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Investigation into the surface finish produced in micro ball-end milling

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Abstract

Production of high quality surface is one of the prime concerns in any machining process. The process of finishing the surface is the most challenging job especially in micro cutting. The mechanism of material removal in the range of microns is entirely different from macro level and this directly influences the quality of created surface. The process of micro ball-end milling is one of the feasible processes in this regard because it always considered as a finishing process. An experimental investigation on the assessment of finish of micro ball-end milled surface is conducted and presented in this work. Micro ball-end milling experiments are performed on inclined ductile steel workpiece surface using a 0.4 mm diameter carbide tool at wide range of spindle speed (20000–40000 rpm), feed (0.4 to 2.4 μm/tooth) and a constant axial immersion angle (10–40° from the tool axis). The finish of machined surfaces has been assessed using highly precise contact type surface profilometer. Significant influence of size effect is observed at cutting conditions with feed (0.4 μm/tooth) which is below the magnitude of cutting edge radius. A minimum roughness (Ra) value of 52.49 nm was obtained at a cutting parameter combination of 30000 rpm speed, 2.4 μm/tooth feed and 10-40° axial immersion angle. As per authors' best knowledge, possibly this may be the lowest roughness value reported so far in micro ball-end milling of ductile material.

Keywords: Micro ball-end milling, Workpiece inclination, Measurement, Surface roughness, Size effect.

1. INTRODUCTION

Micromachining is a process of producing components with features having at least one dimension in the range of 1 to 500 micrometers. Increasing demand for miniaturized products gives popularity to micro machining process. Micromachining is being widely applied in various fields like micro fluidics, Micro Electromechanical Systems (MEMS), nanotechnology, and in optical, mechanical, electrical, medical etc. [1]. Tool based micro manufacturing systems are widely used for making precise and complex geometries. Micro ball end milling is a tool based process, which is highly potential for competitive micro machining. It is widely used in the industries because of the ease in making complex geometries with complicated contours, better surface finish and having capability to machine materials that are difficult-to-machine by other processes. Recent literature indicates that ball end milling process has the ability to produce good finish with low tool wear [2]. The main difference of micro ball end mill cutter compared to normal end milling process is the varying cutting speed along the cutting edges.

One of the basic differences between micro and macro milling is the involvement of edge radius in cutting. Feed in combination with cutting edge radius decides the mechanism of material removal in micro milling and finish of the product [3]. The cutting mechanism changes from shearing to ploughing when the uncut chip thickness is closer to or lower than the value of cutting edge radius. At lower feed rate conditions the ploughing and elastic recovery are predominant in machining ductile material and it cause poor surface finish in case of micro ball end milling [4]. The thickness of chip at edge engagement and disengagement regions are very small, the mechanism of material removal changes to ploughing in the presence of edge radius. Change in the edge form during machining is another issue in micro cutting. Increase in edge radius due to wear, further causes ploughing dominant cutting [3]. This is also considered to be responsible for poor surface finish in micro milling. On the other hand, machining of brittle material with a very low uncut chip thickness produces better surface due to brittle to ductile transition [5].

The radius of cutting element with reference to cutter axis varies from zero to ball end mill radius. This ultimately causes variation of cutting speeds along the axis of tool. Involvement of low velocity bottom tip region in cutting induces rubbing effect. This results in poor surface quality due to the unfavourable sliding action [5]. In order to avoid the bottom tip rubbing effect, ball end mills are generally employed with CNC machines having more than 3 degree of freedom.

In ball end milling, a significant effect of surface inclination angle on surface roughness is observed when it is below 10° [3]. The best surface finish (~ 30 nm) is found at a surface inclination of 45° while machining of brittle material with a nano level feed of 33 nm/rev [5]. An average surface roughness of 60 nm is obtained in hybrid micro ball end milling (laser assisted) of hardened A2 tool steel [6]. Other than these, average roughness values of 150-200 nm in hardened steel [7], 270-710 nm in Al7075 [8], 100-390 in NiTi alloy, stainless steel 304 and 316L with coated and uncoated tool [9], 400–1300 nm in hardened steel with a feed range of 2–40 μm/tooth [10] and area roughness of 150-200 nm in brass machining [11] are observed.

