Possibility of applying X-ray methods to control the surface quality of a shaft line after finishing

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Abstract. The purpose of the paper is to analyze the application limits of X-ray methods of non-destructive testing of loaded parts; to compare the results of microstresses and deformations of the details' surface layer by methods and by the method of X-ray diffraction analysis for various modes of processing the detail surface layer. The studies are carried out on a “Dron” diffractometer. The technique and algorithm of X-ray structural studies, namely, “sin²ψ”-method are represented. Residual macro $\sigma$ and micro stresses, as well as the sizes of the areas of coherent scattering (D) on the samples surfaces processed in various modes, and their distribution in the near-surface layer are designated. Phase analysis is conducted and the presence of residual austenite. The research object is the operating surface of the 46-19-186 gear tooth after various treatments: after HFC hardening; after HFC hardening, grinding and blasting in depressions; after HFC hardening and fine-finish cutting. The X-ray structural analysis (XRD) technique is presented to determine the residual macro-$\sigma$ and microstresses, the sizes of the coherent scattering regions (D) on the surfaces of the samples processed in different modes. The outcomes of X-ray structural analysis are compared with the outcomes of metallographic studies making. It was determined that the stress relaxation during the manufacture of the sample is no more than 10%, and the total instrumental error of the X-ray spectral analysis method is about 1%.

1. Introduction
The task of increasing the operational reliability and durability of machine parts cannot be solved without an effective system for technical diagnostics of the destruction causes. The rational use of non-destructive testing methods ensures the quality of materials and details, defines the stages of the process with defects and, therefore, identifies and eliminates the causes of defects in the production process, and also monitors the development of defects during the equipment operation. Non-destructive testing is based on the use of fields, radiation and substances to obtain information about the quality of materials and objects. X-ray methods differ in the use of a set of high-tech equipment from all existing methods of non-destructive testing and allow obtaining versatile information about almost all the most important parameters of a substance, such as its composition, crystalline perfection, atomic structure, energy and electronic structures, etc.

Technological parameters designate the macro- and microstructure of the material, which the mechanical properties depend on (strength, hardness, plasticity, viscosity, elasticity, endurance, heat resistance, wear resistance, corrosion resistance, etc.), as well as their physical properties (thermal conductivity, density, thermal expansion, conductivity, magnetic, etc.).
The application limits of structure-sensitive methods are presented in Table 1. Studies in physical material science. The analysis shows that X-ray methods determine the phase composition, lattice parameters, features of the crystal structure, dislocation density of inclusions, fragments, ensembles of dislocations, microcracks, groups of point defects of \(10^{-4} - 10^{-6}\) m order [1].

Table 1. Scale hierarchy correspondence of the internal structure elements of a solid body and structurally sensitive research methods in physical materials science.

| Spatial scale, m | Structural level | Research methods |
|-----------------|------------------|------------------|
| Over 10, \(10^{1}\) | MACRO- Detail, ingot, group of grains, individual grains | Physical: dilatometry, thermometry, electro- and magnetometry, measurement of internal friction |
| \(10^{-1}\) | | |
| \(10^{-2}\) | | |
| \(10^{-3}\) | | |
| \(10^{-4}\) | MESO - Phases, twins, precipitates, inclusions, fragments, ensembles of dislocations, microcracks, groups of point defects | Optical: light microscope, metal microscope, scanning electron microscope, transmission electron microscope, X-ray diffractometry, X-ray spectrometry |
| \(10^{-5}\) | | |
| \(10^{-6}\) | | |
| \(10^{-7}\) | MICRO- Individual dislocations, point defects and atoms | High resolution: atomic force microscope, transmission electron microscope, field ion microscope |
| \(10^{-8}\) | | |
| \(10^{-9}\) | | |

Various factors affect the X-ray method sensitivity:
- constant ambient temperature;
- studied material state: blurring of lines associated with the sample material dispersion, distortion of the crystal lattice, as well as the shift in the maxima positions in monolithic samples caused by residual stresses as a result of elastic deformation, has a significant effect on the accuracy of determining the interplanar distances;
- diffraction angle: the larger the diffraction angle is, the smaller is the relative error in determining the interplanar distance \(\frac{\Delta d}{d}=\text{ctg}\theta\);
- accuracy of determining interplanar distances and lattice parameters depends on the choice of indices (hkl) of reflecting planes for materials with a non-cubic lattice.
- methodological negligence in the experiment, misalignment of instruments, inaccurate sample placement and other factors affecting the recording and measurement of the diffraction angle.

