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Investigation of the Elastic Deformations of the Technological System during Turning of Rotary Surfaces

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Abstract. **In the development, analytical dependencies have been derived for determining the stability of the technological system during turning of rotary parts. Cases such as establishment in a chuck, in dead center and between centers have been analysed. The results of the analytical studies will contribute post-processing accuracy to be determined and predicted.**

Keywords: elastic deformations, accuracy, turning.

I.INTRODUCTION

When performing mechanical processing operations, the system, consisting of the machine, the fixture, the tool, and the workpiece, and called a technological system, suffers a load from the cutting force, the mass of the machined workpiece, the equipment and the machine nodes, from inertial forces and forces of friction. Their action gives rise to displacements of the system elements within the limits of the existing clearances, contact deformations in the contact surfaces and volume deformations of the details. As a final result, the relative position of the workpiece and the tool is changed with respect to the position, achieved during fixing and static dimensioning and the accuracy of the dimensions, the shape and the relative position of the machined surfaces is disturbed.

The change in the relative position of the tool and the workpiece caused by the acting forces and measured in the cutting zone in the direction of dimensioning, is called force deformation of the technological system.

A lot of research work, theoretical and experimental studies have been carried out to determine the stability of a technological system when processing external cylindrical surfaces. The results contribute to increasing the accuracy of machining and creating an automated system, which is capable of predicting and controlling the accuracy of machining, based on the results of analytical and experimental research [1] – [12].

II.MATERIALS AND MRTODS

The paper presents a system for predicting the dimensions of the details during turning, which takes into account the flexibility of the workpiece, the inaccuracy of making the center holes and the error of fixing the workpiece in a chuck when processing.

The system involves determining of the actual radius of the detail, or the distance between the actual workpiece axis and the tip of the turner knife, based on a given input about tool geometry, cutting modes, material properties, fixing conditions, and the error in locating the workpiece.

Three variants of the model are possible:

- fixing in a chuck;
- fixing in a chuck and a specified center;
- fixing between centers.

In all these three cases, on the basis of input data, the program sets the value of the actual radius of the detail at each point of the surface with a specified step. The determining factor, affecting the change of the radius of processing or the value of the workpiece displacement is the axial cutting depth a_p, which, in turn, depends on the deformation of the workpiece, the inaccuracy of producing the center holes and the fixing error. To simplify the calculations, some assumptions are made for the model:

- zero susceptibility of the spindle and the rear center;
- ideal and uniform surface of the workpiece;
- no deflection of the tool.

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A methodology for determining the actual radius of the detail is shown on the example of machining a workpiece, set in a chuck and a rear center. The two other cases, mentioned above, are private and obtained by excluding unexamined parameters.

The formula for calculating the actual cutting depth a_p^{∂}, taking into account the error of fixing the workpiece in the chuck $\Delta_{П}$, the displacement of the center holes $\Delta_{Ц}$ and the sagging of the workpiece Δ_Z under the action of the cutting force, has the following form [13]:

$$a_p^{\partial} = a_p + \Delta_{П} + \Delta_{Ц} + \Delta_Z \tag{1}$$

where a_p is the average set axial depth of cut:

$$a_p = R_Z - R_D;$$

R_Z, R_D are respectively the workpiece radius and the radius of the detail, set in the initial conditions;
$\Delta_{П}$ – the displacement of the workpiece when fixing it in a chuck;
$\Delta_{Ц}$ – the displacement of the center holes;
Δ_Z – the magnitude of deformation of the workpiece under the action of the cutting force.

The workpiece displacement $\Delta_{П}$, expressing the error of locating the workpiece in the lathe chuck for one revolution (Fig. 1), can be determined using the circle displacement equation. Since the displacement of the rear center is assumed to be equal to zero, the equation has the form:

$$\begin{aligned}\Delta_{П} = &\sqrt{R_Z^2 - \left(L_0 / L_Z.\Delta_{П}\right)^2 \sin^2\left(\varphi+\psi\right)} + \\ &+\left(L_0 / L_Z.\Delta_{П}\right)\cos\left(\varphi+\psi\right) - R_Z\end{aligned} \tag{2}$$

where L_0 is the distance from the tailstock centre to the considered section of the workpiece;
L_Z – the length of the workpiece from the chunk to the rear center;
φ - the angle of rotation of the workpiece;
ψ- the angle of non-coincidence of the displacements $\Delta_{П}$ and $\Delta_{Ц}$.

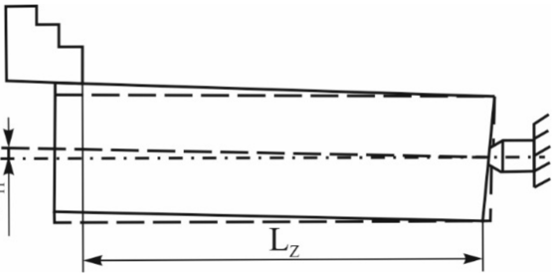


Fig. 1. Displacement of the workpiece as a result of its establishment in the chuck of the machine.

