Numerical Analysis on Temperature Distribution for Drilling Unidirectional Kevlar Composites

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Abstract. Drilling is a common processing method of Kevlar composites and it's easy to produce heat accumulation. In this paper, based on the finite element method, a 3-diamentional (3-D) numerical model for temperature field of drilling unidirectional Kevlar composites was developed. The characteristics of material temperature rise and the temperature field distribution were investigated. Besides, drilling experiments were carried out to verify the proposed numerical model. The results show that the temperature distribution predicted by numerical study has a good agreement with the experimental results. The temperature increases with increasing the drilling depth, and the temperature rise curves are worked out coinciding with cubic curves. Moreover, the distribution of the drilling temperature field shows an ellipse whose longer axis paralleling to the fiber direction.

Introduction

Due to their high strength, low density, and good impact resistance, aramid fiber/epoxy composite materials have been widely used in aviation industry. To realize the further mechanical joining, drilling is one of the most common operations [1]. The superior properties of composite materials make difficulties for drilling process. It always induces burrs, delamination, and thermal damage. Those defects cause many negative effects in reducing the strength and fatigue life of composite materials [2]. Due to the high local flexibility and toughness of aramid fibrils, the machined quality of aramid fiber reinforced plastics (AFRP) composites is worse than that of carbon fiber reinforced plastics (CFRP) composites [3].

For a dry drilling process of AFRP composites, it is difficult to disperse the heat generated by cutting edges due to aramid fiber's low thermal conductivity. When the temperature exceeds the critical degradation temperature of epoxy-based matrix, thermal degradation processes can be triggered [4].

Many researches have been carried out by using experimental and numerical methods to investigate the machining temperature effects of AFRP composites. Sorrentino et al. [5] developed a sensory system for the in process monitoring of the temperature near the machined surface and on the tool during dry drilling of FRP laminates. Wang et al. [6] found that temperature drop has played a positive role to reduce the cutting defects of AFRP composites. Bao et al. [7] developed a drilling temperature model based on the FDM method, and analyzed the characteristics of temperature field. Yilbas and Akhtar [8] used the finite element code ABAQUS to predict the temperature and stress fields along the cutting sections. Sadek et al. [9] developed a novel hybrid analytical-numerical model to capture time-varying forces and temperatures during transient and steady-state drilling of FRPs. Generally, the prediction of the temperature distribution in the workpiece can provide useful information for optimizing the cutting process.

A 3-D numerical model was proposed to investigate the temperature rise and temperature distribution of drilling unidirectional Kevlar composites. Experiments were carried out to verify the proposed numerical model. The effects of spindle speed on drilling temperature were studied as well.

3-D Numerical Model

Homogenization Hypothesis of Thermophysical Parameters. The unidirectional Kevlar composites contain 25 layers, and thickness of each layer is 0.2 mm. Thus, the total thickness of composites is 5 mm. To simplify the model for numerical calculation, it hypothesized that there is no defects in Kevlar composites and aramid fibers are uniformly aligned in the composites.

The thermal conductivity along the aramid fibers is higher than that perpendicular to the fiber direction. The thermophysical parameters of composites are supposed to be homogenized according to the volume of fiber and resin [10]. Based on the Rule of Mixture, the density and specific heat capacity of aramid fiber and resin were calculated by Eq. 1 and Eq. 2. Based on the effective-medium theory, thermophysical parameters along the fiber direction and perpendicular to the fiber direction can be calculated as Eq. 3 and Eq. 4 [11].

$$\rho = \rho_f \times V_f + \rho_r \times \left(1 - V_f\right). \tag{1}$$

$$c = c_f \times V_f + c_r \times \left(1 - V_f\right). \tag{2}$$

$$k_l = k_f \times V_f + k_r \times \left(1 - V_f\right). \tag{3}$$

$$k_t = \left(\frac{V_f}{k_f} + \frac{1 - V_f}{k_r}\right)^{-1}. \tag{4}$$

Where ρ and c are the density and volume specific heat of unidirectional Kevlar composites, k represents the thermal conductivity, and V represents the volume fraction. The subscript f, r, respectively, refers to aramid fiber, resin. The subscript l and t represent the longitude and transverse thermal conductivity of unidirectional Kevlar composites. After homogenizing, the thermophysical properties of unidirectional Kevlar composites are shown in Table 1.

