Diamond tool wear in ultra-precision machining

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Abstract

Diamond has many outstanding properties, such as high hardness, great toughness, high capability up to a nanometric tool cutting edge, high thermal conductivity, low friction and high wear resistance. Accordingly, it is employed as an efficient tool in ultra-precision machining (UPM). However, diamond tool wear (DTW) in UPM is an inevitable physical phenomenon and even a little DTW will produce a direct impact on nanometric surface roughness. With a focus on diamond's physical characteristics, this paper looks at the current investigations of DTW and posits an improved understanding of DTW in UPM. Firstly, the differences in DTW caused by different workpiece materials are reviewed, as are the factors influencing DTW and its effects. Secondly, the DTW mechanisms are summarized, including DTW anisotropy, DTW features and DTW behaviors, with diamond tool performances. Thirdly, DTW measuring, DTW monitoring, DTW controlling and DTW modeling are introduced. Thirdly, different methods for DTW suppression are surveyed with a view to improving the cutting performance of diamond tools. Finally, the challenges and opportunities for DTW, which may be of particular interest for future studies, are discussed with several conclusions.

Keywords: Diamond tool wear, Ultra-precision machining

1. Introduction

In ultra-precision machining (UPM), the achievable machining form accuracy PV and surface roughness Ra are less than 0.2 μm and less than 10 nm, respectively [1, 2]. The major prerequisite is its remarkable precision for controls, tools and machines down the nanometer range [2]. UPM is widely used to manufacture a variety of engineering materials, such as metals, ceramics, plastics and composites. Miniaturization, specialization and functionalization have pushed UPM improvements in the fields of optics, biotechnology, medicine, electronics, communications etc. [3]. The 21st century has witnessed the wide applications of UPM in optics for products such as spherical/aspheric lenses, multi-focal lenses, Fresnel lenses, polygon mirrors, pyramid arrays, micro-structural arrays, anti-reflective channels and v-grooves [4]. It has also been used to economically manufacture complex freeform shapes and miniaturize products, where using other processes would be labor and time intensive, or even impossible.

In UPM, natural diamond is employed as a very efficient tool, since it possesses excellent performances such as high hardness, high capability up to a nanometric tool cutting edge, high thermal conductivity, low friction and high wear resistance [5]. Early, a diamond tool was only limited to machining soft and ductile non-ferrous materials easy-to-cut, such as aluminum and copper. Currently, UPM is capable of machining difficult-to-cut materials, such as silicon and steel, which possess special functions to satisfy the requirements of optics, semiconductor and mold industries.

During the machining of such difficult-to-cut materials or especially large-scale components, the key bottleneck is diamond tool wear (DTW). Additionally, DTW has a significant impact on high precision surface quality of UPM [4, 6]. For such components and materials, DTW is a deterministic condition influencing surface quality and hindering the practical applications of the technology. Therefore, many studies have focused on DTW mechanisms, DTW monitoring and DTW controlling. Fig. 1 shows that certain materials are easy to cut for diamond tools and others cause catastrophic DTW after a short cutting distance [7]. It is strongly related to the chemical activity of the materials/elements. Fig. 2 presents the schematic map of diamond tool life for various workpiece materials. For difficult-to-cut materials the cutting distance is very short on the order of meters, but for easy-to-cut materials the cutting distance is long on the order of kilometers. The DTW differences cannot be explained only by the mechanical properties of the materials, but also by the chemical properties of the materials.

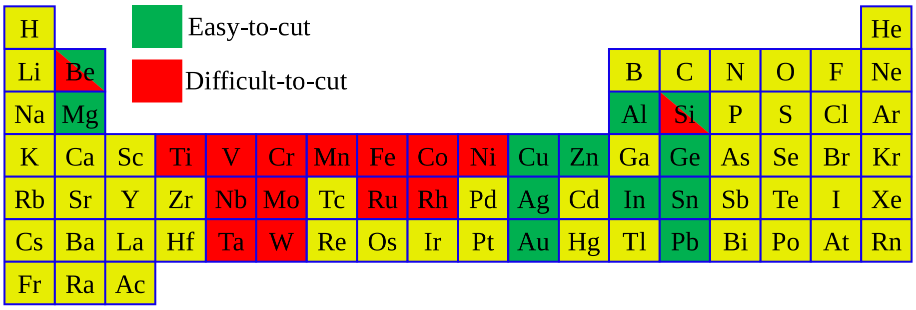


Figure 1. Classification of easy-to-cut and difficult-to-cut materials for diamond tools in UPDM [7]

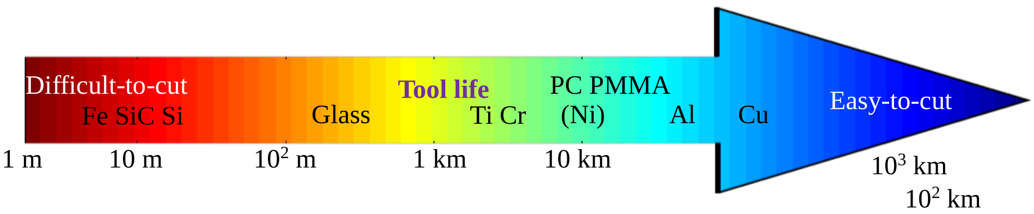


Figure 2. Schematic map of diamond tool life for different workpiece materials

The literature review focuses on DTW in UPM covering ultra-precision diamond turning (UPDT)/single point diamond turning (SPDT) and ultra-precision fly cutting (UPFC) / raster milling (UPRM), namely ultra-precision diamond machining (UPDM). In the current state of the art the investigations of DTW in UPM are surveyed with a major focus on DTW characteristics, DTW mechanisms, DTW measuring, DTW monitoring, DTW controlling and DTW modelling. The review is concluded with a detailed discussion, the challenges and the opportunities associated with DTW in UPDM.

2. DTW characteristics

2.1 Easy-to-cut materials

In UPM, a diamond tool is employed as an optimum selection. For a diamond tool, it is easy to achieve nanometric surface roughness when cutting non-ferrous, easy-to-cut materials such as aluminum, copper alloy, silver, gold, electroless nickel and acrylic plastics [8]. The major reasons are: (1) single crystal diamond can be polished to yield a nanometric cutting edge, which is essential for machining components to nanometric surface roughness; (2) DTW is low and almost negligible which cutting easy-to-cut materials, i.e. a diamond tool can last for a cutting distance of a few hundred kilometers; (3) and the machined surface quality can reach to nanometric surface roughness.

