# CFRP DRILLING MECHANISM AT LOW TEMPERATURE BASED ON THE TEMPERATURE-DEPENDENT PROPERTIES OF RESIN AND INTERFACE

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## ABSTRACT

Currently, researches of CFRP drilling quality mainly focused on the effects of the shape and material of bit tools, processing parameters, there are only few works in the literature that have investigated the effect of the low temperature on drilling quality of CFRP. The influence of the low temperature on the machining quality of CFRP is yet not fully understood. The aim of this study is to study the influence mechanism of the low temperature on the machining quality of CFRP. For this purpose, a CFRP drilling experimental study was carried out in a climatic chamber, and a series of temperature-dependent character experiments of matrix and interface were also carried out. The results have shown that the temperature-dependent properties of resin and interface have a great effect on the drilling quality, and reduce the drilling zone temperature can improve the drilling quality.

## 1 INTRODUCTION

Carbon fiber reinforced polymer (CFRP) materials has been widely applied in aviation and aerospace fields. But defects always occur in connecting holes drilling of CFRP, including delamination, tear, burr, etc., which seriously affect the assembly quality of components, and have been regarded as a key technical issue to be solved urgently. For these reasons, there are a large number of literatures have been studied on these problems to decrease the defects and increase the drilling surface quality[1, 2]. And almost all the studies have tried to answer two main questions: how defects appear under drilling process, and how to reduce the drilling defects. The answers have related to the thrust force and drilling heat[3-5].

Several studies believed that is a "critical thrust force" below which no damage occurs. For example, Tsao et al. [6-8] developed a series of core-special drills with difference shape to correlate the thrust force with the onset of delamination, found that the compound core-special drills have more advantageous in drilling CFRPs. Vaibhav A. et al.[9] investigated the effect of discrete machining parameters on thrust force and torque in drilling CFRPs, observed that the thrust force, torque and delamination damage increased abruptly with an increase in the feed rate, but reduced gradually with increasing cutting speeds. G. V. G. Rao [4] studied the cutting force and their variation with depth of cut, tool rake angle, fiber orientation in UD-CFRP and UD-GFRP composites by micro-mechanical numerical and experimental methods, found that cutting force increases with fiber orientation(15-90°), and is less effected by depth of cut and rake angle. To further reduce thrust force and increase drilling quality, Xu Weixing et al. [10] developed an elliptic vibration-assisted technique to cut fiber-reinforced polymer composites and found that this methods can significantly decrease the cutting force and reduce the subsurface damage.

However, all of above studies do not consider another key factor -- drilling heat, even drilling damaged zone caused by thermally is larger than mechanically[11], and the damage is still difficult to control. Currently, researches about the effect of drilling heat on CFRP drilling quality mainly focused

on the temperature measurement[12], there are poorly studies on the influence mechanism of drilling heat on machining quality. For example, Haddad M at el.[13] analyzed the high speed trimming quality of CFRP using unused and used burr tools, found that machining with unused tools cutting temperature lower than glass transition temperature(Tg) and compared used tools have a well machining surface, while the cutting temperature was higher than Tg when machining with used tools and have a worse machining surface. Xia T at el. [14] investigated the effects of cryogenic cooling on drilling performance and surface integrity characteristics of CFRP, found that cryogenic cooling can enhance the surface integrity characteristics, but a high delamination factor. It is regrettable that this study doesn't make it clear that the influence mechanism between drilling temperature and materials.

So, the aim of this study is to study the influence mechanism of the low temperature on the machining quality of CFRP. For this purpose, a CFRP drilling experimental study was carried out in a climatic chamber with an air compressor, and the drilling environment temperature ranged from -50°to room temperature. In addition, a series of temperature-dependent character experiments of matrix and interface were also carried out to interpretation the test phenomena.

## 2 EXPERIMENTAL PROCEDURE

### 2.1 Work material

The composites specimens were made of T300/ TF1408 tape prepregs with a stacking sequence [0/90]16s, and the thickness is 4±0.2mm. The Tg of TF1408 epoxy resin is 123°measured by DSC test.

