A composite tool for ball endmilling

P Koshy[1], **D K Aspinwall**[1,2] and **R C Dewes**[1]*
[1]Machining Research Group, School of Manufacturing and Mechanical Engineering, University of Birmingham, UK
[2]Interdisciplinary Research Centre in Materials Processing, University of Birmingham, UK

Abstract: The paper reports on the performance of a novel composite ball nose endmill that utilizes cermet and tungsten carbide indexable inserts on the same cutter body, with a view to optimizing both tool life and workpiece surface roughness. The technique exploits the asymmetric design of the cutter to position the cermet and tungsten carbide inserts appropriately, so that their characteristic tribological attributes are consistent with the functions of surface generation and wear resistance. Experimental work on ball endmilling of hardened AISI H13 tool steel is presented to illustrate the concept. The mechanism of performance enhancement of the composite tool is also detailed with reference to the flank wear pattern of the inserts and the morphology of the machined surface.

Keywords: composite tool, ball endmilling, hand milling, material side flow

1 INTRODUCTION

Formulating new tool materials and coatings with enhanced mechanical properties and identifying cutting conditions that exploit these properties are central to developing appropriate machining technology for advanced applications. In many instances, it is imperative that, in addition to optimizing the cutting parameters, innovative tool designs and process variants are developed in order to maximize tool life and workpiece surface quality.

Details of novel techniques aimed at improving the performance of tools abound in the literature. In general, they relate to modifying the tool geometry, engineering the working surface of the tool for better tribological performance, adapting the cutting conditions to counteract dominant wear mechanisms governing tool failure, and other creative tooling concepts. Examples are reviewed in the following.

Komanduri and Lee [**1**] detail a wear-tolerant cemented carbide cutting tool insert comprising a thin ledge that extends beyond the clearance face of the tool along the tool width, which limits the maximum flank wear to the ledge thickness. The geometry employed constrains the wear to progress laterally by a microfracture mechanism, and has been reported to facilitate cutting speeds up to 5 times the conventional speed in turning and facemilling of titanium. In the machining of ductile metals such as commercially pure nickel and copper, the rake face geometry of the tool is generally relieved [**2**] in order to restrict the tool–chip contact length, and thereby reduce cutting forces and improve tool life. This concept is the basis for inserts with sintered-in chip breakers. Chamfering/honing of the cutting edge of tools made of materials such as engineering ceramics and polycrystalline cubic boron nitride (PCBN) to preclude catastrophic brittle fracture of the tools [**3**] are also examples of modifying tool geometry to enhance performance.

Modern cutting tools are coated in order for them to satisfy the rather conflicting requirements of wear resistance and toughness [**4**], the technology of which continues to evolve rapidly. Functionally graded tools [**5**] that comprise a superficial layer of a wear-resistant cermet and a tough cemented carbide interior are a relatively new concept in surface engineering. Here, compressive residual stresses are introduced into the working surface of the tool by tailoring the expansion coefficient of the surface layer to be lower than that of the interior. This precludes the formation of thermally induced cracks in the cermet, which is a primary cause of failure. A related idea is gradient sintering [**6**] of drill-point geometries to provide a microstructural variation in the radial direction that is better able to accommodate the difference in cutting speed along the drill lip.

Rahman *et al.* [**7**] present an innovative approach to restraining the depth of cut notch wear when turning nickel-based superalloys using cemented carbide tools, where material is removed by taking two passes with a linear variation in the depth of cut, as opposed to a single pass with a constant chip width. In so doing, the

The MS was received on 2 March 2001 and was accepted for publication on 20 March 2001.
**Corresponding author: Machining Research Group, School of Manufacturing and Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK.*

position of the maximum depth of cut translates continually along the cutting edge, preventing localization of wear in the form of a notch.

PCBN tools tend to chip at low cutting speeds and call for a higher cutting speed in comparison with carbide tools for the best tool life. A novel ball nose endmill [8] designed in accordance with this principle employs PCBN and carbide segments brazed to the same cutter body, so that their positions along the circular profile of the ball correspond to their individual optimum cutting speeds. The carbide segment is located near the cutter centre where the cutting velocities are relatively low, and the PCBN segment towards the periphery corresponding to higher speeds.

