Int J Adv Manuf Technol (2013) 69:771–776
DOI 10.1007/s00170-013-5079-6

ORIGINAL ARTICLE

Assessment of tool rake surface structure geometry for enhanced contact phenomena

Anis Fatima · Paul T. Mativenga

Received: 7 February 2013 / Accepted: 17 May 2013 / Published online: 29 May 2013

Abstract The tribological conditions for mating surfaces can be improved by surface structuring. For tool rake faces, this can lead to reduced frictional forces. This work suggests a new approach and contributes to the assessment of geometric parameters and location of rake face surface structures. A femto-second laser was used to machine structures to a Taguchi experimental design inspired by contact length modelling. Cutting tests were done to assess feature dimensions/location from the cutting edge. This paper makes a significant contribution to the fundamental design principles for location of rake face structures and their impact on contact phenomena.

Keywords Carbide · Design optimisation · Surface structuring

1 Introduction

Surface structuring can be a novel strategy for improving the tribological conditions of interfacing surfaces. The terminology *structuring* is preferred here in contrast to *textured surfaces* because, as defined by Evans and Bryan [1], *structured surfaces* have a deterministic pattern of usually high aspect ratio geometric features designed to give specific function, while *texture* has a standardised meaning for surface roughness, waviness and lay. Surfaces are engineered if the manufacturing process is optimised to generate variation in geometry and/or near surface material properties to give a specific function. Surface structuring on the cutting tool rake face is a promising technique to improve tool chip contact phenomenon. A number of proof-of-concept studies have explored the benefits of surface structuring when applied to the rake face of cutting tools [2–8]. The benefits of structuring the rake face of cutting tools relate to reducing rake face frictional forces [2–6], providing more effective lubrication through providing a micro-pool for lubricant containment [7], and reduced adhesion between the chip and rake face [8].

Some surface structuring studies have investigated the effect of feature direction, size and shape on the cutting performance of the structured tool [3–5]. Jianxin et al. [3] reported that elliptical grooves were more effective than parallel or perpendicular grooves. Kawasegi et al. [4], Obikawa et al. [5] and Chang et al. [6] reported that structures parallel to, instead of normal to the cutting edge, were more effective in reducing cutting forces. Koshey and Tovey [2] reported that, in order to maximise force reduction, the structure needs to be situated away from the cutting edge at a distance that depends on the feed. Additionally, Obikawa et al. [5] suggested, in machining aluminium alloy A6061-T6, that structures were more effective when created close to cutting edge. They also recommended high depth and small structures (i.e. high aspect ratio cavities).

A crude estimate is that contact length is at least twice the un-deformed chip thickness [9]. The criterion for an overlap between the structures and tool chip contact area has not been addressed by previous research.

1.1 Research motivation

The benefits of structured surfaces are well established in terms of reducing friction forces and providing lubrication sights. It is further established that channels should be fabricated parallel to the cutting edge. Despite these developments, the location and design of the structures, with regards to location from the cutting edge, structure spacing and structure depth, has not yet been explored. The hypothesis for this work was that the rake face structures should

A. Fatima (✉) · P. T. Mativenga
School of Mechanical, Aerospace and Civil Engineering,
The University of Manchester, Manchester M13 9PL, UK
e-mail: anis.fatima@postgrad.manchester.ac.uk

overlap the tool chip contact area and that Taguchi experimental design could be used to establish and optimise the layout of structures.

According to conventional tool rake face design there is a trade-off between aiming for a minimum restricted contact near the cutting edge and the negative effect of accelerating tool wear. According to Sadik and Lindstrom [10], the restricted contact length should be 35–45 % of natural contact length. For example, TCMT 16T308 inserts supplied by ISCAR and Sandvik had restricted contact length, extending for about 0.07 mm from the cutting edge. If the un-deformed chip thickness or the feed and depth of cut process window are known, then the restricted contact length could be evaluated. The importance of the structured area overlapping with the contact area needed further studies, and the motivation for this work was to define the critical parameters for location of rake face structures and its relation to process mechanics.