Table 1. The thermophysical properties of unidirectional Kevlar composites

Thermophysical parameter	Symbol	Value
Thermal conductivity of aramid fiber 49 [W m^{-1} K^{-1}]	k_f	1.365
Thermal conductivity of epoxy resin [W m^{-1} K^{-1})	k_r	0.15
Fiber volume fraction [%]	V_f	60
Density [kg m^{-3}]	ρ	1444
Specific heat capacity [J kg^{-1} K^{-1}]	c	1398.46
Longitude thermal conductivity [W m^{-1} K^{-1}]	k_l	0.879
Transverse thermal conductivity [W m^{-1} K^{-1}]	k_t	0.322

Establish the 3-D Numerical Model. A 3-D numerical model was proposed based on the finite element method to investigate the temperature distribution of drilling process for unidirectional Kevlar composites. For simplification, as shown in Fig. 1, the upper and lower surfaces are regarded as convective boundaries while the rest four surfaces are taken as adiabatic surfaces. Heat flux load q_1 is induced by the major cutting edges, which can be considered as a moving conical heat source. Meanwhile, the side edges can generate q_2. Because the side edges only play a guiding role in drilling, and the value of q_2 is very small, q_2 is ignored in the 3-D numerical model. Compared with solid heat conduction, thermal radiation is also ignored for its low value.

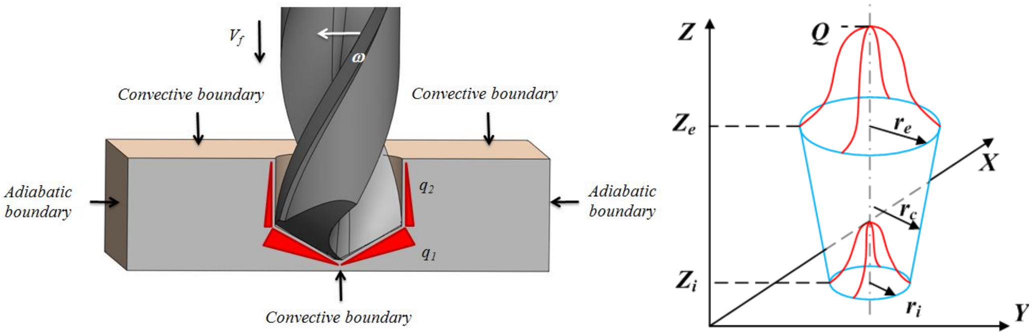

Fig. 1. Schematic of the numerical model and cone-shaped heat source model for drilling Kevlar composites

Most of the consuming energy is converted to heat conducting to the workpiece, chip, tool and the surrounding environment. The body heat flux Q_V is shown as follows, which were calculated by Eq. 5, Eq. 6 and Eq. 7.

$$Q_v = \frac{9Q_0}{\pi(1-e^{-3})} \cdot \frac{1}{(z_e - z_i)(r_e^2 + r_e r_i + r_i^2)} \cdot \exp\left(-\frac{3r^2}{r_c^2}\right). \quad (5)$$

$$Q_0 = \eta P. \quad (6)$$

$$P = M \cdot \omega + F_z \cdot V_f. \quad (7)$$

Where Q_0 is the heat source power, P is the total power, r is a function of x and y, r_c is the thermal distribution coefficient of z, r_e and r_i are the maximum radius and minimum radius, z_e and z_i are the maximum value and minimum value of z direction, η is the energy proportional coefficient, M and F_z are the torque and the thrust force, ω, v_f are the angular velocity and feed velocity of the drill. The above parameters can be determined according to experimental settings.

During the drilling process, the temperature distribution is a non-steady-state along with the heat accumulating. The heat conduction equation of three-dimensional mode can be written as follows:

$$k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + q(x, y, z) = \rho c \frac{\partial T}{\partial t}. \quad (8)$$

Where k_x, k_y, k_z are thermal conductivities in the three directions, respectively. $q(x, y, z)$ is a heat flux, and T is relative temperature rise.