It is advisable to supplement the procedure for defining the phase composition with the X-ray spectral method to designate the sample chemical composition. Moreover, it is expedient to apply rotation of the sample during X-ray photography in order to eliminate the effect of mutual screening of particles in a polycrystalline specimen.

Zonal macrostresses in specimens and metal structures that stably exist in a physical object for a sufficiently long time without the application of external loads, namely, residual stresses affect the increase in the operational reliability and durability of machine details. The physical nature of their occurrence is associated with the technology of manufacturing and processing of details and can be determined by metallographic methods [2,5].
2. Materials and research methods

The research object is the operating surface of a gear tooth of 46-19-186 industrial tractor after various treatments: after HFC hardening; after HFC hardening, grinding and blasting in depressions; after HFC hardening and fine-finish cutting.

The metallographic studies of thin sections of the working surface of gears 46-19-186 after various technological processing modes are described in the papers [3,4]. Thin sections of the working surface were made for metallographic studies [3]. Investigations of the microhardness distribution were carried out on a V-Testor 2 hardness tester according to the Vickers method at loads of 9.8 H. The microstructure for metallographic studies was revealed by etching in a 4% alcohol solution of HNO₃ after grinding and polishing the surface. The microstructure was viewed using a Neofot-21 microscope at magnifications of 400, 1000 times. The values of the martensite and pearlite points were determined visually according to the tables of GOST 8233-56.

X-ray structural studies were carried out on a “Dron-2” diffractometer. Residual macro-σᵣ and microstresses, as well as the sizes of coherent scattering regions (D), were determined on the surfaces of the samples processed in different modes and their distribution in the near-surface layer. Phase analysis was carried out in parallel, and the presence of residual austenite was designated in the surface layer.

The study of the stress state and fine structure was conducted layer by layer from the surface to a depth of 0.4 mm. Metal layers were sequentially removed from the samples by electrolytic etching in an electrolyte of composition (Table 2).

Table 2. Electrolyte composition for etching samples of the gears working surface

| Electrolyte composition for etching samples of the gears working surface |
|---------------------------------------------------------------|
| Orthophosphoric acid   | 520 ml          |
| Sulfuric acid          | 57 ml           |
| Water                 | 90 ml           |
| Chromic anhydride (CrO₃) | 60 g           |
| Electrolyte density   | 1.73            |

The electrolysis installation dimensions caused the necessity to cut the teeth (gear rim length is 46-19-186 - 74 mm) [3,4]. It is essential to estimate the amount of relaxation, since the macrostresses relaxation occurs when cutting the detail. According to the literature [2,5,6,8], deformation occurs along the direction of cutting and grinding. The stress level is assessed before and after cutting. The sample is mounted on the diffractometer so that the direction of grinding is parallel to the axis of the goniometer. The obtained stress values before cutting σᵣ = -99 kgf/mm² and after cutting σᵣ = -91 kgf/mm² differ by the amount of permissible measurement error (~10%).

Electropolishing modes are determined experimentally. The depth of the removed layers is taken into account by weighing due to the formula

\[ h, mm = \frac{\Delta m_g}{\rho g/s m^3 S mm^2}, \]

where

- \( h \) - removed layer depth
- \( \Delta m \) - change in sample weight before and after electropolishing
- \( S \) - X-ray area sector (the rest of the sample is carefully insulated).
- \( \rho = 7.87 \times 10^{-3} g/mm^3 \) - iron density
- \( X \)-rays were taken under the following conditions:
  - Fe Radiation;
  - Speed of counter movement - to measure \( \sigma \) (D),
  - 1 l/min - for specification of residual austenite,
  - 2 l/min – for phase analysis
  - Slots – 0.5-0.5-0.25-12.

