The parameters values choice for the preliminary thermo mechanical effects on polymeric materials before machining

O Yu Erenkov*, I Ya Lopushanskii and D O Yavorskii
Pacific National University, Khabarovsk, 680035  Russia

*erenkov@list.ru

Abstract. In this paper the commonality of the destruction and materials cutting processes is substantiated. The use of preliminary mechanical and thermal effects on polymer composite materials is justified on the base on the provisions of the materials fracture kinetic concept. The ranges of the parameters values for thermal and mechanical effects on polymer composite materials are scientifically sound. Experimental studies of the polymeric materials deformation and fracture processes under uniaxial tension were carried out in order to select rational values of the preliminary mechanical stresses. It has been experimentally proved that the most weakened structure of the material is retained for 5-20 minutes for fluoroplastic and caprolon after preliminary loading. And the rest time between the deformation steps for thermosets such as getinaks and textolite does not affect the formation and change in the material strength.

1. Introduction
The term cutting is generalized and is understood as the part manufacturing methods by removing a material layer from a workpiece as result of all possible types of exposure including mechanical, thermal, electrical, chemical, and combinations thereof.

For cutting by processing difficult materials, which include polymeric materials, combined methods of cutting are applied [1]. The technical essence of such methods consists in directionally changing the state of the processed material to obtain a treated surface of high accuracy and quality. The combined methods effectiveness at materials cutting depends on the following factors: number and types of input external influences; methods for implementing each exposure in a material processing zone; quantitative characteristics of combined effects and their ratio [2].

The aim of this work is to justify the selection and assignment of numerical values of the parameters for thermo mechanical effects on a workpiece made from polymer composite material (PCM) before machining.

2. Theoretical views
The solid destruction is generally the result of overcoming the interaction forces between its atoms and molecules which can occur under the influence of thermal energy, mechanical stress, radiation, electrical discharges, etc. The materials processing by cutting and polymers in particular can be represented as a kind of fracture process. And this process is accompanied by a dynamic effect of the cutting tool edges on the surface to be treated. The commonality of the fracture and cutting processes was established in the works of V.A. Kudinov, Yu.G. Kabaldin, V.N. Poduraev [2, 3, 4]. The authors...
substantiated theoretically and proved experimentally the occurrence of both processes when the acting stresses exceed the tensile strength of the material.

At the present stage, physical ideas about the strength of polymeric materials are based on the kinetic concept of strength. The main relation of the kinetic theory of destruction is written in the form of the S.N. Zhurkov empirical equation [5]:

\[ t = t_0 \exp \left( \frac{U_0 - \gamma \sigma}{KT} \right), \]  

(1)

where \( U_0 \) is the activation energy of the fracture process elementary breaking act in the absence of stress, which is close in magnitude to the chemical bonds energy for polymers; \( \gamma \) is a coefficient depending on the material nature and structure and the \( \gamma \) values change with a variation in the material structure; \( t_0 \) is the time of atoms thermal vibrations in solids; \( K \) is the Boltzmann constant; \( T \) is the absolute temperature; \( \sigma \) is the average stress in the sample.

From the analysis of equation (1) it follows that the durability of the material equally depends on the applied voltage and temperature as both parameters are included in the exponent. This suggests that thermal energy and precisely its fluctuations play a large role in the process of fracture, i.e., in the place of the material where thermal fluctuations become greater than the energy of the bond being broken, the latter is broken. The applied stress makes it possible to accumulate these fluctuations in a certain direction and reduces the gap activation energy and also reduces the potential barrier by law \( U = U_0 - \gamma \sigma \). Such actions facilitate the stressed bonds decomposition under the thermal fluctuations influence. The probability of stressed bonds decomposition depends on the ratio \( \frac{U_0}{KT} \). It was experimentally proved [6,7,8] that chemical bonds are breaking at polymer materials loading. Chemical bonds are deformed under applied stress influence and break under thermal fluctuations influence.

