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Cutting performance and wear characteristics of PVD coated and uncoated carbide tools in face milling Inconel 718 aerospace alloy

A. Jawaid[a], S. Koksal[b], S. Sharif[c,*]

[a]School of Engineering, Coventry University, Priory Street, Coventry CV1 5FB, UK
[b]Faculty of Technical Education, Sakarya University, Adapazari, Turkey
[c]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor, Bahru, Malaysia

Abstract

In this paper, cutting performance and failure characteristics of two PVD TiN coated and an uncoated tungsten carbide grades with identical geometry are presented. Face-milling tests of Inconel 718 superalloy were performed to investigate the effect of cutting speed and feed rate on tools performance under wet conditions. Tools were thoroughly examined under SEM at two stages in order to reveal the failure modes and wear mechanisms. These stages were after cutting for 5 s and when the tool failed. It was noted that the coating resulted in a marginal improvement, as it was delaminated by adhering workpiece material at the beginning of the cut, impeding the performance of the tool for the rest of the experiment. A combination of progressive chipping and flank wear was the general mode of tool failure, former being dominant at high speeds and the latter at the low speed region. Results showed that uncoated tool performed better than coated tools at low cutting speeds while coated tools gave slightly better performance as the speed was raised. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Face milling; Coated and uncoated carbide tools; Nickel-based materials; Tool wear

1. Introduction

Nickel-based superalloys have been widely used in the aircraft and nuclear industry due to their exceptional thermal resistance and the ability to retain mechanical properties at elevated temperatures of service environment over 700°C [1]. However, they are classified as difficult-to-machine materials due to their high shear strength, work hardening tendency, highly abrasive carbide particles in the microstructure, strong tendency to weld and form built-up edge and low thermal conductivity [2,3]. They have a tendency to maintain their strength at high temperature which is generated during machining [4].

Most of the available machinability data on nickel-based superalloys was based on orthogonal and/or semi-orthogonal turning operations where a continuous engagement of tool/work material exists. Despite many publications on the wear behaviour of coated tungsten carbide tools in turning nickel-based alloys [5,6], reports on the performance of coated carbides with respect to face milling of these alloys are still lacking. This could be due to the relative complexity of the milling process as well as the high costs of such exotic materials [7]. Machining data obtained from turning process cannot entirely be used for milling process, whereby cutting is inherently interrupted and tool–workpiece interaction with respect to cutting geometry and mechanics are more complicated [8]. In a milling process, cyclic thermal and mechanical stresses are the two effective factors that play significant role in controlling the tool life, failure modes and wear mechanisms. In most cases, they cause microcracks, chipping and sometimes catastrophic failure of the entire cutting edge [9].

In this respect, the phenomena of ‘point of initial contact’, ‘impact factor’ [10], ‘partial area of engagement’ [11], ‘foot formation’ and ‘negative shearing’ [12] were discovered by detailed studies of the interaction between the tool and workpiece. Each of the above phenomenon, which was common in milling operation can cause premature failure and has a direct effect on the cutting performance. Therefore, it would be of great value to generate data on the performance of cutting tools with respect to milling process through detailed experimental work.

This work is concentrated on the wear behaviour of two different grades of single layer PVD-TiN coated and an uncoated tungsten carbide insert when face milling Inconel 718 at various cutting conditions.

* Corresponding author.

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2. Experimental details

2.1. Cutting conditions

Tests were carried out on a 9 kW CNC vertical machining centre. A general purpose emulsion with 6% concentration was used as a coolant throughout the tests. A face-milling cutter of 63 mm diameter, loaded with three inserts was employed. The cutter has an approach angle of 45°, axial rake angle of 20° and a negative radial rake angle of −8°. The cutter was positioned at the centreline of the workpiece as recommended by the ISO standard [13] in face-milling tests. The coated tools were tested at cutting speeds of 25, 50, 75 and 100 m/min. The purpose of testing the coated tools at cutting speeds of 75 and 100 m/min was to investigate the wear behaviour of the coating at high cutting conditions. Testing of the uncoated carbide tool was done at cutting speeds of 25 and 50 m/min in order to compare with those coated tools under identical conditions of cutting. Depth of cut was 1 mm and feed rates were 0.08 and 0.14 mm per tooth; they were kept constant during the machining trials.

