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Wear and tool life of tungsten carbide, PCBN and PCD cutting tools

J.A. Arsecularatne[a,*], L.C. Zhang[a], C. Montross[b]

[a]School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Sydney, NSW 2006, Australia
[b]Ringwood Superabrasives Pty Ltd, 111 Gladstone Street, Fyshwick, ACT 2609, Australia

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Abstract

The wear mechanisms of cutting tools made of tungsten-carbide (WC), PCBN and PCD were investigated using the tool life and temperature results available in the literature. For tool/work combinations WC/steel and PCBN/hardened-steel, under practical conditions, tool wear was found to be greatly influenced by the temperature. It was concluded that the most likely dominant tool wear mechanism for WC is diffusion and that for PCBN is chemical wear. For PCD, more experimental results and hence further research is required to determine the dominant wear mechanism.

Keywords: Tool wear; Tool life; Tool temperature; Tungsten carbide; PCBN; PCD

1. Introduction

An ability to predict the tool life during machining is necessary for the design of cutting tools and the determination of cutting conditions and tool change strategies. The extensive research in this area during the past century or so has contributed greatly to our understanding of the problem. However, there is as yet no machining theory to provide adequate relationships between tool life and cutting conditions, tool geometrical parameters and, work and tool material properties. Some of the major difficulties are: (i) the complexity of the machining process which involves extreme conditions of very high strains, strain-rates and temperatures, and (ii) lack of suitable data. Moreover, tool life depends on a number of variables which include the machine tool, tool material and geometry, work material and cutting conditions. The situation is further compounded by the continuous development and introduction of new tool materials (e.g. PCD, PCBN and CVD diamond coated tools), work materials (e.g. particulate/fibre/whisker reinforced metal matrix composites (MMCs)) and by the changes in machining conditions (e.g. in high speed machining).

For a practical machining situation, since no machining theory is available to predict the tool life, one is compelled to rely on empirical relations such as those proposed by F.W. Taylor early in the last century. However, in order to predict tool life/wear in a fundamental way, an in-depth understanding of tool wear mechanisms is required.

The present work uses tool life, temperature, and Taylor tool life exponent results available in the literature to investigate the dominant wear mechanisms of the cutting tools made of tungsten carbide (WC), PCBN and PCD.

2. Tool wear

In turning, catastrophic tool failure is to be avoided since it can damage the component, the tool and/or the machine tool and thus interrupt the machining process substantially. Instead, the useful life of a tool can be defined in terms of the progressive wear that occurs on the tool rake face (crater wear) and/or clearance face (flank wear). Of these two, flank wear is often used to define the end of effective tool life. This is also physically more meaningful as the flank wear land width has, once a certain level is reached, a major

* School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Sydney, NSW 2006, Australia. Tel.: +61 2 9351 7150; fax: +61 2 9351 3760.

E-mail address: joseph.arsecularatne@aeromech.usyd.edu.au (J.A. Arsecularatne).

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Notation

A, B	constants in Eq. (2)
A_t, b_t	constant, exponent in Eq. (1)
BN	boron nitride
BUE	built-up edge
CBN	cubic boron nitride
C_t, d_t	constant, exponent in Eq. (7)
C	constant in Eqs. (5) and (6)
D_c, D_d	constants in Eqs. (3) and (8)
d	depth of cut (mm)
E_c, E_d	activation energy in Eqs. (3) and (8)
f	feed (mm/rev)
K_c, K_d	exponents in Eqs. (3) and (8)
ln	natural logarithm
PCBN	poly-crystalline cubic boron nitride
PCBN-H/-L	high/low CBN content PCBN
PCD	poly-crystalline diamond
R^2	correlation coefficient
r_ε	tool nose radius (mm)
t	time
T	tool life
T_f	tool flank temperature (K)
T_t	tool temperature (K)
V	cutting speed (m/min)
VB_B	average flank wear land width (mm)
$W_a/W_c/W_d$	mass loss due to abrasion/chemical-wear/diffusion of the tool
$W_{ao}/W_{co}/W_{do}$	mass loss during life of a tool due to abrasion/chemical-wear/diffusion
w	width of cut (mm)
WC	tungsten carbide

negative influence on dimensional accuracy and surface finish of the component as well as the stability of the machining process. Hence the present investigation mainly concentrates on flank wear and tool life based on this type of wear when machining with WC, PCBN and PCD tools.

2.1. Wear of WC tools

It is well accepted that, during machining of steel work materials with WC tools, several wear mechanisms such as abrasion, adhesion, oxidation, diffusion, etc. can operate simultaneously [1–6]. Thus under a given set of machining conditions, determination of the dominant wear mechanism is difficult. However, Hastings and Oxley [1] and Opitz and Konig [2] have pointed out that, the most likely dominant wear mechanisms and the corresponding cutting speeds/temperatures are: abrasion at low speeds/temperatures, followed by adhesion at moderate speeds/temperatures and then diffusion at high speeds/temperatures. By superposition of these wear mechanisms, they were able to explain the observed variations of tool wear[1] over a wide range of cutting speeds [1,2]. That is, the total wear occurring on a tool contact face (e.g. flank face) is equal to the sum of the wear occurring due to the separate effects of the above wear mechanisms. It should be noted that all of the above wear processes will not occur simultaneously. Moreover, the dominant wear mechanism will depend on the cutting conditions and, tool and work materials.

