UNEVENNESS AT FACE MILLING

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Abstract: The unevenness of milling when working with face milling cutters are manifested significantly more than in slab milling. The reason for this is the small value of the milling width, related to the diameter of the milling cutter, where the coefficient of unevenness is as big as the ratio is small. In the case of incomplete symmetrical face milling with a milling width equal to or less than the diameter of the milling cutter, the unevenness coefficient should be calculated. This paper presents a theoretical model that can be used precisely for this purpose, namely the determination of the unevenness coefficient. The model includes derived mathematical equations that take into account the impact of the parameters affecting the cutting conditions at face milling.

Key words: face milling, face milling cutter, unevenness coefficient

1. INTRODUCTION¶

For simplifying the analysis of the trajectory of movement of the milling tool is considered the instantaneous state of an even rectilinear motion A and an even rotational motion B, [2, 3], (Figure 1).
There are two variants:
-B is movement of the tool and A is movement of the workpiece;
-B and A are movements of the tool.
The machining methods of the above mentioned variants are based on the ratio of the velocities of movement A and B, i.e.:

$$\varepsilon = \frac{V_A}{V_B} \approx 0.005 \quad (1)$$

This ratio in modern metal cutting machines is constantly changing in order to load evenly each individual cutting edge [4, 5, 7].
The relative trajectory shown in Figure 1a) is a planar curve described in the coordinate plane XOZ in which acts movements A and B. The position of "M" is determined by the radius vector r and the polar angle θ.

$$r = a \cdot t \quad \text{and} \quad \theta = b \cdot t \quad (2)$$

where: a, b - coefficients; t – variable parameter.
At $K = \frac{a}{b} = 0.0005 = const.$, the equation of the relative trajectory looks like this:

$$r = K \cdot \theta \quad (3)$$

This is an equation of Archimedean spiral.
The second variant is realized at the ratio:

$$\varepsilon = \frac{V_A}{V_B} = 0.005 \div 0.05 \quad (4)$$

The relative trajectory described by "M" located on a circle with radius r and rolling without slipping along a straight line (Figure 1a, b, c) occupies different positions M_1, M_2, M_3 ... M_6 defining different types of planar curves. Coordinates of "M" are determined by the expressions:

$$\begin{aligned} &-y = r.\varphi - k.\sin\varphi; y = k.\sin\varphi - r.\varphi \\ &-z = k.\cos\varphi; z = -k.\cos\varphi \end{aligned} \quad (5)$$

where: φ - is the angle of which the center of the movable circle displaces relative to its initial position; k – distance from the center of the circle to the current point "M".
At different values of k in equation (5), the type of relative trajectory is changed as follows:
-at k=r – the trajectory is cycloid Figure 1b)
-at k<r – the trajectory is shortened cycloid (Figure 1c).
By the above described approach can be developed different and principle new milling methods, [8], and to forecast a kinematic possibilities of new metal cutting machines, [6, 9], (Figure 1a, b).
This approach allows at milling to determine the torques, the trajectories and their impact on the

durability of operation of the tools, [1], Obviously, the faster failure of the tools in the classical section of the cut metal layer (with varying thickness), [3], and the constant maintenance of a uniform thickness of the chip.

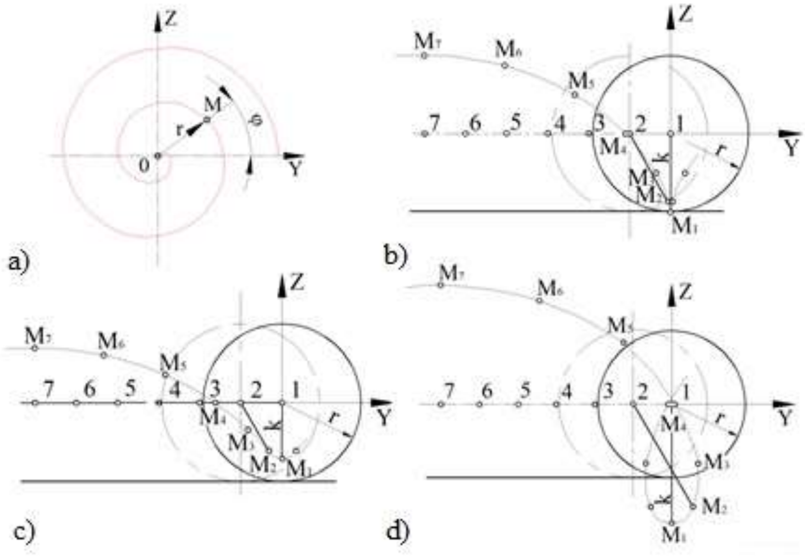


Fig. 1. Relative milling trajectories

a) the trajectory is a planar curve described in the coordinate plane XOZ; b) the trajectory is cycloid; c) the trajectory is shortened cycloid; d) trajectory described by “M” located on a circle with radius r and rolling without slipping along a straight line

2. DEVELOPMENT OF THE THEORETICAL MODEL

The unevenness of milling when working with face milling cutters are manifested significantly more than in slab milling. The reason for this is the small value of the milling width, related to the diameter of the milling cutter $\frac{B}{D}$, where the coefficient of unevenness is as big as the ratio $\frac{B}{D}$ is small.

