Analysis and Control of Surface Delamination Defects During Milling of Orthogonal Aramid Fiber-Reinforced Composites Laminates

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Abstract: The aramid fiber-reinforced composites (AFRC) can increase the durability of corresponding applications such as aerospace, automobile and other large structural parts, due to the improvement in hardness, heat build-up, wear properties and green environmental protection. However, because of its complex multiphase structure and unique heterogeneity and anisotropy, the poor compression fatigue resistance and the incident surface fibrillation are inevitable. To improve the assembly precision of AFRC, mechanical processing is necessary to meet the dimensional accuracy. This paper focuses on the influence of contour milling parameters on delamination defects during milling of AFRC laminates. A series of milling experiments are conducted and two different kinds of delamination defects including tearing delamination and uncut-off delamination are investigated. A computing method and model based on brittle fracture for the two different types of delamination are established. The results can be used for explaining the mechanism and regularity of delamination defects. The control strategy of delamination defects and evaluation method of finished surface integrity are further discussed. The results are meaningful to optimize cutting parameters, and provide a clear understanding of surface defects control.

Key words: aramid fiber-reinforced composites (AFRC); milling process; delamination defects; surface control; prediction model

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0 Introduction

The aramid fiber-reinforced composites (AFRC) can increase the durability of corresponding applications due to the improvement of hardness, heat build-up, wear properties and green environmental protection. However, because of its complex multiphase structure and unique heterogeneity and anisotropy, the poor compression fatigue resistance and the incident surface fibrillation are inevitable.

To obtain the prescribed shape, mechanical processing is needed to meet the requirements of dimensional accuracy and surface roughness. The common mechanical processing methods of AFRC include turning, drilling, grinding, and milling. Due to complicated interactions between the matrix and the reinforcement during machining, there are often surface defects such as burrs, tearing, layering and thermal damage on processed materials surface after mechanical processing. Delamination defects mainly occur in the process of milling and drilling. Hence, this paper mainly discusses the delamination defects.

Several research works have been undertaken to investigate the phenomena and induced mechanism of different machining defects[1-5]. Bunsell[6] found that the fibre showed obvious yield phenome-

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non under tensile force and ductile fracture during tensile process, which was the main reason of burr defects. Shi et al. [7] pointed out that the interface phase formed between the phase and the matrix will affect the macroscopic mechanical characteristics of the materials. A damage zone is developed in the cohesive layer at the crack front of which properties degrade with deformation due to material damage or plastic softening. A stress limit is set for the cohesive zone based on the material strength, which serves as a criterion for the damage initiation. Kim et al.[8-9] investigated the inter laminar fracture toughness through experiments. It is found that the interfacial bonding properties of FRC were poor and the delamination defects were more likely to be produced in mechanical processing. Wollbrett-Blitz et al.[10] conducted interlaminar fracture properties testing, and found that the lamination defects were formed because of the poor interfacial cohesiveness of materials for AFRC.

Works show that the most common defects on the machined surface generated by conventional machining process are delamination defects which are initiated by stresses applied during engagement of the cutting edge[11]. Delamination defects are strongly influenced by fiber content and manufacturing process of composite part. Therefore, it is necessary to conduct further study on the causes and affect factors of delamination defects during milling of AFRC.

Hocheng et al. [12-13] studied the cutting forces and tool wear on the machinability of composite materials. The effects of the fiber orientation on the quality of machined surface were also investigated. Results showed that the delaminating defects tended to increase with an increase of cutting forces. Besides, the propagation of the delamination with increasing tool wear is commonly observed during machining composite materials[14-15]. This leads some researchers[16-18] to predict cutting forces and tool wear for studying machining defects.

It can be noticed that investigation on the delamination defects of fiber-reinforced plastics, are related to the defects control and cutting forces, as a function of cutting conditions, the distribution of staple fibers in the polymeric matrix, and the angle of inclination of staple fibers[19-20]. The available literature on AFRC is limited even though the demand for AFRC is increasing. Milling is the machining operation most frequently used in manufacturing parts of fiber-reinforced plastics, because components made of composite materials are commonly produced in a net-shape manner, which often requires the removal of excess materials to control tolerances.

