Effects of Process Parameters on Cutting Force and Tool Temperature in Drilling Based on Finite Element Simulation

Yuan Gao*, Jie Wang, Qi Wang, Xin Li, Tingyu Zhang and Yang Zhong
Aerospace research institute of materials & processing technology, Beijing, China
* E-mail: zzgaoyuan@163.com

Abstract. Cutting force and tool temperature play significant roles in the drilling process because they are strongly related to drilling performance such as surface roughness, tool wear and tool breakage etc. For difficult-to-machine materials, like titanium alloys, the drilling operation is considered to be complex due to their mechanical and thermal properties, and it is important to find suitable process parameters to avoid too large cutting force or too high tool temperature, which may deteriorate the drilling performance. This paper is dedicated to studying the effects of process parameters, including spindle speed, feed rate and helix angle, on cutting force and tool temperature in drilling based on finite element simulation. A series of drilling simulations are carried out to generate the simulated cutting force and tool temperature data under different drilling conditions. By data fitting, the steady cutting force and tool temperature are predicted. Based on the Taguchi method, the effects of process parameters on steady cutting force and tool temperature are analysed. This paper can provide a basis for suitable selection of process parameters in drilling.

1. Introduction
Titanium alloys are commonly used in the recent years, especially in aerospace and biomedical industries [1] due to their exceptional strength to weight ratio, high temperature performance and corrosion resistance [2]. However, these alloys belong to difficult-to-machine materials because of their low thermal conductivity, high chemical reactivity and low modulus of elasticity [3], leading to large cutting forces and high tool temperatures during machining. Cutting force and tool temperature play important roles because they are strongly related to machining performance such as surface roughness, tool wear and tool breakage [4] etc. It is of great significance to find suitable process parameters before machining to avoid too large cutting force or too high tool temperature during machining, which may deteriorate the final machining quality.

Machining simulation by finite element method can provide an effective way to study the cutting force and tool temperature during machining. Tuğrul and Altan [5] developed a methodology for simulating the cutting process in flat end milling operation. Chip flow, cutting forces, tool stresses and temperatures are predicted by using finite element analysis. Sulaiman et al. [6] simulated the cutting force and tool temperature during high speed machining of AISI 4340 steel, and found the optimum tool rake angle that resulted in the smallest cutting force and the lowest tool temperature. Muhammad et al. [7] developed a three-dimensional simulation model of drilling process and investigated the effect of an external heat source on thrust force and torque, demonstrating that hot drilling had advantages in reducing thrust force and torque.
This paper is dedicated to simulating the cutting force and tool temperature in the drilling operations, and analysing the effects of process parameters, including spindle speed, feed rate and helix angle, on cutting force and tool temperature. The paper is organized as follows: In section 2, the layout of the drilling simulation and the definitions of several process parameters are demonstrated in details. The instantaneous cutting force and tool temperature data can be generated by simulations, and by data fitting, the steady cutting force and tool temperature can be predicted. In section 3, a series of drilling simulations are carried out under different drilling conditions, and the effects of process parameters on steady cutting force and tool temperature are analysed based on the Taguchi method. Finally, conclusions of this study are drawn in section 4.

2. Description of simulation model for drilling

Figure 1 shows the layout of the simulation model for drilling. Cuboid workpiece is adopted in the simulation, with the length \( L_w \), the width \( W_w \) and the height \( H_w \) of the workpiece equalling to 12 mm, 12 mm and 10 mm, respectively. The workpiece material is defined as Ti6Al4V, while the drill material is defined as cemented carbide. A standard drill with diameter \( D_0 \) equalling to 6mm is used. The helix angle \( H_a \) usually varies from 18 degrees to 30 degrees, and is to be investigated in this study. The other relevant tool geometrical parameters are given as follows: the body diameter clearance is equal to 0.15 mm; the web thickness is equal to 1 mm; the flute radius is equal to 1.45 mm; the flute length is equal to 5 mm; and the edge radius is equal to 0.04 mm.

The cutting parameters, including the spindle speed \( N \) and the feed rate \( f_0 \), are to be investigated in this study. The starting depth \( s_d \) is defined as the embedded depth of the drill into the workpiece at the beginning of the simulation time. In this study, the value of starting depth is set as 2.2 mm.

