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Simulation testing of cutting force in the process of barrel milling machining

Badania symulacyjne siły skrawania w procesie obróbki frezem baryłkowym

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The paper presents simulation tests of cutting force in the process of barrel milling. The analyses were carried out on concave and convex surfaces with different radii of curvature.

KEYWORDS: 5-axis milling, barrel mill, cutting force

In industrial practice, an increase in the use of five-axis milling is observed, especially during the production of components with complex shapes, such as rotors, blades and dies. The machining of such parts is most often carried out in a spherical milling strategy (fig. 1a). It allows you to make any shape, but it is characterized by very low efficiency. That is why new milling designs are being sought, which will enable the increase of the surface machining efficiency.

One of such constructions is a barrel mill with a repeatedly increased radius of the cutting edge shape r_n (fig. 1b). This solution contributes to increasing the axial infeed of b_r (machining path width), and thus - repeatedly increasing the surface machining efficiency. However, the change in the axial infeed results in a significant increase in the cross-section area of the cutting layer and the effective cutting edge length [1, 5, 6, 8, 10].

In addition, in the case of a barrel milling cutter, the curvature radius of the machined surface influences the area of the cutting layer (fig. 2). Depending on the sign of curvature ("+" convex, "-" concave) and values, the conditions of contact between the tool and the workpiece change [9].

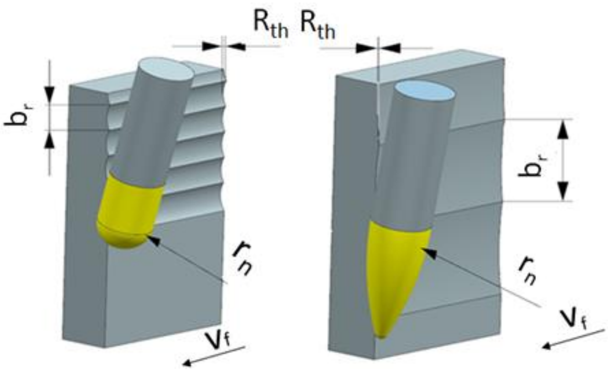

Fig. 1. Five-axis machining: a) ball milling cutter, b) barrel milling cutter [4]

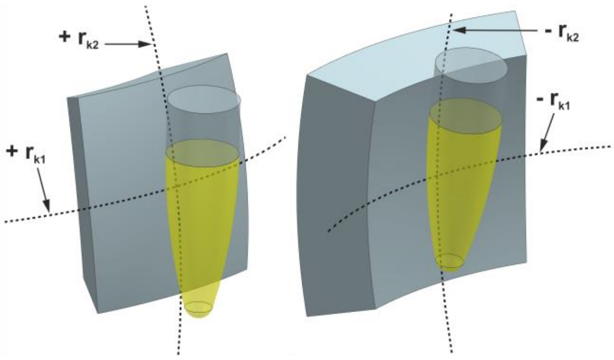

Fig. 2. Radius of curvature of concave and convex surface [4]

The change of these parameters directly affects the values and course of the cutting force components. The cutting force causes elastic deformations of the machine tool – tool - workpiece system and affects the shape errors of the workpiece surface. Therefore, its analysis is extremely important in the process of five-axis machining with the use of a barrel milling cutter, especially considering the radius of curvature of the machined surface [9].

The mechanistic model (1) was adopted for the tests, while the simulation analysis was used to determine the length of the cutting edge *S* and the cross-sectional area of the machined layer *A*. The distribution of the cutting forces for the barrel milling cutter is shown in fig. 3 [1,7].

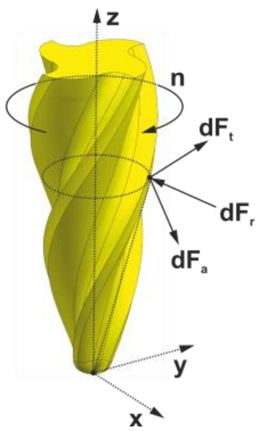

Fig. 3. Distribution of forces on a barrel milling cutter [1]

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$$\begin{cases} dF_t = K_{te}dS + K_{tc}dA \\ dF_r = K_{re}dS + K_{rc}dA \\ dF_a = K_{ae}dS + K_{ac}dA \end{cases} \tag{1}$$

where:
F_t - tangential component of the cutting force,
F_r - radial component of the cutting force,
F_a - axial component of the cutting force,
S - active length of the cutting edge,
A - cross-sectional area of the cutting layer,
K_{te}, K_{re}, K_{ae} - edge proportionality factors affecting the cutting edge, determined experimentally,
K_{tc}, K_{rc}, K_{ac} - proportionality factors related to shear, determined experimentally.

The aim of the research was to determine the courses and values of the components of the cutting force in the machining of concave and convex surfaces with different values of the radius of curvature.

