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MODELING THE SHAPE OF TOOL WEAR DURING CUTTING OF THE COMPOSITE MATERIALS

The process of the shape changing for the tool cutting edge in relation to the initial state due to wear during cutting of polymer composite materials is considered. Modern experimental achievements in the study of the nature of changes in microgeometry in the process of wear are analyzed. Based on the analysis of experimental data, an assumption was made about a slight change in the initial rake angle and the rounding radius of the tool tip during wear. On this basis, a conclusion was made about the one-parameter nature of the change in the geometry of the tool cutting edge in the process of interaction with the composite. A model for removing the volume of material is proposed, which makes it possible to determine the total loss of weight of the tool during the cutting process. The relationship between flank wear, dimensional wear and change in tool weight is shown. A geometric model is used to determine weight loss. The proposed assumptions in the mathematical model are discussed. As a first approximation in the calculations, a simplified definition of the worn area near the tool tip is proposed. A generalized algorithm for step-by-step calculation of the tool tip geometry and the inverse problem of weight loss during operation are considered. As a law of wear, it is proposed to use a hereditary aging model that links volumetric wear with the physical characteristics of interacting bodies and technological processing parameters.

Keywords: cutting of composites, weight loss of the instrument, geometric model, microgeometry of the cutting edge, flank wear, mathematical model.

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МОДЕЛЮВАННЯ ФОРМИ ЗНОШУВАННЯ ІНСТРУМЕНТУ ПРИ РІЗАННІ КОМПОЗИЦІЙНИХ МАТЕРІАЛІВ

Розглянуто процес зміни форми ріжучої кромки інструменту по відношенню до початкового стану за рахунок зношування при різанні полімерних композиційних матеріалів. Проаналізовано сучасні експериментальні досягнення в дослідженні характеру зміни мікрогеометрії в процесі зношування. На основі аналізу експериментальних даних зроблено припущення про незначну зміну початкового переднього кута і радіуса округлення вершини інструменту в процесі зношування. На цій підставі зроблено висновок про однопараметричний характер зміни геометрії різальної крайки інструмента в процесі взаємодії з композитом. Запропоновано модель видалення обсягу матеріалу, що дозволяє визначити загальну втрату ваги інструменту в процесі різання. Показано взаємозв'язок зносу по задній поверхні, розмірного зносу і зміни ваги інструменту. Для визначення втрати ваги використовується геометрична модель. Обговорюються запропоновані допущення в математичній моделі. В якості першого наближення при проведенні обчислень запропоновано спрощене визначення зношеної площі біля вершини інструменту. Розглянуто узагальнений алгоритм покрокового обчислення геометрії вершини інструменту і зворотна задача втрати ваги за час роботи. В якості закону зношування запропоновано використовувати спадково-старіючу модель, яка пов'язує об'ємний знос з фізичними характеристиками взаємодіючих тіл і технологічними параметрами обробки.

Ключові слова: різання композитів, втрата ваги інструменту, геометрична модель, мікрогеометрія ріжучої кромки, знос по задній поверхні, математична модель.

Г. Л. ХАВИН

МОДЕЛИРОВАНИЕ ФОРМЫ ИЗНОСА ИНСТРУМЕНТА ПРИ РЕЗАНИИ КОМПОЗИЦИОННЫХ МАТЕРИАЛОВ

Рассмотрен процесс изменения формы режущей кромки инструмента по отношению к первоначальному состоянию за счет изнашивания при резании полимерных композиционных материалов. Проанализированы современные экспериментальные достижения в исследовании характера изменения микрогеометрии в процессе изнашивания. На основе анализа экспериментальных данных сделано предположение о незначительном изменении первоначального переднего угла и радиуса округления вершины инструмента в процессе изнашивания. На этом основании сделан вывод об однопараметрическом характере изменения геометрии режущей кромки инструмента в процессе взаимодействия с композитом. Предложена модель удаления объема материала, позволяющая определить общую потерю веса инструмента в процессе резания. Показана взаимосвязь износа по задней поверхности, размерного износа и изменения веса инструмента. Для определения потери веса используется геометрическая модель. Обсуждаются предложенные допущения в математической модели. В качестве первого приближения при проведении вычислений предложено упрощенное определение изношенной площади около вершины инструмента. Рассмотрен обобщенный алгоритм пошагового вычисления геометрии вершины инструмента и обратная задача потери веса за время работы. В качестве закона изнашивания предложено использовать наследственно-стареющую модель, связывающую объемный износ с физическими характеристиками взаимодействующих тел и технологическими параметрами обработки.