Tool designs such as the wiper insert [9] are aimed at improving the quality of the machined surface, rather than the tool life as in the cases presented above. Theoretically, the roughness of a surface machined with a single-point cutting tool decreases in proportion to the nose radius of the cutting edge, other cutting conditions remaining the same. Accordingly, facemilling cutters are sometimes equipped with a wiper insert that has a flat equivalent to a large nose radius parallel to the surface generated, and located axially at a slightly lower level in comparison with other inserts in the cutter. Provided that the flat does not compromise cutting stability by initiating chatter and that the flat length is greater than the feed per revolution, the wiper insert truncates the ridges left by other inserts in the cutter. This lowers the roughness of the milled surface.

The techniques reviewed above relate to improving either the tool life or the workpiece surface roughness. This paper presents the concept of a composite ball nose indexable insert endmill that utilizes two different tool materials, namely uncoated cermet and coated tungsten carbide, on the same cutter body in order to optimize machining performance with reference both to the tool life and to the workpiece surface roughness.

2 CONCEPT OF A COMPOSITE BALL ENDMILL

Figure 1 shows a commercially available indexable insert ball nose endmill that comprises two asymmetrical cutting edges. The central insert (Fig. 1a), as the name implies, extends to the centre of the cutter, whereas the peripheral insert (Fig. 1b) stops short of the centre (see Fig. 1c). The inserts and the cutter body are designed

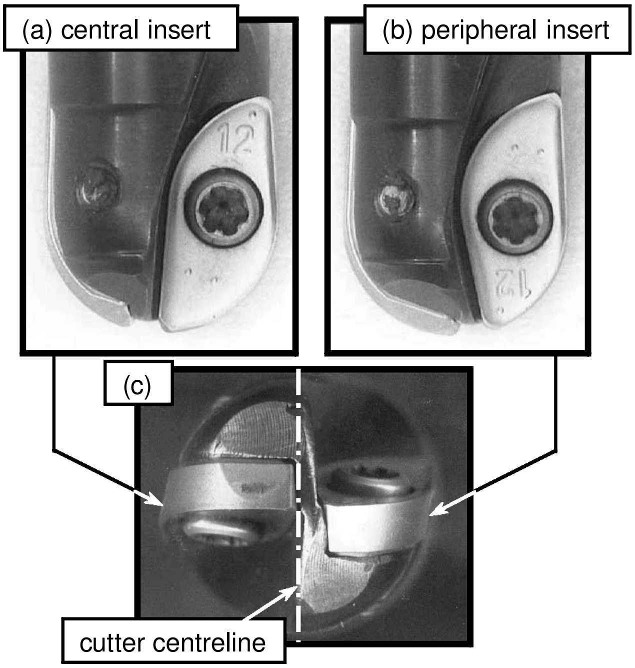

Fig. 1 Commercially available 12 mm diameter ball nose endmill: (a) central insert; (b) peripheral insert; (c) relative positions of the central and peripheral inserts in the cutter body (end view)

to facilitate indexing, by swapping a set of two inserts between the central and peripheral positions. With regard to insert geometry, the central insert would experience a higher chip load in comparison with the peripheral insert; moreover, when the orientation of the workpiece machined is either horizontal or at a small angle to it, only the central insert would generate the surface. The composite ball endmill exploits the asymmetry in cutter geometry to employ inserts made of materials with different tribological responses in order to optimize tool life and the roughness of the surface generated, as explained below.

Experimental work carried out previously to assess the performance of tungsten carbide and uncoated cermet inserts (see Table 1 for specifications) in the ball nose endmilling of hardened (~52 HRC) AISI H13 hot-work tool steel [composition (wt %): Fe, 0.32–0.45C, 4.75–5.5Cr, 1.1–1.75Mo, 0.8–1.2Si, 0.2–0.5Mn] indicated that the machining response of these inserts was dissimilar in terms of tool life and workpiece surface roughness. The tool life provided by the tungsten carbide insert was higher than that of the cermet; however, in the

Table 1 Specification of inserts used

Insert	Cemented carbide	Cermet
Grade description	Tungsten carbide ISO grade P05–P20	Ceramic/metal ISO grade M10–M30
Composition (wt %)	89.5WC–10Co–0.5TaC	25TiC–23TiN–18WC–12Ta(Nb)C–11Co–6Ni–5Mo_2C
Coating	TiCN (~3 μm thick) with visible TiN outer layer	None

former case, the roughness of the machined surface increased with the progression of tool wear, whereas the roughness of the surface generated with the cermet remained essentially stationary. Also noted was the fact that the peripheral insert reached the tool life criterion ahead of the central insert for both the tool materials. It was therefore apparent that a ball nose cutter with a cermet central insert and a carbide peripheral insert could not only furnish a surface with a low and consistent roughness but also provide a better tool life. The experimental work done to verify this premise is presented in the following.