When machining Al-Si alloy [9], oxygen-free high conductivity (OFHC) copper [10], gold [11], aluminum alloy [12], copper [12], brass [12] and electroless nickel [13], DTW is not detected significantly until the cutting distance is in the order of kilometers. The friction between the diamond tools and workpiece affects tool wear [13]. When cutting Al6061 [14], the measureable wear can be observed after a cutting distance of several kilometers. The wear coefficient for Al6061 is lower at 0.057 $\mu m^3 N^{-1} m^{-1}$ [14] and less than half of that for pure aluminum proposed by Crompton et al. [15]. Fig. 3 shows the SEM images of diamond tools after cutting 7.5 km of Al6061 and cutting 15 m of Steel1215. DTW behaviors very much depend on the workpiece materials due to great differences in wear resistance [14].

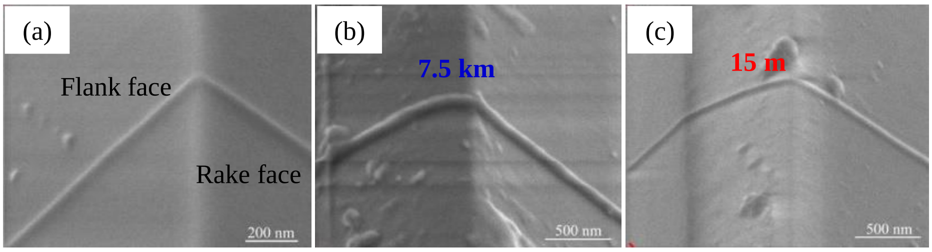


Figure 3. SEM images of diamond tool cutting edges with flat-nose: (a) new diamond tool; (b) worn diamond tools after cutting 7.5 km of Al6061; (c) and worn diamond tool after cutting 15 m of Steel1215 [14]

When machining electroless nickel for a cutting distance of several tens of kilometers, DTW is obvious. In brief, diamond tools are suitable for machining electroless nickel [16] and nickel-phosphorus alloy [17] to obtain mirror surface quality. Gubbels et al. [18] conducted cutting tests for two amorphous polymers, polycarbonate (PC) and polymethylmethacrylate (PMMA). The relatively large DTW may be an issue. They found after a cutting distance of 85 km, the large DTW in dry cutting takes place, while the less DTW in wet cutting occurs [18].

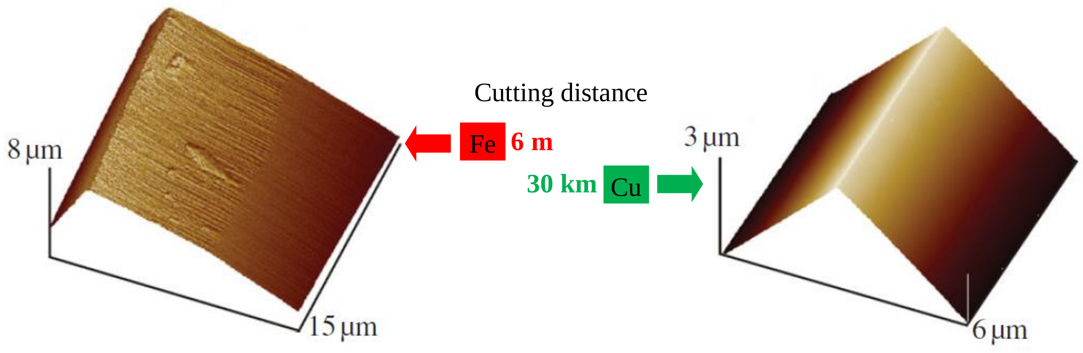
Overall, DTW in cutting of easy-to-cut materials is low with a low wear coefficient/superior wear resistance. Diamond tool life can last for a cutting distance of several thousand kilometers. The tool life of easy-to-cut materials is from Cu, Al, to electroless Ni, as shown in Fig. 2. The wear rate is strongly relevant to the machined materials. In view of the very low DTW rate they are rightly termed easy-to-cut materials. Generally, DTW can be ignored in UPM of easy-to-cut materials, but for large-scale components or for long-time cutting it will become of great significance to influence surface quality.

2.2 Difficult-to-cut materials

UPDM has been extended for machining difficult-to-cut materials like glass for optics, ferrous materials for dies and molds under high efficiency for generating complex shapes with high precision surface quality [19] over ultra-precision grinding and polishing. Currently, UPDM is employed for cutting crystal materials such as silicon, silicon carbide, germanium, selenide and zinc sulfide, as presented next. However, rapid DTW still restricts the UPDM applications in this field for machining of difficult-to-cut materials.

In machining glass, rapid tool wear is a serious issue. Fang et al. [20] proposed that after a cutting distance of 4 km, the maximum flank wear has been Wp to 70 μm Wnder dWctile-mode cutting. Jia and Zhou [21] observed DTW for glass soda-lime after a cutting distance of 50 m and the cutting-mode transition from ductile to brittle after a cutting distance of over 150 m. In cutting optical glass, the main reason for hindering the practical application of UPDM is the high tool wear rate.

UPDM of silicon is limited by rapid DTW, which is detected significantly after a cutting distance of only one kilometer [22, 23]. For silicon carbide (SiC), it is successful in technical feasibility and economic viability of SiC UPDM [24, 25]. For nanometric surface roughness, the prerequisite is ductile-mode cutting. Due to high hydrostatic pressure in cutting and its special properties, DTW is still intolerable. After a cutting distance of only a few tens of meters, obvious DTW takes place [24, 25].



(a) (b)

Figure 4. Scanning force microscope images of DTW after cutting (a) iron for 6 m and (b) copper for 30 km [7]

In machining ferrous metals for high precise and complex surfaces, diamond tools are subject to catastrophic wear, which subsequently downgrades surface quality. The DTW rate is very high [26]. The DTW rate in turning mild steel is 10^4 times faster than in turning brass of comparable hardness [26]. Fig. 3 shows that the DTW rate for Steel1215 is significantly higher than that for Al6061 [14]. Brinksmeier and Preuß [7] conducted cutting tests of iron and copper. The outstanding difference of DTW between the materials is shown in Fig. 4. After a cutting distance of 30 km in diamond-cutting of copper, DTW is not obvious, which is due to mechanical wear. However, after a cutting distance of only 6 m in cutting iron the diamond tool has been worn severely, which owes to chemical wear.

A little research also has focused on other difficult-to-cut materials. When cutting titanium (pure titanium and Ti6Al4V), diamond tool life reaches up to several kilometers [27].

Abou-EI-Hossein et al. [28] observed that the flank wear land is 8 μm after a cWtting distance of W Wp to 6.28 km for Cu-Cr-Zr alloy.

