The Methodology of Calculation of Cutting Forces When Machining Composite Materials

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Abstract. Cutting of composite materials has specific features and is different from the processing of metals. When this characteristic intense wear of the cutting tool. An important criterion in the selection process parameters composite processing is the value of the cutting forces, which depends on many factors and is determined experimentally, it is not always appropriate. The study developed a method of determining the cutting forces when machining composite materials and the comparative evaluation of the calculated and actual values of cutting forces. The methodology for calculating cutting forces into account specific features of the cutting tool and the extent of wear, the strength properties of the processed material and cutting conditions. Experimental studies conducted with fiberglass milling cutter equipped with elements of hard metal VK3M. The discrepancy between the estimated and the actual values of the cutting force is not more than 10%.

Introduction

Widespread in modern industry are composite materials of polymer-based [1 – 3]. Their products in comparison with metals and alloys have a number of advantages, such as specific strength, resistance to corrosion, cost, etc. Machining composites has specific features in comparison with the processing of metals. These include increased wear of the cutting tool, the need to increase the front and rear corners of the cutting, the use of equipment with high-speed processing, the presence of local and general ventilation, etc. [4 – 10]. Modern production methods and technologies enable the manufacture of parts with high surface quality, performance, but do not always satisfy the requirements of form and dimensions of the product [11, 12]. For surfaces of different shapes is widespread milling. When milling of composite materials is recommended to use high-strength tool materials, such as cemented carbide and superhard materials [5, 13 – 15]. Difficulties in the use of these materials is the formation of a cutting edge with a small angle of sharpening, but this problem can be solved through the use of electro-technology diamond sharpening in a double etching [16 – 18].

The parameters include the milling process productivity, operability of the cutting tool, cutting power and surface finish. Urgent problem is to evaluate the cutting forces because they determine the processing capacity, the pressure on the cutting edge and chip character etc. Known research mainly aimed at finding the experimental methods for determining the cutting forces [19, 20], however, is not always advisable to conduct laboratory tests.

The aim of the study is to improve the technology for milling of composite materials, and the task is to develop methodology for calculating cutting forces, conducting an experiment for comparing the calculated and actual values of cutting forces.

1. Method for determining the cutting forces during milling

To determine the parameters influencing tool life in milling used the theory of strength of materials and cutting theory. We select the time when the forces acting on the "cutting tool - detail" system will have maximum values (Fig. 1). And refine them.

When cutting the material on the cutting edge of the tool by cutting layer the force of friction F_f^{ed}, which affects the degree of tool wear and the size of the chamfer wear. This force is related to the elastic resistance of the processed material and the appearance of the reaction N_{ed}. Frictional force F_f^{ed} direction is determined by the chamfer wear, which is taken tangent to the cutting surface, and the direction of reaction N_{ed} perpendicular to the direction of force F_f^{ed}.