Ключевые слова: резание композитов, потеря веса инструмента, геометрическая модель, микрогеометрия режущей кромки, износ по задней поверхности, математическая модель.

Introduction. Formulation of the problem. One of the distinctive features of the mechanical processing of polymer composite materials (FRP) reinforced with glass or carbon fibers is the intense wear of the tool cutting part. Observations have shown that the physical nature of wear is completely different from tool wear in metal processing. This is a consequence of the high abrasive properties of the filler material and the heterogeneity of the FRP structure.

Numerous experimental studies are devoted to the description of the wear process during mechanical processing of FRPs, which made it possible to formulate several basic statements and principles describing the process of tool wear during processing of polymer composites. These include:

- dominant in most cases is abrasive wear, which intensifies with the appearance in the cutting zone of surfactants arising from the destruction of the polymer binder;
- the general view of the curve of the wear

parameters dependence on the operating time of the tool has two stages – intensive wear at the initial moment of operation (running-in) and the stationary wear period (normal wear), and, as a rule, the period of catastrophic wear is absent, Fig. 1;

- occur the geometry of the cutting edge is change unusually because there is a slight wear on the front surface of the tool, while the main quantitative wear occurs along the flank surface, which is a consequence of the contact interaction of the processed material and the rear surface of the tool;
- physical wear of the cutting edge (removal of tool material), occurs according to the actual area of contact on the flank surface, and only partially due to rounding of the cutting edge.

The initial geometry of the tool cutting edge already during the running-in period (Fig. 1) changes sharply and by the beginning of stationary wear it acquires a certain shape, which subsequently changes slightly without distorting the stable running-in shape. It can be concluded that the initial geometry of the cutting edge, chosen from rational considerations or as a result of solving the optimization problem, serves only for efficient cutting during the running-in period, after which its effect on the further tool operation under stationary wear conditions is not significant.

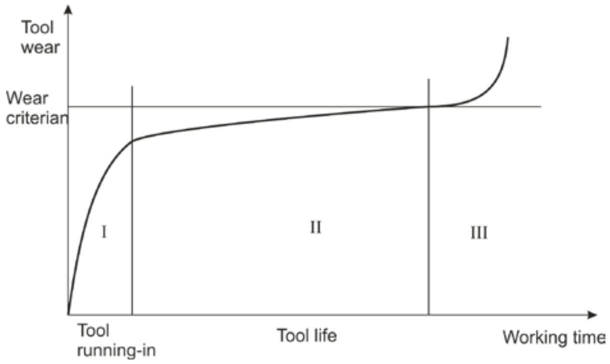

Fig. 1. Stages of tool tip wear:
I – running-in; II – stationary wear; III – accelerated or catastrophic wear

Analysis of achievements and publications on the problem. Researchers were firstly interested in the issue of predicting tool wear from the point of view of deterioration in the quality of product processing, i. e. how long the tool can be used under the given operating conditions. In continuous contact with sliding between a rigid tool and an anisotropic material, there is a constant change in such factors of the cutting process as contact load, temperature, coefficient of friction, which does not allow us to unambiguously formulate the regularities of the tool wear process and predict its durability. However, attempts to formulate empirical patterns have taken place and are used for assessment at the present time [1, 2].

It should be noted that to create empirical models for predicting the wear process, it is necessary to carry out a huge number of laborious and expensive experiments [3, 4], numerous numerical calculations by the finite element method (FEM). Moreover, the greatest difficulty is caused not by the description of the FRP material removal process itself, but by a reliable description of the tool wear [4, 5]. Experimental works [6–8] presented a fairly reliable and clear picture of tool wear due to a change in the shape of the cutting edge, as well as a change in the microgeometry of the cutting edge during orthogonal cutting.

Purpose of work. Construction of a mathematical model for predicting changes in the geometry of the tool tip based on the formulation regularities of the relationship between the loss of tool weight and linear wear along the flank surface.

Main part. The main idea of the research is as follows. One of the most effective, simple and accurate methods for determining tool wear is weighing it before and after the operation. The resulting absolute loss of weight by the tool falls on the cutting edges, which, in the process of contact interaction, change their shape due to the removal of material under conditions of force loading and thermal heating. It is known that, when processing FRP, the wear on the flank surface is taken as the main criterion for tool wear. This is due to the specific structure of the composite material and the nature of fracture in contact with the tool. Thus, having a reliable analytical apparatus predicting the shape and nature of the change in the geometry of the tool cutting edges and the value of the loss of weight by these edges, one can try to determine the distribution of the lost weight over the geometric shape of the tool and, most importantly, over the back surface of the tool. In other words, the task is to relate the loss of tool weight during cutting with a linear change in the amount of wear along the flank of the tool.

