The investigation on the machining process of BTA deep hole drilling

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Abstract

In this paper, a computer-based approach is presented to the investigation of machining mechanisms in boring and trepanning association (BTA) deep hole drilling processes. The cutting mechanisms investigated are focused on the chip deformation and associated drilling forces in deep hole situation in particular. The machining models are further investigated for such processes. The models are evaluated and validated based on the data acquired with a computer-based acquisition system. It is found that the chip deformation cut by the centre edge is the largest, whereas the change tendency of the cutting force and the sum of chip deformation cut by three blades of drill are about the same. This paper also describes the measurement and analysis of the forces including the axial force in BTA deep hole machining.

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Keywords: BTA deep hole drilling; Chip deformation; Cutting force; Wear

1. Introduction

In machining processes such as turning, milling and shaping, a large chip discharge space is normally available and the chip breaker is often big enough to ensure the chip discharging. But in the process of drilling, deep hole drilling in particular, no sufficient discharging space is available, and so peck drilling, axial vibration and pressurised cutting fluid are often used to help chip discharging. A satisfactory chip discharge is essential for implementing successful deep hole drilling.

The interaction between the drilling tool and the work-piece in BTA deep hole machining has been studied to determine the influence of various machining conditions on the chip deformation, cutting forces and the tool wear [1–3]. Since the resultant drilling force in axial direction consists of the cutting force, fluid pressure force, burnishing force and friction, using a complete theoretical approach based on derived equations to precisely estimate the resultant force would be difficult and impractical [4].

In this paper an experiment based approach is proposed to investigate the BTA deep hole drilling process. The investigation is focused on the chip deformation, tool wear and the associated drilling forces. A computer-based data acquisition system and an optical fibre force sensor is used for sampling the machining data. This study is essential for further developing an on-line monitoring system for controlling the machining process.

2. Experimental procedure and equipment

The experimental system is mainly composed of the deep hole drilling machine tool and the data acquisition/analysis system as shown in Fig. 1. The system details are as follows:

1. Cooling system:
   - cutting fluid flow rate, \( q = 1001/\text{min} \);
   - cutting fluid pressure, \( p = 2.50 \text{ MPa} \);
   - cooling liquid, emulsions.
3. Small signal amplifier:
   - accuracy, 1\%;
   - response frequency, 2 \text{ kHz};
   - output draft amount, <2 mV.
4. Drill material: carbide blade.
5. Workpiece material: AISI1045, 200 HB.

Fig. 2 shows the configuration of a typical BTA drilling tool head. The head nose is designed offset from the axis of the head. 30\degree negative rake angle is chips in C shape which must be small enough to go out introduced to strengthen the cutting edge in that area. In order to obtain narrow chips, the
cutting edge is divided into three parts. This depends upon the hole diameter and the material properties of the workpiece. Chip breakers are also required to produce small pieces which can move freely through the very restrictive chip exit mouth and throat. The tool life test was performed with the self-piloting drills with respect to the requirements of the industrial standards (ANSI/ASME B94.55M-1985). The average width of the flank wear land \( VB_{b\text{cr}} \) is 0.3 mm that was chosen as the tool life criterion; such a value is common for this type of drilling tools.

The specifications of BTA deep hole drills used in the trials are shown in Table 1.

### 3. Chip deformation

#### 3.1. Chip deformation on the three cutting edges

Based on the metal cutting theory [5–7], the chip deformation can be obtained using the following equations:

\[
\gamma = \frac{\cos \alpha}{\sin \varphi \cos (\varphi - \alpha)}
\]

(1)

where

\[
\cot \varphi = \frac{(t_2/t_1) - \sin \alpha}{\cos \alpha}
\]

(2)

\( t_1 \) is the undeformed chip thickness. The mean chip thickness \( t_2 \) can be obtained by measuring the length, \( l \), and weight, \( W \), of a piece of chip. So the mean thickness \( t_2 \) is

\[
t_2 = \frac{W}{\rho w l}
\]

(3)

Using the Eqs. (1)–(3), the chip deformation can be obtained with the data from the machining trials.