2.2. Cutting inserts

Two types of commercially available PVD/TiN-coated tungsten carbide inserts (Tools A and B) and an uncoated insert (Tool C) were tested. The properties of coating and substrate are given in Tables 1 and 2, respectively. The axial and radial run-out of the cutter were checked while the cutter was mounted into the machine spindle. All the inserts have identical geometry designated by the ISO as SEKN 1204 AFN which denotes a basic square geometry with a wiper edge at the corners. The uncoated grade has a honed rake face and a radius of approximately 0.02 mm at the cutting edge as depicted in Fig. 1.

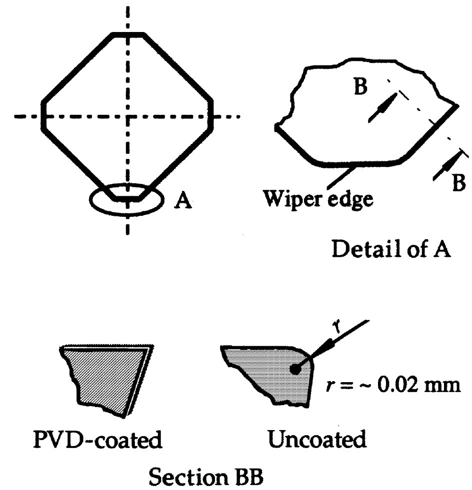

Fig. 1. The detail of the fine cutting edge geometry of PVD-TiN-coated and -uncoated tools.

The tool life was determined based on any of the following tool wear criteria:

1. Average wear on the main flank and/or nose is 0.3 mm.
2. A maximum flank wear of 0.7 mm.
3. When severe flaking or chipping larger than 0.4 mm width occurs.

Wear measurements were performed on an optical tool makers microscope without removing the inserts out of the cutter by using a special fixture. Thus avoiding any possible shortcomings as a result of removing and replacing the inserts.

2.3. Workpiece material

Cutting tests were performed on precipitation hardened Inconel 718 block with final dimensions of 400 mm ×

Table 1
Physical properties of the coating

Coating (PVD-ion plating)	TiN
Thickness (μm)	2–3.5
Hardness (HV)	2200
Hot hardness	800
Adhesion strength (indent, kg)	45
Thermal conductivity (W/mK)	25
Thermal experimental coefficient (10^{-6}/K)	9.35

Table 2
Physical properties of the substrates of the tools

	Tools		
	A	B	C
Coating	PVD-TiN	PVD/TiN	Uncoated
Composition (wt.%)	86 WC, 11.5 Co, 2.5 TaC	93.5 WC, 6.0 Co, 0.5 Cr_3C_2	90.1 WC, 9.5 Co, 0.4 VC
Grain size (μm)	1–6	1–3	0.8
Hardness at 25°C (HV)	1460	1830	1550
Thermal conductivity (W/mK)	67.4	78.8	85
Thermal expansion coefficient (10^{-6}/K)	5.26	5.31	5.5
Compressive strength (GPa)	4.84	6.71	4
Fracture toughness (MPa $m^{1/2}$)	12.6	8.7	15
TRS (GPa)	2.61	2.77	3.6

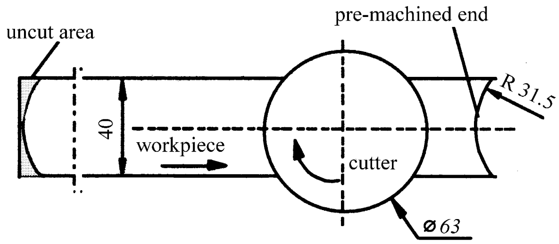

Fig. 2. Cutter–workpiece relative position and the end geometry of the workpiece (dimensions are in millimetre).

125 mm × 40 mm. All surfaces of the block were pre-machined to the above dimensions by removing a layer of 3 mm depth prior to the machining tests.

In order to provide a constant entry and exit angles during the trials, one end of the workpiece was pre-machined with respect to the cutter diameter, while the other end was left uncut, as shown in Fig. 2. The workpiece was securely clamped directly onto the machine table by means of a fixture in order to provide maximum rigidity. The mean hardness of the workpiece was 486 HV. The nominal chemical composition of the material is given in Table 3.