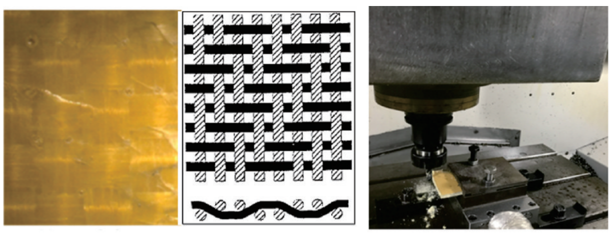
Machining of composite materials is based on brittle fracture mechanics theory. Machined surface defects are the most direct parameters to evaluate the cutting process. In the estimation of delamination defects, the modeling is critical to the accuracy of assessment. It is postulated that the cutting of composites materials should be based on fracture mechanics theory, as chip separation occurs due to fracture rather than plastic deformation. However, currently few analytical models are proposed for composite machining and many proposed models for these materials are either empirical or using the same shear plane theory as for metals. Among different predictive modeling techniques used, mechanistic modeling method is the most robust, simple and efficient one.

In this paper, a series of milling experiments are conducted for analyzing the mechanisms of delamination defects. The effects of cutting conditions and the fiber cutting angle are considered. The control strategy of different types of delamination defects and evaluation method of finished surface integrity are discussed. A computing method and model based on brittle fracture for delamination defects are established. The control strategy of delamination defects and evaluation method of finished surface integrity are further discussed. The established results could contribute to control the defects and improve machining process during milling of AFRC laminates.

1 Experiment

1.1 Experimental procedure

The milling experiments are conducted on a three-axis CNC machine center with a maximum spindle speed of 28 000 r/min. The composite material used in the tests (epoxy matrix reinforced with 55% of aramid fiber), supplied by Beijing spacecraft factory, is produced by autoclave with a fiber orientation of 0/90° as shown in Fig.1(a). The fixation of the composite material (plate) is made as observed in Fig.1(b), to eliminate the vibrations and displacement during experimental procedure. Machined surface is observed by scanning electron microscope (SEM) to clarify the surface defect caused by the cutting process.



(a) Workpiece (b) Machining process

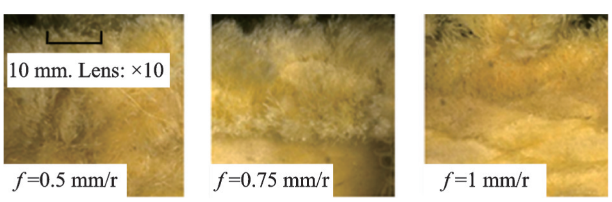
Fig.1 Workpiece and experimental setup for the test

A 6 mm four-flute cemented carbide end mill is used for milling tests, and the diameter is manufactured according to ISO. The helix angle is 30° and the rake angle is 10° with the clearance angle of 9° and flute length of 10 mm. Down milling process is adopted in this paper. The spindle speed is 8 000 r/min, and the feed speeds are selected to be 0.5, 0.75 and 1 mm/r. The axial depth-of-cut is the thickness of the workpiece. The radial depth-of-cut is set to be 1 mm.

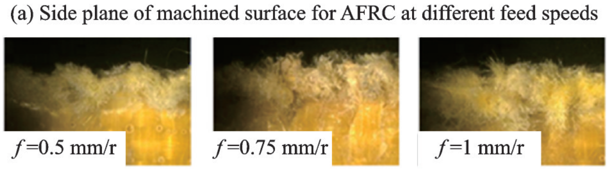
1.2 Experimental results

Fig.2 shows the AFRC machined surface of side and top planes for machining directions at 0° with different feed speeds.

Fig.3 shows the AFRC machined surface of side and top planes for machining directions at 45° with different feed speeds.

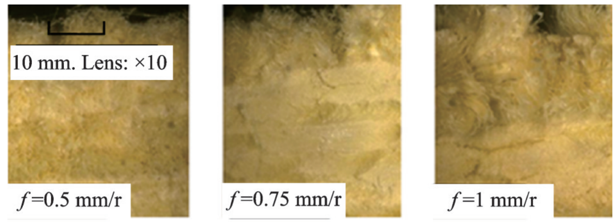


(a) Side plane of machined surface for AFRC at different feed speeds

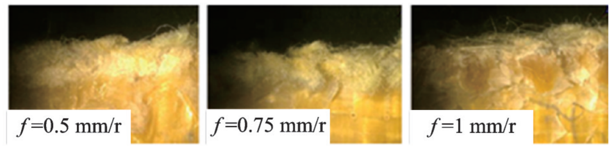


(b) Top plane of machined surface for AFRC at different feed speeds

Fig.2 Delamination defects for AFRC for machining directions at 0°



(a) Side plane of machined surface for AFRC at different feed speeds



(b) Top plane of machined surface for AFRC at different feed speeds

Fig.3 Delamination defects for AFRC for machining directions at 45°

2 Results Analyses and Discussion

The delamination defects can be recognized as the chipping and protruding of fibers. Fig.4 shows the development and propagation of delamination during milling process.

