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DETERMINATION OF THE COEFFICIENT SLIDING FRICTION VALUE IN THE CONTACT THE CUTTING TOOL-COMPOSITE

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Keywords: friction coefficient, abrasive wear, filler content, reinforcement direction, tool wear.

Introduction. The problem formulation. One of the characteristic features mechanical processing polymer composite materials (PCM) is the intense wear of the tool cutting edge. This fact is primarily the result of a physical, chemical and thermo mechanical phenomena combination in the process of cutting the composite. At the same time, in its appearance, wear is a pronounced abrasive nature. In the process of interaction the zone of transition from the rake to the flank surface of the tool cutting edge its intensive wear occurs (the tool tip material removal). In fact, there is continuous contact with sliding between the high strength tool tip with an inhomogeneous material that is significantly inferior in its strength characteristics, but has high abrasive properties.

This circumstance leads to deterioration in the product processing quality and the replacement or tool regrind. Numerous theoretical, experimental and numerical studies were devoted to the study of the abrasive wear problem, in which the issues of predicting tool wear were considered.

Like any physical process, wear in the contact of the tool tip-PCM must obey a certain law (wear law), which describes the removal of material in time and makes it possible to predict the tool's performance (durability or tool life). Numerous theoretical and experimental studies show that the wear rate depends on various factors in the process of interaction. These include the interacting body’s materials physicochemical properties, surfaces roughness, the presence of lubricant, the load-speed regime, the temperature and composition of the environment, etc. All these factors, to one degree or another, must be taken into account in the wear law. One of the variants in the form of a hereditary aging model is presented in [1].

According to the proposed formulation it is assumed that wear is abrasive, i.e. the harder material is removed by cutting or splitting another less hard material. For the abrasive wear law is proposed relation for the change (removal) rate the tool tip material volume in time (the density is considered constant) in the form

$$\frac{dv(t)}{dt} = K_{wear} \cdot \frac{\mu \cdot F_n}{[\tau_{sh}]} \cdot \frac{HV_{fill}}{HV_{tool}} \cdot V \cdot e^{-\frac{Q}{R \cdot T}}, \quad (1)$$

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

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

Taking into account such a physical effect as friction and determining the friction coefficients in mathematical models of contact interaction composites with the tool material differs most significantly from the determination of friction coefficients in the processing of the homogeneous materials. The structure heterogeneity and the anisotropy of the composites properties make it impossible to apply the classical contact theory. The friction coefficient, in addition to the juvenile contact surface, is also determined by the presence of destruction products of the binder and filler in contact at a sufficiently high temperature. As a result, the contact interaction occurs through the existing elastic-porous or viscoelastic layer due to the molten binder.

A contact interaction model construction, undertaken for example in [2], between bodies, one of which is a composite, allowed us to conclude that the friction coefficient mainly affects the size of the contact spot. However, most studies do not answer the main question – what is this value and how it changes in the process of contact interaction (product processing).

In the present work, it is assumed that the value of the friction coefficient depends on the following factors. First of all, the filler orientation in the composite and its total amount, as well as the magnitude of the contact pressure, the mutual slip rate and the temperature in the contact interaction area. The study of the nature and magnitude of the friction coefficient in the contact tool-cut layer is a separate and extremely difficult task.

State of the art and publications of the problem. When constructing real mathematical models of PCM cutting processing, it is impossible to do without taking into account the physical friction factor and determining the friction coefficients. The heterogeneity of the PCM structure and the anisotropy properties make it impossible to apply the classical contact theory and use the Coulomb-Amonton relationship.

The traditional approach to determining the friction coefficient is to assign it equal to some constant empirical quantity, which is recommended to be calculated from experiments. However, the experimental studies described below have shown that the friction coefficient is not a constant value and depends on many factors.

In fact, we can say that the first proven numerical values for the friction coefficient were obtained on the basis of the experiments processing in [3]. Three types of composite materials were considered: unidirectional carbon fiber with 60% filler content; Kevlar-49 / Epoxy with 65% content of reinforcing elements and two-dimensional fiberglass reinforced with microfiber. The friction coefficient was measured for unidirectional carbon fiber with four directions of composite reinforcement: $\theta = 0, 30, 45$ and 90°, Fig.1.

