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Study of thermophysics during diamond drilling of fibreglass and carbon fibre-reinforced polymer composites

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Abstract: This paper examines thermophysics of the drilling process of polymeric composite materials, such as carbon-fibre-reinforced plastics (CFRP) and fibreglass by tubular diamond drill bits. Features of the COMSOL Multiphysics engineering software package were used. We employed Fourier heat equations, which express the intensity of heat gain by a mobile source in a moving coordinate system. The research was performed using the proprietary method of modelling spatial thermal action upon drilling polymer composite materials (fibreglass and carbon-fibre-reinforced plastics) in the COMSOL Multiphysics software environment. A tubular diamond drill bit with a diameter of 10 mm with two slots was chosen as a model cutting tool. Solid plates with a thickness of 5.5 mm made of layered fibrous polymer composite materials (fibreglass, carbon-fibre-reinforced plastic) were used as a preform. As a result of computer calculations, we obtained temperature fields of fibreglass and carbon-fibre-reinforced plastic during diamond drilling with a tubular tool. When studying the thermal behaviour of fibreglass and carbon-fibre-reinforced plastics, maximum temperature fields were located. The study revealed that the temperature reaches 413.6 and 448.7 K during CFRP and fibreglass drilling, respectively. It was shown that the distance of heat transfer from the edge of the hole into the preform was 6.42 and 6.40 mm for CFRP and fibreglass, respectively. A method of modelling the thermal effects when cutting polymer composite materials developed in the COMSOL Multiphysics environment allows complex analytical calculations of temperatures induced by drilling to be simplified. In addition, its use prevents overheating of a preform during drilling, allows assessing the depth of heat distribution inside the preform from the edge of the formed hole in different polymer composite materials. These measures increase the machining quality of polymer composite materials.

Keywords: thermal physics, drilling, cutting, polymer composite materials, temperature, heat capacity

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Исследование теплофизики при алмазном сверлении стеклопластиков и углепластиков

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Резюме: Цель – исследование теплофизики процесса сверления трубчатыми алмазными сверлами полимерных композиционных материалов типа углепластиков, стеклопластиков на основании возможностей инженерного пакета Comsol Multiphysics. В работе использованы уравнения теплопроводности Фурье, выражающие интенсивность притока теплоты движущимся источником в подвижных координатах. Исследования проводились с применением авторской методики моделирования пространственного термического воздействия при сверлении полимерных композиционных материалов (стеклопластиков и углепластиков) в среде Comsol Multiphysics. В качестве модели режущего инструмента была выбрана конструкция алмазного сверла трубчатого типа диаметром 10 мм с двумя прорезями. В качестве модели заготовки были спроектированы твердотельные модели пластин толщиной 5,5 мм из слоистых волокнистых полимерных композиционных материалов: стеклопластика, углепластика. В результате компьютерного расчета были получены температурные поля стеклопластика и углепластика при сверлении алмазным трубчатым инструментом. При изучении термического воздействия стеклопластиков и углепластиков установлены дислокации максимальных температурных полей. В проведенном исследовании было выявлено, что температура при сверлении углепластика достигает 413,6 К, а температура при сверлении стеклопластика – 448,7 К. Показано, что расстояние, на которое распространяется тепло от краев отверстия внутрь заготовки, у углепластика составляет 6,42 мм, а у стеклопластика – 6,40 мм. Разработанная методика моделирования термического воздействия резания полимерных композиционных материалов в среде COMSOL Multiphysics позволяет значительно упростить сложные аналитические расчеты возникающих при сверлении температур, помогает избежать перегрева заготовки при сверлении, позволяет оценить глубины распространения теплоты внутрь заготовки от края образованного отверстия различных типов полимерных композиционных материалов, что повышает качество механической обработки деталей из полимерных композиционных материалов.

Ключевые слова: теплофизика, сверление, резание, полимерные композиционные материалы, температура, теплоемкость

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INTRODUCTION

Polymeric composites are multi-component materials comprising a plastic matrix and a filler – reinforcing fibres with a high strength, stiffness and other properties. Combining different source components yields an advanced composite material with new properties uncharacteristic of its original constituents. One can obtain a wide range of polymer composite materials with the required properties by varying the composition of the matrix and filler, their ratio, the orientation of reinforcing fibres. Many polymer composite materials (PCM) surpass conventional engineering materials and alloys not only in their mechanical properties, but also lightness. Using polymer composite materials allows the weight of the constructions to be reduced while maintaining or improving their mechanical characteristics.

According to Melentyev et al., machining, in particular, PCM drilling, has a number of specific characteristics, determined by particularities of their structure, mechanical and thermophysical properties [1–4]. Nevertheless, PCM machining is accompanied by the same phenomena as that of metals, i.e., chip formation, power and thermal effects, intensive wear of the cutting tool. Each of these phenomena has its own specifics when cutting metals; therefore, it is necessary to evaluate the thermophysical effects of PCM cutting to control the entire process [4, 5].

