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# Simulation of the processes of drilling polymer composite blanks using digital twins

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***Abstract:*** Polycrystalline composite materials made of carbon fibre reinforced plastics have more and more widespread application in mechanical engineering and become the main material for the production of modern types of high-speed transport. Thus, their share has already reached 35–45 % in the structural design of passenger aircrafts. However, the technology of machining surfaces of parts made of these materials, in particular, holes, is characterized by insufficient knowledge, the absence of regulatory standards for cutting modes, and is most often based on the production experience of enterprises. When changing the processing conditions and the material, the pre-production engineering duration causes a significant increase in the cost of manufacturing parts due to the need for experimental selection of the cutting mode rational elements. To exclude the empirical selection of rational elements of the machining equipment cutting mode, the authors considered the possibility of using digital twins, for studying the processes of drilling holes in the blanks made of composite materials. The authors included those with the ultrasonic field energy introduction into the new surface shaping zone (to improve the processing quality and productivity). When modelling, the LS-DYNA program was used. The authors prepared the models and processed the results using the LS-PrePost 4.8 program. During the study, an explicit modelling method was used with preliminary validation and calibration of the results of tests of composites. The authors carried out calibration on test operations of tension, three-point bending, and interlaminar shear of the ВКУ-39 polymer composite material based on carbon fibres (carbon fibre reinforced plastic) widely used in domestic engineering. The developed finite element computer models allow simulating drilling procedures without carrying out rather complicated and expensive field tests. As a result of modelling, a simulation file was obtained, which reflects the process of drilling holes in a polymer composite material blank, as close as possible to the real-life situation with chip removal.

***Keywords:*** drilling of composite materials; ВКУ-39; ultrasonic field energy; ultrasound; drilling process simulation; digital twin.

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## INTRODUCTION

Numerous studies performed by some authors established a significant difference in the processes of edge cutting machining of polymer composite and metal blanks [1–3]. Drilling holes in the blanks made of carbonfibre-based polymer composite materials (PCM) is particularly difficult [4–6], which is explained, on the one hand, by the fibre-matrix system fragility and heterogeneity, and, on the other hand, by different operating conditions of various sections of the drill cutting edges, due to the cutting speed variability when removing stock (from zero to maximum values on the outer surface of a drilling tool).

When drilling holes in PCM, the material removal, in contrast to cutting metals, occurs through a series of successive ruptures, which is facilitated by the different nature and uneven distribution of the load between the matrix and fibres [7; 8]. Such chip formation is caused by the composite material brittle fracture, due to the crack initiation and propagation in the primary shear zone after the partial formation of a cleavage and forces to make appropriate adjustments to the software. Since brittle fracture is the dominant process occurring when machining a composite material, the powdery dust segment chips are formed. However, these type of chips, which are formed when drilling holes in PCM, depend largely on the properties of fibres and the matrix. In some cases, “continuous/flow” chips may form, like in metal processing [9; 10]. Moreover, with an increase in the fibre volume fraction, most of the composite materials can be removed by successive destruction due to non-uniform plastic deformation, contributing to the formation of segment chips. It is worth noting that the chip type depends on the cutting mode inputs such as cutting speed and feed. The main factor reducing the efficiency of PCM edge cutting machining is the abrasive nature of the filler [11]. The abundance of carbon or other types of fibers in the PCM structure ensures rapid tool wear (mainly along the flank surface). The listed differences in the stock removal processes are simultaneously accompanied by the almost complete absence of cutting modes when processing composite materials.

As known, the ultrasonic (US) field energy introduction into the machining zone contributes to a significant reduction in the friction force between the cutting tool and the blank [12; 13]. This both speeds up shaping and significantly improves the quality of new surfaces, primarily by reducing the probability of defects in the form of delamination, cleavages, cracking, thermal damage and polymer matrix melting, microcracks between the fibre and the binder, etc. [14; 15].

When designing new technological processes, including ones with the ultrasonic vibrations introduction into the processing zone, the selection of the hole-drilling mode elements is carried out, as a rule, empirically. Experimental selection of drilling mode elements is characterized by high labour intensity, high cost and time expenditures.

Reducing the time expenditures for designing the technological process of manufacturing any mechanical engineering products, especially products from composites, can be achieved using Computer-aided engineering (CAE) systems [16; 17]. Creating a model in CAE systems allows obtaining information about stresses, temperature, distribution of forces in the processing zone, and deformations [18; 19].

The purpose of the study is to create computer models of the processes of drilling polymer composite blanks, including those with the introduction of ultrasonic field energy into the new surfaces shaping zone.

## METHODS

### Tests

At the first stage, tests of the composites’ mechanical characteristics were carried out. The results of these tests were required for calculations on mathematical models.