When rotating milling cutter operates the centrifugal acceleration a_c^n and the presence of the tool imbalance can occur inertia force F^n directed in the opposite direction with respect to the centrifugal acceleration a_c^n. Since all rotating tools are subjected to balancing, the value of the imbalance in this case can be neglected, and take the position that the mass center of the cutter lies on the axis of rotation, $F^n = 0$.
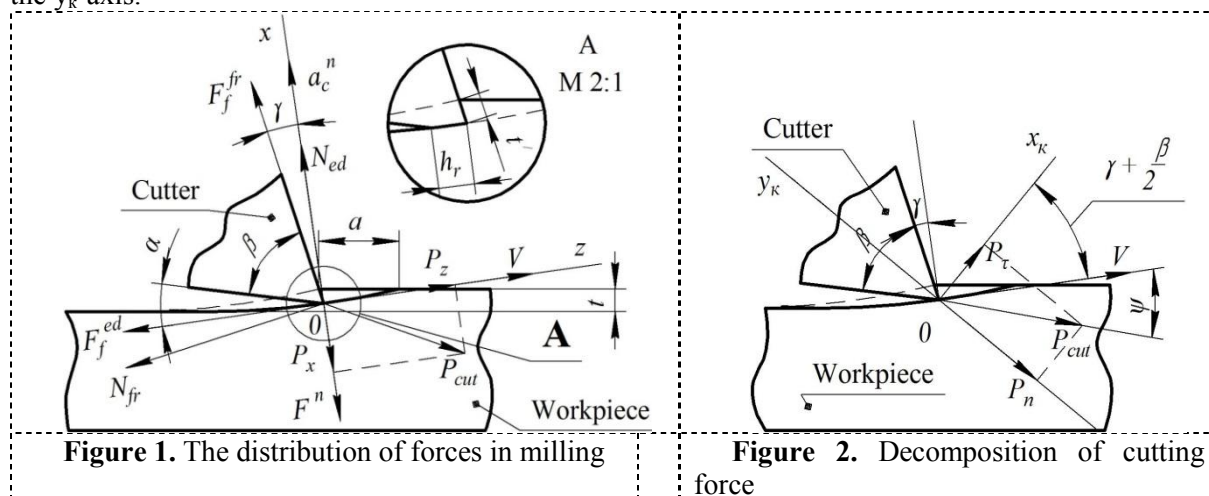
Also at the cutting edge the force of friction F_f^{fr}, which is connected with the elastic resistance of the treated material and the appearance of the reaction N_{fr}. The force F_f^{fr} is directed along the front surface of the cutting wedge and the reaction N_{fr} is directed perpendicular to the friction force F_f^{fr}.

Removal of material from the surface is effected by the cutting force P_{cut} which can be decomposed into two components: P_z and P_x, directed along the axes OX and OZ respectively. The axes of the projections are directed as follows: OZ axis is parallel to the vector velocity V; and OX - perpendicular to the OZ axis.

Cutting force P_{cut} is determined by the formula, knowing its components:

$$P_{cut} = \sqrt{P_z^2 + P_x^2} \qquad (1)$$

The cutting force P_{cut} affects flexural and compressive cutting edge of the tool axes $y_к$ and $x_к$ (Fig. 2). The $y_к$-axis is directed along the bisector of the angle wedge, on the $x_к$-axis perpendicular to the $y_к$-axis.

Figure 1. The distribution of forces in milling

Figure 2. Decomposition of cutting force

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Thus, the force P_n directed along the $y_к$ axis, will affect the value of the compressive stress in the cutting edge during milling, and the force P_τ, directed along the $x_к$ axis, - the value of the bending stress. Moreover, the direction of the cutting force P_{cut} is deflected from the direction of the velocity vector V on the angle ψ. According to the scheme in Fig. 2, this angle is $\psi = arctg\left(\dfrac{P_x}{P_z}\right)$.

The value of the stress caused by the influence of the cutting forces will be:

$$\sigma_n = \frac{P_n}{B \cdot h_r} = \frac{P_{cut} \cdot \sin(\psi + \gamma + \beta/2)}{B \cdot h_r} \tag{2}$$

$$\sigma_\tau = \frac{P_\tau}{B \cdot h_r \cdot \sin\gamma} = \frac{P_{cut} \cdot \cos(\psi + \gamma + \beta/2)}{B \cdot h_r \cdot \sin\gamma} \tag{3}$$

where h_r – value chamfer wear along the rear surface of the cutting tool, mm; B – the width of the shear layer, mm; γ – the rake angle of the cutting tool; β – sharpening angle of the cutting edge.

Under normal conditions, the cutting stress must not exceed the strength properties of the cutting blade.

Cutting forces are determined based on the fact that the sum of the projections of the forces on the axis OZ and OX is equal to zero:

$$\sum F_i(z) = 0: \ P_z = N_{fr} \cdot \cos\gamma + F_f^{fr} \cdot \sin\gamma + F_f^{ed} \tag{4}$$

$$\sum F_i(x) = 0: \ P_x = -N_{ed} - F_f^{ed} \cdot \cos\gamma + N_{fr} \cdot \sin\gamma \tag{5}$$

$$F_f^{ed} = N_{ed} \cdot f \tag{6}$$

$$F_f^{fr} = N_{fr} \cdot f \tag{7}$$

where f – the coefficient of friction between the tool and the workpiece.

