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Heat partition in dry orthogonal cutting of unidirectional CFRP composite laminates

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ABSTRACT

Carbon fiber reinforced polymer (CFRP) components can be generally prepared near-net-shape, however, they still need machining after manufacturing to meet the geometrical accuracy with excellent surface quality required for assembly. Due to the cutting temperature is prone to exceed the glass-transition temperature of the resin, the irreversible chemical and mechanical degradation are therefore difficult to avoid. It becomes a crucial challenge to eliminate the particular thermal effect on the composite machining process. In comparison with the temperature measurement, the analytical model not only can reveal the physical essence of thermal effect, but also can predict the temperature field distribution to provide the reasonable cutting parameters. In particular, a key parameter for calculating the cutting temperatures is the heat partition ratio. However, the research work on this issue was rarely found. In this paper, a fiber orientation-based analytical model was developed to predict the heat partition ratio based on the classical Hertz contact theory. The finite element model was also built with the validation of the experimental measurement from the thermal imaging tests. The results suggest the heat partition ratio is mainly determined by the cutting parameters. Moreover, the fiber orientations have a remarkable impact on this ratio. Due to the heat partition ratio is considerably larger in a CFRP workpiece than the cutting tool, more heat energy was transferred to the CFRP during machining. Therefore, a small depth of cut leads to a reduced tendency for thermal effect on the CFRP composites.

1. Introduction

Carbon fiber reinforced polymer (CFRP) composites make it better choice for the field of advanced technology that requires the light weight but superior mechanical properties, such as the aeronautical and space technologies, military and civilian aircraft etc. [1,2]. To meet the high accuracy of assembly of such applications, the manufactured CFRP components have to be properly machined, referring to the designed dimensional tolerances and surface quality. However, the low glass-transition temperature of resin makes it more sensitive to the temperature change [3]. A decrease of the inter-laminar shear strength and the longitudinal ultimate tensile strength with increasing temperature are found by Refs. [4,5]. Therefore, the cutting temperature becomes an importance challenge during machining of the CFRP components. It has to be noticed that once the machining resulted temperature is over the glass-transition temperature, the irreversible chemical and mechanical degradation might be caused [6,7]. Consequently, the dimensional accuracy and surface quality of the CFRP components cannot be guaranteed anymore. Moreover, this issue may result in rejection of the expensive CFRP composite parts [8,9]. Therefore, it is important to eliminate the particular thermal effect on the composite machining process.

So far, extensive studies have been carried out on the cutting temperature of machining composites. By machining experiments, Wang et al. [10] found that the thermal degradation of resin occurred when the cutting temperature exceeded the glass transition temperature, and then the resin could not provide enough support to the carbon fibers, and therefore resulted in poor machining quality. Brinksmeier et al. [11] and Pecat et al. [12] discussed the influence of different CFRP workpiece temperatures on the machining quality. They found that the length of a bending carbon fiber was relevant to the depth of heat affect zone, which indicated that the cutting temperatures could affect the machining quality and cutting-induced damage. Kim et al. [13] found that the transverse crack propagation and the interlaminar delamination growth were dependent on the change of temperatures. Sorrentino et al. [14] developed a new method for temperature measurement. Geng et al. [15] analyzed the mechanisms of temperature reduction in rotary ultrasonic elliptical machining. Sorrentino et al. [16] deals with

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the problem of damage due to the high temperatures reached during the FRP dry drilling process. In the work of Ghafarizadeh et al. [17], the cutting speed and fiber orientation were reported to be determinative on the cutting temperature, while the maximum cutting temperatures were achieved for the fiber orientations of 90°. Ramirez et al. [18] indicated the importance of the abrasive wear of the cutting edge to determine the cutting temperatures. Merino-Pérez et al. [19] obtained the correlation between cutting speed and heat dissipation. Yashiro et al. [20] employed three types of measuring methods to study the cutting temperatures in the endmill machining process. There was no damages observed at the surface even if the cutting speed was over 300 m/min. Kerrigan et al. [21] claimed that the workpiece thickness and depth of cut have considerable impact on milling process temperature.

Unlike metals, CFRP composites have lower thermal conduction and their properties exhibit strong temperature dependence. Therefore, the cutting heat tends to remain concentrated in the cutting zone, causing a rise of the cutting temperature. In order to eliminate the thermal effect, many cooling techniques, such as cryogenic cooling [22], minimum quantity lubrication (MQL) [23], liquid nitrogen [24] and chilled air [25], have been applied in machining of CFRP composites. The results showed that a better surface quality of CFRP workpiece could be generally obtained when the various cooling techniques were adopted. Nevertheless, machining of CFRP composites under dry conditions is still recommend by the manufacturing industry due to the economic and environmental reasons. The analysis of the heat transfer during machining of CFRP composites is hence necessary. In comparison with the temperature measurement, the analytical model can help to reveal the physical essence of thermal effect, but also predict the temperature field distribution to provide the reasonable cutting parameters.

