Design of internal flow passage of internal chip removal drill for suction-type internal chip removal system

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Abstract
Currently, hole making processes in carbon fiber reinforced polymers (CFRP) generate powdered chips that cannot be automatically recovered in real time. The present work attempts to solve this problem using a new drilling-chip removal system called the suction-type internal chip removal system. It can discharge the powdery chips generated in the CFRP hole making process in a timely and effective manner during the drilling process. Based on the requirements of the drill bit used in this system, the following studies are carried out in this work: (1) Using statistical methods, the chips produced in CFRP hole making were classified, the chip distribution was analyzed, and the study of the influencing factors of chip size were completed; (2) based on these studies and the gas–solid two-phase fluid mechanics, a FLUENT simulation is used to define the center distance and center angle of the inner runner for the design of the drill bit. The influence of the center distance of the inner runner, the center angle of the inner runner, and the cross-sectional shape of the inner runner on the chip removal effect of the inner runner of the tool is given. Finally, by fabricating the chip removal system and drill, the correctness of the internal flow channel structure design of the internal chip removal drill was verified.

Keywords Suction-type internal chip removal system · CFRP · Chips · Internal chip removal drill · Internal runner

1 Introduction
Carbon fiber composite materials are widely used in the manufacture of aircraft structural parts, such as rudders, elevators, upper cabin floor beams, and rear panels due to their excellent physical and mechanical properties, such as light weight, high specific strength, high specific rigidity, and good formability [1–3]. Structural parts like fuselage, horizontal tails, and ailerons generally need to be mechanically processed before being equipped, among which hole processing is a main method. For example, there are 55,000 assembly holes on a single important CFRP structural part on the Airbus A350 [4–6].

Since CFRP has the characteristics of low interlayer bonding strength, high hardness, and good wear resistance, problems such as delamination, burrs, and easy wear of processing tools often occur during processing [7–9]. According to available literature, the generation of delamination defects and burr defects are directly related to tool wear [10, 11]. Analysis shows that the main cause of tool wear is the grinding effect among the tool, chip, and workpiece. Among them, the cutting chips act as abrasive particles and are the main reason for the aggravation of the tool wear that reduces the grinding action among the tool-chip-workpiece and improve the service life of the tool and the quality of hole making. This work introduces a hole making process method that can effectively discharge the chips in real time during CFRP drilling, namely, the suction-type internal chip removal drilling processing method. During the drilling process, the chips can be recycled by the chip recovery device in real time and effectively through the internal runner of the tool, internal runner of the internal chip removal tool holder, and related chip removal pipeline. Secondly, based on the chip formation mechanism and chip distribution law, FLUENT is used to study the influence of the position and shape of the runner on the chip evacuation performance of the tool, and finally the design of the internal
chip evacuation tool is completed. Finally, a test platform was built to verify the simulation and theoretical analysis, and to provide a basis for subsequent research on the internal chip removal process.

A survey of existing literature indicates that the analysis of the critical condition of the internal chip removal system and the internal flow channel design of the internal chip removal tool are relatively rare at home and abroad. However, the design of the internal flow channel of the chip removal tool or the calculation of the critical condition of the internal chip removal system is related to the gas–solid two-phase fluid mechanics. However, the current research on gas–solid two-phase fluid mechanics has a certain foundation: For example, Dai et al. [12] used Savage’s particle dynamics model to study the flow characteristics of high-concentration pulverized coal pneumatic conveying in an elbow and established a mathematical model for the transportation of high-concentration pulverized coal. The model is also used to simulate the pressure drop and flow distribution law in a vertical-turning-horizontal 90° elbow. Li et al. [13] established a mathematical model for the pneumatic conveyance of carbon black in elbows to obtain the relationship between the transportation pressure drop of the carbon black and the ratio of the diameter and length of the elbow. Ji [14] improved the numerical simulation algorithm for a three-dimensional flow field, and the resultant porous jump method is used to analyze the distribution of gas phase fluid in a vacuum cleaner, leading to the conclusion that the main factor that affects the working effect of the vacuum cleaner is the gas flow field. Ottjies [15] simulated the movement of solids in a small-caliber horizontal pipe and modeled the collision of solid particles with the pipe wall under the action of Magnus lift. Lu et al. [16] conducted experimental and simulation studies on the fluid flow characteristics in the elbow during the pneumatic conveying process and obtained the axial velocity distribution of the gas–solid two-phase fluid at different positions in the elbow. Sommerfeld and Lain [17] conducted a numerical simulation analysis of gas–solid two-phase fluid particles in a circular tube; the particle trajectories for different pipe diameters and different cross-sectional positions of the same pipe diameter are predicted. Dzido et al. [18] studied the movement of particles in a vertical pipe as the research object; based on the analysis of the flow characteristics of solid particles in the acceleration zone, combining existing fluid mechanics models, the velocity field and pressure field distribution of spherical particles and non-spherical particles moving in a vertical pipeline are accurately predicted. This work studies the internal flow channel design of the internal chip removal drill bit used in the suction-type internal chip removal system in combination with gas–solid two-phase fluid mechanics.

