ISSN: 2664-9640

Optimization of Boring Process for Carbon Fiber Reinforced Plastics

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Abstract

Aiming at the problems of orifice burrs and low machining efficiency in the boring of RTM joint in Carbon Fiber Reinforced Plastics (CFRP) spoiler at A350, this paper applies Six Sigma quality management tools to analyze the influence of key factors on the quality and efficiency during the boring process, such as the structure of boring tool, the tool path of rough boring, and the fine boring removal. Then a new type of integrated boring tool is designed and the boring process is optimized, which effectively solving the problem of orifice burrs and greatly improving the efficiency of boring. The experiments indicates that the defect rate has been reduced intensely from 100% to 0%. Meanwhile, the average number of boring per part has been reduced from the previous 6 times to 1 times, and the feedrate has been improved from 30mm/min to 250mm/min.

Keywords

Carbon Fiber Reinforced Plastics; Six Sigma; integrated boring tool; process optimization.

1. Introduction

Carbon Fiber Reinforced Plastics (CFRP) have become the mainstream material for aviation structural parts by virtue of their high strength, high specific rigidity, low density, and corrosion resistance, and increasingly used in aircraft structures [1]. The amount and application position of CFRP in aircraft have already become important indexes to measure the advancement of aircraft structures [2]. However, CFRP are anisotropic and the properties of each component phase vary greatly. So it have the characteristics of high hardness, low interlayer strength, and easy softening when heated, which leads to machining defects such as fiber delamination, tearing, orifice burrs under the influence of force and heat during the milling processing [3]. Therefore, CFRP belongs to the typical difficult to machine material. Usually, CFRP components are connected through holes in the aircraft structure, so the machining quality of the connecting holes is directly related to the assembly quality and the life of the aircraft, and normally the number of processing holes is huge. For example, the F-16 fighter jet has 240,000 connecting holes, and Boeing 747 aircraft have more than 3 million ones. Therefore, it is of great significance to study how to improve the machining quality of the holes of CFRP.

In terms of cutting principles, Everstine [4] studied the cutting force generation mechanism of CFRP, and established the cutting force prediction model of 0° fiber direction by using the method of continuous mechanics. Hanasaki [5, 6] investigated the cutting mechanism of CFRP and concluded that the fracture of carbon fiber during the machining is due to the shear stress in the vertical axial direction exceeds the interlayer shear strength no matter what angle the fiber direction is. Karpat [7] conducted cutting experiments on unidirectional fiber materials and studied the cutting force and machining quality of carbon fiber under different orientations. In terms of high-precision boring, Dong [8] conducted the boring experiments with the PCD tool on CFRP, and analyzed the cutting parameters and the law of tear factor at the orifice, then providing a feasible scheme for the design of boring tool of CFRP. Wang [9] explored the influence of cutting parameters on boring quality through experiments, and deduced the

ISSN: 2664-9640

empirical formulas of axial force and plane cutting force. The existing research of cutting mechanism of CFRP provides a theoretical basis for the design of boring processing technology, but the research on the machining technology of high-precision hole mainly focuses on drilling, little research on boring. Meanwhile, it is mainly aimed at the improvement of boring tool structure and material, few studies on the influence of processing technology on the boring quality. Therefore, further research on the boring process of CFRP is necessary.

Aiming at the problems of orifice burrs and low machining efficiency in the boring of CFRP, this paper takes the high precision hole of RTM joint of A350 aircraft wing spoiler, shown in Figure 1, as the research object to analyze the factors that affect the quality and efficiency. Six Sigma quality management tool is applied to investigate the key factors such as the structure of boring tool, the tool path of rough boring, and the fine boring removal. Based on the analysis, an integrated boring tool is designed and the boring process is optimized to solve the problem of orifice burrs and realize high quality boring.