Machining of precise and high quality channels is very much essential for micro fluidic applications. Micro end milling is considered to be a key method to produce channels for these applications. This leads to the requirement of in-depth study on the surface created by micro end milling. This work is an attempt to study the effect of cutting parameters such as speed and feed on roughness of the surface created by micro ball-end milling.

2. EXPERIMENTAL PLAN

Machining parameters for the present experimental study are selected by considering the machine capability and cutting edge radius value. The experiments are conducted with three different spindle speeds (20000, 30000 and 40000 rpm) and

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feeds (0.4, 1.4 and 2.4 µm/tooth) at a constant axial immersion angle limits of (κ_l = 10^o and κ_u = 40^o). Upper and lower axial immersion angle limits are selected to create slot with enough width for roughness measurement and to exclude burr region in the measurement. Out of these feed values, the lowest one (0.4 µm/tooth) is comparable to the cutting edge radius value of 0.48 measured by following the procedure presented in Baburaj et al. [12]. Experiments are conducted on high speed high precision 5-axis micro machining centre.

Micro slots are machined on a precisely oriented rectangular workpiece to engage the selected cutting edge region. This facilitates alignment of workpiece during roughness measurement. The workpiece-dynamometer assembly is tilted by an angle of α_{si} = 25^o in clockwise direction about Y_m axis as shown in Fig. 1 with a precision of <5″. Infrared touch probe with 0.1 µm positional accuracy is used to set datum for inclined surface machining. This is also verified by touching tool on to the workpiece surface by moving it by 0.1 µm steps and this is repeated before machining each slot. Scanning electron microscopic (SEM) image of micro ball end mill used for experiment and slot made at a spindle speed of 20000 rpm, feed of 1.4 µm/tooth and κ_l =10^o (3.04 µm) and κ_u =40^o (46.79 µm) are shown in Figs. 2 (a) and (b) respectively.

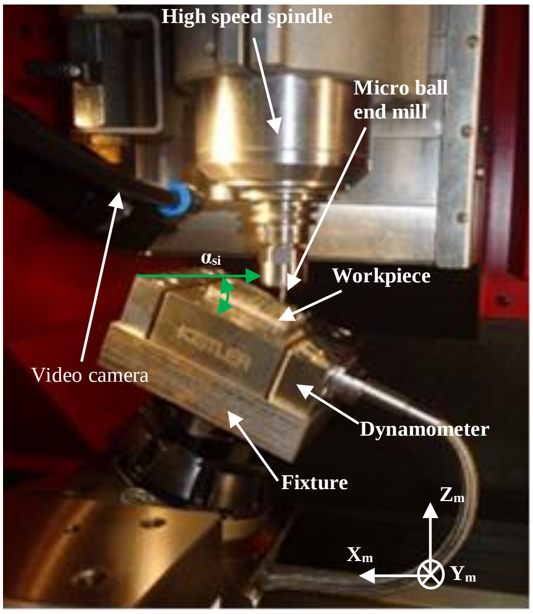
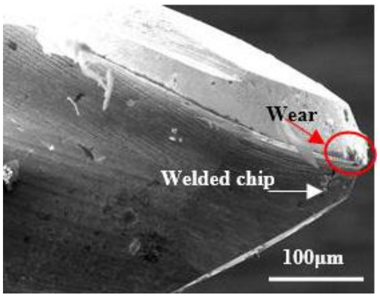
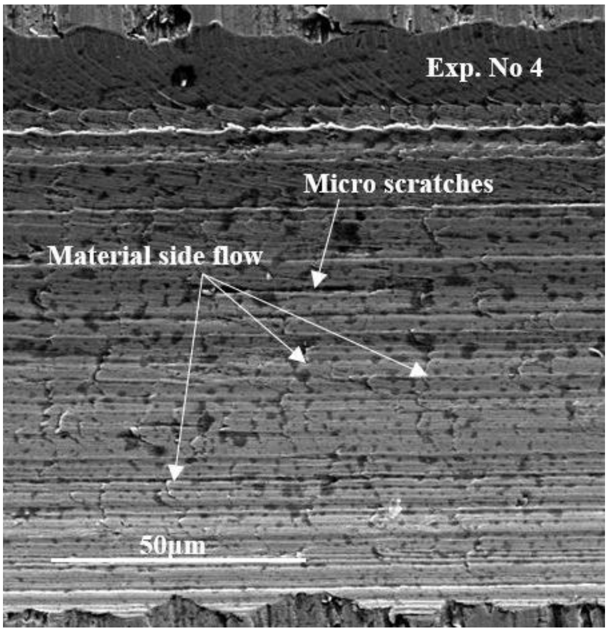


