

Design of tools with the cutting part of the original profile for high-speed milling

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Abstract. This paper considers and justifies the design of the cutting part of multi-edge contour mills with the increased performance and surface quality. The numerical experiments using the finite element method (FEM) allow determining stresses and deformations in the layer of the material being cut when processed by multi-edge mills of a new type, i.e. they allow to evaluate indirectly the unit loads during milling. The required shape and dimensions of the cutting wedge were determined taking into account various values of the geometric parameters of the cutting part, the properties of the workpiece material and cutting conditions. All the above resulted in a 3D model of the end mill, which had got a trapeze-shaped tooth located along two intersecting helical lines with tilt angles of 22 and 85 degrees. Along with improving the quality of the processed surface, the experimental studies also showed a change of chip shape. The chip has a finely crushed structure; the sizes of its elements are about 2 μm , which agrees nicely with the results of the FEM preliminary estimates.

Introduction

The development and active use of multi-axis machines with a high-speed spindle provide high precision machining and highly efficient manufacturing of complex shapes. It is possible to machine a workpiece surface by controlling the cutting edge geometry and angles of end mill which provide the reducing of the cusp height and improve the surface roughness [1]. Micromilling with high geometrical complexity of tool enables reducing the volume and sizes of chips and the cutting force as well as producing 3D micro-components of a wide variety of metallic and non-metallic materials, most significantly composites. Additionally, turning with the use of a single-point cutting tool is proposed to be substituted with end-mill turning, so-called turn-milling [2]. When the chip volume decreases, the cutting thickness can be similar to the tool edge radius size. This chip formation mechanism causes the so-called size effect – a phenomenon characterized by a substantial increase of the specific cutting force for machining processes at small cutting thicknesses, i.e. a reflection of the increase in a part shear flow stress due to the decreasing cutting zone [3]. The use of the known analytical methods of calculation based on the geometric and stereological models is limited or unsuitable to design high-speed mills because it does not take into account the high intensity and rate of deformation processes. The experimental studies also investigate the size effect and chip formation in microscale cutting [4]. Using the analytical and numerical approaches and the finite element model, we can determine the minimum thickness of the material uncut with the chip, and the geometry of tools [5, 6]. Therefore, the development of new cutter designs and methods of numerical evaluation of the deformation processes in the cut layer based on the finite element method (FEM) is a topical and practically significant task.

The aim of this research is to optimize the geometry of multi-bladed contour mills in order to increase productivity and quality of processing.

The mill design

Several types of milling routers by SANDVIK Coromant and ISCAR, which combine the principles of milling and crushing, have been selected as the base objects for a comparative study. Many researchers use specific cutting force when milling regardless of other parameters to evaluate the processing with the use of such mills. This approach is feasible as, despite the same cutting conditions and cutting section, the specific cutting force during micromilling is 90% greater than during macromilling. This fact indicates that when changing the geometry of the cut layer section (i.e. the shape of the cutter tooth) and the shape of the chip, there appear different specific cutting forces. Analyzing the relationship of feeds per tooth and the cutting depth on the specific cutting force, we can conclude that their influence is not significant for micromilling, in contrast to macromilling [2]. Thus, we can consider that specific cutting force is a more important parameter which influences processing and surface quality of a workpiece during high-speed micromilling. It is assumed that decreasing the specific cutting force will improve the efficiency and quality of machining.

The first stage of the study was an efficiency analysis of new end mill geometry with the increased number of cutting edges which was carried out with the use of common models. We optimized the geometric parameters of the cutting part and developed a 3D model of the mill (figure 1) based on the conducted numerical experiments. This new design is supposed to have an increased number of cutting cycles in comparison with its counterparts, which means that the specific cutting force on each tooth edge will be minimized, and the profile of a surface being processed should have a reduced roughness value.