[1] Typically, tool wear rate increases with increase in cutting speed within the speed range normally used in practice. At lower speeds, the wear rate curve has one or more turning points which are attributed to changes in the tool wear mechanism.

2.2. Tool wear/life relationships

The well-known Taylor equation [7] which is the most widely used tool life relation in machining can be written as:

$$T = \frac{A_t}{V^{b_t}} \tag{1}$$

where T is tool life, V is cutting speed and A_t, b_t are constants. Although this equation was originally developed for machining with high-speed steel tools, it has been applied in machining with WC as well as PCD and PCBN tools. On the other hand, it has been shown that, for a given tool/work material combination, the above equation does not agree well with experimental results over wide ranges of cutting conditions [8]. This has been attributed to the changes in the dominant tool wear mechanism with changes in cutting conditions. Nevertheless, reasonable agreement has been shown over ranges of speeds normally used in practice [4].

It has also been shown that there is considerable evidence, both theoretical and experimental, that the tool temperature has a great influence on tool wear rate and tool life [1,9]. In fact, in Eq. (1), cutting speed seems to influence tool life through temperature. The evidence also supports the observation that, for a particular tool/work material combination, the tool life and tool temperature are related by the empirical equation [1,9]

$$T = AT_t^{-B} \tag{2}$$

where T_t is tool temperature and A and B are constants. The validity of Eq. (2) depends on the existence of a dominant, temperature dependant wear mechanism [1,9]. It has been shown that, for carbide tools, at practical cutting speeds (where no built-up edge is observed and the tool temperatures are normally above 800 °C), the dominant wear mechanism is diffusion [1,9–16][2].

In their investigation on tool flank wear, Takeyama and Murata [16] argued that the amount of tool flank wear is given by the sum of the wear due to abrasion and temperature sensitive diffusion. They considered abrasion to be proportional to the cutting distance and independent of tool temperature. Diffusion was considered to be temperature dependant and the wear rate could be represented by Arrhenius type equation

$$\frac{\mathrm{d}W_\mathrm{d}}{\mathrm{d}t} = D_\mathrm{d}\,\mathrm{e}^{-E_\mathrm{d}/K_\mathrm{d}T_\mathrm{t}} \tag{3}$$

where D_d and K_d are constants, E_d is activation energy and T_t absolute tool temperature. Note that tool life T is normally defined by the machining time for an average flank wear land width[3]. Assuming T_t is approximately constant (with varying wear land width), from Eq. (3), the mass loss due to wear during the life of the tool W_do is [16]:

$$W_\mathrm{d0} = D_\mathrm{d}\,\mathrm{e}^{-E_\mathrm{d}/K_\mathrm{d}T_\mathrm{t}}T \tag{4}$$

In [16], tool temperature, tool life and tool wear rate results were obtained when machining steel and cast iron using P10 grade WC tools. It was shown that the experimental results for temperatures above 800 °C could be represented well by Eqs. (2)–(4) thus indicating that wear of tested tools was dominated by diffusion.

Oxley [9] and his co-workers [18–20] have shown that experimental tool life values could be used in conjunction with temperature values determined from a machining theory,[4] as opposed to experimentally measured temperatures, to obtain the constants A and B in Eq. (2). When compared with pure empirical methods, the theoretical method appears far more effective in predicting tool life as it allows tool geometrical parameters and cutting conditions to be combined into the single parameter of temperature. Since Eq. (2) has only two constants, they were determined using a relatively small number of tests and the resulting equation was used to predict tool life over a much wider range of conditions. This approach was initially applied to orthogonal [9] and oblique [18] conditions with plane face tools. Later it was extended to tools with restricted contact and commercial chip grooves [19,20] with considerable success. It is noteworthy that in the investigations reported in [9,18–20], diffusion was considered to be the dominant tool wear mechanism.

Wear mechanisms abrasion and oxidation of WC tools were considered by Hastings and Oxley [1] and Trent and Wright [10]. They have pointed out that, when machining steel work materials, these mechanisms are unlikely to be dominant under the conditions normally used in practice (i.e. at relatively high cutting speeds). This is due to (i) the insufficient amount of abrasives present in the work material, (ii) insufficient hardness of abrasives to abrade WC and (iii) inability to detect any significant signs of abrasive wear in extensive metallurgical studies. However, there are certain conditions under which abrasive wear of WC tools have been observed. These will be discussed later in the paper.