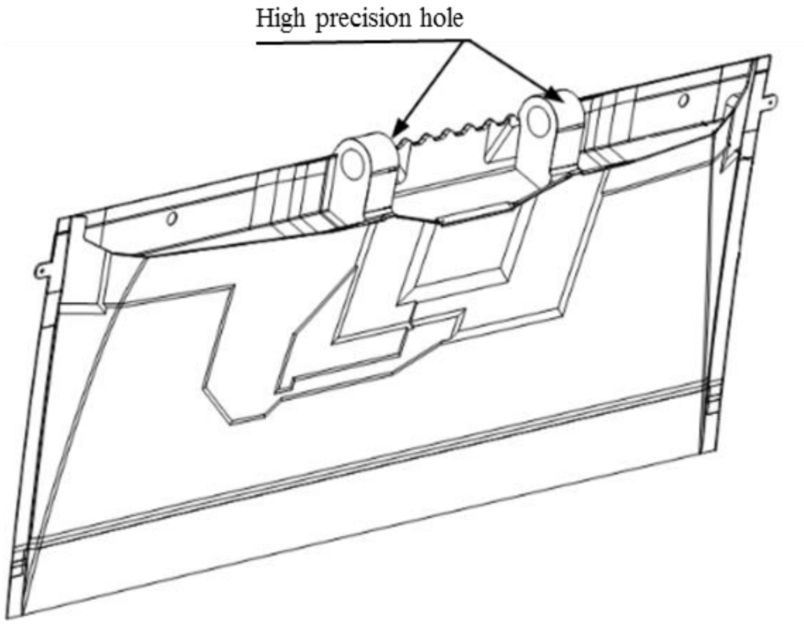

Figure 1. The schematic diagram of RTM joint of A350 spoiler

The remaining of the paper is organized as follows. Section 2 analyzes the problem of the boring process. Section 3 proposes the method to optimize and control the boring process. Section 4 draws the conclusion.

2. Analysis of Boring Process Problems

2.1. Problems in the Boring of CFRP Components

As a typical high precision hole, the straightness requirement of RTM joint hole is $\Phi 0.1$, and the tolerance of the aperture is only $\Phi 5.8(+0.01 \sim +0.03mm)$. The RTM joint structure has poor openness, so the traditional machining plan which uses an angle head clamping a boring tool to boring exists the following problems:

Low machining efficiency

When the common boring tool is used to machine the RTM joint, the cutting parameters is F=30mm/m, which machining speed is very slow. The structure of the common boring tool is shown in Figure 2. What' more, in order to ensure the accuracy, the operator not only needs to adjust the boring tool several times to carry out the rough boring with the same feed, but also perform the fine boring twice through fine adjustments according to the margin. Such a process method seriously affects the batch production capacity and becomes a bottleneck restricting the speed of the batch production.

ISSN: 2664-9640

Figure 2. The structure of common boring tool

High quality risk

From December 2018 to January 2020, a total of 768 parts of the A350 spoiler had different degrees of burrs and tears at the end of the orifice during the boring of the RTM joint, as shown in Figure 3. According to production requirements, orifice burrs belong to machining defects, which needs to be polished manually. It is not only time-consuming, but also has a high quality risk.

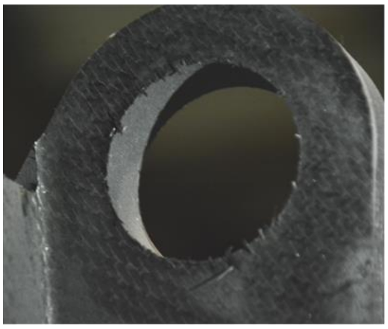

Figure 3. The orifice burr of the RTM joint

2.2. Defect cause analysis

In response to the above problems, we used Six Sigma quality management tool to improvement the machining quality [10]. The definition and measurement phase of the project are shown in Figure 4.

