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Influence of high-modulus filler content on critical load on tribocouples made of microheterophase polymer composite materials

V.V. Aulin[1*], S.V. Lysenko[1], A.V. Hrynkiv[1], O. D. Derkach[2], D.O. Makarenko[2]

[1] *Central Ukrainian National Technical University , Ukraine*

[2] *Dnipro State Agrarian And Economic University, Ukraine*

** E-mail: AulinVV @ gmail.com*

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Abstract

The influence of the content of high-modulus filler on the assessment of the critical load on the conjugation of polymeric composite materials is theoretically substantiated from the tribological point of view. Various cases of destruction of polymeric composite materials are considered. The conditions under which the setting of polymeric composite materials is observed, as well as the conditions of their destruction are formulated. Both viscous and brittle fracture of polymeric composite materials are considered. The main focus is on critical loads and stresses depending on the content of high-modulus filler, taking into account the modulus of elasticity of the polymer matrix and filler and the nature of their destruction.

Key words: polymer composite material, microheterophase composite, high modulus filler, triad coupling of parts, critical load, setting, failure

Introduction

When the influence of the structure and composition of polymer composite materials (PCM) on the value of the critical pressure should be considered in the contacts of different types of microheterophase composites. In this case, the size of the structural components of PCM is much smaller than the size of the contact spot, and therefore we can consider the contact of two PCM as the contact of homogeneous materials [1]. In such PCM, the physico-mechanical and tribological properties of the friction surfaces depend on a number of factors. Conditions for efficient operation of triad couplings of parts with PCM at a critical setting load depend on the following factors [2]:

– volume content of high-modulus filler of conjugated PCM of the same phase composition and with the same volume content;

– differences in the volumetric content of the high-modulus filler when contacting conjugate parts with PCM of the same phase composition;

– physical-mechanical and tribological properties of structural components of PCM conjugations with the same volume content of fillers;

– physical-mechanical and tribological properties of structural components of PCM conjugations at different volume content of fillers;

– bond strength of filler particles with the matrix in PCM;

– particle size of fillers.

Consideration of these factors will make it possible to design the PCM in accordance with the operating conditions of the moving couplings of machine parts, without reaching the critical values of the load and the observation of setting and failure.

Literature review

By introducing particles of brittle high-modulus fillers into the plastic polymer matrix, the nature of deformation and destruction of PCM with increasing their bulk content c_f will change [1,2]. The low content (concentration) of high-modulus filler particles indicates that the yield strength σ_T PCM increases with c_f increase, and elongation at destruction ε_R – decreases. As the yield strength of PCM in contact increases, the critical σ_T setting pressure p_c for a single microroughness on the conjugate surfaces of the parts increases in accordance with the equation I.V. Kragelsky [3-6]:

$$p_c = C_u \sigma_T . \quad (1)$$

Since the geometry of roughness slightly depends on the properties of PCM [7-9] at low roughness of friction surfaces of conjugation of parts, it can be assumed that the geometry of their contact with increasing volume fraction of filler c_f remains unchanged.

With increasing c_f plastic properties of ε_R PCM decrease according to equation [10]:

$$N_{M_1-M_2} + \sum_{j=1}^{m} N_{j_{M_1-M_2}} = N \quad (2)$$

It was found that c_f > 0.15 value ε_R changes c_f slightly with increasing. In this regard, for PCM with c_f >0.15 the ability of the irregularities of the conjugate surfaces of the parts to plastic deformation can be assumed to be almost the same [11,12]. The diameter of the contact spot for such PCM is about 1...5 μm. This indicates that the dislocation processes will not change dramatically with the change in the diameter of the contact spot. For PCM with c_f >0.15 the value of the coefficient of proportionality C_u can be assumed to be constant and in accordance with the recommendations of I.V. Kragelsky at a value equal to 3...4. The value of the critical pressure p_c in tribocouples with microheterophase PCM will mainly depend on the value of the yield strength of the material σ_T .

When strengthening polymeric materials with spherical incoherent filler particles, the yield strength is equal to:

$$\sigma_T = \sigma_{PM} + \gamma_{PCM} c_f^{1/n} , \quad (3)$$

where $n = \overline{1,6}$; γ_{PCM} – coefficient that takes into account the shear modulus and Burgers vector of the polymer matrix, as well as the size and shape of the filler particles in PCM [13,14].

