Heat Modeling and Experiment of Micro-drilling with Multi-parameter Influence

Zhenhe Wu\textsuperscript{1,a}, Faping Zhang\textsuperscript{2,b*}, Kuikui Feng\textsuperscript{3,c}

\textsuperscript{1,2,3}School of Mechanical Engineering, Beijing Institute of Technology, Beijing, China

\textsuperscript{a}email: 18756980552@163.com,

\textsuperscript{b*}Correspondence author: \textsuperscript{b}email: zhangfaping@bit.edu.cn,

\textsuperscript{c}email: fk19901014@qq.com

Abstract: Cutting temperature is essential to improve machining technology in micro drilling of hard material. As the unreasonable temperature distribution will increase the complexity of tool-workpiece surface contact, affect the machining quality of tool and the surface integrity of hole wall. In this paper, the cutting process model is combined with the analytical temperature rise model based on time to study the change rule of surface contact conditions. The 40Cr sample was used to carry out drilling experiments. The results show that the high feed micro drill tool is prone to structural differences at high temperature, large area size effect. It makes the contact conditions change significantly, and the heat distribution of system changes, which affects the stability of cutting.

1. Introduction

Micro drilling is a miniaturization of traditional drilling method and its cutting characteristics are similar to traditional drilling. However, the reduction of aperture size makes some negligible factors in traditional drilling become necessary. For example, size magnitude reduction changes mechanical properties and size effect occurs \cite{1-2}. These factors increase the complexity and uncertainty of the thermodynamics research of micro drill.

In this study, an analytical model of temperature rise with tool-workpiece as system is established by heat conduction theory, and the variation of heat distribution under different cutting parameters is studied.

2. Experiment design

In this study, the temperature rise of the workpiece surface are measured experimentally, to confirm the heat flux flowing into the workpiece, and evaluate the influence on tool wear. There is experimental device, 40 Cr sample with $\Phi100\times4$mm nitriding treatment, with a yield strength of 785 MPa, placed on a Kistler 9275 bench dynamometer to measure cutting force during cutting. Temperature is measured by 40ThemoView+TV40 thermal imager, equipped with GigE Vision interface standard of high-performance industrial thermal imager, supporting Ethernet power supply (POE), to achieve high-speed data signal transmission.

To measure the temperature rise of the workpiece, the thermal imager should be fixed on the triangular support and placed on the machine table. The distance between the thermal imager lens and the workpiece is 25 cm, and the angle between the lens and the machine platform should be more than 45°. Carbide drill is used as the machining tool, and its parameters are shown in Table 1. Because the diameter of the cutter is far less than the thickness of the workpiece, the machining method of peck
drilling is adopted, and 2mm is drilled each time.

### Table 1 Tool parameters

| Cutting diameter | Diameter of transverse blade | Edge angle |
|------------------|-------------------------------|------------|
| mm 1             | 0.3 mm                        | 118 deg    |
| Feed             | Cutting speed                 | Speed      |
| 5~20μm/rev       | 18.8 m/min                    | 6000 r/min |

3. **Thermal analysis of drilling process**

3.1. **Determination of heat distribution coefficient**

The micro-drilling process can be divided into five stages [3]: 0-\( t_1 \) stage, the workpiece is extruded by the tool indentation surface and cut by the second cutting edge orthogonally, the workpiece is subjected to the thrust of the indentation surface and the cutting force of the second cutting edge; \( t_1-t_2 \) stage, the main cutting edge skews to remove material; \( t_2-t_3 \) stage, the drill tip is drilled into the workpiece completely; \( t_3-t_4 \) stage, indentation surface and the second cutting edge drill through the workpiece; \( t_4-t_5 \) stages, part of the main cutting edges drill through the workpiece until the cutting force is completely eliminated at \( t_5 \) time.