AIM

Mechanical processing of PCM has been poorly studied for several reasons[1] [6]. Thermal effects play an important role in the machining process.

PCMs have a pronounced anisotropy of not only physical-mechanical but also thermophysical properties, which complicates the problem.

The aim of this study was to determine temperatures in the cutting zone of polymer composite materials, i.e. fibreglass and carbon-fibre-reinforced plastic (CFRP), drilled with a diamond tool, as well as to establish the depth of heat distribution from the edge of the hole inside various PCM samples.

Thermophysical analysis conducted to manage thermal processes during operation is a possible approach to product quality improvement [7].

The temperature in the cutting zone can be determined experimentally or calculated. Two numerical methods are used to calculate temperature fields in the cutting zone: finite element method and finite difference method [8].

The thermal solution during cutting is considered time-consuming [9–16]. For the fibrous polymer composite parts, the complexity increases manifold [17, 18]. Engineering packages such as computer-aided engineering (CAE) ANSYS, Abaqus, COMSOL Multiphysics and other computer-aided design systems have been developed to facilitate thermal and other related problems.

The above-mentioned CAEs interpret the process of solving engineering and scientific problems using numerical methods. Add-in modules contain specialised tools for modelling the processes and effects in electrodynamics

[1]Dudarev AS. Increasing the efficiency and quality of machining the holes based on stabilising the drilling of the polymer composite materials: thesis … PhD Tech.: 05.02.08. Perm, 2009. 170 p. / Дударев А.С. Повышение эффективности и качества обработки отверстий на основе стабилизации процесса сверления изделий из полимерных композиционных материалов: дис. … канд. техн. наук: 05.02.08. Пермь, 2009. 170 с.

and optics, mechanics and acoustics, hydrodynamics and heat transfer, chemistry and electrochemistry, etc.

A numerical simulation of drilling was performed in the COMSOL Multiphysics engineering package.

Numerical simulation of cutting during machining gives the following advantages in comparison with analytical and experimental research methods [19]:

– timely, three-dimensional representation of power characteristics and heat transfer processes;

– consideration of the effect of temperature and its propagation rate on the physical and mechanical properties of materials when modelling the moulding process;

– relatively low-budget research.

RESEARCH METHOD

The COMSOL Multiphysics environment was used to simulate thermal effects when drilling polymer composite materials.

A tubular diamond drill bit with a diameter of 10 mm with two slots was chosen as a model cutting tool (fig. 1). The structure was subjected to preliminary industrial tests [20].

Fig. 1. Example of tubular drill bit (diameter of 10 mm)
Рис. 1. Общий вид трубчатого сверла (диаметр 10 мм)

Constructing the geometry is one of the first steps in developing a machining process. The COMSOL package offers various geometric operations, tools and functions to render geometry, including inbuilt geometry primitives, as well as logical, splitting and other CAD operations.

Our study included surface modelling of a cutting tool and polymer composite preforms (fibreglass and CFRP). Then the interconnection was established, and the calculation began.

A three-dimensional model of the tubular diamond drill bit with a diameter 10 of mm is shown in fig. 2.

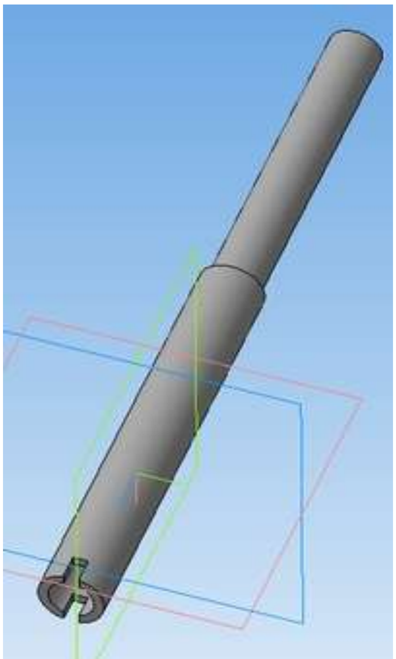

Fig. 2. Three-dimensional model of a tubular drill bit (diameter of 10 mm)
Рис. 2. Трехмерная модель трубчатого сверла (диаметр 10 мм)

When creating a preform model in the form of a PCM plate (polymer binding matrix and reinforcing fibres), a Rectangle command was used. Cross-section of PCMs comprises a laminated structure of fibres and a matrix; therefore using simple cylinders and rectangles in the cross-section model is reliable. Using simple figures, we built a layered plate structure with a total height of 5.5 mm and set cohesion bonds between the layers. The plates comprised reinforcing glass fibres with a binder and carbon fibres with the binder. The thickness of the binder was 50 μm, the thickness and diameter of fibres were 150 μm.

