Experimental study of residual stresses relaxation in ring details during multicyclic loading

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Abstract. The paper presents the results of experimental studies of vibro-mechanical mechanism of residual stresses relaxation in ringed parts. There was described the mechanism of vibro-mechanical relaxation that includes machining of ringed parts among three rotating rolls under pressure. This leads to multicyclic loading due to which there occurs relaxation of residual stresses. To study the process of vibro-mechanical relaxation a complete factorial experiment was carried out. As a result of experiments we obtained empirical dependence of residual stresses on processing factors.

1. Introduction
Ringed parts have a wide application in the industry. The highest demands are made to geometric accuracy of rings in rolling bearings. Manufacturing of bearing rings is associated with high material and time expenditures which are caused by a high accuracy of form and ring fragility. Even small residual stresses occurring in the workpieces of bearing rings during machining and heat treatment result in significant deformation of rings and loss of geometrical accuracy during the manufacturing process. During the operation of rolling bearings under the cyclic loads there occurs residual stress relaxation, accompanied by elastic-plastic deformation and a corresponding change in the contact conditions of rolling elements, in particular the contact area and the amount of preload. Changes in operating conditions lead to a decrease of bearing life. Therefore, to reduce the internal residual stresses before the final machining, all rings are subjected to process step of size stabilization.

2. Relevance
To reduce the residual stresses and stabilize geometrical parameters of metal products, methods based on different physical action find their applications in the production. The most common ones include: method of natural aging, thermal, chemicothermal, electron-beam and mechanical methods of stabilization.

Natural aging [1] has low productivity that is measured in years; temperature and cold tempering [2] in addition to poor performance have high cost of the equipment. The last one is also accompanied by a significant distortion of geometric shape of the product during the tempering, which does not provide a complete stress relief.

The laser and electron-beam methods [3] provide sufficiently high stability in the distribution of residual stresses due to the high controllability of the process; however, along with the high performance they have high cost of the equipment. Therefore, the reasonability of these methods is justified only during the stabilization of precision products with complex shape.
The method of application of nanostructured coatings and chemicothermal methods [4] have high cost and low performance compared to mechanical methods of stress stabilization. They are used to provide the required physical and mechanical properties of the surface layer of the workpiece.

The methods of mechanical stabilization [5] do not require expensive equipment, while ensuring high stability of distributed residual stresses with a relatively high productivity. Among the mechanical methods, vibro-mechanical one has the best performance. Due to multicyclic loading of a product, the performance of this method can be tens of seconds [6], which is much higher in comparison with other methods of stress relief.

3. Description of stabilizing method

The method of vibro-mechanical stabilization consists of repeated cyclic loading of products [6, 7]. In the device for residual stresses relaxation of ringed parts the basing of machined rings is carried along the cylindrical surface of the rolls with equal diameters and crossed rotation axes at an angle α. Crossed axes of the rolls allow longitudinal movement of the rings at a speed V. At mutually opposite turning of the support rolls at an equal angle α along the vertical plane the trajectory deviates from a straight line. Kinematics of the centerless running in cylindrical products during vibro-mechanical stabilization is similar to kinematics of the centerless superfinishing described in detail in [8, 9]. From the work [9] it is known that the curvature of the trajectory is greater, if the angle of the rolls rotation α is greater.

After installation of the ring between the rolls, radial load does not change throughout the whole treatment cycle consisting of a set of cycles for the running-in of parts.

Multiple running-in of parts leads to an accumulation of internal energy in the areas of residual stresses. When this energy reaches critical values, in these areas there begin shears of material micrograins, accompanied by relaxation of residual stresses. This low speed energy storage for plastic flow of the grains does not have time to cause a change in the shape and size of the processed ring. The radial load P, produced by the third roll, is applied to the ring at a point equidistant from the places of contact between the ring and basing rolls. One of the basing rolls imparts rotary motion n to the ring, resulting in a uniform elastic deformation of the material along the entire circumference of the ring by the value of process induced distortion Δ.

4. Experiment description

To assess the influence of processing factors on the quality of relaxation of residual stresses and stabilize the geometrical parameters, the method of complete factorial experiment was used. The following processing factors were selected as independent ones: the deformation value of stabilized part - Δ, conditioned by the radial load applied by the work roll to the processed ring; the rotation frequency of the roll - n; the angle of mutual turning of the rolls in the vertical plane - α, conditioning the value of parts traverse and the time of processing cycle. Based on the equipment capabilities, for the selected processing factors there was defined an area boundary in the form of the upper and lower levels of variation that are presented in Table 1.

| Levels   | Process factors in units |           |
|----------|--------------------------|-----------|
|          | Δ, mm        | n, min⁻¹ | α, grad |
| Lower    | 0.02         | 20       | 1       |
| Main     | 0.0325       | 28       | 1.25    |
| Upper    | 0.045        | 36       | 1.5     |
| Variability interval | 0.025 | 16       | 0.5     |

Table 1. Studied factors with real values.
There were selected 24 outer bearing rings SH20.01 GOST 3635-78 as experimental samples subjected to multicyclic loading. Bearing rings were made of steel SH-15 and went through all the process steps prior to stabilization.