For PCM with a small value c_f when contacting irregularities of the same composition, the critical pressure in the triad couplings of the parts is:

$$p_c = C_u \left(\sigma_{PM} + \gamma_{PCM} c_f^{1/n} \right). \quad (4)$$

From the last equation it follows that at n>1 the increase in critical pressure p_c with increasing c_f gradually slows down. Note that the slowdown occurs the faster the value of n [15]. Despite the decrease in PCM elongation with increasing c_f , such composites have a viscous nature of fracture, and therefore setting when reaching the pressure in tribocouples p_c will occur mainly by the mechanism of active centers [16-18]. The destruction of the micro-irregularities of the conjugate surfaces of the gripping parts, when shifting one of them relative to the other will be cohesive in nature with the formation of growths on one of the surfaces, which in some cases can scratch or plow another surface. Note that the formation of such growths is possible with equal probability on both contacting directed surfaces of the parts and there are also traces of the process of plowing on the surfaces of the triad.

Purpose

The aim of this work is tribophysical theoretical substantiation of the influence of changes in the content of high modulus filler in polymer composite material on the magnitude and nature of changes in the critical pressure on the tribocoupling of materials and their critical stress when varying the modulus of elasticity of polymer matrix and filler.

Results

As the filler content c_f in the polymer matrix of the material of the tribocouple parts with the considered type of contact of their working surfaces increases, the critical setting pressure will increase, and the wear at pressures close to p_c will decrease slightly. The latter suggests that with increasing value, the c_f efficiency of tribocoupling of parts with PCM should increase, which indicates an increase in their tribological efficiency .

It is possible to predict that in PCM there is such a filler content when the value of its yield strength exceeds the value of the yield strength. In this case, the viscous nature of the destruction of PCM will turn into brittle fracture fracture [13]. In this case, equation (1) will change and take the form:

$$p_c = B\sigma_c , \tag{5}$$

where B – the coefficient that for fragile materials takes into account the same parameters as the coefficient C_u ; σ_c – tensile strength of PCM.

Since for this class of materials with a change in the c_f value of B is likely to change slightly, the value of p_c , as in the previous case, will mainly be determined by the value σ_c .

The dependence σ_c on c_f for PCM can be represented by the Kramer-Griffiths-Orovan equation:

$$\sigma_c^2 = AE_p\left(1-c_f\right)+k_r , \tag{6}$$

where E_{pM} – the modulus of elasticity of the polymeric material (PM), A and k_r are the coefficients characterizing the structural and phase state of PCM.

At high contents of the filler (c_f ≥0.6), taking into account the data [10-12] with a high probability we can assume that the modulus of elasticity of PCM can be estimated by the formula:

$$E_p = \beta E_f c_f , \tag{7}$$

where β – the coefficient experimentally determined for PCM or calculated from condition (2) for the lower limit, at c_f =0,6:

$$E_{pM} H_M ((1-c_f)E_{pM} + C_f E_{pM}) \le E_p \le (1-c_f)E_{pM} + c_f E_{pM} . \tag{8}$$

It is also possible to write the following equations:

$$\sigma_c^2 = \beta AE_{pf}c_f\left(1-c_f\right)+k_r ; \tag{9}$$

$$p_c = B\left[\beta AE_{pf}c_f\left(1-c_f\right)+k_r\right]^{\frac{1}{2}} . \tag{10}$$

From equation (10) it follows that with increasing the c_f value of p_c critical pressure in the tribocouples of parts should decrease.

The moment of transition from the viscous nature of the destruction of PCM to brittle with increasing content of filler theoretically can not be estimated. At the same time, the value of p_c with increasing c_f passes through the maximum. This gives grounds to introduce the criterion of maximum bearing capacity of triad couplings of parts made of PCM. At the optimal value of the filler content c_{fopt} , at which σ_T = σ_c , and the value $C_u = B$.