3 EXPERIMENTAL DETAILS

Experiments were conducted on a Bridgeport VMC1000 vertical machining centre with a maximum spindle speed of 10 000 r/min. As in the previous work, the workpiece material used was AISI H13 tool steel with a nominal hardness of 52 HRC. A 12 mm diameter ball nose endmill was used, which was held in a hydraulic tool holder. The geometry of the endmill entailed an axial rake angle of -10°, a radial rake angle of 0° and a primary relief angle of 9°. The overhang was $\sim$40 mm, and the radial runout was maintained at $\leqslant 12\,\mu$m. The workpiece was oriented horizontally, with a length cut per pass of 105 mm.

The cutting conditions used were as follows: a cutting speed of 150 m/min (7198 r/min), an axial depth of cut of 1 mm, a radial depth of cut of 0.5 mm and a feed per tooth of 0.15 mm (2159 mm/min linear feed rate). These conditions were chosen to correspond to a high material removal rate, and to show that the workpiece surface roughness need not necessarily be a constraint to increased productivity when using the composite tool. Cutting was done dry, in a down milling configuration.

In all, four insert combinations were tested, as indicated in Table 2. Each of the tests was replicated to ascertain the reliability of the results. Tests 1 and 2 were done to benchmark the performance of the carbide and cermet inserts respectively, against which the performance of the composite tool (test 3) could be compared. Test 4 entailed a composite tool with the central cermet insert appropriately relieved further to enhance the tool life, as discussed later.

Flank wear measurements were made periodically until the maximum width of the flank wear land reached the failure criterion of 0.3 mm. The transverse workpiece surface roughness was measured using a Mitutoyo Surftest 301 portable roughness tester, employing a cut-off length of 0.8 mm. Roughness was measured as a function of the length cut, and at each section, three measurements were made along the width of the workpiece to assess the variability. Three-dimensional topographs of the machined surface were obtained using a stylus contact profilometer.

Table 2 Insert combinations tested

Test number	Central insert	Peripheral insert
1	Tungsten carbide	Tungsten carbide
2	Cermet	Cermet
3	Cermet	Tungsten carbide
4	Cermet (with relief)	Tungsten carbide

4 EXPERIMENTAL RESULTS

Transverse workpiece surface roughness, R_a, data expressed as a function of the length cut, for the four insert combinations listed in Table 2, are presented in Fig. 2. The solid symbols refer to results from replicated