2 Experimental details

Taguchi L9 orthogonal array was selected to study the structure layout parameters of (1) width of slots, (2) depth of slots, (3) distance of first slot from cutting edge and (4) the distance between slots. Tables 1 and 2 show the levels and experimental runs respectively.

The slots were made parallel to the cutting edge as established in the literature, and they were designed to be rectangular. The structures were created on tungsten base uncoated flat cemented carbide inserts (Sandvik TCMW 16T308 5015), using a Ti:sapphire femto-second laser and wavelength of 800 nm. An average pulsed energy of 1 mJ was used, and the repetition rate was 1 kHz. The laser spot size was 50 μm, and this was scanned at a speed of 10 mm/s. The cutting inserts were clamped on a Computer numerical control (CNC) translation stage, which has a resolution of 10 nm. After structuring, the cutting inserts were washed in deionised water under ultrasonic vibration for 10 min for removal of debris. Structures were created as shown in Fig. 1. The required dimensions on average varied by ±5 μm.

Table 1 Factors and their levels

	Factors	Level 1	Level 2	Level 3
A	Width of slots, *W* (μm)	50	100	150
B	Depth of slots, *D* (μm)	10	15	20
C	Distance from the cutting edge, *d* (μm)	100	150	200
D	Distance between slots, P (μm)	50	100	150

Table 2 Taguchi orthogonal L_9 array

Experiment number	Factors and their levels			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Cutting tests were performed on a Denford lathe machine. A Sandvik STGCR 2020k-16 tool holder was used. This tooling system had a zero rake angle and a 7° clearance angle. Orthogonal cutting tests were performed on AISI/SAE 4140 high tensile alloy steel. The workpiece was machined to a tube of thickness 2.5 mm with an outer diameter of 200 mm. A constant speed of 283 m/min was used as determined from the mid-point of the insert manufacturer's process window. The feedrate was also kept constant at 0.1 mm/rev. This feedrate helped to set the structure distance from the cutting edge in Table 1. Trefolex cutting compound (lubricant) from Warren Bestobell was applied on the tool rake face. The tests were randomised and repeated. Cutting forces were measured with a Kistler dynamometer type 9263 in directions of cutting velocity and feed. Due to the zero degree rake angle, the feed force was the friction force on the tool rake face. Temperature was measured using IR thermal image FLIR ThermaCAM® SC3000. The emissivity value of 0.48 was used as established from furnace measurements. The average temperature was recorded on the rake face at a distance of 1 mm from the cutting edge (to avoid chip obstruction) and at 12 equally spaced points.