### 2.2 Drilling experimental device and test conditions

Low temperature drilling tests at different temperature were carried out by a cryogenic cooling drilling system (Fig.1), which was composed of vertical drilling-milling machine, climatic chamber, cryogenic cooling devices and temperature measuring devices. Specimens were placed inside the chamber in a steel support and clamper (Fig.1). A thermocouple was connected to a temperature controller and measured the environment temperature of chamber. The temperature controller regulated the opening of an electrovalve, which controlled the volume of cold air to enter the chamber.

A FLIR SC7300M infrared camera was used to measure the drilling zone temperature through a barium fluoride window during each drilling process. A vertical drilling-milling machine with maximum spindle speed 3000 rpm, was used in drilling experiments conducted in this study. An uncoated carbide conventional twist drill (Fig.1) was used in this study, and the diameter is 8mm, the point angle of this drill is 118 °.

Four different test environment temperatures:23 to 0, -25, and -50 °were designed in this study, and the fresh drill was used in each test run, all the cutting speed in this study is 1000r/min, all the feed rates is 30mm/min. Five specimens were made for each temperature of test.

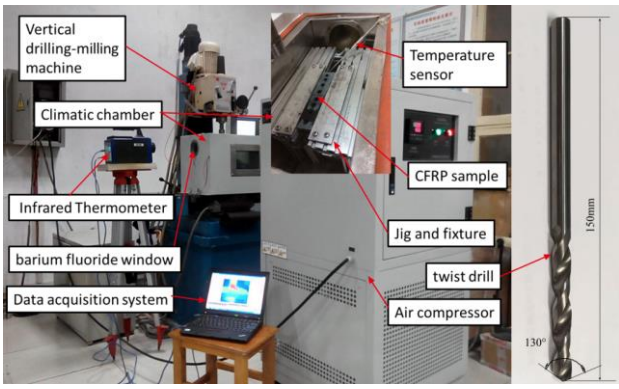


Fig.1. Experimental device for low temperature drilling tests

### 2.3 Drilling quality measure

In order to investigate the surface integrity of machined CFRP: the laser scanning confocal microscope(OLS400) was used in this study to measure the average surface roughness (Ra) respectively along x and y-axis; the field emission scanning electron microscope (SEM su-8010) was used to analyze the morphology of machined surface. In order to study the relationship of delamination areas versus drilling temperature, the scanning acoustic microscope (SAM D9500) was used in this study.

### 2.4 Mechanical testing

The Interfacial shear strength (IFSS) is a key parameter of CFRP that influences the adhesion performance between the fiber and matrix [15-17]. However, IFSS becomes unstable as it is affected by the service temperature[18]. The temperature dependence of IFSS was tested by microbond method [17] with HM410-microdroplet test equipment from TOHEI SANGYO, Japan. The testing temperature ranged from 20°C to 150°C and five tests were performed in every 10°C.

A dynamic mechanical analyzer (DMA Q800) was used for measure the modulus versus temperature curve of epoxy matrix. DMA tests were conducted using three-point bending modes (ASTM D5023-15) as it can provide the most analogous approach to normal mechanical testing method [19]. The test temperature scanning measurements were performed from 0°C to 200°C at a heating rate of 3°C /min and an oscillation frequency of 1 Hz.

## 3 RESULTS AND DISCUSSION

### 3.1 The relationship between drilling area temperature and the state

Fig.2 shows the drilling zone temperature versus ambient temperature of chamber. It is observed that the relationship between drilling ambient temperature and drilling zone temperature is changing in a linear. And with the increasing of the environment temperature, the drilling zone temperature is increasing, when environment temperature is lower than 0°C, the drilling zone temperatures is lower than the Tg of epoxy matrix (123°C ).