Equating the right parts of equations (4) and (10), we obtain:

$$\left(\sigma_T + \lambda c_{fopt}^{1/n}\right) = [\beta AE_{popt}(1-c_{fopt}) + k_r]^{1/2} . \tag{11}$$

Hence we can find c_{fopt} at which p_c has a conditional maximum value of $p_{c.opt}$. Since the c_{fopt} values in σ_T the environment σ_B change smoothly, the value *of* p_c will also change smoothly and the effective performance of PCM in triad couplings of parts can be realized in some interval c_{fopt} . At friction of microroughness of conjugate surfaces of details can be in the conditions of comprehensive uneven compression that promotes manifestation of plasticity and effective values c_f should be a little more than c_{fopt} . Depending on the composition and particle size of the filler should be effective PCM with c_f =0.6...0.9. With a relatively high content of brittle filler on conjugate surfaces, it is possible to observe cracks, and with less – traces of setting.

When contacting PCM with different contents of the same filler, as for single-phase materials, the value of p_c will depend on the nature of deformation and destruction of contacting PCM, as well as their modulus of elasticity. When contacting PCM with $c_f > c_{fopt}$ value of p_c will be determined by the strength of the more fragile PCM and the ratio of their modulus of elasticity. At these values of p_c, the modulus of elasticity of PCM, with increasing c_f , increases in dependence close to rectilinear, and σ_c decreases along a smooth curve. In the case of a small increase in the filler content c_f compared to c_{fopt} can be expected to even increase the value of p_c . In this case, the probability of setting by the mechanism of active centers with increasing E_M of one of the materials of the parts will decrease, and the strength will decrease slightly. This is especially observed in conditions when the micro-irregularities of the conjugate surfaces of the parts are in uneven all-round compression, ie at small values of equilibrium roughness. In cases where the material of one of the parts c_f is much more c_{fopt} and p_c will be lower than the pressure when the PCM has c_{fopt} .

When contacting PCM conjugate parts with $c_f < c_{fopt}$ in case of increase c_f in one of the materials of the part, the value of p_c will increase in all cases, because the values of the modulus of elasticity E_p and σ_T PCM with large c_f will be higher, and accordingly will be lower and the probability of setting materials.

In tribocouple contacts of parts in which one of the PCM has $c_f > c_{fopt}$ and conjugate – $c_f < c_{fopt}$, the value of p_c for tribocoupling will be determined by the same conditions as in the contacts of brittle single-phase polymeric material with plastic material. Since the values σ_T in σ_B these PCMs are higher than in the polymer matrix and the brittle filler, respectively, the p_c in such contacts will be higher than in the contact of the filler with the matrix. In addition, high values of the modulus of elasticity E_p PCM at $c_f > c_{fopt}$ will reduce the probability of setting on the mechanism of active centers. Since the number of active centers increases with increasing c_f PCM under the condition $c_f > c_{fopt}$, the values of p_c will be higher the higher the content of filler c_f in this PCM. However, in PCM under the condition $c_f < c_{fopt}$ we have: with increasing c_f the resistance of the dislocations will increase, and the number of dislocations in the cluster before the boundary of the contact surfaces will decrease. The maximum value of p_c in this type of contact will be when the value c_f in one of the conjugations of parts with PCM is slightly smaller, and in the other – slightly larger c_{fopt} .

Analyzing the results of the dependence of p_c on the content of high-modulus filler c_f in different materials of the tribocouple parts, it can be noted that the highest values of p_c should be expected when contacting them, provided that conjugate PCM have different filler content c_f . Moreover, in one of the PCM the value c_f should be close to c_{fopt} , and in the second - should be greater c_{fopt} by a value at which the effect of increasing the modulus of elasticity E_p in the tribocontact prevails over the effect of reduction σ_c . Approximately can be c_f taken equal to half the range of effective values when contacting PCM of the same composition (c_f = 0.75...0.85).

Mechanical and tribological properties of matrix and filler materials, other things being equal, will also affect the value of p_c . In such PCMs, according to the Kramer-Griffiths-Orovan equation , the values of the modulus of elasticity and the σ_c PCM as a whole increase as the modulus of elasticity of the filler E_{pf} increases. The value of p_c will also increase with increasing E_{pf} . The maximum value of p_c will be in the PCM contacts, in which the same c_f modulus of elasticity of the filler is maximum. Contacts of two conjugate PCMs with a low value of E_{pf} will be the least efficient.

