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Development of a user-friendly drilling evaluation database system of CFRP

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Abstract: The drilling process of carbon fiber reinforced plastics (CFRP) is the main secondary processing in the entire production cycle. However, there is no standard theory that could be used to estimate the hole quality and to quantify the assessment. Therefore, in this article, several influential factors of drilling quality, such as drilling parameters and materials, were utilized to establish the classification tree model. A comprehensive evaluation model [three-dimensional (3D) evaluation factor] was presented to measure and quantify the quality of the hole. Then a series of experiments were designed based on existing conditions. Further, a mathematical software (Origin) was used to fit and analyze the relationships of the drilling parameters and the 3D evaluation factor. Then a user-friendly drilling database system of CFRP was established based on the historical data of drilling experiments and the fitting function. In addition, in order to contrast the optimization results of the fitting function, the drilling experiments have been conducted, and the results have verified that the drilling database system could optimally predict the drilling schemes with a minor error.

Keywords: carbon fiber reinforced plastics; data fitting; drilling database system; drilling quality; 3D evaluation factor.

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1 Introduction

In the recent years, carbon fiber reinforced plastic (CFRP) materials have been applied extensively in many areas such as national defense, and the automobile, electronic, and medical industry; therefore, an increasing number of studies have been carried out by academics. In order to reduce, as much as possible, the weight of structures on the premise of guaranteeing the properties, CFRPs are deemed as the ideal materials because of their special performance, including specific strength, stiffness, lightweight, etc. Drilling is the last and major machining process for making holes to assemble the composite structures, but there are also many defects that happen during the drilling period, owing to the anisotropy and the inhomogeneity of the composite laminates, making it difficult to meet requirements.

In order to reduce the defects such as delamination, surface quality, burr, and tool wear, enormous work has been conducted to obtain the optimal result of drilling. Eneyew and Ramulu [1] analyzed the delamination at the entry and exit sides as well as the surface damage and then showed that thrust force is the direct influencing factor. Many authors studied the effect of spindle speed and feed rate on the delamination and force [2–4]. They considered that high speed and low feed rate could reduce the defects; particularly, the feed rate is the remarkable influential parameter affecting delamination [5]. Reasonable tool geometries provide a positive role on the drilling quality [6, 7]. Hocheng and Tsao built the theoretical models of drilling process on various drill bits [8], which could predict the critical thrust force effectively. In addition, the pull out at the exit induced by chisel edge was also confirmed [9]. With the development of nanotechnology, the coated drills are superior to conventional drills in the aspect of improving hole surface quality [10]. Xu et al. [11] considered that the high-strength reinforced fiber is a good solution for enhancing the performance of composite structures and diminishing the defects. Several researchers reported that the influence of fiber orientation and stacking sequence on the mechanical properties of composite is impressive [12, 13], and furthermore, the variation of cutting force with the fiber orientation angle has been focused mostly on the cutting mechanism [14]. Moreover, temperature has a crucial effect on the resin in the drilling procedure [15]. Besides, under some conditions, the guide device, the support in the back, and the predrilled hole would be the positive factors for the hole quality [16–18].

Simulation models have a significant impact on the drilling process and could make a prediction with the same parameters as the experiment for the drilling result, allowing certain parameters to be changed according to the requirement. The finite element method has been presented in plenty of research [19–21]. Numerical models are a vital way to also achieve aims [22]. In addition, the application of a variety of mathematic methods is novel to some degree, and the methods could decide the optimal scheme or parameters in advance when the experiment conditions were restricted [23–25].

Thus, many scholars have researched into the influential factors of drilling quality and summarized numerous approaches to predict and reduce the damage during drilling. In addition, the selection of machining parameters has a huge significance on production processing. Especially, a machining data system including massive information data and ideal service capability can affect the production quality and efficiency, further reducing the operating costs and improving the competitive ability of these enterprises. Some developed countries have already established the machining databases such as MDC (America), INFOS (Germany), and COROCUT (Sweden), which consist of various types of processing. In recent years, a cutting database of specialization and miniaturization has been the mainstream direction for metal materials [26–28]. However, a comprehensive and large-scale drilling quality database containing all of the important impact factors, just as for some databases in other domains, has rarely been reported in the composite domain. In order to meet the needs of composite industries, a data system like a drilling quality database containing various significant factors needs to be built urgently. Considering the complexity, the database has been divided into several parts. In this paper, the effect of the drilling parameters and their interaction on the drilling quality have been emphatically analyzed based on drilling tools. Using the analysis of fitting, the multiple linear regression models for delamination were established in terms of the spindle speed and feed rate based on drilling instances, which could lay the foundation of developing a comprehensive drilling quality database.

2 Modeling

The drilling database system includes the various drilling parameters and the different drilling tools and drilling materials, and then the establishment of the drilling database system also needs the support of enormous and statistical drilling data. Furthermore, the task for the whole procedure is complex and tremendous, so the drilling database system will be divided into several parts to meet the requirements by stages. The main concern of this paper is to build up the drilling database system based on the current equipment and materials, especially in the aspect of drilling tools.

For the sake of creating an intelligible classification tree model, the major influential factors of drilling quality have been further studied in Table 1.

First, the composite of an epoxy resin matrix was chosen as the object of research. The reinforced fibers play a significant role in the loading capacities of the composite, and the tensile strength and modulus are deeply affected by the type of the fiber. Meanwhile, the composite materials possess a good designability; therefore, the stacking sequences are responsible for the diversity of the mechanical properties of the composite laminates. The different types of tools possess various drilling qualities [29], and the effects of certain tool geometries are even better [30]. The hole quality, especially the surface roughness of the holes, could be influenced by the materials of the tools. Owing to the grain refinement of the coating, the coated drills have a superior performance in abrasion resistance and drilling quality. In detail, the appropriate geometrical parameters, such as cutting angle, chisel edge, helical angle, and diameter, also account for the acceptable drilling qualities. Moreover, the spindle speed and the feed rate were considered as the most influential factors for the drilling quality. The better result of hole quality can be obtained when a combination of higher spindle speed and lower feed rate is used. Using that condition, the defect mainly caused by the thrust force will be lower. Therefore, the drilling database system will be established based on spindle speed and feed rate.

As it can be seen from Figure 1, the partition of the classification tree starts from the reinforced fibers, and the root node is divided into several leaf nodes. Further, every root node presents the different drilling parameters (the reinforced fibers, the stacking sequences, the types of the tools,

Table 1: Tool geometrical parameters.