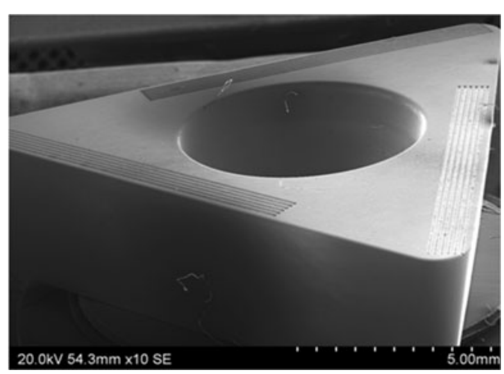

Fig. 1 Structured insert for optimum spacing conditions

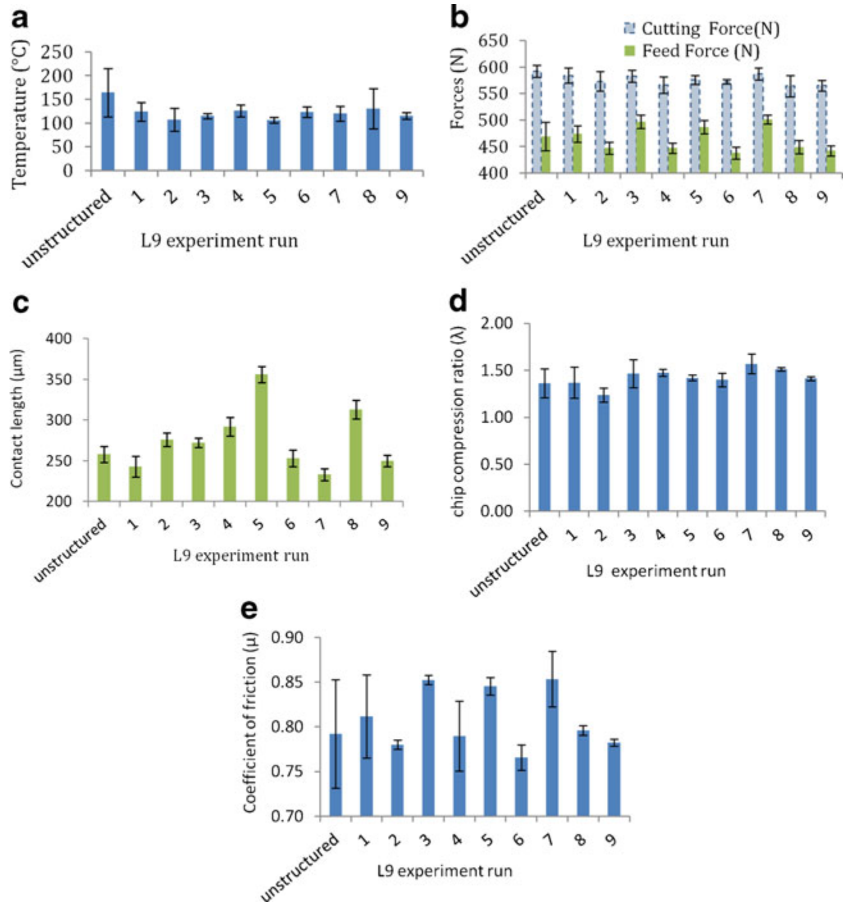

Fig. 2 **a** Rake face temperature at 1 mm from the cutting edge. **b** Cutting force and rake face frictional force. **c** Tool–chip contact length. **d** Tool–chip compression ratios. **e** Coefficient of friction on tool rake face

3 Results and discussions

Figure 2 shows the machining performance in terms of rake face temperature, cutting forces, contact length, compression ratio and coefficient of friction.

The best outputs for each response measure can easily be seen from Fig. 2 (the minimum values). Analysis of variance (ANOVA) is a statistical technique used to investigate how significant the effect of independent variables is on the response (process outputs). Minitab 16.0 software was used for ANOVA analysis. Table 3 shows the *P* values of ANOVA analysis for each factor on each response. Based on ANOVA at 95 % confidence level (α=0.05), only feed force was found to be statistically and significantly influenced by structures geometry parameters. A *P* value of 0.004 indicates that distance of structures from the cutting edge is a significant structure geometric parameter. Its contribution on feed forces is about 84 %, and at same time, it is the only statistically significant parameter of sole importance (Table 4).

These results indicate that there is no consistent trend or there is a weak co-relationship in terms of how structures control rake face temperature, cutting force, contact length, compression ratio and coefficient of friction. More improvements are still needed in fabrication methods in order to shape the slot mouth geometry and enhance mass flow to improve machine and/or wear performance. Additionally, structures can also be nature inspired.

Based on Taguchi orthogonal array (Table 2) and using Minitab software 16.0, the optimum for reducing feed force

Table 3 Summarised ANOVA result for each response for each factor

Source	Temperature	Feed force	Cutting force	Contact length	Compression ratio	Coefficient of friction
	P value					
Width	0.690	0.798	0.467	0.054	0.532	0.532
Depth	0.548	0.776	0.600	0.090	0.617	0.613
Distance	0.155	0.004	0.114	0.912	0.403	0.194
Pitch	0.440	0.996	0.719	0.486	0.528	0.442

Table 4 Contribution percentages for feed forces

Feed force			
Source	*P* value	Contribution (%)	Result interpretation
Width	0.798	7	Not significant
Depth	0.776	8	Not significant
Distance	0.004	84	Significant
Pitch	0.966	1	Not significant

occurs at the minimum points in Fig. 3. The optimum level settings are 2, 3, 2 and 2 for width, depth, distance and pitch, respectively, which means a slot of a width of 100 μm, depth of slot of 20 μm, distance from cutting edge of 150 μm and slot spacing of 100 μm.

