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Study on the cutting force in machining of aluminum honeycomb core material

Kunxian Qiu [a], Weiwei Ming [a], Lifeng Shen [b], Qinglong An [a,*], Ming Chen [a]

[a] State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] Shanghai Institute of Spaceflight Control Technology, Shanghai 201109, PR China

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ABSTRACT

Honeycomb sandwich structure has been widely used in the aerospace industry due to its high strength and stiffness to weight ratio. But the poor machinability of honeycomb core is a key factor that limits its application owing to its weak rigidity in in-plane direction of cellular materials. This paper introduced typical machining defects and studied the machining characteristics of honeycomb core. Almost all the cutting burrs and defects were found to locate on the line with entrance angle is equal to 80° and 170°. A cutting force model was proposed to predict the milling force under different spindle speed, feed rate and tool angle. A series of cutting simulation of honeycomb cell wall with tool blade were conducted to determine the cutting force of a single cell wall. The accuracy of proposed model was verified by a group of experiments under different conditions and the average percentage error is below 5% in Y direction and 10% in X direction.

1. Introduction

As one of the most representative advanced composite material, composite sandwich structures have been widely used in the aerospace industry and automotive industry, such as aircraft tail fin, helicopter propeller and satellite force cabin, due to its high strength and stiffness to weight ratio [24]. Composite sandwich structure consists of honeycomb core material bonded between two panels, makes it a more efficient structure in specific stiffness compared with solid material [25]. With a 3% increase in weight of core material, the specific stiffness can be increased by 7 times. However, the unique material characteristics of honeycomb core, and the defects caused during the machining process are major challenges to its application. The precession request of sandwich component's complex shape and size has to be guaranteed by the advanced machining process [26]. Therefore, researches on the characteristics of cutting process and influence of machining parameters are essential.

A series of researches have been carried out to investigate the machining process of different type of composite materials in the past decades using theoretical and experimental technology [21–23]. Most of the literatures focused on the machining mechanisms, cutting force, tool performance and cutting defects of carbon fiber reinforced composites. The influence of machining parameters and tool geometry on the cutting force and defects during trimming process of carbon fiber reinforced composite was investigated by Madjid [5]. It was found that the cutting defects were mainly caused by the cutting force and cutting conditions. The relationship between the cutting force and the machine quality was also studied by Davim [6], Xu[7] and Wang[8,9] etc. Neelesh [1] believed the selection of optimum machining parameters requires elaborate experiments which is costly and time consuming. The author proposed optimization models based on genetic algorithms to optimize the machining parameters for advanced engineering materials such as polymers, ceramics and composite structures. Qinglong [4] systematically studied the machining mechanism of T700/800 UD-CFRP composites by studying the cutting force and specific cutting energy under conditions of different fiber orientation, tool angle and cutting parameters. These research results provide evidence for improving the machinability of composite materials. Zhang [2] divided the cutting zone of fiber-reinforced composite into chipping, pressing and bouncing regions and proposed a force prediction model based on the three regions for orthogonal cutting of fiber-reinforced plastics. The developed model captured the major deformation mechanisms in the cutting process of composite materials and gave a comparatively accurate

* Corresponding author.
E-mail addresses: jxtkqkx@126.com (K. Qiu), mingseas@163.com (W. Ming), fdchrist@126.com (L. Shen), qlan@sjtu.edu.cn (Q. An), mchen@sjtu.edu.cn (M. Chen).

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Nomenclature

a^i	coefficient of ith honeycomb wall
a_w	cutting width
b^i	constant of ith honeycomb wall
E	Young's modulus
e	mean square error
F	cutting force of cell wall
F_j^{pre}	jth prediction force
F_j^{test}	jth experiment force
F_{max}^{test}	maximum experiment force
F_{Xh}	cutting force in Xh direction
F_{Xw}	cutting force in Xw direction
F_{Yh}	cutting force in Yh direction
F_{Yw}	cutting force in Yw direction
$f(x)$	tool path function
$H_1(x)$	conditional function
$H_2(x)$	second conditional function
J	number of the experiments
l	length of honeycomb cell
n	spindle speed
p	percentage error
R	tool diameter
t	time
Vs	cutting speed
v_f	feed rate
w	angular velocity of tool
Xh-Yh	coordinate system of cell wall
Xw-Yw	coordinate system of workpiece
x_0^i	X-coordinate of the start point of ith honeycomb wall
$x(t)$	X-coordinate of tool center
α	rake angle
γ	orientation angle
θ	entrance angle
μ	Poisson's ratio
ρ	density
$\sigma_{0.2}$	condition yield stress