Analysis of the available experimental studies [4–8] made it possible to draw a number of qualitative conclusions on the physical essence of the process, which takes place during tool wear. First of all, there is an almost identical change in the initial shape of the cutting edge, Fig. 2. This form of wear is typical for intensive material removal along the flank of the tool and practically no wear on the rake surface.

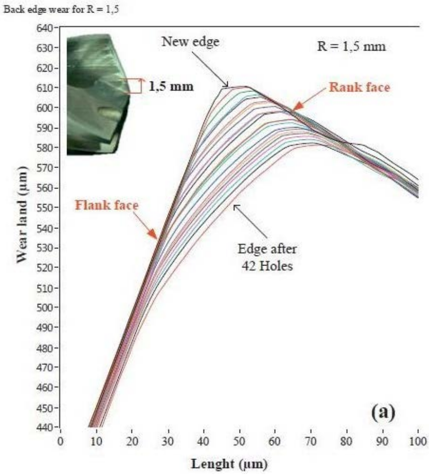

Fig. 2. Change in flank edge wear depending on the number of holes [6]

Various authors have proposed micro-level models describing tool tip wear as a major value to overall tool wear. Analysis of these studies of cutting edge wear showed that there is a strong correlation between the appearance of wear, an increase in force loading, temperature stress, and the appearance of various defects in the machined surface [4].

Monitoring the cutting process, in fact, as the process of fracture material, the magnitude of the cutting force, the temperature of the tool and workpiece, makes it possible to analyze the wear and predict the service life of the tool [6]. However, it is extremely difficult to trace this interaction of the tool with the workpiece in the contact zone. Therefore, various predictive theories have been proposed, confirmed or refuted by numerous experiments. Expensive and laborious experimental studies are required to describe accurate models.

Quantification of wear is important in practice for determining the tool life criterion and designing the technological process as a whole. Wear can be measured directly on the cutting tool or a copy thereof, or assessed indirectly by measuring secondary factors, such as cutting forces and power, and, from their values, infer the degree of tool wear. The most common way to directly measure tool wear is by measuring the width of the wear pad. This value is denoted in Fig. 3 as V_b in the English-language literature or denoted as l_z in the domestic one. The shape of the worn cutting edge during FRP processing is curved (Fig. 2) and the rake and flank wear surfaces are curved. Therefore, their measurement with an optical microscope can have large deviations. Fig. 3 shows a highly distorted cutting edge profile as a result of operation. For a quantitative assessment of wear, various geometric features of this profile were taken into account [9].

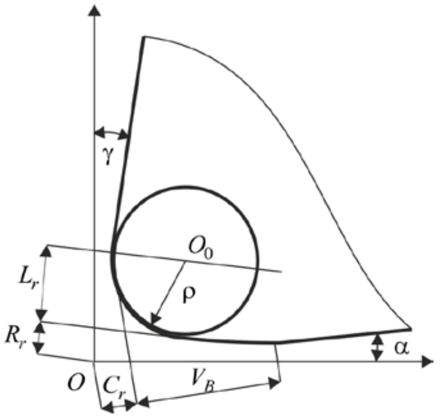

Fig. 3. The profile of the worn cutting edge and the values of various measurements [10]

Most often, the following values are referred to as parameters of various models, Fig. 3 [10]: R_r or R_d – rake recession or rake deflection, which describes the retraction of the front most point of the profile in a direction parallel to the rake, reduction of the gap; C_r or F_d – flank recession or flank deflection, which describes the retraction of the cutting edge parallel to the flank, the wear surface of the leading edge; L_r or R_{ws} – rake wear land or rake wear surface.

Based on experimental studies, mainly on orthogonal cutting of carbon fiber reinforced plastic, a number of qualitative conclusions and statements were made on the physical nature of the tool cutting edge wear. So in [4] it was confirmed that the wear of the cutting edge (rounding) is asymmetric, the magnitude and intensity of which is, first of all, a function of the tool original geometry (initial sharpening) and the reinforcement orientation.