During the research, an explicit modelling method with preliminary validation and verification of test results was used. Verification was carried out on tension, three-point bending, and interlaminar shear test operations. For modelling, the authors used the LS-DYNA program. To prepare models and process the results, the LS-PrePost 4.8 program was used.

240×12×3 mm strips cut from the ВКУ-39 material were used as sample models.

In the composite, 10 layers were modelled using 8-node thick-walled shell elements with reduced integration. The size of one cell of the composite was 2×2 mm. The thickness of each layer was 0.3 mm.

The ВКУ-39 composite initial parameters were taken based on the works [19; 20]. During simulation and validation, the parameters were adjusted to match the composite used.

As a material model, a model of a composite orthotropic material with destruction was taken.

For the convenience of calculations, the authors used a system of units other than the SI system (length in millimeters, time in seconds, and mass in tons). The following parameters were set in the material model [20]:

– density – $1.525 \cdot 10^{-6}$ kg/mm$^3$;
– Young’s modulus (EA, EB) – $6.39 \cdot 10^4$ MPa;
– Poisson’s ratio PRBA – 0.3;
– shear modulus – 4080 MPa.

In the material model, the failure under the action of tensile stresses, as well as the values of failure strain, were specified. Compression and shear strains were overestimated as only tensile strains affect the fracture process.

To model an adhesive layer, the authors used an automatic “surface-to-surface” contact with the tiebreak annex (cohesive breakable contact) with a crack discrete model, power dependence, and damage models with a normal and shear stress of 80 MPa and a fracture energy of 4 mJ. These parameters were adjusted by tests when validating the process.

In addition, the authors considered the assessment of the influence on the resulting moment of the coefficient of friction between a drilling tool and a composite, which changes due to the ultrasonic field introduction into the new surface formation zone, at values equal to 0, 0.1, and 0.2.

Fig. 1, 2 present the initial test models. Fig. 3 shows the pattern for testing the ВКУ-39 composite samples.

### Mathematical simulation

At the second stage of the research, the updated parameters of the composite material model and its adhesive layer were used when developing mathematical models based on digital twins.

At the second stage, the authors carried out mathematical simulation of the processes of drilling ВКУ-39 polymer composite blanks, with the ultrasonic field energy introduction into the shaping zone. The main tasks were the digital model adjustment and the assessment of the ultrasonic vibrations effect when changing the amplitude from 6 to 13 μm, and the friction coefficient in the tool-blank contact zone – from 0.1 to 0.2 (the values were taken from the data of numerous studies of the 50–60-ies of the last century). The ranges of changes in these parameters are presented in Table 1. The following cutting mode elements were chosen as constant parameters in mathematical simulation of the process of drilling holes with a diameter of 5 mm

