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Determination of technological residual stresses in the surface layer of parts with thin-walled elements during turning

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Abstract At manufacture of heavy-duty parts, one of the important factors ensuring their safety operation is directional formation of technological residual stresses, nature of distribution of the latter having direct effect on the reliability indices. Concept of the deforming ability of the technological residual stresses was formulated as the moment load intensity adjusted to the surfacce. The method was proposed for calculation of torques from the effect of the technological residual stresses’ deforming ability as applicable to discrete models of parts with thin-walled elements at turning. Methodical specifics of the computation scheme formation for elastic after-effect of the technological residual stresses’ deforming ability at machining were discussed. Variants of schematization for standard elements of the parts were presented. Pre-requisites were formed for solving the task of controlling residual deformations of parts with thin-walled elements at turning.

1. Introduction
At manufacture of heavy-duty parts, one of the important factors ensuring their safety operation is directional formation of technological residual stresses, nature of distribution of the latter having direct effect on the reliability indices that, in turn, are directly related to the quality of manufacture [1-3]. At lathe turning of step-shaped hollow shafts with some cylindrical or end elements thickness of walls making 0.3-0.8 mm, the problem of ensuring shape stability and surface-to-surface accuracy after machining occurs [15-17]. The problem is particularly topical when the parts are manufactured of titanium alloys and stainless steels [5-8]. One of the governing factors directly influencing accuracy of the shafts manufacturing is elastic after-effect of deforming ability of technological residual stresses (TRS), generated in the superficial layer of the workpiece resulted from the contact interaction of the cutting tool and the workpiece [4,9].

Deforming ability \( I(h) \) of TRS \( \sigma(h) \) according to the depth \( h \) of their occurrence integrally defines measure of their action and is quantitatively calculated according to the formula [14]

\[
I(h) = \int_0^h \sigma(h) dh
\]

TRS’ deforming ability \( I(h) \) can be physically presented by the moment load intensity \( I(h) \) adjusted to the part’ surface (Figure 1).
Figure 1. Effects of the residual stresses’ deforming ability in the form of moment load intensity

Figure 1 demonstrates the following function chart. Axes $\xi$, $\eta$ of $O\xi\eta\zeta$ coordinates system are situated on the part’ surface. In Figure 1, axis $\xi$ is not marked, but it is perpendicular to $\eta\Omega\zeta$ plane [21]. The surface is machined using temperature-force technological action. The said technological action results in the technological residual stresses generation in the superficial layer. TRS diagram is presented in $h\xi\sigma$ coordinates system [10-13]. The coordinates system origin is situated on the part’ surface in point A. Axis of abscissas $h$ is directed normally into the material’ depth [18-20]. Axis of ordinates $\sigma$ is situated on the part’ surface, and in the discussed case it is co-directional with axis $\eta$. Deforming ability $I_{\xi}(h_m)$ is measure of action of TRS all the way down to their occurrence $h_m$ and is quantitatively defined according to the formula (1). It can be presented as composed function $\mathcal{I}_{\xi} = I_{\xi}(h_m)$. TRS’ deforming ability can be defined both by computation and experimentally.

Then, moment load from the action of TRS’ deforming ability adjusted to to the parts’ surface $\xi\Omega\eta$ in the coordinates system $O\xi\eta\zeta$ at the $a\times b$ area is defined as set of moments $m_{\xi}$ and $m_{\eta}$ relative to axes $O\xi$ and $O\eta$ (Figure 2). Moments $m_{\xi}$ and $m_{\eta}$ are defined in accordance with the expressions:

$$m_{\xi} = \mathcal{I}_{\xi} a b, \quad m_{\eta} = \mathcal{I}_{\eta} a b.$$

2. Materials and methods

At solving the task of TRS’ elastic after-effect at turning of stepped shafts with thin-walled elements, peculiarities of building discrete models of the machined parts should be considered. This is due to the fact of existing of multiple configurations of their elements, some of them being as follows:

- discs (simple; of complex space form; with thickening; with thinning);
- rings (cylindrical; conical; stepped; combined; of complex surface shape);
- hubs (thin-walled; thick-walled);
- shafts (cylindrical; conical; stepped; multipiece).

The point at issue is schematization of the part structure’ breaking down into elements and adjusting the residual stresses’ deforming ability to the said elements. Two principal types of structure can be accepted:

1) Disc (Figure 3).

![Figure 3. Scheme of discretization for disc-type part](image)

The sector area is outlined by diametrical lines passing through points i and i+1 on axis ox, and by radial lines passing through points j and j+1 in the plane xoy.

The local coordinates system x1o1y1 is selected within the outlined area. Components of the residual stresses’ deforming ability $\mathcal{R}_x$ and $\mathcal{R}_y$ considered to be constant within the outlined area are defined. Based on the produced meanings of the components of the residual stresses’ deforming ability, the local power characteristics acting within the area are defined. Thus, all the local areas are described. The common model of the elastic after-action on the plate in whole is formed in the coordinates system xoy according to mechanics rules.