According to kinetic concepts the destruction process of PCM is carried out in the following sequence: the interatomic bonds excitation by applied mechanical force; the rupture of excited bonds in polymer chains by thermal fluctuations; the grouping of elementary gaps and the primary microscopic cracks formation; the fracture crack occurrence from the initial micro crack and its growth to the sample rupture.

3. Parameters justification

In this paper, on the basis of the considered facture process physical representations the new approach to PCM cutting is formulated. The approach essence is that the polymer material proposed for turning is previously subjected to mechanical, thermal or combined thermo mechanical action. Such influence by stress \( \sigma \) and temperature \( T \) or together on the material provides the interatomic bonds excitation by the applied mechanical force and some of the excited bonds in the polymer chains are broken by thermal fluctuations in accordance with the kinetic concept of strength. Thus, a weakened structure is formed in the material volume in which part of the bonds is broken and part is strained. This leads to decreasing of the polymer bonds activation energy and at further interaction of the material with the tool cutting wedge to the cutting force reduce.

When implementing the proposed approach it seems very important to choose the right values of thermal and mechanical effects parameters.

It is known [7,8] that polymeric materials performance is limited by the temperature range

\[ T_{br} < \Delta T_{oper} < T_{ql}, \]  

(2)

where \( T_{br} \) is the temperature of the material brittleness; \( T_{ql} \) - the material glass transition temperature; \( \Delta T_{oper} \) - the operation temperature range of products made from the studied material.

In this connection, the heating temperature is selected from the \( \Delta T_{oper} \) range of a particular material in accordance with the technical specification, standards and technical conditions.
The magnitude of the compressive or tensile force is selected using the mechanical diagram of the material. The loading stress is chosen from the curve region corresponding to elastic deformation until the development of the forced elasticity phenomenon. In this case the forces applied to the workpiece must satisfy the following condition

$$\sigma_n < (0.6 - 0.8) \sigma_v,$$

where $\sigma_n$ is the stresses created in the workpiece by tensile or compression force; $\sigma_v$ is the limit of forced elasticity of the polymer material. In the case of thermosetting plastics, the value of breaking stress $\sigma_v$ should be substituted for $\sigma_r$.

As noted by several researchers [6,7] when condition (3) is fulfilled the solid polymer bodies destruction has a purely thermal fluctuation mechanism. The noticeable deviation from the linear dependence is observed for the initial portion of the loading curve if the stresses created in the workpiece are exceeded $(0.6-0.8) \sigma_v$.

4. Experimental studies

The experimental studies of the polymeric materials deformation and fracture processes under uniaxial tension were carried out to correctly select the parameters values of the preliminary mechanical action. The time interval for the existence of the polymer material weakened structure after the load termination experimentally had been established. This period of time is very favorable for workpiece turning.

The samples were subjected to uniaxial tension using a loading device of the WDW-50E universal testing machine. The design of the testing machine allows providing experiments high accuracy, the possibility for implementing several types of samples mechanical loading and processing data using its own mathematical software in real time. The tests are conducted in fixed conditions; the temperature, humidity, speed, and load correspond to the recommendations of State Standard 11262–80 for uniaxial extension. Representatives of thermoset and thermoplastic plastics, most common in various industries, were selected as the materials of the experimental samples: Caprolon, Teflon, Polymethacrylate, Getinaks and Textolite.

Research was carried out in several stages. The first stage goal was to determine the limiting characteristics of the studied materials such as tensile stress for thermosts and the forced elasticity limit for thermoplastics. The second stage purpose was to determine the relaxation time of stresses after samples preliminary loading. The samples were preloaded to a value of $06 - 08 \sigma_v$ for caprolon and fluoroplastic and $06 - 08 \sigma_r$ for getinaks and textolite according to condition (3). The sample was released from the installation grips after loading was stopped and was kept without load for a certain fixed time interval. After the expiration of the corresponding time interval the sample was loaded until fracture or plastic flow. The obtained experimental data in the form of dependences $\sigma = f(\tau)$ are presented in Figure 1, 2, 3 and 4.

