Temperature Field Distribution Model in Drilling of CFRP/Ti Stacks Structure

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Abstract. CFRP and Ti alloy, which have several excellent properties, are widely used in the field of aircraft manufacturing. CFRP/Ti stacks is one kind of common structure in aircraft assembly process. Drilling is one of the key processes to assemble such structure. Heat concentrated and high drilling temperature may happen during drilling CFRP/Ti stacks due to their low thermal conductivity, and it may lead to hole damages. The paper gets the heat flux to workpiece through analyzing the heat source during drilling CFRP/Ti stacks, base on which a model to predict the drilling temperature field during drilling CFRP/Ti stacks is established by the Fourier’s law. The drilling temperature field is calculated by the finite difference method, and the experiment of drilling CFRP/Ti stacks is carried out. The analytical result agrees well with experimental data. The model can be used to predict the temperature field of stacks drilling process.

Keywords: CFRP/Ti stacks; Drilling temperature field; Drilling heat; Heat transfer.

1. Introduction
Carbon Fiber Reinforced Polymer/Plastic (CFRP) has unique properties such as high strength-to-weight ratio, good corrosion and impact resistances, as well as excellent design flexibility [1, 2], which has become increasingly popular in aerospace, automobiles and other industries [3, 4]. The proportion of CFRP in mechanical structure is increasing, thus, many components are made of the combination of composite materials and metals, such as CFRP/Al, and CFRP/Ti stacks. It is necessary to drill the stacks to obtain connection holes. In order to improve the drilling efficiency, the integrated drilling process are adopted for these stack structures gradually.

CFRP and titanium alloys have poor thermal conductivity [5]. The concentration of heat always causes high temperature in the drilling CFRP/Ti stacks, and leads to CFRP matrix burned, which affects the strength and life of structures. Ben Wang et al. [6] analyzed the hole morphology of the CFRP/Ti stacks structure after drilling, and concluded that the high temperature during drilling caused thermal degradation of matrix and reduced the surface quality around the hole. Montoya M et al. [7] obtained the temperature field distribution of CFRP/Al stacks for drilling by establishing numerical simulation, and verified the accuracy of the model through experiments. Qi [8] converted the drilling process into a right-angle cutting. Through simulation analysis, the temperature and stress nephogram of the machining models with different fiber orientation angles were obtained, and the correlation between the analysis of cutting force and cutting heat was analyzed. All these provide a reference for the
analysis of temperature field in CFRP/titanium alloy laminated drilling. Therefore, the stacks sturtures drilling heat is a serious problem and it is necessary to study it. In this paper, the source of drilling heat of CFRP/Ti stacks structure is analyzed, and the drilling heat flux to the workpiece is obtained. On this basis, the drilling temperature field model of CFRP/Ti stacks is established, and the finite difference method is used to solve the model. The drilling test data is used to verify the correctness of the temperature field model.

2. Drilling Temperature Field Model for Stacks Structure

2.1. Analysis Drilling Heat Source of CFRP/Ti Stacks

When drilling CFRP/Ti laminated structures, the drilling heat source is mainly distributed on the contact surface between the tool's chisel edge and the workpiece material, the contact surface between the tool's main cutting edge and the workpiece material, and the contact surface between the tool's secondary edge and the workpiece. One can use $Q_1$ and the latter is represented by $Q_2$, as shown in Fig. 1. The force of the tool during drilling is mainly from the tool chisel edge and the main cutting edge, so the heat source $Q_2$ will be much larger than $Q_1$. In the drilling process, the energy consumed by drilling (work done by the cutting force) will be converted into heat by 97% to 99%\[9\]. Therefore, in order to simplify the problem, it is assumed that all the work done by the drilling force is converted into heat. Then according to the law of conservation of energy, formula (1) can be obtained.

$$Q_1 + Q_2 = \left( \frac{1}{6 \times 10^4} F_z V_f + \frac{\pi}{30} M n \right) t$$

In the formula: $F_z$ is indicates axial force, $V_f$ is indicating the feed rate, $M$ is indicates torque, $n$ is indicates the speed, $t$ is indicates time.