Similarly, the displacement of the workpiece $\Delta_{Ц}$, resulting from an inaccuracy in the manufacture of the center holes, is determined (Fig.2), and the displacement of the workpiece due to an inaccuracy in locating it in the lathe chuck is not taken into account.

$$\begin{aligned}\Delta_{Ц} = &\sqrt{R_Z^2 - \left(\frac{L_Z - L_0}{L_Z}\Delta_{Ц}\right)^2 \sin^2\varphi} + \\ &+\frac{L_Z - L_0}{L_Z}\Delta_{Ц}\cos\varphi - R_Z\end{aligned} \tag{3}$$

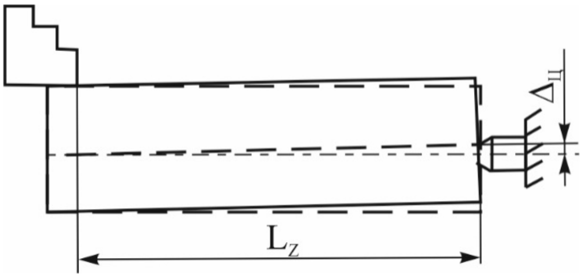


Fig. 2. Displacement of the workpiece as a result of an inaccuracy in the manufacture of the center holes.

The sagging of the workpiece A_z under the action of the cutting forces F_p and F_c in the direction of the axes *y* and *z* (Fig.3) is considered as a beam, established on two supports, and calculated according to the formula:

$$\Delta_{zy} = \frac{F_p L_0^2 \left(L_Z - L_0\right)^2}{3EIL_Z} \tag{4}$$

$$\Delta_{zz} = \frac{F_c L_0^2 \left(L_Z - L_0\right)^2}{3EIL_Z} \tag{5}$$

where *E* is the modulus of elasticity of the material of the workpiece.

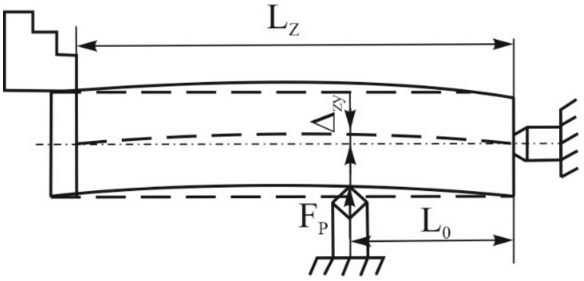


Fig. 3. Displacement of the workpiece as a result of the action of the cutting force F_p.

The dependence for calculating the actual depth of cut when establishing the workpiece in the chuck and the rear center is determined from the dependences (2) - (5) by the formula (1):

$$a_p^{\partial} = \sqrt{R_Z^2 - \left(L_0 / L_Z . \Delta_{\text{П}}\right)^2 \sin^2\left(\varphi + \psi\right)} + \\ + \left(L_0 / L_Z . \Delta_{\text{П}}\right) \cos\left(\varphi + \psi\right) + \\ + \sqrt{R_Z^2 - \left(\frac{L_Z - L_0}{L_Z} \Delta_{\text{Ц}}\right)^2 \sin^2 \varphi} + \\ + \frac{L_Z - L_0}{L_Z} \Delta_{\text{Ц}} \cos \varphi - R_Z - \sqrt{\left(R_D + \Delta_{zy}\right)^2 + \Delta_{zz}^2} \quad . (6)$$

From the analysis of the obtained formula, it can be established that when the planes in which the displacements $\Delta_{\text{П}}$ and $\Delta_{\text{Ц}}$ are located do not coincide, they compensate and complement each other, and the actual cutting depth changes.

By setting the displacements $\Delta_{\text{П}}$ and $\Delta_{\text{Ц}}$, and then calculating the deformation of the workpiece under the action of the cutting force at a set depth a_p, the actual cutting depth a_p^{∂} is found. Substituting its value in the empirical dependences for calculating the cutting force, the actual displacement of the workpiece is also determined.

The displacement leads to a change in the actual depth of cut, and thus to a change in the cutting force, which, in turn, results in a further change in the depth of cut. Such a method of calculation, used in the mathematical model, allows to determine the value of the actual radius of the workpiece for each point of its surface, taking into account the previous value.