In brief, in terms of tool life the problem in UPDM for difficult-to-cut materials is not due to high cutting forces, but to rapid DTW as shown in Fig. 2. It shows that workpiece material is the essential factor influencing DTW. Although ductile-mode cutting for brittle materials can be achieved, the bottleneck commercially limiting the technology for practical use is still large DTW. The successful commercial application of UPDM to difficult-to-cut materials will be a great step toward high quality surfaces.

2.3 Cutting conditions

DTW is a critical challenge in UPM. As aforementioned, DTW is strongly dependent on the physical and chemical nature of workpiece materials, which essentially determine the DTW rate in machining. For example, in cutting copper, the wear rate is very low, while for iron or steel the wear rate is considered intolerable [7]. Cutting conditions, such as cutting parameters, tool geometries and coolant types, will also suppress or promote tool wear, as presented next. Material properties are considered as the internal causes and cutting conditions are the external causes.

2.3.1 Cutting parameters

Cutting parameters include feed rate, spindle speed and depth of cut. The change in cutting speed is believed to be one of the main causes of uneven wear along the cutting edge. In brittle-mode cutting DTW is more serious than in ductile-mode cutting [22]. The cutting mode is determined by uncut chip thickness, which is directly relevant to cutting parameters. Generally, high cutting speed leads to low DTW [27], high depth of cut produces high DTW and high feed rate results in high DTW [27].

However, different views on the general understanding of the effects of cutting parameters on DTW have been proposed. Thornton and Wilks [26] found that when cutting mild steel at high cutting speed the DTW rate increases with increasing cutting speed but at low cutting speed reversely. The major reason for this may be that the transition between the metal-carbon reaction and the oxygen-metal-carbon reaction takes place. Casey and Wilks [9] conducted tool wear experiments on Al-Si turning and found that the DTW rate is independent of cutting speed and that the intermittency of cutting does not affect DTW.

Born and Goodman [29] found that tool wear increases as feed rate for a fixed area decreases, since the cutting distance increases. As chip size related to depth of cut increases, the tool wear decreases. That is because the tool rubs on the machined surface when chip size decreases. Abou-El-Hossein et al. found that with increasing cutting speed and feed rate, DTW changes from abrasive wear to larger-scale chipping in UPDT of Cu-Cr-Zr alloy [28], which is contrary to the result in Ref. [29]. Also, it has been found that DTW in UPDM of RSA 905 (rapidly solidified Al6061, RSA) tends to be more intensive at the middle value of the feed rate [30], which is not consistent with Refs. [28, 29].

Although it is controversial, cutting parameters, such as cutting speed, feed rate and depth of cut, have a definite impact on DTW in UPDM. Partially, it may be induced by the different criterion in tool wear estimation. The general view is that there exists a critical cutting speed, feed rate and depth of cut to minimize DTW. More importantly, cutting efficiency and surface quality should be taken into account.

2.3.2 Tool Geometries

Tool geometries comprise tool nose radius *R*, tool rake angle α, tool side rake angle β, tool cutting edge radius *r* and tool included angle ε. Durazo-Cardenas et al. [23] carried out UPDM of silicon using three diamond tools with rake angles α of -15°, -25° and -45°. It is proved that the diamond tool with the rake angle α of -25° is more conducive to diamond turning silicon with present conditions, yielding a relatively long cutting distance other than -15° and -45° diamond tools.

Born and Goodman [29] found that in diamond turning of large single-crystal silicon optics less tool wear occurs with negative rake angle tools and the side rake angle β does not significantly affect tool wear. Yan et al. [31] proposed that as the rake angle α becomes negative, micro-chippings and wear on the edge decreases significantly. It means that a negative rake angle α can improve tool life. Zhou et al. [32] proposed that the included angle ε and nose radius *R* have dramatic effects on tool wear. They found that a tool with a bigger nose radius *R* or a larger included angle ε causes less tool wear. Enlarging the tool nose radius *r* or/and the included angle ε can extend tool life.

2.3.2 Cutting fluid

Cutting fluids provide lubricating and cooling to reduce friction, cool the cutting region, suppress tool wear and improve surface roughness. It plays an extremely important role in affecting DTW and surface quality in the cutting process. It not only influences material removal mechanisms but also tool life.

Born and Goodman [29] reported that cutting fluids (Polyalkaline Glycol (PAG), PAG with water and PAG with water and tri-potassium phosphate) do not significantly affect tool wear in diamond turning of large single-crystal silicon optics. Yan et al. [22] found that the coolant induces a longer ductile-mode cutting distance and whereby prolonged tool life in ultra-precision cutting of single crystal silicon although the coolants (Kerosene and water) leads to a decrease in critical chip thickness. Durazo-Cardenas et al. [23] found that the diamond tool life in UPDM of longer when using the water-based coolant than when using the oil-based coolant. The reason may be that the water-based coolant has a higher specific heat than the oil-based coolant.

Also, Yan et al. [33] employed four types of nanoparticle lubricants (MoS_2, GF, Cu and CuO) for lubricating RB-SiC diamond turning. The results showed that the 10%-Cu nanoparticle grease produces the highest surface quality and the lowest tool wear. Moreover, it has also been proposed that grease containing MoS_2 micro-particles provides better lubrication than kerosene mist in ultra-precision cutting of SiC [31]. It is possible to prolong tool life by using an appropriate coolant. Zhang et al. [34] found that ultra-sonic vibration with gas-liquid (CO_2 and CCl_4) atomization cooling effectively prolongs the tool life in cutting tungsten-based alloy. The liquid flow rate *Q*, gas flow rate *Q*, gas-liquid mass ratio and gas-liquid pressure ratio significantly affect DTW.

The main reasons why effective lubricant and coolant can mitigate DTW are: (i) it lubricates the contact surface to reduce friction; (ii) it reduces the cutting temperature between tool and workpiece; and (iii) a thin film is formed at the tool tip to protect the diamond tool from directly contacting cutting chips.

2.4 DTW effects

The single crystal diamond tool has been employed for UPM due to its excellent performances. A worn diamond tool is still a rigid body that imprints its geometry on the machined surface to influence surface roughness and form accuracy. Zhang et al. [35] studied the relationship between DTW and surface generation and chip formation in UPRM. They found that tool fracture wear imprints on the machined surface and the cutting chips. For high precision surface quality, micro/nanometric wear can make a significant impact on surface roughness. Tool wear causes the loss of the original profile accuracy of the cutting edge to be reproduced on the machined surface, which results in a higher PV value by plastic side flow, degrades form accuracy and confuses surface topography [36, 37].