Tool type	Helical angle (°)	Point angle (°)	Coating thickness (mm)	Diameter (mm)
Carbide drill	30	140	0	5
DLC drill	30	140	0.02–0.03	5
PCD drill	30	140	0.05	5

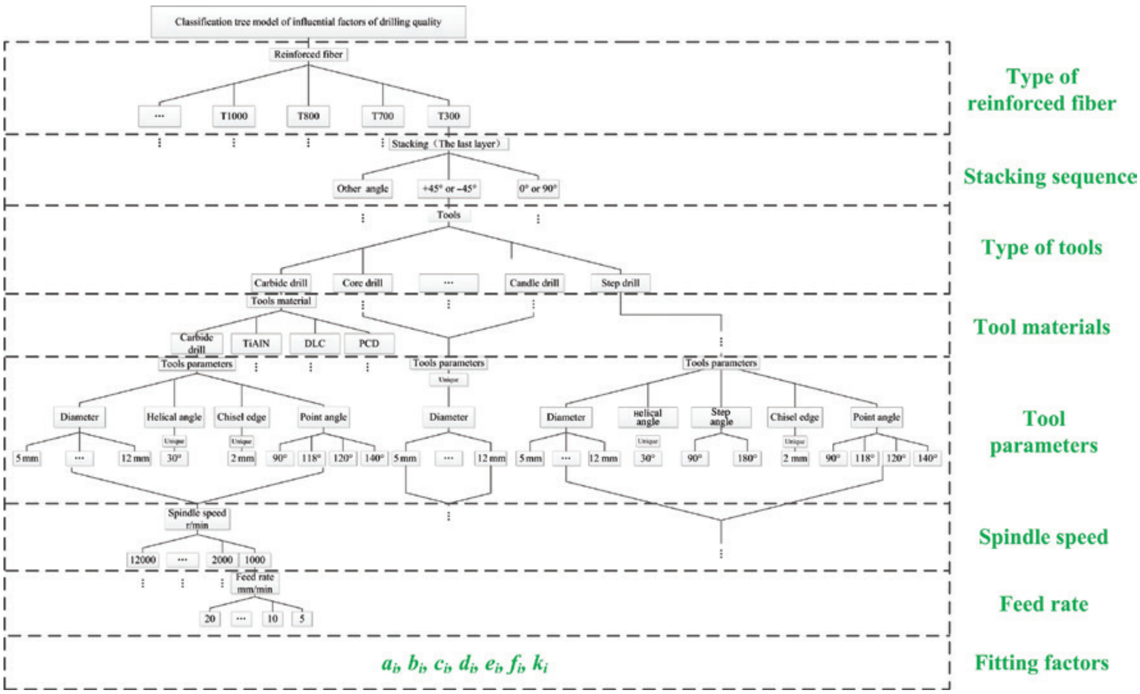


Figure 1: Classification tree model of influential factors of drilling quality.

the tool materials, the geometrical parameters, the spindle speed, and the feed rate), and each leaf node branch is part of the selection of the drilling parameter. For the maximization of the branches, the selection of the drilling parameter is comprehensively considered as far as possible. So far, owing to the restriction of materials and experimental conditions, some of the drilling parameters will be omitted temporarily, which will be studied further in the future. Therefore, several values of the drilling parameters such as the types of reinforced fibers and tool, which will not be considered, are listed in the form of ellipses. In addition, for the ellipses in the growth direction from root to leaves, this means that the selections of drilling parameters are the same for the identical root. Meanwhile, the layout of the classification tree can also be simplified by this method. At the last level of the figure, there are series of fitting factors for various branches. The fitting factors play an important role for the drilling database system, which will be further interpreted below. Finally, a relative comprehensive classification tree has been built, possessing the guiding significant for experimental procedures and the establishment of a drilling database system.

In order to establish the drilling database system, there is a requirement to build the relationship of the drilling parameters and the drilling results. Therefore, a quintic polynomial system reflecting the above classification tree was proposed in Equation (1), which could quantify the drilling quality to compare the different drilling schemes conveniently.

$$Q=(a+b\times x+c\times x^2+d\times x^3+e\times x^4+f\times x^5)\times k \qquad (1)$$

where, in the left side of the equation, Q presents the evaluation factor of the three-dimensional (3D) level that contains three different evaluation subfactors (Q_i) as follows (Figure 2): Q_1, delamination; Q_2, surface roughness; and Q_3, burrs. Meanwhile, the weighting coefficients (a, b, c) are distributed in the three different evaluation subfactors (Q_i), which reflect the extent of the contribution to the evaluation factor Q, as shown in Equation (2).

$$Q=a\times Q_1+b\times Q_2+c\times Q_3 \qquad (2)$$

Moreover, the hole quality will be comprehensively evaluated by using the evaluation factor of the 3D level (Q). In the right side of Equation (1), x presents the spindle speed or feed rate, which can be adjusted as required. What counts is the confirmation of the exponential of x. In the previous studies [4], a quadratic relationship between drilling results and drilling parameters has been introduced. Similarly, inspired by this approach, the type of interactions between drilling quality and drilling parameters have been proposed. According to the above content in Equation (1), the quadratic relationship was regarded as the actual reflection between drilling quality and spindle speed (feed rate). This

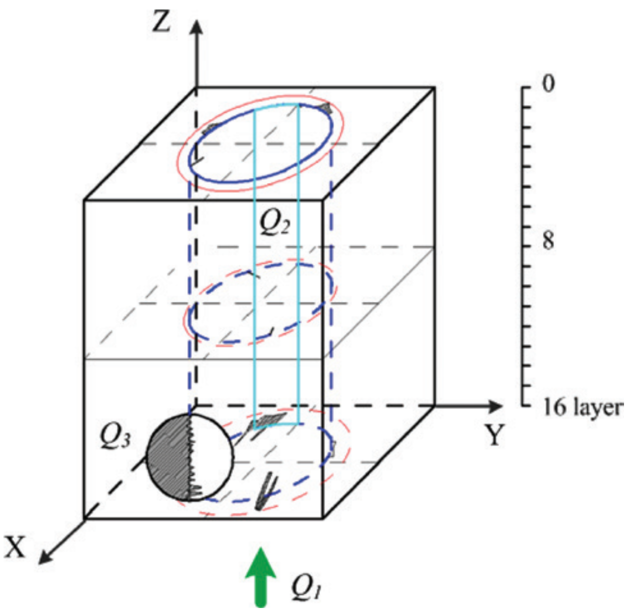


Figure 2: Diagrammatic sketch of the evaluation method of the 3D level.

quadratic relationship between drilling quality and spindle speed (feed rate) could also be verified by the historical drilling data. Then, the more refined the drill coating is, the better the hole quality will be. Basing on the analysis of the historical drilling data, the tool materials were considered to be the second parameter, which could offer a homologous relationship with the drilling quality. Hence, the linear relationship was introduced as the actual reflection between drilling quality and tool materials. However, as for the other drilling parameters (reinforced fiber, stacking, tools, and tool parameters), similar mathematical connections with the drilling quality have never been found, because there were no constant relationships to serve as a reference. Furthermore, depending on the superposition principle, the individual effects on the drilling quality (the exponential of x) were united to form the quintic polynomial system.