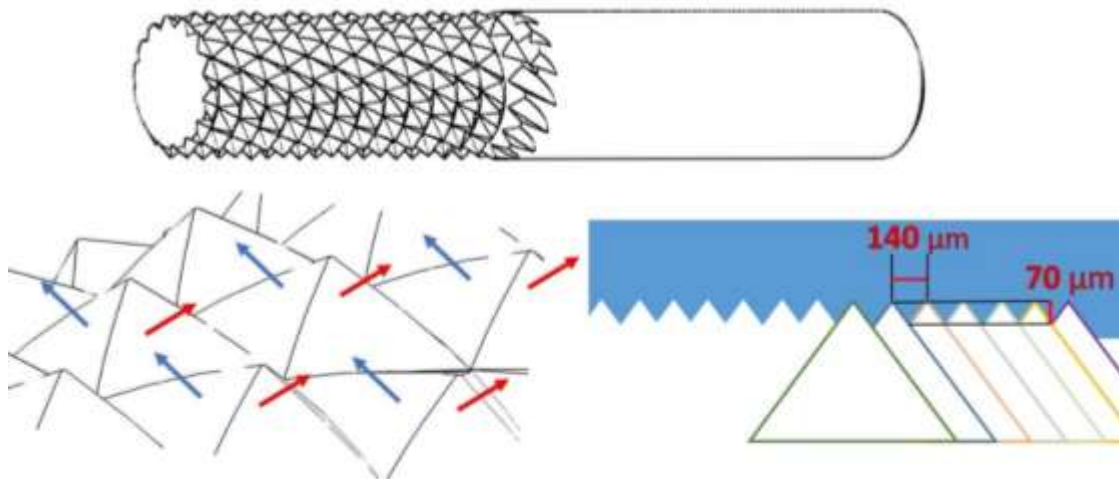


Figure 1. 3D model of the developed cutter

This study used sophisticated calculation methods to adequately compare the effectiveness of the milling process for various tool designs.

Table 1. The parameters used in calculations

№	Parameters	Units	Values
1.	cutting speed	m/min	125
2.	feed per tooth	mm/ tooth	0.15
3.	depth of cut	mm	8
4.	cutting width	mm	9.5
5.	tool rotary speed	rpm	4000

Analytical calculation formulae for determining the volume of cut material per minute (Q , cm^3/min) and the number of cutting cycles per second (N , s^{-1}) used (formulae 1 - 3).

$$Q = a_p \times a_e \times V_f / 1000 \quad (1)$$

a_p – depth of cut, mm;
 a_e – cutting width, mm;
 V_f – feed per minute, mm/min.

$$V_f = n \times f_z \times z_n \quad (2)$$

n – tool rotary speed, rpm;
 f_z – feed per tooth, mm/tooth;
 z_n – number of tooth.

The number of cuts per second (N , s^{-1}) in this case can be determined by formula 3.

$$N = n \times z / 60, \quad (3)$$

z – number of cutting edges per tool diameter at height of 9.5 mm;

Parameter z for mills: z_1 for ISCAR = 50 cutter edges; z_2 for SANDVIK = 3 cutter edges;

The range of cutting conditions during the calculations:

$v = 125$ m/min or approximately $n = 4000$ rpm (for mill diameter $D = 10$ mm);

$f_n = 0.15$ mm/tooth feed per tooth;

$a_p = 8$ mm and $a_e = 9.5$ mm depth of cut and cutting width respectively.

The ranges of cutting modes were:

- cutting speed 100 – 200 m/min;
- feed per tooth 0.01 – 0.02 mm/tooth.

The calculation data of the efficiency of various mill models according to parameters of Q and N depending on the cutting speed are presented in the diagrams in figure 2.

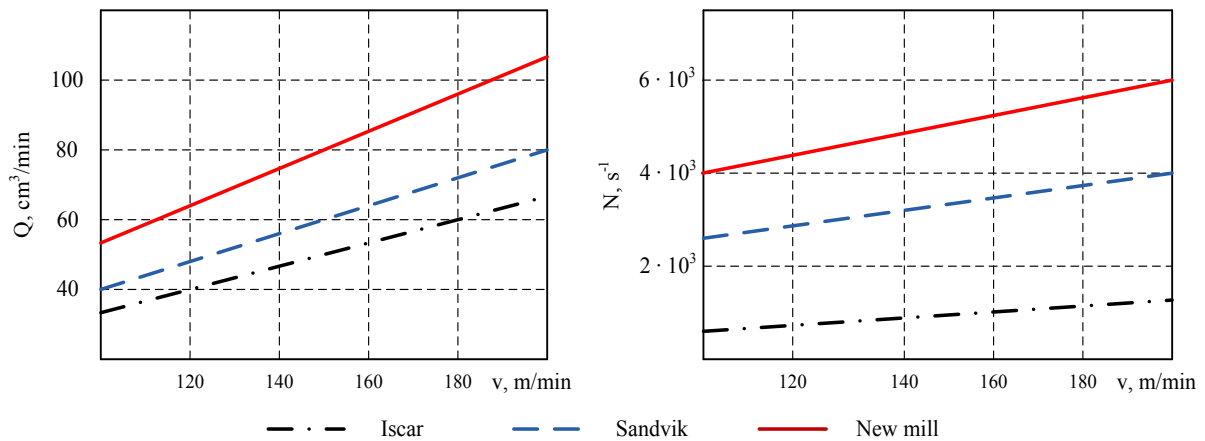


Figure 2. The effect of cutting speed on the volume of the material to be removed and on the number of cuts per second

The calculation data show that the intensity of deformations during the processing using the new geometry significantly increases in contrast to analogical mills. The number of single-chip cutting microcycles varies within the interval: the new mill – 4000-6000 s^{-1} ; SANDVIK – 2500-4000 s^{-1} ; ISCAR – 800-1500 s^{-1} .