Residual macrostresses were established by \( \sigma \)² method. Several radiographs taken at different angles to the surface were taken. Residual stresses of the first kind in the diffraction patterns are mani-
fested in the shift of diffraction lines, that is, in changing $\theta$ angle.

Diffraction patterns were taken from the sample surface at angles:

$\psi_1 = 0$; $\psi_2 = +20^0$; $\psi_3 = +40^0$; $\psi_4 = +45^0$

stresses were calculated by the formula

$$\sigma_\varphi = \frac{E}{1 + \mu} \cdot \tan \theta \cdot (\theta_{\varphi} - \theta_{0})$$

$E$– Young’s modulus of steel ($E=23600$ kg/mm$^2$)

$\mu$– Poisson’s ratio ($\mu=0.26$)

$\theta_{0}$ - diffraction angle at $\psi=0^0$

$\theta_{90}$ - diffraction angle at $\psi=90^0$

$\theta_{90}$ cannot be obtained experimentally, it is defined by extrapolating a straight line constructed for several values of $\psi$. The formula includes only the difference in $\theta_{0}-\theta_{90}$ angles, the determination of stresses is based on a change in $\theta$ angle depending on $\psi$ observation angle.

The error in calculating stresses $\sigma_\varphi$ is associated with the inaccurate finding of $\theta$ angle, since the diffraction maxima are strongly blurred due to various structural and physical factors.

To clarify the values of $\theta$, the Kukol method - a method for identifying the position of the profile maximum is the most efficient. $K_\alpha$ is the doublet constituent over a relatively narrow section of the doublet profile, within which the asymmetry from stacking faults is small and does not practically appear. This method does not require measurement of the profile tails and does not involve modeling the profile with analytical expressions. The function is built without highlighting the component profiles

$$Y(x) = 2Y(x-x_0) - Y(x-x_0)$$

This graph is close to a straight line near the doublet profile (Figure 1) and has a common point S that lies in the middle between the maxima of the doublet components. Having the value of $X_0$ ($X_0=0.35^0$ for a diffraction line (211) Fe along 20), and determining the position of S point, the position of components maxima at a distance of $0.5 X_0$ to the left and right of S point can be found. The gravity center of a line with an inseparable doublet is at a distance of $1/3 X_0$ from the maximum components with higher intensity:

$$\theta_{G.C.} = \theta_s - \frac{1}{2} + \frac{1}{3} X_0 = \theta_s - 0.058$$

(20 for Fe)

Thus, the angular positions of the reflection maxima are defined at various $\psi$ by the extrapolation method designated as $\theta=90^0$, which is applied in (1) formula for definitions of macrostresses.

**Figure 1.** Doublet profile of surface diffractogram

**Figure 2.** Corrections graph for $\alpha_1-\alpha_2$ – doublet
Microstress determination method $\Delta a / a$ and blocks of coherent scattering of Dis based on a broadening change of interference lines. If the veritable physical broadening of (hkl) line is caused either by microstresses, grinding mosaic blocks to a value less than 0.1 $\mu$m, then $\Delta a / a$ and D are calculated by the formulas:

$$\Delta a / a = \frac{\beta}{4 + \tan \theta_{hkl}}$$  \hspace{1cm} (1)$$

$$D = \frac{0.94 \lambda}{\beta \cos \theta_{hkl}}$$  \hspace{1cm} (2)$$

B-veritable physical broadening of the line  
$\theta$ – diffraction angle  
$\lambda$ – X-ray wavelength

