Investigation of Workpiece Surface Roughness when Micromilling Hardened AISI D2 Steel

J. B. Saedon[1,2]*, S. L. Soo[2], D. K. Aspinwall[2] and A. Barnacle[3]

[1]Faculty of Mechanical Engineering, Universiti Teknologi MARA, Malaysia
[2]Machining Research Group, School of Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham, UK
[3]MMC Hardmetal UK Ltd., Tamworth, UK
*E-Mail: jurisaedon41@salam.uitm.edu.my, juri41@yahoo.com

Summary: The paper details an experimental evaluation of workpiece surface roughness following slotting of hardened AISI D2 (~62HRC) high carbon, high chromium cold work tool steel (employed extensively in the mould and die industry) using 0.5mm diameter coated (TiAlN) tungsten carbide end mills. A full factorial experimental design was carried out to investigate the influence of variations in cutting speed, feed rate and depth of cut, each at 2 levels. Results were assessed using analysis of variance (ANOVA) while main effects plots and percentage contribution ratios (PCR) for the primary variable factors were calculated. The ANOVA suggested that cutting speed had the greatest influence on surface roughness (38% PCR) followed by feed rate and depth of cut at 24% and 18% respectively, all 3 parameters being statistically significant at the 5% level. Surface roughness (measured in the feed direction) was found to be a minimum when operating at 50 m/min cutting speed with a feed rate of 1 µm/tooth and depth of cut of 15 µm, and varied between 0.11 to ~0.15 µm Ra over a 520 mm cut length.

Keywords: Machinability, Micromachining, Steel, Surface Integrity

1. Introduction

Micromilling generally refers to the end milling process with cutters ≤ 1 mm diameter operating at high rotational speed ≥ 30,000 rpm. The basic kinematic movements such as rotation of the tool and translational feed motion through the workpiece are however similar to those in conventional milling. It is apparent from the literature that the current underlying science and technology of microscale mechanical machining has been derived from down-scaling of conventional macroscale metal cutting theory/practice. As the diameter of the tool is reduced however, the phenomenon of 'size effect' arises, which impacts on cutting forces, tool wear, and chip formation. Anticipated reasons for this are related to the ratio of undeformed chip thickness to the tool cutting edge radius [1-3], and the microstructure of the workpiece material with respect to cutting parameters and cutter dimensions [4]. The greater demand in recent years for miniaturised products have led to the increased use of micro high speed milling due to its advantages over MEMS technology. These include the ability to fabricate complex 3D structures, comparatively high material removal rates and the capability for machining a wide variety of conventional engineering materials.

Surface finish is a key consideration which can influence the functional properties of micro components, particularly for assembly operations involving mating or sliding faces. In microscale cutting, key factors that have been found to affect the machined surface roughness include minimum chip thickness value [5], tool cutting edge radius [6], workpiece material [4, 7] and operating feed rate [5]. The accumulation of plastically deformed material in the main ridges of the machined surface together with smearing of workpiece material behind the tool are common features and can lead to detrimental results, particularly at large ratios of tool edge radius to undeformed chip thickness [8]. Wang et al. [9] employed statistical experimental techniques (full factorial design) to examine the effect of tool diameter (0.2 – 1.0 mm), spindle speed (60000 – 80000 rpm), depth of cut (10 – 40 µm) and feed rate (12 – 48 mm/min) on surface roughness in micromilling of brass. Tool diameter was found to be the most significant factor affecting surface roughness in micromilling due to stiffness considerations. Similarly, use of neural networks and Taguchi fractional factorial methods to study the effects of spindle speed (30000 – 50000 rpm), feed rate (10 – 50 mm/min) and axial depth of cut (10 – 30 µm) on surface roughness, has been reported [10]. Here, the results suggest that surface roughness decreased with higher spindle speed but increased with larger magnitudes of feed rate and depth of cut.

2. Experimental procedure and equipment

All trials were performed on a commercial 3-axis, linear motor, ultra high speed machining centre having a maximum spindle velocity of 60k rpm and corresponding torque of 0.7 Nm at a power rating of 4.5 kW. Micro tools utilised were 4-flute TiAlN coated ∅0.5 mm square edged carbide end mills, with a cutting length of 1.0 mm, helix angle of 30° and 6 mm shank diameter. These were held via shrink fit tool holders with a 20 mm overhang while tool setting was achieved using a laser measurement system with a repeatable accuracy of ±0.15 µm. The cutting edge radius was between 5 - 7 µm and was measured using an Alicona Infinite Focus Microscope (IFM) unit. In order to avoid quality variations, all end mills were sourced from the same production batch with scanning electron microscope (SEM) images taken prior to and after machining. The associated rake and clearance angles were 0° and 12° respectively, see Figure 1.