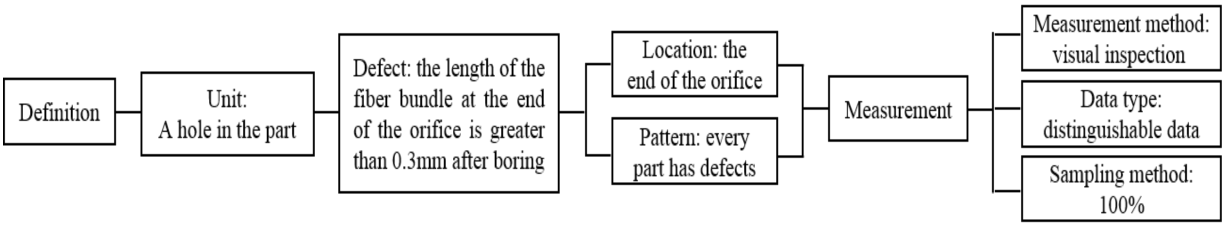

Figure 4. The definition and measurement phase

In the analysis phase, we use the cause and effect diagram to analyze the possible causes of the above problems, including personnel, equipment, materials, methods, environment, and measurement, as shown in Figure 5. When the defect appears, the operator's specifications, the material's quality, the environment of the workshop and measurement methods are reviewed to ensure that the entire process is in accordance with the established specifications. However, the defect still exists after machining repeatedly. Therefore, the process methods and equipment are mainly analyzed and improved to address the machining problem.

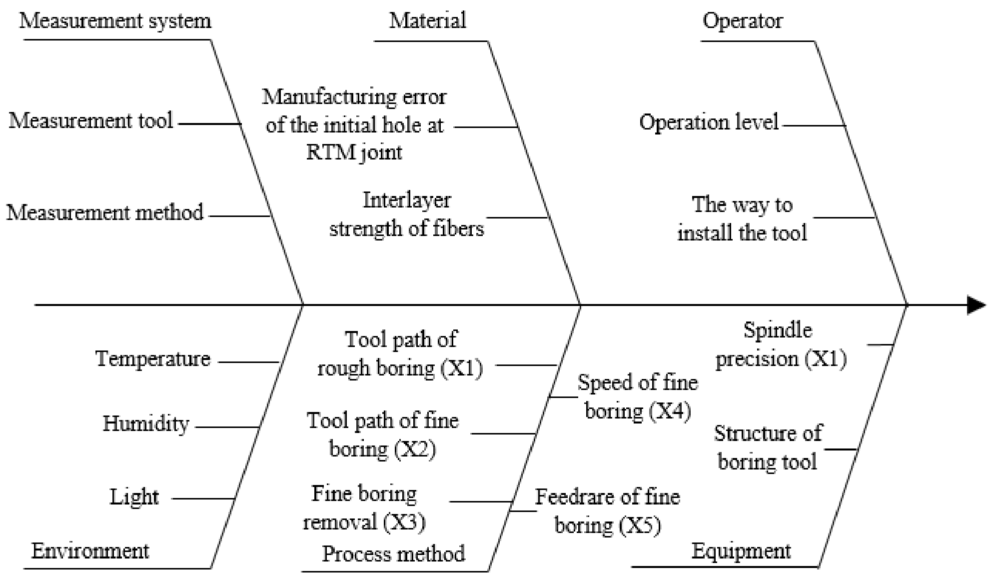

Figure 5. Causal analysis diagram

The accuracy of the machine tool spindle used in the existing processing has been tested, and it meets the standard of boring. On the other hand, the tool is an important factor that affects the machining efficiency and quality, so determining the structure of the boring tool (X1) as one of the key factor in the causal analysis. In the traditional machining scheme, a common boring tool embedded with one blade is used to boring unilaterally, which cannot achieve a large margin boring in one time. So the machining efficiency is very low.

In the current process, the spindle speed is S=1200r/min, the feedrate is v_f=30mm/min, and the diameter of boring tool is Φ=56.82mm. Then the feed per revolution can be calculated by the following formula:

$$f_{r=}\frac{v_f}{S}=0.025\text{mm/r} \tag{1}$$

The linear cutting speed can be calculated by the following formula:

$$v=\pi\Phi S=214.1\text{m/min} \tag{2}$$

It can be concluded that the feed per revolution and the linear cutting speed are in line with the standard parameters, which are not key factor.

According to the requirements of the surface quality and the coaxially of the hole, the tool path of the fine boring at the same hole must be straight in the same direction, so the tool path of fine boring (X3) is fixed, not considered as a key factor to study.