Figure 2 shows the chip formation process in the drilling simulation. The total angle of rotation of the drill is 1080 degrees. The simulated cutting force and tool temperature data are shown in Figure 3.
The cutting forces in the tangential direction and radial direction are theoretically equal to zero, while the cutting force in the axial direction is principal. In this study, only the axial cutting force is considered, and in the rest part of this article, the concept of cutting force represents the axial cutting force.

\[ F_{in} = F_{ax} = a_1 \]  

where \( a_1 \) is a constant fitted from the original cutting force data shown in Figure 4. Therefore, the cutting force in the steady state \( F_{ste} \) can also be predicted to be equal to this constant:

\[ F_{ste} = a_1 \]  

The simulated tool temperature increases from the initial value and will reach to a steady state with enough time. The instantaneous tool temperature \( T_{in} \) can be expressed as follows:

\[ T_{in} = a_1 \left( 1 - \exp(-b_2t) \right) + b_1 \left( 1 - \exp(-b_3t) \right) \]  

where \( b_1, b_2, b_3, b_4 \) are four constants fitted from the original tool temperature data shown in Figure 5. Therefore, the steady tool temperature \( T_{ste} \) can be achieved when time \( t \) is infinite, and can be expressed as follows:

\[ T_{ste} = b_1 + b_3 \]
3. Effects of process parameters on cutting force and tool temperature

In this study, a series of drilling simulations are carried out with different combinations of process parameters, including spindle speed, feed rate and drill helix angle.

**Table 1.** Process parameter levels.

| Symbol | Parameter | Unit | Parameter levels |
|--------|-----------|------|------------------|
| A      | $N$       | rpm  | 1000 2000 3000   |
| B      | $f_0$     | mm/rev | 0.2 0.3 0.4     |
| C      | $H_a$     | degree | 18 24 30      |

A L27 orthogonal array with 3 columns and 27 rows is applied. Each column represents one process parameter, and each process parameter has three levels, as given in Table 1. After 27 set of drilling simulations, the fitting coefficients are obtained from the simulated data, and the steady cutting force and tool temperature are predicted according to Eq. 2 and Eq. 4. The fitting coefficients and the corresponding cutting force and tool temperature results are summarized in Table 2.