A processing model was created first in the form of a 2D rough drawing in 2D Axisymmetric (fig. 3). Further, the obtained rough drawing was turned through 360°, thus creating a 3D surface of a slot.

The Point command was utilised to separate the block scope of the figure through the boundaries. A separate boundary was formed for further application of the thermal effects.

To simulate the heat effect, the Heat Transfer submenu was selected in the physics section. The Heat Transfer interface and thermal multi-physical links were used to simulate heat transfer by thermal conductivity, convection and conjugated heat transfer.

Heat Transfer in Solids function is based on the Fourier Law. The stationary mode was selected. For heat transfer, the stationary mode is used to calculate the temperature field at thermal equilibrium.

The inbuilt COMSOL library allows material with the characteristics and properties of a polymer composite to be used. Each material is characterised by properties and defined functions. The library provides 24 main temperature-dependent characteristics. In the COMSOL software complex, material properties can be presented in a graph, and new components can be added to the library.

For models of the contact problem arising from the interaction of a diamond-tube tool with various polymer composite preforms, it is necessary to choose fibreglass and carbon-fibre-reinforced plastic.

As known [21], polymer composite materials comprise the layers of filler (fibreglass, carbon fibre) and binder (epoxy resin matrices). Therefore, we build the layers, set the properties (table) layer by layer and the cohesion bonds between them.

In addition, thermophysical properties of polymeric composite materials (glass and carbon fibres, binder) were assigned average values (table).

Heat-balance calculations for diamond drilling of polymer composite materials were performed using the thermal conductivity equation for deformed bodies. This heat equation - the energy equation - is derived from the law of thermodynamics [22].

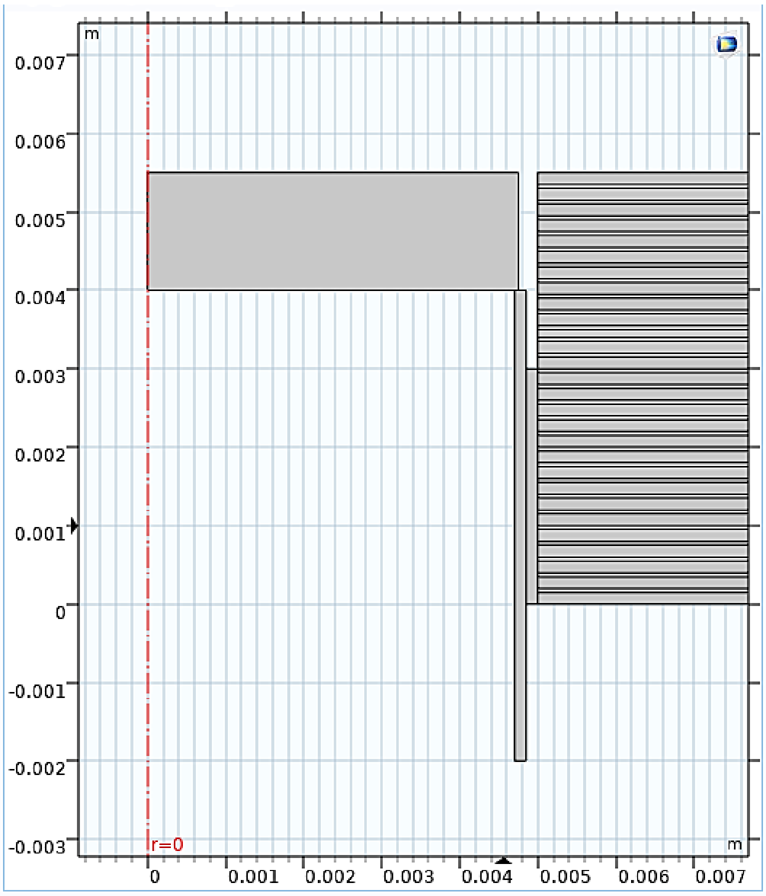

Fig. 3. Longitudinal section of a half drill bit and a polymer composite preform
Рис. 3. Продольное сечение половины сверла и заготовки из полимерных композиционных материалов

Thermophysical properties of polymer composite materials
Теплофизические свойства полимерных композиционных материалов

Material	Heat capacity C_p, J / (kg K)	Density r, kg / m^3	Thermal conduction coefficient λ, W / (m K)
Binder (epoxy resin)	1110	1200	0,5
Glass fibre	1700	2580	40
Carbon fibre	1100	1200	100

The COMSOL Multiphysics heat equation is as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \overline{\nabla T} + \overline{\nabla} \cdot \mathbf{q} = Q, \quad (1)$$

where ρ is the density, kg/m^3; C_p is the specific heat, J/(kg·°C); **u** is the velocity vector, m/s; $\overline{\nabla T}$ is the temperature gradient, °C/m; **q** is the heat flow vector, W/m^2; Q is the power of heat source per unit volume, W/m^3.