In order to study the influence of structure of boring tool, tool path of rough boring, and fine boring removal, it is necessary to analyze the boring machining mechanism of CFRP. Stacked and solidified by multiple layers with different angles, the interlayer strength of CFRP is low. When boring to the end of the orifice unilaterally, the carbon fiber layer at the bottom lacks the support from the fiber bundle, then the cutting force of the material is greater than the bonding strength between layers. As a result, the material at the end of the orifice is prone to produce tearing and orifice burrs, as shown in Figure 6.

The traditional machining scheme is shown in Figure 7. The tool path of rough boring is unidirectional boring with an equal volume for 4 times, and the initial hole of Φ52mm is boring to Φ56.56mm. Each boring requires manual adjustment of the size of the boring tool, which is time-consuming and laborious, and the boring unilaterally will lead to fiber tearing and orifice burrs. The unilateral removal of the original scheme is 0.12mm. The research in the literature [3] shows that the three-way cutting force tends to increase with the increase of back cutting depth in the hole machining of CFRP. It means that larger cutting amount will cause excessive cutting force, which exceeds the interlayer bonding strength of CFRP, causing the material to

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tear. Therefore, both the tool path of rough boring and the fine boring removal are the key factors that cause defects in parts.

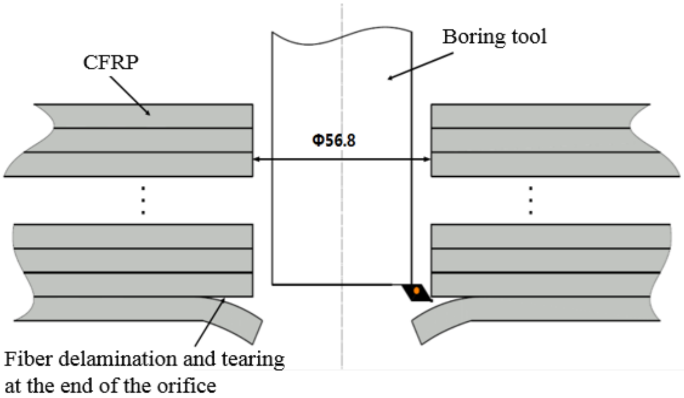

Figure 6. The schematic diagram of fiber tearing at the end of the orifice

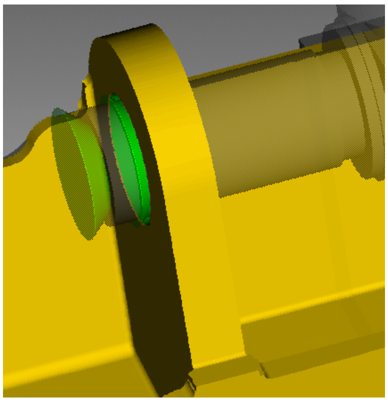

Figure 7. The unidirectional boring scheme

Through the analysis above, it is determined that the key factor in the causal analysis diagram are the structure of boring tool (X1), the tool path of rough boring (X2) and the fine boring removal (X4).

3. Optimization and Control of Boring Process

In this section, the optimization and control methods of the structure of boring tool (X1), the tool path of rough boring (X2) and the fine boring removal (X4) are studied respectively.

3.1. Improvement of the structure of boring tool

In order to improve the machining efficiency of RTM joints, we design a new integrated boring tool, as shown in Figure 8. The new boring tool is embedded with two rough boring blades and one fine boring blade. The two rough boring blades are arranged collinearly on the tool body, and the diameter is still Φ56.68mm. While the diameter of the fine boring blade is adjustable. The collinear design of the double rough boring blades in the integrated boring tool realizes large margin boring, and the cutting parameters can be raised to S=1200r/min and F=250mm/m. At the same time, the integration of rough and fine boring enables the boring in place in one step, processing good coaxiality and small runout. Thereby the number of boring is reduced and the machining efficiency is improved. This improvement is controlled by changing the process file.

