Design and Experiment of High-speed Deep Hole Drilling for Difficult-to-Cut Materials

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Abstract. Objective: Difficult-to-cut materials are the mainstream of the current machining research. The purpose of the study is to apply high speed deep hole drilling technology to difficult-to-cut materials, but ordinary high-speed drilling technology can not deal with problems of difficult-to-cut materials in the field of processing. Materials and Method: The study starts with multi-edge BTA deep hole drilling for its greatest advantage in cutting TC4—the most typical difficult-to-cut materials. This paper proposes a viewpoint for reducing the friction force of the guide block so as to improve the cutting speed. Results: By means of testing, the author obtains the function relation between the tooth width of drilling bits and the force in cutting titanium alloy and redesigns the width and position of the high-speed deep-hole drilling bit, completing the cutting tooth material and the geometric angle of the cutting tooth. Conclusion: He verifies the viewpoint and optimizes the parameters of the drilling bit. These provide the theoretical basis for the design of high-speed deep-hole drilling bits.

1. Introduction
The earliest deep-hole processing technology appeared in the process of military industrial gun barrel. Later, with the progress of science and technology, several new technologies of deep-hole processing were developed successively. Respectively, they are the gun drill, BTA drill, ejector drill and DF drill [1].

The processing of the hole is very difficult and the reliability requirement is extremely high. If the design requirement is not met, it will lead to the overall scrapping of the tube plate. At the same time, there are some problems such as the difficulty of cutting, the bit wear fast and the short life span in the actual process [2].

In order to solve those series of problems, many people have done different aspects of this research. Griffiths et al established the mechanical model of BTA deep hole drilling, analyzed the force of the two guide blocks. On this basis, he optimized the position angle of the guide block to get the target function with the minimum pressure of the guide block [3]. With the basis of Griffiths’ optimization, Gao et al studied the cutting force of BTA deep-hole drilling bit. By the test, he obtained the deformation curve of each cutting edge of the drilling bit under the given cutting parameters and the wear curve of the bit under different cutting parameters [4]. Then Latinovic et al studied the force of deep hole drilling in single blade. In this research, he inferred the mathematical relation between the counterforce on the guide block and the Angle of cutting edge tool. On the basis of this, he optimized the design of BTA deep hole drilling bit with single blade [5]. Different from Gao’s study, not only did Yang et al studied the relationship between the forces and cutting parameters of deep-hole drilling bit, but he also obtained a cutting parameter that reduces the force of bits during drilling through the experiment [6]. By the finite element simulation of the drilling process, Dirk et al analyzed the
influence of machining parameters on the vibration of drilling bit and machining precision [7]. On the basis of these, Gao JY et al mainly studied the balance of deep-hole drilling bits under high-speed drilling and how to apply fluid knowledge to solve the difficult problem of high-speed drilling chip removal. And then, he redesigned the cutting edges and the flow channel [8]. In order to reduce the vibration, many researchers started to study ultrasonic vibration cutting. Wang et al Combined with the advantages of high speed cutting and ultrasonic vibration drilling. By means of the testing, he found that ultrasonic vibration aided high-speed drilling, compared with the ordinary drilling, is able to process micro deep holes with higher precision and smaller roughness [9]. In the field of difficult-to-cut materials, Tsai et al made high speed drilling of carbon fibre composites experiment. The test results showed that feed and bit blade angle has a significant impact to the delamination, but spindle speed and drilling diameter has smaller influence on it. By the test, he obtained the minimum combination of layered parameters [10].

In order to apply high speed deep hole drilling technology to difficult-to-cut materials, the optimization of the drilling bit under complex cutting environment is the central task.

2. Mechanical Analysis

2.1 Mechanical model

On the drilling bit, the author divides the force into cutting force, friction force and positive force [11]. Because the workpiece contacts with not only the lips but also both guide blocks around the drilling bit for support and positioning during working. The force of drilling bit is shown in Fig.1. After simplification, the resultant cutting force and torque are shown as

\[
\begin{align*}
F_{\text{hor}} &= \sum F_{yi} \\
F_{\text{ver}} &= \sum F_{zi} \\
M_s &= \sum m_0(F_{zi})
\end{align*}
\]

where \(F_{\text{hor}}\) is y direction resultant force; \(F_{\text{ver}}\) is z direction resultant force; \(M_s\) is resultant torque from \(F_{zi}\) to point O.