The presented results showed an increase in the friction coefficient of more than 2.5 times for the normal orientation of the fibers, which the authors refer to as $\theta = 0°$, compared with the longitudinal $\theta = 90$ °. On the other hand, the experimental studies shown in [6] show an inverse relationship when the coefficient of friction increased from $\mu = 0.3$ at $\theta = 0°$ to $\mu = 0.88$ at $\theta = 90$ °.

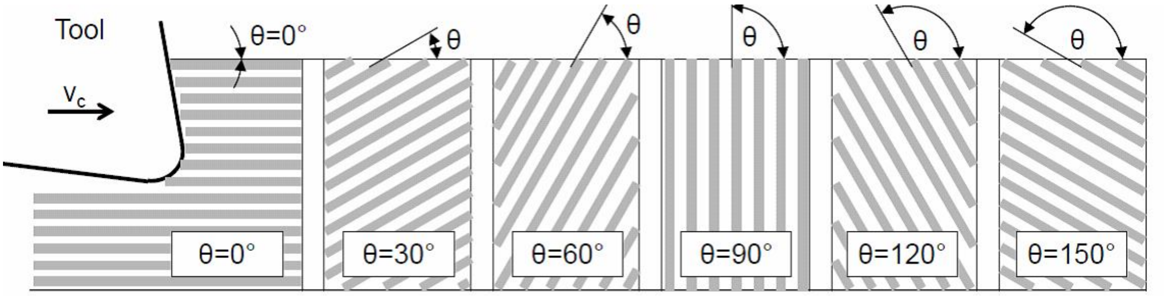

Figure 1 – Determination of the reinforcing fibers orientation in accordance with [4,5] adopted in this article

On the one hand, this contrast is explained by the fact that, in principle, with all the quality of the use of laboratory tribometers, their interaction conditions do not reflect the contact conditions during processing and do not use juvenile, just generated surfaces typical for continuous processing [7, 8]. On the other hand [5], it was concluded that experiments to determine the friction coefficient [6] carried out on a pin-on-disk setup with variable orientation of PCM fibers sliding on high-speed steel (HSS) under a normal load of 120 N provides more accurate modeling than presented in work [3] modeling on the device "pin on a ring" for different orientation of graphite-epoxy fiberglass fibers on steel. The author believes that in [3] and [6] the opposite definition of the fibers orientation relative to the sliding direction is used. If this discrepancy is corrected, then the friction coefficient will increase from $\mu = 0.3$ at $\theta = 0°$ (longitudinal) to $\mu = 0.88$ at $\theta = 90°$ (normal), which means that the normal orientation of the fiber relative to the sliding surface has more high frictional resistance.

The cutting force in macromechanical parameters [6] is in good agreement, but the axial force has a significant discrepancy compared to the measured one. In fact, we can say that the existing methods of determining the friction coefficient on closed tribometers such as "pin on disk" or "pin on ring" do not quite accurately simulate the conditions of continuous sliding contact typical for machining with continuous removal of material by the tool.

In [9], using an analytical solution in a closed form for an anisotropic half-plane, the contact characteristics of unidirectional reinforced continuous composites are investigated when interacting with a rigid parabolic stamp. The influence of the PCM material, friction coefficient, fiber material, fiber orientation and volume fraction on the surface contact pressure is considered. The results obtained are evaluated by comparison with experimental data and the results of the finite element method. Based on the analytical results, several important trends in the change in the contact wear characteristics of reinforced plastics are explained and discussed. It was concluded that the friction coefficient of composites has little effect on the contact pressure for different fiber orientations. The value of the friction coefficient has a really significant effect on the symmetry of the contact patch, except for the orientation $\theta = 0°$.

On the other hand, experimental work [10] on the woven epoxy glass wear and carbon fiber reinforced plastics in the normal load range of 20-80 N and speeds of 2–5 m/s showed that the samples weight loss and friction coefficient significantly increase with increasing load and tends to a slight decrease with increasing slip rate for both materials. It was concluded that, in general, CFRP has a lower friction coefficient than fiberglass, which has material characteristics that contribute to frictional properties. At the same time, the wear during sliding of woven CFRPs is significantly superior to that of fiberglass.