Table 3
Chemical composition of Inconel 718

Inconel 718 composition	wt.%
Ni	53.3
Nb	4.98
Ti	0.94
Cr	19
Cu	0.04
Mo	3.03
Al	0.56
Si	0.1
Fe	18.5
Mn	0.1
C	0.034

3. Results and discussion

3.1. Effect of cutting speed and feed rate on tool life and tool wear

In terms of tool life, the uncoated tool (Tool C) outperformed both the coated tools (Tools A and B) at cutting speed of 25 m/min and at both feed rates of 0.08 and 0.14 mm per tooth with respective tool lives of 32 and 22 min.

At low feed rate of 0.08 mm per tooth, Tool B gave longer tool life than Tool A at all cutting speeds. Both the coated tools (Tools A and B) outperformed uncoated tools (Tool C) considerably at cutting speed of 50 m/min as shown in Table 4. At speed of 75 m/min, Tool A recorded a tool life of less than 1 min compared to Tool B which lasted for 2.5 min. However, both tools experienced severe chipping or breakage when cutting speed was raised to 100 m/min, generating a short tool lives of under 1 min.

At high feed rate of 0.14 mm per tooth and the speed of 25 m/min, Tools A and B gave equal tool life performance. Increasing the cutting speed to 75 and 100 m/min, both tools gave tool lives of under 1 min, due to dominant wear modes of cutting edge breakage and severe chipping.

In terms of the volume of metal removed, all tools gave their best results when cutting at high feed rate of 0.14 mm per tooth and at cutting speed of 25 m/min. The highest volume of metal removal was achieved with Tool C at these cutting conditions (Table 4).

The flank wear developed either on the main cutting edge or on the nose, controlled the tool life at all cutting conditions for all the three types of inserts. Wear rate was observed to increase with increase in cutting speed as shown in Figs. 3 and 4, for both feed rates of 0.08 and 0.14 mm per tooth. These figures suggest that a sharp increase occurred in the wear rate when cutting at low feed rate of 0.08 mm per tooth and at cutting speed of 75 m/min and above. Similar increase in wear rate occurred at cutting speed of 50 m/min with a feed rate of 0.14 mm per tooth.

Table 4
Tool lives and corresponding volume of metal removed when face milling Inconel 718

Cutting speed (m/min)	Tool	Feed = 0.08 mm per tooth		Feed = 0.14 mm per tooth	
		Tool life (min)	Removed material (cm^3)	Tool life (min)	Removed material (cm^3)
25	A	13	156	14	296.8
	B	23	276	14	296.8
	C	32	384	22	466.4
50	A	7	168	3	127.2
	B	10	240	0.7	29.6
	C	3	72	2.6	110.2
75	A	0.5	18.2	0.3	19
	B	2.5	91	0.5	31.8
100	A	0.15	7.2	0.1	8.4
	B	0.7	33.8	0.3	29

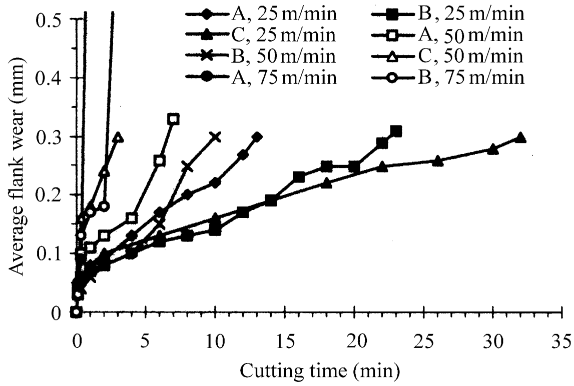

Fig. 3. Development of average flank wear when face milling Inconel 718 at feed rate of 0.08 mm per tooth.

3.2. Tool wear and associated mechanisms

In order to understand the development of tool wear, the worn tools were examined thoroughly under scanning electron microscope (SEM) at two stages. The first stage was after machining for 5 s and the second stage was at the end of tool life. The observed wear modes at both stages are presented in Table 5.

3.3. Initial tool wear

The dominant wear modes observed at the early stage of cutting (after 5 s) were galling and adherence of workpiece material with associated coating delamination and substrate pitting or plucking. In addition, discrete micro-chipping of the cutting edge was observed at low cutting speeds of 25 and 50 m/min. The scale of chipping at this initial stage increases when high cutting speeds of 75 m/min and above were employed, thus causing severe breakage of the insert along the nose and main cutting edge. These were the dominant wear modes over the passage of time with discrete micro-chipping evolving into severe pitting, chipping or breakage of the cutting edge. Similar phenomena were observed on both coated and uncoated tools.

