Comparative study of residual stresses when turning HSS-5 steel with varying feed

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Abstract. The purpose of this article is a comparative analysis of the parameters of residual stresses in the steel HSS-5 after turning with a change in the longitudinal feed. The tasks posed in this study are: calculating the impact of the feed during turning on the parameters of residual stresses formed in the surface layer of the material; comparing the results of radically different methods for studying residual stresses. When conducting research, the method of XRD-analysis and the mechanical method for calculating residual stresses were used. The presented methods are most widely used in the determination of technological residual stresses in samples of various metals and alloys. These methods are widely used both under laboratory and in production conditions; they are characterized by satisfactory accuracy and convergence of results.

1. Introduction
Extensive experience in the aviation equipment products operation, numerous studies show that technological residual stresses affect corrosion resistance, wear resistance, fracture life, product fatigue strength and other properties. Fatigue strength determines the life of the product and is an important dynamic property that is strongly influenced by the state of the surface that occurs during machining. A fatigue crack, as a rule, originates on the workpiece surface, and then spreads in volume. Consequently, the stress condition on the surface where a crack forms has paramount importance. This stress condition is the sum of the stresses caused by the applied load and the residual stresses that occur during processing. Residual stresses are the result of various mechanical and thermal processes that occur in the treatment area. Residual stresses can be tensile or compressive depending on the processing conditions, the material’s characteristics and the cutting tool geometry [1-3].

Compressive residual stresses usually improve the performance and service life of the product, as they reduce operating stresses and prevent crack nucleation. In turn, tensile residual stresses can significantly increase operational stresses, which can lead to premature product’s breakdown and even destruction.

Consequently, information on the distribution of residual stresses in the surface layer will be useful in the design and manufacture of parts. Therefore, it is important when determining the parameters of the machining process to consider their effect on the residual stresses’ distribution. This contributes to the selection of such machining parameters, which would increase the fatigue life, causing favorable residual stresses (compressive stresses). To ensure this, it is necessary to conduct a series of experiments to calculate the residual stresses at different processing modes, the tool used, the technology, as well as the use of various methods for determination residual stresses to verify the obtained data.

The residual stresses formation during blade processing is caused by the deformation experienced by
of the material’s surface layer due to the cutting tool movement [4, 5].

High strength stainless steels are widely used in the aviation and aerospace industry due to their ability to withstand high loads. Residual surface stresses caused by the machining of such alloys are tensile on the surface and quickly decrease in depth [6, 7].

The residual stresses are estimated by the components of the stress-strain state tensor. The longitudinal turning model assumes that the stress state during processing is flat — this allows considering two normal tensor components: the axial $\sigma_x$ in the direction of the feed vector and the circumferential $\sigma_z$ in the directions of the cutting speed vector, and one tangent component $\tau_{xz}$ in the machining plane [8-10]. Most experimental studies are carried out with a simplified measurement scheme and the definition of one or two normal components [11], which distorts the results and leads to the choice of incorrect technological regimes.

In the residual stresses’ standard piece, the prevailing factor is ensuring the comparability of the results obtained using various methods and techniques for determining residual stresses.

Thus, the purpose of this work is to identify the feeding effect when turning HSS-5 steel on the parameters of residual stresses, as well as conducting a comparative analysis for the convergence of results when determining residual stresses by mechanical and XRD method.

2. Experimental determination of residual stresses

To determine the residual stresses in the surface layer during turning, “hub” type samples were made of high-strength HSS-5 stainless steel (see Figure 1, a). The chemical composition of this steel is shown in Table 1, the mechanical and physical properties in Table 2.

| Mass fraction of elements, % |
|------------------------------|
| C   | Cr  | Ni  | Mo  | N   | Si  | Mn  | S   | P   |
|-----------------------------|
| 0.11-0.16                   | 14.0-15.5 | 4.0-5.0 | 2.3-2.8 | 0.05-0.10 | ≤0.7 | 1.0  | 0.02 | 0.03 |

| Mass fraction of elements, % |
|------------------------------|
| $\sigma_v$, MPa | $\sigma_{0.2}$, MPa | $\delta$, % | $\varphi$, % | $E$, MPa | $\rho$, kg/m$^3$ |
|---------------------|
| 1380-1600            | ≥920                  | ≥15          | ≥55          | 190000    | 7820         |

Initially, the sample blanks had dimensions shown in Figure 1; b. Samples were processed at the DMG NEF400 turning center: the hubs were fixed to the center mandrel with a nut. The mandrel was clamped into a three-jaw chuck of the turning center (see Figure 2).