The veritable physical broadening of (hkl) line is caused by both the refining of blocks and the presence of microstresses and is measured by the formula:

$$\beta = \frac{n \cdot m}{\int N(x)M(x)dx}$$

$N(x)$ - grating distortion function  
$M(x)$ - block crushing function

For metals with a cubic structure, with a sufficient degree of approximation, $M(x)$ function is approximated by the equation $\frac{1}{1 - \gamma x}$, and $N(x)$ function – the equation $\frac{1}{(1 + \varepsilon x^2)^2}$

To designate the blocks of coherent scattering and microstresses, a graph of corrections for $\alpha_1 - \alpha_2$ doublet is used (Figure 2), as well as corrections graph for geometric broadening (Figure 3) and a nomogram for sharing influence $\Delta a / a$ and D (Figure 4).

**Figure 3.** Corrections graph for geometric broadening  
**Figure 4.** Nomogram for separating the effects of microstresses and block dispersion. Fe Radiation, lines (110) and Fe –$\alpha$ (211).
The graphs are calculated theoretically. Corrections graph on $K_{\alpha}$-doublet and geometric broadening are introduced in order to exclude the influence of these factors on the interference line width. The calculation of $\frac{\Delta \alpha}{\alpha}$ and D is carried out on two lines of (110) and (211) $K_{\alpha Fe}$.

3. Results and discussion

Gear tooth material after annealing at $T = 900^0C$, $\tau = 2$ hours and cooling in the oven was used in X-ray photography as a reference.

**Determination of $\sigma$ microstresses of one of the finishing turning samples** at a depth of 30 microns is considered as an example. Diffraction reflections from family of (211) planes are used to compute by observing the plane at different angles:

\[
\psi_1 = 0^0, \quad \psi_2 = +20^0, \quad \psi_3 = +40^0, \quad \psi_4 = +45^0
\]

The gravity center of the diffraction maximum is defined by the Kukol method. For three arbitrary points of $x_1$, $x_2$, $x_3$ close to the diffraction maximum, for example, for

\[
\psi_1 = 0^0 : \quad x_1 = 111.6^0, \quad x_2 = 111.7^0, \quad x_3 = 111.8^0
\]

we establish the function

\[
Y = 2Y(x - x_0) - Y(x - x_0)
\]

where $x_0 = 0.35$ - interdoublet scattering for Fe.

\[
Y_1 = 2Y(x_1 - x_0) - Y(x_1 - x_0) = 28 - 13.5 = 14.5
\]

\[
Y_2 = 2Y(x_2 - x_0) - Y(x_2 - x_0) = 30.6 - 13.4 = 17.2
\]

\[
Y_3 = 2Y(x_3 - x_0) - Y(x_3 - x_0) = 32.8 - 12.5 = 20.3
\]

The graph intersection point of this function and the diffraction curve corresponds to the S point, which lies in the middle between the maxima of the doublet components. The gravity center of a line with an inseparable doublet at a distance of $1/3 \ x_0$ from the component maximum with higher intensity and is computed by the formula:

\[
\theta_{G.C.} = \theta_i - \frac{1}{2} + \frac{1}{3} x_0
\]

In our case

\[
\theta_{G.C.} = \theta_i - 0.029^0
\]

for $\psi_1 = 0^0 :

\[
2\theta_i = 111,873^0, \quad 2\theta_{ST} = 111,873^0 - 0.058^0 = 111,815^0, \quad 2\theta_S = 55,908^0
\]

$\theta_S$ are similarly defined for reflections from (211) plane angled at:

\[
\psi_2 = +20^0 \quad \theta_{G.C.} = 55,929^0 \quad \text{UTT - G.C.}
\]

\[
\psi_3 = +40^0 \quad \theta_{G.C.} = 55,995^0
\]

\[
\psi_4 = +45^0 \quad \theta_{G.C.} = 56,010^0
\]