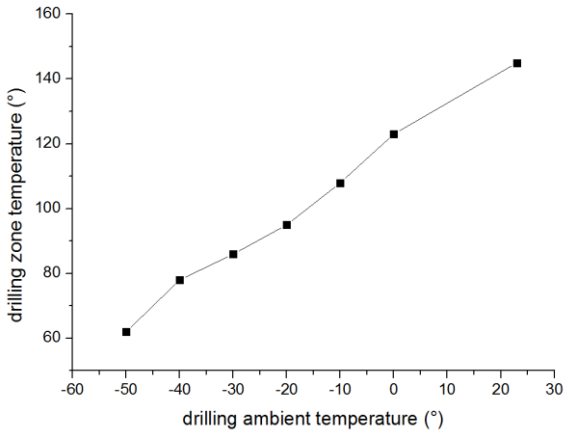


Fig.2. the results of drilling zone temperature versus drilling ambient temperature

### 3.2 The influence mechanism of the low temperature on surface roughness analyses

Fig.3 illustrates the evolution of surface roughness (Ra) as a function of environment temperature. It is observed that the Ra is significantly influenced by the drilling environment temperature both along feed direction and vertical feed direction. And the Ra is declined sharply when drilling ambient temperature ranged from room temperature to -25°C, but when temperature ranged from -25 to -50°C the Ra begin to flatten.

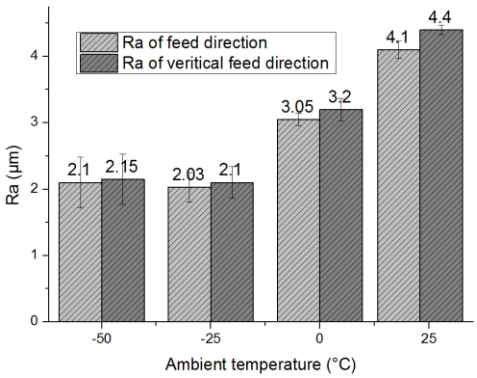


Fig.3. Influence of drilling environment temperature on the surface roughness

Fig.4 presents the cross-section microstructure of drilling surface for various drilling environment temperature under 100X. It is clear from this image, with the decrease of drilling environment temperature the areas of matrix degradation are decrease. In addition, the upheavals that located in two layers are not obvious with drilling ambient temperature reducing, especially when the temperature lower than -25°C. The reasons for forming the upheavals are: i) the thermal expansion coefficient of single carbon fiber laminate (αf) is anisotropic, and the thermal expansion coefficient of resin (αm) is far greater than carbon fiber; ii) the distribution of resin inside CFRP is uneven, the content of resin between two layers is at least twice as like as other place of CFRP; iii) the irreversibility of thermoset resin when the temperature higher than Tg. So, during the process of drilling, the material in drilling zone will expand with the drilling temperature increasing, for the difference of thermal expansion coefficient among up layer, resin interface and down layer, the expansion volume of the resin interface will be greater than the others. When completed the drilling the drilling zone temperature will be down to room temperature, the material will shrink, but for the irreversibility of resin when the temperature higher than Tg, there will be a upheaval between two layers. This is the reason why the size of upheaval will be smaller when the drilling zone temperature decreasing.

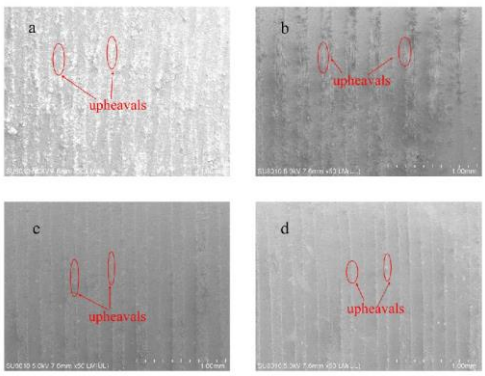


Fig.4. SEM observation of drilling surface for various drilling environment temperature (a)drilling under room temperature; (b) drilling under 23°C; (c) drilling under 0°C; (d) drilling under-25°C; (e) drilling under -50°C;

### 3.2 The influence mechanism of the low temperature on drilling delamination analyses

Delamination is the most serious damage during the service process of CFRP, a lot of research shows the delamination damage always occurred in the exit-ply[20,21]. This phenomenon also occurred in this study (fig.5.a-a1, fig.5.b-b1), but the delamination is significantly reduce when drilling ambient temperature lower than -25°C (fig.5.c-c1, fig.5.d-d1). In order to evaluate the delamination areas, ultrasonic C-scan was used in this study.