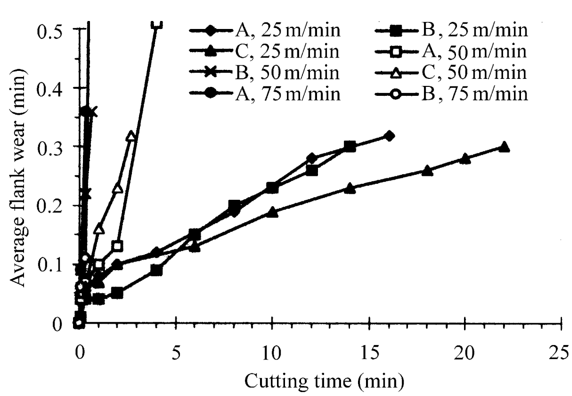

Fig. 4. Development of average flank wear when face milling Inconel 718 at feed rate of 0.14 mm per tooth.

Table 5
Wear modes observed on the tools at an early stage of 5 s cut and at tool failure[a]

Cutting speed (m/min)	Tool	Initial wear modes	Wear modes at failure	
			LF[b]	HF[c]
25	A	g, mc, p, ca, cd	g, pc	g, pc
	B	g, mc, p, ca, cd	g, pc	g, pc
	C	g, mc, p, ca	g, pc	g, pc
50	A	g, mc, p, ca, cd	g, pc	g, pc, fl
	B	g, mc, p, ca, cd	g, pc	g, sc
	C	g, mc, p, ca	g, sc	g, sc
75	A	g, sc, p, cd	g, b	g, b
	B	g, sc, p, cd	g, sc, fl	g, b, fl
100	A	g, sc, p, cd	g, b	g, b, fl
	B	g, sc, p, cd	g, b, fl	g, b, fl

[a] g: galling, pc: progressive chipping, sc: severe chipping, ca: chip adhesion, fl: flaking, cd: coating delamination, p: pitting or plucking, b: breakage.
[b] Low feed rate.
[c] High feed rate.

SEM micrographs in Figs. 5–7 clearly show the presence of galling on the rake and flank faces in addition to the adherence of small chip particles at the sharp section of cutting edge of coated tools (Tools A and B) and uncoated tool (Tool C) after cutting for 5 s.

The adherence of the workpiece material can be attributed to its austenitic f.c.c. structure that work hardens rapidly and also to the reactivity of nickel-based material with the tool material [14]. The grinding marks left on the rake (Figs. 6 and 7) and flank (Fig. 5) faces of the tools may have cause the initiation of workpiece adhesion in the form of galling within the ridges. This phenomenon became more significant when the grinding marks were not parallel to the direction of the chip flow, which will then act as mechanical barriers.

Figs. 5 and 6 suggest that the PVD-TiN coating was removed from the contact zone over the rake face of the

Fig. 5. An SEM image of Tool A after cutting for 5 s, showing galling and pitting on the rake and flank faces (at 25 m/min and 0.14 mm per tooth).

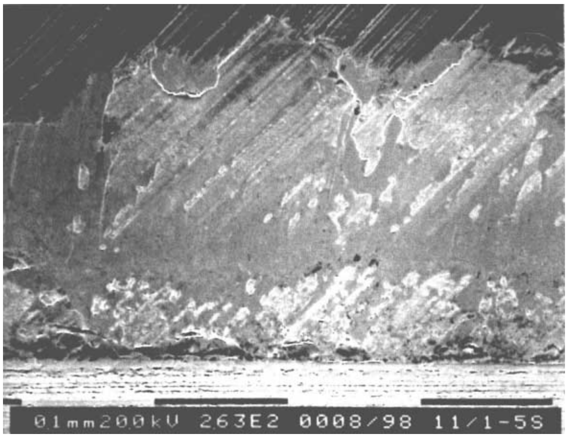

Fig. 6. An SEM image of Tool B after cutting for 5 s, showing galling, coating delamination and pitting on the rake face and adhesion of relatively large chip particles at the cutting edge (at 25 m/min and 0.08 mm per tooth).

tools by the removal of strongly adhered workpiece layer causing separation at coating/substrate interface. This separation was so obvious at the back region of the tool–chip contact zone when grinding marks on the substrate were easily distinguished. While in the front region next to the cutting edge, substrate pitting or plucking were observed as shown in Figs. 5 and 6.