Then, for the coefficients of x, it is considered that the coefficients (a, b, c, d, e, f) are the fitting coefficients of the drilling database model, and these coefficients can be calculated using the fitting method based on the historical drilling data. Especially, k is the correction factor whose value is generally taken as 1. For each branch, there will be a particular set of fitting coefficients. Similarly, it will obtain a series of drilling quality results according to the various combinations of the drilling parameters. For instance, the last branch of the classification tree is the feed rate as in Figure 1; the values of the coefficients of the feed rate would be attained according to the drilling parameters and then adjusted when the drilling parameters have been changed. For the whole classification tree and the various drilling parameters, there is a great demand for the fitting functions indicating the relationship of the drilling parameters and the drilling results. Consequently, a series of coefficients will be acquired through the mentioned fitting method; the fitting functions and the coefficients are the important points for the establishment of the drilling database system.

As a result, a classification tree model for drilling quality of composite materials was summarized, and the relevant fitting functions indicating the relationship of the drilling parameters and the drilling results were also proposed. In this classification tree, every branch has reserved several regions to extend the categories of parameters or to further subdivide them. With the aim of exploring the relationship of the drilling parameters and the drilling results, the experiments would be designed and conducted according to classification tree as well. In addition, on account of the restrictions of the experiment conditions, there is no need to repeatedly conduct similar work. Therefore, some branches of the classification tree model were just selected to illustrate the validity of this fitting conception.

3 Materials and methods

On the basis of the current experiment conditions and the abovementioned methodology, a large amount of experiments were carried out around the classification tree model.

3.1 Materials

The composite laminates were fabricated by the carbon fiber/epoxy matrix prepreg (Type 6501/G15000, Weihai GuangWei Composites Co. Weihai, Shandong, China) using the autoclave (Zhejiang Catamount Special Equipments Co., Ltd. Taizhou, Zhejiang, China) method, and the thickness was approximately 1.5 mm made up of 16 plies. The prepreg was a unidirectional T300 reinforced fiber without scrim, which has a standard modulus and a 33% resin content volume fraction. There were three different stacking sequences of the laminates, namely, $[0°]_{16s}$, $[0°/90°]_{8s}$, and $[0°/0°/0°/45°/0°/0°/-45°/0°]_{2s}$. The drilling specimens were shaped into the size of 25 mm × 30 mm in order for them to be easily clamped by the fixture.

The three kinds of drilling tools (Nachreiner Co. Germany) such as the 5 mm carbide drill, 5 mm diamond-like coated (DLC) drill, and 5 mm polycrystalline diamond coated (PCD) drill were chosen to carry out the experiment, and the detailed tool geometrical parameters are listed in Table 1.

3.2 Experimental design

The experiments were performed on an improved vertical drilling machine (XKA714C, BYJC Co. Beijing, China) with a computer numerical control unit, which was also equipped with a dynamometer (Kistler 9273, Kistler Instruments Co., Beijing, China) and a charge amplifier (Kistler 4624AK, Kistler Instruments Co. Beijing, China) to acquire the thrust force. A properly designed fixture was placed on the drilling platform to clamp the work pieces. The schematic diagram of the experimental setup was shown in Figure 3. The spindle speed and the feed rate were designed into different levels for the experiments, which can be seen in Table 1.

3.3 Evaluation method

With the aim of investigating the effects of drilling parameters on the hole quality, the defects were assessed in terms of the comprehensive indicators consisting of delamination, hole surface roughness, and burrs, which were mentioned in Equation (2). First, with regard to the degree of importance of each evaluation factors Q_1, Q_2, and Q_3, a set of corresponding coefficients were calculated by an expert evaluation approach based on a series of drilling applications on the composite spars and the skin of a certain type fighter, $(a, b, c)=(0.6, 0.1, 0.3)$. To evaluate the damage, the delamination factor, the surface roughness, and the burrs were quantified to describe the defects, as shown in Equations (3)–(5).

$$Q_1 = D_{max}/D_{nom} \tag{3}$$

$$Q_2 = Ra/Ra_{max} \tag{4}$$

$$Q_3 = \sum a_i/D, i=1, 2, 3, \ldots, n \tag{5}$$

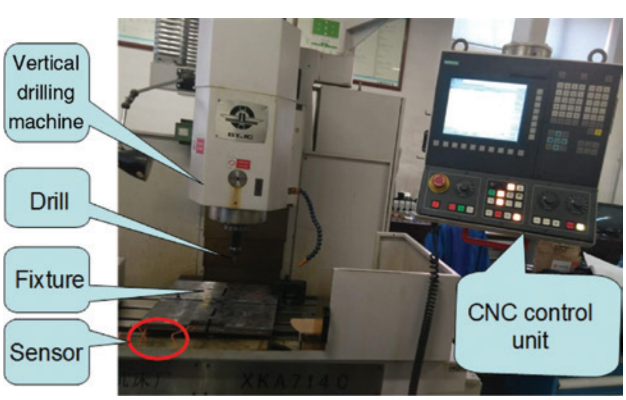


Figure 3: Schematic diagram of the experimental setup.

where D_{max} is the maximum delamination diameter and D_{nom} is the drill diameter; Ra is the average surface roughness and Ra_{max} is the maximum value of the surface roughness; a_i is the length of the burr, D is the nominal diameter of the hole, and I is the indicator of the burrs.

Therefore, the 3D evaluation factor in the numerical level was derived and described in Equation (6). Moreover, for the hole quality, the higher the values of each evaluation factors Q_1, Q_2, and Q_3, the worse the hole quality will be. Namely, there is an inverse relationship between the 3D evaluation factor Q and the hole quality.

$$Q = 0.6\times Q_1 + 0.1\times Q_2 + 0.3\times Q_3 \tag{6}$$

In the experimental level, for the comparison purpose, the scanning electron microscope (SEM) (Philips 505, SEMTech Solutions, Inc., North Billerica, MA, USA) was utilized to examine the quality results. SEM is a very effective means of detection and is extensively employed to survey the surface microstructure of the defects. However, for the internal defects, it could be available to measure the cross section of the hole wall for the inspection of the hole quality. In addition, the values (Ra, Ra_{max}) of the surface roughness were carried out for several times using the surface roughness instrument with a probe stylus.