A blunt tool will cause cutting forces, especially thrust forces, to increase greatly, as schematically shown in Fig. 5. It induces the cutting-mode change from cutting to ploughing. Ultimately, the loss of the original cutting-edge accuracy and the consequent fluctuation in cutting forces will degrade machining accuracy. DTW increases cutting forces, which accordingly influences residual stress, material properties, chip formation, form accuracy and surface roughness. Table 1 summarizes DTW effects and Fig. 6 presents the relationship of DTW effects on surface integrity in UPDM. Especially in cutting brittle materials, DTW results in an undesirable ductile-brittle transition [22] that further deteriorates surface quality and shortens tool life. Although it is evident that a little DTW does deteriorate surface integrity [6], the relationship among DTW effects involved in Table 1 and Fig. 6 is also extremely complicated. Some attempts have been made to discuss the effects of DTW on surface integrity.

Tool wear is dynamic and inevitable during the cutting process, which will induce poor surface quality if the tool is worn severely. Also, tool wear can affect surface integrity either directly or indirectly. Fig.7 summarily shows the mutually effects of DTW and cutting force on surface generation. Tool wear causes cutting forces to increase and those consequent forces promote vibration in the cutting process, which further worsens surface quality. Further, the increased cutting forces increase cutting temperature and pressure to promote DTW. They are mutually promoted by each other. Another mutual promotion takes place when cutting brittle materials, where DTW causes an undesirable ductile-brittle transition, which further downgrades surface quality and shortens tool life.

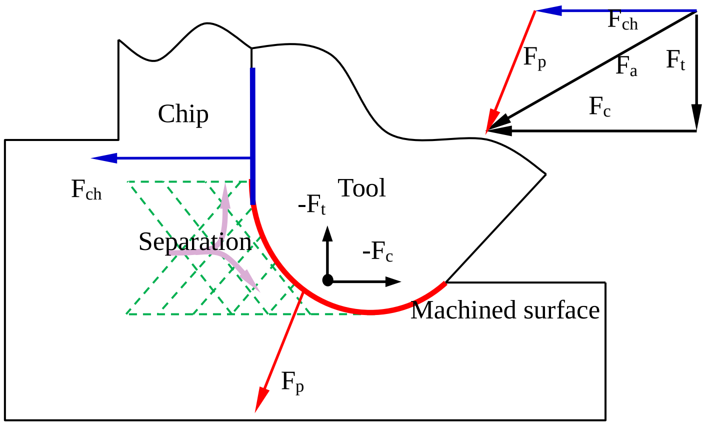


Figure 5. Schematic map of DTW effects on cutting force and chip formation

Table 1. DTW effects (↑ increasing, ↓ downgrading)

No.	Effects	References
1	Surface roughness ↑	[16, 21, 22, 39]
2	Form accuracy ↑	[38]
3	Force ↑	[16, 22, 27]
4	Change from cutting to ploughing ↑	[39]
5	Chip formation ↓	[22, 35]
6	Ductile-brittle transition ↑	[21, 22]
7	Surface topography/quality ↓	[22, 27, 35, 37]
8	Material properties ↓	[6]
9	Plastic side flow ↑	[40]

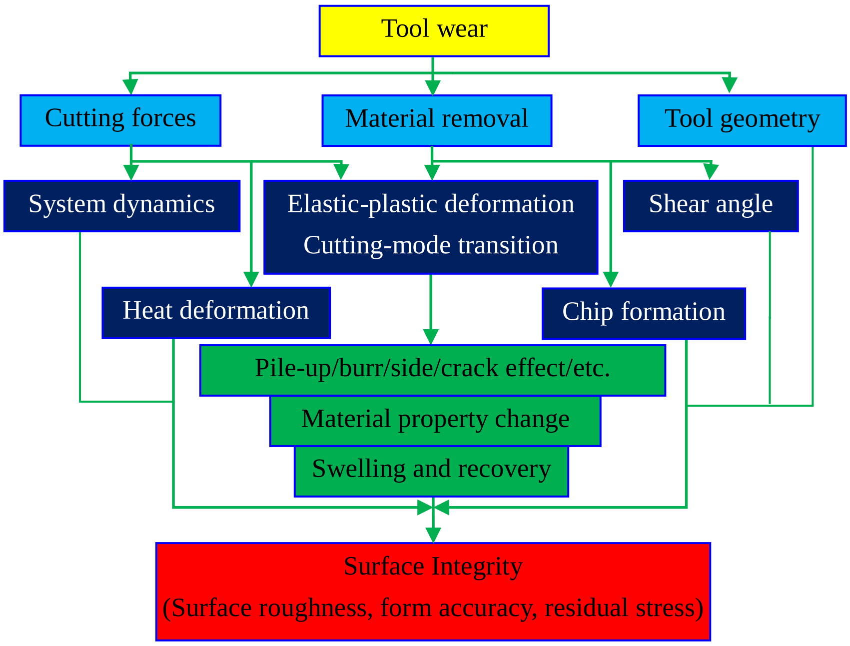


Figure 6. The relationship among DTW effects on surface integrity

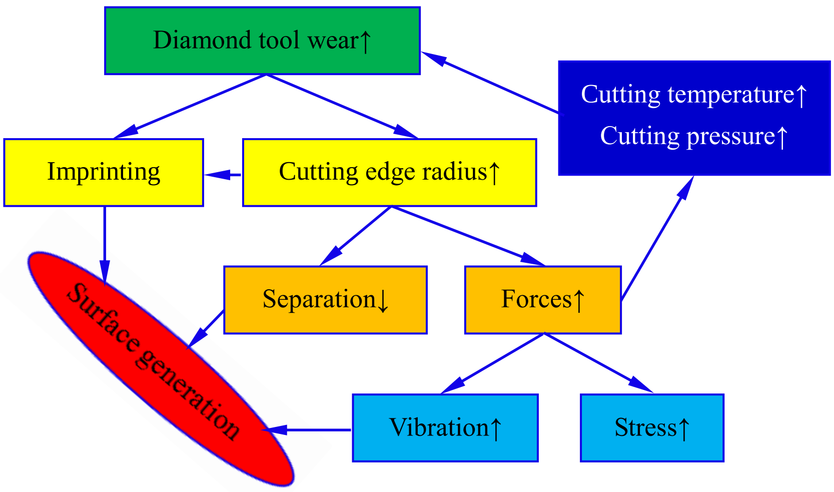


Figure 7. The mutual effects of DTW and cutting force to further influence surface generation

3. DTW mechanisms

DTW mechanisms are naturally determined by diamond tools and the machined workpiece materials. They can be classified into mechanical, chemical and physical wear. Mechanical wear includes abrasive wear, fatigue and adhesive wear. Chemical wear covers chemical reaction, graphitization, amorphization and diffusion. Physical wear involves thermo-chemical wear, tribo-electric wear, anisotropy and defect. Table 2 summarizes DTW mechanisms with the corresponding features. They are presented next.