An EDAX analysis (Fig. 8) taken over the plucked areas of Tool A indicates that the coating has been removed from at the coating/substrate interface. During initial cutting, it was found that the plucked areas on the substrate and removal of coating layers were caused by the chips leaving the tool at the moment of cutter exit or re-entry. When chip samples were inspected, patches of tool material were found attached to the lower end of the chips as shown in Fig. 9. EDAX analysis in Fig. 10 shows the presence of the tool material (W) at the back side of the lower end of the chip. Microscopic analysis on the uncoated tool (Tool C) at this early stage of cutting revealed the presence of galling

Fig. 7. Galling and pitting on the rake face of Tool C after cutting for 5 s. Adhesion of relatively large chip particles at the cutting edge was also observed (at 50 m/min and 0.14 mm per tooth).

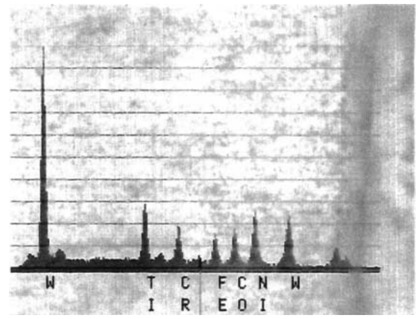

Fig. 8. An EDAX analysis performed on the pitted areas of the rake face of Tool A showing the presence of tungsten which indicates the exposure of the substrate within 5 s of cutting (at 25 m/min and 0.14 mm per tooth).

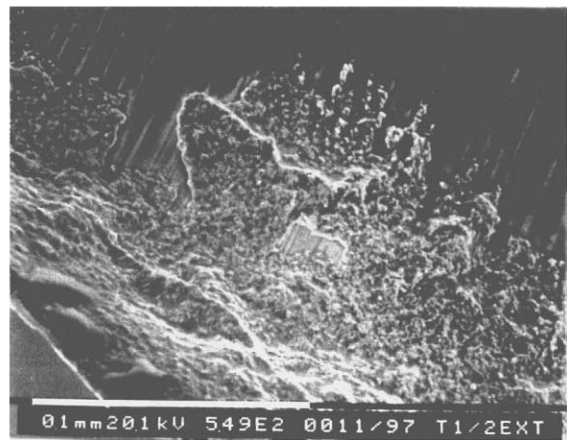

Fig. 9. An SEM image showing adhered tool material at the lower end of a chip which was produced by Tool A after cutting for 5 s at 50 m/min and 0.08 mm per tooth.

and plucked areas on the rake face. This suggested that similar mechanisms to that of coated tools occurred, but to a lesser degree due to the low cutting speed (25 m/min) employed.

Fig. 11 clearly shows that galling consists of a few thin layers of smeared workpiece material which were formed on top of each other. These layers were easily distinguished by the position of their edges next to the border of a pitted area on the rake face of the coated tool (Tool B) after 5 s of cutting at speed of 75 m/min and feed rate of 0.14 mm per

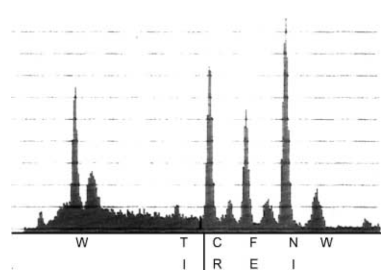

Fig. 10. An EDAX analysis on the worn region of Tool A in Fig. 9, indicating the presence of adhered tool material (W) to the end section of the chip.

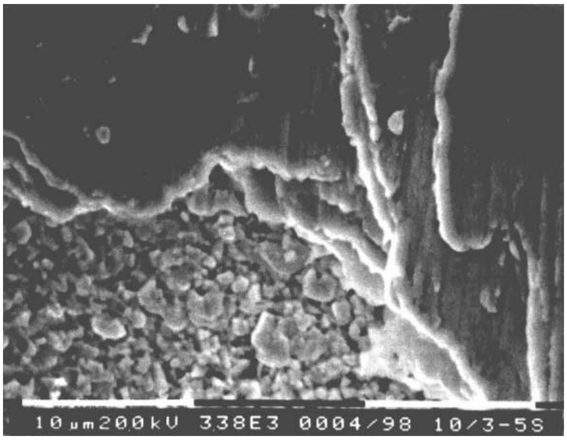

Fig. 11. An SEM image of worn region of Tool B after cutting for 5 s, showing severe galling that consists of a few thin layers of smeared workpiece material (at 75 m/min and 0.14 mm per tooth).

tooth. This strongly indicates that the chips have undergone a secondary shear process across the tool–chip contact zone with complete seizure taking place over a large portion of the tool–chip interface. Under the conditions tested, the removal of coating layer from the rake face of the coated tools (Figs. 5 and 6) indicates that the bond between the adhered material and the rake face is stronger than the one between the TiN coating and the carbide substrate. As a result, separation of the coating layer took place when the adhered workpiece was forced and pushed away by the shearing action due to the chip flow or by the detachment of the chip at cutter exit or entry.