Separately, there are experimental studies devoted to the determination of the friction coefficient between glass or carbon fiber and diamond tools in real cutting conditions [11–13]. Here we can only talk about the values of the friction coefficient exclusively in special cases. For example, in [11], data are presented for the friction coefficient, which varies for lubrication conditions during the interaction of single crystal diamond and carbon fiber reinforced plastic, depending on different contact pressures and interaction rates. The data on the friction coefficient between single-crystal diamond and CFRP are presented depending on different contact pressures, sliding speeds (20 m/min and 40 m / min), the CFRP layer orientation, and the use of a cutting fluid is considered. Experimental friction coefficients for CFRP-diamond are significantly less than any other value reported in the literature and range from 0.08 to 0.12 for dry and 0.06 to 0.07 for lubrication conditions. Due to the CFRP shape probe (sheet material) and the absence of unidirectional material, the effect of fiber orientation was not analyzed.

In [12], the temperature effect on the friction coefficient between epoxy carbon fiber and single-crystal diamond at low sliding speeds is considered. The authors obtained values for the friction coefficients $\mu = 0.125$ for a fiber orientation of 0° and $\mu = 0.175$ for a normal orientation of 90°. With increasing temperature, the friction coefficient increases to $\mu = 0.4$ at 125 °C and decreases sharply when the glass transition temperature is exceeded due to changes in the epoxy resin properties.

On the other hand, [13] analyzes the effect of very high sliding speeds (up to 800 m/min) on the friction coefficient between polycrystalline diamond (PCD) and arbitrarily structured CFRP. Values are given from $\mu = 0.05$ to $\mu = 0.08$ or less, which is lower than those obtained between single-crystal diamond and carbon fiber reinforced plastic in [11]. Note that different CFRP materials have been tested. For high speeds (> 100 m/min), the effect of sliding speed on the friction coefficient is small.

Objective. To develop a theoretical model for determining the friction coefficient, which makes it possible to take into account the composite fibers orientation, the fibers total content , the contact pressure magnitude, the temperature in the contact zone, the contact interaction rate, etc. The main goal is to propose and show the feasibility of using the proposed mathematical model for calculating the friction coefficient in relation (1).

The main part. The available experimental literature data are extremely scanty and the overwhelming majorities are devoted to the study of the influence of any one material factor on the value of the friction coefficient, for example, the fibers orientation in unidirectional epoxy carbon composite [6]. At the same time, such a factor as the filler volumetric content and its properties were not considered. On the other hand, experimental data for an epoxy composite with 60% volumetric filler content are presented in [3]. In the majority of numerical studies by the finite element method (FEM) [14, 15], a constant value of the friction coefficient of 0.2 or 0.3 is used, which is in no way justified.

In almost all experimental studies and FEM numerical calculations, the conditions under which the data on the friction coefficient were obtained were limited. These conditions were quite different from the real ones, and when processing the results, traditional simplifications of the type were accepted:

- the material of the composite is anisotropic, but locally homogeneous;
- the cutting tool is considered to be absolutely solid and does not experience deformations;
- the process is considered as quasi-static, whence the analysis of its modeling follows;

- the effect of heat generation during processing simulation is not taken into account (since it is considered that the cutting speed is limited to a small value);
- the effect of discrete contact between the flank of the tool cutting edge and the cut material on the friction coefficient is not taken into account.

In [6], the results in the value of the friction coefficient change depending on the fibers orientation are presented, Fig. 2. The general orientation in the range of fiber tilt angles from 0 to 90° has a character close to linear.

It is proposed to take the following priority of the various factors influence the friction coefficient value: fiber orientation, total fiber content, temperature in the contact zone, and interaction speed. At the first stage, it is proposed to calculate the friction coefficient from the ratio

$$\mu=\left(k_{\mu}\cdot\theta/\theta_{90}+\mu_0\right)\cdot K_{vr}, \tag{2}$$

where θ – angle of reinforcing elements inclination ($\theta=0$) – longitudinal reinforcement, $\theta_{90}=90$ – normal reinforcement, degree, but not more 90 in absolute terms); k_{μ} – constant coefficient determined from experimentation or experiences; K_{vr} – coefficient taking into account the effect of the reinforcing elements volumetric content in the composite on the friction coefficient; μ_0 – accepted initial value of the friction coefficient for conditions of longitudinal reinforcement ($\theta=0$). For reinforcement at $\theta>90$, relation (2) will be written in the form $\mu=\left(k_{\mu}\cdot(180-\theta)/\theta_{90}+\mu_0\right)\cdot K_{vr}$.