3.4 Experimental result

According to the classification tree, a series of experiments were designed and carried out based on the Taguchi method, and the drilling results were assessed by the 3D evaluation factor (Q). Table 2 shows the various drilling schemes and the 3D evaluation factor responses. However, owing to the repeatability of the drilling experiments, only the stacking sequence of $[0°/90°]_{8s}$ was taken into account, and the representative drilling data were selected out as an instance to analyze. In addition, three different drills with the same geometrical parameters, the spindle speed and the feed rate, were involved into the main consideration. The causal relationship of the drilling parameters and the defects was quantified by using Equations (3)–(5) mentioned in the Section 3.3.

3.4.1 Fitting equation

Combining the historical drilling data, a series of quintic polynomials can be fitted through the mathematical software (ORIGIN) (OriginLab Corporation, Northampton, MA, USA). However, only several typical quintic polynomials with respect to the three drills (carbide drill, DLC drill, and

Table 2: Various drilling schemes and the 3D evaluation factor responses.

Scheme	Spindle speed (rpm)	Feed rate (mm/min)	3D evaluation factor		
			Carbide drill	DLC drill	PCD drill
1	1000	5	1.724	1.484	1.364
2	1000	7.5	1.743	1.52	1.396
3	1000	10	1.788	1.592	1.45
4	1000	12.5	1.88	1.636	1.528
5	1000	15	1.996	1.676	1.604
6	1000	17.5	2.051	1.763	1.671
7	1000	20	2.084	1.848	1.712
5	2000	5	1.7	1.476	1.312
6	2000	7.5	1.728	1.491	1.335
…	…	…	…	…	…
…	…	…	…	…	…
…	…	…	…	…	…
…	…	…	…	…	…
11	3000	17.5	1.91	1.496	1.4
12	3000	20	1.949	1.528	1.484
…	…	…	…	…	…
…	…	…	…	…	…
45	7000	10	1.38	1.01	0.95
…	…	…	…	…	…

PCD drill) were selected out in order to simplify the description, as shown in Equations (7)–(10). Equations (7)–(9) represent the relationship of the 3D evaluation factor (Q) and the feed rate for the three drills under the same spindle speed (1000 rpm), while Equation (10) shows the relationship of the 3D evaluation factor (Q) and the spindle speed for carbide drill under the feed rate of 10 mm/min. These relational expressions were expected to provide relatively reliable foundations for the damage measurements of the hole and could give full expression to the hole quality at the 3D level. Furthermore, in Figure 4, the four expressions have ideal goodness of fit (0.99799, 0.99972, 0.99966, and 0.97927, respectively). Then there is a lower standard of error for all the fitting factors, indicating the reasonability of the fitting results. Subsequently, the first derivative and the second derivative were calculated using MATLAB. From the inflection points and the extreme points, every curve offers a monotonic relation between the parameter and response. Obviously, the four graphs could be divided into three phases according to the derived functions, namely, low feed rate (spindle speed) area, medium feed rate (spindle speed) area, and high feed rate (spindle speed) area. Specifically, for Figure 4A–C, the 3D evaluation factor (Q) increases with the rising feed rate, while the trend is inverse for Figure 4D. In Figure 4A, at stage I, the contribution of the lower feed rate to the drilling quality is minor; hence, the growth of the 3D evaluation factor (Q) is slight. For stage II, the effect of the feed rate comes into action, and the Q tends to increase severely with the feed rate due to the wear of the carbide drill. Until stage III, the abrasion becomes stable at the high feed rate level; therefore, Q enters into the slow-growth phase. For Figure 4B, the 3D evaluation factor (Q) slightly increases at stages I and II, then the curve turns into a steep slope at stage III. The cause of this phenomenon is due to the coating of the DLC which plays a leading role, and the peeling is hardly happening at stages I and II, while at stage III, the considerable impact caused by the high feed rate level leads to a major abrasion of the coating. Moreover, the same circumstance can be found in Figure 4C. However, the curve is obviously divided into two phases and is fairly smoothed for the PCD coating. There is no sharp increase found in the curve, which may be due to the more compact combination of diamond grits. From Figure 4D, for the carbide drill, it can be observed that the growth of the spindle speed seems to play a minor role in the drilling quality at stages I and II and the higher speed can offer a distinct decline for the curve at stage III. Certainly, the variation of these curves indicates the roughly changing roles, and the curves have their own features for the different drills and even drilling schemes.

$$Q=(0.62814+0.5812\times x-0.11564\times x^2+0.01074\times x^3-4.55\times10^{-4}\times x^4+7.17\times10^{-6}\times x^5)\times1 \tag{7}$$

$$Q=(2.88607-0.73662\times x+0.14129\times x^2-0.01236\times x^3+5.11\times10^{-4}\times x^4-8.02\times10^{-6}\times x^5)\times1 \tag{8}$$

$$Q=(1.28614+0.03861\times x-8.92\times10^{-3}\times x^2+1.09\times10^{-3}\times x^3-4.98\times10^{-5}\times x^4+7.68\times10^{-7}\times x^5)\times1 \tag{9}$$

$$Q=(1.63286+3.33\times10^{-4}\times x-2.39\times10^{-7}\times x^2+7.10\times10^{-11}\times x^3-1.01\times10^{-14}\times x^4+5.42\times10^{-19}\times x^5)\times1 \tag{10}$$

3.4.2 Data analysis

Through classifying the data from Table 3, a more concise graph has been calculated. Figure 5 further shows the typical interrelation of the drilling quality with the spindle speed and the feed rate for the three different drills [(A), (B), and (C)], respectively. The increase of the 3D evaluation factor can be observed with the increase in the feed rate and the decrease in the spindle speed, and the feed rate is a highly significant factor because the variation trend of the 3D evaluation factor (Q) is more obvious. From Figure 5, it can be seen that a good combination of 4000 rpm and 5 mm/min can lead to a minimum 3D evaluation factor for