For solid bodies, heat equation (1) has a slightly different form in the COMSOL Multiphysics program window:

$$\rho C_p u \cdot \nabla T + \nabla q = Q + Q_{ted}, \quad (2)$$

where Q_{ted} is the correction for change from an external thermal source, W/m^3.

The velocity vector can be rewritten in the following form:

$$\mathbf{u} = u_x \mathbf{i} + u_y \mathbf{j} + u_z \mathbf{k}, \quad (3)$$

where u_x, u_y, u_z is the component of the motion speed of the point in a thermally conductive medium, m/s; $\mathbf{i}, \mathbf{j}, \mathbf{k}$ are the unit vectors in the Cartesian coordinate system.

A temperature gradient $\overline{\nabla T}$ is a vector directed normally to the isothermal surface towards the temperature increase and numerically equal to temperature change per unit length.

$$\overline{\nabla T} = \mathbf{n} \frac{\partial T}{\partial n},$$

where $\mathbf{n}$ is the unit vector; n is a normal; $\overline{\nabla}$ is the Hamiltonian (Nabla), a symbolic vector that replaces a gradient symbol.

Based on (2), ∇T can be expressed as follows:

$$\nabla T = \frac{\partial T}{\partial x}.$$

In case heat is distributed along three axes:

$$\nabla T = \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z}.$$

A vector of heat flow rate: $q = -\lambda \overline{\nabla T}$, where λ is the thermal conduction coefficient, W/m °C.

Analysis of the thermal field during diamond drilling is based on solving the Fourier three-dimensional differential heat equation using common descriptions of heat flows from instantaneous point heat source.

To calculate heat fields, we selected heat-load lines applied to the polymer composite preforms from a cutting grit of the tool and set heat flow values: $q = 40 \cdot 10^{6}$ W/m^2. The heat flow value was taken from the following work [2]. The other used constants are shown in the table; the following additional literature sources were used. [23–25].

RESULTS

A solution to the discussed complex practical problem was derived based on solving the Fourier heat equation (2) for a three-dimensional case.

As a result of calculating the drilling process, performed on carbon-fibre-reinforced plastic, the temperature fields in the hole were obtained (fig. 4). The temperature distribution plot in the material from the edge of the hole is demonstrated in fig. 5.

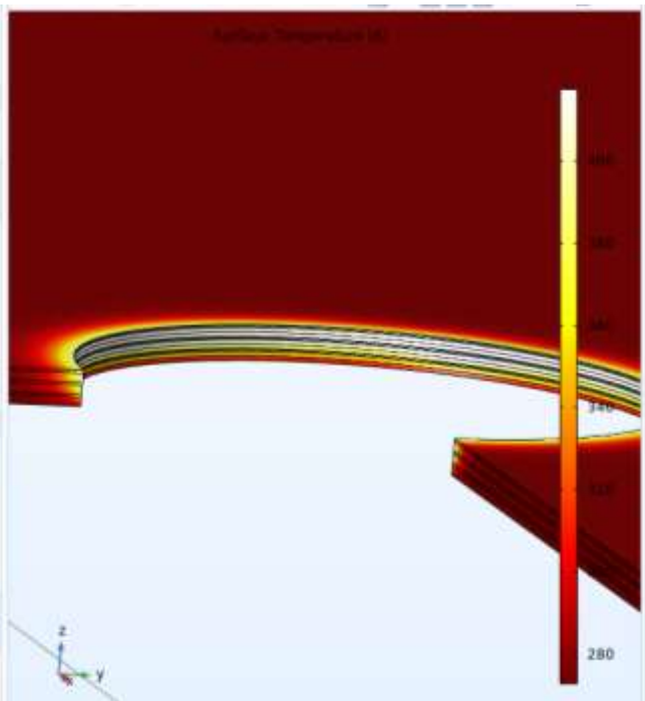

Fig. 4. Results of thermal field distribution in the cross-section of the hole in carbon-fibre-reinforced plastic
Рис. 4. Результаты распределения тепловых полей в сечении отверстия углепластика