2 Composition and working principle of suction-type internal chip removal system

The suction-type internal chip removal system is composed of the machine tool, CFRP, internal chip removal drill, external rotation internal chip removal tool holder, chip removal pipeline, and chip collection device, and the structure is shown in Fig. 1. Among them, the internal chip removal drill bit and the external rotation internal chip removal tool holder have chip removal channels inside.

The function of the system is to discharge the chips generated in the CFRP drilling process through the chip removal channel in real time, reducing labor and material costs, improving tool life and hole quality, and realizing green and efficient CFRP processing. The working principle of the system is such that when the machine tool is working, the spindle drives the drill installed on the outer turning inner chip handle for drilling. At the same time, the fan in the chip collection device provides chip suction power (negative pressure), and the system uses negative pressure to suck out the chips through the chip suction channel of the drill bit. It is sucked into the chip collection device through the chip removal channel of the drill and the outer turning and internal chip removal tool holder with the chip removal channel, thereby completing the drilling process. One of the key factors that result in the timely and effective recovery of chips generated during processing is the design of the flow channel of the internal chip removal tool used by the system. Therefore, the following experimental study involves the chips generated during CFRP hole processing and studies the influencing factors of chip size and the main distribution area after chip generation.

![Fig. 1 Schematic diagram of suction-type internal chip removal drilling system](image-url)
3 Research on chips produced by CFRP drilling

In order to carry out the flow channel design of the internal chip removal tool for the suction-type internal chip removal system, this section details the experimental methods used to classify the chips generated in CFRP drilling; secondly, details of the different types of chips are given; finally, the main factors that affect the chip size and main distribution area of the chip are analyzed.

3.1 CFRP chip classification and formation analysis

1. Experimental conditions

The CFRP used in the experiment was provided by Hafei Industry Co., Ltd. Its density is 1760 kg/m³, longitudinal elastic modulus is 235 GPa, transverse elastic modulus is 14 GPa, Poisson’s ratio is 0.2, shear modulus is 28 GPa, tensile strength limit is 3.59 GPa, and compressive strength limit is 2.7 GPa. Its structure has an orthogonal ply with a thickness of 4.5 mm. The drill used in the experiment is a special CFRP drill bit (SD205-7.963–40-8R1-CX31) produced by Seco; the processing equipment used in the experiment is a VDL-1000E CNC milling machine produced by the Dalian Machine Tool Factory; the process parameters used in the experiment are shown in Table 1; the chip size was measured with an ultra-depth-of-field microscope (Keyence VHX-1000).

2. Experimental results and analysis

Carry out the cutting experiment according to the machining parameters shown in Table 1, and a selection of the results obtained from the experiment are shown in Fig. 2. Strip chips, micro-circular chips, rice chips, fiber pull-out chips, and C-shaped chips are obtained during the machining of CFRP. Chips with a maximum length of less than 100 μm are called rice chips. However, the above conclusions are only applicable to drilling, and milling or other hole making methods need further investigation.

3.2 Analysis of the causes of different types of cutting

Formation of rice-shaped chips: In the CFRP drilling process, the material will be squeezed under the action of the shear force of the drill chisel edge and will be misaligned with the cutting edge to form tiny, irregularly shaped crushed chips (i.e., rice-shaped chips), as shown in Fig. 3.

Formation of strip chips and micro-circular chips: During the drilling process, the feed amount is fixed; that is, the distance that the chip cutting edge of the drill moves in a unit time is a certain fixed amount, and the thickness of the chip is determined. The cutting edge is inclined relative to the material to be cut, and there is an uncertain torque effect. So, the material to be cut fails and fractures easily, and there will be no chips at both ends. That is, strip-shaped chips and micro-circular chips will be produced as shown in Figs. 4 and 5. Further analysis shows that the length of the chip depends on the length of the cutting edge and the thickness of the chip is related to the feed rate. The reason is that the longer the cutting edge of the tool, the longer the length of the chip.

