Fabrication of circular end micro slots using micro ball-end milling

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Abstract. Circular end slots are extensively utilized in micro-fluidics due to its improved hydraulic and thermal performance. Present work targets the efficient fabrication of circular end slots on copper by micro ball-end milling. However, due to its complex cutting mechanism, size effect and tool tip rubbing effect its process parameters and their effects on cutting forces, surface roughness and profile accuracy with single and multi pass are to be investigated. Present work suggests proper parametric combination for the minimization of cutting force and surface roughness. Profile accuracy is also verified by measuring the dimensions of the machined micro slots and found to be in good agreement.

1. Introduction

The new era of advancement in the miniaturization technology, emphasizes the fabrication of complex micro-features on different range of materials. It creates huge attention to the research society, especially in the field of product development as miniaturization, can substantially improve the functional performances and contributes to the industrial economic growth [1]. Some of the specific applications of these micro-features products are in the field of micro-fluidics, micro reactors, aerospace, electronics, integrated chips (IC) cooling, lab-on-chip, biomedical, tribology and many others [1-4]. Micro slot is one the important micro-features which can be highly utilized in the field of micro-fluidics and heat transfer application [3-5]. Its different shape, size, aspect ratio and surface roughness significantly affect the functional performance of the device [5]. Circular end micro slot is one of them which provide edge free surface, better hydraulic and thermal performances of the micro-fluidic devices [6, 7]. Zhang et al. [8] found that circular end channel has better cooling performance and highest pressure drop compared with rectangular channel for similar flow rate and cross-sectional area, while, performance of trapezoidal channel is the best compared to circular end and rectangular channel. Kayansayan et al. [9] found that heat transfer rate of the impingement surface improved by providing the concave curvature compared to flat surface.

Due to several advantages and applicability of circular end micro slot, it attracts the research community for development of efficient fabrication technology for such applications. The earlier and most popular fabrication approach for such micro-features are mostly limited to unconventional processes like; focused ion beam (FIB) process, laser process, isotropic wet etching, soft lithography, etc [1-2, 4, 10]. Even though laser is a faster approach, it is limited by the surface profile control and
heat affected zone, while, other processes are most accurate but limited to the low material removal rate (MRR), higher processing time and initial cost [1-2, 11-14]. Therefore, to satisfy the growing market need it requires an efficient fabrication approach which is the trade off between the limitations of MRR and precise profile control. Here the traditional micro-tool based approach which has the advantage of higher MRR, applicability of wide range of materials, a lot of choice for tool geometry, and reasonably good in dimensional accuracy, etc., comes into picture [1-2, 14]. However, due to miniaturization of tool and size-effect, it is necessary to select the proper combination of process parameters, which can significantly reduce the cutting forces, improve the tool life as well as improve the surface quality by reducing the surface roughness [15-17]. It will also help to achieve the desired profile accuracy by reducing the progressive tool wear and premature tool failure.

Circular end micro slots can be efficiently fabricated by micro ball-end milling due to its unique hemispherical end geometry. However, its complex cutting mechanism and size effect require better understanding for the selection of proper process parameters [15-18]. Addition to size effect, micro ball-end milling having issues of tool tip rubbing due to variable cutting speed (V) along the hemispherical portion of the cutting edge and profile variation with the change in axial depth of cut (a_d) up to the tool radius [13, 19]. Even for any small discrepancy in the flatness of the workpiece, it can affect the profile [20]. This phenomenon is schematically represented by figure 1, where the tool tip rubs the workpiece due to zero velocity at tool tip and slot width (W) variation occurs due to change in axial depth of cut. However, by increasing the axial depth of cut and spindle speed one can reduce the effect of rubbing zone up to some extent. The rubbing phenomenon can be also avoided by inclining the cutting tool, but it will affect the shape and aspect ratio of the circular end slot [20]. Berestovskyi et al. [13] investigated the flute length effect and showed vertical and taper wall along with circular end of the machined surface. Chen et al. [21] observed that the top burr reduced with the selection of ball-end tool which is helpful in reducing the leakage problem in the micro-fluidic devices.