The helical angle ω (up to 15°) at the face milling cutters is considerably smaller than those angles of the slab milling cutters. When milling with face milling cutter width (depth) of the milling is relatively small. For this, it is not possible to achieve full evenness in the case of face milling.

In the case of incomplete symmetrical face milling, is achieved a cutting conditions with the smallest possible force fluctuations by selecting values for t/D where μ has a value close to one.

The coefficient of unevenness at incomplete symmetrical face milling is determined graphically with satisfactory accuracy.

In the case of incomplete symmetrical face milling with a milling width equal to or less than the diameter of the milling cutter, the unevenness factor is calculated for the milling cutter with straight teeth and without a corner edge.

$$N_e = \frac{2^{-\frac{m}{2}} \cdot C_p \cdot n^{-m} \cdot B^{l+1} \cdot s^{m+1} \cdot z^{-m} \cdot D \cdot \left[1-(1-\frac{t}{D})\right]}{1000 \cdot 4500} \qquad (6)$$

where: m – exponent which depends on the quality of the treated material having a fractional and negative value; C_p – coefficients which depends on the quality of the treated material and cutting angle; z – number of teeth; D – diameter of milling cutter, mm; B – milling width; n – rotational frequency, [min^{-1}]; s – feed, [mm/min].

From the average power, the average milling force is determined

$$P_{aver} = \frac{2^{-\frac{m}{2}}}{\pi} \cdot C_p \cdot B^{l+1} \cdot s^{m+1} \cdot z \cdot \left[1-(1-\frac{t}{D})^{\frac{m+2}{2}}\right] \qquad (7)$$

from where instantaneous tangential force is obtained

$$\sum P = C_p \cdot s^{m+1} \cdot B^{l+1} \cdot \sum \sin^{m+1} \delta \qquad (8)$$

where: δ – angle of the current position of the milling cutter's tooth.

Hence the coefficient of unevenness is given by the equation 9.

$$\mu = \frac{(\sum P)_{\max}}{P_{aver}} = \frac{\pi \cdot (\sum \sin^{m+1}\delta)_{\max}}{2^{-\frac{m}{2}} \cdot z \cdot \left[1-(1-\frac{t}{D})^{\frac{m+2}{2}}\right]} \quad (9)$$

It can be seen from the expression (9) that the changing of z and t also changes the coefficient of unevenness. On μ also influences $(\sum \sin^{m+1}\delta)_{\max}$ since it depends on z and t/D. By changing the numerator and the denominator, the coefficient μ is also changed. Therefore of particular interest to determine under what conditions the coefficient of unevenness reached its maximum and minimum. For illustrating the changing of μ is used Figure 2. If the milling width $t = t_1$ (at z = 12) is obtained:

$$\left(\sum \sin^{m+1}\delta\right)_{\max} = \sin^{m+1}\delta_1 + \sin^{m+1}\delta_2 + \sin^{m+1}\delta_3 + \sin^{m+1}\delta_4 \quad (10)$$

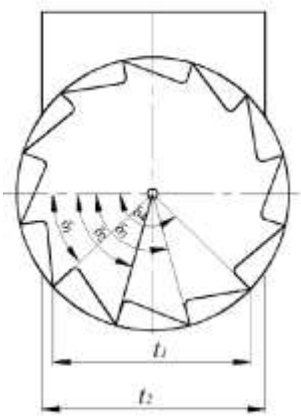


Fig.2. Central angles defining the position of the teeth of the milling cutter

If the expression (10) is replaced in (9), the coefficient of unevenness μ is obtained.

As can be seen from Figure 2, in a symmetrical arrangement of the four teeth of the cutter relative to the axis of the tool, t can be changed to $t = t_1$ while the numerator will not change its value. At $t = t_2$, the denominator is the largest and the coefficient gets its minimum value (at $z_e=4$), and at $t=t_3$ it has a maximum value.