![Fig. 1 Force coordinate system for drilling bit](image)

When the forces on the drilling bit get balanced, \(N_3\) and \(F_{f3}\) are ignored. And then, mechanical model of deep hole drilling bit in y-z plane can be established in Fig. 2 (b).The mechanical balance equation is shown as

\[
\begin{align*}
F_{\text{hor}} + N_1 \cos \delta_1 + N_2 \cos \delta_2 - F_{f1} \sin \delta_1 - F_{f2} \sin \delta_2 &= 0 \\
F_{\text{ver}} + N_1 \cos \delta_1 + N_2 \cos \delta_2 - F_{f1} \sin \delta_1 - F_{f2} \sin \delta_2 &= 0 \\
M_s + F_{f1} \frac{d_0}{2} + F_{f2} \frac{d_0}{2} - M_b &= 0
\end{align*}
\]
where $M_b$ is the torque from drilling pipe to drilling bit; $d_0$ is diameter of the drilling bit; $\delta_1$ is location angle of guide block 1; $\delta_2$ is location angle of guide block 2; $\mu$ is friction coefficient between workpiece and guide block.

![Mechanical model of drilling bit](image)

**Fig. 2 Mechanical model of drilling bit**

### 2.2 Calculations about drilling force and torque

Through plenty of cutting tests and mathematical processing, cutting force values from empirical equation are figured out. The empirical equation is shown as

\[
\begin{align*}
F_x &= C_x a_x \alpha_{Xp} K_{F_x} \\
F_y &= C_y a_y \alpha_{Yp} K_{F_y} \\
F_z &= C_z a_z \alpha_{Zp} K_{F_z}
\end{align*}
\]

(3)

which shows the cutting force is relative with cutting data. Then assume average speed from teeth as the true speed, and assume the feed rate and cutting speed constant, the equation can be simplified as

\[
\begin{align*}
F_x &= C_x a_x \alpha_{Xp} \\
F_y &= C_y a_y \alpha_{Yp} \\
F_z &= C_z a_z \alpha_{Zp}
\end{align*}
\]

(4)

Finally, (4) is written in the convenient form as

\[
Y = bX + a
\]

### 3. Structural design

According to the current design theory of deep hole drilling, the guide block ensures the stability of the guide while subjected to a large positive pressure. When drilling speed becomes faster, frictional heat will increase rapidly and drastically, which makes guide blocks and lips increasing the wear and tear. Up to a certain cutting speed, frictional heat becomes the main reason of drilling wear. Therefore, the first point in the optimization should be less frictional heat, which means the positive pressure on the guide block should be minimum.

The choice of tooth width directly determines the stress on drilling bit during the process, but currently, there is no quantitative analysis for the influences of positive force from tooth width and position. Therefore, the only way to obtain the relevant parameters of (3) is doing experiment.

In this experiment, the author selects medium diameter size of drilling bit[12]. The basic parameters of drilling bit are listed in Table 1; the tooth structure basic parameters are listed in Table 2; global design of the drilling bit is shown in Fig 3[13-14].

| Table 1. The basic parameters of drilling bit |
|----------------------------------------------|
| **Form** | Three cutting teeth are radially distributed |
| **Diameter** | $d_0=38\text{mm}$ |
| **Shank** | The connection structure uses four rectangular square thread and |
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| shaft shoulder positioning |
|----------------------------|
| Chip hole d=20mm; The outlet shapes like a cone or bell, the angle of which is $\theta = 25^\circ$ |
| Outside diameter $d_1=34.5$ mm |
| Connecting form Weld |