The heat flux produced by metal cutting process comes from three plastic deformation zones: the deformation heat of shear surface \( q_s(t) \), the friction heat between front tool surface \( q_f(t) \) and chip, and the friction heat between flank tool surface and machined surface \( q_f(t) \) [4]. The micro-drilling also considers the heat generated by the indentation surface extruding the workpiece, which can be regarded as the friction between the indentation surface and the material generated in the extrusion direction and flows into the tool and the workpiece. Assuming that the heat flux of each zone is uniformly distributed, the corresponding heat flux is calculated according to the cutting force model of each zone.

\[
\begin{align*}
q_s(t) &= \frac{(F_{ms}(t)v_{ms} + F_{ss}(t)v_{ss})}{A_s(t)} \\
q_f(t) &= \frac{(F_{mf}(t)v_{mchip} + F_{sf}(t)v_{schip})}{A_f(t)} \\
q_i(t) &= \frac{F_i(t)v_{ic}}{A_i(t)} \\
q_l(t) &= F_l(t)v_{lc}
\end{align*}
\]  

(1)

In Formula (1), on primary cutting edge, \( F_{ms}(t) \), \( v_{ms} \) are the shear force and shear velocity along the main shear plane, \( F_{mf}(t) \), \( v_{mchip} \) are the frictional force and chip velocity between the front tool face and the workpiece, \( F_{mcmd}(t) \) is the frictional force between the back tool face and the workpiece and \( v_{mc} \) is the cutting velocity along the cutting direction. Similarly, \( F_{ss}(t) \), \( F_{sf}(t) \), \( F_{scw}(t) \) and \( v_{ss}, v_{schip}, v_{sc} \) are the same type of forces and directions on the second cutting edge, \( F_i(t) \) and \( v_{ic} \) are the cutting forces and extrusion speeds on the indentation surface. \( A_s(t), A_f(t), A_i(t) \) are the contact areas of the corresponding zones. The total heat flow \( q(t) \) generated in the cutting process is the sum of four parts.

Part of the heat flux \( q_{wp}(t) \) and \( q_{ct}(t) \) flow into the workpiece and tool, and the ratio of the total heat flux \( q(t) \) is the heat distribution coefficient \( B_{wp}, B_t \) and the coefficient is related to the cutting speed, feed speed, uncut chip thickness, contact length, thermal conductivity and machining time [5]. In this paper, the relationship between the heat distribution coefficient of 40Cr material and the feed speed is estimated based on the characterizing model of the tool-workpiece interface heat distribution of common materials [6] and a series of inverse heat conduction experiments [7], as shown in Figure 1.
3.2. Modeling of temperature rise

In the cutting process of micro-drilling, the temperature rise of the workpiece is caused by three parts of heat source, the heat source of the shear surface of the workpiece $q_{wp}(t)$, the friction heat source of the back surface of tool to the workpiece $q_{wp}(t)$ and the friction heat source of the indentation surface to the workpiece $q_{wp}(t)$. Assuming that the heat flux on the contact surface is uniformly distributed, the heat source conduction process is shown in Figure 2.

![Figure 2 Heat source conduction diagram of workpiece](image)

Based on the theory of inclined moving heat source conduction and the temperature prediction model of cutting area, the contact surface between workpiece and tool is set as adiabatic boundary, and on the basis of considering the indentation surface, cutting edge radius and other special conditions, an analytical temperature rise model for a point $M(x, y)$ on the workpiece was established, as shown in Formula (2):

\[
\begin{align*}
T_{wp}^s (t) &= \frac{q_{wp}^s(t)v}{2\pi \lambda_{wp} a_{wp}} R_s \\
T_{wp}^f (t) &= \frac{q_{wp}^f(t)v}{2\pi \lambda_{wp} a_{wp}} R_f \\
T_{wp}^i (t) &= \frac{q_{wp}^i(t)υ_c}{2\pi \lambda_{wp} a_{wp}} R_i
\end{align*}
\]

(2)

In the formula, $a_{wp}$ is the thermal diffusivity, $\lambda_{wp}$ is the thermal conductivity. $R_s$, $R_f$ and $R_i$ are the relative distance between the three heat sources and the M point, satisfying Formula (3).
\[ R_0 = \int_0^{l_1} e^{-\frac{R_1 x}{2d_{wp}k_0R_x}} dl_{12} + \int_0^{l_1} e^{-\frac{R_1}{2d_{wp}k_0R_x}} dl_{2} \]  

\[ R_f = \int_0^{l_2} e^{-\frac{R_2 x}{2d_{wp}k_0R_2}} dl_{2} + \int_0^{l_3} e^{-\frac{R_3 x}{2d_{wp}k_0R_3}} dl_{3} \]  

\[ R_i = \int_0^{l_4} e^{-\frac{R_4 x}{2d_{wp}k_0R_4}} dl_{4} \]  

