Calculation of Thermal Fields when Drilling Small-Sized Holes in Carbon Fiber Reinforced Plastic

Aleksandr S. Dudarev*

Perm National Research Polytechnic University, Perm, Komsomolsky prospekt, 29, 614990, Russia

Abstract. The Purpose of the paper. The study of thermal physics of the process of drilling polymer composite materials based on the capabilities of the engineering package Comsol Multiphysics. Determination of the values of temperatures arising in the cutting zone when drilling with a cutting tool in polymer composite materials, namely, in carbon fiber. Establishment of the depth of heat propagation inside the workpiece from the edge of the formed hole of the polymer composite material. In this work, the Fourier heat equations are used. Numerical simulation of the drilling process wascarried out in the engineering package COMSOL Multiphysics. A technique for modeling thermal effects during drilling of carbon fiber reinforced plastics in the Comsol Multiphysics environment has been developed. As a result of computer calculation, temperature fields were obtained at the edge of the carbon fiber reinforced plastic hole. The study of the thermal state of carbon plastics has been carried out. On the basis of the conducted research, it was revealed that the temperature during drilling of carbon fiber reaches 650 K. The distance over which heat spreads from the edges of the hole into the workpiece for carbon fiber is 3 mm. The developed technique for modeling the thermal impact of cutting polymer composite materials in the COMSOL Multiphysics environment can significantly simplify complex analytical calculations, help to avoid overheating of the part during drilling, which improves the quality of processing.

Introduction

Polymer composite materials are multicomponent materials consisting of a plastic matrix and filler - reinforcing fibers with high strength, rigidity, etc. Many polymer composite materials are superior to traditional structural materials and alloys in their mechanical properties and at the same time they are lighter. The use of polymer composite materials makes it possible to reduce the weight of the product structure while maintaining or improving mechanical characteristics.

Machining, in particular, drilling of polymer composite materials has a number of specific features, determined mainly by the peculiarity of their structure, mechanical and thermal properties [1]. At the same time, the process of cutting polymer composite

* Corresponding author: fanta88@mail.ru

materials is accompanied by the same phenomena as when cutting metals, i.e., chip formation, force, thermal phenomena, and intense wear of the cutting tool are observed. Each of the listed phenomena differs from similar phenomena during metal cutting, therefore, to control the processing of polymer composite materials, it is necessary to evaluate the thermophysical phenomena that occur during their cutting [2].

Purpose of the study

The mechanical processing of polymer composite materials has been little studied [3]. Among the processes accompanying mechanical processing, an important place belongs to thermal phenomena.

Polymer composite materials have a pronounced anisotropy of not only physical and mechanical, but also thermophysical properties, which significantly complicates the solution of the problem.

The purpose of the study presented in this article was to determine the temperatures that occur in the cutting zone when drilling with a spiral tool in polymer composite materials, namely, in carbon fiber. As well as establishing the difference in the depth of heat propagation inside the workpiece from the edge of the formed hole of a certain type of polymer composite materials - carbon fiber.

Carrying out thermophysical analysis in order to control thermal processes during technological operations is one of the reserves for improving the quality of products [4].

The calculation of the thermal problem during cutting is considered to be very time consuming [5, 6], and for parts made of fibrous polymer composite materials it is many times more difficult [7, 8]. To significantly facilitate the solution of thermal, as well as various related problems, engineering packages have been developed in our time, such as CAE systems ANSYS, ABAQUS, COMSOL Multiphysics [9] and other CAD systems.

These CAEs interpret the workflow for solving engineering and scientific problems using numerical methods. Extension modules contain specialized tools for modeling processes and phenomena in the field of electrodynamics and optics, mechanics and acoustics, hydrodynamics and heat transfer, chemistry and electrochemistry, etc.