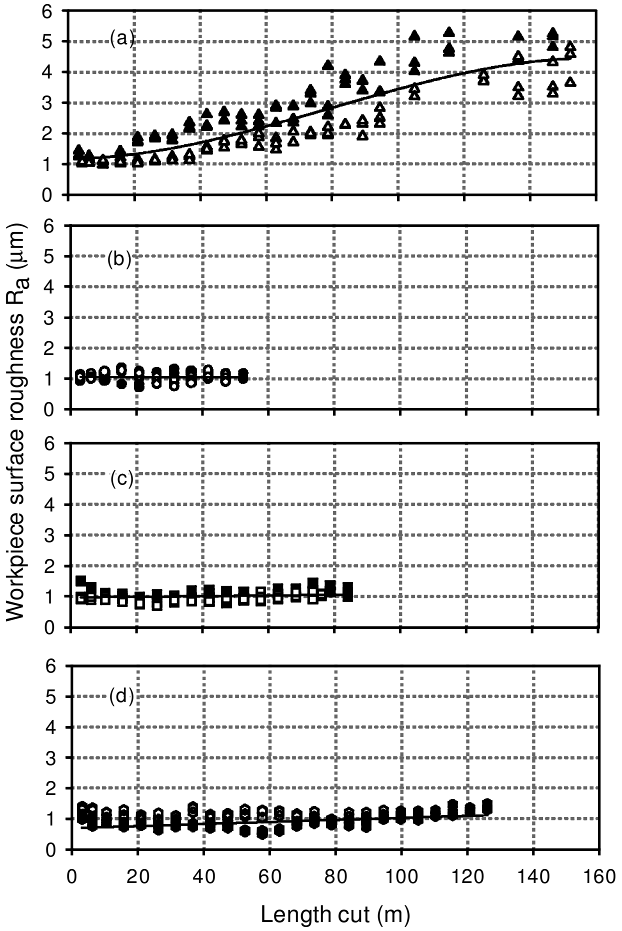

Fig. 2 Transverse workpiece surface roughness versus length cut characteristics for the various insert combinations tested (the solid symbols refer to replicated experiments): (a) tungsten carbide central and peripheral inserts; (b) cermet central and peripheral inserts; (c) composite tool with cermet central and carbide peripheral inserts; (d) composite tool with relieved central insert and carbide peripheral insert

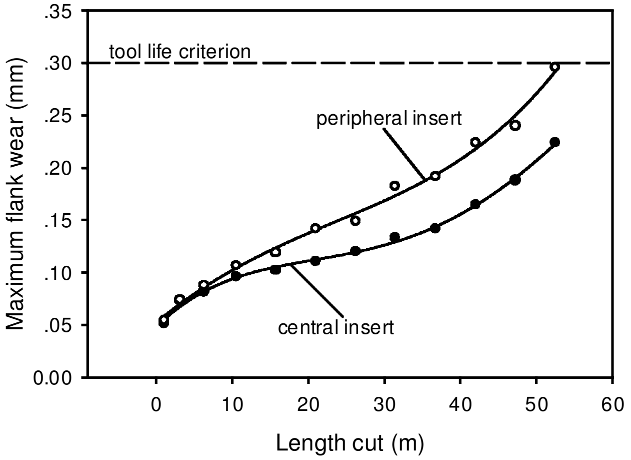

Fig. 3 Typical progression of the maximum width of the flank wear land when using cermet central and peripheral inserts

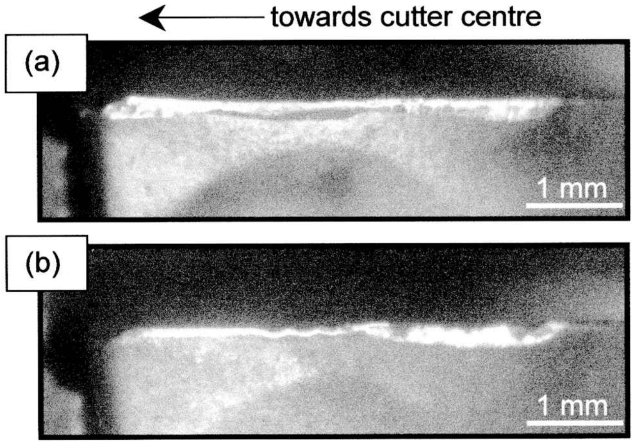

Fig. 4 Representative flank wear patterns on the central insert: (a) tungsten carbide; (b) cermet

experiments. Figures 2a and b clearly illustrate the difference in the performance of the tungsten carbide and cermet inserts respectively. The carbide inserts provided a tool life corresponding to ~150 m cut length, which was about 3 times higher than the cermet tools. The maximum variability in tool life between replicated experiments was of the order of 15 per cent. The workpiece surface roughness provided by unworn tools was identical, irrespective of type. However, during the course of testing, the roughness increased to approximately 5 times the initial value in the case of carbide inserts. In contrast, the roughness relating to the cermet inserts remained essentially constant with the progression of tool wear. Furthermore, the scatter in surface roughness corresponding to the carbide inserts was dependent on the length cut, unlike that of the cermet insert.

Figure 3 details the typical progression of maximum flank wear land width on the central and peripheral cermet inserts. The peripheral insert reached the failure criterion of 0.3 mm ahead of the central insert. Based on this observation, and considering the fact that the central insert generated the surface, it was evident that, if the peripheral cermet insert was replaced by the more wear-resistant carbide insert, the tool life could be extended, without having to incur an increase in the workpiece surface roughness. Experimental results shown in Fig. 2c confirmed that the tool life could indeed be enhanced by about 60 per cent in comparison with the cermet inserts, with the surface roughness maintained at the same level, when using the composite tool.