2) Thin-walled hub (Figure 4).

Median surface of the thin-walled hub is broken down, with the pre-set discretization, into local areas having the shape of curvilineal rectangles. The local area is outlined by diametral lines passing through points i and i+1 on the median surface of the hub, and by the lines on the median surface of the hub passing through points j and j+1 in parallel to axis oz.
Figure 4. Scheme of discretization for the shell part

The local coordinates system $z_1o_1y_1$ is selected within the outlined area. Components of the residual stresses’ deforming ability $\mathcal{F}_z$ and $\mathcal{F}_y$ considered to be constant within the outlined area are defined. Further plotting is performed similar to the disk case.

More complex models are formed based on the simple ones. Using the said approach, the complete computational scheme is formed from the elements followed by defining values and directions of the moment loads from the action of the residual stresses’ deforming ability. Based on the calculations made using the produced models, a package of requirements to the quality of the workpiece’ superficial layer is developed within the scope of the defined set of requirements.

3. Discussion of the results
Let us discuss a cup made of titanium alloy VT14 (Russian Standard) as a part example (Figure 5). It has got four thin-walled elements, three cylindrical and one end-type: 1 – cylindrical, 0.3 mm thick; 2 – cylindrical, 0.5 mm thick; 3 – end-type, 0.9 mm thick; and 4 – cylindrical, 0.3 mm thick.

It should be kept in mind that the cup is manufactured from high-strength thermally hardened titanium ($\alpha+\beta$)-alloy VT14 having improved strength limit up to 1300 MPa. The problem of machining the said thin-walled contours is that at choosing cutting speed up to 50 m/min, technological residual compression stresses are formed in. When the cutting seed is increased generation of technological residual tensile stresses in the superficial layer is started. While in operation, residual stresses relaxation takes place, which results in the residual deformations of the discussed thin-walled contour. In turn, this exerts influence on the part’s shape and causes changes in the accuracy characteristics.
Figure 5. A cup with four thin-walled elements

Technological residual stresses in the metal of the cup’ superficial layer in the process of the part’ lathe turning at cutting speed $V = 40$ m/min (Figure 6), $V = 60$ m/min (Figure 7) and $V = 80$ m/min (Figure 8) were defined using computation-experimental method. In accordance with formula (1), TRS’ deforming ability integrally characterizes action of the residual stresses as follows.

At $V = 40$ m/min, the diagram is characterized by dominance of contracting TRS (Figure 6). Compression stresses of about 400 MPa are formed on the surface, which characterizes cold work hardening. After zero-crossing point, maximum tensile subsurface stresses do not exceed 80 MPa. The TRS’ profile (epure) is asymmetric, and deforming ability has minus sign.

At $V = 60$ m/min TRS’ diagram distribution pattern is changed (Figure 7). Compression stresses of about 180 MPa are formed on the surface, which characterizes cold work hardening. After zero-crossing point, maximum tensile subsurface stresses are about 100 MPa. The TRS’ diagram is symmetrical, and deforming ability is close to zero. The most favorable situation occurs. Tensile stresses are present on the surface. TRS’ diagram is balanced. Elastic after-action of TSR’ deforming ability is absent. The situation is ideal specifically for thin-walled low-rigid parts, when shrinkage and tendency to shape stability loss is absolutely absent in the presence of TRS.
Figure 6. TRS diagram at lathe turning of the cup’ outer surface, $V = 40$ m/min

Figure 7. TRS diagram at lathe turning of the cup’ outer surface, $V = 60$ m/min
At $V = 80 \text{ m/min}$, the diagram is characterized by the tensile TRS dominance (Figure 8). Tensile stresses of about 25 MPa are generated on the surface, which characterizes softening of the surface. Maximum subsurface stresses are also tensile and make 125 MPa. The TRS’ diagram is asymmetrical, and deforming ability has plus sign. The said case is the most unfavorable one from the point of view of the operating characteristics. The superficial layer is susceptible to defects formation and shape stability loss.

![Figure 8. TRS diagram at lathe turning of the cup’s outer surface, $V = 80 \text{ m/min}$](image)

Conclusions
The set of studies performed gives grounds for drawing the following conclusions:

- Concept of the TRS’ deforming ability in the form moment load adjusted to the surface is formulated.
- Machine processing leads to occurrence of elastic after-action of the TRS’ deforming ability that causes shrinkage of parts with thin-walled elements.
- Apart from defining the TRS and their deforming ability, methodical aspects of solving elastic after-action problem envisage geometrical analysis of the part’ structure accompanied by the computing model construction.
- Prerequisites are formed required for solving the problem of controlling residual deformations of stepped shafts with thin-walled elements and similar parts at machine processing by turning.

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