Results of simulation and discussion

The conventional analytical calculation models exclude the geometrical features of the new mill geometry; that is why when determining the numerical values of the cutting forces we use the calculation formulae obtained based on the full-scale experiments. However, the nature of the load distribution and the numerical value of the specific cutting forces can be determined using the finite element analysis method [7]. A series of numerical experiments using FEM allows determining stresses and deformations in the cut material layer when processing with multi-blade mills of the new type (figure 3), i.e. it allows to indirectly evaluate the unit loads during milling. Besides, the calculation data allow predicting the shape and size of the chips that may appear in case of processing by the new mill.

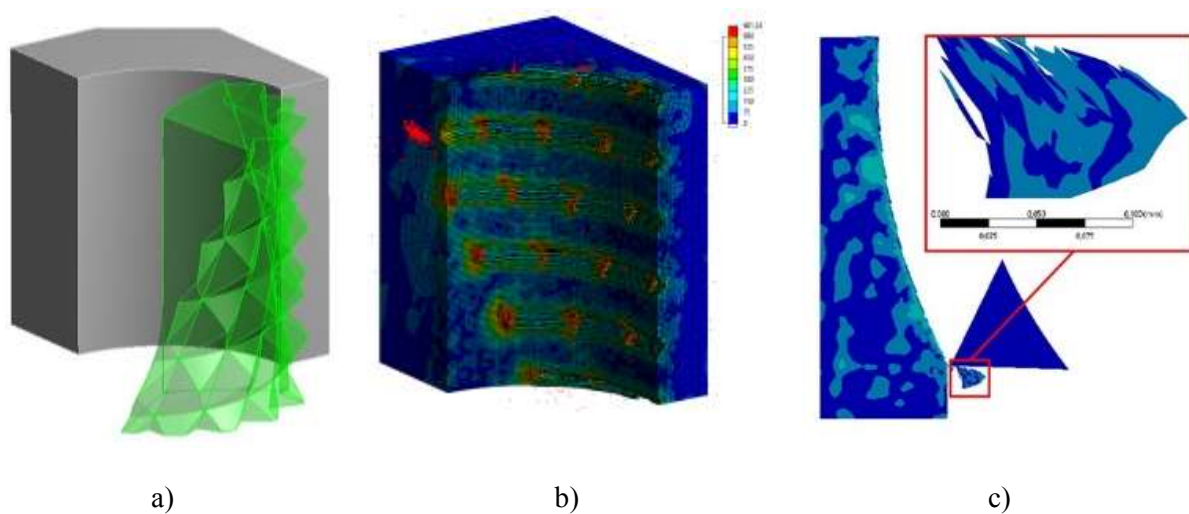


Figure 3. The model and the calculation result of the cutting process
(a) tool – detail interface; (b) scheme of cutting and stresses; (c) one cycle of tooth movement and chip formation

Graphic representation of the deformation processes illustrates the kinematics and the sequence of the material layer cutting process. The material is not cut (unlike when standard milling is applied) but it is crushed and removed from the cutting area in the form of microparticles. The new mill works similarly to an abrasive tool combining the processes of cutting and crushing. The studies based on the FEA method show that the specific load when using the new mill geometry is reduced, whereas the maximum values of stresses arising on the surface of a workpiece and the cutting part of the tool do not exceed 500-5000 MPa (figure 3 b, c). In this case, the maximum stress values concentrate in a thin surface interface layer. This fact, as well as the predicted finely crushed type of chips, is a prerequisite for reducing the roughness of the processed surface and at the same time increasing the productivity of milling. The required shape and dimensions of the cutting edge were determined by given various values of the geometric parameters of the cutting part, the properties of the workpiece material and cutting conditions. As a result, 3D model of the end mill was created having the original tooth profile in the form of trapezia (figure 4), located along two intersecting helical lines with tilt angles of 22 and 85 degrees.

