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ORIGINAL ARTICLE

CBN tool wear in hard turning: a survey on research progresses

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Abstract Direct machining steel parts at a hardened state, known as hard turning, offers a number of potential benefits over traditional grinding in some applications. In addition, hard turning has several unique process characteristics, e.g., segmented chip formation and microstructural alterations at the machined surfaces, fundamentally different from conventional turning. Hard turning is, therefore, of a great interest to both the manufacturing industry and research community. Development of superhard materials such as polycrystalline cubic boron nitride (known as CBN) has been a key to enabling hard turning technology. A significant pool of CBN tool wear studies has been surveyed, in an attempt to achieve better processing and tooling applications, and discussed from the tool wear pattern and mechanism perspectives. Although various tool wear mechanisms, or a combination of several, coexist and dominate in CBN turning of hardened steels, it has been suggested that abrasion, adhesion (possibly complicated by tribochemical interactions), and diffusion may primarily govern the CBN tool wear in hard turning. Further, wear rate modeling including one approach developed in a recent study, on both crater and flank wear, is discussed as well. In conclusion, a summary of the CBN tool wear survey and the future work are outlined.

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1 Introduction

Steel parts that carry critical loads in everything from automotive drive trains and jet engines to industrial bearings and metal-forming machinery are normally produced by a series of processes, including time-consuming and costly grinding and polishing operations. An efficient and less costly method would be to precisely forge hot metal into near net-shaped parts, then harden and machine, or cut, the parts using a process known as hard turning. The hard turning process differs from conventional turning because of the workpiece hardness, the cutting tool required, and the chip formation mechanism involved. By directly machining the parts after they have been hardened, hard turning offers a number of potential benefits over traditional form grinding, including lower equipment costs, shorter setup time, fewer process steps, greater part geometry flexibility, and elimination of the use of cutting fluid [1–3]. If hard turning could be applied to the manufacture of complex parts, manufacturing costs could be reduced by up to 30%, and US industry could reap annual gains of up to $6 billion [4].

Material developments for the cutting tool, one of the most critical elements in metal cutting, have always been characterized by an increase in wear resistance to machine harder, tougher, or chemically reactive materials. For example, superhard materials such as CBN have been one of the main keys to enabling the hard turning technology to be an alternative to grinding processes. Of the presently available cutting tool materials, CBN is the best candidate and is presently being widely used in hard turning. Even though CBN tools have been used for over 20 years, due to the high material and fabrication cost of CBN tools and rapid tool wear, better understanding of the wear mechanisms and patterns in hard turning, and further modeling of the tool-wear rates are continuously needed to optimize cutting conditions and tool geometry to alleviate tool wear.

The objective of this paper, is to survey the recent research progresses on CBN tool wear research in hard turning. It is believed that the current research is still far from a solid understanding of CBN tool wear, but such a progress survey will help move this tool wear research further. It is expected that a general appreciation on the state-of-the-art research in CBN tool wear will help solve the challenges presented by this survey.

In this survey, wear mechanisms and patterns in metal cutting are first introduced as a background. Then, the wear patterns and mechanisms of CBN tools in hard turning are surveyed and the wear mechanisms are further discussed. Wear rate modeling approaches are presented as well. In conclusion, a summary and discussion of the future work are outlined.

2 CBN Material and Tool

Boron and nitrogen can form a compound, BN, using reactions, such as [5]:

$$BCl_3 + NH_3 \Rightarrow BN + 3HCl \quad (1)$$

This boron nitride (BN), like graphite, exhibits a hexagonal structure and is a soft, slippery, and friable substance. Just as hexagonal carbon (graphite) can be transformed into a cubic structure (diamond), hexagonal boron nitride (HBN) can be transformed into cubic boron nitride (CBN) by high temperatures and high pressures, as shown in Fig. 1. The phase equilibrium diagram for this transformation is shown in Fig. 2. In order to increase the transformation rate, solvents/catalysts, mostly metals, are generally added. In addition to enhancing the transformation rate, the solvents/catalysts also effectively reduce the required pressure and temperature to a more easily attainable level of about 6 GPa and 1,500°C, respectively. Once the CBN grains grow, by dissolving unwanted matrices, they can be liberated and recovered for subsequent processing [5].

Polycrystalline CBN is obtained by either bonding (sintering) individual CBN crystals together or bonding with binder materials such as ceramic binders to form a large mass [7]. The sintered polycrystalline CBN, consisting of randomly oriented anisotropic crystals, is an isotropic compound. The resultant compound may have either a ceramic or a metallic binder phase which is from the catalysts or solvents.

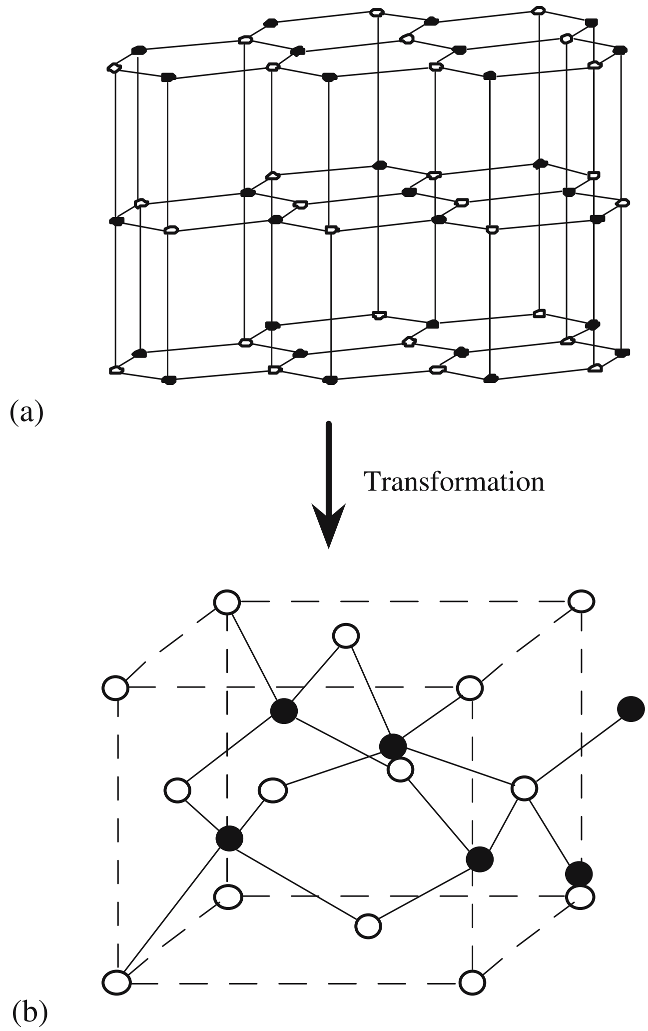

Fig. 1 The arrangement of atoms in boron nitride: **a** hexagonal and **b** cubic structure [6]