Fig. 1. Machining setup for roughness measurement

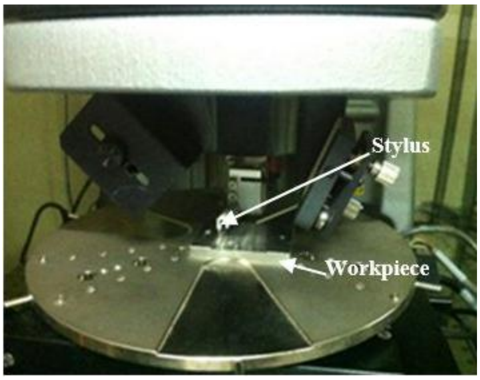
A total of nine slots are made on the inclined workpiece surface and the surface is cleaned prior to the roughness measurement. Surface undulations are traced corresponding to the bottom of groove using a contact type surface profiler (Dektak 150) with a 2.5 µm radius stylus. This measurement device has a stage resolution of 0.5 µm and 1 µm repeatability. The sample viewing system attached with this device is utilized to reduce alignment error between stylus-tip and groove-bottom. The setup used for measuring surface roughness is shown in Fig. 2 (c). Surface profiles are traced for a traversing length of 1750 µm with a cut off length of 250 µm.



(a) SEM image of ball end mill



(b) SEM image of the micro slot ball-end milled at 20000 rpm and 1.4 µm/tooth



(c) Roughness measurement setup

Fig. 2. Assessment of micro ball-end milled surface

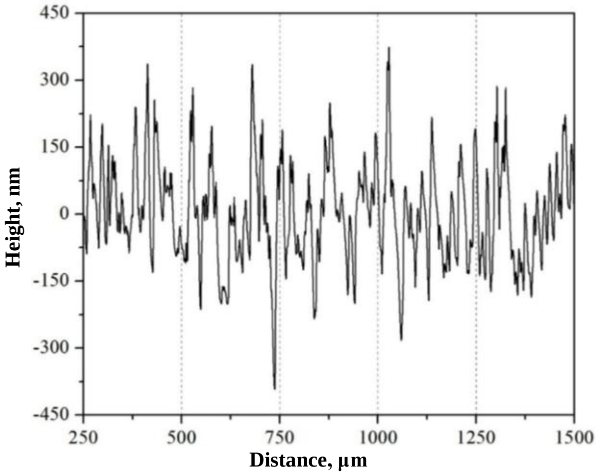
3. RESULTS AND DISCUSSIONS

Surface roughness is assessed in terms of average roughness (Ra) for all the machined grooves. It is observed that the value of roughness varies along the length of the groove. Surface roughness is measured at three different places on the groove and average value is reported as surface roughness. This variation in roughness may be due to built-up edge and the chatter. Table 1 summarizes the average roughness obtained for all machining parameter combinations. The effect of feed and spindle speed on machining are studied from Table 1. Average surface roughness is found to be very high at the lowest feed rate (0.4 µm/tooth) condition compared to other two feeds. This is due to the size effect in micro cutting, the magnitude of feed in this condition is on the lower side of cutting edge radius. The cracked or disturbed chip segments with higher severity are observed in full slot micro ball end milling at 0.4 µm/tooth feed is a supporting evidence for significant size effect in machining. At very low feed cutting condition, machining with high negative effective rake angle due to size effect, effect of ploughing action, elastic recovery and other dynamic effects in machining also play an important role in roughness. At 1.4 and 2.4 µm/tooth feeds, the magnitudes of feed values are much higher than cutting edge radius. The measured roughness values at these two feeds are low because the mechanism of material removal changes to shearing dominant cutting.