Cutter of Sandvik Coromant production was used when turning: the holder C3-DCLNL-22045-12 and the plate CNMG 12 04 08-MM 2025.

Experimental passes were performed with feeds $F_n = 0.1; 0.3$ and 0.5 mm / rev. The cutting speed $V_c = 100$ m/min and the cutting depth $A_p = 0.5$ mm were taken constant and were not changed during the experiment.
Figure 1. “Hub” type samples

Figure 2. Fastening hub samples in the turning center DMG NEF400

2.1. Determination of residual stresses by mechanical method. For the mechanical method implementation, the research complex UDION-2 developed at FSUEI HE “INRTU” (Figure 3) [12] was used. The installation allows simultaneously measuring up to four different elementary samples, with the registration of their bending and twisting, i.e. it has eight measuring channels operating simultaneously. The installation’s basic equipment set consists of a scrubber (air purification system) 1, devices for securing samples 2, a bracket for devices 3, a fume hood 4, a pickle 5 and a thermostatic bath 6, a bath lifting device (lifting mechanism) 7, a personal computer 8, a strain gauges data collection systems 9.
The auxiliary equipment engineered for carrying out intermediate measurements of the sample parameters includes a thermostat, a set of end-plane-parallel length measures, a micrometer, an analytical balance, a device for measuring the deflection.

The installation provides continuous removal of layers from the studied elementary samples’ surface by chemical etching in the electrolyte solution in bath 5, the stability of the etching process is provided by a thermostatic bath 6 with heating elements controlled by a PID controller.

**Figure 3.** Installation UDION-2 for measuring residual stresses by mechanical method

**Figure 4.** Elementary samples (rings and strips), used to determine the residual stresses by mechanical method on the installation UDION-2

**Figure 5.** Diagram of cutting the original hubs into elementary samples: 1 - a ring cut at the tool inlet; 2-3 - rings, cut at the exit tool; 1п-3п - strips cut along the axis of the hub; 4 - sample for non-destructive methods
Elementary samples (rings and stripes) are cut out from the test parts (Figure 4) when measuring the residual stresses in this installation. Considering cylindrical parts, the mechanical method is also known as the strip and ring method.

In this case, rings and stripes were cut out from the original sample hub according to the scheme shown in Figure 5. The cutting was performed on a Struers Discotom-10 cutting machine (Figure 6).

For accounting the initial deformations, the initial displacements are measured when calculating the residual stresses after cutting the elementary samples from them. These movements are deflections $f^0$ ($F^0$) and twist angles $\psi^0$ of strips, as well as changes in diameters $\delta^0$ and axial displacements $\omega^0$ of ring cutting surfaces (Figure 7).

Elementary samples are fixed in a special device installation (figure 8). On this device clips are mounted for fixing elementary samples, as well as strain gauges.

With the continuous chemical removal of layers from the samples’ surface, residual stresses are released, which leads to deformation (bending and torsion) of the samples under study, which, in turn, is transmitted to the strain gauge through a double-arm lever.
Receiving, visualizing, processing and storing data from strain gauges is provided by the LTR-EU-2-5 installation data acquisition module under the ACTest software control. Information from strain gauges is formed as an array of deformation curves and is displayed in real time (Figure 9).

The subsequent calculation of residual stresses was made according to the data obtained as a result of preparing the experiment using deformation curves’ array aided by the residual stress calculation program specially developed for the UONDON-2 installation; the formulas for the calculation are given in [13].