The removal of coatings and the substrate material in this manner was probably due to the cyclic thermo-mechanical stresses which are inherent in the milling process. The interface between the coating and substrate was disturbed due to the differences in thermal expansion coefficients of the substrate and coatings (Tables 1 and 2) and also due to the fluctuating mechanical forces. On the other hand, high shear force in the flow zone under seizure condition influences the coating/substrate interface by imposing a stress in the direction of chip flow. In an earlier work, Wright and Chow [15] reported that the shear strain generated within the chip at the tool/chip interface under seizure condition was very much higher (between 20 and 50) than that of the primary shear zone (between 2 and 5) when machining Inconel 718. As a result of high shear strain combined with the high-temperature strength of nickel-based alloys, a steep temperature rise is generated at the interface thus facilitating good adhesion and lowering the strength of the tool material. Based on the above phenomena, coatings and/or WC grains from the substrate may well be picked up by the chip leaving the tool during the cutter exit where a momentary tensile force was induced due to sudden release of the compressive forces [16] and the tendency of self-evacuation of the chip which aided by its weight. If, however, the chip remains attached to the cutting edge after exit, it will be removed during the next entry by the newly formed chip.

The second type of adhesion was the welding of relatively large chip particles to the sharp sections of the cutting edge and the chipped areas, this is shown in Figs. 6 and 7. Based on the size and shape of the adhered material at the tool edge, it is most likely that the end section of the chip had remained attached when the main body was torn away. This type of adhesion can be very detrimental if it stays at the tip of the cutting edge. The new cutting edge adversely affects the chip flow and the shear pattern in the primary and secondary deformation zones [17]. This kind of adherence was observed during the entire cutting period which increased gradually towards the end of tool life.

The rough and uneven characteristic of the plucked tool surface (Figs. 5 and 7) and clear separation of the coating from the substrate (Fig. 6) were possibly due to attrition wear mechanism whereby fragments of tool material were removed from the contact zone of the tool face. The main reason for this kind of wear mechanism appears to be the localised tensile stresses imposed on the tool by intermittent chip flow [18] during interrupted cutting. The tensile stresses are imposed by the chip detachment during the tool exit and by the sudden ejection of the adhered chip on the next entry.

3.4. Chipping and breakage of the cutting edge

Micro-chipping was observed to occur in a discrete manner on both coated and uncoated tools along the cutting edge after 5 s of cutting, an example is shown in Fig. 12. However, the occurrence of micro-chipping was relatively more frequent on the PVD-coated tools and it became very severe when cutting speed and feed rate were increased (Fig. 13). The lack of chipping resistance of the PVD-coated tools when compared to uncoated tool could be attributed to its sharp cutting edge which was more sensitive to stress concentration and to cyclic impacts and vibration generated during the milling process. The honed edge combined with a cutting edge radius of ∼0.02 mm (Fig. 1) increased the chipping resistance of uncoated tool (Tool C) in addition

Fig. 12. An SEM image of the worn region of Tool B after cutting for 5 s, showing micro-chipping at the main cutting edge (at 25 m/min and 0.08 mm per tooth).

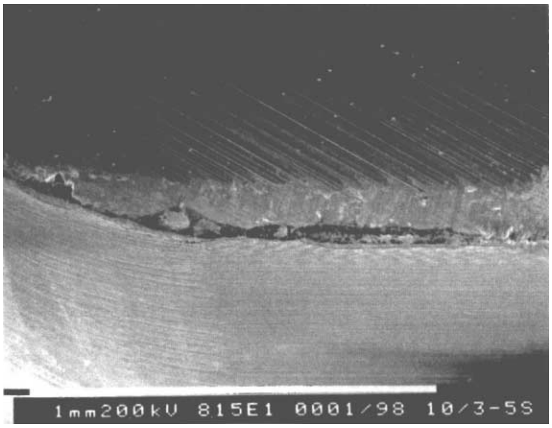

Fig. 13. An SEM image of Tool B after cutting for 5 s, showing micro-chipping along the main cutting edge at high cutting speed (at 75 m/min and 0.14 mm per tooth).

