Predictions of tool wear by estimating weight loss during polymer composites processing

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Abstract: - The main criterion for wear of the tooltip when processing polymer composites is a technological criterion, namely the conventional amount of wear on the tool flank face. The cutting edge wear is asymmetrical, and it was assumed that during the wear process, the initial tip of the sharpened tool moves along the rank surface. Then, in the plane of the tool top, you can calculate the change in area and find the weight loss over a certain period. A geometric model was developed that allows you to relate the amount of tool weight loss and the classical determination of the wear value on the flank face. Using experimental data on fiberglass processing, the relationship between the conditional amount of wear on the back surface and the loss of weight and the change in the shape of the cutter for various technological parameters of processing - feed, speed, and depth of cutting - was established. Generalized dependencies were obtained, which connect the amount of weight loss by the tool with technological parameters and processing duration.

Key-Words: - polymer composites, cutting edge wear, weight loss, geometric model.

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1 Introduction

Mechanical processing of composites, despite the low values of cutting forces and temperature in the tool-workpiece contact, is accompanied by high wear of the cutting part of the tool. This is explained by the intense abrasive effect of the reinforcing elements in combination with the low thermal conductivity of the polymer matrix of the composite. In turn, this leads to the appearance of specific processing defects such as chipping, fluffing and pulling out of fibers, cracking, etc.

As the tool wears out, the likelihood of defects increases. Wear leads to a change in the nature of the interaction between the tool and the workpiece, the appearance of high elastic recovery stresses of the processed layer of material, and, as a consequence, intensification of wear. Experimental studies have shown **[1,2]** that the nature of wear has significant differences from the classical case of metal cutting, where wear can be divided into many different independent phenomena that arise in addition to direct abrasive wear.

The wear of the tooltip when cutting (turning) composite materials has a pronounced asymmetrical character **[1,2]**. The main features are the dominance of wear on the flank surface of the tool and the virtual absence of wear on the front surface, Fig. 1 **[3]**. This leads to the initial conclusion that the tooltip is worn due to an increase in the radius of curvature of the cutting edge, which is not obvious with asymmetrical wear.

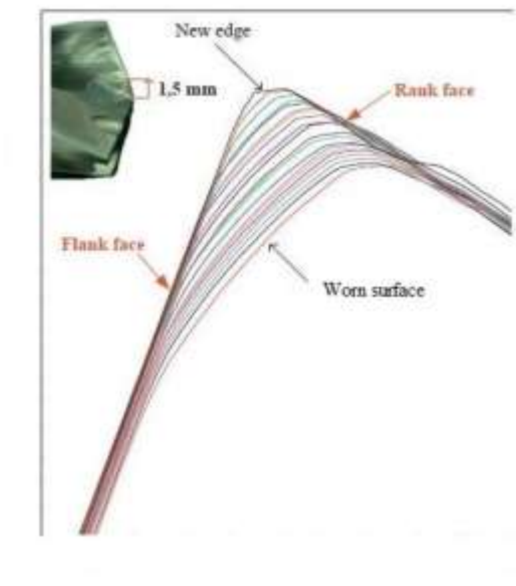

Fig.1. *Wear of the cutter tip on the flank surface depending on the number of drilled holes* [**3**].

The easiest way to determine the distortion of the cutting edge shape during wear is to display the geometry in any way after some time of operation. This is a direct characteristic, based on which one can unambiguously conclude the further performance of the tool and the nature of its wear during operation.

Another indirect characteristic for assessing tool wear may be weight loss due to removed material during operation. This is an integral characteristic that does not give an idea of the distortion of the shape of the cutting part, but it can serve as a reliable indicator of the possibility of its further operation. The main advantage of this characteristic when predicting the performance of a tool is the ease of its determination by weighing it before starting and after finishing work. Weight loss reflects all the phenomena that took place during the operation of the tool, that is, it reflects everything that happened to it: changes in force, heating and cooling, oxidation, etc.

Numerous studies have been done to predict the wear rate and tool life **[4]**. Various prognostic theories have been proposed, confirmed, or refuted experimentally. Creating accurate models requires an expensive and time-consuming study of the problem in practice. Therefore, an important part of research is numerical modeling, primarily the finite element method (FEM) **[5]**. The application of homogeneous material cutting models to multiphase composites also did not give satisfactory results. To satisfactorily model the cutting process, it is necessary to take into account the properties of fibers, matrix, and fiber-matrix joints, as well as tool-fiber, tool-matrix, and fiber-matrix interactions **[6, 7]**.