It is well known that the heat partition ratio plays a key role for calculating the cutting temperatures in cutting metal materials [26,27]. Nevertheless, little attention has been paid on the heat partition ratio of machining composites. Liu et al. [28] developed an unsteady state three-dimensional heat transfer model to investigate the temperature field distribution of composite workpiece in helical milling process. They found that 40% of heat flowing was dissipated by the workpiece in the helical milling process. This method has provided some insight into temperature distribution in machining of CFRP laminates, however, the measured values of practical application were significantly constraint. This is mainly because the temperature measurements could be only performed at a large distance from the heat source, which results in large temperature measurement error. José Díaz-Álvarez et al. [29] presented a thermal analysis on composite drilling by numerical approach. But the accuracy of their method is limited, which might be due to the fixed value of 50% was used as the percentage of heat energy transfer to the composite workpiece. Therefore, it is important to figure out the heat partition in machining of CFRP composites, so that the percentage of heat transfer to the composite workpiece can be well controlled to obtain the ideal machining quality with minimum thermal effect.

This paper aims to help find the appropriate cutting parameters to avoid excessive cutting heat generated in the cutting zone conducted into the composite workpiece. An analytical model to predict the heat partition ratio is developed based on the assumption of all mechanical works contributing towards the heat generation. In this model, the contact area between the cutting tool and the composite workpiece with various fiber orientations is determined based on the classical Hertz contact theory. Finally, the heat partition ratio obtained from the analytical model is applied to a finite element model where numerical prediction is validated by the thermal imaging results. This paper also contributes the estimation of the cutting heat and the effect of fiber orientation on the percentage of heat transfer into composite workpiece. In addition, the influences of cutting and geometrical parameters of tool on the heat partition ratio at different fiber orientations are presented. The proposed approaches will be expected to help optimize the cutting parameters and reduce the thermal effect on the machining process.

The rest of the paper is organized as follows. Section 2 provides theoretical analysis on the heat partition ratio in machining of composites, and describes the analytical model verification method. Section 3 presents the simulation results based on the calculated heat partition ratio, and discusses the influence of various parameters on the heat partition ratio. The last section of the present paper is the conclusion.

2. Materials and methods

The heat transfer mechanism of machining composites is remarkably different from that of metals due to the anisotropic and heterogeneous characteristics of composites. The direct application of the heat transfer analysis known from metal cutting theory therefore cannot be used to reveal the complex effect of fiber orientation of composites on the heat generation and the heat partition. The particular heat transfer mechanism of machining composites needs to be revealed in depth. In order to better understand the fiber orientation-based heat partition of composite, the definition of fiber orientation and the simplified assumptions are required in deriving the analytical model, which will be introduced below.

In general, CFRP components toned to be properly machined to further improve the dimensional accuracy after initial manufacturing. The fiber orientation is a determinative factor on the strength and stiffness of the unidirectional CFRP composite. Therefore, the heat transfer behavior of the composite is recognized to strongly depend on the fiber orientation (θ) which is the priority to be considered as a key variable. In this study, the fiber orientation is defined by considering the direction of fiber axis and the direction of motion of the cutting tool. It is measured clockwise direction with reference to the direction of motion of the cutting tool, as shown in Fig. 1.

2.1. Model simplification and assumptions

In dry machining, the heat source generated from machining of CFRP composites is remarkably different from those in metal cutting process. The reason is that the plastic deformation dominates the metal removal process and the continuous chip formation. There are three heat sources produced in metal cutting: 1) the plastic deformation

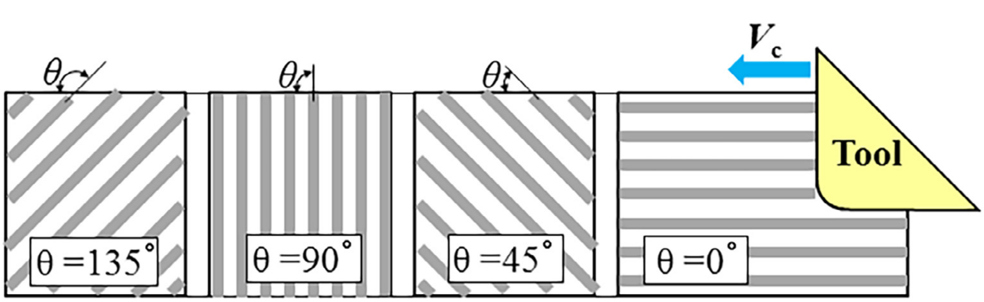

Fig. 1. The schematic of different fiber orientations.