Examination of the wear scars on the central cermet and carbide inserts (Fig. 4) indicated that the flank wear patterns were rather distinct. The width of the wear scar on the carbide insert (Fig. 4a) was largely uniform along the contact length. In contrast, the wear of the cermet insert (Fig. 4b) adjacent to the centre was small in comparison with the wear away from the centre. This presented the possibility of relieving the flank surface of the cermet insert coincident with the zone of maximum flank wear, as shown in Fig. 5. Part of the chip load could thus be transferred to the carbide insert, which was more wear resistant. Comparison of the performance of the composite tool utilizing the relieved cermet insert (Fig. 2d), with that of the carbide insert indicated that about 80 per cent of the tool life could be obtained, with the workpiece surface roughness sustained at the initial level.

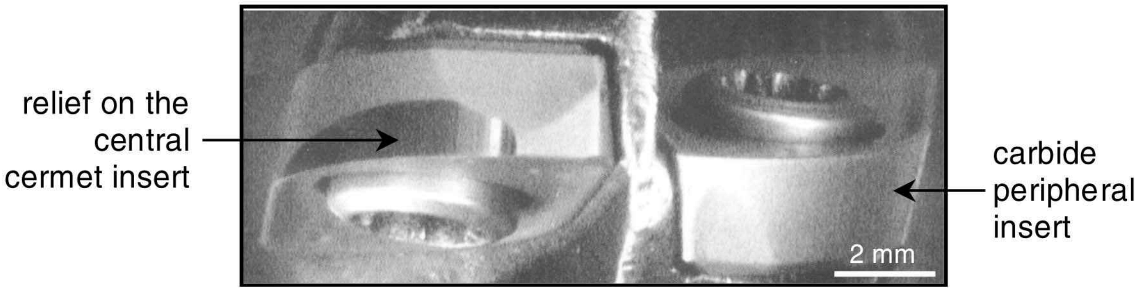

Fig. 5 End view of the ball nose endmill, showing the relief provided on the central cermet insert to transfer

5 DISCUSSION

Two of the observations that fostered the composite tool approach were the disparity in the rate of wear of the central and peripheral inserts and the difference in the evolution of roughness of the machined surfaces with respect to flank wear progression when using cermet and tungsten carbide inserts. These aspects are discussed in the following. Limitations of the composite tool are also presented.

5.1 Differential wear rate of central and peripheral inserts

With reference to its higher circumferential contact length, the central insert would account for higher cutting forces in comparison with the peripheral insert. However, the peripheral insert experienced a higher wear rate and reached the tool life criterion ahead of the central insert (refer to Fig. 3) when identical tool materials were used. A simple two-dimensional geometric model explains this counter-intuitive phenomenon by comparing the thermomechanical load per unit contact length incident on the inserts.

Figure 6 is a schematic representation of the indexable insert ball endmill, where AB and CD refer to the central and peripheral inserts respectively. For a cutter diameter of 12 mm and an axial depth of cut of 1 mm used in the present work, the angles ∠AOB and ∠BOC were measured to be 33.6° and 18.2°, and the arc lengths AB and CD were 3.52 and 1.62 mm respectively. The temperature at point P is related to the instantaneous cutting velocity at the point, which is proportional to $\sin\phi$. Similarly, the undeformed chip thickness at point P can be assumed [**10**] to be proportional to $\sin\phi$ for a constant feed/tooth. An estimate of the total thermomechanical load on each of the inserts can be obtained by integrating the product of the instantaneous cutting velocity and the undeformed chip thickness, formulated as $\sin^2\phi$, over the angles subtended by the individual inserts. The total load per unit circumferential contact length for the inserts can be obtained by normalizing the computed total load with reference to the respective insert contact lengths. Thus, a measure of the thermomechanical load per unit circumferential contact length on the peripheral insert would be given by

$$\frac{1}{1.62}\int_{18.2}^{33.6} \sin^2\phi \, d\phi \tag{1}$$

and on the central insert by

$$\frac{1}{3.52}\int_{0}^{33.6} \sin^2\phi \, d\phi \tag{2}$$

The ratio between the numerical values of expressions (1) and (2) works out to be 1.8, which indicates that the peripheral insert would be subject to a higher thermomechanical load per unit contact length, which qualitatively accounts for the higher rate of wear on the peripheral insert.

