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Machining with End Mills

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Abstract—Research shows that, in the machining of plane surfaces and mating contours by opposed end mills, the mill diameter must be taken into account in selecting the cutting depth so as to improve the machining precision.

Keywords: opposed milling, mating surfaces, machining precision, end mills
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In improving airplane designs, it is important to reduce the mass without loss of strength or rigidity. That entails the use of structural elements of complex shape, with closed and semiclosed channels and external and internal recesses (Fig. 1).

As a rule, such components are produced by means of end mills, which are characterized by low rigidity. In the machining of external and internal contours, metal is most often removed by machining with opposed mills, at the lateral surface or both the lateral and end surfaces of the tools. The mill axis is parallel to the contour surface to be machined.

Less vibration is observed in opposed milling than in unidirectional milling, thanks to smoother tooth insertion in the workpiece. Therefore, there is no need for increased rigidity of the workpiece in the supply direction nor for an axial gap between the drive screw and the nut of the supply mechanism.

In opposed milling on a horizontal machine tool, the vertical component of the cutting force from the mill on the workpiece varies not only in magnitude but also in direction, depending on the ratio of the cutting depth and the mill diameter. Thus, the vertical force may act upward or downward. That reduces the machining precision.

This relationship was established theoretically in [1]. For the opposed milling of plane surfaces, it was confirmed experimentally in [2].

The mill and workpiece may move apart or toward one another. In those conditions, a mill of low rigidity experiences greater elastic deformation (Fig. 2).

There will be no vertical component of the force if

$$t = Dk^2 \Big/ \left(1 + k^2\right),$$

where $k = P_y/P_z$; t is the cutting depth; and D is the mill diameter.

The relation between the cutting depth t and the mill diameter D determines the mill–workpiece contact angle φ. That angle, in turn, determines the direction and magnitude of the vertical force. When $k =$

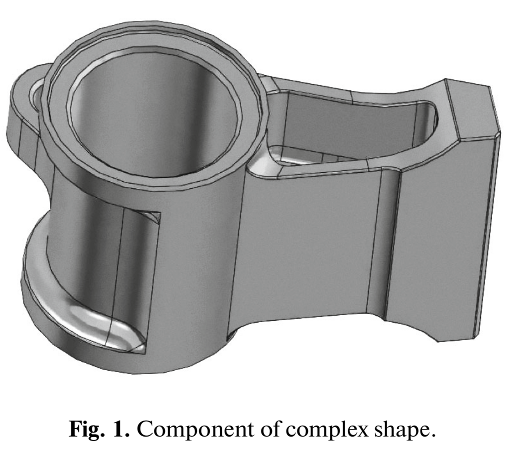

Fig. 1. Component of complex shape.

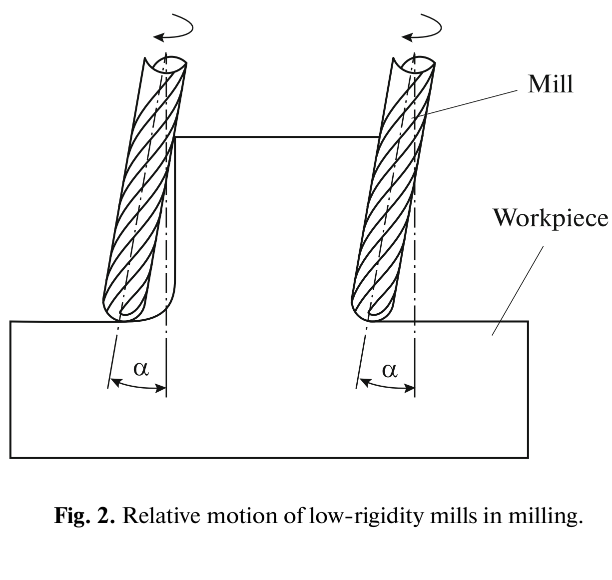

Fig. 2. Relative motion of low-rigidity mills in milling.