Experimental studies on orthogonal cutting of carbon fiber plastic have shown that the wear of the cutting edge (rounding) is asymmetrical **[3, 8]**, the magnitude and intensity of which depends, first of all, on the initial geometry of the tool (initial sharpening) and the degree of sharpening, the orientation of the reinforcing elements **[3, 8]**.

The mechanism of brittle fracture when cutting PCM assumes the absence of a stagnation zone characteristic of metal cutting in the row of the cutting edge, which is an accumulation of workpiece material and protects the cutting edge. The absence of such a zone leads to preferential abrasive wear **[9]**. According to **[10]**, tool wear primarily increases in a small area near the cutting edge, where the transition between the rake and flank cutting edges occurs.

To quantitatively describe the wear process as a phenomenon of corresponding rounding of the cutting edge, several models of the contact area between the cutting part of the tool and the processed material have been proposed. Thus, in **[10]**, a model with five parameters was considered, where the working part of the cutting edge is described by simple geometric objects of the "straight-ellipse-straight" type.

The geometry of the various tool types is fairly clearly defined by the flank and rake angles, as well as the actual cutting edge as the transition between the flank and rake edges. As indicated in **[11]**, rapid initial wear determines the further condition of the tool and its suitability for processing polymer composite materials (PCMs). Therefore, a detailed determination of tools microgeometry is of great practical importance, and solving this problem is an urgent task of PCM processing technology.

As a technological wear criterion, a conditional value was proposed - a change in the linear size along the flank surface, Fig. 2, **[12]**. A symmetrical wear scheme is proposed, from which a relationship is obtained that connects flank surface wear with the current and initial rounding radius of the cutting edge, or a relationship that connects the current rounding radius with flank surface wear h_z.

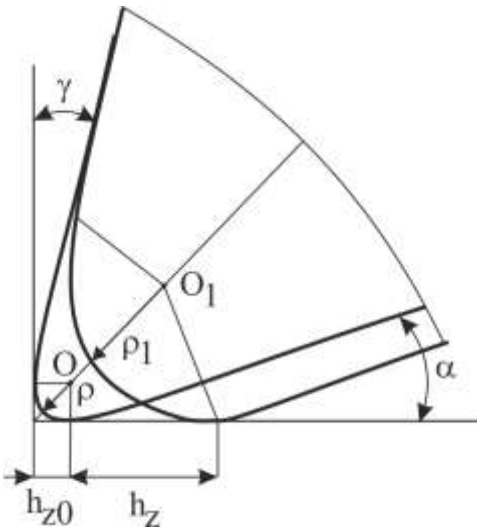

Fig.2. *Scheme of symmetrical wear and the conditional value wear* h_z *calculation on the flank surface* [**12**].

However, experimental studies **[3, 8]** have shown that the wear of the cutting edge has a pronounced asymmetric shape. Intensive tool wear during PCM processing dramatically changes the initial geometry of the tool being sharpened, which significantly affects machinability and increases the appearance of various defects in the material being processed. Analysis of experimental data showed that the intensity of wear along the flank surface of the tool most significantly depends on the orientation angle of the reinforcement θ relative to the processing direction.

2 The relationship between the change in the tool tip geometry and the loss of weight

The general formulation of the problem comes down to determining the shape of a worn tool and establishing a relationship with weight loss. In other words, it can be formulated as follows. It is necessary to establish a connection between the total weight loss of the tip of the cutter and wear on the flank surface, which is accompanied by a change in the value of the clearance angle, or to relate the weight loss of the tool during its operation with its wear on the flank surface.

As a working hypothesis, it was assumed that during the wear of an initially sharpened tool, its tip conditionally moves along the rake surface, i.e. there is a constant displacement of the initial rounding of the tip of the sharpened tool along its rake surface, Fig. 3. In this case, it is assumed that there is no change in the value of the rake angle. This assumption became possible from the analysis of the profile of the worn tip of the cutter, presented in **[3]**, **[8]**, **[13]**.