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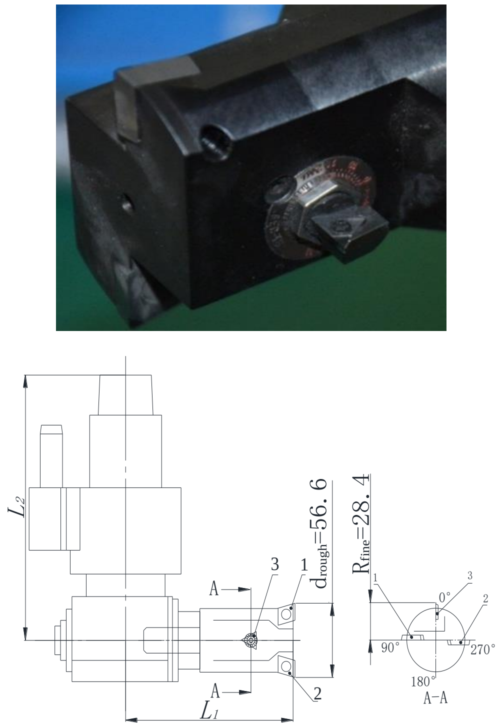


Figure 8. The structure of the new integrated boring tool

3.2. Optimization of the tool path of rough boring

The traditional machining scheme is boring unilaterally and the rough and fine machining are both fed from the right side, as shown in Figure 9. In this machining scheme, the carbon fiber at the end of the orifice is unsupported and it is easy to squeeze outward when the tool is boring out the hole, resulting in fiber delamination.

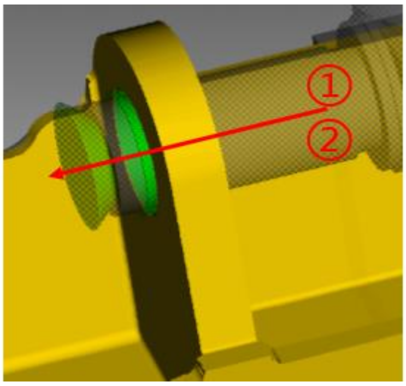


Figure 9. The tool path of rough boring before improvement

According to the above analysis of the boring mechanism of CFRP, the tool path of rough boring is changed to boring 5mm from the left side at first and then boring through from the right side, as shown in Figure 10. In this processing scheme, the boring tool moves from the outside to the inside when the large margin at the end of the orifice is removed. Therefore, the material to be cut is supported by the internal fiber layer, which will not cause fiber delamination and tearing. Changing the NC program to achieve this improvement.

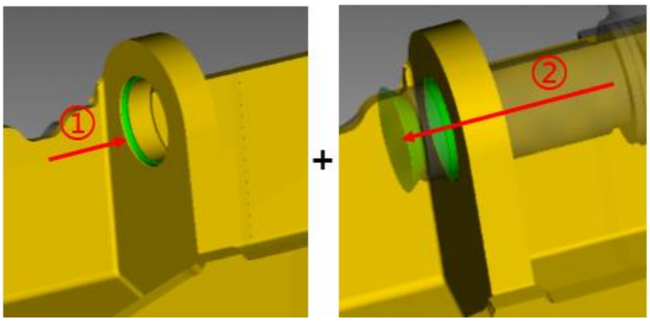


Figure 10. The tool path of rough boring after improvement

3.3. Optimization of the fine boring removal

In view of the fiber delamination caused by excessive cutting force during the fine boring, it is necessary to reduce the cutting parameters to minimize the cutting force as possible. The fine boring removal is changed from 0.12mm to 0.06mm, and the process specification is revised.

3.4. Experimental design and verification

Considering the three factors of the structure of boring tool, the tool path of rough boring, the fine boring removal, as well as two machining levels before and after improvement, the minitab Taguchi experimental design method [11, 12] is used to design a total of $2^3 \times 2$, namely 16 experiments. The response of the experiment is whether there are burrs at the orifice. The experimental design is shown in Table Ⅰ.

Table Ⅰ. Experimental design

Factor	Structure of boring tool	Tool path of rough boring	Fine boring removal
level	single-edged boring tool	unidirectional feeding	0.12
	integrated boring tool	bidirectional feeding	0.06

The device of the machining experiment is shown in Figure 11. And the results of 16 experiments are shown in Table Ⅱ.

