Study of High-Speed Mechanical Micro Drilling Process Fundamentals for Small Holes

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Abstract. High-speed mechanical micro drilling would be a promising process for small hole fabrications with high productivity and high quality. But there are limited studies on this topic. Fundamental questions such as the minimum undeformed chip thickness (MUCT) due to the size effect in microcutting, burr size, cutting force, and optimal parameters are discussed for high-speed mechanical micro drilling in this paper. Based on finite element method (FEM) modelling, the MUCT is identified as 0.86 μm for copper C26000 with the cutting edge radius of 5 μm from both chip generation and force variation analyses. The ratio of MUCT to the cutting edge radius is 0.17, which is smaller than that (usually 0.2 or 0.25 for copper) in micro shaping and micromilling processes. This result has been successfully verified by experiments with the drill with a diameter of 1 mm and the spindle speed of 80,000 min-1. Burr width at the hole entrance reaches the maximum value when the undeformed chip thickness (UCT) is smaller than the MUCT. Experimental optimizations with the integrated considerations of cutting forces and burrs have been conducted. The optimal high-speed micro drilling parameters have realized a material removal rate (MRR) of 25% increasement compared with conventional micro drilling.

1. Introduction
Small holes with the diameter from 0.1 mm to 2 mm are widely used in fuel injection nozzles, cooling channels in turbine blades, printed circuit boards, ink jet printers, etc. Small holes can be machined by various machining processes, among them mechanical micro drilling is gaining more and more importance because its improved productivity and expanded applicability to most of the engineering materials [1]. Experimental characterization of the micro-drilling process with the nanofluid minimum quantity lubrication has been studied [2]. It turned out that both drill life and the qualities of drilled holes are enhanced based on the technique. Mathematical models have been built to predict micro-drilling forces for plain and glass-reinforced epoxy sheets and the results have been successfully evaluated with experimental data [3]. Experimental studies have been conducted for vibration assisted deep hole micro-drilling [4]. Comparisons with conventional drilling showed the vibration assisted one has a better performance. Two kinds of micro drills were experimentally compared for mechanical micro-drilling of Nimonic 80A super alloy [5]. Results showed TiAlN-coated micro-drill were better than the uncoated micro-drill. High-speed micro drilling in printed wiring boards has been studied with the cutting speed of 1.68 m/s [6]. Higher level of hole quality and processing efficiency compared with conventional non-step drilling have been achieved. Even though some studies have been
conducted for micro drilling, there are limited studies in fundamental questions associated with high-speed mechanical micro drilling of small holes.

Micro drilling is within the microcutting domain. In microcutting processes, material is subjected to an elastic-plastic deformation without chips formation when the cutting thickness is less than the MUCT due to the size effect [7]. Size effect and the consequent MUCT existing in microcutting need to be studied since the machining quality has a close relationship with that. Therefore, fundamental questions of high-speed mechanical micro drilling are studied in the paper. First, FEM models are created and analyzed for micro drilling to identify the MUCT. Second, experiments are conducted to evaluate the FEM analyses and burrs are discussed. Then, micro drilling parameters are optimized and the MRR is discussed.

2. Modeling and Analyses

2.1. Modeling

Two-flute carbide twist drill without coating is used to drill blind holes on the material copper C26000. The geometrical parameters of the drill are show in table 1. To realize the high-speed micro drilling, the spindle rotational speed is 80000 min\(^{-1}\) and the consequent cutting speed is 4.2 m/s. Workpiece are pre-processed to shorten the simulation time and to make sure the micro drilling is at the steady state, where all cutting edges of the drill are engaged in the microcutting. The meshed tool-workpiece assembly in the software Deform 3D is shown in figure 1. Meshes near the tool-workpiece interfaces are refined for higher simulation accuracy. The shear friction model is applied to the model with the friction coefficient of 0.6. The conjugate gradient solver and direct iterative algorithm integrated in the software Deform 3D are applied to the model.

| Drill diameter \(D_t\) (mm) | 1.0 | Clearance angle \(\delta\) (°) | 12 |
|--------------------------|-----|-----------------------------|----|
| Point angle \(2\phi\) (°) | 118 | Chisel edge angle \(\phi\) (°) | 125 |
| Helical angle \(\alpha\) (°) | 18 | Cutting edge radius \(r\) (μm) | 5 |

Figure 1. The meshed FEM assembly of micro drilling

Figure 2. \(F_z\) vs. \(f\) by simulations

2.2. Chip Generation Analyses

Drilling parameters must satisfy that the UCT is equal to or larger than the MUCT in order to realize the removal of materials in a shear mode rather than a plastic deformation mode. Therefore, the identification of the MUCT is very important in micro drilling. Chip generations and force variations are investigated to judge whether the MUCT is reached. The axial feed \(f\) (in this paper uses the unit of μm/rev-tooth and simplified as μm/z) varies from 0.5 μm/z to 4.0 μm/z with the increment of 0.5 μm/z for the simulations.
Figure 2 shows the simulation results of cutting chips. From figure 2, chips are generated when the feed \( f \) is equal to or larger than 1.0 \( \mu m/z \). According to the size effect theory in microcutting and the equation for the undeformed chip thickness \( t_c \), which is defined in terms of the feed \( f \), and half point angle \( \phi \) [8], the MUCT is calculated as 0.86 \( \mu m \).

\[
t_c = 0.5 f_r \sin \phi = f \sin \phi
\] (1)

Where \( f_r \) refers the feed with the unit of \( \mu m/rev \).