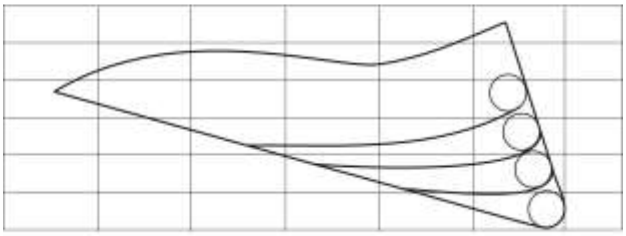

Fig.3. *Offset of the sharpened tool top initial rounding along the conventional rake surface*

In the presented formulation, there is also an inverse problem, when, based on the existing value of the amount of wear on the flank surface (weight loss) of the tool, it is necessary to determine the overall change in the geometric shape of the tool and the weight loss (amount of wear on the flank surface). In addition, it is assumed that by using an apparatus for geometrically changing the surface area of the tooltip (actually losing weight), it is possible to calculate the size of wear along the flank surface and determine the tool life under given processing conditions.

When machining composite materials, the standards of different countries provide a limit value for the size of wear on the flank surface, which on average usually does not exceed 0.3 mm. Upon reaching this value, unacceptable processing defects appear during the cutting process, and the tool itself must be replaced and, if possible, re-sharpened.

Two practical tasks follow from the formulated formulation: given a given weight loss of a tool, calculate its shape and, above all, the change in size on the flank surface. The second task is to determine the expected weight loss for a given value of flank wear, and hence the tool life.

Considering that the wear rate changes with time, and also with the appearance of wear, the stress state in the contact changes, the tooltip heats, and the friction conditions (friction coefficient) change, both settings have a clearly expressed nonlinearity. To solve such problems, it is necessary to use step-by-step algorithms that take into account the hereditary change in the shape of the tooltip.

Thus, the actual wear of a tool during its operation can be represented as the difference in the surface areas of the cutter tip, calculated for two successive moments in time, multiplied by the width of the cutting edge and the density of the tool material.

3 Geometric wear model

Analyzing the change in the shape of the tool tip during the wear process, presented, for example, in works [1,8], one can notice that the tip of the initially sharpened tool seems to move along the line of the front surface, Fig. 3. With some error, we will assume that the configuration of the rake surface does not change its original position during the operation of the tool. Physically this means there is no wear on the rake face, which is not the case. The amount of wear is much less than on the flank surface and, therefore, can be neglected. Taking this assumption into account, we will assume that the conditional initial rounding of the sharpened tool seems to move along the rake surface. In this case, in the plane of the tooltip, Fig. 4., during the wear process, the area of the tooltip adjacent to the rake surface changes. The change in the position of the contour of the flank surface is wear itself, i.e. tool weight loss. Thus, the weight loss during operation is proportional to the change (removal) of the area, assuming a constant value of the width of the cutting edge of the cutter.

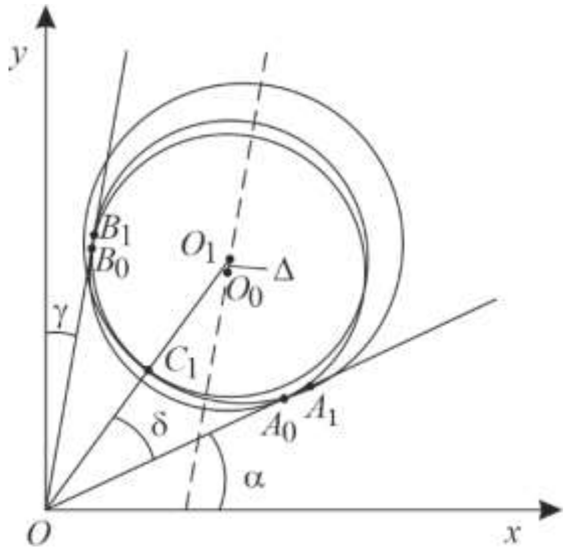

Fig.4. *Geometric model of the incisor tip worn profile.*

Thus, the weight loss is proportional to the difference between the nominal surface area of the tool cutting edge after working for some time and the initial nominal area of the unworn edge, the width of the cutting edge, and the density of the tooltip material.

The main parameter that determines the change in area in the geometric model is the displacement of the center O_0 of the initial circle, which determines the rounding of the cutting edge, along a straight line parallel to the rake cutting edge – Δ, Fig. 4.

