

Numerical approach in defining milling force taking into account curved cutting-edge of applied mills

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Abstract. The paper tackles the task of applying the numerical approach to determine the cutting forces of carbon steel machining with curved cutting edge mill. To solve the above-mentioned task the curved surface of the cutting edge was subject to step approximation, and the chips section was split into discrete elements. As a result, the cutting force was defined as the sum of elementary forces observed during the cut of every element. Comparison and analysis of calculations with regard to the proposed method and the method with Kienzle dependence showed its sufficient accuracy, which makes it possible to apply the method in practice.

1. Introduction

The application of mills with curved cutting edge operating in high and ultrahigh feeds is one of the most perspective and high-performance machining methods, which was widely used in rough and semi-finish machining in mechanical engineering.

There is a wide range of manufacturers producing this tool (Fig. 1), such as GARANT, Seco Tools, Sandvik Coromant, Hoffmann Group, etc.

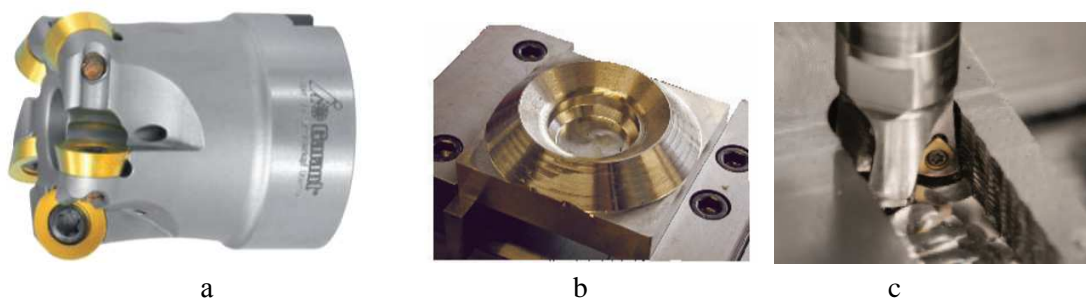


Figure 1. Curved cutting edge tool: a, b – GARANT mill and thus machined workpiece; c – SECO mill

The study of technical information [7, 8, 11] showed that such mills are widely used in high-feed machining ranging from 0.3 to 1.4 mm/tooth, and the ratio value may reach $f_z/t \approx 0.75...1.5$. In case of ultra-high feeding, value f_z may reach 4 mm/tooth with the cutting depth of 2 mm.

It is true that such severe operating conditions of the tool and entire equipment require careful and sound approach to the choice of machining modes with a special focus on cutting force. It is



commonly known that this parameter defines such power characteristics as the driving power of the primary motion and the developed torque. Besides, this parameter serves the main value, which is considered in force and design calculations of tools and removable cutting inserts of machine units and elements.

Scientific and technical literature [1-6] refers to main dependences used to define the cutting force of machining. However, despite a variety of works and studies in this field, the use of obtained analytical results is oftentimes complicated due to some reasons, which mainly include a great number of physical values used in those methods that cannot be considered in operating conditions, as well as due to a curved cutting edge of the tool itself.

Taking this into account, the main task of the research is to develop methods to determine the cutting force of mills with curved cutting edges. The method shall only consider the most suitable standard reference data taken from machining stock.

2. Materials and methods

The set task was solved on the basis of the numerical approach, which included the following:

- the curved cutting edge was exposed to step approximation (Fig. 2), and the tip face was split into rectangular surface elements with width a_i ;
- the volume of cut-off metal represented the set of discrete elements at width a_i and height h_i , every cut of which is made by the corresponding i -surface element of the cutting surface (Fig. 2);
- the cut of every separate element is made under the action of elementary force P_{zi} applied normally from the surface element of the tip face.

Let us determine elementary force P_{zi} using the dependence presented in [1, 2]

$$P_{zi} = K_p \cdot \sigma_B \cdot S_i, \quad (1)$$

where K_p – cutting value; σ_B – rupture strength, MPa; S_i – sectional area of chip elements, mm^2 , which may be expressed with the scheme presented in Fig. 2:

$$S_i = a_i \cdot h_i. \quad (2)$$

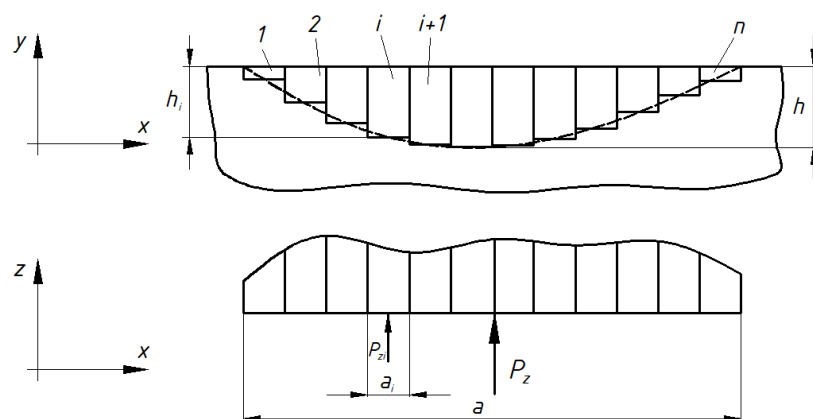


Figure 2. Numerical model of cutting

It should be noted that this approach is rather suitable due to popularization of various CAD-systems providing for relatively precise and convenient approximation of a curved edge with subsequent measurement of a_i and h_i values if the graphic model of a tool or its drawings are available.