2.2. **Determination of residual stresses by XRD-analysis.** An XStress 3000 G3 / G3R diffractometer from Stresstech Oy was used to study the residual stresses by X-ray diffraction analysis (PCA) (Figure 10). The research complex consists of a protective cabinet with an alarm system 1, a goniometer 2, a table with a movable platform for fixing samples 3; the control unit 4 and the amplifier of rotation of the displacement engines 5.
Figure 10. XStress 3000 G3 / G3R X-ray Diffractometer

The measurements were carried out directly on the samples’ surface (see Figure 11). An x-ray tube with a chromic anode was used in the measurement. Type of used goniometry $\Psi$, regulated by standards for the determination of residual stresses by diffraction methods.

Figure 11. Determination of residual stresses in the studied samples by XRD-analysis method

The parameters of X-ray: the voltage and current on the X-ray tube are 25 kV and 5.5 mA, respectively, the exposure time is 5 seconds, the diffraction angle is 156.4 °, and the shooting mode is modified $\chi$ [14].

3. Results and discussion
Analysis of the data obtained shows that on the samples’ surface normal residual stresses components are predominantly tensile (see Table 3), and then change their sign to compressive and at a depth of 30 ... 50 μm get minimum values (-275 ... -440 MPa). After reaching the minima, the components of $\sigma_x$ and $\sigma_z$ with increasing depth almost coincide.

The distribution of the tangent component $\tau_{xz}$ in depth is exponential, with the maximum located on the surface of the material ($\tau_{xz,0}$). It is possible to trace the change in the value of this maximum depending on the flow rate $F_n$: as the flow increases, the value of $\tau_{xz,0}$ decreases from 160 to 90 MPa. The tangential stresses in this case are positive; this is confirmed by twisting the elementary sample-rings into the right-hand helix after they are cut along the generatrix. It should also be noted that the effect of the feed on the depth of the residual stress curve $\Delta$: with an increase in the feed, $\Delta$ also increases (from 65 to 130 μm).
Curves of residual stresses components constructed using the mechanical method in samples of HSS-5 steel after turning with a change in feed are presented in Figure 12.

**Figure 12.** Residual stress curves after turning HSS-5 steel, measured by a mechanical method at: a - \( F_n = 0.1 \) mm/rev; b - \( F_n = 0.3 \) mm/rev; c - \( F_n = 0.5 \) mm/rev
### Table 3. Parameters of residual stress obtained by mechanical and roentgenostructural methods

| $F_n$, mm/rev | PCA (XRD) | Mechanical method |
|---------------|-----------|-------------------|
|               | $\sigma_{x0}$ | $\sigma_{y0}$ | $\sigma_{z0}$ | $\tau_{x0}$ | $\sigma_{x min}$ | $\sigma_{y min}$ | $\Delta x min$, mm | $\Delta y min$, mm | $\Delta z min$, mm |
| 0.1           | 256        | 217             | 288         | 202         | 152             | -278            | -311                | 0.026               | 0.030               | 0.078               |
| 0.3           | 212        | -32             | 235         | -122        | 122             | -386            | -431                | 0.031               | 0.031               | 0.121               |
| 0.5           | 370        | 209             | 416         | 229         | 99              | -322            | -379                | 0.045               | 0.057               | 0.179               |

$F_n$ – feed;  
$\sigma_{x0}, \sigma_{y0}, \tau_{x0}$ – residual stresses on the surface (at a depth 0 mm) of the appropriate component;  
$\sigma_{x min}, \sigma_{y min}$ – minimum residual stress in the depth;  
$\Delta x min, \Delta y min$ – depth of the minimum residual stress;  
$\Delta$ – the depth of the active area of the residual stress diagrams.

### 4. Conclusion

The experimental studies ascertain the effect of the supply when turning HSS-5 steel on the residual stresses parameters over the depth of the surface layer: the depth of the minimum residual stress increases as well as the depth of the residual stress’ curves active part, but the tangential stress $\tau_{x0}$ decreases on the surface of the sample material.

Comparison of the results of determining the residual stresses’ normal components directly on the samples’ surface by the mechanical method and the method of XRD-analysis shows a rather high comparability of the measurement results (the average difference of the results is about 25 MPa, maximum - 46 MPa).

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