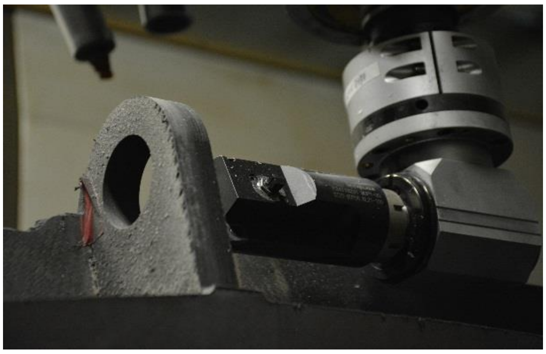


Figure 11. The machining experiment with integrated boring tool

Table Ⅱ. The results of machining experiments

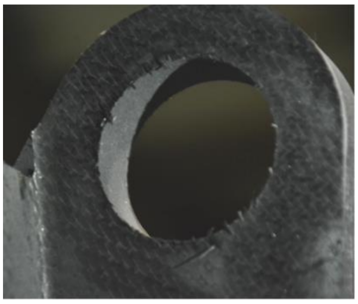
No.	Structure of boring tool	Tool path of rough boring	Fine boring removal	Whether there are burrs
1	single-edged boring tool	unidirectional feeding	0.06	1
2	single-edged boring tool	unidirectional feeding	0.06	1
3	single-edged boring tool	unidirectional feeding	0.12	1

ISSN: 2664-9640

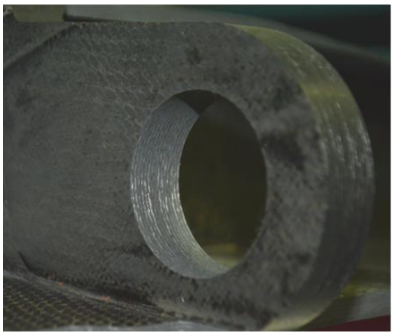
4	single-edged boring tool	unidirectional feeding	0.12	1
5	single-edged boring tool	bidirectional feeding	0.06	1
6	single-edged boring tool	bidirectional feeding	0.06	1
7	single-edged boring tool	bidirectional feeding	0.12	1
8	single-edged boring tool	bidirectional feeding	0.12	1
9	integrated boring tool	unidirectional feeding	0.06	1
10	integrated boring tool	unidirectional feeding	0.06	1
11	integrated boring tool	unidirectional feeding	0.12	1
12	integrated boring tool	unidirectional feeding	0.12	1
13	integrated boring tool	bidirectional feeding	0.06	0
14	integrated boring tool	bidirectional feeding	0.06	0
15	integrated boring tool	bidirectional feeding	0.12	1
16	integrated boring tool	bidirectional feeding	0.12	1

where 1 means there are burrs, and 0 means there are no burrs.

Though the analysis of the experimental results, it can be concluded that there are no burrs in the situation that using the integrated boring tool to process boring by bidirectional feeding method with a fine boring removal of 0.06mm. The remaining situation all have orifice burrs, as shown in Figure 12. In addition, the boring time for each part of the traditional machining scheme is 30 minutes. While the average boring time for each part with the new integrated boring tool is only 7.5 minutes.



(a) The quality of the orifice brfore improvement



(b) The quality of the orifice after improvement

Figure 12. The results of machining experiments

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The time series diagram of the project is shown in Figure 13. In this figure, 1 means there are burrs, which are unqualified parts, and 0 means there are no burrs, which are qualified parts. It can be seen that there are no orifice burrs in the parts of RTM joint after adopting the new machining scheme.