When the PCM is strengthened by the Ansell and Lenel mechanism [3,13,16-18] , the value σ_c of the three-coupled parts increases with increasing shear modulus of the reinforcing phase and the volume fraction of filler particles in this phase. Under conditions of uneven comprehensive compression PCM with small values of constant elasticity of the filler E_f will be more prone to setting. To reduce the adhesion of conjugate PCM it is necessary to increase c_f in both PCM; in contacts with such PCM the value of p_c with increasing c_f outside c_{fopt} will increase to large values c_f than in PCM with large modulus of elasticity of the filler E_{pf}. Values p_c for contacts in which one of the PCM has a filler content with a higher, and in the other – with a lower value of the modulus of elasticity E_{pf}, ie should acquire intermediate values.

For this type of PCM contacts with a smaller modulus of elasticity, the values σ_c are smaller and to increase the efficiency of these PCM contacts with a smaller modulus of elasticity, the filler content should be closer to c_{fopt}. In the case of PCM with a large modulus of elasticity E_p can be taken with both smaller and larger c_{fopt}. Due to the fact that the probability of adhesion by the mechanism of active centers with increasing E_p decreases, it is more appropriate in such contacts in PCM with large E_{pf} should take the value $c_f > c_{fopt}$. The limit value c_f in these contacts may be greater than in the contacts of two conjugate PCM with a larger E_p. With a large difference between E_{p2} and E_{p1} for PCM with large E_p effective are the following values of filler c_f =0.95...0.98.

Assuming that basically, the setting of the friction surfaces is determined by the mechanism of formation of the general step of microroughnesses, the value of p_c can be estimated by equations of the type:

$$\sigma_c = 2\bar{\sigma}\left(\frac{l_\partial}{l_c}\right)^{1/2}\left(\frac{3B_T\varepsilon rT}{V}\right)^{1/2}\exp(U_0/3rT) + \left(\frac{3B^f\varepsilon rT}{V^f}\right)^{1/2}\exp(U_0'/3rT)\left(1-2\left(\frac{l_\partial}{l_c}\right)^{1/2}\right). \quad (12)$$

Taking p_c proportional $\bar{\sigma}$, we have:

$$p_c = C_u\bar{\sigma} = 2C_u\left(\frac{l_\partial}{l_c}\right)^{1/2}\left(\frac{3B_T\varepsilon rT}{V}\right)^{1/2}\exp(U_0/3rT) - C_u\left(\frac{3B^f\varepsilon rT}{V^f}\right)^{1/2}\exp(U_0'/3rT)\left(1-2\left(\frac{l_\partial}{l_c}\right)^{1/2}\right). \quad (13)$$

Lack of data on the value of C_u, l_∂, B, U_0 i U_0^f impossible to determine a specific value p_c. However, it is known that the value p_c is greater the greater U_0 and U_0^f .

If we take into account the results of the study of the evolution of the structure of multiphase PCM, we can conclude that the deformation processes during friction PCM with fillers with low and medium modulus of elasticity more accurately describes the Ansell-Lenel mechanism [4-6]. Knowing the values of the average PCM stresses and fillers by the equations:

$$\bar{\sigma} = \sigma_T = \sigma_{TM} + \left(\frac{G_M G_f b}{2L_p c_p}\right)^{1/2}; \qquad \sigma_f = \sigma_T^f = \sigma_{TM}^f + \left(\frac{G_M^f G_f^f b^f}{2L_p c_p}\right)^{1/2}, \quad (14)$$

you can estimate the value of p_c when contacting two conjugate PCM:

$$p_c = B^f\sigma_c = 2B^f\left(\frac{l_d}{l_c}\right)^{1/2}\left(G_{TM} + \left(\frac{G_M^f G_f b}{2L_p c_p}\right)^{1/2}\right) + \left(1-2\left(\frac{l_d}{l_c}\right)^{1/2}\right)B^f\left(G_{TM}^f + \left(\frac{G_M^f G_f^f b^f}{2L_p c_p}\right)^{1/2}\right). \quad (15)$$

From equation (15) it follows that to increase p_c tribocoupled parts with PCM it is necessary to choose matrices with high σ_{TM} and shear modules G_M, and fillers – with high modulus of elasticity and such content that the distance between particles l_p close to its minimum value , in which the Ansell-Lenel mechanism still works. The value of l_p equal to 1.5...2.5·10^{-2} μm, at d_p = 0.5...2 μm, is observed if the volume fraction of binding is 1...5% .