Research methodology

The values of the cutting force components were determined using Boolean operations carried out between the test model and the tool model. The model assumes a barrel milling cutter with a radius of cutting edge r_n = 85 mm. The feed per tooth was f_z = 0.2 mm. The test models were surfaces with different radii of curvature (tab. I).

First, test models of the workpiece were prepared in the NX 11 system. Next, the test bodies were imported into the hyperMill system, where they were used to develop machining paths for each model and an intermediate code was generated.

The next step was to model the tool, which was copied in a pattern created based on the previously imported intermediate code. 80 copies per one revolution of the tool were made. Then, the tool models were subtracted from the object model. As a result of this operation, the cross-sectional area of the cutting layer and the length of the active cutting edge were obtained (fig. 4). These parameters (tab. II) were applied in mechanistic formulas allowing to determine the components of the cutting forces occurring in the process [2, 4, 11].

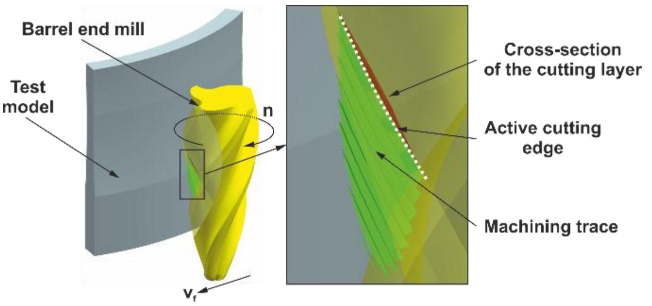

Fig. 4. Analysis of the cross-section area of the cutting layer determined by Boolean operations

TABLE I. Values of radii of curvature of test models

Number	r_{k1}, mm	r_{k2}, mm
1	25	∞
2	-25	∞
3	50	∞
4	-50	∞
5	∞	300
6	∞	-300
7	∞	∞

TABLE II. Parameters adopted for analysis

Feed per blade f_z, mm/z	0,2
Tool diameter d, mm	10
Radius of the cutting edge contour r_n, mm	85
Axial infeed b_r, mm	4
Material	AW 6060
K_{tc}, MPa	1450
K_{rc}, MPa	280
K_{ac}, MPa	-110
K_{te}, N/mm	21,29
K_{re}, N/mm	42,5
K_{ae}, N/mm	-3,1

Analysis of results

Figs. 5-11 present graphs of dependences of the cutting force F_t, F_r, F_a for different values of curvature radius r_{k1}, r_{k2} as a function of the angle of rotation of the tool φ.

To compare the effect of the radii of curvatures r_{k1}, r_{k2}, the values of the cutting force components obtained by simulating the flat surface machining were first examined (fig. 5).

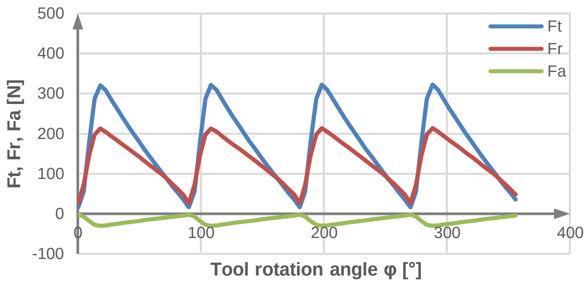

Fig. 5. Course of the components of the cutting force of a flat surface

From the presented waveforms, the tangential component F_t obtained the highest value - about 310N. The value of the radial component F_r reached approx. 210 N and the axial component F_a - approximately 30N.

Subsequently, tests were carried out for a concave surface with a radius of curvature r_{k1} = -25 mm (fig. 6).

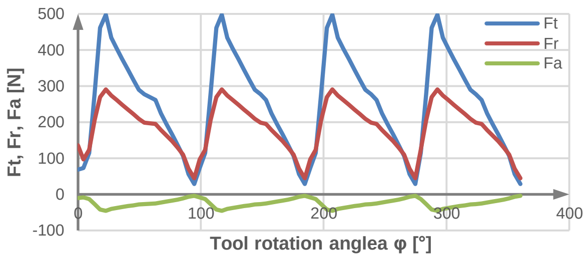

Fig. 6. Course of the cutting force components for the concave surface with curvature r_{k1} = -25 mm

On the basis of the presented courses of the cutting force components, it can be stated that the maximum value of the F_t component is 500 N. In relation to the results obtained during the flat surface machining, an increase of approx. 60% took place. In the case of the F_r component, the maximum value reached 290 N, which is also an increase compared to the results obtained for the flat surface machining by approx. 60%. However, the value of the F_a component was a maximum of 45 N, which indicates an increase of approx. 50% in the flat surface machining.

The test results for the concave surface with the radius of curvature r_{k1} = -50 mm are shown in fig. 7.