Adhesive wear[5] of WC tools has also been investigated. Usui et al. [22] and Kitagawa et al. [23] assumed that, under practical conditions, wear of WC tools was due to adhesion, that wear rate could be represented by a relation similar to Eq. (3) and that wear should increase with the normal stress on the tool flank. This is one of the major drawbacks of these studies since reliable experimental results or an analytical method to determine this stress is not yet available. Another is that the predicted results in [22,23] indicate elastic contact at flank/work interface in spite of experimental evidence of plastic contact reported by Trent and Wright [10]. Moreover, Iwata et al. [21] showed that adhesion between WC and steel (hence adhesive wear rate) becomes a maximum at ~600 °C and thereafter falls off rapidly with further increase in temperature.

2.3. Abrasive wear

Mechanical abrasive wear is considered to be due to microscopic hard abrasives contained in the work material and/or dislodged abrasive grains from the tool material abrading the tool. This is essentially a micro-cutting process that produces chips and leaves grooves [1]. This type of wear is closely related to the distance of cut as well as shape, hardness and distribution density of the abrasives. Assuming that abrasive wear is independent of the temperature, the wear rate due to abrasion is given by [16]:

$$\frac{\mathrm{d}W_\mathrm{a}}{\mathrm{d}t} = CV \tag{5}$$

[2] Diffusion wear is due to the migration of atoms/molecules of the tool and/or work materials through the interface to form an alloy locally [10,11]. Trent and Wright [10] cited smoothly worn through carbide grains on tool flank under near seizure conditions at the flank/work interface as evidence of diffusion to be dominant wear mechanism for WC tools. From their static diffusion tests with ferrous work materials and WC tools, Narutaki and Yamane [11] showed that, under temperatures encountered in machining, Co, C and W diffused from tool to the work material while Fe diffused from work material to the tool.

[3] According to the ISO [17], the criterion for tool life of WC tools is 0.3 mm for average flank wear land width VB_B or 0.6 mm for the maximum groove depth.

[4] This theory takes account of variations in work material flow stress with strain, strain-rate and temperature and of thermal properties with temperature has been applied with considerable success in predicting cutting forces, temperatures, etc. from a knowledge of the work material properties and cutting conditions.

[5] This type of wear is due to cyclic adhesion of work material to the tool followed by failure within the tool [8].

where C is a constant[6]. Since tool life, T is the time to reach a predetermined wear value W_{ao}, it is obtained from Eq. (5) as:

$$W_{a0} = CVT \quad (6)$$

That is, tool life is inversely proportional to the cutting speed.

The experimental results in [16], for conditions of low speeds (and low temperatures) show that tool wear mainly depends on cutting distance and is approximately independent of temperature as indicated by Eq. (6). More recent results on this topic will be presented later in the paper.

2.4. PCBN tools

Compared to WC tools discussed above, PCBN tools are relatively new. Since their introduction, a number of research investigations on wear of these tools in hard turning have been reported. From the literature, it is clear that there are considerable differences with regard to the most likely dominant wear mechanism of these tools.

On machining of hardened steels, two reviews have been presented by Tonshoff et al. [24] and Konig et al. [25]. The PCBN tools considered in most of the reported investigations had either high CBN content (∼90% CBN with metallic binder) referred to as PCBN-H or low CBN content (50–70% CBN with ceramic binder) referred to as PCBN-L. Wear of PCBN tools seem to be influenced by the composition/hardness/microstructure of the steel work material [26–30], tool geometry [31] and cutting conditions [32,33]. A characteristic wear curve similar to that observed with WC tools has also been noted for PCBN [30,34]. That is, tool wear rate increases with increase in cutting speed within the speed range normally used in practice. At speeds below this range, the wear rate curve has one or more turning points which are attributed to the changes in the dominant tool wear mechanism.

It has been observed that when machining high speed steel (HSS), PCBN-L tools show higher wear rate than PCBN-H. With other hardened steels (e.g. case hardened steel, AISI-52100, etc.) and softer steels (e.g. plain carbon steels), PCBN-L tools show lower wear rate than PCBN-H [29,35,36]. In order to explain this wear behaviour, Narutaki and Yamane [35] argued that wear of PCBN-L when machining HSS was mainly due to abrasion by hard carbide particles in HSS. Wear of PCBN-H was attributed to attrition. Based on an SEM study of the built-up layers[7] on the flank wear scars of PCBN-L and PCBN-H tools, Chou et al. [36] argued that the built-up layers on PCBN-L are not as strongly bonded as those on PCBN-H tools and that adhesion interacted with built-up layer was a dominant wear mechanism. The observed stronger adhesion on PCBN-H was attributed to higher affinity of the metallic binder to the built-up layer.

Luo et al. [26] and Poulachon et al. [27,28] studied the wear of PCBN-L tools when turning different hardened steels. Based on the observed grooves on flank wear scars of these tools, they concluded that tool wear is mainly due to abrasion of the tool/binder by hard carbide particles in the steel work materials. In another interesting investigation on hard turning with mono-crystalline CBN (MCBN) tools, Tsuji et al. [37] observed rapid tool flank wear which did not depend on the tool crystal orientation.