![Figure 1. Distribution of heat source.](image)

The heat transferred to the workpiece is derived from the total heat $Q_1+Q_2$, which generated during the drilling process. Since $Q_1$ is small relative to $Q_2$, we assume that the workpiece does not exchange heat at the contact surface with the tool secondary edge (the hole wall is considered as adiabatic boundary condition), and only the workpiece facing the tool chisel edge and the main cutting edge transfers heat to the workpiece. Based on this, in order to simplify the model, the heat source of the workpiece is regarded as a disc-shaped heat source that moves from top to bottom over time, as shown in Fig. 2. Also, assuming that the heat transferred to the workpiece occupies $\eta$ among the total calories, the quantity $q$ of heat transferred to the workpiece per unit area per unit of time can be expressed by equation (2).

$$q = \frac{4\eta \left( \frac{1}{6 \times 10^4} F_z V_f + \frac{\pi}{30} M n \right)}{\pi D^2}$$

Where, $q$ is denotes the average heat flux to the workpiece, $D$ is indicates tool diameter, $\eta$ is represents the proportion of heat transferred to the workpiece.
2.2. Model the Temperature Field

A space rectangular coordinate system $O-xyz$ is set up in a CFRP/Ti laminate structure workpiece, as shown in Fig.2. Assume that the thicknesses of the upper and lower materials are $h_1$ and $h_2$ respectively.

2.2.1. Thermal Conduction Differential Equation

In the CFRP/Ti drilling process, the workpiece temperature field will continue to change with time, which means the workpiece temperature field is unsteady. Assume that during the drilling process, the thermal conductivity, specific heat capacity, etc. will not be changed, and the heat source disc will be regarded as one of the boundaries of the workpiece. This becomes a three-dimensional non-steady property with constant property and no internal heat source. According to the law of conservation of energy and the law of Fourier heat conduction, a three-dimensional unsteady heat conduction differential equation of constant property, no internal heat source, is established in the coordinate system $O-xyz$, as shown in equation (3), where temperature $T$ is a function of $t$, $x$, $y$, and $z$.

$$
\begin{align*}
\rho_1 c_1 \frac{\partial T}{\partial t} &= \lambda_{11} \frac{\partial^2 T}{\partial x^2} + \lambda_{12} \frac{\partial^2 T}{\partial y^2} + \lambda_{13} \frac{\partial^2 T}{\partial z^2} \\
(0 \leq z \leq h_1) \\
\rho_2 c_2 \frac{\partial T}{\partial t} &= \lambda_{21} \frac{\partial^2 T}{\partial x^2} + \lambda_{22} \frac{\partial^2 T}{\partial y^2} + \lambda_{23} \frac{\partial^2 T}{\partial z^2} \\
(h_1 \leq z \leq h_2)
\end{align*}
$$

(3)

In the formula: $T$ and $t$ represent temperature and time respectively; $\rho_1$ and $c_1$ are the density and specific heat capacity of the upper material respectively; $\rho_2$ and $c_2$ are the density and specific heat capacity of the underlying material respectively; $\lambda_{11}$, $\lambda_{12}$, and $\lambda_{13}$ represent the thermal conductivity of the upper layer material along the $x$, $y$, and $z$ directions; $\lambda_{21}$, $\lambda_{22}$, and $\lambda_{23}$ indicate the thermal conductivity of the underlying material in the $x$, $y$, and $z$ directions.

2.2.2. Initial Conditions and Boundary Conditions

In order to solve the temperature field distribution of the specific heat conduction problem, additional conditions describing the specific problem should also be given. The initial condition is the condition that describes the internal temperature distribution at the initial moment. It can assumes that the temperature inside the workpiece is equal to the ambient temperature at the initial time.

The boundaries of the model have adiabatic boundary condition A, B, C, D, E, F, G, H, and I (in Fig. 2). The boundary A is described the value of the heat flux at the boundary; the boundary B is described by the adiabatic boundary condition; the boundary C to H are defined the boundary between the workpiece and the surrounding fluid, which are the surface heat transfer coefficient and the temperature of the surrounding fluid; and the boundary I is described by the interface continuous condition.

