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Machining by End Mills with Overlapping Cutter–Workpiece Contacts

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Abstract—This study addresses the influence of cutting forces and mill deformation on the surface quality obtained in machining. A mathematical model is proposed for calculating the trajectory of mill deformation in the shaped surface. Tests confirm the adequacy of the model.

Keywords: end mill, milling, machined surface, overlapping contact

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Milling, which is widely used in manufacturing, is a discontinuous cutting process: the area of the cut layer changes constantly, while the considerable load applied to the mill is distributed both in space (over the cutting edge) and time [1]. These factors result in complex dynamics of end mills, which are not very rigid. That complicates the selection of the best milling conditions. As a result, manual selection of the milling conditions is required in CNC systems. Accordingly, further study of milling is required.

In the present work, we study the shaping of the workpiece surface in machining by end mills, in order to predict the surface quality obtained.

SURFACE SHAPING BY AN END MILL

To calculate the milling forces and deformation, we calculate a succession of states from the onset of milling to a steady state. The cut-layer area may be calculated from the formula [2]

$$S_{\Sigma} = \frac{k_t s_{\text{cu}}^{(0)}[t_{\text{cu},0}(2R - t_{\text{cu},0})]^{0.5}}{2\sin\theta}, \tag{1}$$

where R is the mill radius; $t_{\text{cu},0}$ is the cutting depth; $s_{\text{cu}}^{(0)}$ is the supply per tooth; and the coefficient k_t ($k_t \le 1$) determines the relation between the supply per tooth and the maximum cut-layer thickness.

We will consider the case where $R > t_{\text{cu},0}$. We may write Eq. (1) in the form

$$S_{\Sigma} = \frac{k_t s_{\text{cu}}^{(0)} D[k_D(1 - k_D)]^{0.5}}{2\sin\theta},$$

where D is the mill diameter and $k_D = t_{\text{cu},0}/D$. Then

$$S_{\Sigma} = \frac{0.5k_t}{\sin\theta}\Phi(t_{\text{cu},0} - X_1)\int_{t-T}^{t} v_{2,\Sigma}(v)d\varsigma,$$

where $\Phi(t_{\text{cu},0} - X_1) = \{(t_{\text{cu},0} - X_1)[2R - (t_{\text{cu},0} - X_1)]\}^{0.5}$ and $v_{2,\Sigma}(t) = v(t) + v_2(t)$ are the total longitudinal velocity of the table and the elastic strain of the tool, respectively, while T is the time between two successive contacts of the cutting teeth. In particular, for small cutting depth and large mill diameters ($t_{\text{cu},0}/D <$ 0.05), we may write

$$S_{\Sigma} = 0.5k_t(t_{\text{cu},0} - X_1)\int_{t-T}^{T} v_{2,\Sigma}(\varsigma)d\varsigma.$$

To calculate the forces and deformation, we consider a succession of states from the onset of milling to a steady state.

Suppose that we specify the modulus F_0 of the cutting forces. Then the deformational displacements in the X_1, X_2 directions may be determined from the system

$$\left.\begin{aligned} cX_1 &= F_0(\chi_1\sin\varphi_0(0) + \chi_2\cos\varphi_0(0)); \\ cX_2 &= F_0(\chi_1\cos\varphi_0(0) - \chi_2\sin\varphi_0(0)), \end{aligned}\right\} \tag{2}$$

where c is the mill rigidity; χ_1, χ_2 are angular coefficients. We may assume that $\Phi(t_{\text{cu},0} - X_1)$ is a monotonic function. Therefore, for specified $t_{\text{cu},0}$, it may be linearized, since $t_{\text{cu},0} \gg X_1$. Then

$$\Phi(t_{\text{cu},0} - X_1) = \Phi(t_{\text{cu},0}) - k_{\Phi}X_1, \tag{3}$$

where $k_\Phi = \partial\Phi(t_{cu,0} - X_1)/\partial X_1$. Hence, taking account of Eqs. (2) and (3), we may write

$$\left.\begin{aligned} cX_1 &= \rho_s[\Phi(t_{p,0}) - k_\Phi X_1]\left[\int_{t-T}^{t} v_{2,\Sigma}(\varsigma)d\varsigma\right]\{\chi_1 \sin\varphi_0(0) + \chi_2\cos\varphi_0(0)\}; \\ cX_2 &= \rho_s[\Phi(t_{cu,0}) - k_\Phi X_1]\left[\int_{t-T}^{t} v_{2,\Sigma}(\varsigma)d\varsigma\right]\{\chi_1 \cos\varphi_0(0) - \chi_2\sin\varphi_0(0)\}, \end{aligned}\right\} \quad (4)$$

where ρ_s is the chip pressure on the front surface of the mill; and $\int_{t-T}^{t} v_{2,\Sigma}(\varsigma)d\varsigma$ is an integral operator.

On the basis of Eq. (4), we may calculate the strain at time t if it has previously been determined at time $t - T$. Thus, with specified initial strain, we may construct the deformation trajectory. In Fig. 1, we show an example of the establishment of steady conditions.

We assume that the severity of the process ρ = 200 kg/mm; the tool rigidity c = 400 kg/mm; the cutting depth $t_{cu,0}$ = 10 mm; the supply per tooth $s_{cu}^{(0)}$ = 0.1 mm; the cutting speed is 80.0 m/min; the surface width H_0 = 12.0 mm; the tooth inclination is 35°; and the angular coefficients are $\chi_{1,e}$ = 0.722 and $\chi_{2,e}$ = 0.691.