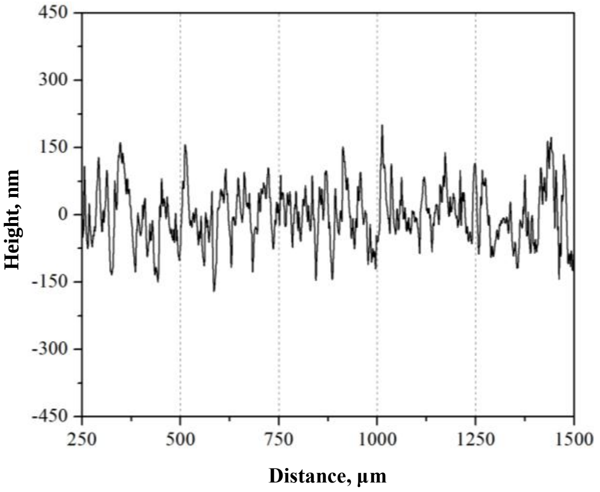
Table 1 Average surface roughness obtained from measurements

Sl. No.	Spindle speed, rpm	Feed, µm/tooth	Axial immersion limits, deg	Roughness (Ra), nm
1	20000	0.4	10–40	89.97
2	30000	0.4	10–40	164.54
3	40000	0.4	10–40	232.66
4	20000	1.4	10–40	60.07
5	30000	1.4	10–40	59.54
6	40000	1.4	10–40	67.85
7	20000	2.4	10–40	55.47
8	30000	2.4	10–40	52.49
9	40000	2.4	10–40	65.43

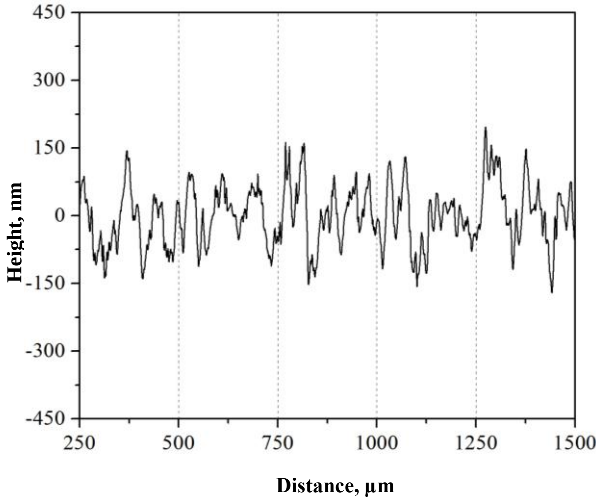
Three different speeds (20000, 30000 and 40000 rpm) are selected and the effect of feed on roughness is analyzed at each speed. A decreasing trend in roughness is observed (as in Table 1) with increase in feed for all spindle speeds (20000, 30000 and 40000 rpm). This is because of increase in uncut chip thickness with increasing feed rate. Very less variation in roughness is observed at a spindle speed of 40000 rpm and feeds of 1.4 and 2.4 µm/tooth. The unavoidable dynamic variation due to high spindle speed in machining with smaller tools is found to be the reason for this. Fig. 3 shows typical roughness patterns observed at three different feeds of 0.4, 1.4 and 2.4 µm/tooth, spindle speed of 20000 rpm and axial immersion limits of κ_l =10° and κ_u =40°. Fig. 3 (a) is the roughness profile corresponding to 0.4 µm/tooth feed and the profile is found to be erratic in nature. The presence of irregular peaks with high magnitude in the profile is evident for size effect in machining. The peaks in Fig. 3 (b) and (c) is observed to be almost uniform. The significant influence of material side flow on surface roughness is observed from the machined surface shown in Fig. 2 (b) and surface profiles shown in Fig. 3. The chip collected at this condition also analyzed under scanning electron microscope (SEM). The SEM images obtained at speed of 20000 rpm and feed of 1.4 µm/tooth are shown in Fig. 4. Fig. 4 (a) is showing the free side of chip and (b) is the zoomed view of the rake face side of chip. Sticking of material is observed on the back side of chip in Fig. 4 (b). This is possibly due to either side flow of material during machining or chip welding on to the rake face. This indicates the influence of friction and machining zone temperature in micro machining.