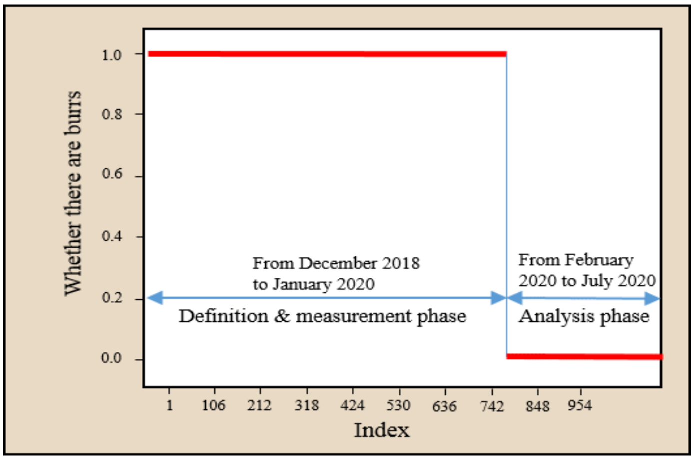

Figure 13. The time series diagram

4. Conclusion

In this paper, aiming at the problems of orifice burrs and low machining efficiency in the boring of RTM joints at A350' spoiler, we analyze the key factors in the machining process through Six Sigma quality management tools. Based on the analysis results, we design a new integrated boring tool and propose an improved process scheme. The main results are as follows:

(1) A new type of integrated boring tool has been designed, which can achieve large margin machining. The average number of boring per part has been reduced from the previous 6 times to 1 times, and the feedrate has been improved from 30mm/min to 250mm/min. As a result, the machining efficiency increased by 75%;

(2) The new process scheme has been optimized so that the DPMO (Defects per million opportunities) of the orifice burrs of RTM joint from 100,000 to 0, realizing an improvement of 100%.

References

[1] N. Li, P. H. Chen, "Experimental Investigation on Edge Impact Damage and Compression-After-Impact (CAI) Behavior of Stiffened Composite Panels," Composite Structures, 2016, 138, pp. 134-150.

[2] J. Wei, H. J. Wei, "High Quality Hole Drilling Process for Carbon Fiber Composites," Journal of Nanjing University of Aeronautics & Astronautics, 2009, 41(S1), pp. 115-118.

[3] H. J. Zhang, W. Y. Chen, R. Fan, D. C. Chen, "Drilling of High Quality Hole of Carbon Fiber Reinforced Plastics," Aeronautical Manufacturing Technology, 2004(03), pp.55-57.

[4] G. Everstine, T. Rgers, "A Theory of Chip Formation of FPR Composite Materials," Journal of Composite Materials, 1971(05), pp. 94-106.

[5] S. Hanasaki, M. Nomura, "Analysis of Carbon-Fiber-Reinforced Plastic Cutting Mechanism by Finite-Element Method Fracture Behavior of Fiber at Entry of Cutting," Transactions of the Japan Society of Mechanical Engineers Series C, 1995, 61(583), pp. 1163-1168.

[6] Y. Hasegawa, S. Hanasaki, M. Nishikimi, "Wear Mechanism of the Tool in Cutting GFRP," Journal of the Japan Society of Precision Engineering 50(1984), pp. 1747-1752.

[7] Y. Karpat, O. Bahtiyar, “Mechanistic Force Modeling for Milling of Unidirectional Carbon Fiber Reinforced Polymer Laminates,” International Journal of Machine Tools and manufacture, 2012, 56, pp.79-93.

[8] X. Dong, M. Li, H. Li, H. S. Zhang, “Influence of Cutting Parameters on Cutting Forces and Hole Exit Tear in Boring CFRP,” Aerospace Materials & Technology, 2012,42(06), pp. 79-82.

[9] M. H. Wang, N. Liu, Y. X. Xu, “Experimental Study on Milling Force and Hole Milling Quality of Helical Hole Milling for Carbon Fiber Reinforced Plastics,” Machine Tool & Hydraulics, 2015(19), pp. 40-45.

[10] Z. He, G. Yue, “Six Sigma Management and Its Implementation,” Application of Statistics and Management, 2007, 26(6), pp. 1049-1055.

[11] F. Z. Zeng, X. Zhao, “Taguchi Method and Its Standardized Design,” Machinery Industry Standardization & Quality, 2003(11), pp. 7-9.

[12] Z. He, Y. Pan, Z. X. Liu, S. H. Zhang, “A Comparative Study of Fractorial Experiment, RSM and Taguchi Method”. Machine Design, 1999(11), pp. 3-5.