5. Discussion of research results

Let us analyze the results of testing samples from caprolon and fluoroplast-4 which were held without loading for 5, 20 and 60 minutes after preliminary loading.

The strength of plastic solid materials is characterized by two limiting states: the transition from elastic to plastic deformation and the transition from plastic deformation to fracture. This is confirmed by the presence of two characteristic sections in the corresponding diagrams (Figures 1-2, curves 1). The maximum stresses occur at points where sharp kinks are observed in the corresponding tensile diagrams. The stress at these points is 82 MPa and 16 MPa and these values can be considered as the forced elasticity limit of caprolon and fluoroplastic respectively.

Analysis of the graphically presented data shows that the strength of caprolon samples (Figure 1) depends on the sample exposure time without load. This is evidenced by the values of the forced elasticity limit $\sigma_v$, which are significantly lower than the base value (82 MPa) and amount to 42, 50 and 60 MPa after the samples resting for 5, 20, and 60 minutes, respectively.
The values of the of forced elasticity limit $\sigma_v$ for fluoroplastic samples (Figure 2) also differ significantly from the base value (16 MPa) and are 6, 10 and 12 MPa for 5, 20 and 60 minutes of the samples resting respectively.

Figure 1. Mechanical diagrams of loading samples from caprolon: 1- basic diagram; 2- sample exposure without load 5 min; 3- sample exposure without load 20 min; 4- sample exposure without load 60 min.

Figure 2. Mechanical diagrams of loading samples from fluoroplastic: 1- basic diagram; 2- sample exposure without load 5 min; 3- sample exposure without load 20 min; 4- sample exposure without load 60 min.

This change in the strength of the studied thermoplastic materials depending on the samples resting time after preloading is explained as follows.

There are microcracks of various sizes [6, 7] in the polymeric materials due to random fluctuations in the characteristics of the feedstock and the instability of the production process.

As is known [6, 8] a local forced highly elastic deformation occurs in a small vicinity of the crack tip when a polymer is loaded. This type of deformation is due to the macromolecules gradual unwinding under the applied forces action from initially chaotic conformations to more elongated ones corresponding to equilibrium conditions in the stress field. After removal of the load, the highly elastic deformation gradually disappears over time and the chaotic initial conformations of the polymer chains and accordingly the material strength $\sigma_o$ are restored. This is evidenced by an increase in the
value of the forced elasticity limit $\sigma_v$ under caprolon and fluoroplastic tension with an increase in the samples exposure time without load before secondary loading. Thus, relaxation processes occur in the material and the initial structure and properties are restored to a certain extent depending on the samples relaxation time.

So the minimum values of the forced elasticity limit for samples from caprolon and fluoroplastic after rest for 5 minutes are 42 and 6 MPa, respectively (Figure 1). It is obvious after initial loading a significant part of the polymer chains has elongated conformations and is in a stressed state due to forced elastic deformation. For 5 minutes of the sample resting time the relaxation processes do not have time to reduce the material local overstrains to the initial level. And therefore there are loaded chemical bonds in the sample material before secondary loading. According to the provisions of the thermo fluctuation theory of the solids strength [5, 6] the stronger the chemical bonds and accordingly the polymer chains, the more likely the bonds to break and the faster the body is destroyed.

The forced elasticity limit of the samples material have maximum values of 60 and 12 MPa respectively after samples resting for 60 minutes. These facts indicate about more complete restoration of the structure transformed during preliminary stretching to its initial state.

The final strength restoration does not occur because when tensile polymer samples microcracks are formed not only on the surface but also in the volume of the sample material. The cracking is an irreversible process. The sample long exposure after load relief leads to the crack size decreasing but not to its complete disappearance [8]. The crack remains and in the event of subsequent loading of the sample begins to grow again. This explains the fact that upon repeated stretching the sample is more easily deformed and reaches the forced elasticity limit in a shorter time.

