Increase of bending rigidity of long-dimensional shaft by surface plastic deformation

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Abstract. The results of computer simulation of bending stiffness of cylindrical part are presented. The effect of residual stresses on the maximum bending is considered. It is established that the formation of residual stresses in the surface layers of a certain thickness have a positive effect on increasing the rigidity of the cylindrical pieces. The influence of the degree of relative deformation with the covering surface plastic deformation on the flexural rigidity of long shafts is determined. It is established that the degree of relative deformation in the range from 0.4 to 1.0% has a positive effect on the flexural rigidity of the shafts. The process in question can be implemented without the use of environmentally hazardous lubricating cooling technological means, which makes it possible to attribute it in the future to one of the types of green mechanical processing technologies.

1. Introduction

Shafts, axles and other similar elements are widely used in engineering products. They are the main elements in machine tools, transport equipment, technological machines, in marine installations and many other technical systems. The reliability of individual components and the whole structure depends on their reliability [1, 2].

While in service, such parts must comply not only with the strength and stiffness conditions [3, 4]. Movement arising from the operation of the shafts have a significant impact on their performance and related parts (bearings, gears, couplings), as well as on the accuracy of the nodes, for example, spindles in metalworking machines [5, 6].

During rotation, the length shafts under the action of centrifugal forces bend even from their own weight. To increase the flexural rigidity of parts such as shafts and axles is very difficult. Practically such questions are solved by constructive measures, for example, they increase the number of intermediate supports.

Among the factors that affect the rigidity of core parts, we can note the temperature and the physical properties of the material. Studies carried out by Gerasimov V.Ya., Komarov V.A., Resler I., Smirnov
V.S., Friedman Ya.B., Harders H. and other authors showed very little effect of temperature and modulus the elasticity of the material to change the structural rigidity of parts. In this work, it is proposed to use technological residual stresses of the first kind, which are distributed in the volume of the deformed body, to increase the bending stiffness of the shafts [7, 8].

The aim of the work is the development of technology of surface plastic deforming (SPD), ensuring the formation of rational fields of residual stresses that increase the flexural rigidity of long cylindrical parts [10, 11].

2. Modeling and numerical calculation of bending stiffness of long shafts under the action of residual stresses.

It was previously established [9] that in calibrated rods, of which lengthy shafts are usually made, on the surface and in the central zone the residual stresses in the first approximation are equal in magnitude and opposite in sign. Based on this information, a bar model is adopted, which is a composite cylinder consisting of a core and a shell (bushings) subjected to the action of stresses of different magnitudes and signs.

To simulate the bending stiffness of the shafts depending on the size and nature of the distribution of axial residual stresses, two schemes were used: 1 — residual compressive stresses in the surface layers and tensile stresses in the inner layers (figure 1, a); 2 - residual tensile stresses in the surface layers and compressive stresses in the inner layers (figure 1, b).

![Figure 1](image_url)

**Figure 1.** Schemes for determining the effect of residual stresses on the bending stiffness of the walls: a is the tensile scheme; b - compression scheme.

For the simulation of the residual stresses, a geometrical model of a rod consisting of thin-walled tubes, 0.2 mm thick, was adopted. Each tube was loaded with tensile or compressive stress.

The analytical calculation of the deflection of the rod is made by the Cauchy – Krylov method [7]:

$$
\gamma_{\text{max}} = -\frac{Fl^3}{48E I_x + 6\sigma_z A l^2},
$$

$$
\gamma_{\text{max}} = -\frac{Fl^3}{48E I_x - 6\sigma_z A l^2},
$$

where $E$ – Young’s modulus of the material; $I_x$ – the moment of inertia of the cross section; $A$ – cylinder cross-sectional area; $\sigma_z$ – axial residual stresses.

Formula (1) allows to determine the maximum deflection of the shaft under the action of transverse force $F$ under axial tension, and formula (2) - under axial compression of the cylinder. Calculated dependences show that the value of the maximum deflection in the case of tensile stresses is less than under the action of compressive stresses.
To assess the effect of the shaft geometry and the physico-mechanical properties of the material on the bending stiffness, smooth cylindrical specimens with a length of \( l = 500 \text{ mm} \) and a diameter of \( d = 16 \text{ mm} \) under the action of a transverse load \( F = 250 \text{ N} \) were used.

It has been established that the stiffness of long shafts linearly depends only on the magnitude of the lateral load, the other parameters studied influence nonlinearly. For real shaft geometry, the stiffness value can be changed only by transforming the elastic modulus of the material \( E \). So, in a bimetallic rod with a hard shell, the rigidity is greater than in samples with a soft shell and even more than in homogeneous samples.

Figure 2 shows the simulation results of transverse shaft deflection (material steel 45 \( \sigma_T = 360 \text{ MPa} \)) under the action of axial stresses of different signs and different thicknesses of the layers in which they are distributed. Deflection was determined in the middle of the shaft, where it has the maximum value.

The possibility of increasing the rigidity of lengthy parts such as shafts and axles due to the formation of residual stresses has been established. Axial residual stresses according to the tensile scheme (see figure 1, a) in the presence of thin surface layers \((t / R <0.3)\) contribute to the increase in stiffness and reduce the amount of deflection. Thus, to increase the stiffness of the shafts, it is advisable to form axial compressive stresses in the surface layers, and tensile stresses in the central zone. In this case, the deflection of the waves can be reduced by 2–3 times, depending on the magnitude of the acting stresses and the size of the layers in which they are distributed.