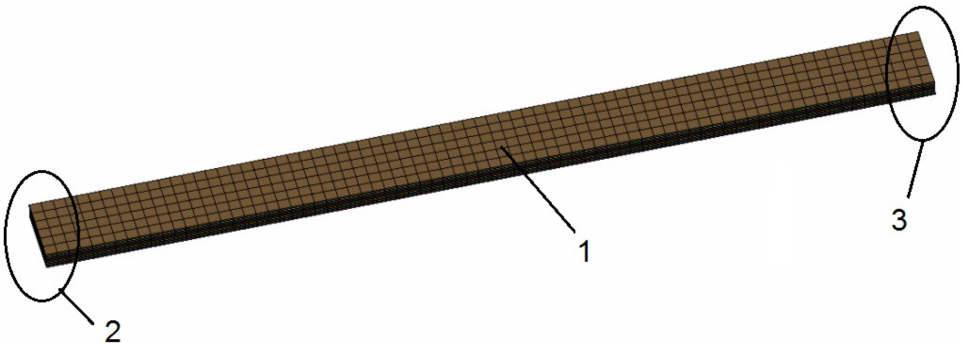
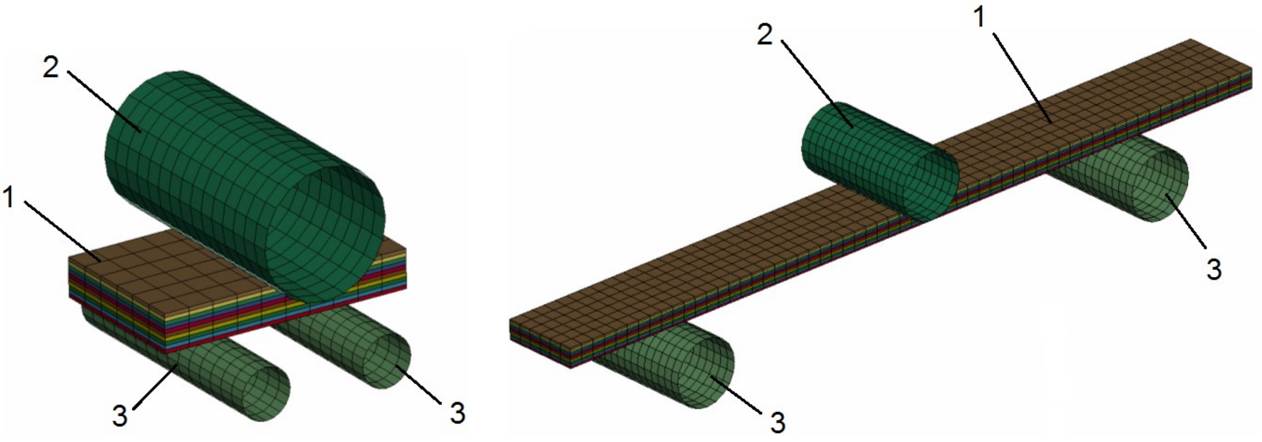
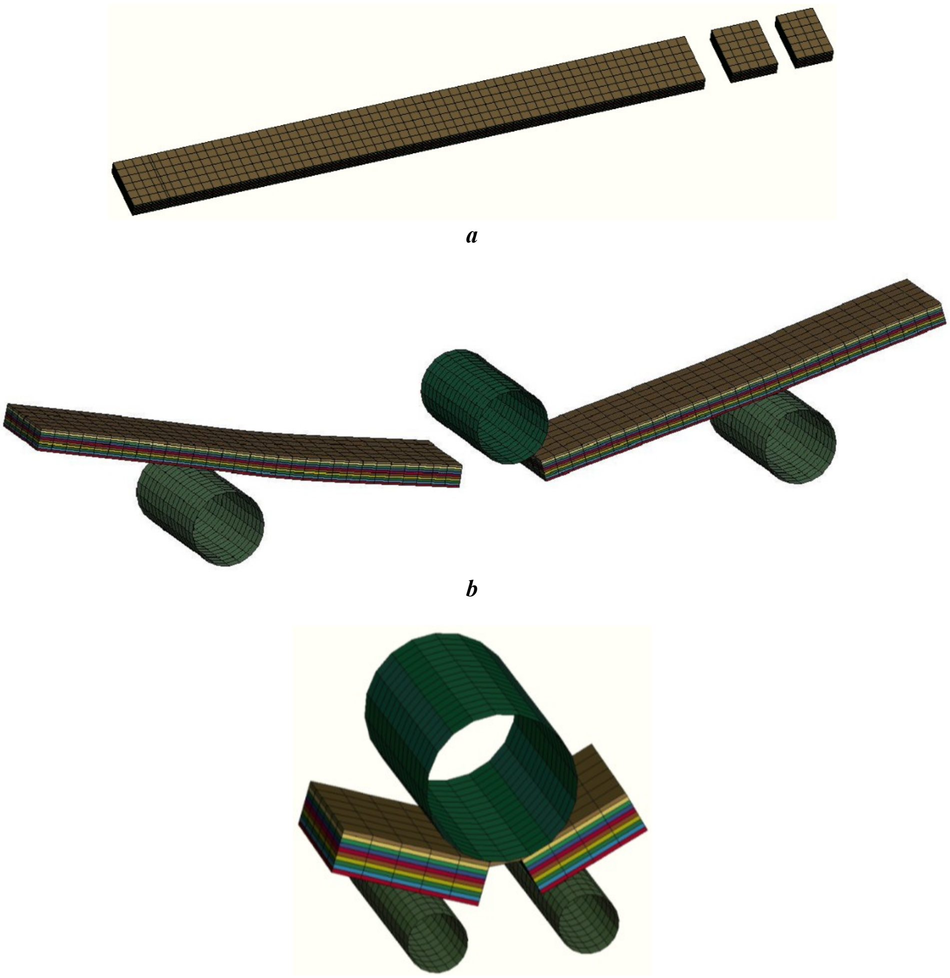


*Fig. 1. A model for mathematical simulation of uniaxial tension of a composite:*
*1 – a composite; 2 – a gripping support; 3 – a movable support*



*a* *b*

***Fig. 2.*** *Models for mathematical simulation:* ***a*** *– for interlaminar shear;* ***b*** *– for three-point bending.*
*1 – a composite, 2 – a press-on force plunger, 3 – a support*



*a*

*b*

*c*

***Fig. 3.*** *Test patterns:* ***a*** *– for uniaxial tension;* ***b*** *– for three-point bending;* ***c*** *– for interlaminar shear of a composite*