2.3. Force Analyses
Axial forces are simulated and analyzed since other force components are rather smaller than axial forces in drilling. The forces are collected and averaged for each value of the feed when micro drilling proceeds to the steady state, as shown in figure 3.

From figure 3, the axial cutting force \( F_z \) descends first from 9.54 N to 8.87 N and ascends then from 8.87 N to 29.68 N when the feed \( f \) varies from 0.5 \( \mu m/z \) to 4.0 \( \mu m/z \). The inflection point is located at the feed value of 1.0 \( \mu m/z \). The reason for the inflection of the axial cutting force is that work material mainly deforms elastically and plastically without chip generations when the feed \( f \) is 0.5 \( \mu m/z \). Therefore, the axial cutting force is large. When the feed \( f \) is 1.0 \( \mu m/z \), the UCT is the MUCT and material is removed in a shear mode with chip generations. Therefore, the axial cutting force is small according to the size effect phenomenon. Then the axial cutting force becomes larger with the continuous increasement of the UCT. It shows a good agreement with that from chip generation analyses.

3. Experimental Analyses
3.1. Experimental Setup
A desktop three-axis micromilling machine tool 3A-S100 [9] is used for the experiment. Each axis is driven by a linear motor and has the final positioning accuracy smaller than 0.6 \( \mu m \). A high-speed electrical spindle Nakanishi NR-3080S with ceramic bearings is changed to this machine tool. The spindle has a higher stiffness than previously used spindle ABS800 in 3A-S100. The rotational speed is from 0 to 80,000 min\(^{-1}\). Radial and axial runout of the spindle is smaller than 1 \( \mu m \). The dynamometer Kistler 9257B is used for cutting force measurements. Work material and the drill used
are the same as that for FEM simulations. The machine tool and the experiment set up is shown in figure 4. The antirust oil based cutting fluid HYQ-507 is used for the micro drilling.

3.2. The MUCT Analyses
Experimental micro drilling parameters remain the same as that for FEM simulations in order to make comparisons. Three holes are drilled for each feed parameter and totally 24 holes are drilled. Micro drilling forces are collected and averaged for each feed when micro drilling is at the steady state. They are used for the judgment of the MUCT.

According to the collected force data, we found that axial forces are rather larger than other force components in micro drilling. Therefore, axial force \( F_z \) is processed for the analyses as shown in figure 5.

![Figure 4. Machine tool 3A-S100 and the experiment setup](image)

![Figure 5. \( F_z \) vs. \( f \) by experiments](image)

![Figure 6. Burr width measurements](image)

From figure 5, the axial cutting force \( F_z \) descends first from 13.49 N to 12.82 N and ascends then from 12.82 N to 22.01 N when the feed \( f \) varies from 0.5 \( \mu m/z \) to 4.0 \( \mu m/z \). The inflection point is located at the feed value of 1.0 \( \mu m/z \). Even though the force values are different, but the tendency and inflection point are in good accordance with that analyzed from FEM simulations. Therefore, the critical feed \( f \) for the MUCT is 1.0 \( \mu m/z \).

3.3. Burrs at the Hole Entrance
Furthermore, burrs are analyzed as shown in figure 6 based on scanning electron microscope (SEM) measurements. Figure 6 shows the variation tendency of the averaged maximum width of burrs of each experiment with the variation of the feed \( f \).

From figure 5 and figure 6, burr width varies from 10.34 \( \mu m \) to 53.38 \( \mu m \). Burr width reaches the largest value 53.38 \( \mu m \) when the UCT is smaller than the MUCT and reaches the smallest value of 10.34 \( \mu m \) when the feed \( f \) is 2.5 \( \mu m/z \).
3.4. Discussion
According to FEM and experimental analyses, the MUCT is 0.86 μm and the ratio of MUCT to the cutting edge radius is 0.17 for micro drilling of copper C26000. Microcutting mechanisms have been conducted for the similar material and the MUCT has been identified in literatures. In literature [10], the ratio of MUCT to the cutting edge radius is 0.25 for micromilling of copper OFHC based on FEM and experimental studies. In literature [11], the ratio of MUCT to the cutting edge radius is 0.2 for micro shaping of copper OFHC based on mathematical and experimental studies. By comparisons of these results, it can be seen that the ratio of MUCT to the cutting edge radius for high-speed mechanical micro drilling is smaller than that for conventional microcutting processes. It means that smaller microcutting parameters could be used in high-speed micro drilling than other conventional microcutting processes. Consequently, it is feasible for high-speed micro drilling of small holes by micro drills with low stiffness since the cutting forces are smaller under those cutting conditions.

