Research Article

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Effect of Cutting Temperature on Bending Properties of Carbon Fibre Reinforced Plastics

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Abstract: High cutting temperatures are easily generated during the machining of carbon fibre reinforced plastics (CFRP) and can induce serious damage during machining such as delamination. The purpose of this paper is to study the influence of cutting temperature on the performance of CFRP after machining. CFRP specimens were heated to temperatures within the vicinity of cutting temperatures generated during machining, then air-cooled and their bending properties investigated. The results showed that temperature had significant influence on the bending stress of CFRP. With increasing temperature, bending stress decreased and was lowest when the temperature was close to the glass-transition temperature. It was concluded that the bending properties of CFRP could be seriously affected if the material temperature was close to the glass-transition temperature and maintained for a period. As a result, cutting temperature should be kept lower than the glass transition temperature during machining.

Keywords: CFRP; Cutting temperature; Glass transition temperature; Bending stress

1 Introduction

Carbon fibre reinforced plastics (CFRP) are characterized by low specific gravity, high specific modulus and high specific strength. They have been widely used, including in aircraft wings as structural components of aerospace craft. Because of their low interlayer bonding strength and anisotropism [1], CFRP are easily damaged in machining and are typically difficult to process. The most common matrix in carbon fibre composites is thermosetting epoxy resin bonded tightly with carbon fibre; however, epoxy resin may be softened, aged and chemically decomposed under certain temperatures [2], which further causes the failure of CFRP-containing parts.

Antonacci et al. [3] tested the mechanical properties of epoxy resin matrices by differential scanning calorimetry and reported that the fatigue performance of the resin matrix changed significantly with temperature. Foreman et al. [4] studied thermodynamic characteristics of resins and found that their elasticity moduli decreased significantly with increased temperature. Koyanagi et al. [5] carried out a mechanical test on CFRP under different temperatures and concluded that temperature had a significant influence on material failures. Lu Dong et al. [6] combined finite element simulation and experimental tests to analyse the damage to composite materials arising from bending, demonstrating that the cracking damage of workpieces increased continuously with increasing stress. Since the thermal conductivity of CFRP is low, the accumulation of cutting heat accelerated to result in an extremely high cutting temperature and softening of the resin matrix once the cutting temperature exceeded a threshold, with transitioning of the resin matrix from a glass state to a rubber state. As a result, the overall performance of the composite material declined, and processing damages occurred [7].

In the cutting process, a heat-affected zone (HAZ) forms on the surface of CFRP. This HAZ can induce processing damages during machining and may influence the usability of materials after machining and cooling [8]. Therefore, it is of great significance to study the influence of cutting temperature on material performance after machining. There have been numerous studies on the processing damages caused by cutting temperature and good methods for detecting processing damage have been developed [9]. Nevertheless, a study on this aspect is also less that concern the usability of materials arising from the HAZ and it is difficult to detect changes in the mechanical properties of materials [10].

In this paper, test samples with certain characteristics were prepared. Based on glass transition temperature de-
Table 1: Material parameters of composite specimens

| Total length L/mm | Actual distance L₀/mm | Width b/mm | Thickness d/mm | Average diameter of carbon fibre /µm | Volume ratio between carbon fibres | Layered pavement of carbon fibre | Curing temperature /°C |
|-------------------|-----------------------|------------|----------------|-------------------------------------|-----------------------------------|----------------------------------|------------------------|
| 85                | 45                    | 12.5       | 2              | 7                                   | 60 ± 5%                           | [0°/45°/−45°/0°]s            | 120                    |

Figure 1: Three-point loading

2 Experimental design

2.1 Test materials

This experiment was designed according to ASTM-D5961 Standard Test Method for Compressive Strength of Laminated Board in Composite Material with Polymer Matrix. The experimental setup is shown in Figure 1.

This experiment used a carbon fibre composite material comprising a layered pavement of carbon fibre and epoxy resin with curing degree of 80% [13]. Its parameters are listed in Table 1.

2.2 Experimental process

Since the cutting temperature of CFRP in practical machining is generally lower than 200°C [14], heating temperatures in this experiment were set to 20°C (room temperature), 60°C, 90°C, 120°C, 150°C and 180°C. Test three times for each group of temperatures. Specimens were heated by the heating device to the pre-set temperature and the temperature maintained for 2 min. Specimens were then removed from the heating device and cooled at room temperature for 30 min prior to the bending test. Figure 2 shows the CSS88100 electronic universal testing machine with a range of 0-100 KN set up for the 20°C test.

2.3 Detection of glass transition temperature

Glass transition temperature (Tg) is an important characteristic parameter of resin matrices and represents the...
main parameter related to resin heat resistance. Internal structure, physical and chemical properties and bending failure stress of materials all change significantly at close to the Tg. Dynamic thermal mechanical analysis (DMA) measures changes in the mechanical modulus and dynamic modulus of materials under vibration loads with temperature. The temperature corresponding to the mechanical loss peak can be viewed as the Tg. The crosslinking densities of epoxy resins can be ascertained according to their relative Tg values. In this paper, DMA was applied to detect the Tg of epoxy resins through the single-cantilever operation mode. The DMA device is shown in Figure 3.

3 Results and discussions

3.1 Changes of mechanical properties

The displacement-load curves under different thermal treatment temperatures are shown in Figure 4. The vertical axis represents the failure stress of the material, which reflects its bending strength and can be calculated according to the load-to-section area ratio of the specimen. The horizontal axis represents the bearing capacity of the material, which reflects its stiffness. The curve slope is the elasticity modulus of the material. As can be seen from Figure 4, specimens that were subjected to 120°C and 150°C developed fracture failure at lower loads than other specimens, with the specimen processed at 120°C being the quickest to fracture under applied load.