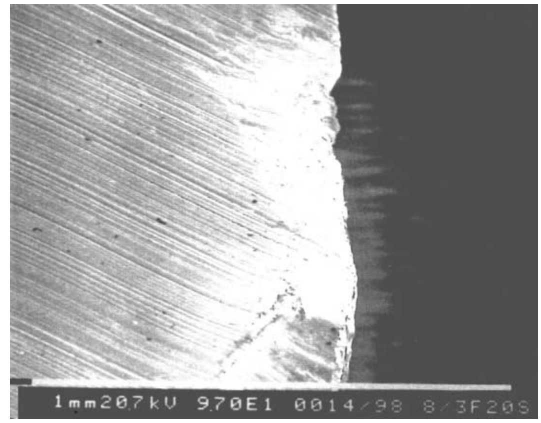

Fig. 15. An SEM image of Tool A at failure showing severe chipping and associated deformation of the entire cutting edge at high cutting speed (at 75 m/min and feed rate of 0.14 mm per tooth).

to its greater transverse rupture strength and fracture toughness when compared to coated tools (Tools A and B) as shown in Tables 1 and 2.

As cutting continued, chipped areas progressed from a microscale to a larger scale by overlapping on each other along the cutting edge (Fig. 13). Chipping was found to develop more into the tool flank than on the rake face particularly at low cutting speed of 25 m/min for both feed rates of 0.08 and 0.14 mm per tooth. The dominant wear mechanisms which resulted in tool failure were a combination of alternating occurrence of galling and progressive chipping and/or plucking and, to a lesser degree of abrasion (Fig. 14). As such, the contribution of the coating layer on the tool flank to resist wear was not significant. Under the conditions tested, easy delamination of the weakly bonded coating at the early stage of machining may encourage formation of galling, progressive chipping and plucking.

At higher cutting speeds of 75 and 100 m/min, severe chipping or breakage with associated plastic deformation occurred along the cutting edge as shown in Fig. 15, thus resulting in premature failure of the tools. The most likely causes of the premature failure are believed to be the high mechanical impact induced due to intermittent cutting and high temperature generated at the vicinity of the cutting edge. The width of the tool–chip contact zone on the rake face of the tools was found to have reduced by $\sim$40% at higher cutting speed of 100 m/min, resulting in a shift of the hottest region towards the cutting edge by the same amount. This suggest that the strength of the cutting edge was significantly reduced when cutting at higher speed making it prone to chipping and/or deformation. Once chipping occurred, the original geometry of the cutting edge was altered which subjected the cutting edge to extreme compressive stresses. In addition to this effect, the sharp sections of the chipped areas also act as stress raisers and lead to a further deformation, mechanical crack initiation or breakage. Initiated cracks are expected to propagate with ease under cyclic thermo-mechanical shocks which are caused during face-milling operation.

Fig. 14. An SEM image of the worn region of Tool C, showing severe chipping and galling on the main edge flank (at 25 m/min and 0.08 mm per tooth).

4. Conclusions

The performance of two PVD-TiN coated and an uncoated tool was studied when face milling Inconel 718 nickel-based superalloy. The conclusions drawn from the study are as follows:

1. The uncoated tool (Tool C) performed better than the PVD-TiN-coated tools (Tools A and B) at the lowest cutting speed of 25 m/min. This was due to its better resistance to attrition wear. The radius at the cutting edge of the uncoated tool gave additional mechanical strength resulting in increased chipping resistance.
2. Premature removal of the coating layers from the tool–chip contact zone hindered the overall performance of the PVD-TiN-coated tools at cutting speed of 25 m/min.

3. PVD-TiN-coated tools gave a better performance than the uncoated tool at cutting speed of 50 m/min and feed rate of 0.08 mm per tooth. This can be attributed to the high wear resistance and low thermal conductivity of TiN coating layer that remained intact on the flank face.
4. At a feed rate of 0.14 mm per tooth and high cutting speeds of 75 and 100 m/min, both the coated tools gave tool lives of less than 1 min. This can be due to the dominant failure modes of cutting edge breakage and severe deformation.

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