The workpiece material was hardened AISI D2 tool steel having a chemical composition of: 1.5% C; 11.5% Cr; 0.8% V; 0.75%Mo and the remainder Fe [11]. Sample blocks with nominal bulk hardness of 62±1 HRC were cut into dimensions of 20 x 20 x 90 mm (W×H×L) for testing. Surfaces of the specimens were ground to achieve squareness and then subsequently face milled in order to ensure flatness and provide a machining datum. An appropriate spindle warm-up cycle was initiated before test commencement to minimise/eliminate effects from spindle thermal growth.

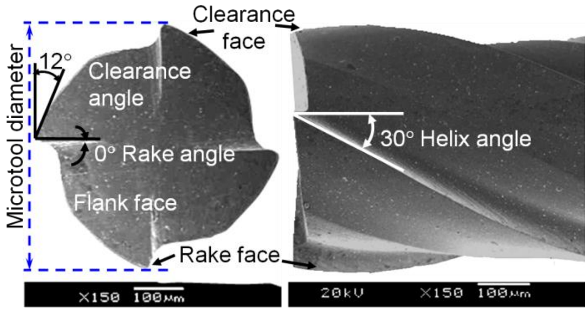

Figure 1. SEM micrograph of a new micro end mill.

As no international standards currently exist relating to testing with microscale tools, a set of preliminary slotting trials were performed over a range of operating parameters to the point of tool failure/fracture in order to determine a suitable end of test criterion. Following on from this, mainstream experiments involving a full factorial experimental design were performed, see Table 1. Both 2D and 3D surface roughness evaluation of the base of the micro slots was undertaken using a Form Talysurf 120L system with a vertical resolution of 10 nm, a stylus angle of 60° and tip radius of 2 µm. For 2D line measurements, a 0.8 mm cut-off and 4 mm sample evaluation length was used with each slot measured at 3 locations (the middle and opposite ends of the slot) along the centreline and averaged. In terms of 3D topographical plots, a 0.25 x 0.25 mm^2 sampling area was specified in the vicinity of the slot centre with the data analysed using appropriate software.

Table 1. Mainstream full factorial experimental array.

Test No.	Cutting speed (A) (m/min)	Feed rate (B) (µm/tooth)	Depth of cut (C) (µm)
1	20	1	15
2	50	1	15
3	20	2	15
4	50	2	15
5	20	1	55
6	50	1	55
7	20	2	55
8	50	2	55

3. Results and discussion

3.1. Preliminary testing

Figure 2 shows the typical progression of slot surfaces with cut length over the range of operating parameters employed. When utilising a new tool, surface roughness of the slot bottom was ~0.2 µm Ra, with no obvious/major signs of flaws or surface defects, see Figure 2(a). The characteristic 'wavefront' shaped feed marks were evident and continued up to a cut length of 520 mm; see Figure 2(b). The surface topography of the slots however deteriorated/became irregular as tool wear increased with machined distance. This was highlighted by workpiece smearing and rounding of the slot corner as shown in Figures 2(c) and 2(d). Although not shown here, corresponding microtool analysis showed severe dulling of cutting edges and material adhesion, which would have exacerbated transfer/re-deposition onto slot surfaces. The 3D topographical map of slot surfaces machined with a new and worn tool detailed in Figure 3 further demonstrates the change in surface roughness with respect to cut length. Based on these initial results, an end of test criterion of 520 mm machined length (equivalent to 26 slots) was specified for the mainstream trials and subsequent statistical analysis.

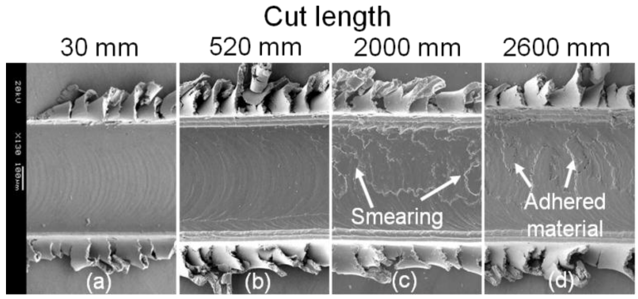

Figure 2. Typical slot surface roughness progression.

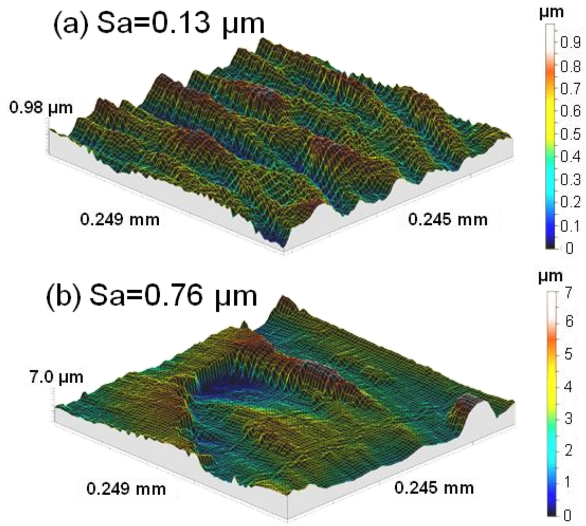

Figure 3. 3D topography plots of surfaces produced using; (a) new, (b) worn tools (2600 mm cut length).