An immense range of polycrystalline products can be made of CBN. For example, changes in grain size, the solvent/catalyst employed, different binder phase, degree of

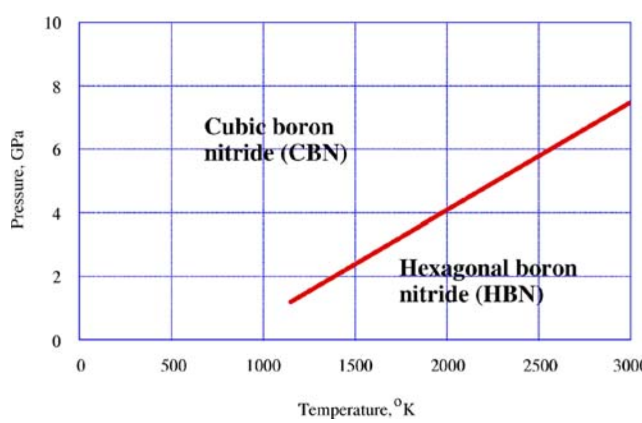

Fig. 2 The equilibrium phase diagram of hexagonal boron nitride and cubic boron nitride [6]

sintering, particle size distribution, and the presence or absence of inert ceramic, metallic, or nonmetallic fillers, all have profound effects on the mechanical, physical, and thermal properties of the CBN tool products.

CBN, a superabrasive, is second in hardness and abrasive resistance only to diamond. Produced at a high temperature and pressure, CBN tools also have a unique characteristic over diamond tools, i.e., the chemical inertness with steel. As a tool material, CBN has the following physical properties [7]: density, 3.48 g/cm^3; Young's modulus, 71×10^3 kg/mm^2; hardness, 4,500 Hv; thermal conductivity, 13 watt/cm°C at room temperature; and thermal expansion as 4.7×10^{-6}/°C from room temperature to 800°C.

Although commercial CBN tool products are generally called CBN tools, they are actually made of varied CBN contents with some additives from the manufacturer. In general, there are two categories of polycrystalline CBN tools. One has about 0.9 volume fraction of CBN grains with metallic binders (e.g., cobalt), referred to as high CBN content tools. The other has about 0.5 to 0.7 volume fraction of CBN grains with ceramic binders (e.g., titanium nitride *TiN*, titanium carbide *TiC*), referred to as low CBN content tools.

3 Tool wear mechanisms and wear patterns in metal cutting

Different classifications of tool wear processes have been addressed in the literature. Basically, five wear mechanisms or any combinations of them are involved in tool wear. These are abrasion, adhesion, fatigue, dissolution/diffusion, and tribochemical process [8, 9]. Attrition as a tool wear mechanism was reported as well [10]. Dissolution/diffusion wear was further illustrated by Suh [11], and the proceeding of tribochemical wear was articulated by Gahr [12]. It is well accepted that the tool wear mechanisms in metal cutting involve more than one wear mechanism and it is difficult to predict the relative importance of any one of them.

The cutting edge of an insert is subjected to a combination of high stresses, high temperatures, and perhaps chemical reactions which cause the tool wear due to one or several mechanisms. These mechanisms depend on the tool and workpiece material combination, cutting geometry, the environment, and mechanical and thermal loadings encountered. The main observed wear patterns are crater wear, flank wear, depth of cut notching, thermal shock cracks, nose wear, chipping, tool breakage, and built-up edge as classified by North [13]. Figure 3 illustrates typical wear patterns such as crater wear and flank wear of a finishing tool. Crater and flank wear are the most reported wear patterns in metal cutting. Crater wear is mainly caused by physical, chemical, and/or thermomechanical interactions between the rake face of the insert and the hot metal chip. A crater is caused by dissolution of the tool material into the chip, adhesion due to microwelds between the insert and the chip, abrasion of possible free/embedded abrasive particles on the insert, and/or a tribochemical reaction between the tool rake face and the chip. Flank wear occurs primarily by rubbing of the flank face against the spring-backed workpiece surface and can be minimized by raising the tool red hardness under elevated temperatures. A detailed description on wear patterns can be found in [13].

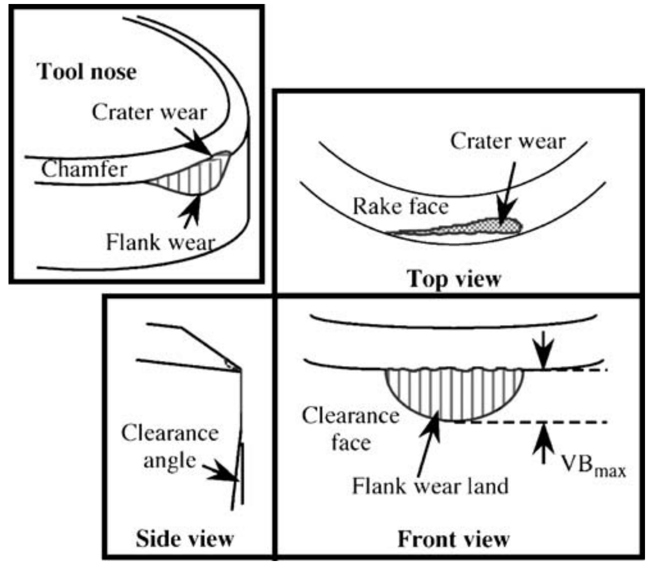

Fig. 3 Typical wear patterns on a finishing tool [14]

4 CBN tool wear in hard turning

Different wear patterns were reported in hard turning. Takatsu et al. [15] showed that the CBN tool life (GE BZN series) is mainly limited by flank wear and edge chipping. It was also shown that flank wear is influenced by both the inherent wear resistance of the CBN compacts and the adherence of the work materials around the tool cutting edge [15]. König et al. [1] observed that predominant wear pattern of a CBN tool in machining of hardened gray cast iron is microchipping, similar to that of ceramic tools. In addition to chipping, fine grooves were formed both on the rake and crater wear surfaces of the CBN tools in milling flame hardened Cf53 steel. The origin of these grooves was traced to the thermal crack formed at the cutting edge. Both crater and flank wear (including nose wear) were observed when machining 50CrMo4 heat treatable steel. A large nose radius can significantly reduce the tool wear. Hodgson and Trendler [16] reported the wear notching during turning high-speed steel M2 using chamfered CBN tools (De Beers Amborite), but no wear notching when using a sharp edge CBN tool. Based on the experiments in turning hardened steel AISI 4615 (60 HRC), Kishawy and Elbestawi [17] concluded that the flank wear with a trailing edge notch and a depth of cut notch are the main tool wear patterns. Chryssolouris [18] reported that the wear pattern of CBN cutting tools is characterized by crater and flank wear, as well as small cracks on the cutting edge, depending on cutting conditions. Tönshoff [19] reported that high specific forces and temperatures in the small contact area between the tool and the workpiece are dominating factors for tool wear in hard turning, and the wear patterns of a CBN tool are characterized by typical fine scorings. It can be seen that the main CBN tool wear patterns in hard turning can be crater wear, flank wear, nose wear, notching, cracks, and microchipping as observed in typical metal cutting; the observed wear patterns depend on the CBN tools used, workpiece material composition, and cutting conditions.

