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Improving the Precision of Complex Parts in External Turning

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Abstract—The use of cut-layer simulation to determine the cutting forces is considered.

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In manufacturing, the most common type of machining is turning [1]. Numerous factors must be considered in order to predict the quality of the machined surface in the early stages of preparations for production [2]. In analytical determination of the surface microrelief, the shape of the part and the cutting edge is taken into account, as well as the cutting dynamics, with subsequent refinement [3]. The difference between the shaping motion and the motion of the lathe's working elements is associated with displacement of the contact point of the tool and part on account of elastic deformation and other factors [4].

The deformation of the tool and part is determined by the cutting forces [5], which may be established from the area of the chip removed and the specific cutting force for the given part [6]. The area of the chip removed depends on the shape of the machined surface (cylindrical, conical, complex), the shape of the tool's cutting edge (the primary plane angle φ and auxiliary plane angle φ_1, the tool's tip radius r), and the cutting conditions (the supply S, cutting depth t), as illustrated in Fig. 1. In machining complex profiles, the margin removed in a single turn varies over the part's profile; thereby creating fluctuation of the load [6]. The force on the tool's front surface is proportional to the area F_{ch} of the chip removed and the specific cutting force K_s [7]:

$$P_z = K_s F_{ch}.$$

In external turning, the specific cutting force K_s depends on the material:

Material	K_s, MPa
Structural carbon and alloy steels	1470–2500
Gray iron	980–1175
Bronze	540
Copper	930–1125
Aluminum	400

To analyze the chip formation, we introduce the coordinate system XY of the part, corresponding to the programmed coordinate system for a numerically controlled lathe. The profile of the blank (diameter D_1) in the coordinate system XY is $F_1(x) = D_1/2$; the profile of the part (diameter D_2) after the roughing pass is $F_2(x) = D_2/2$; the profile of the part (diameter D_3) after machining is $F_3(x) = D_3/2$ (Fig. 2).

The following formulas permit the determination of the area F_{ch1} of the chip removed in roughing and the area F_{ch2} of the chip removed in finishing a cylindrical surface by means of a tool with tip radius r.

(1) When the surface microrelief of the part is generated by the radial section of the cutting edge [8]:

$$F_{ch1} = \int_L^{L+S} F_1(x)dx - \int_L^{L+S} F_2(x)dx - \frac{1}{2}S(r - \sqrt{r^2 - S^2/4});$$

$$F_{ch2} = \int_L^{L+S} F_2(x)dx - \int_L^{L+S} F_3(x)dx - \frac{1}{2}S(r - \sqrt{r^2 - S^2/4}).$$

(2) When the surface microrelief of the part is generated by the primary or auxiliary cutting edge and the radial section of the cutting edge:

$$F_{ch1} = \int_L^{L+S} F_1(x)dx - \int_L^{L+S} F_2(x)dx - \frac{1}{2}S(r - r\sin(\psi + \varphi)),$$

where

$$\psi = \arcsin\left(\frac{\left(S - \dfrac{r}{\sin\varphi}\right)\sin\varphi}{r}\right);$$

and

$$F_{\mathrm{ch2}} = \int_{L}^{L+S} F_2(x)\mathrm{d}x - \int_{L}^{L+S} F_3(x)\mathrm{d}x \qquad (1)$$

$$-\frac{1}{2}S(r - r\sin(\psi + \varphi)),$$

where

$$\psi = \arcsin\left(\frac{\left(S - \dfrac{r}{\sin\varphi_1}\right)\sin\varphi_1}{r}\right).$$

(3) When the surface microrelief of the part is generated by the primary and auxiliary cutting edges and the radial section of the cutting edge:

$$F_{\mathrm{ch1}} = \int_{L}^{L+S} F_1(x)\mathrm{d}x - \int_{L}^{L+S} F_2(x)\mathrm{d}x$$

$$-\frac{1}{2}S\left(r + \frac{\left(S - \dfrac{r}{\sin\varphi} - \dfrac{r}{\sin\varphi_1}\right)\sin\varphi\sin\varphi_1}{\sin(\varphi + \varphi_1)}\right); \qquad (2)$$

$$F_{\mathrm{ch2}} = \int_{L}^{L+S} F_2(x)\mathrm{d}x - \int_{L}^{L+S} F_3(x)\mathrm{d}x$$

$$-\frac{1}{2}S\left(r + \frac{\left(S - \dfrac{r}{\sin\varphi} - \dfrac{r}{\sin\varphi_1}\right)\sin\varphi\sin\varphi_1}{\sin(\varphi + \varphi_1)}\right). \qquad (3)$$