In the machining trials, however, it was found that there are different chip deformations on the three cutting edges as shown in Fig. 3. The chip deformation cut by the inner edge is the highest, the one by the middle edge is higher, and the

### Nomenclature

- \( d \): deep hole drill diameter
- \( F \): total force
- \( F_r \): run-out tolerance on the drill
- \( F_x \): axial force
- \( F_{ox} \): axial force on the outer edge
- \( F_{mx} \): axial force on the middle edge
- \( F_{ix} \): axial force on the inner edge
- \( f \): feed rate
- \( H \): depth of the breaker
- \( l \): length of the chip
- \( R \): radius of the breaker
- \( t_0 \): depth of cut
- \( t_1 \): undeformed chip thickness
- \( t_2 \): mean chip thickness
- \( v \): cutting speed
- \( W \): weight of a piece of chip
- \( W_d \): width of the breaker
- \( w \): width of chip

### Greek letters

- \( \alpha \): rake angle of the cutting tool
- \( \gamma \): the amount of chip deformation
- \( \varphi \): shear plane angle
- \( \rho \): density of workpiece material
one by the outer edge is the smallest. The reasons are as follows:

- The rake angles on the three cutting edges are different. The right rake angle of the inner edge is $-30^\circ$, as shown in Fig. 2. The rake angles of the other two cutting edges are in the range of $0^\circ$ to $2^\circ$. Due to the chip deformation principles [5], the chip deformation cut by the inner edge will be larger than those by other edges, which is consistent with the trial results as shown in Fig. 4.

- The tangential velocities on the three edges are different. Because there are different radii on the three cutting edges, the speed of outer edge is the highest, the one of middle edge is higher, and the one of the inner edge is the smallest. These determine the chip deformation cut by the inner edge being larger than those by others.

- The breaker and chip mouth wall. When the chip is removed from the workpiece, the up-curling chip cut by the inner edge will strike the chip mouth except when it strikes the breaker and the workpiece. So its

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Specifications of the BTA deep hole drills used in the trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill No.</td>
<td>$D$ (mm)</td>
</tr>
<tr>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>25</td>
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<td>3</td>
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<td>25</td>
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<td>5</td>
<td>25</td>
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</table>
deformation will increase and be bigger than the other two.

3.2. Effects of the machining conditions

The chip deformation will be affected by the machining conditions. In the drilling trials, the effects of tool rake angle, speed and feed rate were investigated. It was found:

- When the cutting speed increases, the chip deformation will decrease (as shown in Fig. 5).
- When the feed rate increases, the chip deformation will increase (as shown in Fig. 4).
- When the rake increases, the chip deformation will decrease (as shown in Fig. 4).

These conclusions are very similar to those derived in turning [7].

4. Cutting force

The cutting force on the drill consists of the cutting force on the three cutting edges, fluid pressure, burnishing force and friction of the pad [8]. In the trials, only the axial force was measured. Considering the experimental conditions, the depth of cutting was the same. The axial force was measured by the optical sensor in the systems, as shown in Fig. 1. It was found:

- When the speed increases, the axial cutting force will decrease, which is shown in Fig. 6.

When the speed increases, the axial cutting force will decrease, which is shown in Fig. 6.

- When the feed rate increases, the axial cutting force will increase too as illustrated in Fig. 7.
- Based on the data from the trials, the empirical equations for the estimation of the axial force in BTA deep hole machining can be expressed as:

$$F_x = 39044f^{0.95}v^{-0.15}$$  \hspace{1cm} (4)

The equation is limited to the depth of cut which is 12.5 mm for the workpiece material AISI1045 steel (HB 200). The empirical equation (4) can be compared with any previously published data as listed in Table 2 [8]. It can be found from the equation that the axial force is not a linear function of feed. This is probably due to the burnishing effect taking place between the wear pads and the drilled hole surface.

The equation is suited for 25 mm diameter, AISI1045 steel deep drilling. Such an empirical equation can be used to understand the influence of process variables, such as feed rate, \(f\), and cutting speed, \(v\), on the mean axial force.