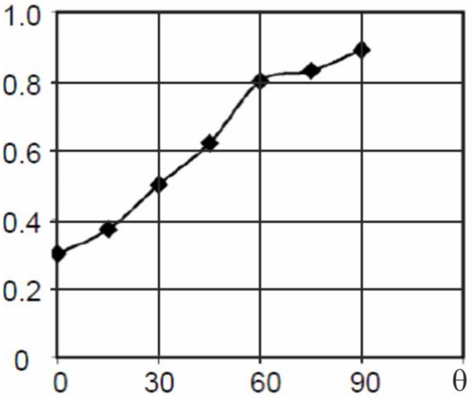

Figure 2 – Dependence of the friction coefficient on the reinforcement angle θ for epoxy fiberglass with 65 % volumetric fiber content [6]

From general considerations, it can be assumed that the friction coefficient will be influenced not only by the laying direction the reinforcing elements, but also by their volumetric content. However, there is no systematic information on this, as well as reliable experimental data. It is logical to assume a certain linear nature of this dependence with a qualitative characteristic of the type, the more fibers in contact, the stronger the effect of the filler. For example, for normal reinforcement, it can be assumed that at 60 % reinforcing fibers, the number of tool contacts will be twice as large as at 30 % reinforcement. However, this is most likely not the case, since destruction products are involved in the interaction process, and the reinforcing elements are not cut at the same height.

The coefficient taking into account the effect of the reinforcing elements volumetric content in the composite on the friction coefficient is proposed to be taken in the form

$$K_{vr} = \mu_{x\%} / \mu_{n\%} ,$$

where $\mu_{x\%}, \mu_{n\%}$ – the friction coefficient for composite with the reinforcing elements volumetric content is *x*% and *n*%, calculated using the law of mixing; $\mu_{n\%}$ – normalizing friction coefficient, with the filler volumetric content for which there are data on the dependence of the friction coefficient on the reinforcement angle θ°. In other words, if we have data on the dependence of the friction coefficient on the reinforcement angle for certain filler content, then the friction coefficient value for this content will be normalizing.

Therefore, to take into account the influence of this factor when calculating friction coefficient, considering the reinforcing elements effect of the volumetric content, it was proposed to use the mixing law in the form [16]

$$\mu_{x\%} = (V_r / \mu_r + V_b / \mu_b)^{-1} , \tag{3}$$

where V_r, V_b – the reinforcing elements and binder volumetric content, and $V_r + V_b = 1$; μ_r, μ_b – friction coefficients of steel on the reinforcing element and binder material.

Then coefficient K_{vr} taking into accounts the influence of the reinforcing elements volumetric content in the composite on the friction coefficient is can be represented, for example, for glass fiber 60% content in epoxy plastic as follows. Let us take the sliding friction coefficient of steel on glass $\mu_r = 0{,}12 - 0{,}14$ and friction coefficient of steel on epoxy resin $\mu_b = 0{,}5$ [17], then $\mu_{60\%}$ = 0.197, for 30% glass fiber content $\mu_{30\%}$ = 0.282, then $K_{vr} = \mu_{30\%} / \mu_{60\%}$ = 1.435.

The dependence on the interaction speed is extremely difficult to assess. However, the information given in experimental studies [10] shows that a significant change in the friction coefficient takes place either at very low or at very high processing speeds. Therefore, we will assume that the presented ratio is still valid in a certain average range of speeds, in which there is no significant change in the value of the friction coefficient from the interaction speed.

As indicated in [5], the friction coefficient sharply decreases when the temperature in the fracture site is exceeded, the glass transition temperature of the binder, in particular, epoxy resin. It is assumed that the processing is carried out in the range of feeds and other technological parameters that ensure the contact temperature is below the glass transition temperature and there is no significant change in the friction coefficient value due to the temperature effect.