Table 1 Table of chip experimental processing parameters

| Cutting parameters | Numerical value |
|--------------------|----------------|
| Speed \( n \) (/r/min) | 2000, 3000, 4000, 4500, 5000 |
| Feed rate \( f \) (/mm/min) | 50, 100, 150, 200, 260 |
the cutting edge involved in cutting, and the longer the cut material and the longer the chip generated.

Analysis of the causes of formation of C-shaped chips and fiber pull-out chips: Due to the poor thermal conductivity of carbon fiber composites, as the processing progresses, the heat accumulation will increase the processing temperature. When the temperature reaches a certain value, due to the action of torque, the strip-shaped chips will become C-shaped with a certain bending angle, as shown in Fig. 6. Meanwhile, the increase in temperature will soften the CFRP material matrix, which will reduce the bonding force between the fiber and the resin, causing the fiber pull phenomenon during the cutting process to form chips with burrs or tearing defects, as shown in Fig. 7.

3.3 Proportion of different types of chips

In order to further understand the proportion of different types of chips during CFRP drilling, five groups of experimental chips were randomly selected, and ultra-depth-of-field microscope observation was used to calculate the chip shape and quantity. The statistical results are shown in Table 2.

According to the chip statistics in the above table, strip chips account for the largest proportion of approximately 74%, followed by nearly 22% of micro-circular chips. C-shaped chips have the smallest proportion, and there are almost no fiber pull-out chips. M-shaped or similar chips account for approximately 2%. Analyzing the above conclusions, strip-shaped chips and micro-circular chips are the
chips produced by the main cutting edge of the drill cutting CFRP material, so they account for the largest proportion. The C-shaped chips and fiber pull-out chips are formed under specific conditions, and so, their share is relatively small.

3.4 Influencing factors of chip size and the law of chip distribution

By observing the chips obtained from the above experiment through the ultra-depth-of-field microscopy, the relationship curve between the cutting parameters and the equivalent diameter of the chip (the equivalent chip diameter is defined in the literature [19]) is shown in Fig. 8.

As shown in Fig. 8, (1) when the speed is constant, the equivalent diameter of the chips obtained from hole making increases with the increase of the feed; (2) when the feed is 50 (mm/min), 100 (mm/min), and 200 (mm/min), the equivalent diameter of the chips obtained by hole making increases with the increase in the speed; when the feed rate is 150 (mm/min), the chip diameter obtained from hole making processing increases first and then decreases with the increase in speed; when the feed rate is 260 (mm/min), the equivalent diameter of the chips obtained from hole making processing will first decrease and then increase with the increase in the speed. Analyzing the causes of the above phenomenon: When the speed is constant, the feed rate increases, and the distance that the drill cutting edge moves per unit time will increase, which will lead to an increase in the equivalent chip diameter; when the feed rate is 150 (mm/min) and 260 (mm/min), as the speed increases, the reason for the change in the equivalent chip diameter is the change in the type of the largest chip produced during processing. (3) From the analysis, we can know the range of the equivalent chip diameter obtained in this experiment as 0.2 mm ≤ d_e ≤ 1.8 mm; (4) when the vertical distance between the drill tip and the upper surface of the CFRP is 14–18 (mm), the angle between the drill bit axis and the chip edge line (definition: the connecting line between the drill tip and the edge of the flying chip in CFRP cutting is the chip edge line) is 12°–20°, and this result can provide a reference for the subsequent determination and simulation of the chip domain.

4 Design of the internal runner structure of the tool

According to the working principle of the suction-type internal chip removal system, the working power (negative pressure) of the system is provided by the fan on the chip collection box. It is the power source for the system to suck the chips, and the medium used is air. The main principle of chip flow in the drill body is that the system uses a fan to form a negative pressure flow field in the chip removal channel and the chip suction channel of the drill body to recover the chips generated in the drilling process. The key to whether the chips can be discharged effectively in time under the action of the negative pressure flow field is the distribution of the pressure field and the velocity field in the flow channel. Therefore, this article adopts a FLUENT simulation method to study the influence of the position and shape of the inner runner of the tool on the chip removal quality of the inner runner, and based on this research, the internal runner design of the tool is completed.