It is clear that the cutting force P_z initiated by the cutting plate for a cut of some volume of material consisting of n elements can be defined as:

$$P_z = \sum_{i=1}^n P_{zi} . \quad (3)$$

Thus, cutting force P_z , taking into account (1) and (2), can be expressed as:

$$P_z = \sum_{i=1}^n K_p \cdot \sigma_b \cdot a_i \cdot h_i . \quad (4)$$

In order to evaluate the accuracy of the above-mentioned model, it was suggested to make concurrent computation of the cutting force using the Kienzle dependence, which became widespread in calculation of the cutting force of various tools. The following equation forms the basis of this method:

$$P_z = k_{c1.1} \cdot a \cdot h^{(1-m_c)} , \quad (5)$$

where $k_{c1.1}$ – value representing the cutting force acting on the chips section of 1mm in width and thickness, N/mm²; a and h – width and thickness of chips respectively, mm; m_c – non-dimensional ratio considering specific cutting force depending on chip thickness, which, for carbon steel, makes 0.25 – 0.26 [8, 9].

According to accepted geometry of the cut layer, the value of the cutting force, considering expression (3) and (5), will be presented as:

$$P_z = \sum_{i=1}^n k_{c1.1} \cdot a_i \cdot h_i^{(1-m_c)} . \quad (6)$$

Then, the proposed methods resulted in the calculation of the cutting force of QT-steel 45 milling (analog – S45 according to [8]), where $\sigma_b = 750$ MPa, $k_{c1.1} = 1,700$ N/mm², GARANT mill equipped with removable carbide plates RDHX 10 [8]. The chip width made $a = 2.4$ mm and the maximum thickness reached $h = 0.15$ mm (Fig. 3).

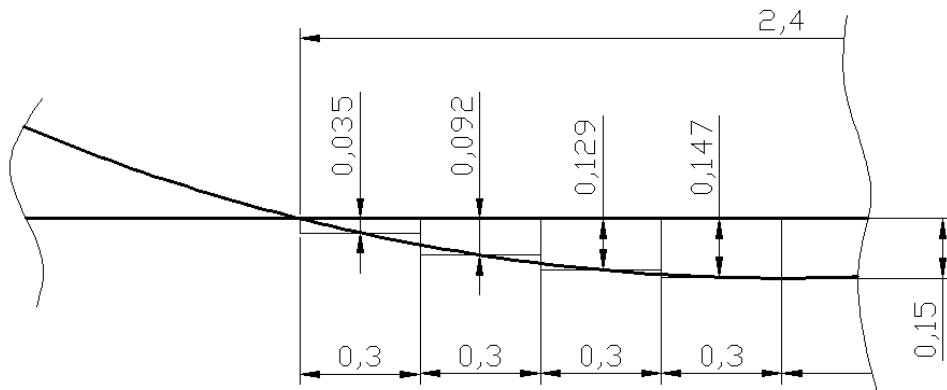


Figure 3. Calculation of cutting force

3. Results and discussion.

The results of cutting force calculation using the above-mentioned method are shown in Table 1.

Table 1. Results of cutting force calculation

Mechanical properties of machined material and other calculation data	Chip width a , mm; Chip thickness h , mm	Cutting force, N; obtained according to		Deviation of calculated values from results obtained through formula (6)	
		(4)	(6)	$ \Delta $	%
$\sigma_p = 725$ MPa $K_p = 2.5$ $m_c = 0.26$ $k_{c1.1} = 1.680$ N/mm ²	$a = 2.4$ $h = 0.15$	459.4	431.7	27.7	6.4

Comparative assessment of calculation results was made via the following expression:

$$k_{P_z} = \frac{|P_{ZK} - P_{Zb}|}{P_{ZK}} \cdot 100\%, \quad (7)$$

where P_{ZK} – calculated value of cutting force according to (6); P_{Zb} – value of cutting force according to (4).

The data presented in Tab. 1 show discrepancy between the cutting force values calculated via expressions (4) and (6) resulting in approximately 6.4%, which, in turn, justifies the accuracy of the proposed method.

4. Conclusions

The analysis of obtained results allows concluding that the proposed method is fairly accurate and convenient, which is justified by the use of standard mechanical characteristics, such as σ_b – rupture strength. This fact, in turn, serves an advantage in comparison with other methods, including the method with Kienzle dependence, which, despite being rather popular, utilizes scattered reference data [8-10]. Thus, for instance, value $k_{c1.1}$ for material corresponding to steel 45 varies from 1,500 to 1,820 N/mm².

All of the aforesaid indicates the possibility of applying the proposed method in calculation of cutting forces for mills with a certain curved cutting edge, as well as in development of mathematical models of machines and equipment utilizing this tool. Besides, the presented results allow posing a question on theoretical and experimental studies of the Kp value in order to specify its values for various machined materials, to advance its application, to identify major physical factors, which mainly determine its value.

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