Klimenko et al. [30,38], investigated wear of PCBN tools when machining hardened steels and found formation of a built-up layer at the work–flank interface due to chemical interactions of tool with work material and atmosphere. They found the built-up layer to be in a molten state possibly due to lower melting temperature of newly formed chemical compound(s) and also found evidence of melt being squeezed out of the tool/work contact zone into the non-contacting tool faces and surrounding atmosphere thus continuing the formation and removal of the reactionary products. These reactionary products were found to consist of borides, carbides, nitrides and oxides of elements iron/chromium/titanium from work piece/tool. They concluded that wear of PCBN tools is mainly due to chemical wear.

The presence of built-up layers and/or different elements on the worn tool surfaces was also noted by Barry and Byrne [29]. They investigated the wear of PCBN-L tools when machining different heats of hardened AISI-4340 steel and suggested that wear of PCBN tools was mainly chemical in nature. Their results showed that the chemical composition of the steel (notably percentage aluminium) had a marked influence on the tool wear rate. The presence of built-up layers on worn tool flank faces was also noted by Farhat [39], who machined hardened P20 tool steel with PCBN-L. However, based on the worn flank topography (presence of shallow ridges and hills), Farhat identified diffusion to be the dominant wear mechanism.

From the above review, it can be seen that different wear mechanisms such as abrasion, attrition, adhesion, diffusion, and chemical wear have all been used to explain the flank wear of PCBN tools. This indicates that wear of PCBN tools is not fully understood yet. This will be further investigated later in the paper.

[6] Another equation widely used to represent the abrasive wear rate is $dW_a/dt = PU/k$ where P normal stress, U velocity and k a constant. The major disadvantage of this equation is that the normal stress at the tool flank is required. As noted earlier, neither reliable experimental results nor an analytical method to determine this stress is available yet.

[7] These relatively thin layers, observed on wear scars of PCBN tools are formed as a result of chemical reactions among elements/compounds in tool/work materials and atmosphere. The reactionary products seem to have a melting point lower than those of tool/work materials [30].

2.5. PCD tools

It has been noted that there is an increasing trend to use aluminium alloy based metal matrix composites (MMCs)[8] in automotive applications, particularly, in the manufacture of engine blocks, connecting rods and pistons [40,41]. However, MMCs are normally considered as 'difficult to machine' materials due to their abrasive nature. A machining investigation on aluminium alloy based MMC reinforced with 20% SiC particulate, using WC, PCBN and PCD tools showed that, PCD gave the best performance (in terms of wear resistance), followed by PCBN. Moreover, PCD tools with larger grains (e.g. 50 μm) showed better performance than those with smaller grains (e.g. 5 μm), when edge chipping did not occur [42]. As a result, PCD has been recommended as the most suitable tool material for machining MMCs. Tool wear/life of PCD when machining MMCs have also been studied during the past 20 years.

Weinert [43] investigated wear of PCD tools when machining MMCs reinforced with Al_2O_3 (short fibre) and SiC and B_4C (particles). Based on the experimental wear rate results and observed topography of worn surfaces, wear of PCD was considered to be due to abrasion by dislodged diamond grains and/or micro-cracking and fatigue.

Lin et al. [44], Antonio and Davim [45], El Gallab and Sklad [46] and Andrews et al. [47] investigated wear of PCD tools when machining aluminium alloy based MMCs reinforced with 20% SiC particles. In [44–46], based on the observed grooves on the flank wear scars of these tools, abrasion was considered to be the dominant wear mechanism. The grooves were assumed to be formed due to abrasion by particles of SiC (reinforcements) and/or Al_2O_3 (formed at the cutting edge). Andrews et al. [47] attributed wear of PCD tools to abrasion and adhesion. Considering that hardness of PCD is higher than SiC, abrasion was considered to be associated with micro-mechanical damage rather than micro-cutting.

From the above review, it can be seen that different wear mechanisms such as abrasion, adhesion and, micro-cracking and fatigue have all been used to explain the flank wear of PCD tools. This indicates that wear of PCD tools is not fully understood yet. This will be further investigated later in the paper.

3. Tool temperature and cutting speed relations

It was noted that the tool temperature has a great influence on tool wear, e.g. in machining with WC tools. This section investigates the relations between tool temperature and cutting speed for the considered tool materials using available experimental results. These relations will then be used in Section 4 where the tool life and cutting speed relations are investigated.

3.1. Tungsten carbide tools

Perhaps, the most widely used method for temperature measurement during machining of steel work materials with WC tools is tool/work thermocouple method that employs the tool and the work as two elements of a thermocouple. However, the method has possible sources of errors, e.g. due to secondary contact when using WC insert tools. Although the method gives the average temperature at tool flank/work and rake/chip interfaces, the measured values were shown to be representative of average tool flank/work interface temperature [1,9]. Hastings and Oxley [1] have also shown that measured temperature values using this method agree well with predicted values using Oxley's theory under identical conditions.