Table 2. DTW mechanisms

Nature	Mechanism	Feature
Mechanical wear	Friction	Abrasive wear Tribo-chemical wear
	Fatigue	Chipping, cracking, fracture
	Adhesion	Adhesive wear
Chemical wear	Chemical reactivity	Complex, like SiC
	Graphitization Amorphization Diffusion	sp^3, sp^2, sp Diamond-like particles
Physical wear	Thermal properties	Thermo-chemical wear
	Electricity	Tribo-electric wear
	Crystal orientation	Anisotropy
	Defect	Impurity

3.1 Diamond tool performances

Natural diamond has significant differences in its physical, mechanical and chemical properties, which are determined by the types and distribution of internal defects and impurities [13, 41]. The major impurity is nitrogen with significant amounts of oxygen and hydrogen [41]. Wong [42] reported that the larger the amount of N-O bond in a diamond tool is, the shorter tool life is. Tamaguchi et al. [10] found that the larger the amount of the defects in any type is, the lower the wear resistance and the larger the amount of the thin plate aggregate of nitrogen atoms, the higher the chipping resistance.

Due to the remarkable variation of diamonds [23], the key selection of raw diamonds for long tool life is very crucial, since their quality significantly influences tool wear. Raw diamonds are classified into Type I and Type II, as shown in Table 3. Type I has low dislocation density and high density of the thin plate aggregate of impurities which make the dislocation movement more difficult to cause plastic deformation. Type Ib has good repeatability of tool life. Type II exhibits extremely good heat conductors and Type IIb is the most resistant of all. However, a little research work has focused on evaluating the influence of the quality of raw diamonds on DTW.

Ikawa et al. [43] found that the higher the infrared absorption coefficient is, the lower the strength. Another factor influencing tool life is considered to be the fracture suddenly caused by the extension of micro-cracks that may be produced during polishing [10]. Tanaka et al. [44] employed a Hertzian strength test with the aid of a high sensitivity load cell and acoustic emission detector to successfully detect the crack initiation of diamond tools.

Diamond tool life varies remarkably, due to the internal defects and impurities of raw diamonds. Therefore, diamond rank is taken into account as a very important factor influencing DTW. Due to the considerable variation of diamond tool life, DTW estimation in experimental results may not be accurate, which may lead to some debate when studying DTW. In general, the mathematical statistics method is a suitable tool for DTW estimation. Cutting experiments should be carried out using at least five different diamond tools. Assuming that the life of the individual tools follows the Weibull distribution, the life at 50% of the cumulative probability curve is regarded as the average tool life [44].

Table 3. Classification of diamonds [3, 13]

Type / Element	Type I		Type II	
	a	b	a	b
Nitrogen (ppm)	~200-2400	~40	~8-40	~5-40
Boron (ppm)	Nil.	Nil.	Nil.	~0.5
Descriptions of Nitrogen form	Clusters	Isolation atoms	Very little	Substantial boron

3.2 Anisotropy of DTW

Natural diamond is anisotropic. Carbon atoms are arranged in a variation of the face-centered cubic crystal structure through tetrahedral and covalent bonds between each atom and its four nearest neighbors. In nature, the most common cubic forms are octahedron and dodecahedron. For diamond tools, the (111), (110) and (100) crystallographic planes are the most commonly used, as presented next.

Diamond polishers usually select soft surfaces that exhibit a high wear rate and are convenient to polish. Softness is determined by the relationship between crystallographic plane and polishing direction [45], denoted by (plane)<direction>. The softest is (110)<100> while the next softest is (100)<100>; (100)<110>, (110)<110> and all directions on the (111) plane are hard [46]. The friction coefficient depends on the crystallographic plane [39] as well as the abrasion direction [46]. The lowest friction is (110) and the highest (100). Generally, (100) and (110) are considered be the tool rake and flank faces, since they are more resistant to abrasion.

Casey and Wilks [9] also observed that in cutting LM13 (Al–12%Si), the tool life with the (100) rake face is 7 times longer than others. Hurt and Decker [11] reported when cutting OFHC copper and gold the wear resistance for the (100) flank face is higher than (110). Yuan et al. [12] demonstrated that the diamond tools with the (100) rake and flank faces possess higher wear resistance than (110) in UPM of aluminum, copper and brass.

In addition, fracture along (111) is amenable to the degradation of the tool cutting edge for (110) [3]. Wilks and Wilks [47] proposed the idea that (111) is the easy cleavage plane. The wear rates in (100)<100>, (110)<100> and (111)<112> are higher than those in (100)<110>, (110)<110> and (111)<112> [47]. The lowest cleavage energy is (111) and the highest (100) [41]. The crystallographic orientation is particularly important for crack propagation along cleavage planes. Hence, (100) is a more suitable rake face for chip resistance than (110) in machining. The likelihood of DTW may be decreased by the selection of the proper crystallographic orientation.

However, published results are contradictory. Zong et al. [48] found in UPM of (111) silicon wafers the tool with the (110) rake face and the (100) flank face (denoted by R(110)F(100)) have the smallest wear land, compared with R(110)F(110), R(100)F(100) and R(100)F(110). Ge et al. [40] observed that the flank wear with R(110)F(100) is one-fifth of R(110)F(110) in UPDT of SiC. Wang et al. [39] found that microchipping is highly dependent on the crystal orientation and the R(110)F(100) tool is more resistant to damage in UPDM of die steel. In machining tests of Al T633, Oomen and Eisses [13] found the wear rate with the (110) rake face and the <100> cutting direction is lower than (001)<1$\underline{1}$0>, (001)<100>, (001)<110>, (110)<001$\underline{>}$ and (110)<11$\underline{1}$>. The best crystallographic orientation for wear resistance relies on the cutting direction. However, Wong [42] announced that tool life is very close to exponential distribution and that crystallographic orientation does not significantly affect it.

For the above contradictions, there are some possible explanations. DTW takes place in two stages. One involves crack formation in polishing and the other involves crack propagation after accumulative fatigue in machining. The life of natural single crystal diamond tools is considered to depend on intrinsic crystalline defects due to nitrogen impurities in raw diamonds crystallographic orientation for wear resistance relies on the way diamond tools are used [47]. Workpiece materials essentially determine DTW but also the uncertainty in the cutting process and diamond tools influence the wear. It is worthy of note that insufficient diamond tools are used in most cutting trials. There can be little doubt that the crystallographic orientation has an internal impact on DTW.