In machining a conical surface, the angle β between the tangent to the machined surface and the axis of the part is taken into account when determining the area of the cut layer [9]. The angle β is assumed positive when the part's diameter is reduced in machining [10]. When the part's diameter is increased in machining, the sign of β is reversed. The area F_{ch1} of the chip removed in roughing and the area F_{ch2} of the chip removed in finishing a conical surface by means of a tool with tip radius r may be determined on the basis of the following functions:

$$F_1(x) = D_1/2; \qquad (4)$$

$$F_2(x) = \arctan(\beta)x + D_2/2; \qquad (5)$$

$$F_3(x) = \arctan(\beta)x + D_3/2. \qquad (6)$$

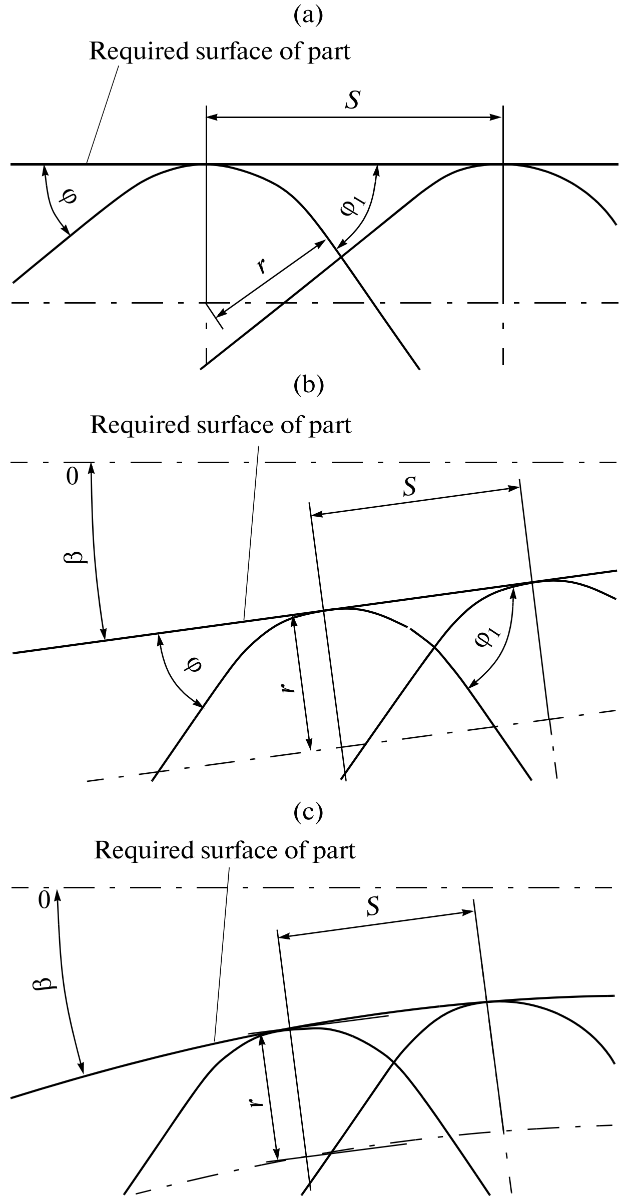

Fig. 1. Formation of cylindrical (a), conical (b), and complex (c) surfaces in external turning. The generatrix of the complex surface is an arc of a circle.

The corresponding formulas are as follows.

(1) When the surface microrelief of the part is generated by the radial section of the cutting edge:

$$F_{\mathrm{ch1}} = \int_{L}^{L+S} F_1(x)\mathrm{d}x - \int_{L}^{L+S} F_2(x)\mathrm{d}x$$

$$-\frac{1}{2}S\left(r - \sqrt{r^2 - \frac{S^2}{4\cos^2\beta}}\right);$$

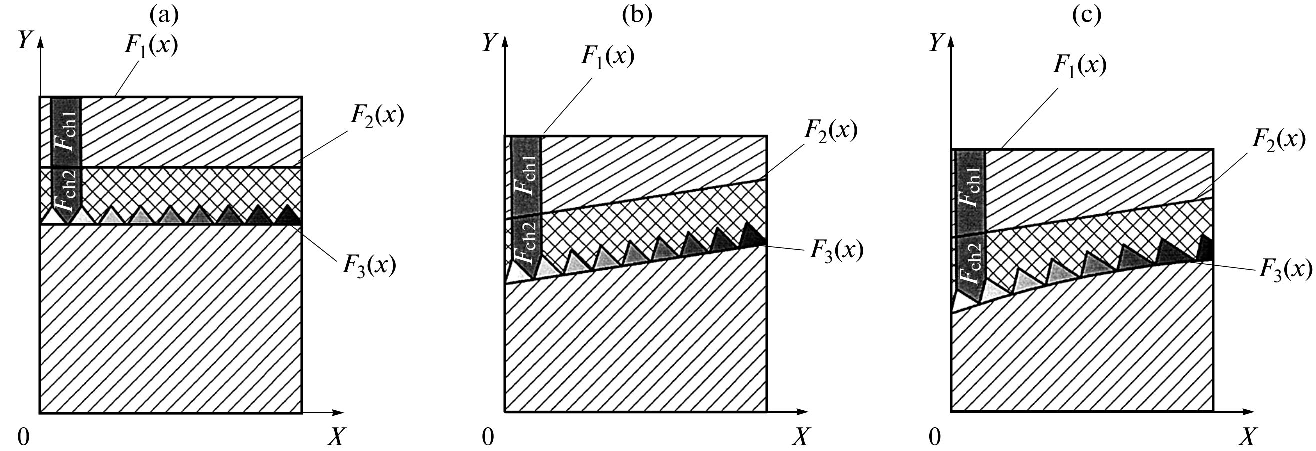

Fig. 2. Functions describing the surface profile of the part after the roughing pass, its initial profile, and the area of the chip removed, for cylindrical (a), conical (b), and complex (c) surfaces.