It has been reported that the relation between experimental temperature and cutting speed can be represented well by a linear relation or a power function relation [48]. Analysis of temperature results obtained from the above method and reported in four studies (Table 1) revealed that, experimental temperatures for plane face uncoated[9] WC tools when machining steel work materials can be represented accurately using an equation of the form

$$T_t = C_t V^{d_t} \tag{7}$$

where C_t and d_t are constants. Note that the high correlation coefficient (R^2) values in Table 1 clearly indicate that the temperature versus cutting speed relation can be represented well by the power function (Eq. (7)). For a linear relation, the corresponding R^2 values were found to be much lower. From Table 1, it can also be seen that the d_t values are in the range 0.1866–0.3558 with all values except one have a range 0.1866–0.2480. The one outside this range, $d_t =$ 0.3558 corresponds to feed 0.05 mm/rev. If this d_t value is neglected (since the corresponding feed is low and is comparable to the cutting edge radius of WC tools), the d_t for the considered tool/work material combination is in the range 0.1866–0.2480.

3.2. PCBN tools

In order to measure the average tool flank face temperature of PCBN-L tools when machining hardened steel, Ueda et al. [52] used a two colour pyrometer. In this method, the infrared rays radiated from the cutting tool flank

[8] A typical MMC consists of a light weight metal as matrix (e.g. aluminium) and ceramic (e.g. Al_2O_3, SiC) fibres/particles/whiskers as reinforcements.

[9] It was noted that temperature results obtained using the tool/work thermocouple method are also available for coated WC tools in the literature. These results are not considered in the present work since the tool coating can form additional contacts and thus become an additional source of errors.

Table 1
The source, test conditions and calculated d_t values for experimental cutting temperature results (obtained from tool/work thermocouple method) for tool/work-material combination WC/steel

Author(s) and reference	Work material; tool material	Tool geometry and cutting conditions	Cut thickness (mm) or feed (mm/rev)	Cutting speed(s) m/min	d_t	R^2	Remarks
Chao and Trigger [49]	AISI-4142 steel; WC	$d=2.5$ mm	0.25	76–198	0.2002	1.0	Only three data points available (hence very high R^2 value)
Shaw [50]	0.44% C steel; P10/P30 grade WC	$w=3$ mm Rake angle $=5°$	0.05 0.10 0.20	50–350	0.3558 0.2270 0.2440	0.921 0.990 0.990	Results of tests where a BUE observed were neglected
Kurimoto and Barrow [5]	En26 low alloy steel; K45 grade WC	$d=2$ mm $r_\varepsilon=0.5$ mm	0.10 0.20 0.32	30–240	0.2480 0.2457 0.2418	0.998 0.990 0.992	Only dry machining results considered
Grzesik [51]	AISI-1045 steel; P20 grade WC	Orthogonal machining with $d=2$ mm	0.16	80–200	0.1866	1.0	Only regression line is available (hence very high R^2 value)

were used for measuring the temperature. The hardened steel work materials, tool geometry and cutting conditions used in [52] are given in Table 2. An analysis of their results revealed that, the measured temperature versus cutting speed relation can accurately be represented by Eq. (7) with R^2 values ≥ 0.9889. The determined d_t values were in the range 0.1550–0.1665 (Table 2).

From the results in Tables 1 and 2, it can be seen that the d_t values obtained for WC/steel tool/work-material combination are slightly higher than the corresponding values for PCBN/hardened-steel combination. This difference may be due to differences in thermal properties of the tool and/or work materials (e.g. thermal conductivity, specific heat) and/or due to differences in the temperature measurement technique (tool/work thermocouple method for WC tools, two colour pyrometer method for PCBN); differences in tool geometry (plane rake face for WC, edge chamfer for PCBN); differences in cutting conditions ($f>0.1$ mm/rev, $d>1$ mm for WC, $d=f=0.1$ mm for PCBN). Note that the higher d_t values for WC than for PCBN indicates that the influence of cutting speed on temperature is greater for WC tools.

It is not possible to consider the tool temperature versus cutting speed relation for PCD tools and MMC work materials due to non-availability of experimental tool temperature results. However, Ueda [53] has stated that the aforementioned two colour pyrometer technique used for PCBN tools can also be applied for PCD tools.

4. Velocity exponent of Taylor equation

As noted earlier, Taylor tool life Eq. (1) has been used to express tool life in terms of cutting speed when machining with WC, PCBN and PCD tools. An attempt is now made to further investigate the possible wear mechanism of these tools based on the reported values of the velocity exponent of Taylor tool life Eq. (1), b_t.