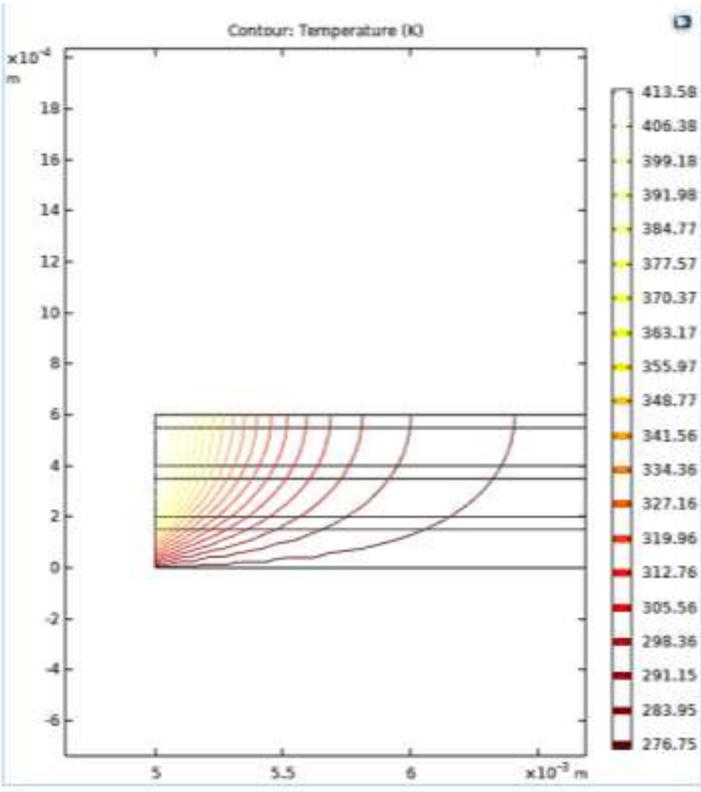

Fig. 5. Temperature as a function of hole boundary in carbon-fibre-reinforced plastic
Рис. 5. Зависимость температуры от границы отверстия в углепластике

As a result of calculating the drilling process, performed on fibreglass, the temperature fields in the hole were obtained (fig. 6). The temperature distribution plot in the material from the edge of the hole is demonstrated in fig. 7.

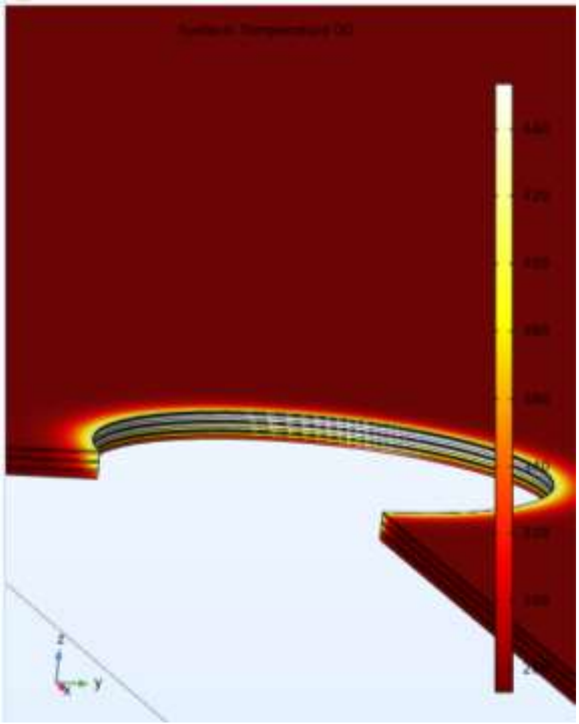

Fig. 6. Results of thermal field distribution in a cross-section of a hole in fibreglass
Рис. 6. Результаты распределения тепловых полей в сечении отверстия стеклопластика

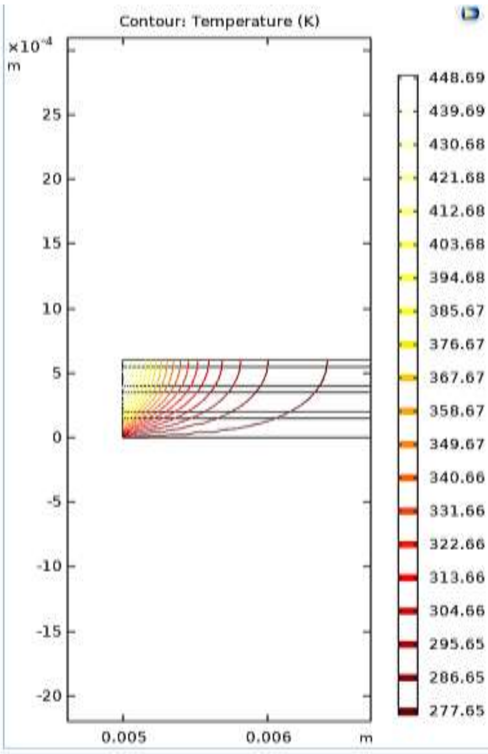

Fig. 7. Temperature as a function of hole boundary in fibreglass
Рис. 7. Зависимость температуры от границы отверстия в стеклопластике

When comparing fig. 5 and fig.7, one can notice a slightly deeper heat distribution in the fibreglass preform in fig. 7 and a higher temperature than that in the CFRP when the tubular drill bit is used.