Further, in the coordinate system of $\theta_{\psi} = f (\sin^2 \psi)$ by the available points, extrapolation is calculated as $\theta_{\psi = 0}^{\exp} = 56,113^0$. Adjustment correction (by armco-iron), which in this case is $0.094^0$

\[
\theta_{\psi = 0}^{\text{vert. sum}} = 56,113^0 - 0.094^0 = 56,019^0
\]

The stresses calculation is made according to the formula:
\[
\sigma_\varphi = -\frac{E}{\mu + 1} \cotg \theta^0 (0^0 - 0_\infty^0)
\]

The values of \(\theta\) angles are written in radians to the formula

\[
\sigma_\varphi = -24kg/mm^2
\]

For 1\(^{st}\) sample after turning at depth of 30 \(\mu\) the definition error \(\sigma_\varphi\) is 10%.

As an example of calculating microstresses and blocks of coherent scattering, the same sample at a depth of 30 microns is considered. For the calculation, diffraction reflections from the family of planes (211) and (110) of the sample under study and the reference were used. Annealed tooth material was used as a reference. According to the above-mentioned method, we designate \(\frac{\Delta \alpha}{\alpha}\) and \(D\) by (1) and (2) formulas.

The outcomes of intermediate measurements are presented in Tables 3, 4 and 5.

### Table 3. General broadening values

| h k l | B\(_{\text{exp.}}\), mm | B, rad | \(\delta/\beta_{\text{tr}}\) | \(\delta/\beta_{\text{tr}}\) | \(b/b_{\text{tr}}\) | \(B/B_{\text{tr}}\) | B, b |
|------|------------------|--------|----------------|----------------|----------------|----------------|------|
| (110)ref | 13 | 236.6*10\(^{-5}\) | 0.4649 | 0.782 | 1.85*10\(^{-3}\) |
| (110)sam | 33.5 | 609.7*10\(^{-5}\) | 0.1804 | 0.960 | 5.85*10\(^{-3}\) |
| (211)ref | 27 | 491.4*10\(^{-5}\) | 0.6105 | 0.714 | 3.51*10\(^{-3}\) |
| (211)sam | 83.5 | 1519.7*10\(^{-5}\) | 0.1974 | 0.950 | 14.43*10\(^{-3}\) |

\(B_{\text{exp.}}\), mm- half-width of the diffraction maximum measured in mm

\(B_{\text{tr.}}\), rad is determined due to the counter speed and belt diagram

\(\delta\) - interdoublet distance

\(\delta\) (110) =1,10*10\(^{-3}\)rad

\(\delta\) (211) =3,00*10\(^{-3}\)rad

\(B_{\text{tr.}}, b_{\text{tr.}}\) - experimental total broadening of the sample and reference.

\(B, b\) - veritable broadening of the sample and reference.

\(b/b_{\text{tr.}}, B/B_{\text{tr.}}\) are computed by the corrections graph on \(\alpha_1, \alpha_2\) – doublet (Fig. 2)

### Table 4. Determination of veritable physical broadening

| \(b/B\) | \(\beta/B\) | \(\beta\) | \(\beta_2/\beta_1\) | \(\cos \theta_1/\cos \theta_2\) | \(\tan \theta_2/\tan \theta_1\) |
|-------|--------|--------|----------------|----------------|----------------|
| (110) | 0.316  | 0.930  | 5.44*10\(^{-3}\) | 2.51           | 1.57           | 2.70 |
| (211) | 0.243  | 0.945  | 13.636*10\(^{-3}\) |               |                |

According to the corrections graph of geometric broadening (Figure 3):

\[
\frac{\beta}{B} = \frac{1}{2} (1 - \frac{b}{B} + \sqrt{1 - \frac{b}{B}})
\]

We find the ratio of \(\frac{\beta}{B}\) and check the inequalities of

\[
\cos \theta_1 < \frac{\beta_2}{\beta_1} < \frac{\tan \theta_2}{\tan \theta_1}
\]
\[
\frac{m_1}{n_1} \frac{n_2}{\beta_1} \beta_1 \Delta \alpha
\]
are computed from the nomogram (Figure 4). As it was mentioned above, D and \( \Delta \alpha \) are designated by the formulas (2) and (1). The outcomes of D and \( \Delta \alpha \) at a depth of 30 microns of the surface layer of the sample after finishing turning are presented in Table 5.