5. Deformation and cutting force

In the deep hole machining, the axial force is equal to the resultant force resulting from those on the three cutting edges, fluid pressure force, burnishing force and friction. But from the trials it was found that the forces coming from the three cut edges are the main ones. They are much larger than other forces. So only the forces coming from the three cut edges are considered. Based on the metal cutting theory [5],

Table 2

<table>
<thead>
<tr>
<th>Investigators</th>
<th>Materials</th>
<th>Axial force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Griffiths (1982)</td>
<td>EN8</td>
<td>(F_{am} = 1912f^{0.06}v^{-0.78})</td>
</tr>
<tr>
<td>Weber (1984)</td>
<td>C60</td>
<td>(F_{am} = 33300f_{ap}V_d^{-1.10}t^{0.026}d^{-0.137})</td>
</tr>
<tr>
<td>SANDVIK</td>
<td></td>
<td>(F_{am} = 0.65n_wf_{ap}K_d\sin x_c)</td>
</tr>
<tr>
<td>Osman (1985)</td>
<td>AISI1020</td>
<td>(F_{am} = 430f_{ap}^{0.082}d^{1.44})</td>
</tr>
<tr>
<td>The authors</td>
<td>AISI1045</td>
<td>(F_x = 39044f^{0.95}v^{-0.15})</td>
</tr>
</tbody>
</table>
the cutting force comes from the deformation. From the trial data, as shown in Fig. 8, it was found that relationship between the axial force in the deep hole drilling and the total deformation of the three cutting edges can be derived as:

\[ F_x = A \sum \gamma + B \] (5)

where \( A \) and \( B \) are the constants relevant with the machining conditions. \( \Sigma \gamma \) is the total deformation of the three cutting edges.

On the other hand, in two-dimensional cutting, the main force \( F \) and the deformation \( g \) have the following relationship [5]:

\[ F = \Gamma G_s \tilde{t} f(1.4\gamma + C) \] (6)

where \( \Gamma \) is the shear yield limit, \( C \) the constant related to the rake angle, and

\[ F_x = kF \] (7)

So Eqs. (6) and (7) yield

\[ F_x = k\Gamma G_s \tilde{t} f(1.4\gamma + C) \] (8)

Using Eq. (8), the axial forces \( F_{ox}, F_{mx}, F_{ix} \) on the outer edge, middle edge and inner edge, can be expressed as:

\[ F_{ox} = k\Gamma G_s \tilde{t} f(1.4\gamma_o + C_o) \] (9)

\[ F_{mx} = k\Gamma G_s \tilde{t} f(1.4\gamma_m + C_m) \] (10)

\[ F_{ix} = k\Gamma G_s \tilde{t} f(1.4\gamma_i + C_i) \] (11)

So the total axial force on the drill is

\[ F_x = F_{ox} + F_{mx} + F_{ix} \]
\[ = k\Gamma G_s \tilde{t} f(1.4\gamma_o + C_o) + k\Gamma G_s \tilde{t} f(1.4\gamma_m + C_m) \]
\[ + k\Gamma G_s \tilde{t} f(1.4\gamma_i + C_i) \]
\[ = 1.4k\Gamma G_s \tilde{t} f(\gamma_o + \gamma_m + \gamma_i) + \gamma \]
\[ + (C_o + C_m + C_i) \]
\[ = M \sum \gamma + N \] (12)

where \( M \) is the constant related with the machining conditions, \( C_o, C_m, C_i, \) and \( N \) are the constant with the rake.

Eqs. (5) and (12) have similar forms. That illustrates, in the BTA deep hole drilling process, the axial force is linear with the sum of chip deformation resulting from the three cut edges.

6. Wear

In deep hole drilling trials, the data of the wear on the BTA deep hole drill can be obtained through measurement. The BTA deep hole drill life curves can be plotted based on the data as shown in Fig. 9. The curves are very similar to the Taylor curve \((VT^n = C)\) [5,7]. The extent of the low wear region decreases with the increase of the cutting speed. The wear rate rises abruptly when the temperature at the trailing edge of the wear land reaches the thermal softening point of the work material.

7. Concluding remarks

In this paper the BTA deep hole drilling machining process was investigated with respect to the chip deformation, cutting forces and wear in the deep hole drilling in particular. It is found that the chip deformation cut by the inner edge is the largest in the three cutting edges of the BTA drill. The chip deformation increases when the feed rate increases, and decreases when the rake and cutting speed increases. The empirical equations of the axial force were developed based on the trial data. The wear curve of the BTA deep drills is very similar to that as shown by the Taylor curve [1]. This research laid down a solid basis for further developing an on-line monitoring and control system for the BTA deep hole drilling processes.

References