4.1. Tungsten carbide tools

As noted by Shaw [4], Takeyama and Murata [16] and Tomac and Tonnessen [54], when machining steel work materials using WC tools under practical conditions, b_t is normally in the range 3.3–5. From an analysis of tool life test results reported in [18], a value of 2.95 was obtained for b_t. These high values of b_t ($\gg 1$) indicate very high influence of V on T. From Eqs. (1) and (7), $T=A_t'/T_t^{b_t/d_t}$ where A_t' is a constant. For b_t in the range 2.95–5 and d_t in the range 0.1866–0.2480 (Section 3.1), the very high influence of temperature on tool life can be seen. This also supports diffusion as the dominant wear mechanism represented by Eq. (3).

Table 2
The test conditions and calculated d_t values for experimental temperature results (obtained from [52]) for the tool/work-material combination PCBN-L/hardened-steel

Work material	Tool geometry and cutting conditions	Feed (mm/rev)	Cutting speed(s) m/min	d_t	R^2
AISI-52100 (510 HV)	$d=0.1$ mm		100–200	0.1665	0.9988
15CrMo4 (650 HV)	$r_\varepsilon=0.2$ mm Rake angle $=5°$	0.1	100–300	0.1658	0.9889
AISI-52100 (700 HV)	Land $=0.1$ mm		100–300	0.1550	0.9925

Heath [40], Hung et al. [42,55] and Tomac and Tonnessen [54] carried out tool life tests using SiC particulate reinforced aluminium alloy based MMCs under low speed conditions (20–80 m/min) using WC tools. Based on the wear scar topography, the observed high flank wear rate was attributed to abrasion. This is to be expected because of low cutting speeds used and the higher hardness of SiC (21.5–29.5 GPa HK [42]) compared to WC (19–21 GPa HK [42]). The determined b_t values of Eq. (1) were in the range 0.86–1.64 and are much lower than those for WC/steel combinations discussed above. Such low b_t values indicate that tool life is not greatly influenced by the cutting speed but mainly by the cutting distance as indicated by Eq. (6) thus supporting abrasive type wear. Ideally, b_t should be 1 if abrasion was the only operating wear mechanism. The departure from 1 may be due to the difficulties associated with accurate measurement of tool wear when machining these aluminium alloy based MMCs. In [42], it was stated that the wear scars were covered by built-up aluminium which needed to be removed before wear measurements. The obtained value of b_t was 1.09 which is very close to unity.

From the result given above, it can be stated that for WC tools when machining steels at speeds normally used in practice, tool life is greatly influenced by tool temperature which supports diffusion as the dominant wear mechanism. On the other hand, when machining highly abrasive aluminium alloy based MMC, tool life depends on the cutting distance thus supporting mechanical abrasion as the dominant wear mechanism.

4.2. PCBN tools

In their tool life tests, Dowson and Kurfess [32] machined AISI-52100 steel (62 HRC) with coated and uncoated PCBN-L tools at cutting speeds in the range 91–183 m/min. Similar tests were carried out by Arsecularatne et al. [33] on AISI-D2 steel (62 HRC) using uncoated PCBN-H tools ($\sim$85% CBN with ceramic binder) at cutting speeds in the range 70–120 m/min. In these studies, testing was carried out until the end of tool life as defined by the limiting value of VB_B and reported that the tool life versus cutting speed relation could accurately be represented by Eq. (1). It was noted that, for all uncoated PCBN tools tested in [32,33], the obtained b_t values were in the range 2.29–2.79. These b_t values are much higher than unity (the velocity exponent of the abrasive wear Eq. (6)), which indicates that abrasion is not the dominant tool wear mechanism. On the other hand, from Eqs. (1) and (7), $T = A_t'/T_t^{b_t/d_t}$ where A_t' is a constant. For b_t in the range 2.29–2.79 and d_t in the range 0.1550–0.1665 (Section 3.2), the very high influence of temperature on tool life can be seen. These results show that the dominant wear mechanism of PCBN tools is highly temperature dependant.

4.3. PCD tools

For PCD/MMC tool/work-material combination, only one value for b_t was found from literature. In their tool life tests, Lin et al. [44] machined an aluminium alloy based MMC (reinforced with 20% SiC particles) using PCD tools at cutting speeds in the range 300–700 m/min. The obtained value of b_t in Eq. (1) was 2.73. It can be seen that this value is in the same range of b_t obtained for PCBN tools discussed above and is much higher than b_t values obtained when abrasion was the dominant wear mechanism.

It is clear that more reliable experimental results are necessary to determine the dominant wear mechanism of PCD tools when machining aluminium alloy based MMCs. It is noteworthy that Andrews et al. [47] has found (from an EDX analysis) that the wear scars of the PCD tools used to machine one of these MMCs (reinforced with SiC particles) were covered by a layer of aluminium alloy. Other investigators have also reported built-up of aluminium on the cutting edge of PCD tools that used to machine aluminium alloy based MMCs [45–47]. It was reported that the flank wear width values obtained before and after the removal of the adhered aluminium film differed as much as by 30% [47]. Therefore, it is essential that adhered aluminium is carefully removed from the wear scars of PCD tools used for machining these MMCs in order to obtain accurate experimental wear rate and/or tool life results. In order to remove the built-up aluminium, etching the tool in 10–15% NaOH solution has been recommended [42].