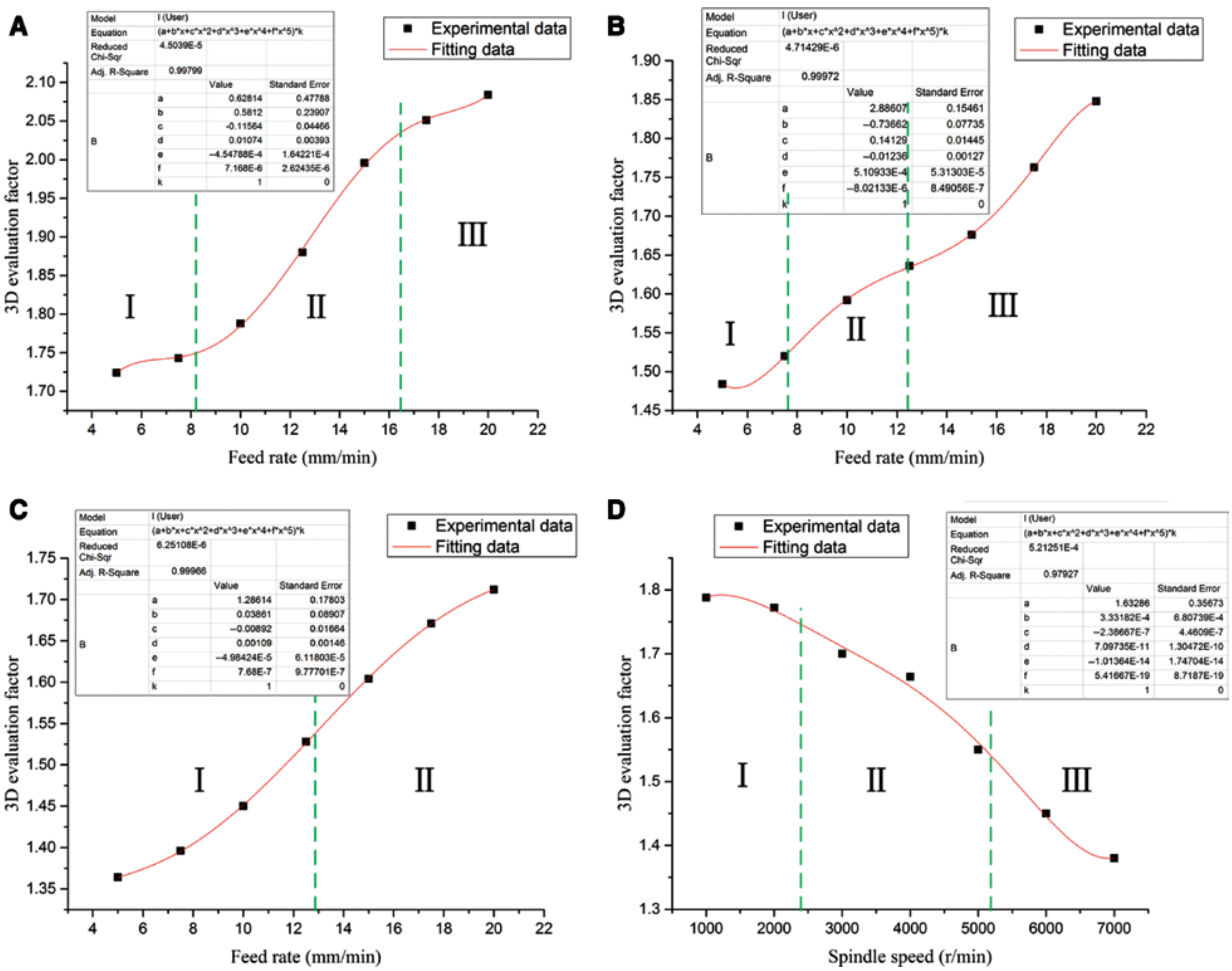


Figure 4: The relationship of the 3D evaluation factor (Q) and the feed rate (spindle speed) for the three drills. (A) Carbide drill under the same spindle speed (1000 r/min), (B) DLC drill under the same spindle speed (1000 r/min), (C) PCD drill under the same spindle speed (1000 r/min), and (D) PCD drill under the same feed rate (10 mm/min).

Table 3: Drilling parameters.

Drilling parameters	Level
Spindle speed (rpm)	1000, 2000, 3000, 4000, 5000, 6000, 7000
Feed rate (mm/min)	5, 7.5, 10, 12.5, 15, 17.5, 20

all drills. Moreover, from the comparison of the relevant values under the same condition, it can be also concluded that the types of the drills have a considerable influence on the drilling quality. In other words, the reasonable drilling configuration and the optimized coating structure are the contributing parameters for the drilling quality.

3.4.3 Thrust force

Figure 6 illustrates the representative variation of thrust force with time during the drilling process for the different feed rate of the DLC drill under the level of 3000 rpm. For the curve of the 20 mm/min feed rate, first, a sharp increase means that the cutting edges are penetrating into the composite laminate. With the increasing of the contact region between the cutting edges and the laminate, the thrust force increases tremendously. Then, the curve of the thrust force maintains transitorily stable, which represents that the tip of the drill fully engages into the laminate and the drilling process steps into the temporarily stable phase. Soon afterward, the resistance of the residual regions is getting smaller as the tip of the drill pierces and the thrust force falls off until the drill pierces through the whole laminate. From Figure 6, it can be observed that the sharply increasing tendency of the thrust force has slowed down following the decrease of the feed rate. By contrast, the curve of the thrust force of the 5 mm/min feed rate expresses relevant moderate changes. Hence, the feed rate reveals the primary role on the thrust force as well.