Knowing or setting this value, you can describe a new circle that approximately follows the profile worn part of the tooltip along the flank surface. To numerically determine the value of the lost area, it is necessary to have an analytical expression that describes the contour of the worn surface of the cutting part along the flank surface. This is practically impossible, even with experimental data. Therefore, it is proposed to replace this curve with a circular arc with a center at O_1, and a point of tangency with the original line of the flank surface configuration – A_1. The difference between the areas for two geometric positions is the loss of area (weight). Next, the process is repeated for a new Δ and a new position of the O_2 center. This procedure is presented in more detail in **[14]**.

4 The relationship between technological processing parameters and the wear criterion in the mathematical model of weight loss

The relationship between technological processing parameters and the wear criterion formulated as weight loss is the most important factor that ensures the tool´s stability. This relationship consists, first of all, of the fact that the technological parameters – cutting speed, feed, and cutting depth – affect the nature and intensity of the force load in the cutting process and thermal heating in the contact.

It should be noted that the variety of composite materials and tools for their processing in many ways makes the task of researching the influence of technological parameters on the force magnitude factors so difficult that its solution requires private research in each specific case. Despite this, there are currently laws that describe the influence of processing parameters on the change in power factors of the process and, as a result, on the wear intensity of the cutting edge**.**

In the work, it is assumed that the general dependence between the tool wear, its working time, and technological parameters has

$$h_z(\tau) = K_h(s,v,t)\cdot\tau^n, \quad (1)$$

where $h_z(\tau)$ – wear on the flank surface, mm; τ – time, min.; s – feed, mm/rev; v – cutting speed, m/min.; t – cutting depth, mm; n is a constant.

The coefficient is most often taken in the form

$$K_h(s,v,t) = K_{h\tau}(\tau)\cdot s^{h_s}\cdot v^{h_v}\cdot t^{h_t}, \quad (2)$$

where h_s, h_v, h_t are constants, the coefficient is $K_{h\tau}(\tau) = K_{h\tau}$, i.e. in most cases, it is taken as constant.

This is a well-known artificial ratio in which the requirements of a direct physical sense are not fulfilled, that is, the dimension in the left and right parts is not observed. However, the use of this ratio is very common due to the ease of finding and because in logarithmic coordinates the dependence (1) has a linear form. By analogy with dependence (1), let's construct a dependence to determine weight loss $w(\tau)$

$$w(\tau) = K_w(s,v,t)\cdot\tau^m, \quad (3)$$

where *m* is a constant.

We will accept the coefficient in the form

$$K_w(s,v,t) = K_{w\tau}(\tau) \cdot s^{w_s} \cdot v^{w_v} \cdot t^{w_t},$$

where w_s, w_v, w_t are constants, $K_{w\tau}(\tau)$ is a coefficient, which in general is a function of time.
The introduction of relation (3) is a statement that the qualitative nature of the weight loss during wear and the linear size of the conventional amount of wear on the flank surface h_z is the same and differs only quantitatively.

5 Tool stability and blunting criterion in the mathematical model of wear assessment due to weight loss

The tool stability and the criteria for its blunting are inextricably linked factors, which are collectively determined by the level of the tool wear. The tool stability, which is understood as the time of work (cutting), after which the degree of wear is reached, is determined by the criterion of its stability. On the other hand, the tool stability criterion is determined or assigned by machining objectives, such as designated acceptable levels of cutting forces, surface quality, dimensional stability of the final part, or machining process performance.

Based on this, the main requirement that determines the amount of wear is the quality of the treated surface. The wear criterion is the technological factor. Therefore, the wear on the flank surface is taken as the criterion for blunting when mechanically cutting PCM products. At the same time, there are recommendations to take the average or maximum value of this value along the cutting edge as a wear criterion. The values of wear on the flank surface set by the norms differ in the standards of different countries and, as a rule, acquire values from 0.1 to 0.4 mm for the average value, and 0.4 to 0.6 mm when using the maximum value of the blunting criterion.

Values are assigned in each specific case and depend, first of all, on the type of processed material (reinforcement and binder), the type of reinforcement (weaving) and the content of the filler, the method of obtaining the processed material, the requirements for the quality of the workpiece final surface, the brand and type processing tool, initial tool geometric parameters and technological factors of processing (speed, feed, cutting depth).

The generalized equation of tool stability, which takes into account the influence of speed, feed and cutting depth on tool stability, in the vast majority of cases, engineers accept in the form

$$K_{tl} = v \cdot s^{k_s} \cdot t^{k_t} \cdot T^k, \quad (4)$$

where *T* – tool life, min; K_{tl}, k, k_s, k_t – constants.