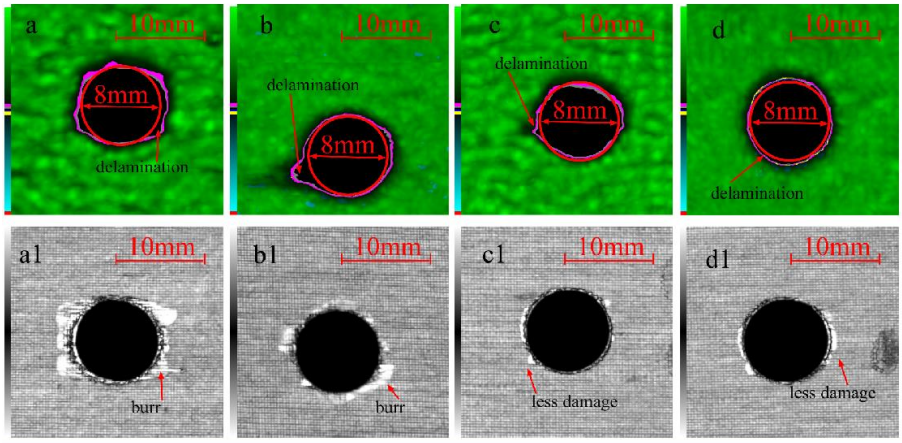


Fig.5. Exit damage under various ambient temperature (a-a1) 23°C, (b-b1) 0°C, (c-c1)-25°C, (d-d1) -50°C. (a-d) Ultrasonic C-scan images showing delamination damage, as indicated by red arrows. (a2-d2) Ultrasonic C-scan images showing damage at the exit surface, as indicated by red arrows.

Previous studies have shown that the delamination damage is related to the adhesion properties of interface and the anti-bending properties of exit stiffness. Fig.6 illustrates results from the thermo-mechanical characterization of epoxy resin and the temperature-dependent properties of interface. It can clearly be seen that the measured IFSS between fiber and resin matrix is significantly affected by the temperature, where IFSS decreases substantially near Tg of epoxy resin. Also, the storage modulus decreases substantially when temperature higher than Tg (Fig.6). So, when drilling zone temperature higher than Tg, the anti-bending properties and the adhesion properties of interface decrease sharply, correspondingly, the delamination damage in this temperature range (Fig.5 a-a1, b-b1) is weaker. When drilling zone temperature in the glass state temperature range (Fig.6), the IFSS and the stiffness of resin hold stable and decrease in the probability of exit delamination damage(Fig.5 c-c1, d-d1).

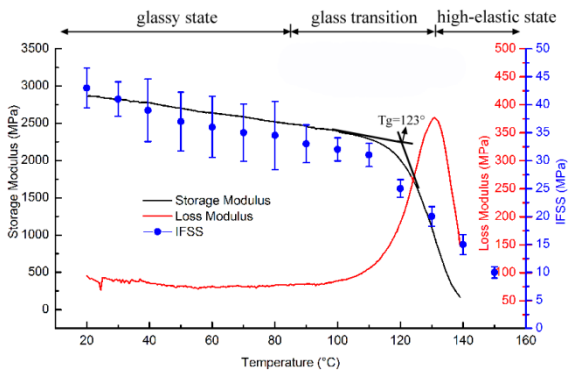


Fig.6. Epoxy matrix storage/Loss modulus and IFSS versus temperature

## 4. CONCLUSIONS

An experimental study was conducted to analyze the impact of cryogenic cooling conditions on holes quality when drilling CFRP laminate. The experimental results showed that the drilling zone temperature has a great influence on the material removal mechanisms and surface integrity of CFRP drilling. Based on the experimental results, the conclusions can be summarized as follows:

1. Cryogenic cooling conditions can improve the uniform of drilling surface, and reduce the creation of defects.

2. The roughness will significantly decline and the upheavals between two layers are not obvious with the drilling environment temperature decreasing. The reason is that the expansion volume of the resin and fiber are difference for the mismatch of αf and αm, but the differences will be decreased at low temperature.

3. The delamination is significantly reduced when drilling zone temperature lower than Tg. The

reason is that the interfacial strength and the stiffness of laminate will be enhanced in low temperature.

4. There will be a well drilling quality of CFRP laminate, when drilling zone temperature is controlled in the range of glassy state.

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