3. Experiment

In order to determine the ratio of heat transfer to the workpiece when drilling CFRP and TC4, and to verify the correctness of the CFRP/Ti drilling temperature field model, a CFRP/Ti lamination drilling test was performed. The experimental platform built is shown in Figure 3. The CFRP used in the test with a size of 40*40*10mm (length*width*height), and the volume content of carbon fiber was 65%. The TC4 has the size of 40*40*6mm. The thermal parameters of CFRP and TC4 are shown in Table 1.
Table 1. Thermal parameters of CFRP and TC₄.

| Parameter                                                                 | Value                      |
|--------------------------------------------------------------------------|----------------------------|
| Density of CFRP (kg/m³)                                                  | 1498~1540                  |
| Specific heat of CFRP (J/(kg*K))                                         | 465.6075                   |
| Thermal conductivity parallel to the direction of the fiber (W/(m*K))    | 4.265~4.51                 |
| Thermal conductivity perpendicular to the direction of the fiber (W/(m*K))| 0.7885~2.2145              |
| Density of TC₄ (kg/m³)                                                   | 4450                       |
| Specific heat of TC₄ (J/(kg*K))                                         | 678                        |
| Thermal conductivity of TC₄ (W/(m*K))                                    | 6.7                        |

In the process of drilling CFRP/Ti stacks structure, the thermocouple is placed inside the workpiece using a small hole, and the temperatures at the measuring point I, II, and III are measured. The position I is at the cross section of the CFRP, parallel to the carbon fiber direction from the hole-wall 2mm; the position II is at the cross section of the CFRP, and the carbon fiber direction is perpendicular to the hole-wall 2mm; the position III is at the TC₄ middle section. The placement of thermocouples is shown in Figure 4. In the drilling process, axial force and torque are also measured and recorded.

Figure 4. Schematic diagram of temperature measurement points.

The test selected tool Φ6, speed 1000r/min, feed rate 40mm/min process parameters to drill holes in the CFRP/Ti stacks structure.

4. Results and Discussions

4.1. Temperature Field Solution

The finite difference method is used to solve the temperature field. First, the time and space are discretized, and the time t is discretized into L+1 nodes, and x, y, and z are respectively discretized into I+1, J+1, and K+1 nodes, as shown in equation (4), (5), (6), (7).

\[
\begin{align*}
\{T_l = l\Delta t \ (l = 0,1,2,L) \\
T_L = T_{total}\end{align*}
\]

(4)

\[
\begin{align*}
\{x_l = x_{down} + l\Delta t \ (i = 0,1,2,L) \\
x_L = x_{up}\end{align*}
\]

(5)
The specific calculation process are carried out in MATLAB. First, the internal node temperature is obtained according to the thermal differential equation, then the boundary node temperature is calculated by the boundary conditions. The node temperature at each time is solved in chronological order. After the calculation is completed, the temperature of all nodes will be stored in the Matrix $T$.

The key point of the model's solution is the dispersion of $t$, $x$, $y$, and $z$. To satisfy the stability and convergence of the calculation, they should satisfy the formula (8). In this paper, $t$, $x$, $y$, and $z$ are discretely divided into 2401, 81, 81, and 33 nodes, $\Delta t=0.01s$, $\Delta x=0.5mm$, $\Delta y=0.5mm$, and $\Delta z=0.5mm$.

$$
\begin{aligned}
\Delta t &\leq \left(2 - \frac{\lambda_{11}}{\rho_1 c_1 \Delta x^2} + 2 - \frac{\lambda_{12}}{\rho_1 c_1 \Delta y^2} + 2 - \frac{\lambda_{13}}{\rho_1 c_1 \Delta z^2}\right)^{-1} (0 \leq k \leq k_s) \\
\Delta t &\leq \left(2 - \frac{\lambda_{21}}{\rho_2 c_2 \Delta x^2} + 2 - \frac{\lambda_{22}}{\rho_2 c_2 \Delta y^2} + 2 - \frac{\lambda_{23}}{\rho_2 c_2 \Delta z^2}\right)^{-1} (k_s \leq k \leq K)
\end{aligned}
$$

### 4.2. Temperatures Distribution Analysis

CFRP heat transfer ratio of 20%, 30%, 40% are used, and corresponding TC4 heat transfer ratio are 60%, 70%, 80% respectively. The results is calculated and compared with the temperature of the test at the temperature measurement point I, II, and III, as shown in Figure 4. As can be seen from the figure, when the proportion of heat transferred to CFRP is 30% and the proportion of heat transferred to TC4 is 70%, the calculated temperature is close to the measured value. And it can be confirmed that under this process parameter and under the cutter, when drilling CFRP/Ti laminations, the proportion of heat transferred to CFRP workpieces is between 20% and 40%, and the proportion of heat transferred to TC4 workpieces is 60%~80%.