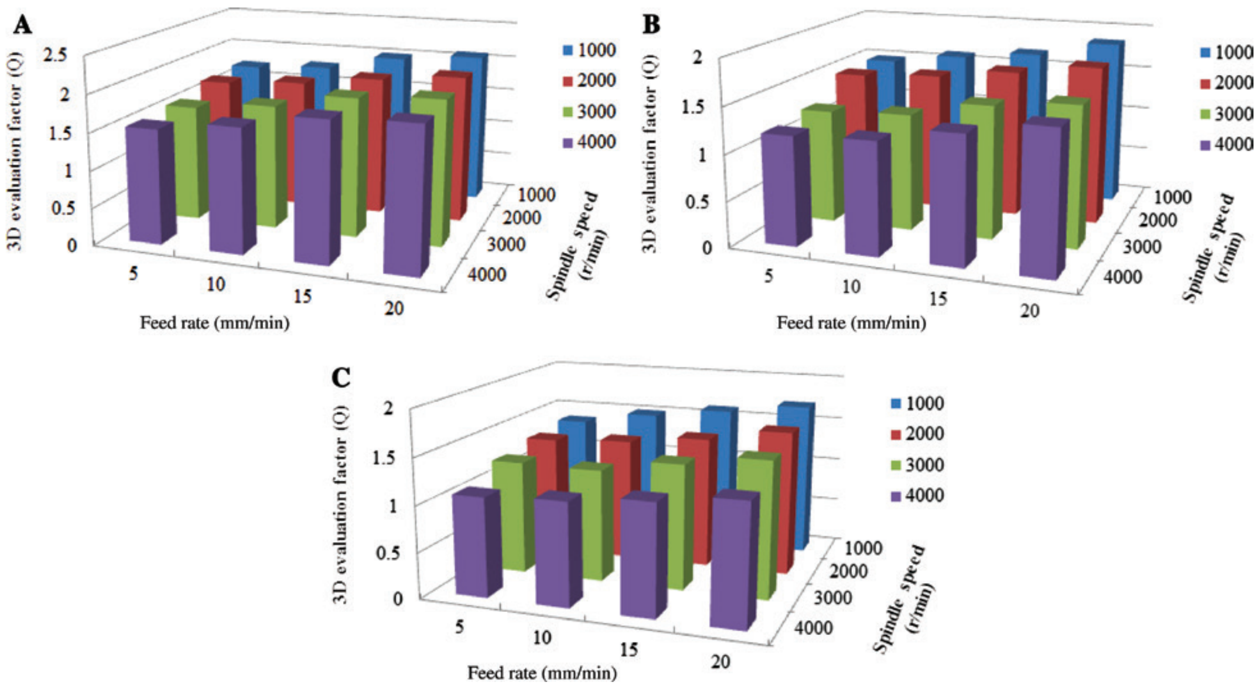


Figure 5: The typical interrelation of the drilling quality with the spindle speed and the feed rate for three different drills. (A) Carbide drill, (B) DLC drill, and (C) PCD drill.

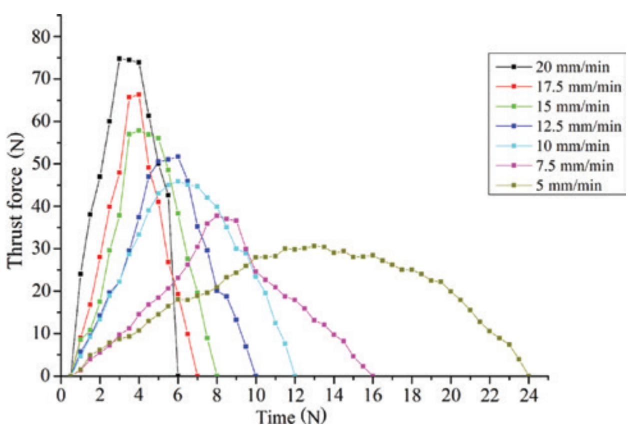


Figure 6: The representative variation of thrust force with time of the DLC drill at a certain condition (3000 rpm).

Moreover, the influence of the spindle speed and the feed rate on the thrust force is also depicted in Figure 7. It is observed from Figure 7 that the higher the feed rate, the more the thrust force will be, and then the thrust force decrease slightly along with the increase of the spindle speed. Furthermore, the effect of the feed rate on the thrust force is remarkable, while the influence proportion of the spindle speed is relatively weaker. Conversely, the superiority of using the coating drills is also depicted. It is obvious that the DLC and PCD drills produce lower forces. The highest force can be found in the carbide drill, while the lowest force can be found in the PCD drill bit. Owing to the refinement characteristic of the polycrystalline diamond coating, the cutting edge on the PCD drill could remove the composite material rapidly without any obstruction. Therefore, there is a lowest thrust force at the same drilling condition.

3.4.4 Example verification

In order to verify the validity of the fitting functions, several confirmatory experiments were conducted. Therefore, four group combinations of the feed rate and spindle speed were selected to demonstrate the fitting functions (7)–(10) under the same other conditions. The parameters are shown in Table 4.

From Table 4, it can be observed that the numerical result is 1.78 > 1.74 > 1.51 > 1.39. Then because the 3D evaluation factor Q and the hole quality have an inverse relationship, the hole qualities present a sequence of sample 3, sample 2, sample 1, and sample 4.

Furthermore, as a contrast, the experimental results of the drilling quality were obtained by measuring the holes. The 3D evaluation method was utilized to give a comprehensive description for the hole quality; hence, four groups of images were listed in Table 5 to exhibit the damage of the holes.

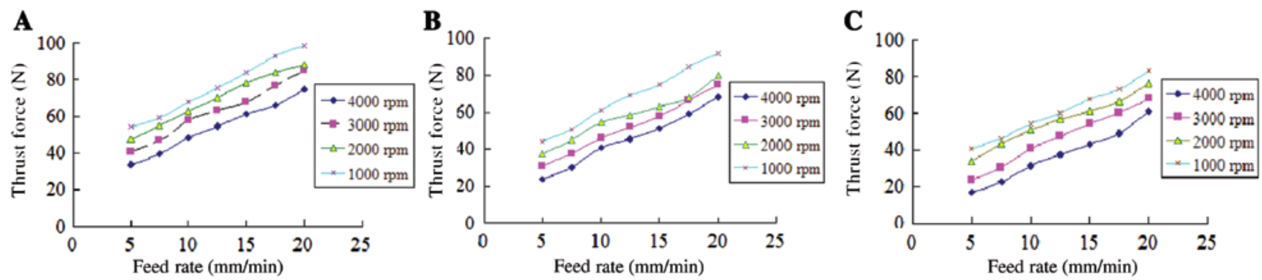


Figure 7: The typical relationship of thrust force with the three different drills. (A) Carbide drill, (B) DLC drill, and (C) PCD drill.

Table 4: Four-group verification schemes.

Sample	Tool	Spindle speed (rpm)	Feed rate (mm/min)	Objective function	*Q* value
1	Carbide drill	1000	7	Equation (7)	1.74
2	DLC drill	1000	7	Equation (8)	1.51
3	PCD drill	1000	7	Equation (9)	1.39
4	Carbide drill	800	10	Equation (10)	1.78

From the typical drilling damage illustrated in Table 5, the experimental results (Q) have approximate values that are comparable with the fitting results shown in Table 4. Under the comprehensive influence of the three evaluation factors (Q_1, Q_2, Q_3), the maximum value (Q) is obtained for sample 4, then followed by sample 1, sample 2, and sample 3. The computational error formula in Equation (11) was used to calculate the error between the numerical and experimental results, and the error value is supposed to be at a minor scale. Generally, the error value is considered acceptable within 20% in engineering applications [31]. For these four experimental samples, E is (–1.59%, 2.13%, 3.10%, 4.31%) less than 20%; therefore, the experimental results and the fitting results are in a correspondingly coincident relationship.

$$E = (Q_E - Q_N) / Q_E \tag{11}$$

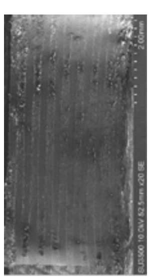
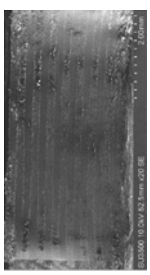
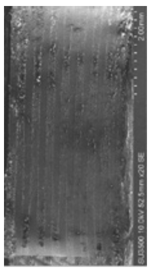
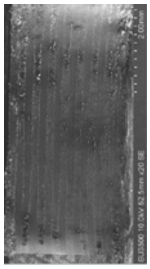
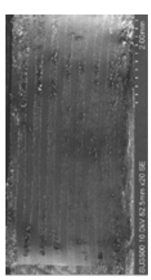
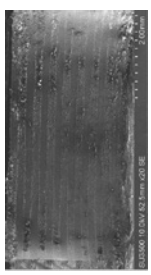
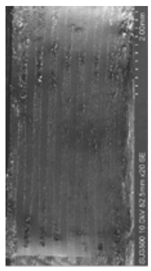
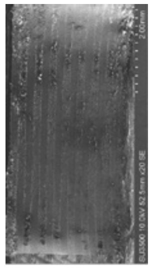
where E is the error value, Q_E is the experimental results of the 3D evaluation factor, and Q_N is the numerical results of the 3D evaluation factor.