**Table 2. The parameters of tooth structure**

| Working approach angle | Rake angle | Back angle |
|------------------------|------------|------------|
| Outer edge 18° | Inner edge 22° | Outer edge 3° | Inner edge -7° | Outer edge 12° | Inner edge 15° |

| Cutting edge inclination | End cutting edge | Chip braker |
|--------------------------|------------------|------------|
| Outer edge 0° | Inner edge 7° | Back angle 8° |
| Margin width 0.5 mm | Width 1.5 mm | Height 1 mm | Radius 0.5 mm |

![Fig. 3 Structure of drilling bit](image)

**4. Experiment**

**4.1 Optimum design of tooth width**

In the experiment of optimizing tooth width by controlling the variable method, the teeth are separated into three main groups to explore the relationship between: the width and cutting force: inner edge, middle edge and outer edge [12]. Taking into account the test cost and least square method, four tooth width values are taken for each group of test listed in Table 3.

**Table 3 Various types of tooth width design value**

| Type | Inner edge of inner tooth | Middle tooth | Outer tooth |
|------|---------------------------|--------------|------------|
| Width (mm) | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 8 | 9 | 10 | 11 |

Then those teeth are used to cut titanium alloy TC4 in the cutting force test on C6140. During the test, the workpiece rotates, cutting tooth does feed movement and the feed is 2mm per revolution. After that, three-dimensional dynamometer, dynamic resistance strain gauge and multimeter are applied into collecting data, which are listed in Table 4.
Table 4 Tooth width test data

| Inner tooth width (mm) | Middle tooth width (mm) | Outer tooth width (mm) |
|------------------------|-------------------------|------------------------|
| 4                      | 5                       | 6                      |
| 10                     | 11                      | 8                      |
| 11                     | 9                       | 10                     |

Radial force (N)  
73 109 163 228 145 204 287 409 151 215 304 426

Tangential force (N)  
108 161 229 328 246 335 461 647 257 341 468 658

Based on least square method, MATLAB can make curve fitting to figure out the tooth width coefficients and indexes of radial force and tangential force, which are listed in Table 5.

Table 5 The coefficients and indexes of radial force and tangential force

| Type        | Radial force ($F_y$) | Tangential force ($F_z$) |
|-------------|----------------------|--------------------------|
|             | Coefficient ($C_{fy}$) | Index ($X_{fy}$) | Coefficient ($C_{fz}$) | Index ($X_{fz}$) |
| Inner tooth | $C_{fy1}=4.412\,a_p^{2.018}$ | $X_{fy1}=2.018\,a_p^{1.970}$ | $C_{fz1}=6.893\,a_p^{3.233}$ | $X_{fz1}=1.970\,a_p^{3.031}$ |
| Middle tooth| $C_{fy2}=0.172\,a_p^{3.262}$ | $X_{fy2}=3.233\,a_p^{3.031}$ | $C_{fz2}=0.440\,a_p^{3.031}$ | $X_{fz2}=3.031\,a_p^{3.031}$ |
| Outer tooth | $C_{fy3}=0.168\,a_p^{2.950}$ | $X_{fy3}=3.262\,a_p^{3.031}$ | $C_{fz3}=0.541\,a_p^{2.950}$ | $X_{fz3}=2.950\,a_p^{2.950}$ |

According to Table 5 and the index equivalent formula of radial force and tangential force, the equations for the quantitative cutting forces in both directions of each tooth are shown as:

Inner tooth:  
\[ F_y = 4.412\,a_p^{2.018} \]
\[ F_z = 6.893\,a_p^{1.970} \]

Middle tooth:  
\[ F_y = 0.172\,a_p^{3.233} \]
\[ F_z = 0.440\,a_p^{3.031} \]

Outer tooth:  
\[ F_y = 0.168\,a_p^{2.950} \]
\[ F_z = 0.541\,a_p^{2.950} \]