![Figure 7. Burrs measured by SEM](image)

4. Optimization
4.1. Experimental Planning
Micro drilling parameters, experimental levels, and parameter values are selected for the optimization experiments. Based on the Taguchi method, the L₁₆ data sheet has been selected and totally 16 experiments have been performed.

4.2. Cutting Force
Figure 8 summarized the axial forces for a direct view. The maximum axial force is 23.48 N when the spindle speed is 50000 min⁻¹ and the feed is 2 μm/z. The minimum axial force is 13.4 N when the spindle speed is 80000 min⁻¹ and the feed is 1 μm/z.
Feed \( f (\mu m/z) \)  

### From statistics, the range analyses of data from figure 8 are conducted, where \( K_i \) and \( k_i \) (\( i \) is the experimental level and \( i = 1, 2, 3, 4 \)) is the sum and the average of the surface roughness of the specific parameter of the \( i^{th} \) level, respectively. \( R \) is the range of the \( k_i \).

\[
R = \text{Max}\{ k_i \} - \text{Min}\{ k_i \}
\]

(2)

Where, Max is the maximum value, Min is the minimum value.

Preliminarily, from the \( R \) value of the range analyses, the spindle speed is more important on micro drilling forces than the axial feed. But the difference of the importance order between the spindle speed and the axial feed is small. This conclusion of importance order needs to be further evaluated by the variance analyses. The results are summarized in table 2, where \( SS \) is the error deviation square sum, \( df \) is the degree of freedom of the experiment, \( MS \) is the average deviation square sum, and \( F \) is the probability distribution.

| Parameter | \( SS \) | \( df \) | \( MS \) | \( F \) | Critical value | Significance |
|-----------|---------|---------|---------|------|---------------|--------------|
| \( n_1 \) | 64.8840 | 3       | 21.6280 | 339.5290 | \( F_{0.01}(3,9)=6.59 \) | ***          |
| \( f \)  | 29.0209 | 3       | 9.6736  | 151.8619 | \( F_{0.01}(3,9)=6.59 \) | ***          |

From statistics, the number of * achieved in table 2 shows the significance of the parameter on the cutting forces. It shows both the spindle speed and axial feed have the same big significance on cutting forces from the variance analyses. Considering the chatter caused by drilling forces and the low stiffness of micro drills, the axial force is the smaller the better. According to the range analyses, the variance analyses, and the axial force summarized in figure 8, the spindle speed \( n_1 \) of 80000 min\(^{-1}\) and the feed \( f \) of 1.0 \( \mu m/z \) are preliminarily selected as the optimal micro drilling parameter since the \( k \) value is the minimum with these parameters. Consequently, higher drilling quality and tool life could be realized.

#### 4.3. Burr Analyses

Burrs at the hole entrance are measured by SEM and analyzed since the burr removal is very difficult for small holes after drilling. The burr width is summarized in figure 9 for a direct view. The maximum burr width is 53.38 \( \mu m \) when the spindle speed is 80000 min\(^{-1}\) and the feed is 0.5 \( \mu m/z \). The minimum burr width is 14.19 \( \mu m \) when the spindle speed is 80000 min\(^{-1}\) and the feed is 2 \( \mu m/z \).

#### 4.4. Discussion

According to the combined consideration of axial forces and the burr width, the finally optimal micro drilling parameters are that the spindle speed is 80000 min\(^{-1}\) and the feed is 2 \( \mu m/z \). The reason for the final selected optimal parameters is that, using these parameters, the burr width is the minimum and
the axial force has an increasement of 8.9 N, which has limited effects on the drill with the diameter of 1 mm. But it should be kept in mind that the axial force must be considered at the first place for the optimum drilling parameters if the drill size is much smaller.

According to Eq. (3), the MRR is calculated.

\[
MRR = \frac{2\pi D_t^2 f n_t}{4}
\]  (3)

The optimal parameters can realize a MRR of 125.7 mm³/min for high-speed mechanical micro drilling of small holes on copper C26000. This MRR is far larger than that of unconventional micro hole drilling processes as summarized in [12]. The same sized small holes were drilled in literature [13], where the hole diameter is 1 mm, work material is stainless steel 316L, and the cutting speed is 0.17 m/s. The MRR is 100.8 mm³/min by optimized micro drilling parameters in literature [13]. The comparison shows that the MRR is 25% higher by high-speed micro drilling than that by conventional micro drilling.

5. Conclusions
High-speed micro drilling process has been studied by FEM simulations and experiments. Results from both FEM and experimental analyses show that the ratio of the MUCT to the cutting edge radius is smaller by high-speed micro drilling than that by other microcutting processes. It means that smaller microcutting parameters could be used in high-speed micro drilling than other conventional microcutting processes. Burr width at the hole entrance reaches the maximum value when the UCT is smaller than the MUCT. Therefore, high-speed micro drilling parameters should be selected to assure the UCT is equal to or larger than the critical value. The optimized high-speed micro drilling parameters have 25% increasement of MRR compared with conventional micro drilling processes. It means that high-speed mechanical micro drilling would be a promising process for small hole fabrications.

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