Numerical simulation of the cutting process during machining provides the following advantages compared to analytical and experimental research methods [1, 9, 10]:

- prompt receipt of three-dimensional maps of power characteristics and heat transfer processes;
- taking into account in the model of the process of shaping the influence of temperature and speed of propagation on the physical and mechanical properties of materials;
- relatively low-budget research.

Research methodology

Modeling of thermal phenomena during drilling of small-sized holes in polymer composite materials was performed using the COMSOL Multiphysics engineering package.

The design of a high-speed twist drill with a diameter of 2 mm was chosen as a cutting tool model (Fig. 1). The drill Ø 2 mm was from IZAR, made in Spain. Drill material high speed steel (HSS) coated with titanium nitride TiN. Plan angle $2\varphi=118^{\circ}$, front angle $\gamma=12^{\circ}$, rear $\alpha=17^{\circ}$. [3].

Fig. 1. General view of drill (diameter 2,0 mm, Spain)

Geometry creation is one of the first steps in building a machining model. To draw geometry in the Comsol package, many geometric CAD operations are available [9].

Our study included the construction of a three-dimensional model of a cutting tool and models of workpieces from polymer composite materials: the workpiece was built from carbon fiber. Then the interaction was arranged and the calculation was started.

A three-dimensional model of a drill with a diameter of 2.0 mm is shown in Fig. 2.

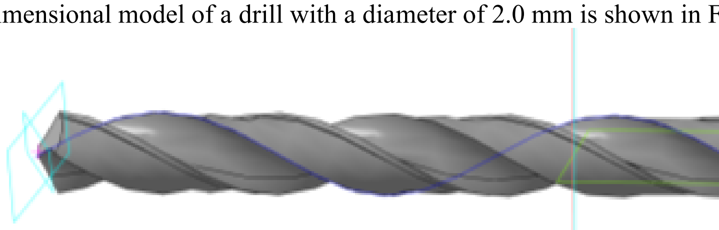

Fig. 2. Three-dimensional model of a spiral drill (diameter 2,0 mm)

When creating a workpiece model in the form of a plate of polymer composite materials (polymer binder matrix and reinforcing fibers), the Ractangle command was used, because polymer composite materials represent in cross section an alternately layered structure of fibers and a matrix. Using the geometry of elementary figures, a layered structure of plates with a total height of 5.5 mm was created from reinforcing carbon fibers with a binder (the thickness of the binder was 50 μm, the thickness or diameter of the fibers was 150 μm). Superimposed cohesive bonds between the layers.

The machining model was first created in the form of a sketch in a flat setting in 2D Axisymmetric (2D axisymmetric), then the constructed sketch was rotated by 360 °, and a three-dimensional hole surface was created.

To divide the scope of a certain part of the geometry by means of boundaries, the Point command was used. A separate boundary was created for further application of thermal action to it.

In the main menu of the program, the Physics section was selected (Fig. 3). Since it was necessary to simulate the thermal effect, the Heat transfer submenu was chosen. The Heat Transfer interface and thermal multiphysics links were used to model heat transfer by conduction, convection, and conjugate heat transfer.