The thermal treatment temperature-bending strength is shown in Figure 5, which shows that temperature can significantly affect the usability of CFRP. The bending strength of CFRP initially decreased and then increased with increasing temperature. The bending strength was high and relatively stable when the thermal treatment temperature was between 20°C and 90°C; under these conditions, the thermal treatment temperature influenced the usability of CFRP only slightly and the CFRP maintained good mechanical properties. The bending strength of CFRP decreased quickly in the temperature range of 90-150°C, with the lowest bending strength occurring at 120°C. The bending strength increased again when the temperature increased from 120-150°C. This was because the curing temperature of CFRP used in this experiment was 120°C and secondary curing occurred in the 120-150°C range as a result of reaction between functional groups of
the resin; this resulted in increased crosslinking density and further improvement of the mechanical properties of CFRP. The bending strength was 192.6 MPa when the temperature reached 150°C, which was 3.11% higher than that at 120°C. The bending strength continued to increase with further increase in temperature due to thermoelastic inversion of CFRP as it transitioned from a glass state to a high-elasticity state [7].

**3.2 Glass transition temperature**

The glass transition temperature of CFRP was determined using DMA, and the results shown in Figure 6. The blue curve is the loss modulus that reflects adhesion of the material. The green curve is storage modulus, that is, the elasticity modulus, and reflects the stiffness of the material. The red curve is the ratio between the loss and storage moduli, that is, the material damping tan δ. δ is the phase angle of stress and strain. The maximum tan δ of CFRP is equal to the glass transition temperature of the material.

It can be seen from Figure 6 that the elasticity modulus of the epoxy resin decreased quickly when the temperature increased from 104.94-154.34°C. The loss modulus fluctuated violently when the temperature increased from 90-150°C, indicating that temperature significantly influenced the adhesion activity of the resin. The apex of the red curve is the glass transition temperature (156.55°C). Material properties changed at this temperature and as the material transitioned from a glass state to a rubber state.

**3.3 Microstructure of the fracture zone**

The bending deformation of the materials is shown in Figure 7, where A is the front view and B is the side view. The
directions of crack development in the materials were observed after specimens were processed at different temperatures. Figure 7 shows that the bending failure of the material increased with increased temperature, with the most serious failure developing at 150°C; however, the degree of failure at 180°C was smaller than that at 150°C.

Further investigation of the material properties was performed under a microscope to determine the material microstructure. Bending-fractured specimens that had been processed at different temperatures were magnified 250x to observe changes to the fractured surface and changes to the internal microstructure. It was found that the degree of bending of the material increased with increasing temperature and that materials were almost fractured at the glass transition temperature (150°C).

Figure 8 shows the interlayer hierarchy at fracture surfaces. The interlayer hierarchy became more pronounced with increasing temperature and was poor at 150°C, indicating that the failure of the interface intensified with increasing temperature. It can be seen from Figure 9 that there were few cracks on the fracture surface, which were mainly due to interlayer resin failure. Materials were almost completely fractured by cracks at 150°C. This also showed that the material failure process arose from the expansion of cracks in the resin matrix. Although there was crack expansion at 180°C, there was slightly less than at 150°C; this reflected that the influence of this expansion was less than that at 150°C. Figure 10 shows the microscope magnifying different multiples at 150°C.

The bending failure of CFRP is shown in Figure 11. Materials developed microcracks upon the application of bending stress, with obvious expansion of cracks when bending stress increased. When the fibre-resin interface strength was higher than the resin strength, microcracks expanded readily in the resin matrix and led to material failure. Microcracks extended readily along the resin-fibre interface when the resin strength was stronger than the fibre-resin interface strength, also leading to material failure.

The whole temperature field distribution in the cutting process is shown in Figure 12. Since the temperature in the cutting process was generally higher than the glass transition temperature of the resin matrix, the bending performance of materials surrounding pores differed according to differential temperature influences. When the cutting temperature was higher than the glass transition temperature of the resin, the material performance initially increased and then decreased after machining along an outward direction from the pore centre. The poorest bending performance of the material was detected in the glass transition temperature zone; therefore, the cutting temperature of the composite material should be lower than the glass transition temperature of the resin. However, the components of the composite material may initially fracture close to the glass transition temperature in
some cases, such as under certain loads after assembly or connection, if the cutting temperature of the composite material is higher than glass transition temperature of resin, rather than fracture close to the pore wall.

4 Conclusions

(1) The glass transition temperature of CFRP was determined to be 156.6°C by DMA. According to the
CFRP bending test, bending strength decreased significantly when the thermal treatment temperature was close to the glass transition temperature; however, bending strength began to increase when the thermal treatment temperature was slightly higher than the glass transition temperature.

(2) Observation of microstructure in the fracture zone of CFRP revealed that microcracks were readily generated and expanded in the interlayer under bending stress when the thermal treatment temperature was lower than the glass transition temperature of the resin matrix. However, microcracks were readily generated and expanded at the resin-fibre interface under bending stress when the thermal treatment temperature was higher than the glass transition temperature of the resin matrix.

(3) The bending performance of the material was poor during machining when the temperature was close to the glass transition temperature. The material zone that experienced temperatures close to the glass transition temperature was the most easily fractured during machining rather than the zone close to the pore wall. Therefore, cutting temperatures close to the glass transition temperature should not be used during machining.

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