymers

In the process of friction treatment in the contact zone of the tool and part under the action of high temperatures and stresses is the decomposition of the technological medium into constituent chemical elements that diffuse into the surface layer. Carbon diffuses into the surface layers, especially during treatment with mineral oil with active additives containing polymers. After friction treatment in the strengthened layer, there is an increased density of dislocations, which on Steel C45 is near the surface of $1.2 \cdot 10^{12} \text{ cm}^{-2}$, and with the depth of the layer decreases to the initial level.

The influence of the technological medium on the residual stresses in the crystal lattice has different effects. Near the treated surface, the technological medium has almost no effect on the distortion of the crystal lattice of the white layer (Fig. 6). With increasing depth of the layer, the stresses in the lattice after friction treatment by using

the mineral oil with active additives containing polymers, first increase, pass through the maximum, and then decrease. After strengthening by using the mineral oil, the most significant stresses are near the treated surface, and the depth of the layer gradually decreases.

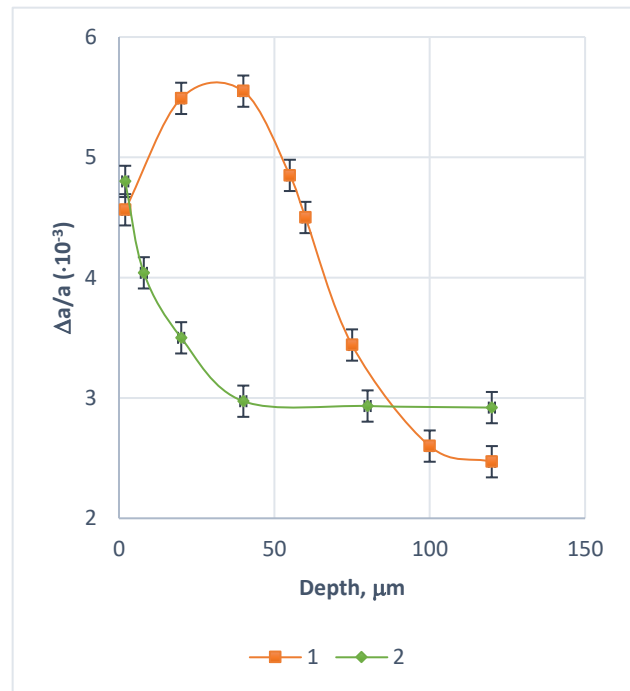


Figure 6 – Distortions of the crystal lattice obtained on Steel C45 (quench hardening and low-temperature tempering) after friction treatment: 1 – with mineral oil; 2 – with mineral oil with active additives containing polymers

Residual stresses are one of the main factors determining the engineering properties of the machined surfaces of machine parts. They should be taken into account when designing and manufacturing various products that are operated under cyclical loads. Although there are many technological methods of processing and strengthening machine parts' working surfaces, developing new processing methods provides a given redistribution of residual stresses.

5 Conclusions

After friction treatment of samples of Steel C45 (quench hardening and low-temperature tempering) using the mineral oil as a technological medium, a surface strengthened layer with a nanocrystalline structure with a thickness of 110-130 μm is formed. The microhardness of the strengthened layer was 7.6 GPa at a hardness of the base metal of 5.1 GPa. When used as a technological medium of mineral oil with active additives containing polymers, the thickness of the strengthened layer increased to 190-220 μm and the microhardness to 8.6 GPa.

The use of mineral oil with polymer-containing additives as a technological medium for frictional treatment increases the magnitude and depth of residual compressive stresses.

The formation of residual stresses is influenced significantly by phase and structural transformations that occur in the surface layers of the metal during the

formation of strengthened white layers with nanocrystalline structures due to high-speed heating and cooling during friction treatment.

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