4.1 Physical properties of research object

In order to ensure the correctness of the simulation analysis, the physical properties of the two research objects, the gas phase and the solid phase, must be evaluated according to the actual situation. Therefore, the physical properties of the two research objects will be introduced below.
The physical properties of the gas: This study uses room temperature air under standard pressure, which is the gas phase medium commonly used in engineering as the research fluid. The parameters are shown in Table 3.

Physical properties of the chips: The chips used in this study are obtained from the experiment in Sect. 2, and the equivalent diameter of the chips used in the simulation is given in Sect. 2. The computation of the equivalent chip diameter is known from literature [19]. The specific physical properties of the chips are shown in Table 4.

1. Fluid domain modeling for simulation
   When using gas–solid two-phase fluid mechanics to analyze actual engineering problems, it is first necessary to establish a flow domain model. The main content of this paper is the chip removal performance of the internal flow channel of the drill bit in the internal chip removal system so that the internal flow channel model and the chip fluid domain model for chip removal of the drill bit can be established. Because the built model has complex three-dimensional surfaces, this paper uses Pro/E to model the internal chip removal channel and the chip removal fluid domain. Based on the above analysis and actual processing conditions, an internal chip removal channel model and a chip removal fluid domain model with a Y-shaped flow channel are established, as shown in Fig. 9.

2. Mesh division
   This paper uses the structured hybrid grid (TGrid) to divide the chip removal fluid domain model and apply the size function to the position where the chip removal channel and chip suction channel in the internal chip removal drill are connected. After the mesh is divided, the total number of grid nodes is approximately 1 million. The mesh quality check using the software shows that this grid division can achieve high-efficiency numerical calculations, and using this grid for the simulation can get high-quality numerical simulation results. The structured hybrid meshing model is shown in Fig. 10.

3. Boundary condition setting for simulation
   The turbulence simulation is applied by second-order implicit propulsion method for the turbulence model, which is established by RNGk − ε simulation method. The wall condition is set as a standard wall function, and the inlet of the flow channel is set as a pressure inlet, and the outlet of the flow channel is set as a pressure outlet. Based on the above settings, the transient characteristics of the fluid domain during the internal chip removal drilling process are described, while the non-slip condition is applied to the rotating domain such as the calculation domain and the rotating wall of the runner. For ensuring the reality of the CFRP internal chip removal drilling processes and tracking the trajectory of CFRP particles in the chip removal channel, the DPM model of Fluent is applied. After that, the researches of particles flow in the tool and the particles quality have been finished.

To use the DPM model to track the trajectory of the CFRP particles, the chip generation quality is calculated according to the instantaneous chip flow formula (1) during the analysis:

\[
Q = \rho_s \pi \left[ \left( \frac{D}{2} + a_p \right)^2 - \left( \frac{D}{2} \right)^2 \right] fn
\]

![Chip removal fluid domain model](image-url)
where $\rho_s$ is the chip density; $D$ the drill bit diameter; $f$ the feed rate; $n$ the rotating speed; and $a_p$ the milling depth.

4.2 Optimized simulation of the flow channel structure in the drill bit

Based on theoretical analysis and simulation settings, FLUENT is used to optimize the simulation of the internal flow channel structure of the internal chip removal drill. Definition: The distance between the top of the cutter body and the intersection of the center line of the chip suction flow channel and the center line of the chip discharge channel is the center distance of the flow channel, represented by $h$, as shown in Fig. 11. The angle between the centerline of the chip suction channel and the centerline of the chip discharge channel is defined as the center angle of the channel, which is represented by $\delta$, as shown in Fig. 11. In order to design the flow channel in the drill bit, first of all, combined with the chip distribution area obtained in the experiment, the range of the center distance of the runner and the center angle of the runner is given as shown in Table 5. Secondly, through calculation, it can be known that the volume of chips discharged per unit time accounts for approximately 20% of the volume of the flow channel in the entire drill bit. The experimental coefficient used in this section is 1.6. Finally, according to the literature [20], when the center angle of the runner is $12^\circ \sim 20^\circ$, the negative pressure required for chip removal in the system is 9 kPa. The processing parameters used in the simulation are shown in Table 5. According to the pressure formula in the Bernoulli equation, the larger the equivalent diameter of the chips, the greater the chip removal speed required for chip removal in the internal runner. In other words, the greater the negative pressure required for chip removal, the greater the negative pressure of chip removal required to discharge chips with the largest diameters. Therefore, in the simulation, this paper selects the chip with the largest equivalent diameter for the simulation, that is, 1.8 mm.