| \( \beta_2 \) | \( \beta_1 \) | \( m_1 \) | \( n_1 \) | \( D, \text{ A}^\circ \) | \( n_2 \) | \( n_2 \) | \( \Delta \alpha \) |
|-----------|-----------|-------|-------|----------------|-------|-------|---------|
| 2.51      | 0.245     | 1.33*10^{-3} | 1558  | 0.887          | 12.095*10^{-3} | 2.042*10^{-3} |

Table 5. Sizes of coherent scattering blocks D (A°) and microstresses \( \frac{\Delta \alpha}{a} \)

X-ray diffraction investigations of the studied sample of the surface layer were carried out to a depth of about 400 microns. The investigation outcomes of the surface and surface layers after the final serial processing - grinding and shot hardening are shown in Figure 5. The level of compressive stresses \( \sigma \) reaches about 90 kgf/mm² on the teeth working surface. The greatest value \( \sigma \) reaches at a depth of 30-40 microns - 115 kgf/mm². This level remains up to a depth of about 90-100 microns and then \( \sigma \) decreases to values of 30-40 kgf/mm², without significant changing. The change nature \( \sigma \) in the second sample after grinding is somewhat different. The maximum \( \sigma \) is observed on the order surface of 100 kgf/mm². Further, the curve character is the same as for the first sample in the depth interval of 100-400 microns. Considering metallographic studies [8,9,10], it can be assumed that this difference is due to various processing modes.

The block sizes of coherent scattering increase after grinding from values of 650-700 A° at a depth of 150 microns, then they monotonically decrease to values of 1500-2000 A° order (Figure 6).

In this case, microstresses vary from values of 1.0*10^{-3} on the surface to 2.0-2.2*10^{-3} at a depth of 150 microns, and then the level \( \frac{\Delta \alpha}{a} \) remains approximately the same (Figure 7).

After finishing turning, the level of compressive stresses on the surface is much lower and amounts to about 15 kgf/mm². Maximum value of \( \sigma \) is reached at depths of 40-100 microns - 35-45 kgf/mm². Further, the stress level decline to values of 20-30 kgf/mm². The block sizes of D coherent scattering in the depth interval of 0-150 microns enhance from the order values of 100 A° to 3000-3500 A°, and then monotonically reduce. Microstresses \( \frac{\Delta \alpha}{a} \) on the surface are much higher than after grinding – 1.60-1.70*10^{-3}. They reach a maximum of (2.40-2.30 10^{-3}) at a depth of 150 microns and do not change anymore.

After hardening with HFC heating and tempering, the level of compressive stresses on the surface is minimal and reaches 20 kgf/mm². At a depth of 60 microns \( \sigma \) grow to values of 50 kgf/mm² and then become lower.

![Figure 5. Graphs of changes \( \sigma \), kgf/mm² in samples surface layers.](image)
The block sizes of coherent scattering on the surface reach about 600 Å (Figure 6), enhance to a depth of 140-150 microns and then do not change. The same nature of changes is in microstresses (Figure 7). The maximum value $\Delta \sigma$ on the sample surface is close to the maximum value $\Delta \sigma$ on the sample surface after finishing turning.

X-ray diffraction studies revealed the complete absence of residual austenite (Fe-$Y$) on the surface of all samples without exception. This means that the heating of the surface layer does not entail phase changes, and the detected stresses were formed only as a mechanical processing result.

Research results show that the level of residual stresses on the surface after finishing turning is insufficient in comparison with serial processing. Generally, the outcomes of preliminary bench tests should serve as a criterion for the optimal level $\phi$. Therefore, the stress level that occurs in the surface layer after grinding can be taken as a criterion at the moment.