The above model is an abstraction of the complex three-dimensional geometry of the ball endmilling process, but it serves qualitatively to explain the difference in the tool wear rate between the central and peripheral inserts. A more realistic approach would involve consideration of the different radial locations of the ball endmill in respect of the cutting to non-cutting time ratios, which would further influence the temperature and wear characteristics. In addition, the central insert flank surface near the cutter centre is subject to an additional thermal component due to rubbing/ploughing effects, which would in fact decrease the thermomechanical load ratio between the peripheral and central inserts. This may be the reason why the difference in wear between the peripheral and central inserts (Fig. 3) was not as high (80 per cent) as that predicted by the model.

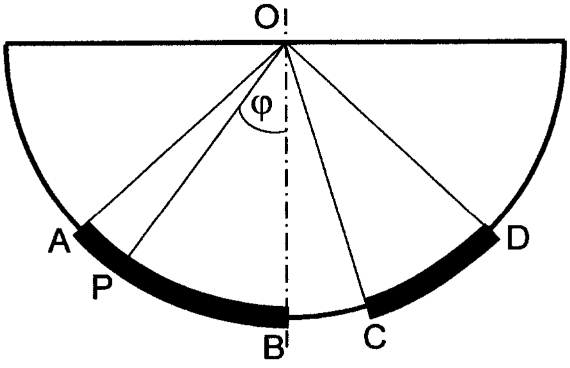

Fig. 6 Schematic of the indexable insert ball nose endmill, indicating the central (segment AB) and peripheral (segment CD) inserts

5.2 Mechanism of surface generation by new/worn cermet and tungsten carbide inserts

Theoretically, the maximum peak to valley roughness parameter in the transverse direction, R_t, for a surface generated by ball endmilling is given by

$$R_t = \frac{a_e^2}{8R} \tag{3}$$

where a_e is the radial depth of cut and R is the radius of the cutter. For the conditions used in the present work, $R_t = 5.2\,\mu m$ according to equation (3). Typically, R_t is ~4 times [**11**] the average roughness parameter R_a, and hence $R_a \approx 1.3\,\mu m$. The roughness obtained with the cermet insert (Fig. 2b) did, by and large, correspond to this value irrespective of flank wear until the end of tool life. In the case of the carbide insert (Fig. 2a), however, the experimental and theoretical values concurred

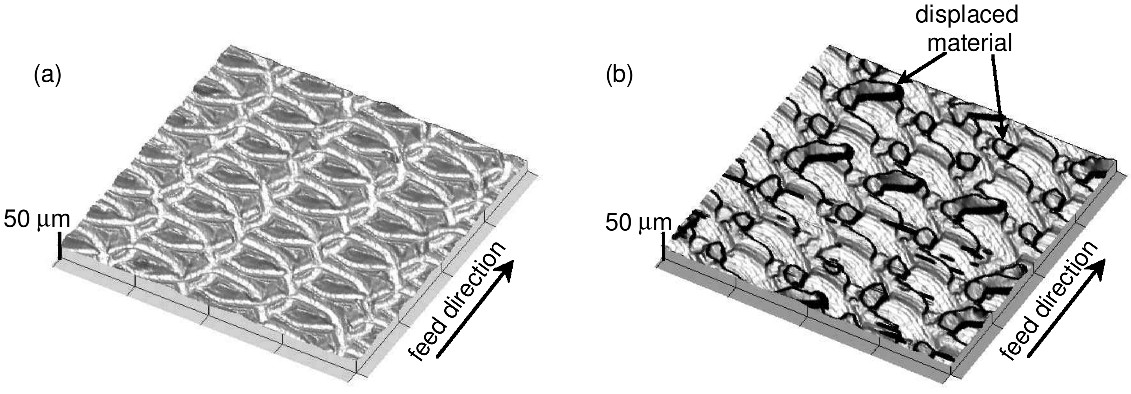

Fig. 7 Three-dimensional topography of surfaces (2 mm × 2 mm) machined with (a) a new carbide tool and (b) a worn carbide tool (0.3 mm maximum flank wear)

only when the flank wear was not appreciable; the deviation between the values was found to increase with flank wear, and the roughness towards the end of tool life was ~5 times the initial value (Fig. 2a). It was therefore considered worthwhile to investigate this difference in performance between the carbide and cermet inserts.