**Figure 1.** Schematic representation of variation in cutting velocity (V) and slot width (W) in micro slot milling by micro ball-end milling

Based on the earlier discussed literature, micro ball-end mill is identified as the strong contender for fabrication of circular end micro slots with burr free and smooth surfaces precisely. However, very few work was reported for the fabrication of micro-slots by micro ball-end milling and mostly limited to steel and titanium based alloys. Further, the proper selection of process parameters depends upon the material as well as the tool type. Therefore, the present work experimentally investigates the effects of process parameters on machining performance (cutting force, surface roughness and profile accuracy with single and multi pass) for the efficient fabrication of circular end micro slots on copper which is extensively utilized in micro-fluidic and electronics cooling. Finally, suitable combination of process parameters has been suggested for the fabrication of circular end micro slots by considering the minimum cutting forces and surface roughness for improvement of the performance of the micro-fluidic devices.
2. Materials and experimental methodology

The proposed experimental work of circular end micro slot milling was performed on the copper workpiece by micro ball-end milling. Prior to the experiment, copper workpiece of dimensions 50 mm × 50 mm × 3 mm were prepared from commercially available copper plate using wire electric discharge machining. After that sample preparation, workpiece was polished with emery paper and further cleaned with acetone solution under ultrasonic environment. Prepared sample was then fixed on the top of mini dynamometer (Type 9256C2, Kistler) which was further clamped on the bed of 3-axis hybrid micromachining centre (Mikrotechnik DT110, Mikrotechnik Pte. Ltd., Singapore). Motion of all the three axes were precisely controlled by its PMAC (Programmable multi axis controller) with the positional accuracy of ± 1 µm. Before the start of experiment, workpiece flatness error was checked with contact probe of micromachining centre and compensated by the facing operation to improve the dimensional accuracy of the generated micro-features. All the experiments were performed on hybrid micromachining centre using air driven high speed spindle which can rotate up to 60000 rpm with maximum tool run out of 2 µm. The utilized experimental setup for circular end micro slot fabrication is shown in figure 2.

![Figure 2. Hybrid micromachining centre (Mikrotechnik DT110) set up for micro slot milling](image)

Fresh two fluted tungsten carbide micro ball-end mill of size 500 µm in diameter and cutting edge radius of 2 µm were utilized for the circular end micro slot milling on copper under different set of experiments as shown in table 1.

| Machining parameters | Unit     | Values      |
|----------------------|----------|-------------|
| Spindle speed or cutting speed (N) | rpm      | 10000, 20000, 30000, 40000 |
| Feed per tooth (f<sub>t</sub>) | µm/tooth | 0.5, 1.0, 1.5, 2.0 |
| Axial depth of cut (a<sub>d</sub>) | µm/pass  | 50          |

All the experiments were repeated thrice to check the repeatability of the measured value and average value were reported. For the present work, cutting force and surface roughness were measured with the variation of machining parameters (spindle speed, feed per tooth) while axial depth of cut was kept constant as 50 µm/pass. Cutting force signals were acquired with the help of data acquisition (Kistler DAQ) system at a sampling rate of 50,000 Hz and root mean square (RMS) value was utilized for the further data analysis. Average surface roughness (R<sub>a</sub>) of the cleaned circular end micro slots was measured along the tool feeding direction using contact type surface profilometer (Mitutoyo, SJ-400) and average of three reading were reported for the analysis. Further, machined surface profile variations and slot width on top surface with change in axial depth of cut for single pass and multi pass was observed with the help of Olympus auto focusing microscope.
3. Experimental results and analysis

3.1. Investigation of cutting force ($F_x$, $F_y$ and $F_z$) and average surface roughness ($R_a$) along slot base

The root mean square (RMS) of the measured cutting forces along X, Y and Z directions and the average surface roughness along the slot base with three repetitions were measured and average of three reading was utilized for the further analysis. The variation in cutting forces along three perpendicular directions and average surface roughness along micro slot based with the variation in process parameters for single pass experiment is shown in the figure 3 (a-d).

From figure 3 (a and b), it is observed that cutting forces in tangential (X - direction) and feed direction (Y - direction) initially decreases with the increase in feed rate from 0.5 µm/tooth to 1.0 µm/tooth for all the cutting speeds. Further, with increase in feed rate, cutting forces start to increase and follow the same trend for all the cutting speeds. This frequent change in nature of cutting forces from low feed rate (0.5 µm/tooth) to high feed rate (2.0 µm/tooth) shows the similar effect to that of minimum chip thickness below which cutting force increases significantly and the value of the minimum chip thickness lies between somewhere 0.5 µm/tooth to 1.0 µm/tooth. Its range is similar to that of the micro flat-end milling of OFHC copper reported by Lai et. al. [22]. Once the undeformed chip thickness or the feed value crosses the transition of minimum chip thickness, the cutting forces is directly proportional to the effective chip area ($a_d \times f_t$). In the present investigation the axial depth of cut ($a_d$) is constant and therefore the change in cutting force only depends upon the feed per tooth. One more important observation with the cutting force variation is the significant value of the thrust force (force in Z - direction) as shown in figure 3 (c), which is generally not observed in case of micro flat-end milling. It is mainly due to the rubbing of ball-end tip with the workpiece along the slot base. However, the rubbing effect is mainly significant for low axial depth of cut and low cutting speed due to the considerable zone of rubbing compared with shearing [20]. Here, the axial...
depth of cut \( (d = 50 \, \mu m/\text{pass}) \) is constant and considerably high to minimize the rubbing effect. It is also observed from figure 3 (c) that thrust force considerably increased with increase in feed rate at lower cutting speed \( (N = 10000 \, \text{rpm}) \) due to tool tip rubbing, whereas, at higher cutting speed \( (N \geq 20000 \, \text{rpm}) \) it is almost independent from feed rate as it minimizes the rubbing zone. However, with increase in cutting speed from \( N = 10000 \, \text{rpm} \) to 40000 rpm the thrust force as well as tangential and feed force significantly decreases for constant chip load or feed value as shown in figure 3 (a-c), which significantly increases the MRR and thus improves the productivity of the fabrication process.