CONCLUSIONS

As a result of computer calculations, we obtained temperature fields for fibreglass and carbon-fibre-reinforced plastic. The temperature field of fibreglass has a higher distribution through the preform volume owing to the higher thermal conduction coefficient of fibreglass (100 W/(m·K)) than that of carbon-fibre-reinforced plastic (40 W/(m·K)).

The temperature of the carbon-fibre-reinforced composite and fibreglass reaches 413.6 and 448.7 K, respectively. The distance of the heat distribution from the hole boundary for carbon-fibre-reinforced composite and fibreglass was 6.42 and 6.40 mm, respectively. Therefore, the difference in the depth of heat distribution for the described materials is insignificant.

The developed method of simulating the thermal effect of cutting polymer compound materials in the COMSOL Multiphysics environment allows possible overheating to be assessed. The overheating of the preform during processing can be avoided, resulting in higher processing quality.

References

1. Melentev RYu. Computer modeling of the thermal field in the elementary volume of polymer composites. *Problemy mashinostroeniya = Journal of Mechanical Engineering.* 2014;17(2):3–8. (In Russ.)
2. Dudarev AS, Svirshchev VI. Evaluation of the temperature field at diamond drilling of polymer composite materials. *Izvestiya Tul'skogo gosudarstvennogo universiteta = Proceedings of the Tula State University*. 2016;3:188–194. (In Russ.)
3. Ismail SO, Dhakal HN, Dimla E, Beaugrand J, Popov I. Effects of drilling parameters and aspect ratios on delamination and surface roughness of lignocellulosic HFRP composite laminates. *Journal of Applied Polymer Science*. 2016;133:42879. https://doi.org/10.1002/app.42879
4. Sadek A, Shi B, Meshreki M, Duquesne J, Attia MH. Prediction and control of drilling-induced damage in fiber-reinforced polymers using a new hybrid force and temperature modelling approach. *CIRP Annals*. 2015;64(1):89–92. https://doi.org/10.1016/j.cirp.2015.04.074
5. Kuklin IA, Dudarev AS, Podvincev AV. On temperature field calculation at cutting. In: *Aerokosmicheskaya tekhnika, vysokie tekhnologii i innovacii: sbornik nauchnyh trudov XX Vserossijskoj nauchno-tekhnicheskoj konferencii = Aerospace equipment, high technologies and innovations: collected scientific articles of XX All-Russian scientific and technical conference*. 19–20 November 2019, Perm'. Perm'; 2019, vol. 2, p. 106–109. (In Russ.)
6. Davim JP. *Machining Composites Materials*. London – Hoboken: John Wiley & Sons; 2009, 262 p.
7. Suslov AG. *Quality of machine part surface layer.* Moscow: Mashinostroenie; 2000, 320 p. (In Russ.)
8. Usachev PA, Noshchenko AN. Calculation of cutting zone temperature fields. *Stanki i instrument*. 1986;2:23–24. (In Russ.)
9. Vorontsov AL, Sultan-zade NM, Albagachiev AYu, Savkin AI. Development of a new theory of thermal cutting processes. 4. Analysis of the basic thermophysical theories of cutting. Part 1. *Vestnik mashinostroeniya = Russian Engineering Research.* 2010;4:68–71. (In Russ.)
10. Vorontsov AL, Sultan-zade NM, Albagachiev AYu, Savkin AI. Development a new theory of thermal cutting processes. 5. General mathematical apparatus of the thermophysics of cutting. Part 1. *Vestnik mashinostroeniya = Russian Engineering Research*. 2010;12:65–73. (In Russ.)
11. Vorontsov AL, Sultan-zade NM, Albagachiev AYu, Savkin AI. Development of a new theory of thermal cutting processes. 5. General mathematical apparatus of the thermophysics of cutting. Part 2. *Vestnik mashinostroeniya = Russian Engineering Research*. 2011:1:61–67. (In Russ.)
12. Vorontsov AL, Sultan-zade NM, Albagachiev AYu, Savkin AI. Development of a new theory of thermal cutting processes. 5. General mathematical apparatus of the thermophysics of cutting. Part 3. *Vestnik mashinostroeniya = Russian Engineering Research*. 2011;2:74–79. (In Russ.)
13. Vorontsov AL, Sultan-zade NM, Albagachiev AYu, Savkin AI. Development of a new theory of thermal cutting processes. 6. Determining the temperature fields and contact temperatures in cutting. Part 1. *Vestnik mashinostroeniya = Russian Engineering Research*. 2011;3:69–74. (In Russ.)
14. Vorontsov AL, Sultan-zade NM, Albagachiev AYu, Savkin AI. Development of a new theory of thermal cutting processes. 6. Determining the temperature fields and contact temperatures in cutting. Part 3. *Vestnik mashinostroeniya = Russian Engineering Research*. 2011;5:63–71. (In Russ.)
15. Dimov YuV, Podashev DB. Cutting temperature when processing with elastic abrasive wheels. *Vestnik mashinostroeniya = Russian Engineering Research*. 2020;8:55–60. (In Russ.) https://doi.org/10.36652/0042-4633-2020-8-55-60
16. Zaslavskiy IYa. Cutter heat conduction and temperature in cutting zone. *Vestnik mashinostroeniya = Russian Engineering Research*. 2015;2:70–73. (In Russ.)
17. Nasonov FA, Bukharov SV. Studying the effect of special modification of epoxy matrices and epoxy matrix-based carbon fiber composites on the temperature in the cutting zone under hole formation. *Vestnik Irkutskogo gosudarstvennogo tehnicheskogo universiteta = Proceedings of Irkutsk State Technical University.* 2018;22(10):141–152. (In Russ.)