Results and Discussion

Single-point Temperature Rise. The Drilling is a semi-closed machining process. Cutting heat is accumulating while the drill goes down. In order to explore the characteristic of temperature rise with low and anisotropic thermal conductivity in the material, three points at the drill exit were selected to monitor the temperature rise. As shown in Fig. 2, the three points were set at the hole center, 0 °direction of hole wall and, 90 °direction of hole wall, respectively. The maximum temperatures of the simulation and experimental results are shown in Table 2. Because simulation errors are less than 9 %, the accuracy of this numerical model is acceptable.

Under the spindle velocity of 1000 r min^{-1} and feed speed of 2 mm min^{-1}, the predicted time-temperature curves at different locations are worked out coinciding with cubic curves as shown in Fig. 2. At the early stage of drilling, the temperature rise was not obvious because little heat was accumulated and there was a distance between the selected points and the drilling tool. Because the heat generated is faster than that loss, thus, as closing to the selected points, slopes of curves increased a lot. Moreover, the maximum value of temperature was obtained when the drill reached the positions of selected points. As shown in Fig. 2, the temperature in the hole center is larger than the others because more than 50 % of the cutting force comes from the chisel edge of drill. Due to the fiber orientation effects, the temperature along the 0 ° direction of hole wall rose more quickly than that along the 90 °direction of hole wall. It found that the temperature was higher than *Tg* of resin matrix after about 125 s.

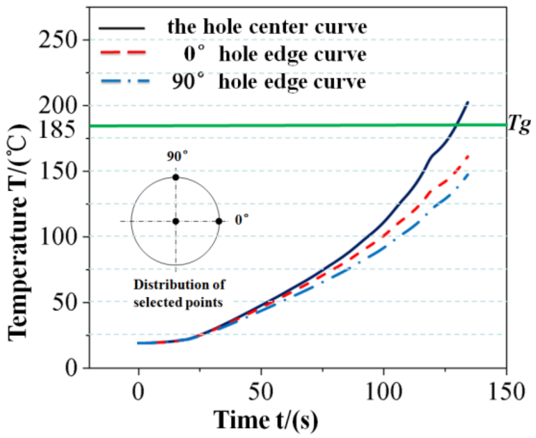

Fig. 2. Predicted time-temperature curves at different locations

Table 2. The maximum temperatures between the simulation and experimental results

The location of the points	Simulation results	Experimental results
The hole center	202.1 ℃	217.4 ℃
0 °direction of the hole wall	165.3 ℃	176.8 ℃
90 °direction of the hole wall	147.7 ℃	156.5 ℃

Simulation of Temperature Distribution. During the drilling of unidirectional Kevlar composites, four particular stages of the drilling process were presented for discussing the processes of heat generation and thermal transmission. Four stages are defined according to the feed of chisel edge at 0.5 mm (stage 1), 1.5 mm (stage 2), 5.0 mm (stage 3), and 6.5 mm (stage 4) away from top surface of composites in thickness direction. At the spindle velocity of 1000 r min^{-1}, the temperature distributions of these four typical moments were shown in Fig. 3. The temperature distribution during the machining process was different from the homogeneous material obviously. The temperature along the 0 ° rose more quickly than the 90 ° direction, which was consistent with the characteristics of the single-point. The temperature distribution showed an elliptical shape whose major axis was parallel to the fiber orientation. The anisotropic thermal conductivity plays a key role to the temperature distribution. And the cutting heat is mainly transferred through the aramid fiber.