This circumstance made it possible to make the assumption that in the process of wear, the initial tip of the sharpened tool shifts along its rake, as shown in Fig. 4. It was also assumed that during the wear process, the initial radius of the tool tip does not change, but rather moves. Then, in the plane of the tool tip, as shown in Fig. 4, you can calculate the change in area and, taking, for example, a constant width of the cutting tool; find the weight loss over a certain period of time.

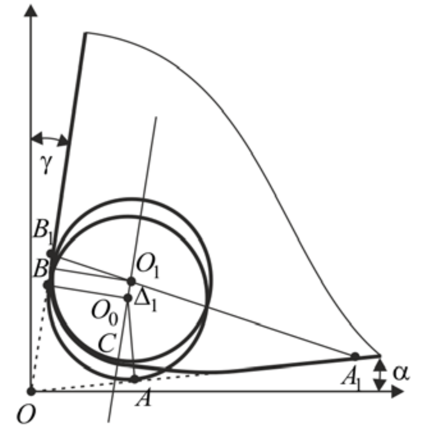

Fig. 4. Geometric model of a worn profile

In other words, taking the designations in Fig. 4, we can write down that the weight loss during the work will be equal to

$$w_i \cdot \rho = (S_i - S_0) \cdot b \cdot \rho ,$$

where is w – the change in the conditional volume of the worn out material of the tool (Fig. 2), kg; S_i, S_0 – the area of the conditional surface of the tool tip after work during the time t_i and the initial conditional area of the not worn tip (Fig. 4), m^2; b – the width of the cutting edge, which in the general case is a variable from the Z coordinate perpendicular to the plane of the drawing in Fig. 2, and which, without much damage to the generality of reasoning, is still assumed to be a constant value, m; ρ – material density, kg/m^3. Thus, the problem of determining the weight loss was reduced to calculating the area of change in the shape of the cutting tool tip during its operation.

On the other hand, the inverse problem is of great practical value, when, according to the value of the weight loss, it is necessary to establish a change in the cutting edge geometry and, first of all, a change in the position of the flank cutting edge (wear along the flank of the tool).

For the numerical determination of areas $S_0, S_1, S_2, \ldots, S_i$ by integration, it is necessary to have an analytical expression for the curve describing the position of the worn surface at any time. Even having experimental data on the type of flank wear [1–5], it can be seen that it is impossible to describe such a curve by one analytical function.

Consider the calculation of the areas S_0, S_1, S_2, …, S_i, where S_0 is the initial area formed by the intersection of the initial position of the rake and flank surfaces (α – the flank angle of inclination of the cutting edge; γ – the angle of inclination of the rake cutting edge) and the radius of rounding ρ, which are considered given.

The area S_0 can be calculated as the difference between the area of the quadrilateral OAO_0B and the sector of the tool top O_0AB. Initial angle at the tip of the tool is $\varphi = \pi/2 - \alpha - \gamma$. Then the area of the quadrangle O_0AB is equal to $\rho^2 \cdot \mathrm{ctg}(\varphi/2)$. The area of the O_0AB sector is equal to $\pi \cdot \rho^2 \cdot (180 - \varphi)/360$. Thus, the area $S_0 = \rho^2 \cdot \mathrm{ctg}(\varphi/2) - \pi \cdot \rho^2 \cdot (180 - \varphi)/360$.

Then, for some time t_1, the center of the circle of radius ρ moved by an amount Δ_1 along a straight line OO_1 parallel to the initial position of the rake surface, Fig. 4. The area S_1 corresponding to the worn part of the tool tip is necessary to calculate.

To do this, draw a straight line through the center point of the circle O_1 of radius p at an angle $\pi/2 - \gamma$ until it intersects with the original line of the tool flank– point A_1 and intersects with the original line of the tool rake – point B_1. The amount of the tool worn part can be calculated as the difference between the areas of the triangle OA_1B_1 and the initial area S_0.

The area of the triangle OA_1B_1 can be calculated from the known values of its vertices coordinates. Points A_1 and B_1 are defined as points of intersection of straight line A_1B_1 passing through O_1 at an angle $\pi/2 - \gamma$. Then the area of the tool tip worn (removed part) is calculated as the difference between the areas $S_1 = \Delta OA_1B_1 - \Delta CA_1O_1 - S_{sekt} - S_0$, where S_{sekt} is the area of the CO_1B_1 sector, equal to $(90 + \gamma)/180 \cdot p^2$.