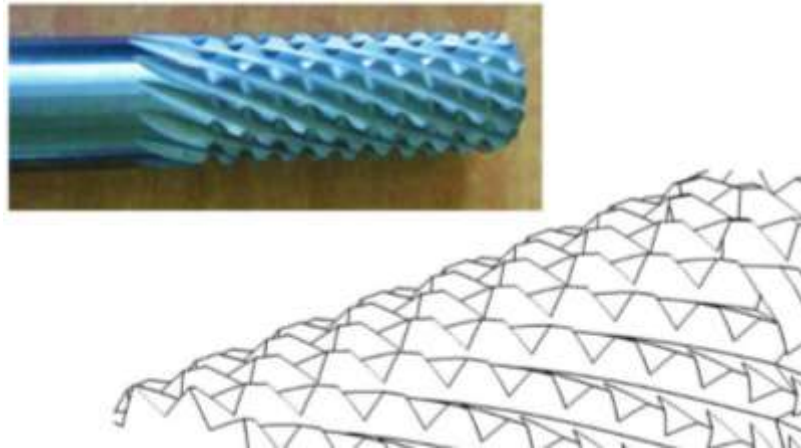


Figure 4. Actual geometry of the cutter tooth's

The manufacturing of tools on ANCA RX7 cutter grinding machine was controlled by a specially developed controlling software. We used rods made of the extruded nanostructured hard-metal composite as a workpiece material for the tool manufacturing. This new hard-metal composite has a number of improved physical and mechanical properties in terms of strength, crack and heat resistance due to the modification of the cobalt binder with the addition of aluminium oxide nanoparticles [8]. A set of these properties is a necessary prerequisite for the effective operation of the developed design of a multi-blade mill at high cutting speeds and under conditions of alternating cyclic loads. The new contour tool was used for testing when cutting composite fibre materials.

Verification by experiments

As the main parameter for the experimental verification of the analytical results obtained from the research, we used the surface roughness values of the machined new mill construction in different cutting conditions when processing composite materials. Such heterophase materials cause particular processing difficulties since, as a result of structural heterogeneity on the machined surface, chips and delaminating (destruction of the binder material) appear, as well as fibre fragments elongated from the bulk of the workpiece. For these reasons, fibre composite materials can be relevant objects to test the efficiency of the new mill design. Along with the improved quality of the processed surface, the experimental studies also resulted in finding a change in the chip shape, where it has a finely crushed structure, with the size of the elements (chip fragments) of about 2 μm (figure 5 c), which is in good agreement with the results of the preliminary FEM estimates.

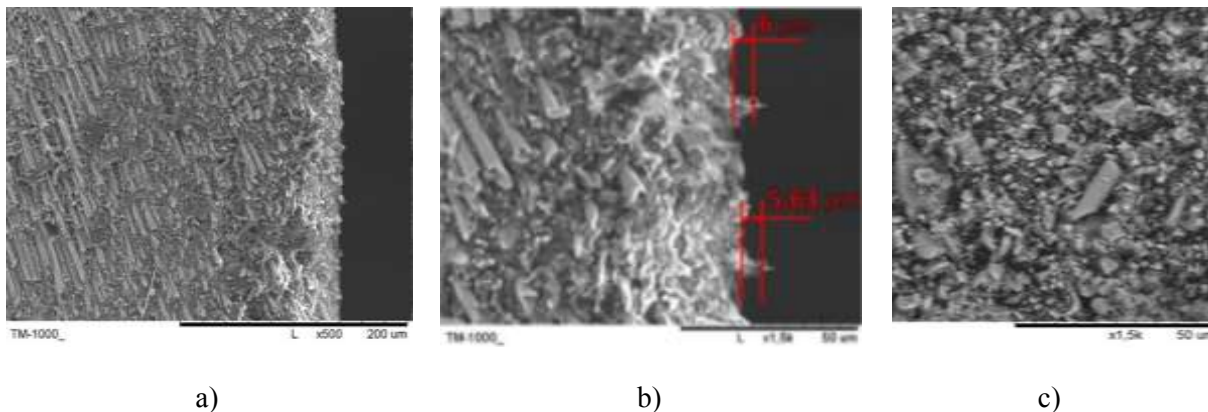


Figure 5. Electron microscope images of the surface topography (a – b) and chips (c)

The surface quality at processing with original milling cutter is obviously higher than at processing with a standard one. It has been ascertained that the values of surface roughness significantly decrease and these values are lower than 6 μm (figure 5 b). It can be explained by the fact that due to the increase in cutting edges and intensity of cutting processes (the number of single cutting cycles is up to 4000-6000 s^{-1}), the composite fibres are easily cut and are not elongated from the matrix material. The chip morphology and sizes correspond to the cutting intensity specific to high-speed micromilling. The chip crushing coefficient at a milling depth of 0.5 mm and a rotational speed of 4000 rpm is equal to $k = 250$. This fact indirectly confirms the increased productivity of the machining process and a decrease of the specific cutting force.

Conclusions

Using conventional analytic models for calculation of deformation processes and methods of final element analysis (FEA), we studied the influence of the geometry of the cutting part of the multi-edge tool and cutting modes on the intensity of the deformation processes of high-speed milling. On this basis, we determined the rational design of the contour mill, and the experimental studies confirmed the efficiency and increased productivity with simultaneous quality improvement when machining by the new mill.

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