In general, any discrepancy between the theoretical roughness value and experimentally obtained results are due to factors such as unstable built-up edge formation, vibration arising out of dynamic instability, inhomogeneity in the workpiece material, etc. Examination of the surfaces generated with carbide inserts suggested that the increase in roughness with tool wear was due to material side flow. Removal of material by cutting rather than by ploughing requires that the undeformed chip thickness be greater than a threshold value, which primarily depends on the cutting edge radius. Material that corresponds to an undeformed chip thickness less than this critical value is not removed but is merely deformed and displaced. This phenomenon is referred to as material side flow and has been observed while machining hardened steel, particularly turning [**12**–**14**].

Figures 7a and 7b show three-dimensional topographs of surfaces machined by new and worn tungsten carbide inserts respectively. The morphology of the surface machined by the worn insert (Fig. 7b) is characterized by lumps of deformed material smeared on the surface. These appear to be responsible for the increase in surface roughness value; furthermore, the inhomogeneous distribution of the displaced material would account for the larger variability in the roughness value towards the end of tool life (Fig. 2a). Such features are absent on the surface machined by the new insert (Fig. 7a), which, however, exhibits a complex albeit regular lay pattern, presumably because of back-cutting.

In ball endmilling, the undeformed chip thickness approaches zero near the cutter centre, and hence the segment of the cutting edge that generates the surface is prone to sustaining material side flow. Its occurrence is also strongly influenced by the magnitude and mode of flank wear [**14**] on account of the effect of flank wear on the cutting edge radius and the normal cutting force. The increase in the cutting edge radius increases the critical chip thickness, which in turn increases the likelihood of the material flowing laterally; the increase in the normal force is associated with a rise in temperature, and these effects in tandem lead to plastification and the subsequent side flow of the work material.

Since the central insert is responsible for surface generation, the resulting workpiece texture would relate in part to the wear pattern of these inserts. The major difference between the flank wear experienced by the cermet and tungsten carbide inserts was that the flank wear land on the carbide central insert was of uniform width, with the wear at the zone that generates the surface (near the cutter centre) being substantial (Fig. 4a). This would equate with an increase in the cutting edge radius, which would in turn promote material side flow and consequently increase the workpiece surface roughness. In contrast, the flank wear on the cermet was not appreciable near the cutter centre (Fig. 4b); moreover, spalling of the cutting edge was observed on the cermet insert, presumably because of its lower toughness, which would maintain a sharp cutting edge similar to self-sharpening of abrasives in a grinding wheel. This would result in a surface free of side flow and hence of low and consistent roughness.

5.3 Limitations of the composite tool

The approach outlined in this paper presents a problem when the composite tool is used in a three-axis vertical machining centre to machine surfaces that are not perpendicular to the cutter axis. When machining an inclined surface, a situation that is common in the machining of dies and moulds, it is the tool periphery rather than the tool centre that is generating the workpiece surface. However, the problem can be circumvented by using the composite tool on a four- or five-axis machine tool. Here, machining of inclined surfaces can be realized by tilting the workpiece, so that the cutting edge in the neighbourhood of the centre of the ball nose endmill generates the surface. Surface generation with the cutter centre rather than the periphery would also be beneficial in terms of introducing compressive residual stresses into the machined surface. This is due to the lower temperatures and the ploughing force components prevailing in the vicinity of the cutter centre in comparison with the cutter periphery, which together tend to promote [**15**] compressive residual stresses.

For hardened AISI H13 tool steel, the tungsten carbide and cermet inserts constitute a suitable pair as established in this paper. It would be essential to identify appropriate tool materials for the central and peripheral inserts with reference to the particular application at hand, since machining characteristics are a function of the workpiece material.