![Figure 2](image1.png)

**Figure 2.** Change in the maximum deflection of the shaft with the thickness of the surface layer \((t)\) and the distribution of axial residual stresses: a - tension scheme; b - compression scheme (see figure 1);

\[ \begin{align*}
1 & - t=0; \\
2 & - t=0.8 \text{ mm}; \\
3 & - t=1.6 \text{ mm}; \\
4 & - \sigma_z =0; \\
5 & - t=2.4 \text{ mm}; \\
6 & - t=2.8 \text{ mm}
\end{align*} \]

The thickness of the surface layer, in which residual stresses act, has a significant effect on the bending stiffness of the shafts. At large thicknesses of this layer, the role of residual stresses in the formation of stiffness may change to the opposite.

To simulate the tangential residual stresses [8], each tube 0.2 mm thick was loaded with tensile or compressive stress around the circumference, which corresponded to the value of the experimental determination.

Figure 3 shows the changes in the maximum deflection of the shaft depending on the thickness of the surface layer and the pattern of distribution of the tangential residual stresses. The results of
modeling and calculations show that the effect of tangential residual stresses on the stiffness of the shafts is directly opposite to the action of axial stresses.

Tangential residual compressive stresses in the inner layers (see figure 1, b) in the presence of thin surface layers (t/R <0.3) contribute to the stiffness of long shafts, and tensile stresses have the opposite effect.

To increase the stiffness of the shafts, it is advisable to form in the surface layers tangential tensile stresses to a certain value, and in the central zone - compressive stresses. In this case, the stiffness of the shafts can be increased by 1.2–1.5 times, depending on the magnitude of the acting stresses and the size of the layers in which they are distributed.

![Figure 3](attachment:figure3.png)

**Figure 3.** Change in the maximum deflection of the shaft with the magnitude and sign of the tangential residual stresses in thin surface layers: a is the stretching scheme; b - compression scheme (see figure 1).

1 – t=0; 2 – t=0,8 mm; 3 – t=1,6 mm; 4 – t=2,4 mm; 5 – σφ =0

The results of calculations showed that radial residual stresses have little effect on the bending stiffness of long shafts [9, 10].

Thus, computer modeling and numerical calculation showed that the bending stiffness of core parts depends on the residual stresses, but this connection is quite ambiguous. Axial and tangential residual stresses have different effects on flexural rigidity. The thickness of the layer in which certain stresses act is also greatly influenced.

To increase the stiffness of long shafts, it is proposed to use a covering surface plastic deformation, in which the necessary residual stresses can be formed over the entire volume of the body.

An annular indenter (matrix) consisting of a conical working part (α is a semi-angle of a cone) and a calibrating part (lK is the length of the calibrating zone) was used as a working tool.

The degree of relative compression Q is determined by the formula:

$$ Q = \frac{D_h^2 - D_k^2}{D_h^2} \times 100\% , $$

where: $D_h$, $D_k$ – workpiece diameter before and after deformation.

The results of determination of residual stresses in cylindrical specimens strengthened by encompassing deformation are described in [6].
Figure 4 presents the generalized results of the curves for identifying the dependence of residual stresses on the degree of relative compression in the surface layers of the billet.

![Figure 4](image)

**Figure 4.** Dependence of maximum values of tangential $\sigma_\phi$ and axial $\sigma_z$ of residual stresses on the degree of relative reduction in the surface layers of the hardened workpiece.

It has been established that residual compressive stresses are formed in the surface layers of the preform with a covering SPD with a relative compression of up to 1%. When compression of more than 1% on the surface of the bars there are residual tensile stresses. Maximum compressive stresses were obtained at $Q = 0.4\%$, with $\sigma_z$ being almost 2.5 times higher than $\sigma_\phi$. With a relative reduction of about 1% on the surface of the rod, the residual stresses are close to zero.

The calculated and experimental results of changes in the flexural rigidity of the shafts, depending on the degree of relative compression after the covering surface plastic deformation, are shown in figure 5.

![Figure 5](image)

**Figure 5.** The change in bending stiffness of cylindrical specimens with the degree of relative compression $Q$ after the covering SPD.

The results of experimental studies are in good agreement with the calculated data. It has been established that, in the range from 0.1 to 0.3–0.4%, the super-low degree of relative compression has very little effect on the change in the initial rigidity of the part. With an increase in the relative
compression from 0.4 to 1.0%, an increase in the stiffness of the shafts was revealed. With compression Q = 1%, the bending stiffness of the samples can be increased by 38%. The thickness of the surface layer of the parts in this case is t = 0.22R [12, 13, 14], which is consistent with the calculated data (t/R <0.3). With an increase in the relative reduction from 1.0 to 2%, a decrease in the stiffness of the shafts was revealed, but in the interval from 1.4 to 2% the stiffness increases slightly compared with the minimum value.

Thus, the method of encompassing surface plastic deformation is sufficiently effective if it is decided to increase the rigidity of machine parts.

The results of computer simulation and experimental studies have shown that the residual technological stresses formed during the encompassing surface plastic deformation are an effective means for increasing the flexural rigidity of long parts such as shafts and axles.

3. Conclusions

- Theoretically proved and experimentally confirmed is the deforming ability of residual stresses of the first kind, acting with a certain regularity in cylindrical layers of a strengthened body.
- The possibility of increasing the rigidity of lengthy parts such as shafts and axles due to the formation of residual stresses has been established. The results of simulation and numerical calculation showed that axial residual stresses in the presence of thin surface layers (t / R <0.3) contribute to an increase in the stiffness of the shafts according to the tensile scheme, and tangential stresses - according to the compression scheme.
- To increase the stiffness of the shafts, it is proposed to use the covering surface plastic deformation, in which the necessary residual stresses can be formed over the entire volume. On the basis of experimental studies, the influence of the degree of relative compression on the flexural rigidity of core parts was established. The possibility of increasing the rigidity of lengthy parts such as shafts and axles by providing a degree of relative compression value from 0.4 to 1%.

Acknowledgments

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