Although different wear patterns of CBN tools were reported, researchers normally regard the flank wear land width (VB, which is also typically referred as flank wear land length) as the tool life criterion [15, 20, 21]; sometimes the crater depth (KT) was also used as the criterion for special cases such as in machining titanium alloy [22]. To improve the cutting edge strength, the cutting wedge angle of a CBN tool is generally greater than 90° with a large negative rake angle. The effective rake angle may turn to be positive as the crater wear progresses when feed rate is larger than the tool edge radius as seen in Fig. 4. Since the CBN tool used in hard turning is brittle in nature, microchipping and/or tool breakage may happen, possibly caused by an increasingly positive rake angle before tool flank wear reaches the pre-specified flank wear width criterion. To better predict the tool life, it is recommended to use the crater-wear depth in addition to the flank-wear width as the tool-life criteria in hard turning, especially under aggressive cutting conditions. A typical worn CBN tool in hard turning is shown in Fig. 4 [23, 24].

Since identifying wear mechanisms involved in hard turning can guide process optimization and tool life improvement, numerous studies have been conducted on this topic. Some notable reports are reviewed and discussed as follows.

4.1 Abrasion in hard turning

Since hardened steels normally contain ultra-hard carbide particles that are cementite with a hardness around 12 KN/mm^2, abrasive wear has been frequently reported as a main wear mechanism in hard turning. The ultra-hard particles may also include, depending on the steel composition, different carbides, e.g., chromium-carbide in hardened AISI 52100 steel, and molybdenum-carbide and vanadium-carbide in most tool steels. The abrasion may also be due to the loose CBN particles since CBN particles of high CBN content tools are easily released as free abrasive particles, which have a hardness of around 45 KN/mm^2. Narukati and Yamane [25] considered that in the case of machining the work materials containing ultra-hard carbides, the tool wear is mainly controlled by abrasion, and the wear resistance increases with the increase of CBN grain content in the tool. Davies et al. [26] found that for high CBN metal matrix tools, interactions between the binder and the work material produce highly adherent layers; bond failure between CBN and matrix presumably leads to the pluck out of CBN grains which causes significant abrasive wear on the tool flank. Based on the experiments in turning hardened AISI 52100 steel, Poulachon et al. [27] concluded that the main wear mechanism of CBN tools is abrasion by hard alloy carbides in the workpiece. Moreover, abrasion of the cutting tool depends on the nature of the carbides, carbide sizes and distributions, etc. Different work materials at the same hardness may not be assumed to be equally unfavorable from the viewpoint of their effects on the tool wear. The authors further suggested a limiting hardness of 50 HRC, above which the material is considered “hard”, the tool wear is mainly dominated by abrasion, and the wear resistance of the tool increases with the increase of the CBN content.

4.2 Diffusion/dissolution in hard turning

Due to the high temperature and high stress in hard turning, diffusion and dissolution mechanisms have received signif-

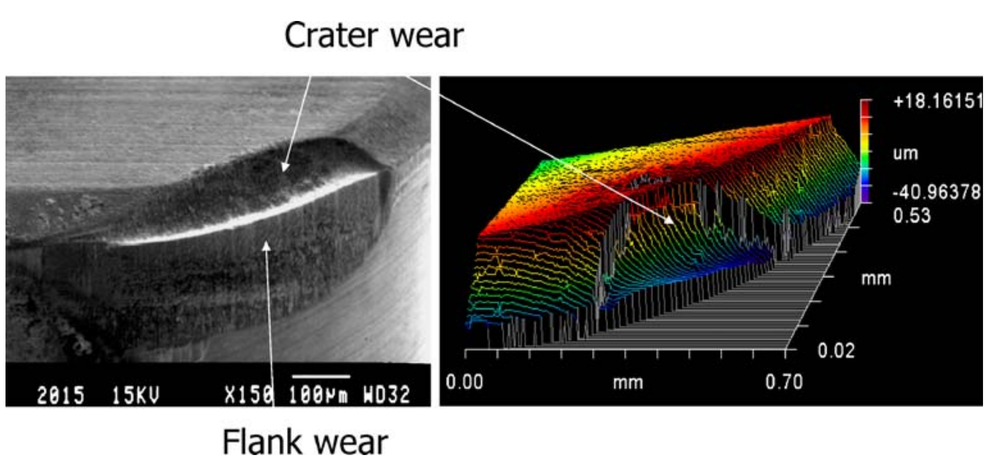

Fig. 4 A typical worn tool with crater wear and flank wear [23, 24]

icant attention as well. Bhattacharyya and Aspinwall [28] observed a very smooth surface with ridging characteristics of diffusion and suggested that diffusion is the primary wear mechanism. Dearnley and Grearson [29] found that the CBN tool is prone to diffusion/dissolution at a high cutting-speed range. Suh [11] mentioned that diffusion/dissolution type mechanism occurs when a hard cemented tungsten carbide or CBN tool is used to cut steel. Kramer [30] mentioned that in machining of steel and superalloys by CBN tools, cutting temperature may reach above 1,200°C, at which the wear rate becomes diffusion-limited and both the chemical stability and the diffusivity control the wear rate.

However, there are no unanimous conclusions on which component of the CBN tool material is diffused in CBN hard turning. Zimmermann et al. [31] concluded that the CBN phase of CBN/TiC tools is subject to diffusion wear. During machining titanium alloy, Bhaumik et al. [22] considered that a high temperature leads to dissolution/diffusion wear, but they mentioned titanium as the diffused materials. Based on the diffusion test of a CBN layer with cast iron, Rai [32] concluded that the tool materials can diffuse in the form of boron and nitrogen movements. Several researchers have argued that the CBN grain itself is relatively stable with iron, and it is rather the structure of the binder that suffers a significant change. Comparing the diffusion tendency, Narukati and Yamane [25] found that CBN grain itself is relatively inert to pure iron at temperatures up to 1,200°C, greater than a normal cutting temperature in hard turning; however, they also found that metal binder and boron can diffuse into carbon steel S55C after being held under 1,200°C for 30 min with a 0.62 Kg/mm^2 pressure. The similar conclusion has been drawn by Eda et al. [33] and König and Neises [2]. However, it is difficult to conclude whether diffusion happens to the CBN grains, because the reported research [2, 25, 33] relied on the simulation results from the given temperature range without the high pressure, to which the CBN tool is subject.