As shown in Fig. 3(a), the higher temperature area for drilling 0.5 mm depth was at the center of the hole, and the predicted highest temperature was 56.8 ℃. The material was mainly removed by chisel edge for this stage. The short contact time and small contact area were the reason that thrust force and torque were not high enough to cause a significant increase in temperature. When the drill moved down and reached 1.5 mm away from the top surface, the main cutting edges began to participate fully in the cutting. Thus, the highest temperature rose up to 138.1 ℃ and the area affected by the heat was enlarged, which was shown in Fig. 3(b). Compared with the first stage, the temperature at the center of the hole increases significantly. The temperature distribution of exit when the chisel edge just reached the bottom was shown in Fig. 3(c). The maximum temperature was 206.3 ℃, which was higher than the *Tg* of resin. It could result in a rapid declined in the mechanical properties of Kevlar composites [12]. After this stage, cutting edges started to move outside. Fig. 3(d) showed the temperature distribution of exit when the main cutting edges were just out of processing totally. The maximum predicted temperature was 216 ℃, which was a little higher than the third stage.

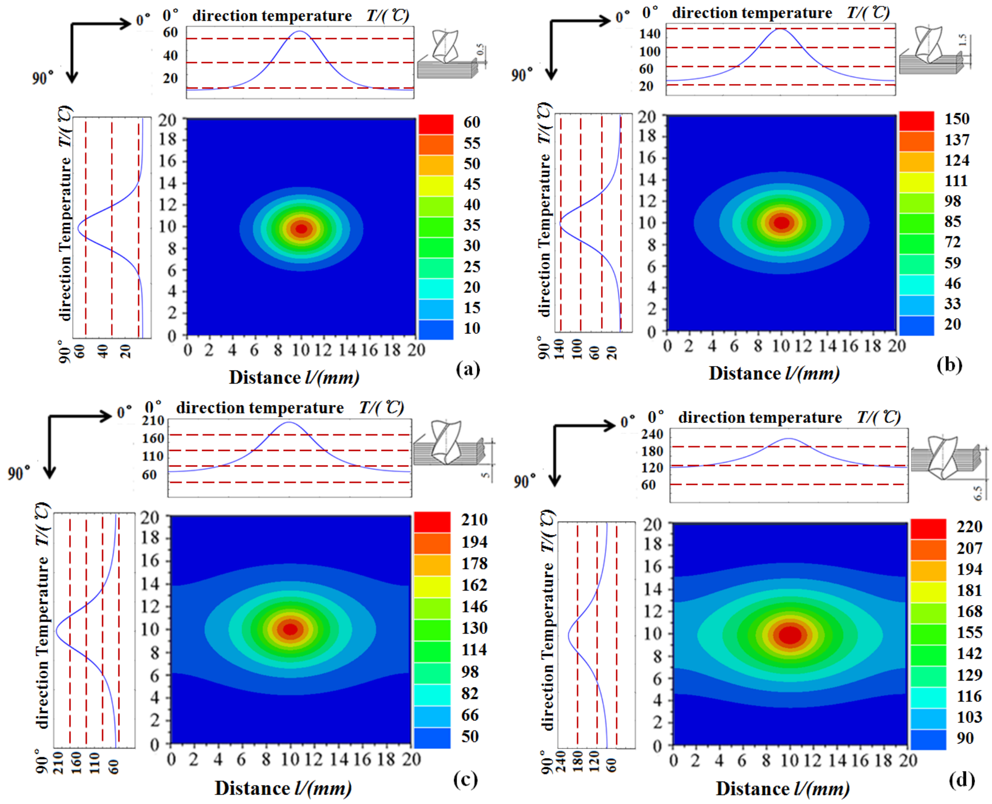

Fig. 3. Temperature distributions of four stages. a 0.5 mm (stage 1). b 1.5 mm (stage 2). c 5 mm (stage 3). d 6.5 mm (stage 4)

Conclusions

Temperature field of unidirectional Kevlar composite materials during drilling process had been investigated by numerical and experimental studies. The temperature distribution predicted by numerical study had a good agreement with the experimental results. Compared with experimental results, simulation errors were less than 9 %. From the results, it was found that temperature increased with increasing the drilling depth, which was caused by the heat accumulation during the drilling process. Moreover, due to large difference of heat conductivity coefficient between reinforcements and matrix in the composite materials, the temperature field of drilling Kevlar composites was different from the homogeneous material obviously. It was found that the temperature field showed an elliptical shape, whose major axis was parallel to the fiber orientation.

Acknowledgments

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