It should be noted that working surface grinding of the gear teeth is carried out with the MCO feed (metal-cutting oil). The finishing turning was tested without the use of MCO due to the ineffective MCO application in a serial scheme. Reconstruction of installations is required for the MCO use in cutting. Consequently, the influence of the heat factor in a thin surface layer affects turning to a greater extent than grinding. In this instance, a decrease in the compressive stresses is observed. This is confirmed by the outcomes of the current studies. The heating degree is mainly identified by the pressure magnitude and deformation source, as well as by the physicochemical material properties, namely, a rise in the cutting force (feed) increases the heating intensity. At applied cutting speeds $U$...
=80 m/s and an axial feed of 2.5 l/mm, tarnishing colors were observed on the working surface that is overheating occurs on the surface. Therefore, if we use the formula

\[ \sigma_{\text{therm}} = 0.5 \Delta T \alpha E \]

Where \( \Delta T \) is a temperature drop in the surface layer, \( \alpha \) - thermal expansion coefficient, E - Young’s modulus, then it is possible to obtain the value of residual tensile stresses of the order of 25-40 kgf/mm², which leads to a decline in compressive stresses on the surface. Thermal stress surfaces may prevail at more intense heating, and then residual stresses appear on the surface.

An increase in the tool load also leads to an increase in the degree of work hardening; however, a thermal factor arises. Therefore, excessive deformation, namely, re-hardening, can cause a reduction in compressive stresses. If we compare the levels of residual stresses on the surface and their distribution over the depth after hardening with HFC heating and after cutting, they are approximately the same. It can be assumed that two competing processes - work hardening as a result of plastic deformation and heating occur during cutting. In this case, heating is prevalent, since metallographic studies have revealed the absence of a work-hardened layer. Therefore, the finishing turning operation must be accompanied by cooling, for example, by spraying MCO.

Reducing the influence of the thermal factor can also be achieved by declining the axial feed.

It should be noted that there is also a positive effect of shot-hardening in depressions. This is a necessary process for hardening the teeth cavities, and, in addition, during such processing, the working surface of the teeth is to some extent exposed to the action of the shot hardening.

4. Conclusion

Current studies provide a basis for using the X-ray diffraction method as a non-destructive means of quality control of mechanical operation. It is required to make a change of \( \sigma_\theta \) on the surface and at a depth of 40-60 microns - in the zone of characteristic changes. Relaxation of stresses during the sample manufacture is no more than 10%.

The limitations of X-ray diffraction analysis are due to various factors:
— errors associated with the sample state, for example, due to their structural inhomogeneity or when the structure changes under the influence of radiation in the process of obtaining diffraction patterns;
— errors associated with the equipment state and methods for measuring the scattered intensity of X-rays - instability of the source and detector, non-uniformity of scanning, inaccuracies in alignment, errors in measuring background radiation;
— errors which occur when processing the measured integral intensities of diffraction reflections to obtain experimental values of structural factors or moduli of structural amplitudes;
— errors arising from the attenuation of the diffraction reflection intensities with simultaneous reflection in cases where different nodes of the reciprocal lattice are simultaneously located on the reflection sphere;

The analysis of similar studies by other authors also reveals a fairly high convergence of the outcomes of measuring residual stresses on the samples’ surface by the mechanical method and by X-ray diffraction analysis.

Studies to determine the phase composition, morphology and defect structure of 35HGS steel in the surface layer of products after various stages and processing modes, carried out by scanning electron microscopy, transmission diffraction electron microscopy, X-ray diffraction analysis, magnetic noise and spectral-acoustic methods for assessing physical and mechanical characteristics of structural materials [9, 10] indicate a change in internal stresses and the presence of structural imperfections in steel after mechanical and thermal impact. The depth of the minimum residual stress, the depth of the active part of the residual stress diagrams enhances with increasing feed, but the value of the shear stress of \( \tau_{zx0} \) on the surface decreases.

According to the data of numerous studies, the total instrumental error of XRD is about 1%.
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