https://doi.org/10.21285/1814-3520-2018-10-141-152
18. Erenkov OYu, Ivakhnenko AG. Modeling of the polymeric material stressed and strained state at cutting considering cracks interaction. *Vestnik mashinostroeniya = Russian Engineering Research*. 2007;5:54–56. (In Russ.)
19. Grinek AV, Rubanov VG, Kalatozishvili IV, Mikhailov VV. Numerical modeling-based study of the cutting speed influence on the temperature and force condition in the machined area. *Vestnik Irkutskogo gosudarstvennogo tehnicheskogo universiteta = Proceedings of Irkutsk State Technical University*. 2016;8:10–19. (In Russ.) https://doi.org/10.21285/1814-3520-2016-8-10-19
20. Dudarev AS. Designs of drills and mills for diamond processings of polymeric composite materials. *Izvestiya Tul'skogo gosudarstvennogo universiteta = Proceedings of the Tula State University*. 2012;1:361–370. (In Russ.)
21. Sirotkin OS, Grishin VI, Litvinov VB. *Design, calculation and technology of aviation equipment connections*. Moscow: Mashinostroenie; 2006, 452 p. (In Russ.)
22. Yakimov AV, Slobodyanik PT, Usov AV. *Thermal physics of mechanical processing*. Kiev – Odessa: Lybid; 1991, 240 p.
23. Barinov DYa, Maiorova IA, Marakhovskii PS, Zuev AV, Kutsevich KE, Lukina NF. Mathematical modeling of temperature fields during curing of thick-walled fiberglass plate. *Perspektivnye materialy*. 2015;4:5–14. (In Russ.)
24. Mihajlovskij KV, Prosuncov PV, Reznik SV. On the development of space structures from high thermal conductivity polymer composite materials. *Vestnik Moskovskogo gosudarstvennogo tekhnicheskogo universiteta imeni N.E. Baumana*. Seriya: Mashinostroenie. 2012;9:98–106. (In Russ.)
25. Phadnis VA, Makhdum F, Roy A, Silberschmidt VV. Drilling in carbon/epoxy composites: Experimental investigations and finite element implementation. In: *Composites. Part A: Applied Science and Manufacturing*. 2013;47:41–51. https://doi.org/10.1016/j.compositesa.2012.11.020