Abbreviation

UD-CFRP unidirectional carbon fiber reinforced polymer

prediction cutting force. A further comprehensive study of cutting force modeling problem was carried out by Karpat et al. [3] In their researches, the authors proposed a mechanistic cutting force model for milling unidirectional composite laminates based on the experimentally calculated cutting force coefficients. The influence of fiber cutting angle on the variation of cutting force was investigated. Also this mechanistic model was capable to predict the cutting force of milling multidirectional composite laminates. More researches on the modeling of cutting force of composite materials were carried out by Santiuste [10], Biswajit [11] and Ravi [12] etc. The traditional modeling method based on cutting force coefficients plays an important role in the research of traditional metal materials. Its principle is to propose an empirical equation with two coefficients and to fit them. But it cannot reflect the characteristics of honeycomb core milling.

As to aluminum honeycomb structures, most researches focused on the deformation mechanism under quasi-static or dynamic compressive loading conditions [13–15]. Gibson [16] and Ashby [17] investigated the mechanism of linear-elastic deformation process, nonlinear deformation process, cell wall buckling process and yielding process of honeycomb structures. Ashab [18] studied the quasi-static and dynamic response of aluminum honeycomb by indentation and compression experiments. During the experiments, it was found that the tearing of cell walls distribute along two edges of the indenter and the debonding defects distribute along the other two edges of the indenter. Khan [19] investigated the crushing properties of honeycomb core through the experiment method. By using the digital image correlation technology, the local deformation response during the crushing was analyzed and the local plastic strain was found mainly distribute in the shear band region. Several numerical modeling methods for simulating the crushing behavior of aluminum and Nomex honeycomb core were discussed by Aktay [20], in order to compare with the experiment results. The author proposed a semi-adaptive numerical coupling model to simulate the extensive compression core crushing failures and validated the accuracy of this model with experiments.

In the machining process of composite materials, the control of machining defects has been one of the most important things. Different composite materials and processing methods usually generate different machining defects, which severely limits the application of composite materials in aerospace industry. As the core component of honeycomb sandwich panel, the honeycomb core material needs to be precisely machined to ensure its complex profile. The processing defects will lead to the degumming in honeycomb sandwich panel and compromise its energy absorption capacity. Therefore, researches on the machining mechanism of honeycomb core are desperately needed.

The most common way to clamp the honeycomb core during the machining process is to cohere it on the workbench with double sided adhesive tape, as shown in Fig. 1(a). In this research, a new clamping method based on the semiconductor refrigeration technology is adopted, as shown in Fig. 1(b). The new clamping device takes advantage of Peltier Effect and freezes water in the platform to seize the honeycomb cell walls in a very short time. This clamping method can effectively reduce the machining defects and temperature in the machining process. Fig. 2(a) shows the common machining defects with double sided adhesive tape clamping, including side defects, core lattice deformation, edge defects, cutting burrs and overcut defects. More close to the edge of the workpiece, the workpiece rigid becomes weaker and more edge defects and core deformation are generated. But there is no significant regularity in the distribution of the cutting burrs and overcut defects. Fig. 2(b) shows the machining defects with ice freezing clamping, including cutting burrs, overcut and side defect. As can be seen from the figure, the distribution of cutting burrs and overcut defects present themselves as a straight line. The entrance angle θ is defined as the included angle between the cutting direction and the honeycomb cell wall direction, as shown in Fig. 2(b). Unlike the defects in Fig. 2(a), the cutting burrs only occur at $\theta = 80°$ and $\theta = 170°$. This is because the machining mechanism of honeycomb is different from that of solid material; each cell wall corresponds to a certain entrance angle, and the cutting process of each cell wall are independent; all these lead to the defects in a particular location. But, after all, cutting force is the key factor in producing all kinds of machining defects. In this research, to improve the machining quality and reduce defects, the cutting process and cutting force of honeycomb cell wall are investigated, a prediction model of cutting force is derived and a series of experiments are carried out to verify its accuracy.