When the proportion of heat transferred to CFRP is 30% and the proportion of heat transferred to TC4 is 70%, the theoretical and experimental maximum temperatures at temperature measurement point I, temperature measurement point II, and temperature measurement point III are shown in Table 2. From Figure 5 and Table 2, we can see that the theoretical calculation temperature and the test measurement temperature have a high consistency, indicating that the established temperature field model is correct.

**Figure 5.** Comparison of theoretical temperature and test temperature.
Table 2. Comparison of the maximum theoretical temperature and test temperature.

| Temperature point | Max-theoretical temperature (°C) | Max-test temperature (°C) | Error |
|-------------------|----------------------------------|---------------------------|-------|
| I                 | 68.48                            | 62.2                      | 10.1% |
| II                | 39.25                            | 36.8                      | 6.67% |
| III               | 98.55                            | 102                       | 3.4%  |

The nodals temperature of the workpiece cross section are calculated when the heat transfer ratios of CFRP and TC₄ are respectively 30% and 70%. The temperature field cloud diagram of the cross section at different times (as shown in Figure 6) are presented. When the tool cuts the CFRP layer, the temperature is significantly lower than the tool cutting TC₄ layer, the maximum temperature of the CFRP is about 200°C, and the maximum temperature of the TC₄ is about 500°C to 700°C. And heat is mainly concentrated near the main cutting edge of the tool.

![Figure 6. The temperature field distribution during CFRP/Ti drilling, (a)5s, (b)10s, (c)18s, (d)21s.](image)

5. Conclusions
In this paper, the drilling source of CFRP/Ti laminated structure was analyzed and the heat flux density of CFRP/Ti workpiece was obtained. Based on this, the temperature field model of CFRP/Ti stacks structure was established. The main conclusions present as follows:

(1) In the drilled CFRP/Ti stacks structure, the influence of heat production on the interface temperature in titanium alloy drilling stage cannot be ignored. The transfer proportion of drilling heat from tool to workpiece in Ti alloy layer is much larger than that of CFRP layer.
(2) When drilling CFRP/Ti alloy stacks, the high temperature area is mainly concentrated in the contact area between the main cutting edge and the chisel edge of the tool and the workpiece.
(3) The temperature field distribution model of stack drilling has high accuracy, which can be applied to other parameters of stack drilling, and can provide reference for temperature control of stack drilling.

In the future work, the researches will focus on three aspects: 1) The anisotropy of the force-heat distribution and the correlation for drilling CFRP will be revealed. 2) Influence of the difference in thermal conductivity between fiber and matrix on drilling heat will be shown. 3) From a meso-scale, the thermal damage of the interface between CFRP and Ti layers will be analyzed.

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References
[1] Tsao C C and Chiu Y C 2011 *International Journal of Machine Tools & Manufacture* (Oxford: Elsevier) p 740
[2] A A N, B A U and A I S J 2020 *Procedia Manufacturing* (Amsterdam: Elsevier) vol 43, p 551
[3] Shyha I, Soo SL, Aspinwall D and Bradley S 2010 *Journal of Materials Processing Technology* (Lausanne: Elsevier) vol 8, p 1023
[4] Maciej G 2020 *Journal of Composite Materials* (London: SAGE Publications Ltd)

[5] Singh AP, Sharma M and Singh I 2008 *J Manuf Technol Today* vol 7(6) p 24

[6] Wang B, Gao H and Cao B 2014 *Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture* (London: SAGE Publications Ltd) vol 228(7) p 698

[7] Montoya M, Calamaz M and Cehin D 2014 *Key Engineering Materials* p 122

[8] Zhenchao Q, Fengcheng L and Erhua Wang 2019 *Tool Technology* (Chengdu: Chengdu Tool Research Institute) vol 10 p 36

[9] Guoping Z, Yongjie B and Hang G 2012 Research on the drilling temperature field model of the unidirectional carbon fiber epoxy composites[J]. *Advanced Materials Research* (Baech: Trans Tech Publications Ltd) vol 565 p 478