 https://doi.org/10.1051/e3sconf/202339801036

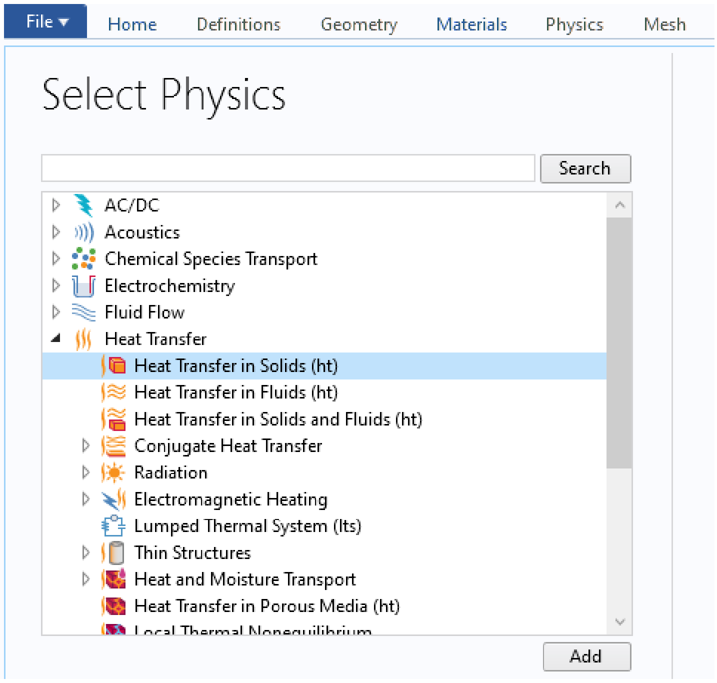

Fig. 3. The Heat Transfer submenu in the Physics section for calculating heat transfer

Then we used the interface of the Heat Transfer in Solids function, the function works according to the Fourier law. After choosing the type of study Select study, then chose the stationary mode. In heat transfer, the steady state is used to calculate the temperature field at thermal equilibrium.

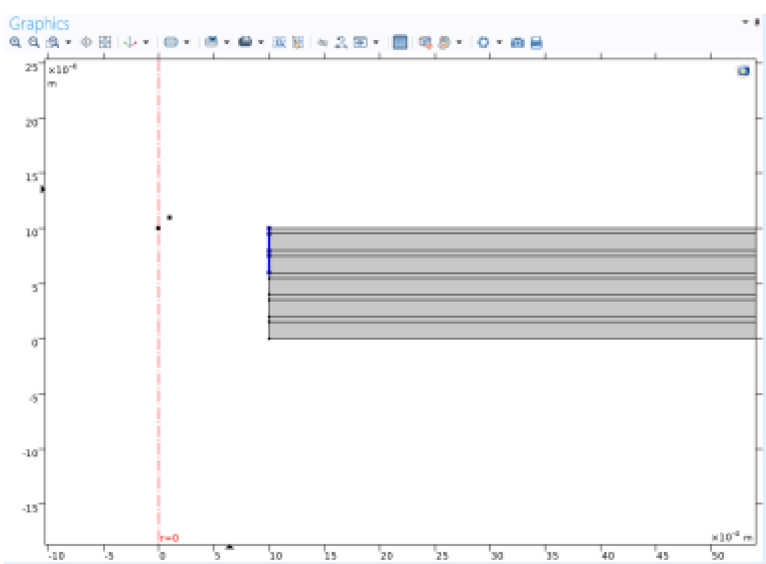

Fig. 4. Longitudinal section of a half of a drill and a workpiece made of polymer composite materials

Comsol's builtin library allows you to select a material with the characteristics and properties of the material being used. Each material is characterized by properties and described functions. The library provides the main 24 temperature-dependent characteristics. In the Comsol software package, it is possible to display the properties of materials in a graph, assign new materials in the library.

As is known, the components of polymer composite materials are layers of filler (carbon fiber) and binder (resin matrix) (Fig. 4), so we build layers, set properties layer by layer (Table 1) and establish cohesive bonds between layers.

At the same time, the averaged values were assigned to the thermophysical properties of polymer composite materials (carbon fibers and binder) (Table 1):

Table 1. Thermophysical properties of polymer composite materials

Material carbon fiber	Heat capacity, C_p J/(kg•K)	Density, *p*, kg/m^3	Coefficient of thermal conductivity, λ, W/(m•K)
Binder (epoxy resin)	1110	1200	0,5
Carbon fiber	1100	1200	100

Calculation of the heat balance during drilling of polymer composite materials was carried out according to the heat conduction equation for deformed bodies. Such an equation of heat conduction - the energy balance equation, follows from the law of thermodynamics [11].