Список литературы

1. Мелентьев Р.Ю. Компьютерное моделирование теплового поля в элементарном объеме полимерных композиционных материалов // Проблемы машиностроения. 2014. Т. 17. № 2. С. 3–8.
2. Дударев А.С., Свирщёв В.И. Оценка температурного поля при алмазном сверлении полимерных композиционных материалов // Известия Тульского государственного университета. Технические науки. 2016. № 3. С. 188–194.
3. Ismail S.O., Dhakal H.N., Dimla E., Beaugrand J., Popov I. Effects of drilling parameters and aspect ratios on delamination and surface roughness of lignocellulosic HFRP composite laminates // Journal of Applied Polymer Science. 2016. Vol. 133 P. 42879. https://doi.org/10.1002/app.42879
4. Sadek A., Shi B., Meshreki M., Duquesne J., Attia M.H. Prediction and control of drilling-induced damage in fibre-reinforced polymers using a new hybrid force and temperature modelling approach // CIRP Annals. 2015. Vol. 64. Iss. 1. P. 89–92. https://doi.org/10.1016/j.cirp.2015.04.074
5. Куклин И.А., Дударев А.С., Подвинцев А.В. О расчете температурного поля при резании // Аэрокосмическая техника, высокие технологии и инновации: сб. науч. тр. XX Всерос. науч.-техн. конф. (г. Пермь, 19–20 ноября 2019). Пермь, 2019. Т. 2. С. 106–109.
6. Davim J.P. Machining Composites Materials. London – Hoboken: John Wiley & Sons, 2009. 262 p.
7. Суслов А.Г. Качество поверхностного слоя деталей машин. М.: Изд-во «Машиностроение», 2000. 320 с.
8. Усачев П.А., Нощенко А.Н. Расчет температурных полей зоны резания // Станки и инструмент. 1986. № 2. С. 23–24.
9. Воронцов А.Л., Султанзаде Н.М., Албагачиев А.Ю., Савкин А.И. Разработка новой теории тепловых процессов резания. 4. Анализ основных теоретических исследований теплофизики резания. Часть 1 // Вестник машиностроения. 2010. № 4. С. 68–71.
10. Воронцов А.Л., Султан-заде Н.М., Албагачиев А.Ю., Савкин А.И. Разработка новой теории тепловых процессов резания. 5. Анализ основных теоретических исследований теплофизики резания. Часть 1 // Вестник машиностроения. 2010. № 12. С. 65–72.
11. Воронцов А.Л., Султан-заде Н.М., Албагачиев А.Ю., Савкин А.И. Разработка новой теории тепловых процессов резания. 5. Общий математический аппарат теплофизики резания. Часть 2 // Вестник машиностроения. 2011. № 1. С. 61–67.
12. Воронцов А.Л., Султан-заде Н.М., Албагачиев А.Ю., Савкин А.И. Разработка новой теории тепловых процессов резания. 5. Общий математический аппарат теплофизики резания. Часть 3 // Вестник машиностроения. 2011. № 2. С. 74–79.
13. Воронцов А.Л., Султан-заде Н.М., Албагачиев А.Ю., Савкин А.И. Разработка новой теории тепловых процессов резания. 6. Определение температурных полей и контактных температур при резании материалов. Часть 1 // Вестник машиностроения. 2011. № 3. С. 69–74.
14. Воронцов А.Л., Султан-заде Н.М., Албагачиев А.Ю., Савкин А.И. Разработка новой теории тепловых процессов резания. 6. Определение температурных полей и контактных температур при резании материалов. Часть 3 // Вестник машиностроения. 2011. № 5. С. 63–71.
15. Димов Ю.В., Подашев Д.Б. Температура резания при обработке эластичными абразивными кругами // Вестник машиностроения. 2020. № 8. С. 55–60. https://doi.org/10.36652/0042-4633-2020-8-55-60
16. Заславский И.Я. Теплопроводность резца и температура в зоне резания // Вестник машиностроения. 2015. № 2. С. 70–73.
17. Насонов Ф.А., Бухаров С.В. Исследование влияния целевого модифицирования эпоксидных матриц и углепластиков на их основе на температуру в зоне резания при образовании отверстий // Вестник Иркутского государственного технического университета. 2018. Т. 22. № 10. С. 141–152.

https://doi.org/10.21285/1814-3520-2018-10-141-152
18. Еренков О.Ю., Ивахненко А.Г. Моделирование напряженно-деформированного состояния полимерного материала при резании с учетом взаимодействия трещин // Вестник машиностроения. 2007. № 5. С. 54–56.
19. Гринек А.В., Рубанов В.Г., Калатозишвили И.В., Михайлов В.В. Исследование влияния скорости резания на температурно-силовое состояние в зоне обработки методом численного моделирования // Вестник Иркутского государственного технического университета. 2016. № 8. С. 10–19. https://doi.org/10.21285/1814-3520-2016-8-10-19
20. Дударев А.С. Конструкции сверл и фрез для алмазно-абразивной обработки стеклопластиков и углепластиков // Известия Тульского государственного университета. 2012. № 1. С. 361–370.
21. Сироткин О.С., Гришин В.И., Литвинов В.Б. Проектирование, расчет и технология соединений авиационной техники. М.: Изд-во «Машиностроение», 2006. 452 с.
22. Якимов А.В., Слободяник П.Т., Усов А.В. Теплофизика механической обработки. Киев – Одесса: Изд-во «Лыбидь», 1991. 240 с.
23. Баринов Д.Я., Майорова И.А., Мараховский П.С., Зуев А.В., Куцевич К.Е., Лукина Н.Ф. Математическое моделирование температурных полей при отверждении толстостенной плиты стеклопластика // Перспективные материалы. 2015. № 4. С. 5–14.
24. Михайловский К.В., Просунцов П.В., Резник С.В. Разработка высокотеплопроводных полимерных композиционных материалов для космических конструкций // Вестник Московского государственного технического университета им. Н.Э. Баумана. Серия: Машиностроение. 2012. № 9. С. 98–106.
25. Phadnis V.A., Makhdum F., Roy A., Silberschmidt V.V. Drilling in carbon/epoxy composites: Experimental investigations and finite element implementation // Composites. Part A: Applied Science and Manufacturing. 2013. Vol. 47. P. 41–51. https://doi.org/10.1016/j.compositesa.2012.11.020

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