**Table 2.** Fitting coefficients, cutting force and tool temperature results

| No. | Parameters | Fitting coefficients | Results | S/N ratio (dB) |
|-----|------------|----------------------|---------|---------------|
|     | $N$ | $f_0$ | $H_a$ | $a_1$ | $b_1$ | $b_2$ | $b_3$ | $b_4$ | $F_{ste}$ | $T_{ste}$ | $F_{ste}$ | $T_{ste}$ |
| 01  | 1000 | 0.2 | 18   | 1474 | 140.4 | 14.58 | 397.5 | 744.5 | 1474 | 537.9 | -63.37 | -54.61   |
| 02  | 1000 | 0.2 | 24   | 1390 | 113.8 | 17.35 | 421.1 | 775.6 | 1390 | 534.9 | -62.86 | -54.57   |
| 03  | 1000 | 0.2 | 30   | 1328 | 123.2 | 18.72 | 415.6 | 883.6 | 1328 | 538.8 | -62.46 | -54.66   |
| 04  | 1000 | 0.3 | 18   | 1978 | 179.4 | 17.98 | 438.5 | 679.6 | 1978 | 617.9 | -65.92 | -55.82   |
| 05  | 1000 | 0.3 | 24   | 1831 | 170.6 | 22.1  | 445.8 | 742.9 | 1831 | 616.4 | -65.25 | -55.80   |
| 06  | 1000 | 0.3 | 30   | 1805 | 175  | 13.22 | 467.8 | 766.9 | 1805 | 642.8 | -65.13 | -56.16   |
| 07  | 1000 | 0.4 | 18   | 2356 | 212  | 16.92 | 463.6 | 630  | 2356 | 675.6 | -67.44 | -56.59   |
| 08  | 1000 | 0.4 | 24   | 2225 | 202.7| 19.74 | 465.9 | 553.5 | 2225 | 668.6 | -66.95 | -56.50   |
| 09  | 1000 | 0.4 | 30   | 2158 | 191.9| 30.19 | 448.7 | 581.1 | 2158 | 640.6 | -66.68 | -56.13   |
| 10  | 2000 | 0.2 | 18   | 1440 | 155.8| 43.87 | 517.5 | 1545 | 1440 | 673.3 | -63.17 | -56.56   |
| 11  | 2000 | 0.2 | 24   | 1423 | 141  | 44.21 | 553  | 1600 | 1423 | 694.0 | -63.06 | -56.83   |
| 12  | 2000 | 0.2 | 30   | 1366 | 137.1| 43.79 | 556.4 | 2035 | 1366 | 693.5 | -62.71 | -56.82   |
| 13  | 2000 | 0.3 | 18   | 1879 | 199.3| 40.41 | 552.4 | 1333 | 1879 | 751.7 | -65.48 | -57.52   |
| 14  | 2000 | 0.3 | 24   | 1827 | 237.6| 48.41 | 535  | 1511 | 1827 | 772.6 | -65.23 | -57.76   |
| 15  | 2000 | 0.3 | 30   | 1762 | 219.8| 30.17 | 567.4 | 1929 | 1762 | 787.2 | -64.92 | -57.92   |
| 16  | 2000 | 0.4 | 18   | 2331 | 253.7| 24.22 | 605.9 | 942.5 | 2331 | 859.6 | -67.35 | -58.69   |
| 17  | 2000 | 0.4 | 24   | 2134 | 259.7| 57.46 | 540.1 | 1370 | 2134 | 799.8 | -66.58 | -58.06   |
| 18  | 2000 | 0.4 | 30   | 2179 | 274.3| 49.93 | 524.8 | 1326 | 2179 | 799.1 | -66.77 | -58.05   |
| 19  | 3000 | 0.2 | 18   | 1435 | 183.7| 33.31 | 617.7 | 2572 | 1435 | 801.4 | -63.14 | -58.08   |
| 20  | 3000 | 0.2 | 24   | 1380 | 181.8| 68.46 | 614.8 | 2306 | 1380 | 796.6 | -62.80 | -58.02   |
| 21  | 3000 | 0.2 | 30   | 1344 | 181.1| 53.13 | 631.8 | 2007 | 1344 | 812.9 | -62.57 | -58.20   |
| 22  | 3000 | 0.3 | 18   | 1869 | 277.2| 81.35 | 571.7 | 2256 | 1869 | 848.9 | -65.43 | -58.58   |
| 23  | 3000 | 0.3 | 24   | 1762 | 283.4| 68.77 | 599.2 | 2433 | 1762 | 882.6 | -64.92 | -58.92   |
| 24  | 3000 | 0.3 | 30   | 1768 | 263.3| 43.55 | 631  | 2299 | 1768 | 894.3 | -64.95 | -59.03   |
| 25  | 3000 | 0.4 | 18   | 2303 | 295.3| 62.01 | 631.4 | 1734 | 2303 | 926.7 | -67.25 | -59.34   |
| 26  | 3000 | 0.4 | 24   | 2178 | 322.5| 82.66 | 582.5 | 2024 | 2178 | 905.0 | -66.76 | -59.13   |
| 27  | 3000 | 0.4 | 30   | 2190 | 288  | 80.73 | 600.8 | 2080 | 2190 | 888.8 | -66.81 | -58.98   |

The signal to noise ratio (S/N ratio) of $F_{ste}$ and $T_{ste}$ are calculated according to the following equation:
\[ SN = -10 \log (MSD) \]  

where MSD is the mean-square deviation for the output characteristic.

The S/N response table and S/N graph for cutting force \( F_{\text{ce}} \) are given in Table 3 and Figure 6, respectively. The S/N ratio is “the larger the better”. It can be seen that the spindle speed has little effect on cutting force. The difference between the maximum S/N ratio and the minimum S/N ratio for spindle speed is only 0.16, and the S/N graph for spindle speed is nearly a horizontal line. Feed rate has the largest influence on cutting force. The difference between the maximum S/N ratio and the minimum S/N ratio for feed rate is 4.05. With increasing feed rate, the S/N ratio decreases apparently, meaning that the corresponding cutting force increases apparently. On the contrary, helix angle has a positive effect on cutting force. With increasing helix angle, the S/N ratio increases as well, meaning that the corresponding cutting force decreases.