The COMSOL Multiphysics heat equation is:

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

where ρ – density, kg/m^3; C_p – specific heat, J/(kg•°C); u – velocity vector, m/s; $\overline{\nabla T}$ – temperature gradient, °C/m; q – heat flux vector, W/m2; *Q* – heat source power per volume unit, W/m^3.

For solids, the heat equation (1) in the program window in Comsol Multiphysics has a slightly different form:

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

where Q_{ted} – correction for change from an external heat source, W/m^3.

The velocity vector can be rewritten as:

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

where u_x, u_y, u_z – velocity components of a point of a heat-conducting medium, m/s; $\mathbf{i}, \mathbf{j}, \mathbf{k}$ – unit vectors or orts in Cartesian coordinates.

Temperature gradient $\overline{\nabla T}$ – a vector that is directed along the normal to the isothermal surface, in the direction of increasing temperature and numerically equal to the change in temperature per unit length.

$$\overline{\nabla T} = \mathbf{n}\frac{\partial T}{\partial n}, \tag{4}$$

where $\mathbf{n}$ – unit vector; n – normal; $\overline{\nabla}$ – Hamilton operator ("Nabla") – symbol vector replacing gradient symbol.

From (Eq. 2), ∇T can be written:

$$\nabla T = \frac{\partial T}{\partial x}. \tag{5}$$

Or, if heat spreads along three coordinates:

$$\nabla T = \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z}. \tag{6}$$

Heat flux density vector:

$$q = -\lambda\overline{\nabla T} \tag{7}$$

where λ – coefficient of thermal conductivity, W/m•°C.

Analysis of the thermal field of diamond drilling is based on the solution of the three-dimensional Fourier differential equation of thermal conductivity using known descriptions of heat flows from an instantaneous point heat source.

To calculate the thermal fields, we chose the lines of application of the thermal load on the workpiece made of polymer composite materials from the cutting edges of the tool and set the values of the heat flux q=20•10^6 W/m2. The value of the heat flux was taken from [12], the other used constants are given in Table. 1, and additionally used the sources [13, 14].

Research results

As a result of the calculation of the drilling process in carbon fiber, the following illustration of temperature fields (Fig. 5) in the hole was obtained, as well as a graph of the dependence of the temperature distribution in carbon fiber on the edge of the hole (Fig. 6).

https://doi.org/10.1051/e3sconf/202339801036

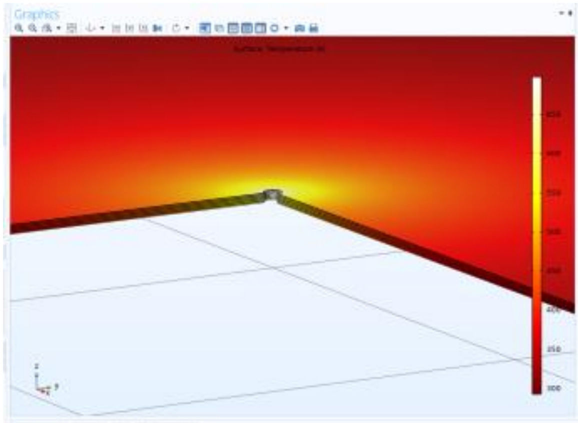

Fig. 5. Results of the distribution of thermal fields in the cross-section of the CFRP hole

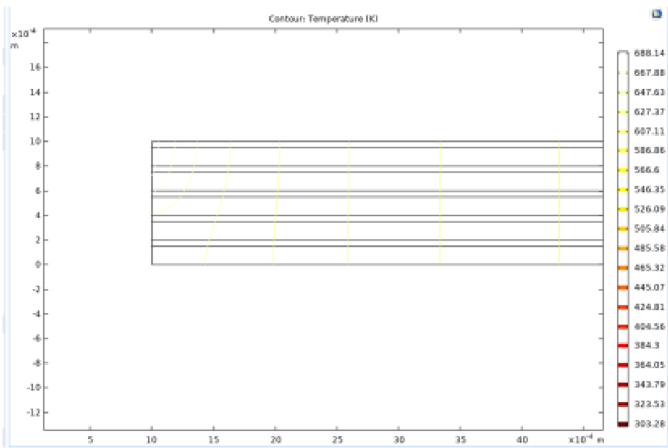

Fig. 6. Results of the distribution of thermal fields in the cross-section of the CFRP hole

Conclusion

As a result of computer calculation, temperature fields were obtained at the edges of holes in carbon fiber with a diameter of 2 mm.