1. The simulation of the center distance of the inner runner center of the inner chip removal bit

Select the drill bit diameter $D = 8$ mm, chip suction channel diameter $d_1 = 2.0$ mm, chip removal channel diameter $d = 4.0$ mm, channel center angle $\delta = 20^\circ$, and chip removal negative pressure 9 kPa; the simulation of the influence of the center distance of the internal chip removal drill bit runner on the chip removal effect of the runner is carried out, and the simulation result is shown in Fig. 12.

By analyzing the simulation results shown in Fig. 12 we can infer that: (1) When using different flow channel center distances for simulating the internal flow channel chip removal, local positive pressure will appear in the drill bit flow channel, which will affect the normal discharge of the chips; (2) as the center distance of the runners increases, the range of local positive pressure in the runners in the drill bit also decreases gradually; and (3) when the flow channel center distance is 18 mm, the local positive pressure range of the flow channel in the drill bit reaches the minimum value, and the pressure field distribution meets the chip removal requirements of this article. In order to further verify that when the flow channel center distance is 18 mm, the pressure field distribution of the flow channel in the drill bit meets the chip removal

![Fig. 10 Grid of inner flow channel and fluid domain](image1)

![Fig. 11 Drill bit inner channel structure](image2)

Table 5 Simulation parameters

| Parameter name                        | Numerical value |
|---------------------------------------|-----------------|
| Speed $n / (r / \text{min})$          | 3000            |
| Feed rate $f / (\text{mm/ min})$      | 200             |
| Channel center distance $h / (\text{mm})$ | 14, 15, 16, 17, 18 |
| Channel center angle $\delta / (^\circ)$ | 12, 14, 16, 18, 20 |
requirements of this article; further analysis of the simulation results obtained in Fig. 12e shows that: (1) the pressure value of the chip discharge channel decreases gradually along the chip discharge direction, which is in line with the normal pressure drop trend; (2) the pressure field distribution at the chip suction channel is relatively balanced, which can ensure the smooth discharge of chips; and (3) there is a small pressure vortex around the flow field of the chip suction channel, which may cause pressure changes but does not affect the normal discharge of chips. In summary, when the flow channel center distance is $h = 18$ mm, the chip removal pressure distribution in the chip removal channel of the internal chip removal drill designed in this paper can enable the chips generated in the cutting process to be discharged smoothly.

2. Simulation analysis of the center angle of the inner runner of the internal chip removal bit

Choose drill diameter $D = 8$ mm, chip suction channel diameter $d_1 = 2.0$ mm, chip removal channel diameter $d = 4.0$ mm, channel center distance $h = 18$ mm, and chip removal negative pressure 9 kPa. The simulation of the influence of the center angle of the internal chip removal bit on the chip removal effect of the channel is carried out. The simulation results are shown in Fig. 13.

As shown in Fig. 13, when using different channel center angles for internal channel chip removal simulation, there will be a local backflow phenomenon in the flow channel of the drill bit, which will affect the normal discharge of chips. Further analysis of the scope of the local backflow phenomenon revealed that as the center angle of the runner increases, the area where the local backflow phenomenon occurs gradually decreases; when the flow channel center angle is 20°, the flow channel velocity backflow phenomenon in the drill bit reaches the minimum value, and the velocity field distribution meets the chip removal requirements of this article.

3. Simulation analysis of the internal flow channel shape of the internal chip removal bit
Using the above simulation, the design of the center distance of the bit runner center and the center angle of the runner can be completed, but the influence of the inner runner shape of the drill bit on the chip removal effect of the system is not considered. So, the following simulation method is used to study the influence of the inner runner shape on the system.

After selecting the drill diameter $D = 8$ mm, chip removal channel diameter $d = 4.0$ mm, channel center distance $h = 18$ mm, channel center angle $\delta = 20^\circ$, and negative pressure of chip removal 9 kPa, a simulation analysis of the influence of the shape of the internal chip removal channel on the chip removal effect of the channel is performed. The three kinds of runners used in the simulation have the same area, and the selected runner shapes are circular with a diameter of 2 mm; elliptical, with a major axis of 2 mm, and minor axis of 1 mm; and square with a side of 2.5 mm. The results obtained are shown in Fig. 14.