III.RESULTS AND DISCUSSION

Increasing the technological system stability can be achieved by increasing its elements stability. It is influenced by all the forces that load the technological system, represented by the equivalent force F_e:

$$j = \frac{F_e}{\Delta} \quad . \quad (7)$$

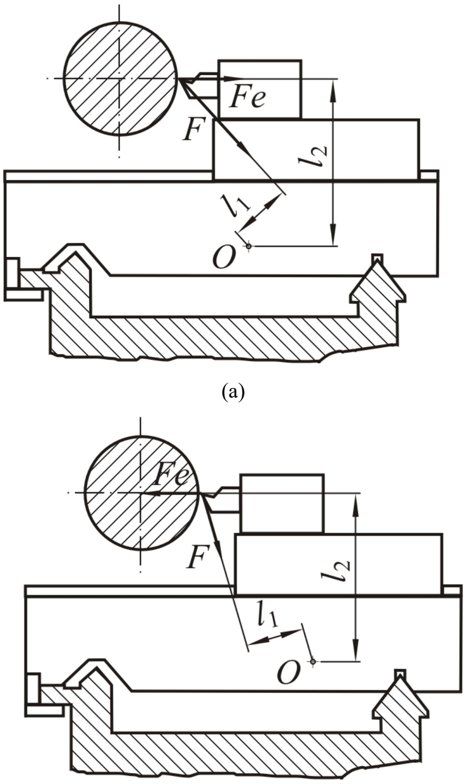
The equivalent force F_e has the directrix coincident with F_p and creates a torque with respect to the instantaneous center of rotation of the technological system, equal to the sum of the torques, relative to this center, for all forces, acting in the system.

Fig. 4 shows a planar model of the technological system in which "flat cutting" is performed (without the presence of the force F_f). It clarifies the determination of the equivalent force.

From the condition of equality of torques, it follows

$$F_e = F \frac{l_1}{l_2} \quad , \quad (8)$$

where l_1 and l_2 are, respectively, the arms of the cutting force and the equivalent force, relative to the instantaneous center of rotation *O*.



(a)

(b)

Fig. 4.

The force deformation of the system is obtained as a sum of the deformations of the machine, the fixture, the tool and the detail:

$$\Delta_{TC} = \Delta_M + \Delta_{\text{ПР}} + \Delta_{\text{И}} + \Delta_{\text{Д}} \quad (9)$$

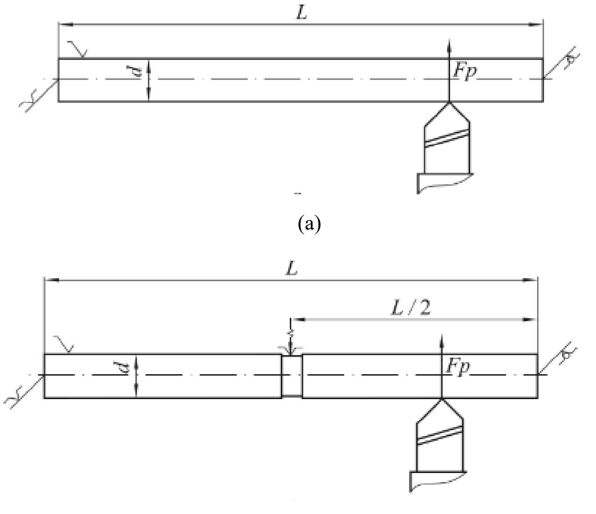
The deformation of each of the elements can be represented by the dependence:

$$\frac{1}{j_{TC}} = \frac{1}{j_M} + \frac{1}{j_{\text{ПР}}} + \frac{1}{j_{\text{И}}} + \frac{1}{j_{\text{Д}}} \quad . \quad (10)$$

Equation (10) gives the relationship between the system stability and stability of its elements, valid under the constraints of the spring model. Expressed by the susceptibilities, the dependence (10) takes the form:

$$W_{TC} = W_M + W_{\text{ПР}} + W_{\text{И}} + W_{\text{Д}} \quad (11)$$

From (10) and (11) it follows that the increase in stability can be achieved with maximum efficiency by increasing the stability of the most unstable element. If the machine, the fixture, and the tool are stable enough, as it is during turning, but the workpiece is long and small in diameter, then, due to its low stability, the overall stability of the technological system will be low. To illustrate the method, examples of turning smooth long shafts will be presented (Fig. 5). For the example from Fig.5, the most unstable element of the system is the detail.



(a)

(b)

Fig. 5.

The deformation of the system is determined by the sagging of the detail under the action of the force F_p. The maximum value of the sag in scheme 5*a* is:

$$y_{\max} = \frac{F_p L^3}{75EI} \ . \qquad (12)$$

If the turning is carried out on two sets using a stationary lunette, set in the middle of the detail (fig. 5*b*), the maximum sag will be:

$$y_{\max} = \frac{F_p \left(0,5L\right)^3}{75EI} = \frac{F_p L^3}{600EI} \ . \qquad (13)$$

From equations (12) and (13) it follows that when using a lunette, the sagging of the workpiece decreases 8 times. Therefore, a significant increase in the stability of the detail and, as a result, in the technological system stability, has been achieved.

IV.CONCLUSIONS

The proposed methodology for determining the magnitude of the elastic deformations in the technological system makes it possible to predict the accuracy of the rotary surfaces, processed by turning, and to reduce the number of experiments, necessary for the statistical studies of the parameters of the cutting process when machining rotary parts.

The obtained optimal dependences for calculating the deformations of the technological system facilitate the assessment of the accuracy indicators of the machined rotary surfaces.

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