The measurement of residual stresses was conducted on ring deformation after the cut and the subsequent calculation using the formula (1):

\[
\sigma_o = \frac{2 \cdot \delta \cdot E \cdot J}{\pi \cdot r^2 \cdot W}
\]

where \(E=2,1 \cdot 10^5\) MPa is the material modulus of elasticity; \(J=76\) mm\(^4\) is the inertia moment of the sample section; \(W=36\) mm\(^3\) is the moment of bending resistance of the ring section; \(r=14,5\) mm is the radius of a neutral layer of the ring; \(\delta\), mm is the ring deformation in cross-section that is perpendicular to the cutting line of the ring along the generating line.

To evaluate the deviation of the optimization parameter from the average value, the error mean square was calculated according to data obtained from the parallel observations of planning matrix at each point of the experiment plan. Verification of the homogeneity of variance hypothesis was conducted using the Cochran's Q test for significance level equal to 5%. The error mean square was determined assuming that there is a uniform experiments variance.

5. Experiment results

Confidence limits of the regression coefficients were determined in order to select statistically significant coefficients. The comparison of the confidence limits of the regression coefficient with the values of the coefficients revealed that the statistically significant coefficients are \(b_0, b_1, b_2\).

Thus, for the found regression coefficients the empirical model took the following form (2):

\[
\sigma_o = 5,43 - 290 \cdot \Delta + 10,51 \cdot \alpha
\]

After finding the variance of calculated values for optimization parameter at each point of the experiment plan, the model adequacy was verified using the F-test.

Based on the obtained regression model (2), there were plotted graphs showing the dependency of the ellipticity on the intersection angle of the rolls (Figure 1, a) and the value of process induced distortion of the ring (Figure 1, b).

Figure 1a shows that increasing the intersection angle of the rolls leads to an increase of residual stresses. It may be due to the fact that an increase in the angle of the rolls rotation leads to an increase
in the radius of curvature of the path. Thus, the action of originally tuned value of the process induced distortion will be in the lower part of the path. For this reason, the maximum effect of the deformation influence on the residual stresses will take less time relative to the duration of the entire cycle of vibro-mechanical processing.

Analyzing the behaviour of the residual stresses depending on the process induced distortion of the ring, figure 1b shows that with the increase of the initial value of the process induced distortion, residual stresses are reduced. Thus, this confirms the findings based on figure 1 that the value of relieved residual stresses depends on the overall work process induced distortion at vibro-mechanical processing. It is defined by both the maximum value of the process induced distortion and the duration of its influence on the product.

Figure 2 shows the dependence of the residual stresses in the experimental samples on the value of their deformation in the area of rolls axis crossing during vibro-mechanical processing.

![Figure 2. Theoretical and experimental dependencies of residual stresses on the value of ring deformation: 1, 2 represent the lower and upper confidence limits of the experimental dependency, respectively; 3 – theoretical dependency; 4 – experimental dependency.](image)

Considering the regression model (2) it can be concluded that the rate of process induced distortion in the selected ranges of processing factors variation that are limited by upper and lower levels of variation, practically has no effect on the residual stress relief.

Firm line 4 on figure 2 shows the regression dependence (2) obtained during the experiment. Dotted lines 1 and 2 represent the lower and upper confidence limits of the experimental dependency, respectively. Chain line 3 shows the theoretical dependence, built on the basis of the mathematical model of vibro-mechanical stabilization presented in [10].

As it can be seen on Figure 3, the theoretical dependence is within the confidence limits of the experimental values of residual stresses. This suggests that the theoretical dependence is adequate to experimental data.

6. Findings and Conclusion
The experimental studies have established a link between processing factors of vibro-stabilizing treatment and the amount of residual stresses. On the basis of the experiment graphs (Figure 1) and the empirical dependency (2) the following conclusions can be drawn:

- the increase of intersection angle of the backup rolls leads to the increase of residual stresses;
- the increase of initial value of process induced distortion leads to the decrease of residual stresses;
the value of relieved residual stresses depends on the overall work process induced distortion at vibro-mechanical processing. It is defined by both the maximum value of the process induced distortion and the duration of its influence on the product;

- rotation frequency of the rings has practically no effect on the change in residual stresses;
- experimentally obtained dependency of residual stresses on the process induced distortion confirms the theoretical dependency.

As a result of experiments there was established dependency of residual stresses of rings in bearings on processing factors. This proves the validity of the theoretical model of vibro-mechanical stabilization.

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