4.3 Tribochemical wear in hard turning

Tribochemical wear, which is not commonly observed in conventional metal cutting, has also been recognized as a wear mechanism in hard turning. A protective layer as the result of tribochemical mechanism was frequently reported, although some researchers refer to it by alternative names such as pile-up layer. By comparing the microstructure and wear of conventional high CBN content tools and TiC modified low CBN content tools, Hooper et al. [34] concluded that the wear of CBN tools involves chemical wear and a thin protective layer. This tribochemical wear was concluded as having occurred due to some unidentified chemical interactions of the tool material with its environment, including the workpiece and the atmosphere. A thin protective layer with a composition similar to the workpiece formed at the tool surface in contact with the workpiece and the chip. At low temperatures, the layer may become unstable and removed periodically, exposing the surfaces of the tool to further wear, and the wear of the rake face was also increased by adhesion of the layer to the base of the chips. The authors claimed that the relatively low thermal conductivity of the low CBN content tool leads to a stable protective layer, and then a longer tool life.

Klimenko et al. [35] noticed a coating resulted from the tool wear process at the rake and flank faces, and the coating consists of compounds of elements entering into the composition of the contacting materials as well as the products of their interaction with oxygen. Further, the authors [36] concluded that the wear of CBN tools (Kiborit) in machining involves the formation of the coating of chemical compounds at the interfaces, the melting of these compounds and the removal of the liquid phase from the contact zone. The coating includes elements from the tool and workpiece composition and their oxidized products. Later, based on the result of an experimental study of the interaction products between the CBN tool and the workpiece within the environment, Klimenko et al. [37] found that CBN tool wear is of a chemical nature when turning hardened steels, typically around 800–1,200°C. It remains, however, difficult to argue that the chemical reaction is the dominant wear mechanism because it depends on the contact stress, temperatures and the chemical composition of the materials in contact. Recently, Klimenko [38] reported that the wear mechanism of a Kiborit CBN tool at various thermal and mechanical conditions is defined by a combination of different phenomena: self-wearing due to abrasive particles (which is an alternative name of abrasion), mechanical fracture and chemical interaction. It should be noted that adhesion tears have not been found in the worn tool region. This suggests that adhesion has only a slight, if any, effect on the wear of Kiborit tools under the conditions considered.

Chou [39] observed that in turning hardened 52100 steel, the piled-up layers at the flank face show different structures and compositions between different CBN tools, and have significant effects on the tool wear process. The piled-up layer on BZN6000 (a high CBN content tool) shows a rough, groove structure, and in addition to iron oxide/carbide, it has a significant amount of silicon dioxide. There was silicon in hardened 52100 steel, and the observed silicon dioxide was suggested as a tribochemical product. The piled-up layer of BZN8100 (a low CBN content tool) shows a smooth, flake-type structure, with iron oxide/carbide as the major component. In assessing the wear resistance of CBN/TiC tools (low CBN content tools) over high CBN content tools, Barry and Byrne [40] found that in machining BS 817M40 steel, the dominant wear mechanism of CBN/TiC cutting tools is chemical in nature since the relative abundance of different elements at the wear surfaces of the tools, which are present in the work material in small (Mn, Si) or very small (Al, S, O) quantities. It was further suggested that the chemical products of the reactions between the BN phase and certain work material inclusive deposits, may offer some protection to the TiC phase against dissolution/diffusion wear. König and Neises [2] observed a protective layer along the crater area, however, the generation and structure of the layer were not exactly identified. Bhaumik et al. [22] observed the formation of an adherent layer of uniform thickness along the main WBN-CBN composite tool cutting edge in machining titanium alloy. The layer contains titanium in certain forms (perhaps titanium diboride or titanium nitride). Once the reaction layer forms, it continuously grows during the machining and attaches to the tool until a critical stress is reached to cause fracture. When machining M2 tool steel, Sista et al. [41] found that the tool flank face is coated with a layer of workpiece materials. SEM results showed a significant amount of iron in the crater and flank regions, indicating some amount of adhesion and material transfer. However, so far this type of protective layer has not been clearly verified as the result of either adhesion or tribochemical wear.

4.4 Adhesion in hard turning

In turning hardened 52100 steel, Chou [39] concluded that adhesive wear associated with the tribochemical process should be considered as the dominant wear mechanism of CBN tools. The cobalt binder in the BZN6000 tends to form strong bonds with the piled-up layer, resulting in more severe adhesive wear. However, the titanium nitride in BZN8100 prevents strong bonds with the piled-up layer, thus alleviating adhesive wear. The above discussion can be visualized by Fig. 5 [42].

4.5 Attrition in hard turning

Dearnley and Grearson [29] observed that the CBN tool is prone to attrition at a low speed range. Davies et al. [26] found that for the low CBN ceramic matrix tools, less adhesive layers and better bonding of the CBN particles in the matrix result in a fine scale attrition dominating the wear process. The reduction in wear rate is correlated with decreasing CBN grain size and with decreasing work material carbide size, both indicating initiation and propagation of microfractures as the main mechanism involved in the fine scale attrition. In continuous finishing hard turning by low CBN content tools (Sumitomo BN series), Chou and Evans [14] found that the governing wear mechanism is fine-scale attrition by microfracture and fatigue. Further, they concluded that carbide sizes of the workpiece have significant effects on tool wear, i.e., large-scale ultrahard carbides in the workpiece enhance fine-scale attrition and results in a higher wear rate, and the wear resistance increases monotonically with decreasing CBN grain size.