$$F_{ch2} = \int_L^{L+S} F_2(x)dx - \int_L^{L+S} F_3(x)dx - \frac{1}{2}S\left(r - \sqrt{r^2 - \frac{S^2}{4\cos^2\beta}}\right).$$

(2) When the surface microrelief of the part is generated by the primary or auxiliary cutting edge and the radial section of the cutting edge:

if $\varphi > \varphi_1$

$$F_{ch1} = \int_L^{L+S} F_1(x)dx - \int_L^{L+S} F_2(x)dx - \frac{1}{2}S(r - r\sin(\psi + \varphi - \beta)),$$

where

$$\psi = \arcsin\left(\frac{\left(S - \frac{r}{\sin(\varphi - \beta)}\right)\sin(\varphi - \beta)}{r}\right);$$

and

$$F_{ch2} = \int_L^{L+S} F_2(x)dx - \int_L^{L+S} F_3(x)dx - \frac{1}{2}S(r - r\sin(\psi + \varphi - \beta)),$$

where

$$\psi = \arcsin\left(\frac{\left(S - \frac{r}{\sin(\varphi - \beta)}\right)\sin(\varphi - \beta)}{r}\right);$$

if $\varphi < \varphi_1$

$$F_{ch1} = \int_L^{L+S} F_1(x)dx - \int_L^{L+S} F_2(x)dx - \frac{1}{2}S(r - r\sin(\psi + \varphi_1 + \beta)),$$

where

$$\psi = \arcsin\left(\frac{\left(S - \frac{r}{\sin(\varphi_1 + \beta)}\right)\sin(\varphi_1 + \beta)}{r}\right);$$

and

$$F_{ch2} = \int_L^{L+S} F_2(x)dx - \int_L^{L+S} F_3(x)dx - \frac{1}{2}S(r - r\sin(\psi + \varphi_1 + \beta)),$$

where

$$\psi = \arcsin\left(\frac{\left(S - \frac{r}{\sin(\varphi_1 + \beta)}\right)\sin(\varphi_1 + \beta)}{r}\right).$$

(3) When the surface microrelief of the part is generated by the primary and auxiliary cutting edges and the radial section of the cutting edge [8]:

$$F_{\mathrm{ch1}} = \int_{L}^{L+S} F_1(x)\mathrm{d}x - \int_{L}^{L-S} F_2(x)\mathrm{d}x - \frac{1}{2}S\left(r + \frac{\left(S - \frac{r}{\sin(\varphi-\beta)} - \frac{r}{\sin(\varphi_1+\beta)}\right)\sin(\varphi-\beta)\sin(\varphi_1-\beta)}{\sin(\varphi_1+\varphi)}\right);$$

$$F_{\mathrm{ch2}} = \int_{L}^{L+S} F_2(x)\mathrm{d}x - \int_{L}^{L+S} F_3(x)\mathrm{d}x - \frac{1}{2}S\left(r + \frac{\left(S - \frac{r}{\sin(\varphi-\beta)} - \frac{r}{\sin(\varphi_1+\beta)}\right)\sin(\varphi-\beta)\sin(\varphi_1+\beta)}{\sin(\varphi_1-\varphi)}\right).$$

In turning a complex surface whose generatrix is an arc of a circle, the area of the chip removed is determined as follows [11]. We regard the complex surface as a cone with variation in β along the profile [12].

The profile whose generatrix is an arc of a circle (radius R) may be described as follows [13]:

• for a concave section

$$F_3(x) = D_3/2 - \sqrt{R^2 + x^2};$$

• for a convex section

$$F_3(x) = D_3/2 + \sqrt{R^2 + x^2}.$$

The analytical formulas for such a profile apply to the interval [0, R].

The area of the chip removed is determined from Eqs. (1)–(6) for a conical part, except that the static angle β is replaced by a kinematic angle β_k in the given section of the profile [14]. In a section at a distance x_1 from the end of the part, we may write

$$\beta_k(x_1) = \arctan\left(\frac{F_3(x)d}{\mathrm{d}x}\right)\left[\frac{180}{\pi}.\right]$$

On the basis of the proposed model, we may determine the cutting forces, taking account of their variation from a minimum to a maximum along the profile of the part [15]. Knowing the cutting force in each section of the part, we may establish the deformation of the tool–part system. That permits the introduction of corrections in the trajectory of the lathe's working elements so as to eliminate machining errors.

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