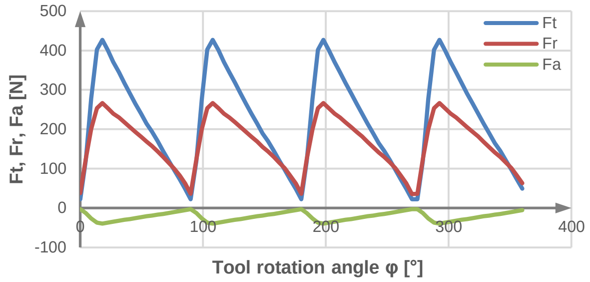

Fig. 7. Course of the cutting force components for the concave surface with curvature r_{k1} = -50 mm

The tangential component was F_t = 426 N, which is a value greater by approx. 38% in relation to the results obtained for the flat surface. Also, the radial component was greater than the value for a flat surface by approx. 38% and was F_r = 180 N. The increase of the axial force was about 22%.

In the case of a convex surface with a radius of r_1 = + 25 mm, the tangent component was F_t = 292 N, which is a value about 16% lower compared to a flat surface (fig. 8). The difference in radial components was 5%, while the axial component reached the value F_r = 26 N - about 13% less than the results obtained for a flat surface.

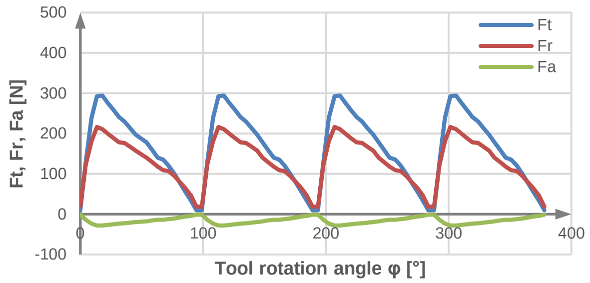

Fig. 8. Course of the cutting force components for a convex surface with curvature r_{k1} = +25 mm

With the increase of the radius of curvature r_{k1} to +50 mm, the components of the forces increase and approach the results obtained for the flat surface (fig. 9).

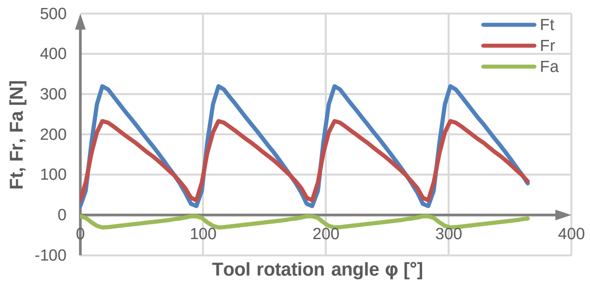

Fig. 9. Course of the cutting force components for the convex surface with curvature r_{k1} = +50 mm

In the case of surfaces with curvature r_{k2} = -300 mm (fig. 10), the tangent component F_t = 350 N, i.e. by about 10% more compared to the flat surface. The radial component, on the other hand, reached the value F_r = 227 N - about 5% more with regard to the machining of a flat surface. On the other hand, the value of the F_a axial component was 32 N. It is important that in the case of machining concave surfaces the values of the minimum values of the courses of the cutting forces are increased.

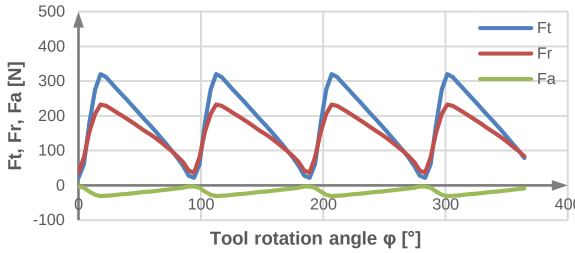

Fig. 10. Course of the cutting force components for the concave surface with curvature r_{k2} = -300 mm

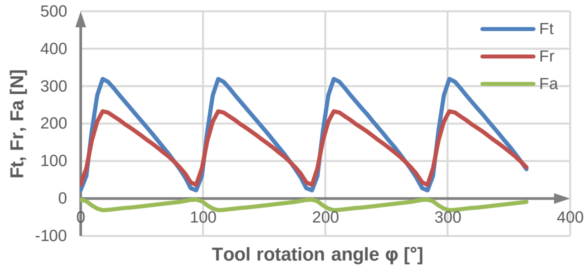

Fig. 11. Course of the cutting force components for the convex surface with curvature r_{k2} = +300 mm

When machining a convex surface with radius r_{k2} = 300 mm, the components of the cutting forces *Ft, Fr, Fa* do not change significantly (fig. 11). In addition, it can be deduced from the graphs of the course of the individual components of the cutting force that always two blades simultaneously have contact with the machined surface.

Conclusions

Simulation tests showed a high variability of the cutting force for different radii of curvature of the machined surface. Differences in the values of the cutting force components were up to 60%. This may result in dimensional and shape errors. Therefore, the values of radii of the curvature of the work surface should be taken into account in the design of the technological process of machining with the use of a barrel milling cutter.

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