For tribocouples of parts made of PCM with a fragile matrix, the amount of stress can be estimated by the formula:

$$\overline{\sigma_n} = \left(\frac{3B\dot{\varepsilon}kT}{V \exp\left(\frac{U_0 k_B}{3T} \right)} \right)^{1/2} . \quad (16)$$

In this case:

$$\sigma_f = \sigma_{TM} + \left(\frac{G_M G_f b_B}{2 l_p c_p} \right)^{1/2} . \quad (17)$$

Then the value of the critical filler can be estimated by the equation:

$$p_c = B^f \sigma_c = 2B^f \left(\frac{l_d}{l_c} \right) \left(\frac{3B\dot{\varepsilon}kT}{V} \right)^{1/2} \exp\left(\frac{U_0}{3k_B T} \right) + \left(1 - 2\left(\frac{l_d}{l_c} \right) \right) B^f \left(\sigma_{TM} + \left(\frac{G_M G_f b_B}{2 l_p c_p} \right)^{1/2} \right) . \quad (18)$$

From equation (18) it follows that in triad couplings of parts with PCM with a fragile matrix must have a high value of U_0 , and the filler is a high modulus of elasticity, ie high modulus. The volume fraction of binding should strive for its minimum allowable value (1...5%). At high values of U_0, the given tribocouples of parts with PCM on the value of the critical setting load may be more effective than tribocouples with a metal matrix. But by the criterion of fragile destruction, they will be inferior to tribocouples with a metal matrix.

The strength of PCM is significantly influenced by the strength of the interfacial boundaries. As noted, the destruction of the interfacial boundary leads to the development of cracks or chipping PCM, the formation of micropores, followed by their fusion in viscous fracture. During friction, due to the presence of sliding conjugate surfaces, the role of the boundaries will depend on the depth of the filler particles in the surface layer of the PCM material. All particles that do not come to the surface of the contact spot will perform the same role as under the volumetric load of PCM. The filler particles coming to the surface of the contact spot during friction will specifically affect the behavior of the material in the contact spot. In the case where the destruction of the interfacial boundaries leads to the appearance of cracking cracks, a network of microcracks will develop on the surface of the contact spot and the bearing capacity of PCM surfaces will be determined by brittle fracture rather than setting, which will reduce p_c.

If micropores are formed during the destruction of the interfacial boundary, then at $d_p \approx 1$ μm they can positively affect the process of friction of the conjugation of parts. The newly formed pores serve as reservoirs for lubrication, which improves the regeneration of the lubricating distribution film on the friction surfaces, reduce the coefficients of friction and heat release in the contact zone, and, accordingly, reduce the likelihood of setting materials of conjugated parts. In this regard, weak interfacial boundaries can be allowed in cases where the destruction of the boundaries do not develop cracking cracks, ie only when using plastic matrices and with such a content of filler particles, when contacts between them are absent. This structure of the material at $d_p \approx 1$μm can be provided in the manufacture of PCM with $c_f < c_{fopt}$.

In addition to improving the lubrication, in case of loss of filler particles, their strengthening effect will be reduced and there will be a positive gradient of shear resistance, which will improve the performance of triad coupling parts with PCM. When using such PCM filler particles with a high modulus of elasticity in the event of loss of most particles from the surface layer on a high modulus substrate, a plastic coating with a thickness of 1 μm is formed, which reduces friction and improves the performance of three-coupled parts. The value of p_c in this case should not be greatly reduced, because the presence of a solid substrate in PCM will limit the ability of Frank-Reed sources and generate dislocations in a thin surface layer, and, accordingly, removing filler particles from the surface layer In order to prevent setting on the mechanism of formation of the general step, from such PCM it is necessary to make only one detail of tribocoupling, and the second – with the high-modulus filler with strong interphase borders.

If we limit ourselves to the effect of improving the lubrication of surfaces due to the formation of micropores on them when the filler particles fall, it is more appropriate to create a combined PCM, when one part has strong interfacial boundaries and the other - weak. In such a PCM, particles with a strong interfacial boundary must have a high modulus of elasticity, and particles with a fragile boundary can have any value of the modulus of elasticity. This expands the number of materials that can be used as filler particles with weak interfacial boundaries and allows you to enter such particles not in one part, but in both conjugate parts, because the development of the setting process by both mechanisms will prevent filler particles with high modulus and elasticity high strength of interfacial boundaries.