***Table 1.*** *The range of variations of conditions of drilling holes in the BKУ-39 polymer composite material during mathematical simulation using digital twins*

| No. | The magnitude of the ultrasonic vibration amplitude, µm | Friction coefficient |
|---|---|---|
| 1 | 0 | 0.0 |
| 2 | 6 | 0.0 |
| 3 | 13 | 0.0 |
| 4 | 0 | 0.1 |
| 5 | 0 | 0.2 |

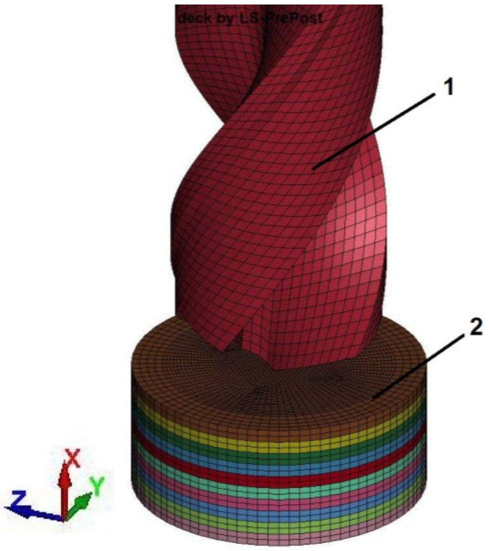


***Fig. 4.*** *A model of a drilling tool and a composite for simulating a drilling process: 1 – a drilling tool, 2 – a composite*

using digital twins: operational cutting speed – 3.14 m/min, axial feed – 0.2 mm/rev. A drilling tool and composite model for simulating a drilling process is shown in Fig. 4.

A spiral two-blade drilling tool with a diameter of 5 mm, a length of 14 mm and an angle at the top of $2\varphi=140$ degrees was taken as a cutting tool model. The model was represented by the solid-state elements with the sides of 0.25–0.3 mm. A cylinder 7 mm in diameter and 3 mm high was the composite blank model. In height, the composite model included 10 layers of interconnected prepregs. Each layer was a model consisting of thick-walled shell elements with dimensions of 0.1–0.15 mm.

As the main model of the material (BKУ-39), the authors used the model of a composite orthotropic material with destruction.

After calibrating the model, the test parameters were adjusted. The failure of the material model was also set from the action of tensile stresses and amounted to 1610 MPa in the longitudinal (*XT*) and transverse (*YT*) directions of the composite. The values of breaking maximum strains of the composite and matrix layers were increased to 0.032.

The following parameters were used:

– normal stresses of the adhesive layer failure – 0.15 MPa;

– shear stresses of the adhesive layer failure – 1.5 MPa;

– failure energy (normal direction) – 0.9 mJ;

– failure energy (shear direction) – 0.9 mJ;

– rigidity (normal direction) – 6.25 MPa.

The failure parameters of the adhesive layer for bonding the layers of the composite were determined, based on the strength data of the applied adhesive compositions after carrying out tests and their validation.

To assess the conditions of the contact between the drilling tool and the composite, as well as the contacts between the layers of the composite itself (after the adhesive bond failure), a single contact taking into account the material failure was set.

To retain the force and the moments from the drilling tool impact, a penalty contact card was used.

To reduce the calculation time, the angular velocity of the drilling tool rotation was significantly increased and amounted to 628 rad/s. Such an increase is allowed in calculations in dynamic analysis programs when tracking the total energy of the process (the dynamic component should not exceed 10 % of the total energy of the process). The axial feed was 0.2 mm/rev.

The composite blank was fixed along the outer surface (Fig. 4, 5) by defining and limiting the nodal set.

After preparing the finite element model in the LS-DYNA version 971 V10.2 program, a double precision calculation was performed.

The stages of drilling a composite are shown in Fig. 6.