Thus, taking into account the proposed assumptions in the model, it is possible to relate the value Δ_1 of the circle center displacement, which simulates the initial radius of cutting edge curvature, with a change in the geometry of the tool tip. The value Δ_1 is included in the geometric calculations of the change in the area of the tool tip through the coordinates of the point O_1 of the circle center position after a certain time of the tool operation Δt_i. This position can be defined using Δ_1 as a shift of the original circle centered at point O along a straight line parallel to the straight line that describes the rake edge of the tool and passes through the point center O at an angle $\pi/2 - \gamma$.

It is known from the experience of FRP processing that the wear of the tool tip has a pronounced nonlinear character. It is characterized by the presence of a enough short running-in stage of the tool, which is accompanied by intense wear, i.e. intensive change in the geometric shape of the top. After this period, the wear rate decreases and stabilizes. As a rule, the period of catastrophic tool wear is absent, as when processing FRP, the technological wear criterion is used, associated with the deterioration of the processed surface quality, up to the appearance of burns. Further, the wear criteria V_b or l_z can be easily determined from the geometric constructions in Fig. 4, if the amount of weight loss (actual value Δ_1) is known. When solving practical problems, the amount of wear along the back plate $V_b > 0{,}3$ mm is considered unacceptable because during processing appears delamination, material loosening and the quality of processing deteriorates sharply. In most cases, each material has its own recommendations for the V_b value, which determines the tool life.

So, we can formulate two main tasks:

- for a given weight loss during operation t_i, determine the change in the tool tip shape and V_b;
- for a given tool shape and V_b, determine the weight loss during operation t_i.

Both formulations of the problem are non-linear, since the physical dependence of wear is characterized by a running-in stage with a high wear rate. To solve such problems, a step-by-step algorithm is used, when the tool operation time (or weight loss) is divided into work intervals with some small step and the problem is solved at each step. The amount of wear and shape change are cumulative.

However, at each step, there is a change not only in the geometric parameters of the tool, but also in the physical quantities characterizing the machining process - cutting forces, temperature, etc. Thus, it is necessary to have a law of wear that connects these values not only with the technological parameters of processing, but also with the end result of the wear process, namely, weight loss.

For a complete analytical presentation of the problem, it is necessary to be guided by the law of abrasive wear, which is proposed in the form of the change rate in the volume of the tool tip material over time (the density is considered constant). As a law of wear, it is proposed to use a hereditarily aging model of the form [11]:

$$\frac{dv(t)}{dt} = K_{wear} \cdot \frac{\mu \cdot F_n}{\left[\tau_{sh}\right]} \cdot \frac{HV_{fill}}{HV_{tool}} \cdot V \cdot e^{-\frac{Q}{R \cdot T}},$$

where dv/dt – the rate of removal the volume of the tool tip material, m^3/s; F_n is the normal component of the cutting force in contact (can be determined experimentally), N; μ – coefficient of friction in contact; $[\tau_{sh}]$ – permissible shear stress of the filler material, N/m^2; HV_{fill}, HV_{tool} – hardness of the filler (reinforcing element) and the cutting tool material, N/m^2; V – relative sliding speed (tool tip movement), m/s; Q – activation energy, J/mol; R – universal gas constant, J/(mol·°C); T – temperature in the cutting zone, K; t – time, s; K_{wear} – the coefficient of volumetric wear, which determines the shape and intensity of the tool surface wear over time.

In the presented relationship, preference is given directly to the parameter of time, and not to some other parameter, for example, the number of holes drilled. This is a more general approach as it takes into account directly the operating time of the instrument, regardless of the operation type and the quantitative equivalent of each operation that it performs.

Thus, the geometric model in combination with the wear law used in the step-by-step algorithm ensures the full realization of the formulated goal of this work, and their practical implementation is the subject of further research.

Conclusions. The change in the geometry of the tool due to wear is represented by a simple one-parameter geometric model, which makes it possible to estimate the distortion of the cutting edge shape along the flank of the tool. Weight loss during cutting is used as the main criterion for measuring tool wear. The creation of such a mathematical model is based on the use of an adequate wear law, which together constitutes a closed system. It is accepted that the law of wear is hereditary and there is a linear dependence of the wear rate on the rate of contact interaction and contact pressure. A step-by-step algorithm for the numerical implementation of the formulated problem is considered. Without measuring the current wear and recalculation in mathematical models with significant difficulties, a simple method based on a geometric model is proposed. This will allow for simple technical control of cutting edge wear and predicting tool life.

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