By analyzing the simulation results shown in Fig. 14, it can be inferred that the speed backflow phenomenon and local positive pressure of the circular chip removal channel are better than those of the other two shapes of chip removal channels (i.e., when the circular structure of the chip removal channel is used for chip removal, the chip removal effect is better than other types). Analyzing the reasons for the above phenomenon, for a certain area of the chip removal channel, the circular channel has the shortest perimeter, equivalent diameter, and maximum Reynolds number in the pipe; that is, the wind speed of the pipe section is the most uniform, and the chips are passing through. When the section is cross-sectioned, the passage area that is pulled by uneven wind speed is the smallest, which is most conducive to the normal discharge of chips.

Fig. 13  Simulation analysis of the influence of the center distance of the runner on the chip removal effect of the runner
5 Experimental verification

5.1 Experimental conditions

To verify the correctness of the simulation analysis of the chip removal drill used in the suction-type internal chip removal system, the chip removal effect of the internal chip removal drill, it is necessary to build a suction-type internal chip removal system. The suction-type internal chip removal system is built as shown in Fig. 15, which includes the machine tool (SYIL-X4), internal chip removal drill (the manufactured inner chip removal drill is shown in Fig. 16; the design and parameter selection of the inner passage part of the internal chip removal bit is given above, and the design and parameter selection of the drill tip is based on [21]), outer turning inner chip removal tool holder, chip collection device, control system, chip removal pipeline (Dongguan Keweidi Pipe Industry Co., Ltd.), and CFRP. In order to facilitate the analysis of the experimental results, the real-time recovery rate of the chips of the inner chip conveyor is approximately 93%, and the real-time recovery rate of the chips of the outer chip conveyor is approximately 85%.

In order to prove the chip removal effect of the internal flow channel of the internal chip removal drill used in the suction-type internal chip removal system, the chip removal situation of the industrial vacuum cleaner with the external chip removal device used in the general factory is now compared and analyzed. The chip parameters may be defined as \( n = 3000 \text{r/min} \) and \( f = 200 \text{r/min} \), chip removal negative pressure \( P = 9 \text{kPa} \), and the tool used is an internal chip removal drill designed and manufactured by ourselves.

A model 202 industrial vacuum cleaner produced by a certain manufacturer is used in the external chip removal device with a working negative pressure of \( P \geq 17 \text{KPa} \).

Through the analysis of the experimental structure, the real-time recovery rate of the chips of the inner chip conveyor is approximately 93%, and the real-time recovery rate of the chips of the outer chip conveyor is approximately 85%.

Through the above experimental analysis, it can be known that when the internal runner designed in this paper is used for drilling and chip removal, both the chip removal quality and the chip removal effect are better than the external chip removal device on the industrial vacuum cleaner. It also further illustrates the correctness of the internal flow channel of the internal chip removal drill designed in this paper.
6 Conclusion

1. The results demonstrated that various types of chips, such as strip chips, micro-circular chips, rice chips, fiber pull-out chips, and C-shaped chips, are generated during CFRP hole making. When the vertical distance between the drill tip and the upper surface of the CFRP is 14–18 (mm), the angle between the drill bit axis and the chip edge line is $12^\circ \sim 20^\circ$.

2. Based on the definition of the internal flow channel center angle and the internal flow channel center distance of the internal chip removal bit, the simulation shows that: (1) With the increase in the flow channel center distance ($h$), the range of local positive pressure in the flow channel in the drill bit decreases gradually; (2) as the center angle ($\delta$) of the runner increases, the area where the local backflow phenomenon occurs in the runner in the drill bit decreases gradually; and (3) the chip removal effect of the circular structure chip removal channel is better than the other two shapes of the chip removal channel.

3. The establishment of a suction-type internal chip removal system through experiments shows that when the internal runner designed in this paper is used for drilling and chip removal, both the chip removal quality and the chip removal effect are better than the external chip removal device of the industrial vacuum cleaner.

Author contribution Theoretical analysis and model construction were completed by Xu Chengyang, Wang Yiwen, and Zou Aili. The experimental design and analysis were completed by Xu Chengyang and Jin Lei. The thesis was written by Xu Chengyang, Yao Songyang, and Wang Meng. The supervision and optimization of the paper were completed by Wang Yiwen and Wang Gongdong.

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Data availability All data generated or analyzed during this study are included in this published manuscript.

Declarations

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