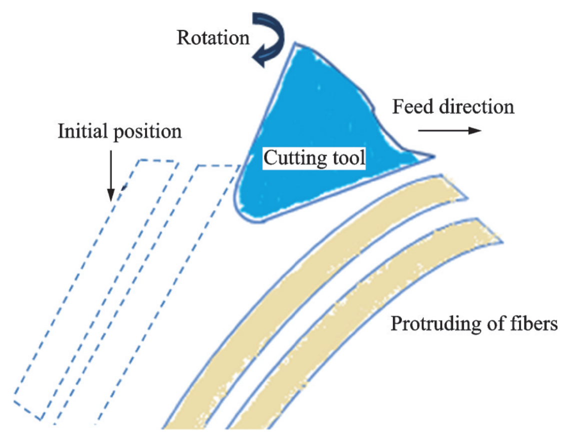


Fig.4 Schematic of the development of delamination

By comparing the experimental results, the presence of delamination defects on the machined edge of the composites materials is categorized. Two types of delamination are observed and schematically shown in Fig.5. Type I delamination describes areas where the surface fibers have been broken and removed some distance inward from the machined edge, which is called tearing delamination. Type II delamination consists of uncut fibers that protrude outward from the machined edge, which is

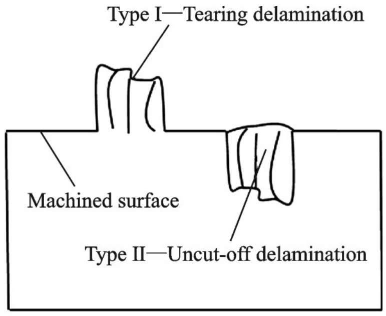


Fig.5 Types of delamination for machined surface

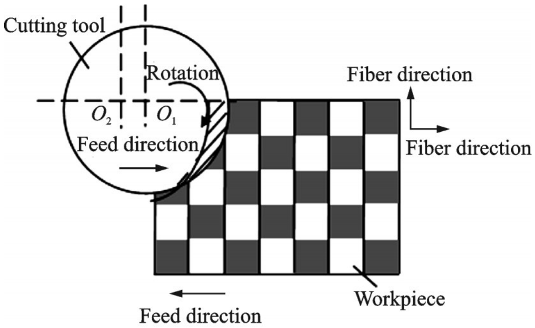
recognized as uncut-off delamination.

According to the experimental results, the best surface quality in terms of surface roughness and lowest damage is at the 0° machining direction. While for the side surface of the machined workpiece, the surface in the 45° fiber direction shows good surface quality.

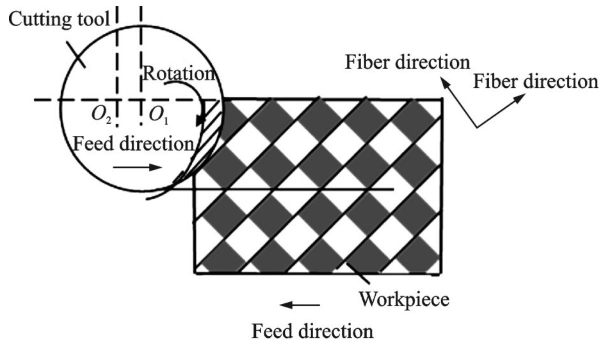
It can be seen that when the cutting direction is in 0°, the fiber directions are in 90° and 0°(perpendicular to each other). The delamination defects are both in the machined surface and in the side surface, as shown in Fig.2. While for the cutting direction in 45°, the fiber directions are in 45° and 135° (perpendicular to each other). The delamination defects are all in machined surface according to Fig.3.