Table 3. S/N response table for cutting force.

| Symbol | Parameter | Mean S/N ratio (dB) |
|--------|-----------|---------------------|
|        |           | Level 1 | Level 2 | Level 3 | Max-Min |
| A      | N         | -65.12  | -65.03  | -64.96  | 0.16    |
| B      | \( f_0 \) | -62.90  | -65.25  | -66.95  | 4.05    |
| C      | \( H_a \) | -65.39  | -64.93  | -64.78  | 0.61    |

Figure 6. S/N graph for cutting force.

An analysis of variance (ANOVA) is carried out for cutting force. The results are given in Table 4. The F-value of 623.57 implies the investigated model is significant. There is only a 0.01 percent chance that the F-value of this large could occur due to noise. The p-values for feed rate and helix angle are less than 0.05, indicating that these two parameters have significant effects on cutting force.

Table 4. ANOVA for cutting force.

| Symbol | Sum of Squares | DF | Mean Square | F-value | p-value |
|--------|----------------|----|-------------|---------|---------|
| Model  | 76.38          | 6  | 12.73       | 623.57  | <0.0001 |
| N      | 0.11           | 2  | 0.057       | 2.79    | 0.0852  |
| \( f_0 \) | 74.42        | 2  | 37.21       | 1822.61 | <0.0001 |
| \( H_a \) | 1.85         | 2  | 0.92        | 45.29   | <0.0001 |
| Error  | 0.41           | 20 | 0.020       |         |         |
| Total  | 76.79          | 26 |             |         |         |

The S/N response table and S/N graph for tool temperature \( T_{\text{ce}} \) are given in Table 5 and Figure 7, respectively. It can be seen that both spindle speed and feed rate have negative effects on tool temperature. With larger spindle speed and feed rate, the S/N ratio for tool temperature decreases. The S/N graph for helix angle is nearly a horizontal line, indicating that the helix angle has little effect on the tool temperature. The difference between the maximum S/N ratio and the minimum S/N ratio for helix angle is only 0.04.

Figure 7. S/N graph for tool temperature.
Table 5. S/N response table for tool temperature.

| Symbol | Parameter | Mean S/N ratio (dB) |
|--------|-----------|---------------------|
|        |           | Level 1  | Level 2  | Level 3  | Max-Min |
| A      | N         | -55.65   | -57.58   | -58.70   | 3.05    |
| B      | \( f_0 \) | -56.48   | -57.50   | -57.94   | 1.46    |
| C      | \( H_\alpha \) | -57.31   | -57.29   | -57.32   | 0.04    |

The ANOVA for tool temperature is given in Table 6. The F-value of 138.81 implies the investigated model is significant. The p-values for feed rate and helix angle are less than 0.05, indicating that these two parameters are significant. The p-value for helix angle is larger than 0.1, indicating that this parameter is not significant.

Table 6. ANOVA for tool temperature.

| Symbol | Sum of Squares | DF | Mean Square | F-value | p-value     |
|--------|----------------|----|-------------|---------|-------------|
| Model  | 53.04          | 6  | 8.84        | 138.81  | <0.0001     |
| \( N \) |               | 2  | 21.46       | 336.98  | <0.0001     |
| \( f_0 \) |             | 2  | 5.06        | 79.41  | <0.0001     |
| \( H_\alpha \) |          | 2  | 0.003       | 0.048  | 0.9530      |
| Error  | 1.27           | 20 | 0.064       |         |             |
| Total  | 54.31          | 26 |             |         |             |

4. Conclusions
This paper studied the effects of spindle speed, feed rate and helix angle on cutting force and tool temperature in drilling based on a series of finite element simulations. Feed rate was found to be the most influential process parameter on cutting force, while spindle speed was found to be the least influential one. Both spindle speed and feed rate had negative effects on tool temperature, while helix angle had little effect on tool temperature. This paper can provide a basis for suitable selection of process parameters for drilling operations.

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