Average surface roughness \( (R_a) \) also shows the similar nature to that of cutting forces in tangential and feed direction and influenced by minimum chip thickness phenomenon. From figure 3 (d), minimum surface roughness is found at cutting speed of 40000 rpm and feed rate of 1.0 \( \mu m/\text{tooth} \) which is the transition range for switching the ploughing dominant zone to shearing zone. Here, the cutting forces in tangential and feed direction as well as average surface roughness of the slot base display the same trend and all of them are affected by minimum chip thickness, whereas, cutting forces in thrust direction follows the linear relation with feed rate at low speed as shown in Fig. 3. Despite of slightly conflicting nature of the observed performance variables within transition limit, minimum values of all the process responses are observed at cutting speed \( (N) \) of 40000 rpm and feed rate of 1.0 \( \mu m/\text{tooth} \).

3.2. Variation in surface profile for single pass and multi pass circular micro slot milling

Variation in machined surface profiles for single and multi pass (2 pass) experiment was also analyzed by measuring the slot width at top surface and the depth of the micro slots. Its variation in surface profile along with the measured dimensions for single pass and multi pass (2 pass) experiments with 50 \( \mu m/\text{pass} \) axial depth of cut is shown in figure 4.

From figure 4, it is observed that slot width at top surface increases with the increase in number of passes or depth of slot due to the hemispherical shape of the micro ball-end mill. The targeted value of slot width and height for single pass is 300 \( \mu m \) and 50 \( \mu m \) whereas, for multi pass (2 pass) it is 400 \( \mu m \) and 100 \( \mu m \) respectively. It is observed that micro slot dimensions are closer to the targeted values. However, once the slot depth approaches to the tool radius it produces straight walls with slot width of equal to the tool diameter as shown by the schematic representation in figure 1. Similar observations were also reported by the Berestovskyi et al. [13].

4. Conclusions

The present work emphasized the advantage of hemispherical end micro-tool popularly known as micro ball-end mill for the efficient fabrication of circular end micro slots on copper for the micro-fluidics and thermal application. Effect of process parameters on machining performances (cutting forces, surface roughness and profile accuracy with single pass and multi pass) are experimentally investigated. Based on the experimental observations, proper combinations of the process parameters
has been suggested for machining of circular end micro slots on copper by consideration of minimum cutting forces and reduced surface roughness. Based on the experimentally observed results critical findings are pointed below:

- The present article provides the efficient way for the fabrication of circular end micro slots by utilizing the advantage of hemispherical end geometry of the micro ball-end milling.
- Effect of minimum chip thickness and tool tip rubbing effect on the performance characteristics of micro ball-end milling process is described with the help of variation of process parameters. It was found that minimum chip thickness is mainly influenced by feed rate whereas; tool tip rubbing is the combined effect of cutting speed and axial depth of cut.
- Minimum value of cutting forces in all the three perpendicular directions as well as lower average surface roughness is found nearer to the transition region for the maximum value of cutting speed. Its values are cutting speed (N) of 40000 rpm and feed rate of 1.0 μm/tooth, where the cutting phenomenon switch from ploughing dominant region to shearing zone.
- Micro slots top width increases with increase in axial depth of cut or number of passes. Once the slot depth approaches to tool radius it produces straight walls with circular end slots having top width equals to tool diameter.
- For multi pass experiments the net machining area will also changes until the slot depth approaches tool radius due to variation in top width with axial depth and thus also affects the cutting force and surface roughness.
- Micro slot dimensions clearly indicated that, micro ball-end milling is capable to produce precise micro-features.

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