4.6 Discussion of CBN tool wear mechanisms

There is no general consensus in CBN tool wear mechanisms in hard turning. Not only tool geometry and cutting conditions, but also the CBN content, binder phase, chemical stability of CBN tools, and composition of the workpiece materials are inherent factors influencing tool wear mechanisms in hard turning [43]. Contradictive observations have also been frequently reported under similar machining conditions, which may be due to different CBN tool material properties, different tool geometry, and/or different workpiece material properties and preparation; however, some basic conclusions can be drawn from the reported observations for further research reference. Regarding wear mechanisms involved in CBN hard turning, abrasion, adhesion, and diffusion can be generally considered the main tool wear mechanisms, and the contribution from each mechanism depends on mechanical and thermal loading during machining, CBN content, binder phase and chemical stability of CBN

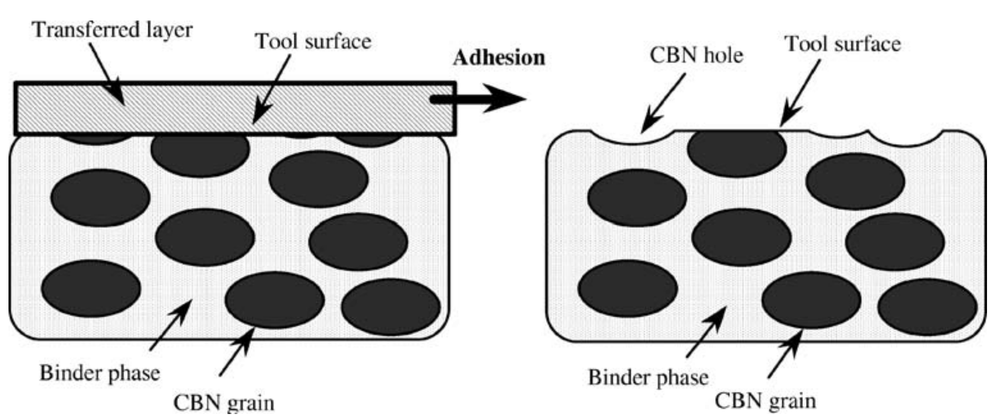

Fig. 5 A simple model of adhesive wear process with the interaction of a transferred layer [42]

tools, and composition of the workpiece materials. Good understanding of CBN tool wear mechanisms is the indispensable step toward a viable hard-turning technology. Some further discussion about CBN tool wear mechanisms is presented as follows.

4.6.1 Open questions

Despite of numerous reports on CBN tool wear mechanisms, there is still no agreement on several important tool wear characteristics. Some open questions need further attention as outlined in the following:

- Diffusivity of different elements of CBN tool: There is a call for well-controlled experiments to identify the element diffusivity of each element for each tool-workpiece pair by closely simulating temperature and stress conditions under different cutting conditions.
- Tribochemical interaction in hard turning: Tribochemical interaction has been proposed as one of the wear mechanisms for more than a decade; however, there are still no solid experiments to support and quantify its existence. For example, the observed protective layer was also suggested due to adhesion and material transfer [41]. The following questions are still of great interest: How to verify the existence of tribochemical interactions in hard turning; Why do tribochemical interactions prevail in hard turning but not in conventional machining; What types of tribochemical interactions have happened among tool material, workpiece, and atmosphere; and, What is the effect of the formed protective layer on the CBN tool wear progression?
- White layer in hard turning: White layer is typically observed on chip and machined workpiece surface in hard turning when a tool is worn; however, there is not enough attention given to the relationship between the white layer and the tool wear. An interesting question would be: Does the white layer affect the tool wear mechanisms or vice versa?

4.6.2 Coexisting of different wear mechanisms under different cutting regimes

Numerous researchers proposed that different wear mechanisms coexist for a given machining condition. Hooper et al. [34] concluded that the wear of CBN tools involves chemical wear and adhesion effects. König and Neises [2] reported that the thermally induced recrystallization of the binder phase components is the dominant wear mechanism of CBN, and plucked-out partial CBN grains possibly further induce three-body abrasion to the CBN tool. Chou [39] concluded that adhesive wear associated with the tribochemical process should be considered as the dominant wear mechanism for CBN tools. The cobalt binder in the BZN6000 tends to form strong bonds with the piled-up layer, resulting in more severe adhesive wear, but the titanium nitride in BZN8100 prevents strong bonds with the piled-up layer, thus alleviating adhesive wear. Klimenko [38] claimed that the mechanism of a Kiborit CBN tool wear at various thermal and mechanical conditions is defined by a combination of different phenomena: self-wearing, mechanical fracture and chemical interactions. It should be noted that adhesion tears have not been found in the worn area of a CBN tool. In continuous finishing processes by low CBN content tools (Sumitomo BN series), Chou and Evans [14] found that the governing wear mechanism is fine-scale attrition by microstructure and fatigue. Based on a study of CBN tool wear with interrupted turning of hardened M50 steels, Chou and Evans [44] suggested there are different dominant wear modes at different cutting speed ranges, e.g., mechanical wear at low cutting speed, and thermal wear at high cutting speed for both kinds of CBN tools. The mechanical wear is due to transient vibration, induced speed and depth of cut fluctuations during the tool engagements. As seen from the above discussion, it is necessary to consider the effect of different cutting regimes, which are defined by stress and temperature distributions and determined by tool and workpiece materials, tool geometry, and cutting conditions on the observed wear mechanisms. The different wear mechanisms may coexist under different cutting regimes. Even when the same tool-workpiece pair is used, the wear mechanisms may be different since different cutting conditions bring the tool into significantly different cutting regimes.

4.6.3 Effect of tool red hardness and tribochemical interaction/adhesion

Researchers have also noticed interesting CBN tool-wear characteristics in hard turning. Intuitively, tool wear should mainly depend on the red hardness of the tool material, as Nakayama [45] reported that in machining hard materials tool wear is due to the abrasion and high cutting temperature; some believed that chemical constituents and chemical reactions play an important role in CBN tool wear as seen in the section Tribochemical wear in hard turning. Hitchiner [46] stated that the hardness of the workpiece, though significant, is not the only factor in determining the wear. The chemical composition of the workpiece may, under certain circumstances, be a more important factor than the hardness. The protective layer as a product of tribochemical mechanism has been discussed in detail in the section Tribochemical wear in hard turning. However, the observed protective layer was also suggested due to adhesion and material transfer [41], and the underlying mechanism of chemical reactions is still to be further explored. Only when the effect of tool red hardness and tribochemical interaction is well understood, can more advanced tools be developed or invented for hard turning.

4.6.4 Cutting performance difference between high and low CBN content tools

It is well accepted that high CBN content tools with metal binder have been recognized as being economical for roughing or semi-finishing, and low CBN content tools with a ceramic binder are recommended for finishing, mainly due to its relatively longer tool life compared with that of high CBN content tools under the same conditions [40, 41]. According to the designed tribological tests, König and Neises [2] reported that the thermally induced recrystallization of the binder-phase components is the dominant wear mechanism of PCBN, and wear of the CBN grains also contribute to the wear of the CBN composite tool, so the low CBN content tool should have higher wear rate than that of the high CBN content tool. However, the real cutting test showed the contradictory result. Several explanations have been proposed as to why low CBN content tools have better tool performance in finishing hard turning, including reduced adhesive wear [25, 39], the effect of increased protective welding quantity of the workpiece on the tool [15, 47], less etching wear due to a lower dislocation density in low CBN tools [47], and the thermal softening effect due to the lower thermal conductivity of low CBN tools [48, 49] when turning hardened steel. Recently, Barry and Byrne [40] reported that the -nature of chemical mechanism contributes to the superior wear resistance of CBN/TiC tools (low CBN content tools) and this wear resistance is due to the greater wear resistance of the TiC phase compared to the BN phase. They further suggested that the chemical products of the reactions between the BN phase and certain work material inclusion, may afford a degree of protection to the TiC phase against dissolution/diffusion wear. Although different explanations have been proposed, the answer to the superior wear resistance of low CBN tools still remains debatable.