According to Fig. 1, the force of y direction (radial) and z direction (tangential) are shown as:

\[ F_y = F_{y(F)} + F_{y(e)} - F_{y(C-e)} - F_{y(A)} \]
\[ F_z = F_{z(A)} + F_{z(e)} - F_{z(C-e)} - F_{z(F)} \]

where $F_{y(F)}$, $F_{z(F)}$ are the radial force and tangential force of middle tooth; $F_{y(e)}$, $F_{z(e)}$ are the radial force and tangential force of inner edge of inner tooth; $F_{y(C-e)}$, $F_{z(C-e)}$ are the radial force and tangential force of outer edge of inner tooth; $F_{y(A)}$, $F_{z(A)}$ are the radial force and tangential force of outer tooth. The resultant of z-direction and y-direction is:

\[ F = \sqrt{F_y^2 + F_z^2} \]

Then put the design parameters into (6)(7)(8), the tooth width optimization of the minimum positive force of guide block are figured out and listed in Table 6.

Table 6 Optimization of tooth width

| Tooth width (mm) | Inner tooth | Middle tooth | Outer tooth | Offset | Overlap |
|------------------|-------------|--------------|-------------|--------|---------|
| Plan A           | 8           | 5            | 8           | 3      | 1       |
| Plan B           | 8           | 5            | 7           | 3      | 0.5     |
| Plan C           | 8           | 5            | 8           | 4      | 1       |

4.2 Testing and analysis of the optimization

In order to verify the optimization, it is necessary for those three plans to get cutting experiment. After that, take average values many times listed in Table 7.
Table 7 Testing data of optimization plans

| Testing number | Cutting force (N) | Plan A | Plan B | Plan C |
|----------------|-------------------|--------|--------|--------|
|                |                   |        |        |        |
| Y-direction    |                   |        |        |        |
| 1#             |                   | 43.231 | 17.009 | 5.134  |
| 2#             |                   | 38.979 | 15.134 | 4.205  |
| 3#             |                   | 44.648 | 16.153 | 7.591  |
| 4#             |                   | 43.122 | 18.426 | 7.738  |
| 5#             |                   | 41.813 | 18.426 | 6.153  |
| Average values |                   | 42.368 | 17.030 | 6.164  |
| Z-direction    |                   |        |        |        |
| 1#             |                   | 274.364 | 229.043 | 166.975 |
| 2#             |                   | 266.154 | 235.304 | 159.017 |
| 3#             |                   | 270.943 | 236.817 | 155.955 |
| 4#             |                   | 255.207 | 234.669 | 174.630 |
| 5#             |                   | 257.943 | 241.113 | 168.507 |
| Average values |                   | 264.922 | 235.389 | 165.017 |

According to Table 7, plan C is the best one, which also proves the correctness of optimization. So finally, the optimization program is: middle tooth width (F) is 5 mm; inner tooth width (C) is 8 mm; outer tooth width (A) is 8 mm; offset (e) is 4 mm; overlap is 1 mm.

5. Conclusion

1) To solve the universally difficult problem of applying high-speed deep hole drilling technology to difficult-to-machine materials, the author puts forward the viewpoint of reducing the friction force of the guide block so as to improve the cutting speed.

2) By means of testing, he obtains the function relation between the tooth width of drilling bits and the force in cutting titanium alloy as (6):

\[
\begin{align*}
F_y & = 4.412a_p^{0.018} \\
F_z & = 6.893a_p^{1.970}
\end{align*}
\]

\[
\begin{align*}
F_y & = 0.172a_p^{3.233} \\
F_z & = 0.440a_p^{3.031}
\end{align*}
\]

Middle tooth

\[
\begin{align*}
F_y & = 0.168a_p^{3.262} \\
F_z & = 0.541a_p^{3.950}
\end{align*}
\]

Outer tooth

3) He redesigns the width and position of the high-speed deep-hole drilling, optimizing the new BTA drilling bit. The optimization parameters of Φ38m Titanium alloy deep-hole drilling are described as: middle tooth width (F) is 5 mm; inner tooth width (C) is 8 mm; outer tooth width (A) is 8 mm; offset (e) is 4 mm; overlap is 1 mm.

4) These provide the theoretical basis for the design of high-speed deep-hole drill bits.

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