(3)

In the formula, \( R_{1x}, R'_{1x}, R_{2x}, R_{3x} \) and \( R_{4x} \) are the distance between the \( M \) and the heat source point \( dl_{12}, dl_{2}, dl_{3} \) and \( dl_{4} \) in the x axis, \( K_0 \) is a 2-type Bessel function of order zero, which depends on relative distance.

The temperature of the point \( M \) rises from \( T_{(x_1,z_1)}(0) \) to \( T_{(x_1,z_1)}(t) \) under the influence of the three heat sources, as shown in Formula (4).

\[ T_{(x_1,z_1)}(t) = T_{(x_1,z_1)}(0) + T_{wp}^s(t) + T_{wp}^f(t) + T_{wp}^i(t) \]  

(4)

Similarly, the heat source conduction principle of the tool is analyzed. The temperature rise of the tool is transmitted from the front tool surface to the tool friction heat source \( q^f(t) \), the back tool surface to the tool friction heat source \( q^b(t) \) and the indentation area friction heat source \( q^i(t) \). Unlike the workpiece heat source analysis, the workpiece-tool contact surface is no longer considered as an adiabatic boundary \([8]\). In addition to the friction heat source, the shear heat source is transmitted to the induction heat source \( q^f(t) \) and \( q^i(t) \) through the front and back tool surfaces. The heat source conduction process through the front and rear tool surfaces as shown in Figure 3. According to the conduction law, an analytical model of temperature rise at a certain point \( N(x_2,z_2) \) on the tool can be established, as shown in Formula (5).

In the formula, \( \lambda_t \) is the thermal conductivity of the tool.

3.3. Experiment of cutting temperature

As described in section 3.1, because of the small size magnitude of micro-drill, it is affected by the size effect significantly. As a result, the temperature rise of the workpiece and the tool is changed, so it is
necessary to correct the temperature rise model according to the temperature rise data measured by the experiment. Figure 4 represents the workpiece-tool temperature measurement process, the A and B represent the workpiece temperature measurement point, C represents the tool temperature measurement point, which are the average value of the cell. A thermal imager is used to measure the temperature of three points at different feed speeds combined with the predicted values ($P_A$, $P_B$ and $P_C$) calculated by above formulas (prediction curve only calculates the temperature rise process, and the temperature drop after drilling is the same as the experiment). The time-varying data of cutting temperature are obtained, as shown in Figure 4.

![Figure 4 Measuring experiment of workpiece-tool temperature](image)

From the Figure 5, the predicted temperature of A and B two points on the surface of the workpiece is higher than the actual measured temperature, which confirms that the heat distribution coefficient of
the workpiece of micro drilling is smaller than that of the ordinary drilling. The temperature rises slowly, especially in the middle process when the tool is completely drilled to the point of drilling out, indicating that the heat flow into the workpiece decreases greatly during the period of \( t_2 \sim t_3 \). From the point C of the tool, the predicted value and the measured value before complete drilling are basically the same, which reflects that most of the heat flow produced by cutting goes with the chip flow. However, the actual temperature rise of the tool after complete drilling is significantly faster than the predicted value, because the chip removal zone is small and the chips are piled up in it, and the heat flow on the chip flows into the tool. Meanwhile, the resistance caused by the ploughing effect also increases the heat flow.