If the milling width is reduced to $t_3 < t$, both the numerator and the denominator are changed. The change of the numerator is carried out intermittently at $t = t_2$, since it reduces the number of simultaneous working teeth from $z_e = 4$ to $z_e = 3$ or:

$$\left(\sum \sin^{m+1}\delta\right)_{\max} = \sin^{m+1}\delta_I + \sin^{m+1}\delta_{II} + \sin^{m+1}\delta_{III} \quad (11)$$

where δ_I, δ_{II} and δ_{III} are the instantaneous angles determined by the position of the three teeth at a symmetrical placement.

If the formulas (10) and (11) are compared, it is obtained:

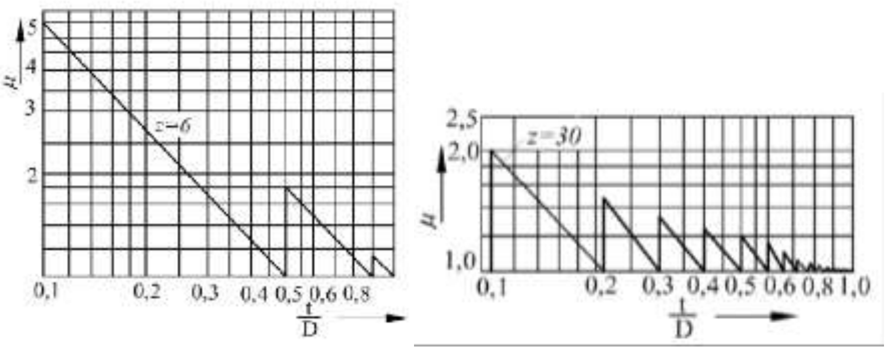
$$\sin^{m+1}\delta_1 + \sin^{m+}\delta_2 + \sin^{m+1}\delta_3 + \sin^{m+1}\delta_4 > \sin^{m+1}\delta_I + \sin^{m+1}\delta_{II} + \sin^{m+1}\delta_{III} \quad (12)$$

3. ANALYSIS AND CONCLUSIONS

A). By decreasing the t/D the numerator remains constant for some time, whereby the coefficient of unevenness μ increases gradually. With a milling width $t = t_2$, $t = t_3$, the numerator suddenly changes its value, the coefficient μ decreases and takes its minimum value (for a given z_e). Further decreasing the t/D causes again an increase in μ and so on, and the maximum values of μ at different values of t/D are different. Figure 3 shows graphically the nature of the changing of μ. By comparing the graphs in Figure 3a and Figure 3b shows that increasing the number of teeth of the milling cutter and increasing the ratio t/D reduces the maximum value of the unevenness coefficient. The jumps of μ from minimum to maximum corresponds to exactly defined ratios t/D, namely:

$$\frac{t}{D} = \sin\left(\frac{k}{2} \cdot \frac{360}{z}\right) \quad (13)$$

where: k is the largest number of operating teeth of the milling cutter at a given ratio t/D.



a) b)

Fig.3. Graphical representation of changing of μ depending on the number of teeth of the milling cutter z
a) at z=6; b) at z=30

B). The number of jumps of μ at an even number of teeth is equal to $\frac{z}{2}-1$, and at odd is equal to $\frac{z-1}{2}$. Because of the nature of its change for the same ratio t/D and a certain number of teeth of the milling cutter z, μ has two values at the same time – maximum and minimum. In fact, before the tooth 3 has reached point B, the chip removed from the tooth 1 has separated before the tooth 1 has reached the point A so that there are only two teeth under load (Figure 4) whereby μ gets less value.

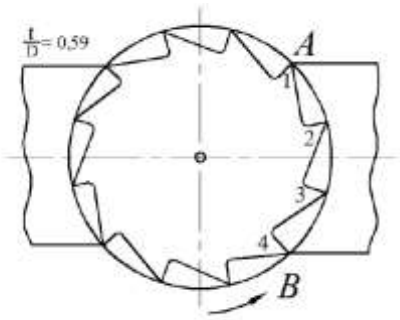


Fig.4. Scheme for determining the simultaneously working teeth

C). The ratio t/D defined by the formula (13) always provides the lower value of μ and is most advantageous for achieving evenness of the cutting process.

From the comparison of the graphs shown in Figure 4, it can be seen that the increase in the number of teeth leads to a reduction of μ. From everything said so far, it can be deduced the importance of the conditions under which the face milling cutter works. With only a slight deviation from the values defined by formula (13), a significant increase in the coefficient of unevenness can be obtained, i.e. a significant exceedance of the maximum tangential force above the average. It also increases power consumption and operating conditions deteriorate due to higher fluctuations in the forces absorbed by machine parts. In order to avoid the above, it is necessary to determine the coefficient of unevenness after the selection of the cutting conditions, and for the shortest time. Data for selecting μ are taken from reference materials.