According to Figs.2,3, it also can be seen that, when cutting direction is fixed, feed rate is the key parameter which influences the surface quality in milling of AFRC composite materials. Fig.6 shows the explanation of how feed rate affects the delamination defects.

When feed rate is low, the volume of materials involved in machining per tooth is less, and the fibers can be broken easily. Hence, there is minor lamination defects when feed rate is low in the directions of 0°and 45°. The value of feed rate should be selected as low as possible.



(a) Fiber direction in 0°



(b) Fiber direction in 45°

Fig.6 Explanation of feed rate effects on delamination defect

3 Prediction Model for Delamination Defects

3.1 Analysis of type I defects

According to experimental results, type I defects cause bending fracture in plane, and the fibers yield in feed direction. The type I defects can be analyzed by adopting minimum bending radius theory. The minimal fiber curvature radius $r_{\min}$ is decisive to attain the transverse rupture strain. It depends on the ultimate tensile strain ε_B and the fiber diameter d_{fiber} as shown in Eq.(1).

$$r_{\min}=\frac{1}{2}\left(\frac{1}{\varepsilon_B}-1\right)d_{\text{fiber}} \tag{1}$$

The values of ε_B and d_{fiber} are listed in Table 1 for the materials used in this paper.

Table 1 Materials properties for AFRC

AFRC	ε_B/%	d_{fiber}/μm
Value	1.8	7

When the workpiece is placed in 45°, by using the minimal curvature radius, swerve mechanisms in two perpendicular directions can be modeled. Fig.7 shows schematically how the fibers avoid the cutting tool in the laminate plane for cutting fiber direction in 45° and 135°.

As shown in Fig.7, to ensure the fibers bend around the radius $r_{\min}$, the fibers must move freely at a depth of Δ_1 and Δ_2 in laminate plane, i.e., they must be delaminated. Δ_1 and Δ_2 can be calculated according to Fig.7.

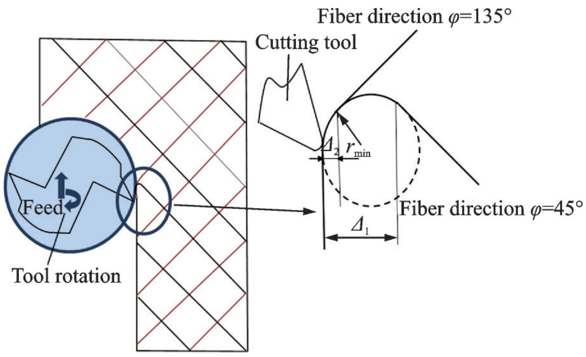


Fig.7 Bending of fibers in laminate plane at different fiber directions

$$\Delta_1 = r_{min}(1+\cos\varphi) + d_{fiber} = r_{min}(1+\cos 45°) + d_{fiber} \quad (2)$$

$$\Delta_2 = r_{min}(1+\cos\varphi) + d_{fiber} = r_{min}(1+\cos 135°) + d_{fiber} \quad (3)$$

3.2 Analysis of type II defects

Fig.8 schematically shows when the workpiece is placed in 0° during the machining process, and how the fibers avoid the cutting tool in the laminate plane and in the vertical plane for cutting fiber direction in 90° and 0°.

As shown in Fig.8, to ensure the fibers bend around the radius r_{min}, the fibers must move freely at a depth of Δ_1 in laminate plane and at a depth of Δ_2 in vertical plane. Δ_1 can be calculated according to Fig.8 as

$$\Delta_1 = r_{min}(1+\cos\varphi) + d_{fiber} = r_{min} + d_{fiber} \quad (2)$$

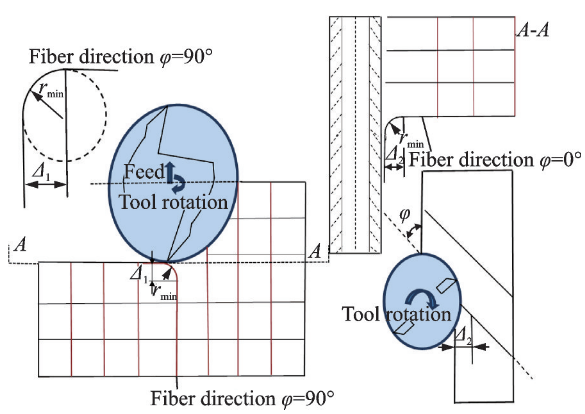


Fig.8 Bending of fibers in laminate and vertical planes

As for the fibers in 0°, the fibers are bended in vertical plane which is perpendicular to the laminate plane. It is assumed that the tool moving along the feed path represents a level obstacle for protruding fibers. To ensure the fibers bend at this angle around the respective radius r_{min}, they must move freely at a depth of Δ_2 from the component edge. According to Fig.8, Δ_2 can be calculated from φ and d_{fiber} as