In Fig. 2, we may observe the main features of the surface in milling with contact overlap. The right side ($\Delta L_1^{(1)}$) corresponds to running-in, after several passes with supply in the last stage not exceeding 0.02 mm per tooth.

In this initial section, the dimensional deviation along the L_3 axis is no more than 0.01 mm. This is the reference line used in measuring the dimension in the section ($\Delta L_1^{(2)}$). However, variation in size along the L axis is also seen in this section, on account of residual spindle wobble. The section $\Delta L_1^{(2)}$ obtained after the first pass is of most interest.

Its relief may be divided into three regions $\Delta L_2^{(1)}$, $\Delta L_2^{(2)}$, and $\Delta L_2^{(3)}$, with the following characteristics.

(1) In regions $\Delta L_2^{(1)}$ and $\Delta L_2^{(3)}$, the dimensional fluctuation and its dispersion with respect to the mathematical expectation are markedly less than in region $\Delta L_2^{(2)}$.

(2) In region $\Delta L_2^{(2)}$, the spacing between the microprojections is about twice that in regions $\Delta L_2^{(1)}$ and $\Delta L_2^{(3)}$. (The regular periodic variation in this spacing leads to surface undulation.)

(3) In region $\Delta L_2^{(2)}$, the height of the microprojections is much greater.

In addition, adjacent to the boundaries of these regions, we note irregularity of the microrelief and the formation of marked undulation along the L_1 axis. The surface roughness and undulation will be different in different regions.

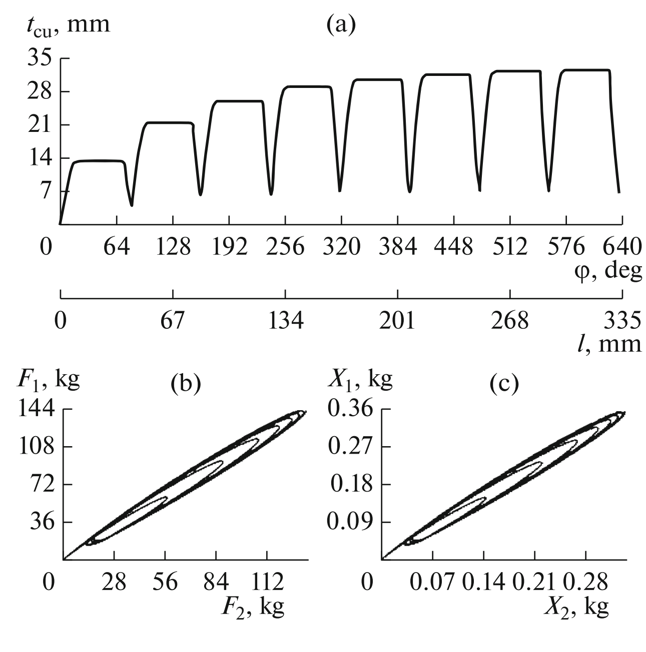

Fig. 1. Cutting depth t_{cu} as a function of the mill's positional angle φ and the cutting path l (a); and relations between the forces F_1 and F_2 (b) and between the tool's deformational displacements X_1 and X_2 (c) in establishing steady trajectories.

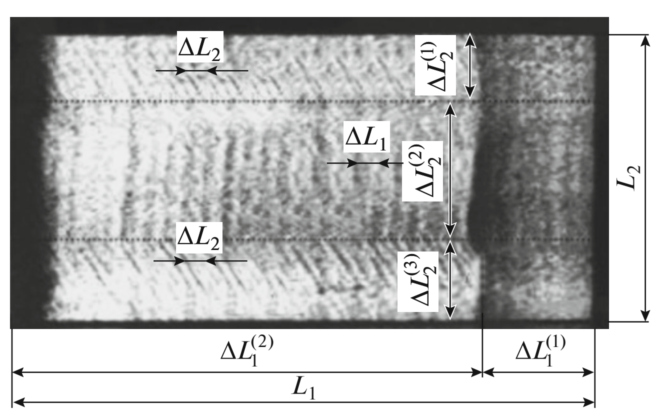

Fig. 2. Macrosurface in milling by an unworn tool.

First, we analyze the surface deformity in terms of the dynamics of the process. In milling a bar of width $L_2 = 30.0$ mm, the relief is approximately the same over the whole machined surface. Thus, these features are characteristics only of milling tools with large overhang [3].

The margin here is such that two or more contacts of the tool with the surface may be possible, depending on the angle of rotation. In the example considered, one or two contacts are possible. In addition, in machining, mills with right inclination of the teeth are usually chosen. Then the axial component of the force runs in the direction of tool attachment in the clamp. By that means, the preliminary displacement in joints that are not completely tight may be eliminated.

CONCLUSIONS

(1) We have shown that, in machining by helical end mills, sections of overlapping contact are characterized by both increase in the milling forces and change in their orientation.

(2) In milling, the forces normal to the machined surface are dominant. That produces variation in the strain normal to the surface. The cut-layer thickness is a maximum here. These components of the force are characterized by considerable variation and are sensitive to the tool's geometric parameters (which include errors) and to variation in the margin.

(3) Consequently, in sections of overlapping contact, we observe deviation of the dimension and also increase in its dispersion with respect to the mathematical expectation. In addition, the spacing of the microprojections is often doubled in such sections. This is evident in Fig. 2, where ΔL_2 is equal to the supply per tooth, while $\Delta L_1 \approx 2\Delta L_2$. This may be explained in that the deformational displacements in sections of overlapping contact are greater than the cut-layer thickness in the contact region.

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