Case study. Let's calculate the coefficients in the formula (2) using the data presented in the work [6]. First, let us determine the volumetric content of reinforcing elements in the material for which the experimental data are obtained in Fig. 2. The modulus of elasticity along the fibers from [6] fiberglass is E_c = 48 GPa, E_f = 72.5 GPa is the reinforcing glass fibers modulus of elasticity, E_m = 3.1 GPa is the epoxy binder modulus of elasticity. According to the law of mixtures, the fiberglass modulus of elasticity

$$E_c = E_f \cdot V_f + E_m \cdot V_m,$$

substituting the values of the terms, we obtain $V_f = 0{,}65$ and $V_m = 0{,}35$.

Linear regression of the data in Fig.2 gives: $\mu_\theta = 0{,}645 \cdot \theta / 90 + 0{,}295 = 0{,}725$ and for the reinforced angle $\theta = 60^\circ$, the volumetric content of reinforcing elements 65 %, $K_{vr} = 1{,}051$, then μ = 0,762. Using formulas (2) and (3), for example, for CFRP with 45 % reinforcing elements and fiber orientation $\theta = 45^\circ$ will get $K_w = 1{,}238$, μ = 0,617×1,238 = 0,764. Thus, it can be assumed that CFRP with a reinforcing component of 65 % and a reinforcement angle of 60° will have approximately the same friction coefficient with CFRP with a reinforcing component of 45% and a reinforcement angle of 45°.

Conclusion. An attempt to leave the contact interaction calculation of a tool and a composite material from the traditional consideration of the friction coefficient as a constant value, the value of which is often given without any reason is considered. It is proposed through this value to take into account the volumetric content and the inclination angle of the reinforcing elements when considering the contact interaction of the tool tip and the unidirectional composite in time (wear law). The ratio is based on the use of limited experimental information provided by various authors. The model does not take into account the effect of contact pressure, mutual sliding velocity and temperature on the value of the friction coefficient, which will be the subject of further research in this direction.

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ВИЗНАЧЕННЯ ВЕЛИЧИНИ КОЕФІЦІЄНТУ ТЕРТЯ КОВЗАННЯ В КОНТАКТІ РІЖУЧИЙ ІНСТРУМЕНТ-КОМПОЗИТ

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Однією з найважливіших характеристик при розрахунку зносу ріжучого інструменту при контактній взаємодії при обробці композиту, є коефіцієнт тертя. У більшості розрахунків, у тому числі і методом скінчених елементів, коефіцієнт тертя зазвичай задається як постійна величина, значення якої часто приймається з досвіду без жодної підстави. Однак при механічній обробці армованих композитів є дуже багато факторів механічного і технологічного характеру, які дуже сильно впливають на величину коефіцієнта тертя. Цей вплив пов'язаний не лише з початковою неоднорідністю композиту, а й постійною фактичною зміною умов контакту у часі, що викликано зносом різальної частини інструмента. Значення величини коефіцієнта тертя в реальних умовах контактної взаємодії має дуже складний фізичний вміст через присутність в контакті продуктів руйнування волокон і сполучного, часткового розплавлення сполучного при температурі контакту, присутності нерівномірно зрізаних волокон.

У цій статті представлено формулювання, що дозволяє розраховувати величину коефіцієнта тертя в залежності від об'ємного вмісту та кута нахилу елементів армування. Запропоновано розраховувати значення коефіцієнта тертя як добуток двох спів-

множників, один з яких відповідає за об'ємний вміст наповнювача, а інший за орієнтацію елементів армування. У розрахунках застосовуються співвідношення теорії сумішей. Подані вирази для розрахунків базуються на використанні обмеженої експериментальної інформації, представленої різними авторами. Наявні дані часто мають суперечливий характер і стосуються, як правило, прогнозування якості обробленої поверхні односпрямованих скло- та вуглепластиків. У той же час величина коефіцієнта тертя в розрахунках значно впливає на уявлення зношування і стійкості інструменту. Модель не враховує вплив на величину коефіцієнта тертя контактного тиску, швидкості взаємного ковзання і температури, що буде предметом подальших досліджень у цьому напрямку.