$$\Delta_2 = r_{min}\sin\varphi + d_{fiber} = r_{min} + d_{fiber} \quad (2)$$

The lamination defects depth can be obtained according to Eq.(2) and Eq.(3) for fiber direction in 0° and 90°. According to Eq.(4) and Eq.(5), the lamination defects depth can be determinated for fiber directions in 45° and 135°.

Fig.9 shows the prediction model and the experimental results.

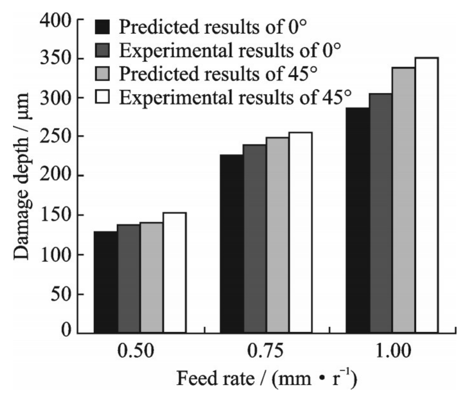


Fig.9 Comparison between prediction and experimental results

The prediction results of the model agree well with the experimental results. It implies that the establish model can be used to control the defects of delamination during milling of orthogonal AFRC.

4 Conclusions

Delamination defects lead to a significant reduction in fatigue life for composite laminates. The proposed model can be used for predict delamination which can avoid serious accidents in the areas of aeronautical and aerospace engineering, and automotive industry.

From the developed model and the cutting experiments, the following conclusions can be obtained:

(1) The delamination growth behavior, characterized by arc shape crack, is well predicted via the numerical method by considering the geometric and

mechanical properties of AFRC laminates.

(2) Two deflection mechanisms of fibers protrusions are distinguished and the mechanism of different delamination defects is explained.

(3) The numerical model can predict fiber delamination accurately in the milling process. Comparing the numerical and experimental results, a good agreement within an error of 5% between the numerical predicted and experimental results has been confirmed.

(4) The feed rate has a negative effect on surface integrity. The delamination defects become serious when feed rates increase. Hence, for AFRP composites, low feed rate is preferred to get better surface quality.

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Author contributions Profs. **SHI Zhenyu** and **WANG Zhaohui** designed the study, complied the models, conducted the analysis, interpreted the results and wrote the manuscript. Mr. **DUAN Ningmin** contributed to the discussion. Mr. **LI Xin** contributed to the background of the study. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: ZHANG Tong)

正交芳纶纤维增强复合材料层合板铣削过程中表面脱层缺陷的分析与控制

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摘要: 芳纶纤维增强复合材料(AFRC)由于比强度高、比刚度高、耐疲劳性好、耐高温防热防腐蚀且可设计性好等特点,被广泛用于航空航天、汽车等大型结构件。由于纤维具有方向性,常常表现为一维织构化,在特定方向上性能较差,材料层间剪切强度小,成为材料在使役过中的重要隐患。为了提高芳纶纤维复合材料结构件的装配精度,通常采取制备材料后通过进行二次加工即切削加工的方法得到规定的形状,满足尺寸精度、表面粗糙度和装配工艺的要求。作者研究了铣削过程中铣削参数对层合板分层缺陷的影响规律,并进行了一系列的铣削试验。针对加工过程中存在的两种不同分层缺陷,撕裂和未切断分层缺陷进行了研究。论文建立了基于脆性断裂的两种不同分层型式的计算方法和模型并阐述了分层缺陷形成机理和规律。并进一步讨论了分层缺陷控制策略和已加工表面完整性的评价方法。论文的研究结果对于优化铣削参数以及表面缺陷的控制具有重要的指导意义。

关键词: 芳纶纤维增强复合材料;铣削过程;分层缺陷;表面控制;预测模型