Given that the reactions N_{ed} and N_{fr} are dependent on the elastic properties of the material being processed, we obtain:

$$N_{ed} = \sigma_{el}^{pr} \cdot S_{cut} \tag{8}$$

$$N_{fr} = \sigma_{com}^{pr} \cdot S_{pr} \tag{9}$$

where σ_{com}^{pr} - the compressive strength of the processed material, MPa; σ_{el}^{pr} - elastic stress arising from the cutting material, MPa; S_{pr} - sectional area of a cut-off stratum in the direction, perpendicular to the reaction N_{fr}, mm^2; S_{cut} - sectional area of a cutting element in the direction, perpendicular to the reaction N_{ed}, mm^2.

$$S_{pr} = B \cdot t' \tag{10}$$

where t' - the maximum thickness of cutting layer for milling, mm.

Maximum thickness of cutting layer depends on cutting conditions and cutter diameter and is defined by the formula:

$$t' = \frac{S_z \cdot t}{R \sin\left(\arccos\left(1 - \dfrac{t}{R}\right)\right)} \tag{11}$$

where S_z – feed to the cutter tooth, mm/tooth; R – cutter radius, mm; t – cutting depth, mm.

$$S_{cut} = B \cdot h_r \tag{12}$$

2. Method of the experiment

To establish the conformity of the calculated and the actual measurements of cutting forces set up an experiment to process composite glass fiber brand STEF-1 cutting tool equipped with inserts made of sintered carbide VK3M.

The study was conducted on the test bench, created on the base of the machine 3D642E model modernized under the processes of milling of composite materials with the possibility of establishing a high spindle speed and equipped with a number of local ventilation. The limits of variation of cutting conditions are set as follows: cutting depth $t = 0.5 - 1.5$ mm, feed to the cutter tooth $S_z = 0.16 - 0.33$ mm/tooth. Cutting speed V was set as much as possible that provide installation spindle speed $n = 6000$ min^{-1}. Given that the torque from the motor to the spindle of the machine is carried by a belt transmission, characterized by belt slippage, and the cutting diameter of 150 mm and the cutting speed $V = 45\pm2$ m/s.

The limits of variation, tool and processed materials are selected based on the recommendations on the treatment of polymeric materials reinforced with high-strength fibers and fabrics [5, 13 – 15].

When processing polymeric composite materials characterized by tool wear on the back surface, so the process stability criterion is the value chamfer wear along the rear surface of the cutting tool $h_r = 0.35$ mm. Its further increase would lead to poor quality of the machined surface [5]. The value of chamfer is optically controlled.

During the experiment were monitored using cutting power meter K506. Calculation of cutting forces when power measurements carried out according to the formula:

$$P_{cut} = \frac{N_{cut}}{V} \tag{13}$$

where V – cutting speed, m/s.

3. Results and Discussion

According to the experimental results obtained by mathematical relationship of the cutting force of the processing modes:

$$P_{cut} = 4.2 + 166S_z - 3t + 168S_z t \tag{14}$$

According to the above method calculated the cutting forces during milling fiberglass brand STEF-1 hard alloy VK3M with varying treatment regimens. The input parameters for the calculation were as follows: the rake angle $\gamma = 25°$; Compressive strength $\sigma_{com}^{pr} = 400$ MPa; Cutter radius $R = 62.5$ mm; The cutting width $B = 10$ mm; the coefficient of friction $f = 0.5$; chamfer wear along the rear surface $h_r = 0.35$ mm.

For comparison of the calculated and experimental data plotted as the cutting force of the feed and depth of cut (Fig. 3, 4).