Ключові слова: коефіцієнт тертя, абразивний знос, вміст наповнювача, напрямок армування, зношування інструменту.

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ОПРЕДЕЛЕНИЕ ВЕЛИЧИНЫ КОЭФФИЦИЕНТА ТРЕНИЯ СКОЛЬЖЕНИЯ В КОНТАКТЕ РЕЖУЩИЙ ИНСТРУМЕНТ-КОМПОЗИТ

Одной из важнейших характеристик при расчете износа режущего инструмента при контактном взаимодействии с обрабатываемым композитом является коэффициент трения. В большинстве расчетов, в том числе и методом конечных элементов, коэффициент трения традиционно задается как постоянная величина, значение которой часто принимается из опыта без всякого на то основания. Однако при механической обработке армированных композитов имеется слишком много факторов механического и технологического характера, которые оказывают очень сильное влияние на величину коэффициента трения. Это влияние связано не только с начальной неоднородностью композита, но и постоянным фактическим изменением условий контакта во времени, вызванным износом режущей части инструмента. Значение величины коэффициента трения в реальных условиях контактного взаимодействия имеет очень сложное физическое содержание из-за присутствия в контакте продуктов разрушения волокон и связки, частичного расплавления связующего при температуре в контакте, неравномерности присутствия срезанных волокон.

В настоящей статье представлена формулировка, позволяющая рассчитывать величину коэффициента трения в зависимости от объемного содержания и угла наклона армирующих элементов. Предложено рассчитывать значение коэффициента трения как произведение двух сомножителей, один из которых отвечает за объемное содержание наполнителя, а другой за ориентацию армирующих элементов. В расчетах используются соотношения теории смесей. Представленные выражения для расчетов базируются на использовании ограниченной экспериментальной информации представленной различными авторами. Имеющиеся данные зачастую носят противоречивый характер и касаются, как правило, прогнозирования качества обработанной поверхности однонаправленных стекло- и углепластиков. В то же время величина коэффициента трения в расчетах оказывает значительное влияние на представление изнашивания и стойкости инструмента. Модель не учитывает влияние на величину коэффициента трения контактного давления, скорости взаимного скольжения и температуры, что будет являться предметом дальнейших исследований в данном направлении.

Ключевые слова: коэффициент трения, абразивный износ, содержание наполнителя, направление армирования, износ инструмента.

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DETERMINATION OF THE COEFFICIENT SLIDING FRICTION VALUE IN THE CONTACT THE CUTTING TOOL-COMPOSITE

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One of the most important characteristics in calculating the cutting tool wear in contact with the processed composite is the friction coefficient. In most calculations, including the finite element method, the friction coefficient is traditionally set as a constant, the value of which is often taken from experience without any reason. However, when machining reinforced composites, there are too many mechanical and technological factors that have a very strong effect on the friction coefficient value. This influence is associated not only with the initial heterogeneity of the composite, but also with the constant actual change in the contact conditions over time, caused by the wear of the tool cutting part. The friction coefficient value in real conditions of contact interaction has a very complex physical content due to the presence of products of fibers and binder destruction in the contact, partial a binder melting at a temperature in contact, and the unevenness of the cut fibers presence.

This article presents a formulation that allows you to calculate the value of the friction coefficient depending on the volumetric content and the inclination angle of the reinforcing elements. It is proposed to calculate the friction coefficient value as the product of two factors, one of which is responsible for the filler volumetric content, and the other for the reinforcing elements orientation. The calculations use the mixtures theory relations .The presented expressions for calculations are based on the use of limited experimental information presented by various authors. The available data are often contradictory and relate, as a rule, to predicting the processed surface quality of unidirectional glass and carbon fiber reinforced plastics. At the same time, the friction coefficient value in the calculations has a significant impact on the representation of tool wear and life. The model does not take into account the contact pressure effect, mutual sliding velocity and temperature on the friction coefficient value, which will be the subject of further research in this direction.

Keywords: friction coefficient, abrasive wear, filler content, reinforcement direction, tool wear.