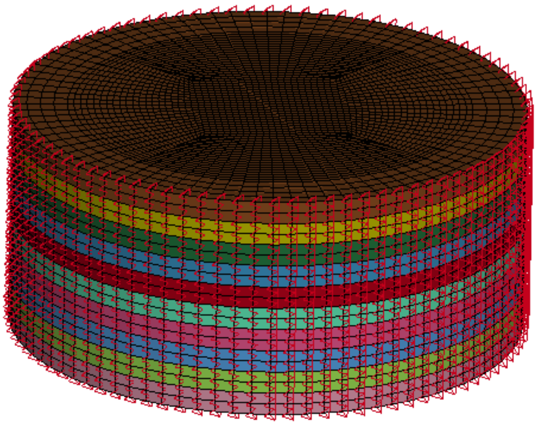
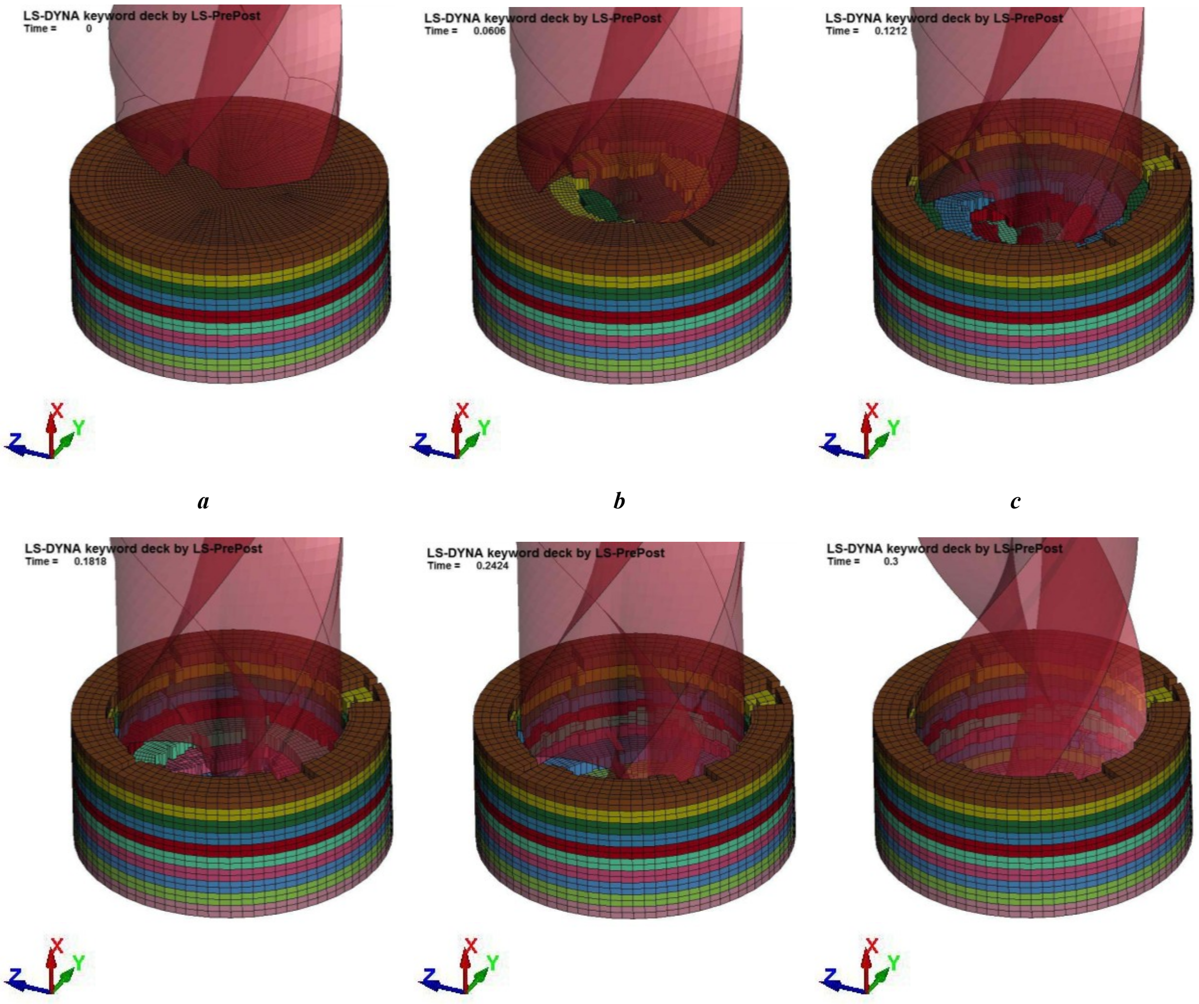


***Fig. 5.*** *Angle restriction along the external cylindrical section of a composite blank*



***a*** ***b*** ***c***

***d*** ***e*** ***f***

***Fig. 6.*** *Composite drilling stages:* ***a*** *– 0 s;* ***b*** *– 0.06 s;* ***c*** *– 0.12 s;* ***d*** *– 0.18 s;* ***e*** *– 0.24 s;* ***f*** *– 0.3 s*

The influence of changes in the ultrasonic vibration amplitude and the ratio of friction between a rotating drilling tool and a composite blank on the efficiency of drilling composite material blanks was studied.

The ultrasonic vibrations were applied to the tool in the direction of the drill feed (along the *X*-axis). For this purpose, the motion function was specified in the initial settings. The following dependence on *time* was used as a function:

$$0.006 \cdot \sin(125600 \cdot \mathrm{time}) + 6 \cdot \mathrm{time}\ ,$$

where the parameter 0.006 is the vibration amplitude, in this case equal to 0.006 mm (6 μm);
parameter 125600 was determined from the dependence 2πω, where ω is the vibration frequency equal to 20 kHz.