D). Using data from reference materials, e.g. for power 4hp at maximum permissible torque M_{maxp}=822.59 N/m^2, t=120mm, B=10mm, D=200mm, z=10, η=85, m=-0.0315, l=-0.09, is obtained for the ratio $\frac{t}{D}=\frac{120}{200}=0.6$. From the reference materials is accounted for z=10, $\frac{t}{D}=0.6$ and μ=1.41.

If the revolutions with which the milling cutter can work derived from the speed limit and durability of the tool, amounted to 32 min^{-1}, the feeding speed is obtained s = 110mm/min.

Calculated, the average torque is

$$M_{aver} = 622.72 \text{ N}\cdot\text{m} \quad (14)$$

The maximum torque is calculated by multiplying the already obtained unevenness coefficient by the average torque, relation 15.

$$M_{\max} = 1.41 \cdot 622.72 = 878.59 N \cdot m \quad (15)$$

The value obtained for the maximum torque of the machine indicates that under these conditions, can be worked with in feeding speed of the machine table not more than 110mm/min. Greater performance, which would correspond to a higher feed rate, is impossible due to the maximum torque limitation. If a milling tool with the corresponding number of teeth is not available, it is necessary to perform a calculation again in the way shown to establish such a maximum torque that does not exceed the permissible torque of the machine.

E). At trochoidal trajectory of the tool avoids the need to use more passes to achieve the desired depth by performing the cutting process with the entire depth of the tool - the side cutting edges. This leads to reduction in the unevenness coefficient.

The dependencies shown in the paper give a new approach for work that has an impact on the chip area. It directly affects the forces indicated in formula (9), through which can be calculated the coefficient of unevenness. The chip area varies depending on the type of treated material, adding coefficients that take into account the physical and mechanical properties of the treated material.

In the conducted theoretical studies with a designed milling tool using SolidWorks software (Figure 5) a study of the chip area is made which is directly related to the evennes of machining.

The graph shown in Figure 6 creates a realistic picture of the change of the parameters of the chip along the cutting edge (by angle φ). This also gives an idea of the shape of the chip itself and the load of the tool as a whole. In addition, it can also be explained why positive results have been achieved in certain trajectories of movements of the tool, resulting in reduced cutting forces, thermal load and the ability to work with maximum milling depth.

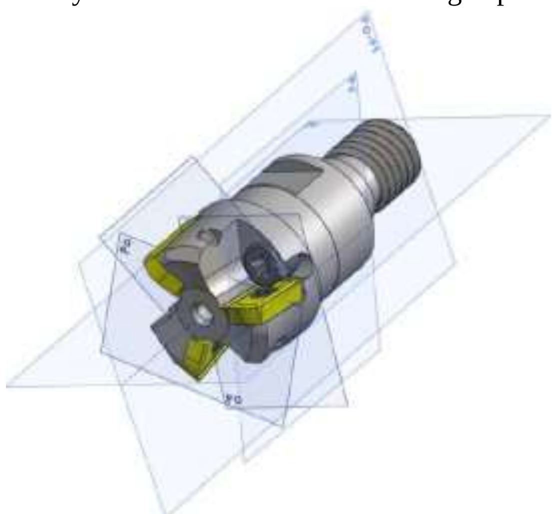


Fig.5. Non-monolithic milling tool with three carbide cutter insert

The analysis of the resulting chip area at different diameters and the position of the cutting edge (Figure 6) makes it possible to determine also the momentary variation of the cutting forces. This makes it possible to track the change in the unevenness coefficient. The aim is to maintain a constant chip area resulting in a reduction of unevenness in the milling.

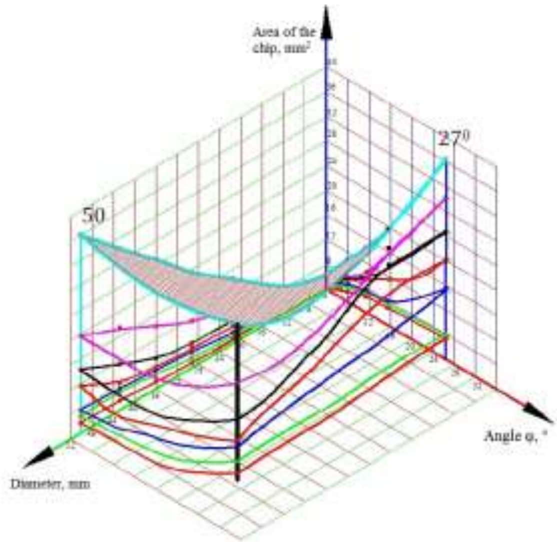


Fig.6. Changing the chip area depending on the angle φ and the diameter of the milling cutter D

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