Ratio (1) is a modification of the well-known empirical Taylor ratio, which is widely used in metal processing.

If we compare relations (1) and (4), we can see that (4) is a limiting case of relation (1), where a linear dependence of the wear on the flank surface on the processing speed is assumed. In this case, the relation (1) can be rewritten in the general form (1) taking into account (2)

$$[h_z] = K_{h\tau}(\tau) \cdot s^{h_s} \cdot v^{h_v} \cdot t^{h_t} \cdot T^n,$$

where $[h_z]$ – given value of the wear limit value on the flank surface, which corresponds to the value of stability *T*.

Then, by analogy with (2) and (3), for the weight loss blunting criterion, we obtain

$$[w] = K_{w\tau}(\tau) \cdot s^{w_s} \cdot v^{w_v} \cdot t^{w_t} \cdot T^n, \quad (5)$$

where [*w*] – the given value of the weight loss limit value, which corresponds to the stability value *T*.

6 Case Studies

To construct the generalized dependencies of the tool weight loss in the wear process and the relationship with wear on the flank surface, we will use the results of experimental studies presented in the paper [**15**].

This monograph presents the results of experimental studies of various glass plastics during turning in a wide range of processing parameters: *v* = 60 – 140 m/min; *s* = 0.075 – 0.51 mm/rev; *t* = 1 – 5 mm. In the course of the experiments, it was assumed that the amount of wear on the tool flank surface does not exceed 0.3 mm, which for most fiberglass provides a processing roughness of at least the 4th class.

Fiberglass turning was carried out with cutters made of VK3M alloy, the geometric parameters were taken as follows: rake angle γ = 10°; flank angle α = 25°; the main angle in plan φ = 45°; the additional angle in the plan φ_1 = 12°; the initial radius of the cutting edge rounding ρ = 0.75 mm. The lengths of the additional cutting edge *l* are equal to 0.5; 1; 3 and 5 mm.

Based on these results, a general relationship between tool wear on the flank surface, tool operating time, cutting speed, cutting depth and feed was established in the form of a power-law relationship (5). As a result of processing experimental data by the method of least squares, a regression equation of the form was obtained

$$h_z = 3{,}57695 \cdot 10^{-6} \cdot V^{2{,}036} \cdot s^{0{,}411} \cdot t^{0{,}556} \cdot \tau^{0{,}523}. \quad (6)$$

The regression equation was obtained using HomeSoftWear, significance $R2 = 0{,}995$, Fisher's test $F = 7645$.

A comparison calculating results of the wear amount on the flank rear surface and that calculated from the ratio (6) for the values of the processing technological parameters *s* = 0.21 mm/rev, *v* = 80 m/min, *t* = 1.5 mm, is presented in Fig. 5.

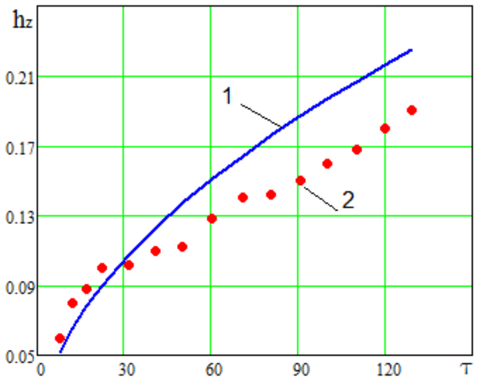

Fig.5. *Comparison calculating results of the wear amount on the cutter flank surface: calculated from (6) – 1; experimental data – 2.*

Let us construct for the data presented in Fig. 5 the dependence of the change in eccentricity Δ, the displacement of the conditional initial circle center on time, Fig. 4. To do this, we use the geometric model discussed in Section 3, Fig. 6.

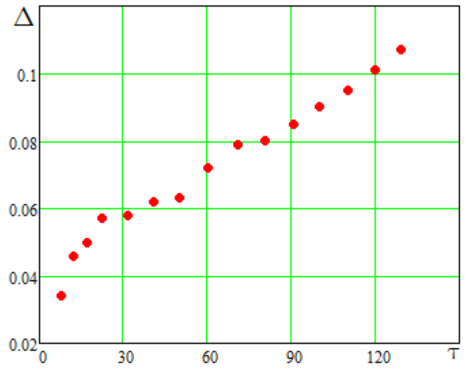

Fig.6. *Dependence of change in eccentricity Δ center displacement conditional initial circle.*

It is clear from the graph that the change Δ practically repeats the change in the experimental values shown in Fig. 5. Next, the dependence of the change in the cutter tip area *S* as a function of eccentricity Δ is presented in Fig. 7.