The role of the size and shape of the filler particles can be determined by two factors [10-12]: cracking of particles and their ability to inhibit the movement of dislocations. It was previously shown that on the spots of actual contact, larger filler particles crack at smaller values σ. However, the mechanism of hardening Orovana at $c_f < c_{fopt}$ and at the same time c_f more effectively increase the size σ_T of the smaller filler particles. Therefore, from the position of cracking and setting at $c_f < c_{fopt}$ more effective should be PCM with smaller reinforcing particles. However, due to the facilitation of the possibility of transverse sliding of the dislocation with decreasing r_p, with r_p slightly larger size of the dislocation nucleus r_0, too small particles will be an inefficient barrier to dislocation and will develop plastic deformation of irregularities on conjugate surfaces, and with it the probability of setting.

Since $r_0 = 4b$ [15,18], the lower value of r_h should be of the order of $5 \cdot 10^{-3}$ μm. Such particles are very difficult to obtain, so we can assume c_{fopt} that c_f with a decrease in the particle size of the filler, the critical setting load will often increase in the case of modern technological methods.

In PCM, the c_f value σ_c increases c_{fopt} when the plastic deformation that develops at the crack tip covers a large volume, ie with a large particle size of the filler. But here the value of r_p has its limits. When r_p increases to a certain value, the crack does not bypass this particle in the plastic phase, but goes through the body of a large particle of brittle material. As a result γ_p, the Griffiths-Orovan equation decreases and the value σ_c decreases. The maximum particle diameter of the filler should be at the level of 10...50 μm. From this analysis it follows that to increase the value of p_c in PCM with $c_f < c_{fopt}$ particle size should be reduced, and in PCM with $c_f > c_{fopt}$ – increase to 1...2 μm. With large diameters of filler particles, the nature of contacting the surfaces changes, so the critical setting pressure will be subject to other laws close to the laws inherent in single-phase materials.

All of the above applies to PCM with a plastic matrix. Further, the possibility of increasing the value of p_c in contacts involving PCM with a brittle matrix should be analyzed, because at close values of the coefficient of thermal expansion of the matrix and filler, not very large difference E_p (not more than 5 times), low temperatures PCM, small diameter filler particles (about 3.5...11 μm) and their small content (c_f <0.3) can increase the strength of PCM.

Conclusions

1 . Thus, based on the strength of the interfacial boundaries, the most effective should be considered three-coupled parts that are made of PCM with high-modulus filler particles with strong interfacial boundaries. When using filler particles with weak interfacial boundaries, good results can be expected in the case of using high-modulus filler particles or a mixture of high-modulus particles and particles with a small modulus of elasticity.

2. It was found that PCM of microheterophase type based on brittle matrices have a strength close to the strength of single-phase brittle materials. The critical setting pressure depends on the same parameters on which the critical pressure of single-phase brittle materials considered for different types of contacts depends.

3. According to the criterion of critical setting pressure, the most effective should be considered triad-coupling of parts in which PCM one of the working surfaces has $c_f > c_{fopt}$ and the size of the filler particles approaching the upper limit of the size of the reinforcing particles, and the other PCM has $c_f < c_{fopt}$ and the particle size the size of the reinforcing particles of the filler.

4. The role and forms of particles of high-modulus filler, as well as its content in the polymer matrix in the formation of the value of the critical load on the moving conjugation of parts are theoretically substantiated.

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Аулін В.В., Лисенко С.В., Гриньків А.В., Деркач О.Д., Макаренко Д.О. Вплив вмісту високомодульного наповнювача на критичне навантаження на трибоспряження з мікрогетерофазних полімерних композиційних матеріалів

В роботі теоретично з трибологічної точки зору обґрунтовано вплив вмісту високомодульного наповнювача на оцінку критичного навантаження на спряження полімерних композитних матеріалів. При цьому розглядаються різні випадки руйнування полімерних композитних матеріалів. Сформульовані умови, при яких спостерігаються схоплювання полімерних композитних матеріалів, а також умови їх руйнування. Розглядається як в'язке, так і крихке руйнування полімерних композитних матеріалів. Основна увага зосереджена на критичних навантаженні і напруження в залежності від вмісту високомодульного наповнювача з урахуванням модулів пружності полімерної матриці і наповнювача та характеру їх руйнування.

Ключові слова: полімерний композитний матеріал, мікрогетерофазний композит, високомодульний наповнювач, трибоспряження деталей, критичне навантаження, схоплювання, руйнування.