5. Discussion

It was noted that, during machining, several wear mechanisms, e.g. abrasion, adhesion, oxidation, diffusion, etc. can operate simultaneously. Thus under a given set of machining conditions, determination of the dominant wear mechanism is difficult. The present work investigated the dominant wear mechanisms and tool wear/life relations for WC (with steel and MMC work materials), PCBN (with hardened steel) and PCD (with MMC) tools.

5.1. WC tools

Based on the results discussed, under practical conditions (i.e. at relatively high cutting speeds), the dominant wear mechanism for WC/steel combination is diffusion. Moreover, an investigation of values of b_t of Eq. (1) and d_t values of Eq. (7) suggests a temperature controlled rate process such as diffusion as the dominant tool wear mechanism. On the other hand, when machining MMC work materials at low speeds, tool wear appears to be due to mechanical abrasion. This is supported by the experimental wear scar topography and the values of b_t in Eq. (1) which indicated abrasive type wear that depends little on temperature.

5.2. PCBN tools

From the review on PCBN tool wear in Section 2.4, it was noted that different wear mechanisms such as abrasion, attrition, adhesion, diffusion, and chemical wear all have been used to explain the flank wear when machining hardened steels. This clearly indicates that wear of PCBN tools is not fully understood yet. This is now investigated.

When machining AISI-D2 steel with PCBN-L tools, a built-up layer and grooves on the flank wear scars were observed by Poulachon et al. [27,28]. Consequently, flank wear was attributed to abrasion by hard carbide particles in the D2 steel work material. A built-up layer and grooves on flank wear scar were also observed by Arsecularatne et al. [33] who machined D2 steel with PCBN-H (having ceramic binder). These latter authors argued that their PCBN tools had ∼85% CBN and that the CBN grains are much harder than any hard carbide particles in the steel work material. They also argued that flank wear was due to chemical wear of binder/BN and that the observed grooves were caused either by dislodged CBN grains (which were swept away due to chemical wear of the binder) or by hard carbide particles in the steel work material when the binder/BN were subjected to chemical wear and formed a built-up layer that seemed to be in a molten state. This is also supported by the investigators who reported emission of liquid phase particles consisting of elements from tool, steel and atmosphere [30,38] and by those who reported relative abundance of elements from tool, steel and atmosphere on tool flank wear scars and/or built-up layers [29,30,38]. The chemical wear of these PCBN tools is also in agreement with observed topography of worn flank wear scars (once the adhered compounds were removed) that shows a porous like structure [29,39] and rapid wear of MCBN tools when machining hardened steels-flank wear did not depend on the crystal orientation [37].

Thus it can be seen that most of the available experimental evidence indicates wear of PCBN tools is of chemical nature. Hence in the present work, flank wear of these tools is considered to be due to continuous formation and removal of chemical compounds resulting from chemical reactions among elements/compounds from the tool, steel and atmosphere. Accordingly, the tool wear rate of PCBN is assumed to be given by the Arrhenius type equation

$$\frac{\mathrm{d}W_\mathrm{c}}{\mathrm{d}t} = D_\mathrm{c}\,\mathrm{e}^{-E_\mathrm{c}/K_\mathrm{c}T_\mathrm{f}} \tag{8}$$

where D_c and K_c are constants and E_c is activation energy corresponding to chemical reaction(s)[10]. Similar to diffusion wear of WC tools discussed in Section 2.2, the relation between tool life and temperature for PCBN is:

$$W_{\mathrm{c}0} = D_\mathrm{c}\,\mathrm{e}^{-E_\mathrm{c}/K_\mathrm{c}T_\mathrm{f}}T \tag{9}$$

That is, a linear relation should exist between ln(T) and 1/T_f. An attempt is now made to explore the possible relation between ln(T) and 1/T_f for PCBN tools using the available experimental results.

It was noted that Ueda et al. [52] measured the average tool flank temperature of PCBN-L tools using a two colour pyrometer. One of the work materials machined was AISI-52100 steel (∼60 HRC). For similar steel and cutting conditions, experimental tool life results were obtained by Dowson and Kurfess [32] for PCBN-L tools obtained from two suppliers (referred to as types A and B). In [32] and [52], the measured parameters, work/tool materials, tool geometry, cutting conditions and the corresponding empirical equations are given in Table 3 (the empirical constants of temperature equation in Table 3 were determined using the experimental results given in [52]). Despite many similarities in the experimental conditions in the above two investigations, some differences were also seen. Notably for tests in [52], tool nose radius r_ε=0.2 mm and depth of cut d=0.1 mm while in [32], r_ε=0.8 mm and d=0.2 mm. However, it is assumed that the differences in r_ε will not influence the temperature greatly. While a larger r_ε tool tends to generate more heat due to larger area of cut, it has also a larger area for heat dissipation. Differences in d are also neglected since, compared to speed and feed, d has much smaller influence on temperature and tool life.