Given that the contact length for the un-structured inserts was over 250 μm, it is clear that beginning to structure at 150 μm from the cutting edge ensures that there is an overlap between the structures and the contact area. The largest distance of structures, from the cutting edge of 200 μm, results in less significant overlap between structures and contact area. Structures at 100 μm from the cutting edge appear to be too close to the cutting edge and would concentrate heat and contact stress in a narrower zone.

Figure 4 shows scanning electron microscope (SEM), energy-dispersive X-ray analysis of Fe concentration on the tool rake face after cutting tests.

In Fig. 4a, the Fe transferred from the workpiece to the rake face of the unstructured insert is shown; 35 % of entire contact area shows a high percentage of Fe. When Fe is transferred to the tool rake face at the elevated temperatures experienced in machining, these conditions promote sticking contact between the tool and the chip. For the condition above, 65 % of entire contact length can be inferred to be in sliding contact. For the unstructured insert, the average Fe weight percent transfer percentage is 32 %.

From Fig. 4b–d, it is evident that structuring on the tool rake face has modified the average iron concentration transferred to the tool and at same time resulted in sporadic transfer. The distance for creating structures on the tool rake face is critical in influencing this sporadic Fe transfer and thus the contact. It can be seen from Fig. 3 that when structures were created at a distance of 100 μm, the average iron concentration was 45 wt% Fe and located on 50 % of the contact area. When structures were created 150 μm from the cutting edge, the average iron concentration decreases to 29 wt% Fe, and significant Fe transfer is only limited to 33 % of contact area. In comparison, structures created at a distance of 200 μm result in significant Fe transfer for the entire contact area with an average concentration of 54 wt% Fe. This shows the importance of controlling the location of the structures relative to the cutting edge as a strategy for reducing and localising the distribution of adhesive contact. Structures should not start at the tool edge and neither should they be restricted to beyond the contact area. Structuring shifts the seizure contact length from occurring adjacent to the cutting edge and relocating it further on the rake face.

The effect of width, depth and pitch of the structures on a tool rake face can be seen in terms of contact mechanism. The width and the depth of the structures influence the potential to entrap the wear debris inside the structures and hold cutting fluid on tool rake face in order to reduce friction and improve lubrication. Figure 5 shows SEM images of tool rake face after cutting test, which shows wear debris and lubricant residue and thus clearly support the above statements.

Structure width and depth are important parameters to consider. For sliding surfaces in lubrication, there is always

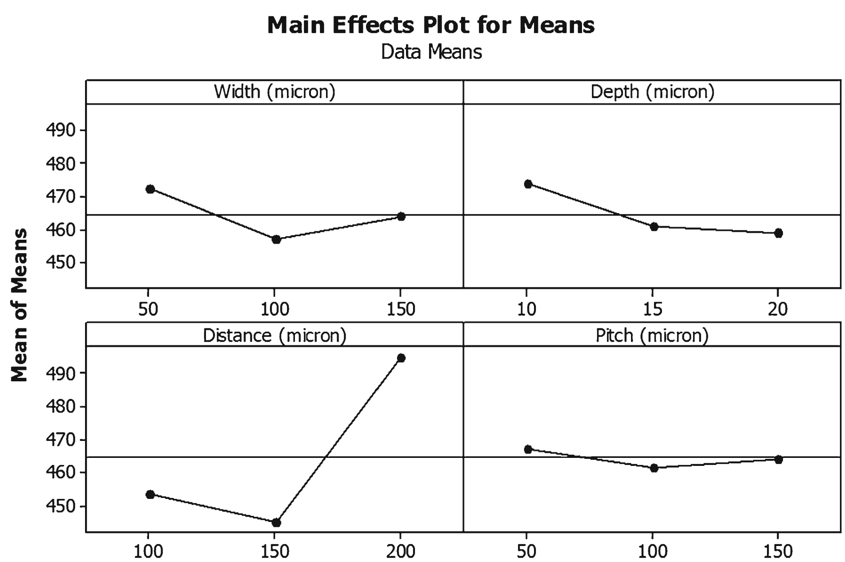

Fig. 3 Mean factor effect on feed force (N)