Let us analyze the results of testing samples from getinaks and textolite which were held without loading for 5, 20 and 60 minutes after preliminary loading.

The strength of brittle solids is characterized by one ultimate state corresponding to the transition from elastic deformation to fracture, as follows from the presented data (Figure 3, 4, curves 1) and the breaking stress is 92 MPa and 78 MPa for getinaks and textolite respectively.

In the case of textolite specimens stretching (Figure 3) the slightly different character of the dependence between the material strength and the specimen resting time takes place. The values of the breaking stress $\sigma_r$ significantly differ from the base value (78 MPa) and have approximately equal values 18, 22 and 24 MPa respectively after the samples unloading for 5, 20 and 60 minutes.

The similar character of the stress distribution is observed (Figure 4) in the case of getinaks samples stretching. After the samples resting for 5, 20, and 60 minutes the breaking stress values are also lower than the stress base value (92 MPa) and are 42, 50, and 44 MPa respectively.

This is explained by the fact getinaks and textolite are polymer composite materials with matrices made from phenol-formaldehyde resin. These materials belong to the thermosetting polymers with a stable spatial structure. Relaxation processes in such structures proceed very quickly due to the low flexibility of polymer chains, links and segments [7, 8] and cannot have a noticeable effect on the material strength change over time.

Wherein the existing microcracks are developed during the preliminary loading of samples from these materials to the value of (0.6-0.8) $\sigma_r$. This fact is confirmed by the results of the study using the acoustic emission method [9]. The process of microcracks development is associated with the breaking of beams and individual reinforcing fibers. In this case irreversible deformations of the reinforcing fibers and decrease in the cohesion degree between the filler and the matrix occur. Thus at the preliminary loading stage of textolite and getinaks samples the defective structure is formed due to irreversible changes which remains during its resting without load. The presence of a defective structure is the main reason for the decrease in the materials strength during samples subsequent secondary deformation regardless of the resting time.
6. Conclusions

The use of preliminary mechanical and thermal effects on polymer composite materials is justified on the base on the provisions of the materials fracture kinetic concept. The ranges of the parameters values for thermal and mechanical effects on polymer composite materials are proposed.

It has been experimentally proved that the most weakened structure of the material is retained for 5-20 minutes for fluoroplastic and caprolon after preliminary loading. And the rest time between the deformation steps for thermosets such as getinaks and textolite does not affect the formation and change in the material strength.

The results of this work are the basis for the development of a new combined method of cutting polymer composite materials using preliminary thermo mechanical effects on the workpiece to ensure high quality processing.
Acknowledgment
The reported study was funded by RFBR according to the research project № 20-08-00039

References
[1] Poduraev V N 1974 Cutting hard materials (Moscow: Higher School) p 578
[2] Poduraev V N 1985 Technology of physicochemical processing methods (Moscow: Higher School) p 264
[3] Kabaldin Yu G, Oleinikov A I, Shpilev A M and Burkov A A 2000 Mathematical modeling of self-organizing processes in technological systems for machining (Vladivostok: Dalnauka) p 195
[4] Kudinov V A 1967 Dynamics of machine tools (Moscow, Mechanical Engineering)
[5] Zhurkov S N 1987 Kinetic nature of the strength of solids Solid State Physics 29 1 p156-65
[6] Kartashov E M, Tsoi B and Shevelev V V 2002 Structural – Statistical kinetics of polymer destruction (Moscow: Chemistry) p 736
[7] Tager A A 1978 Physicochemistry of polymers (Moscow: Chemistry) p 544
[8] Ogibalov P M, Lomakin V A and Kishkin. B P Polymer Mechanics: Textbook for universities 1975 (Moscow: Publishing house of Moscow University) p 528
[9] Erenkov O Yu, Fofonova O V, Khimukhin S N, and Yagubov E Z 2013 Study of damage accumulation within the structure of polymer materials under load Chemical and Petroleum Engineering 48 9–10 p 636-41