Noticeably, although it is fairly hard to visually distinguish the differences of the surface morphology of the four group experimental results (Q_2), it can be identified by using the surface roughness instrument with a probe stylus. There is a slight decline in the surface roughness owing to the usage of the coating drills such as DLC and PCD coatings, which have a reasonably fine grain to polish the wall of the holes to obtain a better surface morphology, like possessing few internal delaminations and burrs. Furthermore, there is the same trend that the more the spindle speeds and the lower the feed rates, the fewer defects will be at the exit site for each drill. From typical surface images recorded using the SEM method for the three different drills, it can be readily observed that sample 4 possesses the worst hole quality. In comparison with sample 1, the lower spindle speed results in a deficient cutting of the exit around the circumference of the hole, and the higher feed rate leads to a considerably obvious thrust force, which is the main role of the push out delamination. Except for the higher spindle speed and the lower feed rate, the coating of the drills is a significant contribution to the exit quality. The DLC and PCD coatings can make the cutting edge much sharper, allowing easier cutting the fiber and resin. Thus, as a contrast, the DLC drill and the PCD drill have more acceptable results than the carbide drill through the comparison under the same spindle speed and feed rate. Therefore, sample 2 and sample 3 have lower delamination and burrs.

4 Drilling database system

In order to adapt to the requirements of the enterprise and improve the efficiency of the industry, a user-friendly drilling database system of CFRP with respect to the classification tree of drilling has been developed. The significant role of this drilling database system is to collect the historical drilling data of the CFRP and to transfer the experiential drilling consequence into the fairly precise mathematical result, which could be used to guide the

Table 5: The experimental results of the four group verification schemes.

Sample	**1**	**2**	**3**	**4**
Surface morphology				
Q_2	$Ra/Ra_{max}=0.81$	$Ra/Ra_{max}=0.73$	$Ra/Ra_{max}=0.68$	$Ra/Ra_{max}=0.94$
Delamination and burrs				
Q_1, Q_3	$Q_1=1.402$, $Q_3=2.6353$	$Q_1=1.306$, $Q_3=2.2878$	$Q_1=1.236$, $Q_3=2.0828$	$Q_1=1.5$, $Q_3=2.8875$
Q	1.71279	1.54294	1.43444	1.86025

production practice. In this system, self-determination of the user could be sufficiently exerted, not only choosing the drilling schemes according to the production practice but also changing some drilling parameters to predict the drilling result without carrying out the experiments.

4.1 Development of a user-friendly drilling database system of CFRP

The user-friendly drilling database system of CFRP was compiled using C# language using the programming tool, Visual studio. It consists of two main graphic view windows, which have several parts included in each view window, such as the classification tree view space, the display view part of the fitting factors and drilling parameters, the drilling parameters selection module, and the display view part of the drilling result.

The first graphic view window is shown in Figure 8. The classification tree view space is designed based on the existing drilling schemes, and for every root node of the classification tree, there is a set of fitting factors and drilling parameters that are related to the drilling schemes. Furthermore, the relevant fitting expressions reflecting the relationship of the 3D evaluation factor (Q) and the drilling parameters are exhibited in the bottom of the window, and the relative the graphs of the experimental data and the fitting data are also depicted.

4.2 Scheme selection and drilling result display

The second graphic view window is designed for the independent selection of the drilling parameters, as shown in Figure 9. After finishing the selection, the fitting factors and the fitting expressions could be defined through a comparison with the historical fitting curve of the drilling data in the program. The error ratio between the fitting result and the experimental result is also added through calculation. In addition, the legend representing the quality of the holes is utilized creatively. The color is used as an indicator of the acceptable level of the drilling quality, where red is unacceptable, yellow shows a minor acceptable level with the constant checking of the holes, and green represents a superior drilling quality with a higher reliability. Subsequently, the surface morphology, delamination, and burrs of the drilling scheme would be displayed in the right corner of the view to offer a reference for the drilling quality. Users can give a direct estimation of certain drilling schemes before conducting