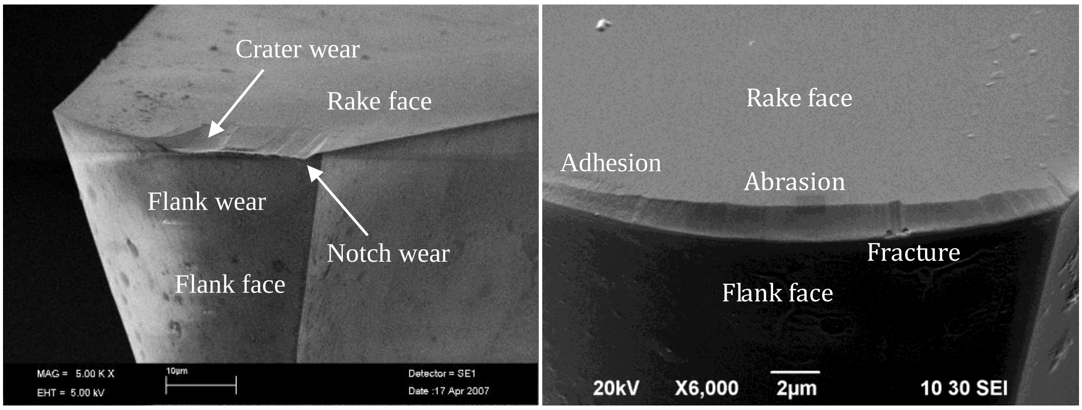


Figure 8. SEM pictures of worn diamond tools

3.3 DTW features

In UPDM, DTW inevitably takes place, which is a dynamic process influencing surface integrity. According to geometrical patterns as shown in Fig. 8, DTW can be classified into flank wear, crater wear, notch wear, nose wear, chipping, groove and fracture [42, 49]. These are external forms of DTW. In most studies [50] on tool condition monitoring (TCM) or tool wear detection, flank wear and crater wear have been focused on and ISO 3685 (1993) identifies flank wear and crater wear as the criteria of tool life. Notch wear is a very important factor because when it grows on the tool face it can cause tool breakage and weaken tool performance. In ISO 3685 (1993), severe notch wear with (VB_N) is also a criterion of tool life. Nose wear occurs in the nose area of the cutting tool. ISO 3685 (1993) also states that it is one of the main factors affecting surface roughness.

DTW mechanisms can be divided into abrasive wear, adhesive wear, diffusive wear, fatigue wear, thermo-chemical wear, tribo-chemical wear and tribo-electric wear, as presented next. These are internal causes of DTW that strongly depend on workpiece materials and ambient conditions. DTW in UPM is a critical challenge due to its complexity and the machined materials intrinsically determines the DTW rate.

In cutting easy-to-cut materials, the dominant wear mechanisms are likely abrasion induced by friction and chipping induced by impurities and adhesion may also be significant [51]. Table 4 presents DTW mechanisms in machining of easy-to-cut materials. Tanaka et al. [44] reported in turning of copper the thermo-chemical erosion of oxygen propagates existing microcracks. Ge et al. [40] observed microwear, chipping, abrasive wear and cleavage in UPDM of SiCp/Al matrix composite. The hard SiCp particles produce microchipping and microwear by abrasion. Hung et al. [52] observed excessive diffusive-abrasive wear on the flank face in dry face-turning Al359 composites. In cutting copper, Yamaguchi et al. [10] detected crater wear with chippings. Choi et al. [53] observed that in cutting Al micro-chippings are dominant but not flank and crater wear.

Table 4. Wear mechanisms in cutting easy-to-cut materials

Materials	Refs.	Wear patterns	Causes
SiCp/Al	[40]	Flank wear Crater wear Microchipping Microwear Cleavage	Mechanical abrasion Impurities Fatigue
Copper	[44]	Flank wear Crater wear Microcracking	Mechanical abrasion Impurities
Al359	[52]	Flank wear	Diffusive-abrasive wear
Al	[53]	Flank wear Crater wear Microchipping	Mechanical abrasion Impurities Fatigue
Cu-Cr-Zr	[28]	Chipping; Grooving	Mechanical abrasion Thermo-chemical wear
RSA 905	[30]	Flank wear Crater wear	Abrasion Thermo-chemical erosion

Abou-El-Hossein [28] noticed that the DTW in cutting Cu-Cr-Zr transits from abrasive wear to chipping and grooving with increasing cutting parameters, since more thermo-chemical wear occurs. At the middle range of the cutting parameters (feed rate of 15 mm/min, spindle speed of 1250 rpm) with depth of cut of 25 μm, abrasion, small chipping and notch have been detected due to the hardening effect. In diamond turning of RSA 905 [30], the wear is uniform without notch, chipping and grooving. It is induced by abrasion and possibly thermo-chemical erosion. Overall, in machining easy-to-cut materials, the DTW mechanism is mainly governed by abrasive wear.

In cutting difficult-to-cut materials, DTW is large. Table 5 presents DTW mechanisms in machining of difficult-to-cut materials. In ductile-mode cutting of silicon, micro-/nano-grooves are dominant with a little chipping. They are produced by SiC and diamond-like particles induced by temperature softening and phase transformation under hydrostatic pressure with abrasive, adhesive and possible diffusive wear [22]. In cutting of SiC, DTW is governed by high-pressure abrasion rather than diamond graphitization, also possibly by thermal-chemical effects [25]. In cutting glass, diffusion effect with thermo-chemical wear, mechanical friction effect and abrasive wear causes uniform and smooth wear with micro-grooves [21].

Table 5. Wear mechanisms in cutting difficult-to-cut materials

Materials	Refs.	Wear patterns	Causes
Si	[22, 54]	Micro-/nano-grooves Chipping Microcracking Gradual wear	Formed SiC and diamond-like particles Mechanical abrasion and adhesion Thermo-chemical wear Diamond graphitization Diffusion
SiC	[25, 55]	Grooves Gradual wear	Tool feed mark Abrasion Diamond graphitization
Glass	[21]	Uniform wear Micro-grooves	Diffusion Thermo-chemical wear Mechanical and abrasive wear
Steel	[26, 47, 49]	Ridges Grooves Gradual wear	Chemical wear Diffusion Abrasion Diamond graphitization

In cutting ferrous materials, the DTW rate is very high. The chemical wear is dominant. In the presence of oxygen, diamond graphitizes at about 900 K. While machining, the graphite is continually removed or carbon diffuses into iron [26]. Paul et al. [49] carried out an extensive investigation into chemical wear for some materials (cerium, ytterbium, neodymium, samarium, palladium, iron, titanium and silicon) in diamond turning, exploring and distinguishing mechanical-abrasive wear and chemical-reactive wear. Due to the high affinity of to carbon in diamond tools [56], chemical wear occurs through diffusion, amorphization, graphitization and carbide formation, especially at relatively high cutting speeds. For these reasons it is extremely difficult for diamond to cut hardened steel parts. Gubbels et al. [18] proposed that crater wear with chipping takes place in cutting amorphous polymers. Although tribo-electric charge has been observed, tribo-chemical tool wear is the dominant wear mechanism.