According to the experimental data of temperature rise, the temperature rise rate of each time period can be calculated. Table 2 shows the heating rates of points A and C at periods 0-\( t_2 \) and \( t_2-t_3 \) when the tool is cutting at various feed rates. The temperature rise rates at feed rates of 15\( \mu \)m /rev and 20\( \mu \)m /rev are much higher than those below 10\( \mu \)m /rev, especially at periods \( t_1-t_2 \). This is because with the increase of cutting force, the macroscopic hard block on the tool surface forms a local thermal junction on the workpiece surface, which leads to the increase of the surface friction coefficient and the change of the material characteristics [9]. The feed rate should not exceed 15\( \mu \)m /rev for drilling micro-holes. According to the manufacturer's data, the maximum feed rate of this type of tool is 30\( \mu \)m /rev.

| Feed (\( \mu \)m /r) | \( t_1-t_2 \) | \( t_2-t_3 \) | \( t_1-t_2 \) | \( t_2-t_3 \) |
|----------------|-----------|-----------|-----------|-----------|
| 5              | 4.05      | 1.08      | 8.81      | 3.11      |
| 10             | 22.38     | 2.68      | 25.71     | 9.50      |
| 15             | 51.14     | 4.36      | 82.14     | 21.09     |
| 20             | 67.18     | 9.56      | 118.10    | 31.84     |

Based on the temperature rise data of point A, B, C, according to the temperature rise model of section 3.2, the temperature matching algorithm of tool-workpiece interface is adopted [10] to calculate the heat flow change \( q_{wp}(t) \) and \( q_{tool}(t) \) of the workpiece and the tool under the condition of multiple feed and solve the corresponding heat distribution coefficient under the condition of the total cutting heat flux \( q(t) \) derived from known formula, as shown in Figure 6. The relationship between feed velocity and heat distribution coefficient can be expressed by power law as: \( B_t = 7.587 - 8.081f^{-0.9774} \) and \( B_{wp} = 1.246f^{-0.4669} \).

3.4. Research of tool surface wear

By combining the obtained thermal distribution coefficient based on feed speed with the measured tool edge radius data, we can study the effect of temperature rise on tool surface wear.

Figure 7 represents a series of surface images collected under a microscope after a cutting process of four drilling-in and drilling-out with a low feed of 5\( \mu \)m /rev. Fig. 7(a) indicate the tool surface is in good condition. Although there are some pits, the wear degree is not serious, and the cutting edge is still in good condition, which can still continue to cut because of the lower cutting force and temperature.
However, the low feed cutting time is longer, resulting in a large amount of debris stains and deposited material remaining on the surface of the drill tip in Figure 7(b). The existence of these defects increases the complexity of the tool-workpiece contact conditions and requires cleaning of tool residue.

Figure 8(a) is the cutting edge after 20μm/rev feed cutting. High temperature burn will reduce the elastic modulus of the material and cause the thermal expansion at the edge. The sharp increase of the radius of the round edge makes there is a long contact length between the drilling surface and the drilling edge, resulting in further increase of cutting force and temperature. The temperature measured by the experiment is higher than the predicted value, indicating the effect of edge deformation. In addition, the high temperature of the edge will also affect the surface integrity of the hole wall, forming burrs and changing the aperture, which is the factor to be considered in the quality study. Therefore, it is necessary to pay attention to the influence of high temperature on edge and hole wall, especially because of the small size of micro-drilling, the influence of the edge deformation on the contact conditions of tool-workpiece surface is greater. When necessary, continuous cooling measures should be taken on the edge, such as the use of water-based cutting fluid.

4. Conclusions
Based on the size effect of drill bit, the thermodynamic problems of drilling tip and drilling surface in 40 alloy Cr are analyzed. In order to study the variation of cutting heat with feed rate, a temperature rise analytical model are proposed to predict the temperature change of tool and workpiece. The results show that the high temperature caused by high feed affects the surface contact condition of tool-workpiece.

(1) On the basis of the original temperature prediction model of cutting region, a mixed analytical model of temperature rise of tool-workpiece system is established by adding the influence factors of edge radius and indentation surface. It can not only study the time-varying law of temperature, but also
correct the heat distribution coefficient in different systems. The model is suitable for micro drilling tools.

2) The study shows that the contact condition of the micro drill tool with the workpiece is more complicated in the high feed state. The contact force affects the cutting temperature, the cutting temperature affects the material characteristics, changes the surface contact coefficient and the contact length, and then reacts on the contact force to form a closed loop response, which results in the temperature change far exceeding the change of feed speed. By further analysis, the feed rate of the tool is controlled below 15μm/rev.

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