4.6.5 Effect of cutting fluid on tool performance

The effect of cutting fluid on tool wear in hard turning has been investigated as well. It was found that when using a coolant, the flank wear rate is smaller than in dry cutting, and there is no significant difference between the flank and crater wear patterns obtained with and without the use of a coolant [41]. Minimal cutting fluid approaches have been pioneered in hard turning too, and reduced flank wear rate has been observed when applying little mineral oil based cutting fluid in turning hardened AISI 4340 steel [50]. Recently, there is an increasing interest in the effect of minimum quantity lubrication on CBN tool performance in hard turning.

5 Modeling of CBN tool wear rate

5.1 Taylor's equation-based modeling approach

The Taylor tool life equation has been widely used in predicting tool life in conventional machining as well as in hard turning. Poulachon et al. [27] reported that the tool life in turning hardened AISI 52100 steel can be expressed as follows:

$$V_c t^{0.285} d^{0.112} f^{0.335} \left(\frac{H}{H_0}\right)^{1.07} = 172 \tag{2}$$

where H_0=60, H is the workpiece hardness in HRC, and t is the tool life in minutes. Equation (2) clearly states that the cutting speed is the dominant role in determining the tool life, followed by feed and depth of cut. The comparable results have been reported by Dawson as well in turning hardened 52100 steel [23].

5.2 Wear mechanism-based modeling approach

Numerous models have been proposed to describe the general volume loss and/or wear rate for different wear mechanisms, including applications in metal cutting such as some well-cited work on abrasive wear by Rabinowicz et al. [51], adhesive wear by Archard [52], Shaw and Dirke [53], and Kannatey-Asibu [54], and diffusive wear by Loladze [55] and Kannatey-Asibu [54]. However, in modeling tool wear, only one or two dominant wear mechanisms are documented, as noted by Usui et al. [56], Kannatey-Asibu [54], Kramer and Judd [57], and Kramer [58]. Huang and Liang have contributed in an effort to predict the flank and crater wear rates in CBN hard turning by modeling the effects of abrasion, adhesion, and diffusion in hard turning as a function of cutting conditions, tool geometry, and material properties [59–61]. Two representative wear-rate models [59, 60] are introduced as follows. For the flank wear rate,

$$\frac{dVB}{dt} = \frac{(\cot\alpha + \tan\gamma)R}{[VB(R - VB\tan\alpha)]}\left\{K_{\mathrm{abrasion}}K\left(\frac{P_a^{n-1}}{P_{\mathrm{t}}^{n}}\right)V_{\mathrm{c}}VB\overline{\sigma} + K_{\mathrm{adhesion}}e^{a\overline{T}}V_{\mathrm{c}}\overline{\sigma} + K_{\mathrm{diff}}\sqrt{V_{\mathrm{c}}VB}e^{-\frac{K_Q}{\overline{T}+273}}\right\} \tag{3}$$

where, VB is the flank wear land width; $K_{abrasion}$, $K_{adhesion}$, a, K_{diff}, and K_Q are the wear coefficients as process related dimensionless abrasive wear coefficient, process related adhesive wear coefficient, hardness constant, process related diffusive wear coefficient, and constant related with activation energy for diffusion, respectively; γ is the absolute value of the measured rake angle at the chamfer zone; α is the tool clearance angle; R is the tool nose radius; P_a is the hardness of the abrasive particle; P_t is the tool hardness; V_c is the cutting speed; $\overline{\sigma}$ and $\overline{T}$ are the average normal stress and temperature at the tool-workpiece interface; and K and n are functions of $\frac{P_t}{P_a}$ as defined in [58]. $\overline{\sigma}$ and $\overline{T}$ can be estimated by finite element method or analytical approaches (stress [62, 63] and temperature [64] models) as discussed by Huang and Liang [59]. For the crater wear rate,

$$\frac{dKT(x)}{dt} = K_{abrasion} K \left(\frac{P_a(x)^{n-1}}{P_t(x)^n} \right) V_{chip}(x) \sigma(x) + \frac{1}{h} K_{adhesion} e^{aT(x)} V_{chip}(x) \sigma(x) + K_{diff} e^{-\frac{K_Q}{T(x)+273}} \sqrt{V_{chip}(x)} \frac{\left(\sqrt{x+\Delta x} - \sqrt{x} \right)}{\Delta x} \quad (4)$$

where, $KT(x)$ is the crater wear depth at the tool-chip interface position x; $T(x)$, $\sigma(x)$ and $V_{chip}(x)$ are the temperature distribution, normal stress distribution, and chip velocity along the tool-chip interface; h is the tool-chip contact length; Δx is the length of the infinitesimal segment along the interface; and other variables are defined same as in Eq. (3). $T(x)$, $\sigma(x)$ and $V_{chip}(x)$ can be predicted using the temperature distribution model [65], the stress distribution model [66], and the chip velocity model [60], respectively. The contact length h can be measured or predicted using the Oxley predictive machining theory [67].

The coefficients in the wear rate models (Eqs. 3 and 4), $K_{abrasion}$, $K_{adhesion}$, a, K_{diff}, and K_Q, require calibrations based on actual machining and wear measurements, and they depend on different tool/workpiece combinations. When cutting hardened AISI 52100 steel (62 HRC) using Kennametal low CBN uncoated tool KD050, these calibrated coefficients are 0.0295, 1.4761×10^{-14}, 9.0313×10^{-4}, 5.7204×10^{6}, and 20460, respectively [59]. Satisfactory agreements between the predictions and the measurements have been observed at most gentle cutting conditions (recommended low cutting speeds and small feeds) [59, 60]. Predictions were made using the proposed unified tool wear modeling approaches (Eqs. 3 and 4); and the tool flank wear was measured using a microscope [59] and the tool crate wear was measured using a Zygo NewView profilometer [60].

Based on the proposed approaches (Eqs. 3 and 4) [59, 60], the contribution of each wear mechanism toward the overall CBN tool wear in hard turning can also be quantitatively compared from the model output, and it has been found that adhesion is the dominant wear mechanism in turning hardened 52100 bearing steel with a hardness of 62 HRC using a low CBN content tool. This finding agrees with the conclusion from an earlier study [39].