The first summand of the function ensured the US vibration excitation; the second summand ensured the drilling tool feed.

## RESULTS

The results of ВКУ-39 composite simulation for uniaxial tension, three-point bending, and interlaminar shear of the composite are shown in Fig. 7, 8.

The initial differences in the force of impact on the samples in some tests were in the range of 30–50 %. Additionally, varying the parameters of the material models in terms of the maximum tensile, and compressive strain of the composite layers, and the adhesive layer (in terms of normal and shear stresses and fracture energy), the authors managed to obtain a difference of no more than 10–15 %.

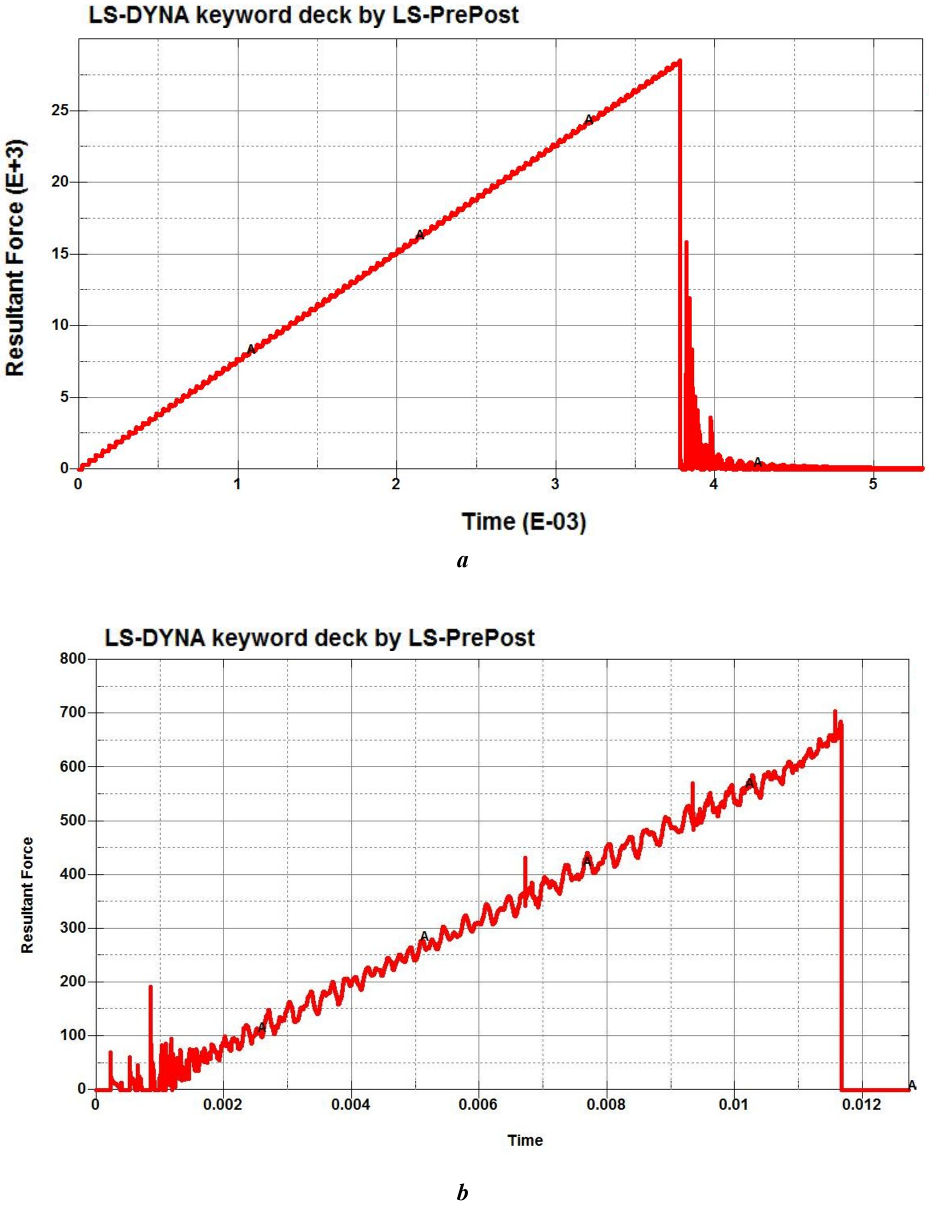
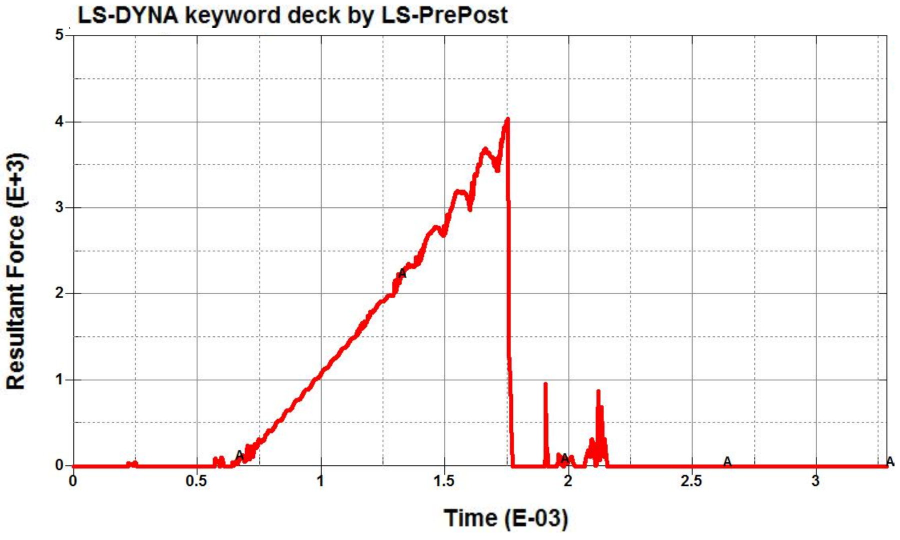