The limiting temperature of carbon fiber reaches 650 K. The distance over which heat spreads from the edge of the hole in carbon fiber is 3 mm.

The developed technique for modeling the thermal impact of cutting a polymer composite material in the COMSOL Multiphysics environment makes it possible to assess possible overheating, avoid overheating of the part during processing, which will improve the quality of processing.

References

1. Melentiev, R.Yu. (2014). Computer modeling of the thermal field in the elementary volume of polymer composites. Journal of Mechanical Engineering, 17(2), 3 – 8.

2. Ivanov Yu.N. Optimization of technology for drilling precise holes in three-layer stacks made of carbon fiber and titanium alloys. Irkutsk: IRNITU, 2018. - 20 p.

3. Dudarev A.S. Improving the efficiency and quality of hole processing based on the stabilization of the process of drilling products from polymer composite materials. Perm: PGTU, 2009. - 20 p.

4. Suslov A.G. The quality of the surface layer of machine parts. – Moscow, (2000). - 320 p.

5. Vorontsov A. L., Sultan-Zade N. M., Albagachiev A. Yu. Savkin A.I. Development of a New Theory of Thermal Cutting Processes. 4. Analysis of basic theoretical researches of cutting thermal physics. Part 1 // Russian Engineering Research. Vol. 30, No. 4, pp. 346-351, 2010. New York, USA.

6. Dimov Yu.V., Podashev D.B. Cutting temperature during processing with elastic abrasive wheels // Journal Russian Engineering Research. 2020. No. 8 - P.55-60.

7. Nasonov F.A. Bukharov S.V. Investigation of the effect of targeted modification of epoxy matrices and carbon plastics based on them on the temperature in the cutting zone during the formation of holes. Bulletin of the Irkutsk State Technical University. 2018. Volume 22, No. 10. pp. 141-152.

8. Yerenkov O. Yu., Ivakhnenko A. G. Modeling of the polymeric material stressed and strained state at cutting considering cracks interaction //Journal Russian Engineering Research. 2007. No. 5 - P.54-57.

9. Dudarev A.S., Gumarov E.Kh. Research of thermal physics in diamond drilling of fiberglass and carbon fiber// Proceedings of Irkutsk State Technical University, 2021; 25. 290–299.

10. Grinek A.V., Rubanov V.G., Kalatozishvili I.V., Mikhailov V.V. Investigation of the influence of cutting speed on the temperature-force state in the processing zone by numerical simulation // Bulletin of the Irkutsk State Technical University. 2016. No. 8. pp. 10-19.

11. Yakimov A.V., Slobodyanik P.T., Usov A.V. Thermophysics of mechanical processing. Kyiv-Odessa: Lybid, 1991. - 240 p.

12. Dudarev A.S., Svirshchev V.I. Estimation of the temperature field during diamond drilling of polymer composite materials. Bulletin of the Tula State University. Technical science. 2016. No. 3. S. 188–194.

13. Barinov D. Ya., Mayorova I. A., Marakhovsky P. S., Zuev A. V., Kutsevich K. E., Lukina N. F. Mathematical modeling of temperature fields during the curing of a thick-walled fiberglass plate. Perspective Materials. 2015. No. 4. pp. 5-14.

14. Mikhailovsky K.V., Prosuntsov P.V., Reznik S.V. Development of highly thermally conductive polymer composite materials for space structures. Herald of the Bauman Moscow State Technical University. Series Mechanical Engineering. (2012). No. 9. 98-106.