6 Summary and future work

Literature of CBN tool wear in hard turning has been surveyed and discussed. For further wear modeling reference, modeling of CBN tool wear rates in hard turning has also been introduced. The main conclusions can be drawn as follows:

- The main CBN tool wear patterns in hard turning can be crater wear, flank wear, nose wear, notching, cracks, and microchipping as observed in typical metal cutting. The observed wear patterns depend on the CBN tools used, workpiece material composition, and cutting conditions. Flank wear land width (VB) is normally used as the tool life criterion, though crater wear depth (KT) should also be considered as an additional measure, especially in aggressive machining.
- Generally, abrasion, adhesion, and diffusion are considered to be the main tool wear mechanisms in CBN hard turning; however, the individual effect of each mechanism depends on the combinations of the CBN tool and work materials, cutting conditions, tool geometry, CBN tool characteristics such as CBN content, CBN grain sizes, and the binder phase, etc.
- In modeling flank and crater-wear rates in hard turning, abrasion, adhesion, and diffusion typically are all considered; and some proposed models can be used to predict the flank and crater-wear progressions and evaluate the relative importance of each wear mechanism.

Better understanding of CBN tool-wear mechanisms and patterns will lead to better utilizations of CBN tools in hard turning. In order to advance hard turning technology, future work on CBN tools and wear mechanisms shall emphasize the fundamental and unresolved issues described below.

- Explanation of the reasons for reported different or contradictive wear mechanisms in similar CBN hard turning conditions
- Research on the diffusivity of CBN tool elements with different workpiece materials by simulating representative cutting conditions
- Experimental and/or analytical characterizations of the protective layer, possibly a product of chemical

reactions or adhesion, and its effects on the CBN tool wear process
- Study of tool wear effects on the white-layer generation on the chip and machined workpiece surface, which may affect the wear mechanisms and patterns, vice versa
- Investigation on the underlying physics for the tool performance difference between high and low CBN content tools in finishing hard turning
- Study of effects of minimum quantity lubrication on CBN tool performance in hard turning
- Assessment of the cutting tool condition based on the tool geometry, cutting regimes, and the nature of tool wear [68] in addition to the traditional VB and/or KT values

No matter which wear mechanisms of the CBN tools are identified, individual contributions toward the overall tool wear should be quantitatively determined based on proper physical and mathematical modeling and suitable measuring approaches. The individual contributions from each wear mechanism are believed to be varied in different hard turning conditions. To achieve comprehensive understanding of CBN tool wear, cutting configuration, process conditions such as cutting temperatures and stresses, and chemical and physical properties of the tool material and the workpiece should be considered together for every hard turning application.

References

1. König W, Hochschule T, Komanduri R, Schenectady D, Tönshoff HK (1984) Machining of hard materials. Annal CIRP 33(2):417–427
2. König W, Neises A (1993) Wear mechanisms of ultrahard, non-metallic cutting materials. Wear 162–164:12–21
3. Tönshoff HK, Arendt C, Amor RB (2000) Cutting of hardened steel. Annal CIRP 49(2):547–566
4. National Institute of Standards and Technology, Advanced Technology Program (2004) Enabling technologies for lean manufacturing of hardened steel applications, http://jazz.nist.gov/atpcf/prjbriefs/prjbrief.cfm?ProjectNumber=00-00-4143. Cited February 2004
5. Heath PJ (1986) Properties and uses of AMBORITE. Ind Diamond Rev 46:120–127
6. Heath PJ (1984) Ultra hard materials. Met Mater 3:105–117
7. Sumitomo Electric Carbide (2001) Sumitomo PCD and CBN Technical presentation, Sumitomo Electric Carbide, New York
8. Moore DF (1975) Principles and application of tribology. Pergamon, Oxford
9. Shaw MC (1984) Metal cutting principles. Oxford University Press, Oxford
10. Turley DM (1974) A scanning electron microscopy study of attrition wear in tungsten carbide pin reamers. Wear 77:259–266
11. Suh NP (1986) Tribophysics. Prentice-Hall, Englewood Cliffs, NJ
12. Gahr KZ (1987) Microstructure and wear of materials. Elsevier, NY
13. North B (1989) Indexable metal cutting inserts. Factors influencing machining and their controls, proceedings of an international conference and workshop, Cincinnati, Ohio, 12–14 September 1989, pp 33–42
14. Chou YK, Evans CJ (1997) Tool wear mechanism in continuous cutting of hardened tool steels. Wear 212:59–65
15. Takatsu S, Shimoda H, Otani K (1983) Effect of CBN content on the cutting performance of polycrystalline CBN tools. Int J Refract Hard Mat 2(4):175–178
16. Hodgson T, Trendler PHH (1981) Turning hardened tool steels with cubic boron nitride inserts. Annals CIRP 30(1):63–66
17. Kishawy HA, Elbestawi MA (1999) Effects of process parameters on material side flow during hard turning. Inter J Mach Tools Manuf 39:1017–1030
18. Chryssolouris G (1982) Turning of hardened steels using CBN tools. J Appl Metalwork 2(2):100–106
19. Tönshoff HK (1995) Hard turning: influences on the workpiece properties. Trans NAMRI/SME 23:215–220
20. Abrao AM, Wise MLH, Aspinwall DK (1995) Tool life and workpiece surface integrity evaluations when machining hardened AISI 52100 steels with conventional ceramic and PCBN tool materials. SME Tech Pap MR95–159:1–9
21. Dewes RC, Aspinwall DK (1996) The use of high speed machining for the manufacture of hardened steel dies. Trans NAMRI/SME 24:21–26
22. Bhaumik SK, Divakar C, Singh AK (1995) Machining Ti-6Al-4V alloy with a WBN-CBN composite tool. Mater Des 16(4):221–226
23. Dawson T (2002) Machining hardened steel with polycrystalline cubic boron nitride cutting tools. PhD Thesis, Georgia Institute of Technology, Atlanta, GA
24. Huang Y (2002) Predictive modeling of tool wear rate with application to CBN hard turning. PhD Thesis, Georgia Institute of Technology, Atlanta, GA
25. Narukati N, Yamane Y (1979) Tool wear and cutting temperature of CBN tools in machining of hardened steels. Annal CIRP 28 (1):23–28
26. Davies MA, Chou Y, Evans CJ (1996) On chip morphology, tool wear and cutting mechanics in finish hard turning. Annal CIRP 45 (1):77–82
27. Poulachon G, Moisan A, Jawahir IS (2001) Tool-wear mechanisms in hard turning with polycrystalline cubic boron nitride tools. Wear 250:576–586
28. Bhattacharyya SK, Aspinwall D (1982) The application of polycrystalline tooling. Mach Hard Mater SME:95–103
29. Dearnley PA, Grearson AN (1986) Evaluation of principal wear mechanisms of cemented carbides and ceramics used for machining titanium alloy IMI318. Mater Sci Technol 2:47–58
30. Kramer BM (1986) A comprehensive tool wear model. Annal CIRP 35(1):67–70
31. Zimmermann M, Lahres M, Viens DV, Laube BL (1997) Investigations of the wear of cubic boron nitride cutting tools using auger electron spectroscopy and X-ray analysis by EPMA. Wear 209:241–246
32. Rai G (1993) The metallurgy of CBN and its wear in high speed machining of ferrous materials. Machining of advanced materials, Proceeding of the International Conference on Machining of Advanced Materials, Gaithersburg, MD, 20–22 July 1993, pp 501–514
33. Eda H, Kishi K, Hashimoto H (1980) Wear resistance and cutting ability of a newly developed cutting tools. Cutting tool materials, Proceedings of an International Conference, American Society for Metals, Ft. Mitchell, KY, 15–17 September 1980, pp 265–280
34. Hooper RM, Shakib JI, Brookes CA (1988) Microstructure and wear of TiC-Cubic BN tools. Mater Sci Eng A105/106:429–433