***Fig. 7.*** *The results of simulating the ВКУ-39 composite:*
***a*** *– for uniaxial tension;* ***b*** *– for three-point bending.*
*In y-direction, a force in N is shown, in x-direction – time in s*



*c*

***Fig. 8.*** *The results of simulating the ВКУ-39 composite for interlaminar shear of ВКУ-39 composite.*
*In y-direction, a force in N is shown, in x-direction – time in s*

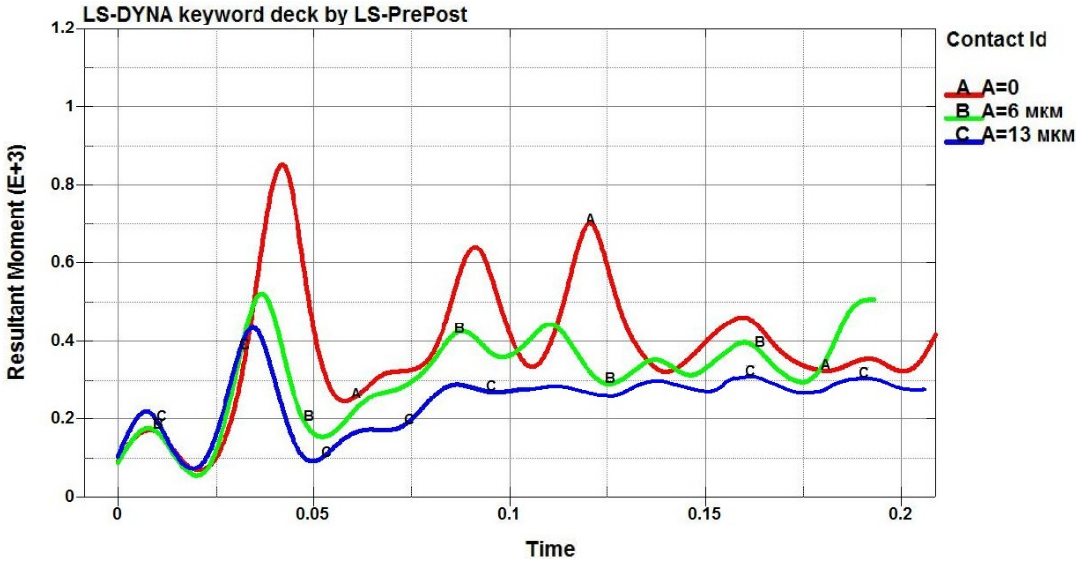


***Fig. 9.*** *The dependence of a resultant moment on the amplitude value when applying ultrasound.*
*In the graph: A – without ultrasound;*
*B – ultrasound with an amplitude of 6 micron;*
*C – ultrasound with an amplitude of 13 micron*

Fig. 9 shows a diagram of the resultant moment dependence on the ultrasound amplitude magnitude. As one can see from Fig. 8, the introduction of ultrasonic vibration energy, with a frequency of 20 kHz and an amplitude of 6 µm into the treatment zone reduces the peak resultant moment from 860 to 515 N·mm. Drilling holes with the introduction of ultrasound with an amplitude of 13 µm allows reducing the peak moment to 430 N·mm.

Fig. 10 shows a diagram of the resultant moment dependence on the friction ratio. As one can see from the presented results, with a friction ratio equal to 0.2, the peak resultant moment is 1680 N·mm. The decrease in the friction ratio to 0.1 reduces the resultant moment to 1250 N·mm. With a friction ratio equal to zero (0), the resultant moment reduces to a minimum value of 810 N·mm.