3.4 DTW behaviors

DTW mechanisms contain mechanical, physical and chemical wear (diffusion, oxidation, amorphization, graphitization and carbide formation) as presented next, which are strongly related to workpiece materials and external elements in gaseous environment and coolant. For easy-to-cut materials, abrasive wear is dominant; whereas for difficult-to-cut materials, chemical wear governs wear mechanisms. For instance, DTW mechanisms in machining of steel and other ferrous alloys are diffusion, oxidation, graphitization and carbide formation under high temperature and high pressure induced by cutting [37]. Overall, DTW is dominated by cutting heat/temperature, pressures, the catalytic action of elements and the activity of the clean surface.

3.4.1 Friction

Friction (tribology) is the surface resistance to the relative motion of two contacting surfaces against each other. In the reviews of Field [41] and Wilks and Wilks [47], it is summarized that the friction coefficient μ of diamond is anisotropic and extremely low, in the range of 0.05 to 0.15. By sliding friction experiments, Miyoshi and Buckley [57] found that the greater the amount of the d-electron bonds of the metal is, the more active its surface and the higher the friction coefficient μ. The adhesion and friction of metals are related to the chemical activity of the metal surface. When exposed to atomic hydrogen or oxygen, since the dangling bonds are saturated, the friction is low and reduces to approximately 0.1 [58], even to less than 0.02, depending on the sliding conditions [41].

Field [41] found that typical lubricants do not affect friction since it is too low and Buzio asserted that the surface is smooth as possibly as to minimize friction [59]. The classic view is that friction is made up of adhesion and ploughing [57]. In addition, due to the irregularity of the contact surfaces, ploughing, rubbing or grinding takes place in micro/nano scale to form friction by elastic-plastic deformation. Temperature is a key factor influencing friction. Hence, as diamond slides on the workpiece material in machining, the abrasion strongly relies on the workpiece material, temperature and deformation.

3.4.2 Thermal properties

Diamond possesses very high thermal conductivity κ, which is about 5 times greater than copper at room temperature. At ambient temperature, diamond is stable and inert. Elements with/without unpaired d-electrons are inert to diamond [49]. Up to 900 K, its mechanical, physical and chemical properties change in essence. At above 900 K, thermal erosion of diamond occurs due to carbon solubility, graphitization, oxidization in oxygen and chemical reaction with other elements such as Si, Ti and Fe.

Generally, higher temperature means more wear. However, as DTW for steel was more than that for iron at high temperature, it was less at low temperature. That is because the ratios of diffusion to graphitization are different for steel and iron and also the hardness is different. Temperature also affects the friction by adhesion. A review by Berman [60] provides more details of thermal properties of diamond.

3.4.3 Chemical reactivity

At ambient temperature, diamond is inert. It will not react chemically with other elements such as oxygen and Fe and not be etched by acids. However, under a high temperature it is activated. At a temperature in the range 800–1,100 K molten potassium nitrate is a commonly used etchant for diamond. Over 900 K, diamond will have a reaction with oxygen to form CO or CO_2. Shimada et al. [61] showed that carbon oxidization is a key factor causing DTW in machining copper. Diamond with other elements will form carbides and solvent/catalyst synthesis of carbon. In UPM, it is possible to achieve the chemical reaction temperature about 900 K at the diamond tool tip.

In 1949, Pauling [62] presented the theory of d-electron band responsible for physical and chemical properties. Paul et al. [49] ascribed chemical wear of diamond tools to unpaired d-electrons of metals. Carbon atoms are pulled from diamond lattices and then diffuse into the workpiece, graphitize, or react with workpiece to form carbides or with oxygen to form CO or CO_2. In cutting steel or iron, diamond graphitizes and diffuses [26, 63] or maybe forms iron carbide (Fe_3C) [64]. In nanometric cutting of silicon, SiC and diamond-like particles are formed [65]. Nickel with two unpaired d-electrons is not easy to cut but electroless nickel with the paired d-electrons of nickel and p-electrons of phosphorous is easy to cut [66].

Table 6. Data for elements with known diamond turning properties (t=tetragonal, f=face-centered cubic, h=hcp, o=orthorhombic, b=bcc, m=monoclinic, d=diamond) [49]

Element	Melting point ^{o}C	Crystal structure	Microhardness Brinell kg/mm^2		No. of unpaired d-electrons	Easy/Difficult to cutting
In	157	t	-	10	0	E
Sn	232	f	-	5	0	E
Pb	373	f	0.022	5	0	E
Zn	420	h	-	51	0	E
Pu	640	m	-	-	0	E
Mg	649	h	30	48	0	E
Al	660	f	-	25	0	E
Ge	937	d	-	721	0	E
Ag	962	f	-	96	0	E
Au	1064	f	-	96	0	E
Cu	1083	f	-	76	0	E
U	1132	o	245	-	1	D
Mn	1244	b	-	384	5	D
Be	1277	h	60	-	0	E
Si	1410	d	-	1,211	0	E/D
Ni	1453	f	-	189	2	D
Co	1495	h	100	247	3	D
Fe	1535	b	50	-	4	D
Ti	1660	h	75	142	2	D
Cr	1857	b	63	250	5	D
V	1890	b	-	248	3	D
Rh	1966	f	-	-	2	D
Ru	2310	h	-	-	3	D
Nb	2468	b	75	128	4	D
Mo	2617	b	162	192	5	D
Ta	2996	b	70	-	3	D
Re	3180	h	250	319	5	D
W	3410	b	-	348	4	D

Other machinable plastics and infrared crystals with no unpaired electrons correlate well with low chemical wear. However, Gubbels et al. [18] reported that the chain scission results in highly reactive radicals, further to form chemical wear in diamond turning of polymers. Paul et al.