3.2. Mainstream experiments

Workpiece surface roughness ranged between 0.15 and 0.32 µm Ra after 26 slots in each of the trials performed. Test 2 exhibited the lowest surface roughness amongst all the tests while the highest value was obtained in Test 7. Despite utilising higher cutting parameters in Test 8 (resulting in greater tool wear levels), the surface roughness (Ra=0.23 µm) was lower compared to Test 7, which suggests that tool wear was not the only factor determining slot surface roughness. A possible explanation for this observation was the formation of built up edge (BUE)/adhered material being more prevalent at low cutting speeds, which influenced the effective tool geometry and reduced edge sharpness; see Figure 4. While the use of cutting fluid/lubrication would have reduced the incidence of BUE formation, this could also have resulted in thermal shock or possibly cutter vibration/chatter and hence lower tool life.

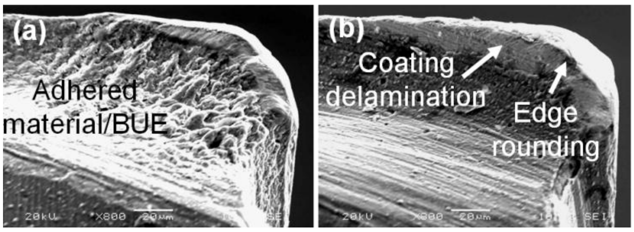

Figure 4. Condition of tools used in; (a) Test 7, (b) Test 8.

The main effects plot for mean surface roughness together with the corresponding ANOVA calculations are detailed in Figure 5 and Table 2 respectively. The former suggests that minimum surface roughness would be obtained by employing high cutting speed (50 m/min) and both low feed rate (1 µm/tooth) and depth of cut (15 µm). Accordingly, the latter revealed that all 3 factors had a statistically significant effect on Ra with cutting speed having the largest influence (38% PCR) followed by feed rate (24%) and depth of cut (18%). Similar observations were reported when micromilling copper and H13 tool steel [3, 12], where surface roughness generally increased with feed rate. In terms of factor interactions however, only feed per tooth x depth of cut (BC) was significant at the 5% level with a contribution of 14%, although cutting speed x feed per tooth (AB) demonstrated a PCR of 5%.

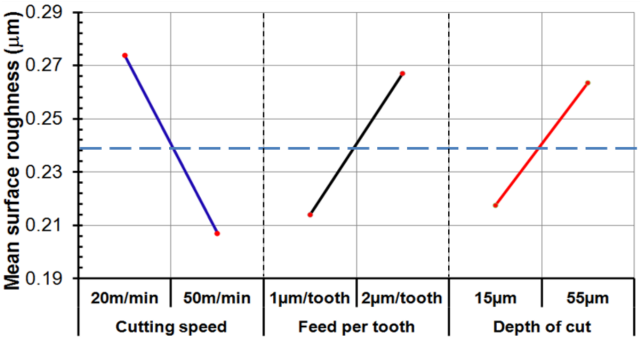

Figure 5. Main effects plot for mean surface roughness.

Table 2. ANOVA results for surface roughness.

Source	Sum of Squares	DF	Mean Square	F-Value	Prob>F	% PCR
A	0.00896	1	0.00896	71716.8	0.002*	38%
B	0.00565	1	0.00565	45198.7	0.003*	24%
C	0.00426	1	0.00426	34077.1	0.003*	18%
AB	0.00117	1	0.00117	9370.2	0.006	5%
AC	1.25E^{-05}	1	1.25E^{-05}	100.0	0.063	0
BC	0.00331	1	0.00331	26503.8	0.003*	14%
Res.	1.25E^{-07}	1	1.25E^{-07}			
Total	0.02337	7		***Significant at the 5% level**		
Std. Dev.	0.00035		R-Squared		0.999995	
Mean	0.2405		Adjusted R-Squared		0.999963	

Cutting speed (A), Feed per tooth (B), Depth of cut (C)

4. Conclusion

Preliminary testing highlighted a decline in surface quality when cut length exceeded ~500 mm. Results from mainstream experiments showed that all 3 variable factors had a statistically significant effect (at the 5% level) on workpiece Ra, with cutting speed exhibiting the largest influence with a PCR of 38%, followed by feed rate (24%) and depth of cut (18%). It was further observed that the interaction between feed rate and depth of cut exhibited a significant PCR of 14%. Although slot Ra was relatively low even after 520 mm cut length (< 0.4 µm), significant burr formation was observed in all trials (average widths of up to ~ 220 µm), particularly at the top of the side walls. Apart from abrasive tool wear, the deterioration of slot surface finish and geometrical accuracy with increasing cut length can be attributed to high levels of adhered material/workpiece re-deposition, fracture of cutting edges and possible deflection of the micro end mills during machining.

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