## DISCUSSION

According to the results of the study, one can argue that a decrease in the friction ratio under the ultrasound action, most certainly leads to a decrease in the resultant moment.

The performed computational investigations prove that the use of the obtained results can significantly reduce the duration or completely eliminate the need for experimental studies and full-scale tests to assess the influence of the cutting mode elements and the cutting tool design

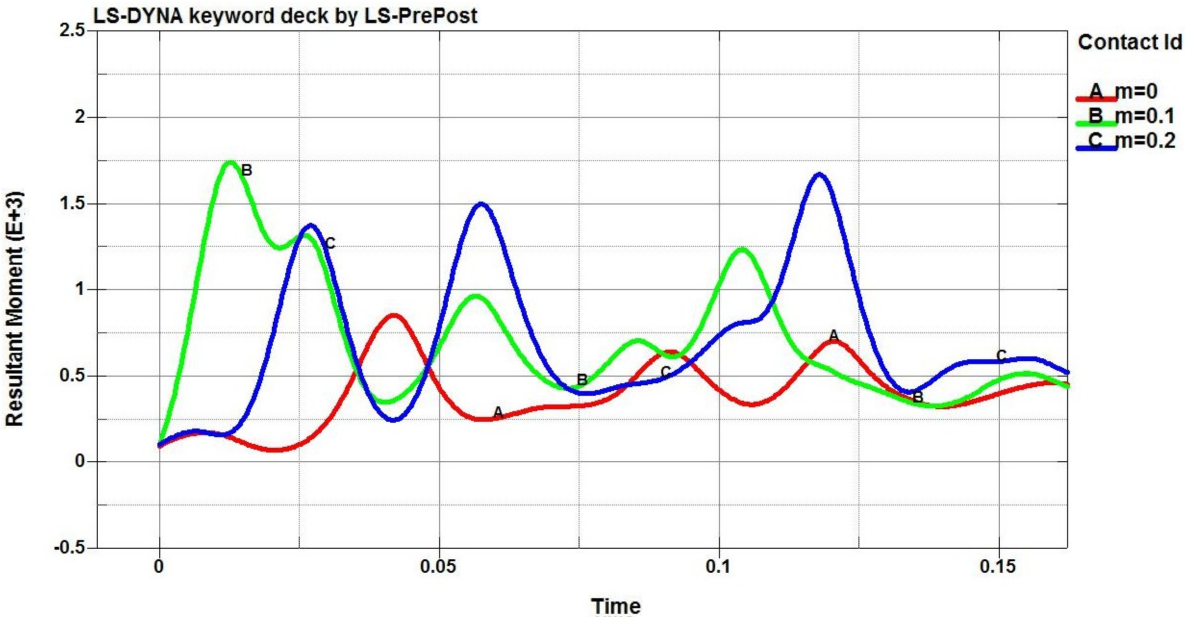


***Fig. 10.*** *The dependence of a resultant moment on the ratio of friction (m) between a drilling tool and a composite*

parameters on the power and energy aspects of the formation of the machined surfaces of parts made of the ВКУ-39 type composite materials. In turn, this will allow significantly reducing the expenditures for technological preparation for manufacturing composite products, which means the achievement of the goal.

It is well known that the introduction of the ultrasonic vibration energy into the treatment zone leads to a decrease in the ratio of friction between the rotating tool and the metal blank being processed [12; 13].

The study visually established that the ultrasonic field energy introduction into the zone of formation of new surfaces, favorably affects the quality of the surface layer of parts made of polymer composite materials, and helps to reduce energy consumption for cutting processes and the cutting tool wear. The latter allows significantly increasing the productivity of processing blanks from such materials and reducing the cost of manufacturing parts from them.

For complete verification of computational investigations of the processes of cutting blanks from other PCMs based on carbon fibres, it is necessary to continue experimental tests on typical representatives of the existing classes of composite materials. The verification results, after making appropriate adjustments to the calculated data, will probably allow expanding the areas of using digital twins for simulating the processes of drilling blanks from other classes of polymer composite materials.

## CONCLUSIONS

Thus, the research results prove that the developed computer models of the processes of drilling blanks made of laminated polymer composite materials, including with the ultrasonic field energy introduction into the zone of the new surfaces formation, are comparable to full-scale tests when testing the selected cutting mode elements, cutting tools, and other mechanical processing conditions. Considering that the use of digital twins to perform this stage of production technological preparation in the conditions of existing enterprises is not associated with expensive operation of machinery, one should expect a significant reduction in the cost of manufacturing components and parts made of similar materials in the industry, primarily in small-scale and single-item production.

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