With increasing feed and depth of cut, the cutting force increases due to the increased thickness of the shear layer of the processed material and the load on the cutting tool. The values of the calculated and experimental curves do not differ by more than 10%. This makes it possible to predict with sufficient certainty value cutting forces at varying grades of composite materials, process conditions and constructional features of the cutting tool.
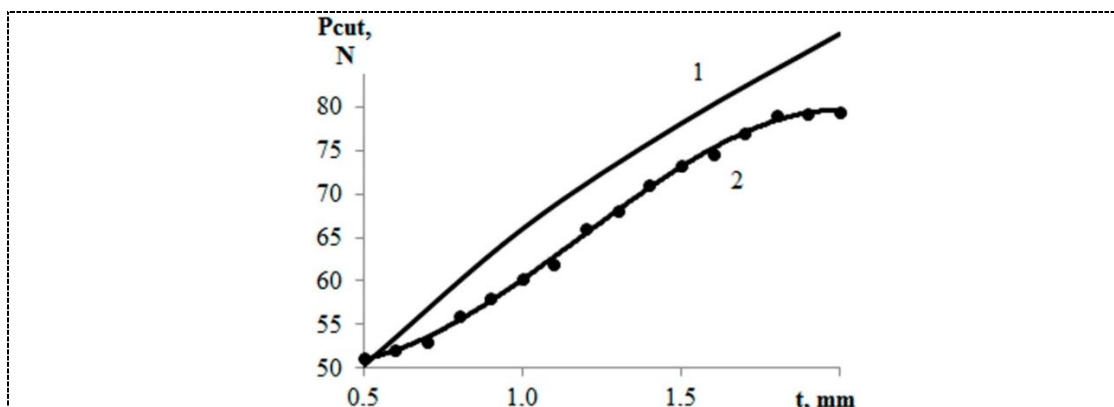
Figure 3. The dependence of the cutting force by the cutting depth: 1 – calculated dependence; 2 – experimental dependence
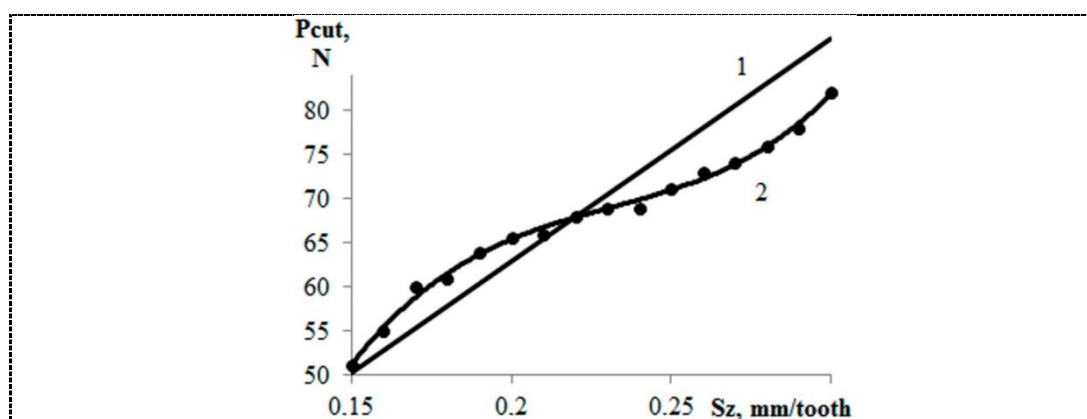

Figure 4. The dependence of the cutting force by the feed per tooth: 1 – calculated dependence; 2 – experimental dependence

Conclusions

Conclusions and recommendations were made on the results of research:

1. An analysis of the scientific literature shows that the composite cutting issues are not well understood, not fully presented studies of the characteristics of their processing.

2. A method for calculating cutting forces during milling of materials based on the provisions of the mechanics and the theory of cutting. The method allows to calculate the cutting force with high accuracy and is used to determine the optimum cutting performance composite materials.

3. The mathematical dependence of the cutting force on the treatment regimes in order to assess the difference between calculated and experimental values. It was found that the error rate of not more than 10%, which is acceptable to the theoretical studies of the process of milling of composite materials and designing manufacturing operations.

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