Using the equations given in Table 3, tool flank temperature and tool life values were predicted for d= 0.1 mm, f=0.1 mm/rev and V=100, 125, 150, 175, 200 m/min. Using these T and T_f results, the obtained ln(T) vs 1/T_f relations are depicted in Fig. 1. Despite considerably different experimental tool life values for the two types (A and B) of PCBN-L tools, excellent linear relations between ln(T) and 1/T_f seem to exist for both sets of results. Note that the near perfect linear relation is due to smoothing of the experimental results using equations given in Table 3.

The above results further support the argument that wear of PCBN tools is due to a temperature controlled rate process represented by Eq. (8) such as chemical wear. The existence of the above linear relation, however, does not necessarily exclude the wear mechanism diffusion, which is also a temperature controlled rate process. However, based on all the experimental evidence given above, chemical wear appears to be the dominant mechanism for PCBN tools under conditions used in practice. It was also shown that the values of b_t of Eq. (1) and d_t of Eq. (7) suggested a highly temperature dependant rate process such as chemical wear as the dominant wear mechanism of PCBN tools.

[10] In support of use of Eq. (8) for chemical wear, it is noteworthy that Whitney and Vaidyanathan [56] who investigated microstructural engineering of ceramic cutting tools pointed out that chemical wear is a thermally activated rate process and hence should confirm to the Arrhenius relationship.

Table 3
The source, test conditions and empirical equations for the experimental temperature and tool-life results given in [32,52] for the tool/work-material combination PCBN-L/AISI-52100 steel

Author(s)/reference	Measured parameter	Work material; hardness	Tool material	Tool geometry	Cutting conditions	Empirical equation(s)
Ueda et al. [52]	Temperature	AISI-52100; ~60 HRC	60% CBN with ceramic binder	$r_\varepsilon = 0.2$ mm	$d = 0.1$ mm	$T_f = 396V^{0.155}$
				Land = 0.1 mm	$f = 0.1$ mm/rev $V = 100$–300 m/min	
Dowson and Kurfess [32]	Tool life	AISI-52100; ~62 HRC	~65% CBN with ceramic binder	$r_\varepsilon = 0.8$ mm	$d = 0.203$ mm	$T = \begin{cases} 2.02 \times 10^6 V^{-2.79} f^{-0.75} & \text{type A} \\ 2.13 \times 10^6 V^{-2.56} f^{-0.42} & \text{type B} \end{cases}$
				Land = 0.1 mm	$f = 0.076$–0.152 mm/rev $V = 91$–183 m/min	

5.3. PCD tools

When machining MMC with PCD tools, wear mechanism such as abrasion, adhesion and, micro-cracking and fatigue have been used to explain tool wear. This indicates that wear of these tools is not fully understood yet. Unfortunately for PCD, because of non-availability of experimental results, it is not possible to analyse tool wear in a manner similar to that for PCBN discussed above. Clearly, more experimental results are required to determine the dominant tool wear mechanism of PCD.

6. Conclusions

In this work, tool wear mechanisms for three tool/work material combinations were considered. It was concluded that, under practical conditions, the dominant wear mechanism for WC/steel is diffusion while that for PCBN/hardened-steel is chemical wear. For this latter tool/work combination, it was also found that the available tool temperature and tool life results could be represented very well using an Arrhenius type rate equation for chemical wear. Moreover, an investigation of values of b_t of tool life Eq. (1) and d_t values of temperature Eq. (7) further supported the aforementioned rate processes as the dominant wear mechanisms for WC and PCBN tools. For PCD/MMC, more experimental results and hence further research is required to determine the dominant tool wear mechanism.

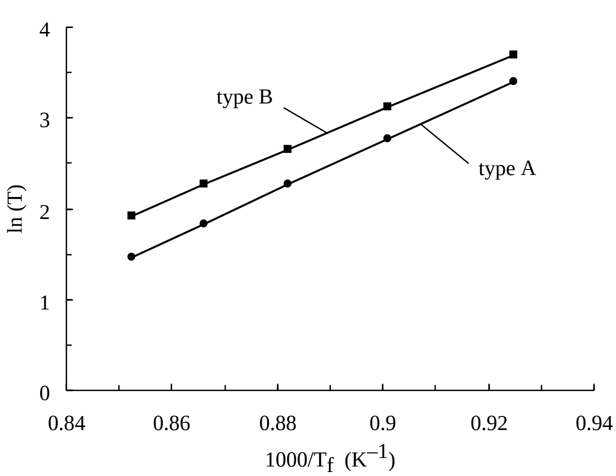

Fig. 1. ln(T) versus 1000/T_f for PCBN tools for data in [32,52].

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