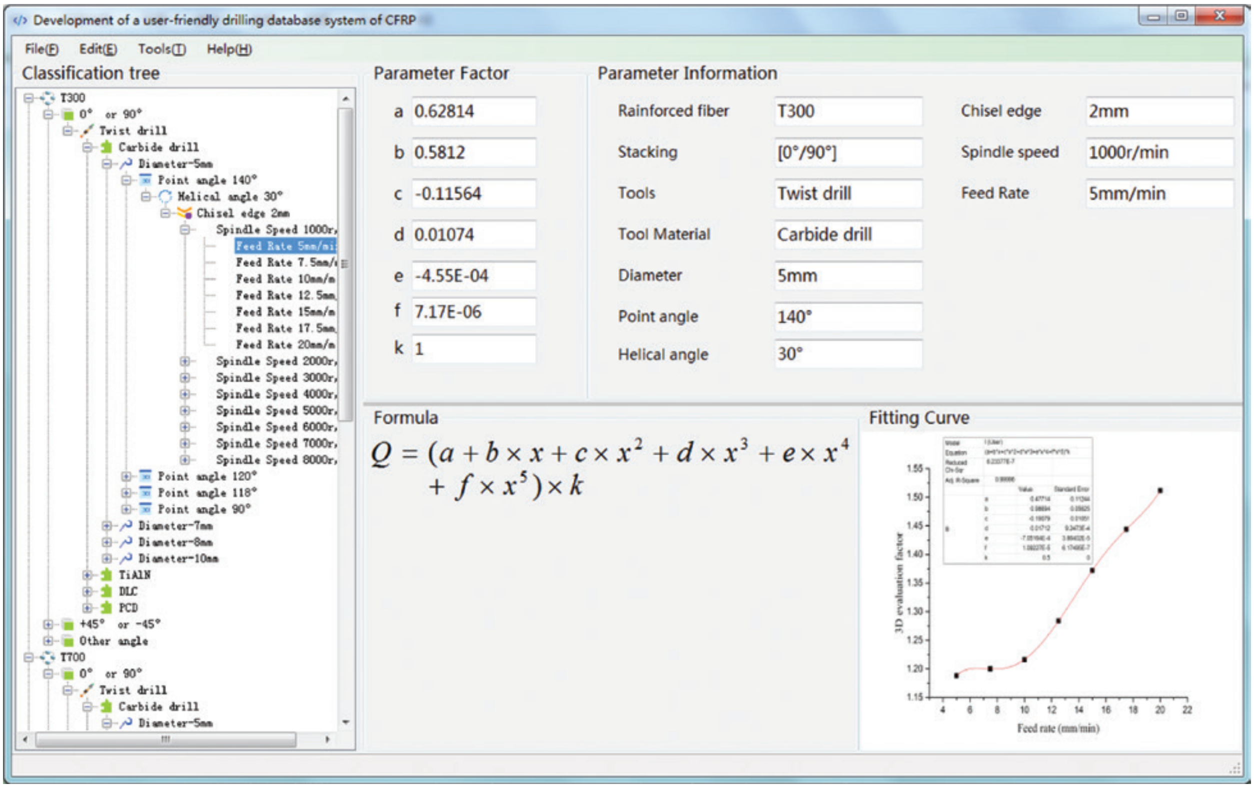


Figure 8: Development of a user-friendly drilling database system of CFRP.

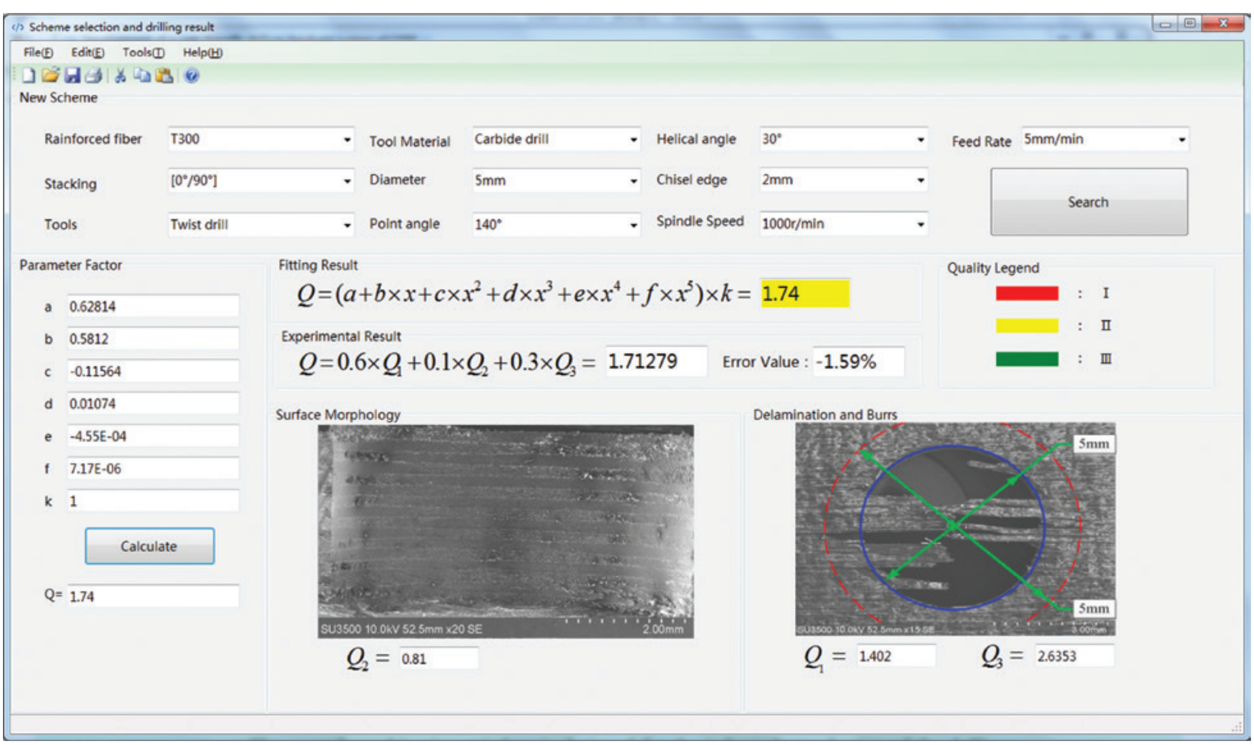


Figure 9: Scheme selection and drilling result display.

the drilling experiments, and in this way, it can reduce the workload of the industry in some comparative exact degree. If the drilling quality is out of the acceptable range when choosing a certain scheme, the drilling parameters can be changed, and then another drilling result will be displayed in the area. Subsequently, a more reasonable drilling scheme will be adopted by evaluating the result. Consequently, the rejection of the products can also decline to some degree. It can ensure that undesirable circumstances could be eliminated by application of the drilling database system. Moreover, the drilling database can be extended by adding the new drilling parameters along with more and more experiments on CFRP. A more complete drilling database system including as many drilling parameters as possible will be established.

5 Conclusions

The user-friendly drilling database system of CFRP was developed by collecting the drilling data and integrating the relationship between the drilling parameters and the drilling quality using the fitting method. The drilling results were assessed by a new approach based on a 3D evaluation factor, which consists of three subfactors that offer a rather comprehensive evaluation of the holes from delamination, surface roughness, and burrs. The main difficulty of this paper is to build a series of mathematical logic expressions reflecting the relationship of the drilling parameters and the drilling quality, which could be transferred into the system. Through selecting and changing the drilling parameters according to the production practice, the relevant drilling information and drilling results would be displayed in the view windows of the system. Operators could prejudge the acceptable degree of certain drilling schemes by comparison of the mathematical results and the experimental results, which would be a highly efficient method, declining the repeated experiments of low level and the rejection of the composite products and improving the production efficiency.

In order to obtain the mathematical relationship, a large amount of experiments were carried out. The drilling parameters such as drills, spindle speed, and feed rate were chosen on the basis of the classification tree. Furthermore, some verifying experiments were conducted to examine the fitting expressions. Also, from the comparison of the experimental drilling quality evaluated by the 3D evaluation factor, the fitting results were considered to be in a minor error range. The typical images such as the hole wall surface and the exit situation were analyzed by using ultrasonic inspection and SEM.

Consequently, the fitting curve demonstrated a good correlation between the drilling parameters and the drilling quality. Hence, based on this fitting method, a drilling database system of CFRP with the purpose of prejudging the drilling schemes and even further industrial application was established.

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