35. Klimenko SA, Mukovoz YA, Lyashko VA, Ogorodnik VV, Vashchenko AN (1988) Wear on cubic boron nitride tools. Soviet J Superhard Mater 10(2):53–57
36. Klimenko SA, Mukovoz YA, Lyashko VA, Vashchenko AN, Ogorodnik VV (1992) On the wear mechanisms of cubic boron nitride base cutting tool. Wear 157:1–7
37. Klimenko SA, Mukovoz YA, Vashchenko AN, Ivas'kevich YV (1993) Contact interaction between polycrystalline CBN cutting tools and a workpiece material. J Superhard Mater 15 (3):39–41
38. Klimenko SA (1995) Kinetics of tool wear in turning martensitic steels. J Superhard Mater 17(2):62–65
39. Chou Y (1994) Wear mechanism of cubic boron nitride tools in precision turning of hardened steels. PhD Thesis, Purdue University, West Lafayette, IN
40. Barry J, Byrne G (2001) Cutting tool wear in the machining of hardened steel, part 2: cubic boron nitride cutting tool wear. Wear 247:152–160
41. Sista PS, Swain SO, Chandrasekar S, Farris TN (1997) Tool wear characteristics of CBN tools in the finish machining of tool steels. Manuf Sci Technol ASME MED 6(2):161–168
42. Chou YK, Evans CJ, Barash MM (2002) Experimental investigation on CBN turning of hardened AISI 52100 steel. J Mater Process Technol 124:274–283
43. Chou Y, Barash MM (1995) Review on hard turning and CBN cutting tools. SME Tech Pap MR95–214:1–12
44. Chou YK, Evans CJ (1999) Cubic boron nitride tool wear in interrupted hard cutting. Wear 225:234–245
45. Nakayama K, Arai M, Kanda T (1988) Machining characteristics of hard materials. Annal CIRP 37(1):89–92
46. Hitchiner MP, Wilks J (1987) Some remarks on the chemical wear of diamond and cubic BN during turning and grinding. Wear 114:327–338
47. Hooper RM, Parry A, Shakib JI, Brookes CA (1989) Mechanical properties, microstructure and wear of DBC50. Ind Diamond Rev 49:170–173
48. König W, Iding M, Link R (1990) Fine turning and drilling hardened steels. Ind Diamond Rev 50:79–85
49. Huang Y, Liang SY (2003) Cutting forces modeling considering the effect of tool thermal property-application to CBN hard turning. Int J Mach Tools Manuf 43(3):307–315
50. Varadarajan AS, Philip PK, Ramamoorthy B (2002) Investigation of hard turning with minimal cutting fluid application and its comparison with dry and wet turning. Int J Mach Tools Manuf 42:193–200
51. Rabinowicz E, Dunn LA, Russell PG (1961) A study of abrasive wear under three-body conditions. Wear 4:345–355
52. Archard JF (1953) Contact and rubbing of flat surfaces. J App Phy 24:981–988
53. Shaw MC, Dirke SO (1956) On the wear of cutting tools. Microtechnic 10(4):187–193
54. Kannatey-Asibu E Jr (1985) A transport-diffusion equation in metal cutting and its application to analysis of the rate of flank wear. ASME J Eng Ind 107:81–89
55. Loladze TN (1981) Of the theory of diffusion wear. Annal CIRP 30(1):71–76
56. Usui E, Shirakashi T, Kitagawa T (1978) Analytical prediction of three-dimensional cutting process, part 3: cutting temperature and crater wear of carbide tool. J Eng Ind 100:236–243
57. Kramer BM, Judd PK (1985) Computational design of wear coating. J Vac Sci Technol A3(6):2439–2444
58. Kramer BM (1986) Predicted wear resistances of binary carbide coatings. J Vac Sci Technol A4(6):2870–2873
59. Huang Y, Liang SY (2004) Modeling of CBN tool flank wear progression in finish hard turning. ASME J Manuf Sci Eng 126 (1):98–106
60. Huang Y, Liang SY (2004) Modeling of CBN tool crater wear in finish hard turning. Int J Adv Manuf Technol 24(9–10):632–639
61. Huang Y, Dawson TG (2005) Tool crater wear depth modeling in CBN hard turning. Wear 258(9):1455–1461
62. Huang Y, Liang, SY (2005) Modeling of cutting forces under hard turning condition considering tool wear effect. ASME J Manuf Sci Eng 127(2):262–270
63. Waldorf DJ (1996) Shearing, ploughing and wear in orthogonal machining. PhD Thesis, Uinv. of Illinois at Urbana-Champaign, IL
64. Huang Y, Liang, SY (2003) Modeling of cutting temperature distribution under the tool flank wear effect. Proc Instn Mech Engrs, Part C. J Mech Eng Sci 217(11):1195–1208
65. Huang Y, Liang SY (2003) Cutting forces modeling considering the effect of tool thermal property-application to CBN hard turning. Int J Mach Tools Manuf 43(3):307–315
66. Li X (1997) Development of a predictive model for stress distributions at the tool-chip interface in machining. J Mater Process Technol 63:169–174
67. Oxley PLB (1989) Mechanics of machining, an analytical approach to assessing machinability, Ellis Horwood, West Sussex, England
68. Astakhov VP (2004) The assessment of cutting tool wear. Int J Mach Tools Manuf 44:637–647