(a) Feed of 0.4 µm/tooth

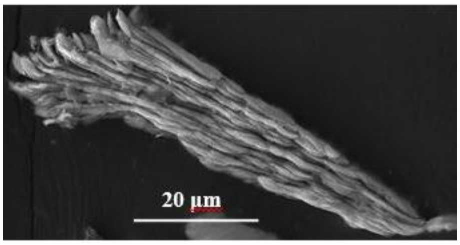


(b) Feed of 1.4 µm/tooth

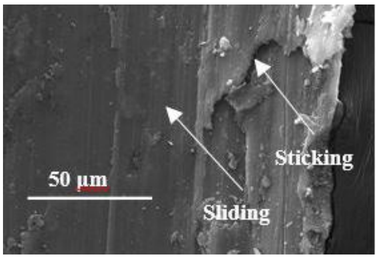


(c) Feed of 2.4 µm/tooth

Fig. 3. Surface profiles obtained at spindle speed of 20000 rpm and different feeds for constant axial immersion limits of κ_l = 10° and κ_u = 40°



(a) Free side of chip



(b) Rake face side of chip

Fig. 4. SEM image of chip formed at 20000 rpm speed and feed of 1.4 µm/tooth

Effect of spindle speed on roughness is also studied from the measured values presented in Table 1. For three different feeds (0.4, 1.4 and 2.4 µm/tooth) selected, the effect of speed on roughness is analyzed. An increase in surface roughness with increase in spindle speed is observed at 0.4 µm/tooth. Here thickness of chips is very low due to very low feed and the increase in spindle speed causes further reduction in chip thickness. This results in ploughing instead of shearing and the machined surface becomes rougher. In other feed conditions (1.4 and 2.4 µm/tooth), the roughness values are observed to be very low compared to that at 0.4 µm/tooth. Here most of the material removal is happening due to shearing action. No definitive trend in roughness with spindle speed is found at either of the feeds of 1.4 and 2.4 µm/tooth. There is not much variation observed when speed increases from 20000 to 30000 rpm at both 1.4 and 2.4 µm/tooth feeds. Roughness at highest spindle speed (40000 rpm) for all feed combinations are observed high due to unavoidable dynamic variations in milling with micron size end mills at high spindle rotation.

It is found from this study that spindle speed and feed combinations of (30000 rpm and 2.4 µm/tooth) and (20000 rpm and 2.4 µm/tooth) seem to be the best choices for machining high quality surfaces. The roughness values obtained at these cutting conditions are possibly the lowest ever reported in micro ball end milling of ductile materials.

7 CONCLUSIONS

Micro ball-end milling experiments are conducted by engaging the cutting edge segment bounded by an angle κ_l =10° and κ_u = 40° (measured from tool axis) on an inclined surface and the surface finish of the grooves is assessed using a highly precise contact type surface profiler.

Decreasing trend in roughness is observed with increasing feed for all the selected spindle speeds. Surface roughness at lowest feed (0.4 µm/ tooth) is found to be very high at all the selected spindle speeds. This indicates the significant influence of size effect in surface formation in micro cutting. It is also observed that there is an increasing trend in roughness with increasing spindle speeds at a feed of 0.4 µm/ tooth. No definitive trend in roughness with spindle speed is found at either of the feeds of 1.4 and 2.4 µm/tooth.

Surface roughness in the range of 50–70 nm is observed at higher feeds (1.4 and 2.4 µm/ tooth). Cutting parameter combinations of (30000 rpm and 2.4 µm/tooth) and (20000 rpm and 2.4 µm/tooth) are found to be the best choice within the selected range for good surface finish. The lowest roughness value of 52.49 nm is observed at a cutting parameter combination of 30000 rpm and 2.4 µm/tooth.

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