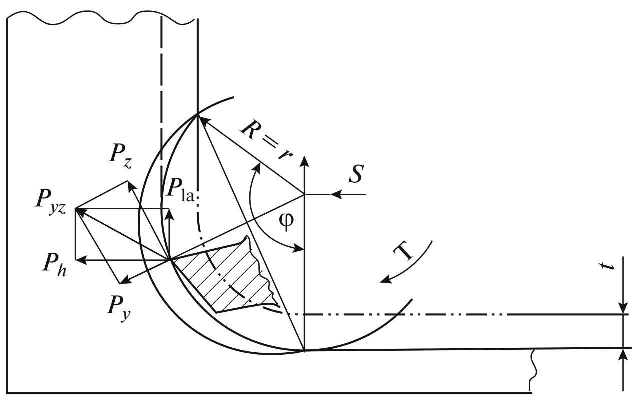

Fig. 3. Forces acting between the mill and workpiece.

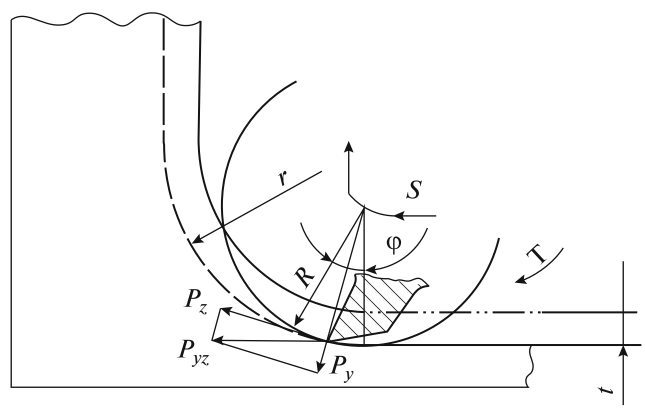

Fig. 4. Milling forces when the radius of the end mills is less than the mating radius of the contour surfaces.

0.4–0.6, the cutting depth must be $t = (0.14–0.26)D$, while the contact angle is $\varphi = 43–62°$. The vertical force acts downward with smaller t and ψ, and upward with larger t and φ. This also applies to the opposed milling of plane surfaces on a vertical milling machine.

We now consider the milling of an internal contour by means of a vertical milling machine, when the contact angle of the surfaces is 90°. The radius R of the end mill must be equal to the mating radius of the contour surfaces. The mill–workpiece contact angle must be more than 90°. The resultant cutting force presses the mill against the workpiece, thereby increasing the machining error. In other words, this leads to overcutting (Fig. 3). The cutting forces in Fig. 3 act in the horizontal plane. Therefore, the vertical component of the cutting force is replaced by the lateral horizontal force P_{la}.

Experience shows that, in contour milling with small cutting depth and supply, we may observe considerable machining imprecision on account of the elastic deformation of the technological system, whose most pliable component is the end mill. Reducing the productivity does not ensure the required precision, since the mill–workpiece contact angle is no less than 90° with minimization of the cutting depth.

A complication here is that, in many cases, it may be necessary to machine contours of great depth (>50 mm), whose mating surfaces may have very small radii (no more than 10 mm). That calls for the use of end mills with great length and small diameter. Such mills are of low rigidity and are elastically deformed under the action of the cutting forces.

To improve the machining precision, it makes sense to use end mills whose radius is less than the mating radius of the contour surfaces ($R < r$). In that case, the mill trajectories must be equidistant from the machined contour surface. That is possible with numerically controlled milling machines. The mill–workpiece contact angle is significantly decreased and the defects noted earlier may be eliminated, but only if the lateral component of the force is minimized (Fig. 4).

The forces acting on the workpiece from the mills are shown in Figs. 3, 4. According to the third law of mechanics, equal forces act in the opposite direction from the workpiece on the mill. (Those components are not shown in Figs. 3 and 4).

To improve the machining precision in the opposed milling of plane surfaces or mating contours, it is important to select the cutting depth correctly on the basis of the mill diameter, so that the cutting forces do not result in relative motion of the mill and workpiece.

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