6 CONCLUSIONS

The paper demonstrates the simultaneous optimization of tool life and workpiece surface roughness in ball endmilling of hardened AISI H13 tool steel of 52 HRC hardness by employing a composite tool. The following conclusions were drawn from the work:

1. By using a composite tool with the central cermet insert appropriately relieved, about 80 per cent of the tool life of tungsten carbide inserts could be obtained, without incurring any significant increase in the workpiece surface roughness, as was the case with the carbide inserts.
2. The wear rate of the peripheral insert was higher than that of the central insert owing to the higher thermo-mechanical load per unit circumferential contact length.
3. The increase in the workpiece surface roughness with increase in the flank wear of the tungsten carbide insert was due to the phenomenon of material side flow. Such a deterioration in surface quality did not occur with the cermet inserts, since the flank wear associated with the segment of the cutting edge responsible for surface generation was not significant.

ACKNOWLEDGEMENTS

The authors would like to thank Prof. A. A. Ball (Head of the School of Manufacturing and Mechanical Engineering), Prof. M. H. Loretto (Director of the IRC in Materials Processing), the TCD, Portway Tool and Gauge Limited, TRT Manufacturing Limited, GTI Corporation Limited, Sandvik Coromant UK, Bridgeport Machines Limited and The Gauge and Toolmakers Association (GTMA) for the provision of facilities, cutting tools and funding. Additional thanks go to Mr Eugene Ng and Dr Dragoş Axinte for discussions on the topic, and finally to Mr Richard Fasham for technical support.

REFERENCES

1 **Komanduri, R.** and **Lee, M.** The ledge tool: a new cutting tool insert. *J. Engng for Industry*, 1985, **107**, 99–106.
2 **Trent, E. M.** *Metal Cutting*, 1991, p. 45 (Butterworth Heinemann, London).
3 **Stephenson, D. A.** and **Agapiou, J. S.** *Metal Cutting Theory and Practice*, 1997, p. 612 (Marcel Dekker, New York).
4 **Childs, T. H. C., Maekawa, K., Obikawa, T.** and **Yamane, Y.** *Metal Machining: Theory and Applications*, 2000, p. 109 (Arnold Publishers, London).
5 **Nomura, T., Moriguchi, H., Tsuda, K., Isobe, K., Ikegaya, A.** and **Moriyama, K.** Material design method for the functionally graded cemented carbide tool. *Int. J. Refractory Metals and Hard Mater.*, 1999, **17**, 397–404.
6 *Rotating Tools*, Catalogue C-1100: 6-ENG, 1999, p. B-4 (Sandvik Coromant).
7 **Rahman, M., Seah, W. K. H.** and **Hung, C. Y.** A novel method to improve tool life during machining of Inconel 718. In Proceedings of 4th International Conference on *Advances in Materials and Processing Technologies* (Eds S. Sulaiman, A. M. S. Hamouda and M. Ahmadun), Kuala Lumpur, Malaysia, 1998, pp. 835–842.
8 **König, M.** New technologies in milling: high speed milling, 3- and multi-axis machining, working of hardened parts. In 7th International Conference on *Tool, Die and Mould Industry*, Bergamo, Italy, 1992 (International Special Tooling Association).
9 *Modern Metal Cutting: A Practical Handbook*, 1994, p. X-51 (Sandvik Coromant).
10 **Kaczmarek, J.** *Principles of Machining by Cutting, Abrasion and Erosion*, 1976, p. 269 (Peter Peregrinus, Hertfordshire).
11 **Boothroyd, G.** and **Knight, W. A.** *Fundamentals of Machining and Machine Tools*, 1989, p. 168 (Marcel Dekker, New York).
12 **El-Wardany, T. I.** and **Elbestawi, M. A.** Phenomenological analysis of material side flow in hard turning: causes, modelling and elimination. *Machining Sci. and Technol.*, 1998, **2**, 239–251.
13 **Kishawy, H. A.** and **Elbestawi, M. A.** Effects of process parameters on material side flow during hard turning. *Int. J. Mach. Tools and Mf.*, 1999, **39**, 1017–1030.
14 **Bresseler, B., El-Wardany, T. I.** and **Elbestawi, M. A.** Material side flow in high speed finish boring of case hardened steel. In 1st French and German Conference on *High Speed Machining* (Eds A. Molinari, D. Dudzinski and H. Schulz), University of Metz, France, 1997, pp. 196–206.
15 **Jacobus, K., DeVor, R. E.** and **Kapoor, S. G.** Machining-induced residual stress: experimentation and modelling. *J. Mfg Sci. Engng*, 2000, **122**, 20–31.