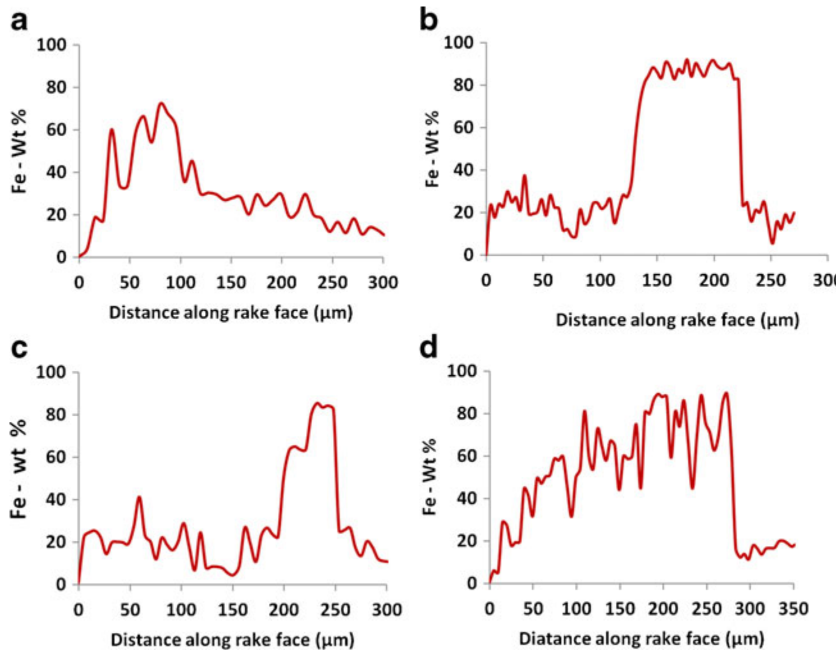

Fig. 4 **a** Fe concentration on rake faces for unstructured insert (contact length of 258 μm and average Fe concentration of 32 wt%). **b** Fe concentration on rake face for structures starting at distance of 100 μm from the cutting edge (contact length of 250 μm and average Fe concentration of 45 wt%). **c** Fe concentration on rake face for structures starting at distance of 150 μm from the cutting edge (contact length of 276 μm and average Fe concentration of 29 wt%). **d** Fe concentration on rake face for structures starting at the distance of 200 μm from the cutting edge (contact length of 294 μm and average Fe concentration of 54 wt%)

a portion of area that is in solid contact [11]. Considering the effect of contact stresses generated at the edge of the structures, it is considered likely that high stresses would generate at the edge of surface structures if structures are large. This effect may increase if the edges are sharp. In addition, because of continuous flow of material during cutting at certain fixed speed, this would suppress the mechanism of derbis entrapment and lubricant retention and may result in tool rake face fretting.

In metal cutting, feed force is required to shear the chip material across the whole real contact. Structures on the rake face affect this real contact. Research studies [2, 12, 13] have shown that, for a high density of structures (lower pitch), relatively lower friction forces were experienced because of the decreased real contact. It is reported that, with regards to advantage of hydrodynamic lift from surface structuring, hydrodynamic pressure is generated on each side of structures [14]. Highly dense structures may interfere with the hydrodynamic pressure distribution. Thus, the pitch should not be too fine as it will interfere with lubrication effectiveness and it cannot be too coarse as this will increase the real contact area and lead to higher forces.

4 Conclusions

Tool rake face structuring is a promising and new technology for modifying contact phenomenon in the chip–tool interface. This work has proved the hypothesis that the location of the structures has to overlap tool chip contact areas for the structures to be effective in reducing feed forces. In this work, geometric and location factors in creating structures on the tool rake face were assessed. Some significant and specific results of this work are summarised below:

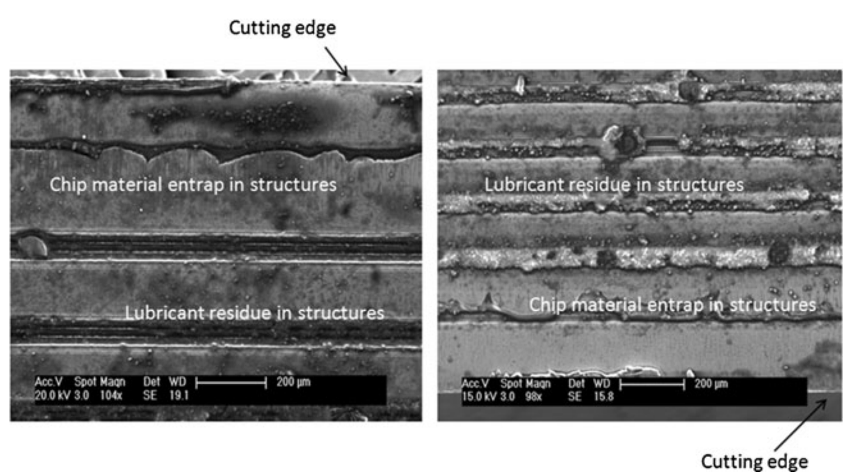

Fig. 5 Cutting tool rake face after machining

1. Surface structuring on the rake face can help reduce the rake face friction forces.
2. The distance the structures are placed from the cutting edge is a dominant factor in influencing machining performance. The criterion should be to aim for an overlap between structures and the tool chip contact area. However, the structures should not start from the cutting edge. At the optimum condition, the structures covered 45 % of the contact area (located away from the cutting edge).
3. Optimal rake face structuring decreases the length of the sticking zone and also reduces the average weight percentage concentration of material transferred from the chip to the tool rake face. Structuring also shifts the sticking zone from occurring adjacent to the cutting edge and locates it further up the rake face. This condition should help to produce more favourable flow conditions about the edge and promote better performance.

References

1. Evans CJ, Bryan JB (1999) “Structured”, “textured” or “engineered” surfaces. CIRP Ann Manuf Technol 48(2):541–556
2. Koshy P, Tovey J (2011) Performance of electrical discharge textured cutting tools. CIRP Ann Manuf Technol 60(1):153–156
3. Jianxin D, Ze W, Yunsong L, Ting Q, Jie C (2012) Performance of carbide tools with textured rake-face filled with solid lubricants in dry cutting processes. Intern J Refract Met Hard Mater 30(1):164–172
4. Kawasegi N, Sugimori H, Morimoto H, Morita N, Hori I (2009) Development of cutting tools with microscale and nanoscale textures to improve frictional behavior. Precis Eng 33(3):248–254
5. Obikawa T, Kamio A, Takaoka H, Osada A (2011) Micro-texture at the coated tool face for high performance cutting. Int J Mach Tool Manuf 51(12):966–972
6. Chang W, Sun J, Luo X, Ritchie JM, Mack C (2011) Investigation of microstructured milling tool for deferring tool wear. Wear 271(9–10):2433–2437
7. Lei S, Devarajan S, Chang Z (2009) A study of micropool lubricated cutting tool in machining of mild steel. J Mater Process Technol 209(3):1612–1620
8. Sugihara T, Enomoto T (2012) Improving anti-adhesion in aluminum alloy cutting by micro stripe texture. Precis Eng 36(2):229–237
9. Iqbal SA, Mativenga PT, Sheikh MA (2009) A comparative study of the tool–chip contact length in turning of two engineering alloys for a wide range of cutting speeds. Int J Adv Manuf Technol 42(1):30–40. doi:10.1007/s00170-008-1582-6
10. Sadik MI, Lindström B (1995) The effect of restricted contact length on tool performance. J Mater Process Technol 48(1–4):275–282
11. Yuan S, Huang W, Wang X (2011) Orientation effects of micro-grooves on sliding surfaces. Tribol Int 44(9):1047–1054
12. Wakuda M, Yamauchi Y, Kanzaki S, Yasuda Y (2003) Effect of surface texturing on friction reduction between ceramic and steel materials under lubricated sliding contact. Wear 254(3–4):356–363
13. Enomoto T, Sugihara T, Yukinaga S, Hirose K, Satake U (2012) Highly wear-resistant cutting tools with textured surfaces in steel cutting. CIRP Ann Manuf Technol 61(1):571–574
14. Xiaolei Wang HY, Wei Huang (2010) Surface texture design for different circumstances. Paper presented at the First International Brazilian Conference on Tribology, Brazil., November, 24th–26th, 2010