The latter circumstance allows us to assume that the loss of cutting edge area *S* and the conditional value of wear on the flank surface is linearly related, Fig. 8.

Thus, to represent the dependence of the material removal area S, you can use expression (6), which will be written in the form

$$S = S_w \cdot 10^{-6} \cdot V^{2{,}036} \cdot s^{0{,}411} \cdot t^{0{,}556} \cdot \tau^{0{,}523}.$$

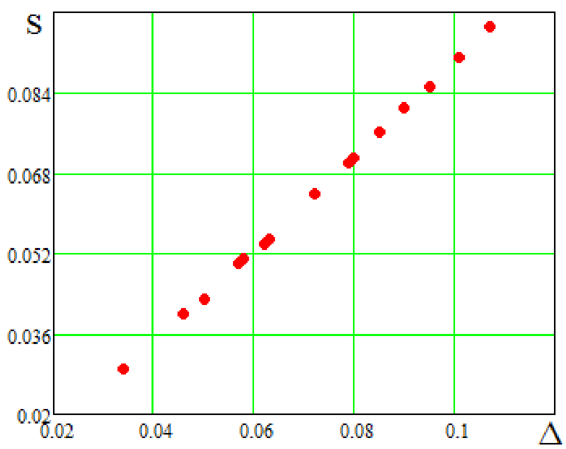

Fig.7. *Dependence of the change in the cutter tip area S as a function of eccentricity* Δ.

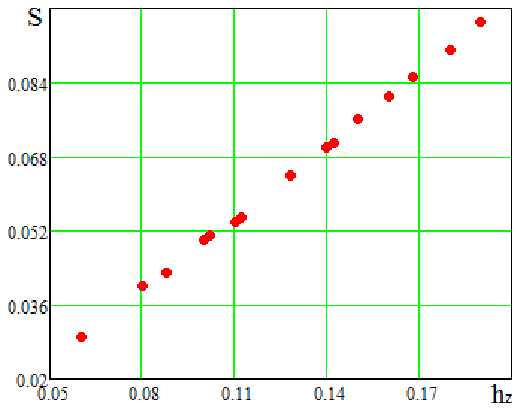

Fig.8. *The relationship between the decrease in the surface area of the cutter tip and the amount of conditional wear on the flank surface.*

This representation makes it possible to use all previously accumulated experimental data and empirical dependencies obtained for conditional wear on the flank surface and determine the amount of the removed area, and, consequently, the weight lost by the tool. On the other hand, experiments carried out to measure the weight of a worn tool after processing can make it possible to determine the value of conditional wear on the flank surface.

7 Conclusion

An approach to solving the problem of wear of tool cutting edges when processing polymer composites is proposed and formulated. As a criterion for dullness, a criterion for the loss of tool weight due to abrasive wear is proposed. Assuming that the rake angle of the tool tip does not change during operation, a geometric model has been constructed that makes it possible to relate the traditionally used conditional value of flank surface wear to changes in the area of the cutter tip. The geometric model is based on several simplifying assumptions that are physically observable during the wear process but do not have a strictly mathematical proof or experimental confirmation.

The ability to relate the change in cutter tip area (weight loss) to the traditional definition of flank wear allows us to adapt existing experimental data on measuring flank wear to the weight loss criterion and vice versa.

An assessment of the available experimental data on turning fiberglass plastics was carried out and a power-law dependence of the amount of wear on the flank surface on the processing parameters and operating time was constructed. It is concluded that there is a linear relationship between weight loss and the conditional value of flank surface wear when processing polymer composites.

The main and further direction of the research is the implementation of experimental work confirming or refuting the proposed methodology, which was interrupted due to objective circumstances. Further analysis of errors in predicting weight loss and calculating the amount of wear on the flank surface.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Gennadii KHAVIN: general idea, formal analysis, methodology and investigation.
Hou ZHIWEN: organized and executed the calculations, article administration and methodology.

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