[49] gave a summary for elements with known diamond turning properties, as shown in Table 6. It well explains DTW for easy-to-cut and difficult-to-cut materials as shown in Fig. 1 and Fig. 2.

The unpaired d-electrons theory implies that (1) materials with more unpaired d-electrons wear more diamond tools; and (2) there exist ways to mitigate chemical wear and to prolong tool life. Chemical wear takes place through carbon-oxygen, carbon-metal or metal-carbon-oxygen complexes, graphitization and diffusion. DTW has also a strong correlation with thermo-chemical reactions, which is attributed to graphitization, diffusion and oxidation at high temperature. The two fundamental prerequisites are temperature and pressure.

3.4.4 Graphitization

Diamond and graphite are called two allotropes of carbon. In diamond the crystal structure is tetrahedral and in graphite the crystal structure is horizontal and hexagonal. Under the appropriate conditions (temperature and pressure), diamond will transform into graphite as graphite converts into diamond [67, 68]. In air, transition takes place at 700 ^{o}C; in vaccum or oxygen-free atmosphere, diamond starts to graphitize at above 1,700 ^{o}C; and up to 2,000 ^{o}C the graphitization rate rapidly increases. The octahedral surface graphitizes with the activation energy of 1,060 ± 80 kJ mol^{-1} as three carbon-carbon bonds are broken. The dodecahedral surface graphitizes more rapidly with the activation energy of 730 ± 50 kJ mol^{-1} as two carbon-carbon bonds are broken [41]. Its extremely high thermal conductivity κ allows the cutting of most materials [41].

Phase transformations may therefore be a very common feature of wear. Hird and Field [69] stated that in diamond polishing sp^3 diamond changes into sp^2 graphite. Chacham and Kleinman [70] reported that the minimum shear stress for diamond graphitization is about 80-100 GPa. In UPDM, Diamond graphitization will take place. Uemura [71] introduced that the diamond graphitization occurs at relatively low temperatures (650–750 ^{o}C) due to desorption of chemisorbed hydrogen. Thornton and Wilks [26] announced that in machining steel, the DTW rate is very high by diamond graphitization, the clean surface of steel activates the graphitization at much lower temperatures and the wear rate is independent of atmospheric pressure. Ge et al. [40] claimed that in machining SiC_p/2009Al diamond graphitizes at about 500 ^{o}C because that copper oxidizes at about 505 ^{o}C, the resultant oxide catalyzes the diamond-graphite transition and then the graphite film is scraped off by the SiC particles. In cutting copper or copper alloys, a thin graphite film is also generated on the tool tip, but the thin graphite film becomes a solid lubricant because the carbon solubility in copper is rather low and the oxygen diffusion is hindered [40].

3.4.5 Amorphization

A new form of carbon is neither diamond nor graphite, but rather a diamond-like amorphous carbon that is a metastable material of growing interest. It has a mixture of sp^2 and sp^3 bonded carbon atoms. The sp^3 and sp^2 bonds are distorted, namely diamond-like and graphite-like amorphous carbons, respectively. The structure is determined by the ratio between diamond-like bonds and graphite-like bonds (i.e. sp^3/sp^2). Graphite is stable at low temperature and pressure. Comelli et al. [72] showed that the sp^2 bond fraction ranges from 60% at 30^{o}C to 90% at 1,050^{o}C. The prerequisite is that under special temperature and pressure conditions the sp^3 bonds are sufficiently distorted and unstable.

For machining, Pastewka et al. [45] used molecular dynamics (MD) to verify that polished diamond suffers from a sp^3-sp^2 order-disorder transition causing an amorphous adlayer. Using an X-ray photoelectron spectroscope, Zong et al. [54] first detected diamond-like particles in cutting silicon wafer from re-crystallization of diffusion carbon.

However, there is no report that the diamond-like particles have been observed during cutting other materials. During cutting, diamond and chip contact and undergo cycle pressure and temperature change, so it is possible for diamond amorphization to take place. Unfortunately, there is a lack of understanding the diamond-like particle formation in cutting.

3.4.6 Diffusion

In cutting, diffusion is one possible DTW mechanism [73]. Diffusion wear is influenced by chemical affinity between diamond and workpiece. Carbon atoms from diamond will diffuse into material vacancies, mainly determined by specific materials, carbon concentration, saturation limit, pressure and temperature. Further, the formed intermediate carbon-metal compound related to the presence of unpaired d-shell electrons will facilitates the diffusion from diamond into workpiece.

DTW in cutting hard high-carbon steel is less than that in cutting low-carbon steel or iron [49]. Cryogenic UPM of ferrous metals with natural diamonds reduces DTW [74]. Shimada et al. [75] found that the cutting temperature affects the diffusion in cutting ferrous metals but it is not the necessary condition for DTW. The fact that the diffusion increases with rising temperature along with experimental results [61, 71, 76, 77] suggests that diamond diffusion in machining ferrous metals is a crucial factor leading to DTW.

Yan et al. [22] and Luo et al. [78] speculated that diffusion might take place in cutting silicon. Diffusion also occurs in cutting nickel [79], electroless nickel [17] and glass [18]. Diffusion is assumed to be an important DTW mechanism occurring at high temperatures, which will lead to a high wear rate for some materials related to their unpaired d-shell electrons. The procedure is generally associated with graphitization [49, 80], namely diffusion of graphitized / graphitic carbon from diamond, which is affected by thermal effects in cutting.

3.4.7 Fatigue

Fatigue refers to structural damage from repeated loading. Under cyclic loading, ring cracks for diamond have been observed [81]. Crompton et al. [15] provided further evidence of fatigue in diamond by rubbing experiments using a pin-on-disc geometry.

In cutting, DTW is influenced by the thermo-mechanical effect and its duration [42] under cyclic loading and cutting heat that causes chipping and cracking. Chipping and cracking have been experimentally observed in machining tungsten carbide [82], silicon [22, 23], reaction-bonded silicon carbide [25], aluminum plate [53], RSA 905 [30] and copper alloy [35]. Besides, Gubbels et al. [18] observed considerable chippings in machining amorphous polymers. Tribo-electric and tribo-chemical wear also plays an important role.

Chipping is normally observed on the tool cutting edge. Cracking and chipping are produced not only by fatigue but by impurities on grain boundaries [10, 49], or/and existing cracking induced by diamond tool polishing [10, 41], tribo-electric and tribo-chemical wear [17, 18], impacting action of freely moving abrasive particles [22, 25], or relative with diamond crystal orientation and hardness [39]. Nevertheless, it can be asserted that fatigue wear definitely occurs in cutting any materials and finally leads to chipping and cracking, but are not the prerequisite for brittle cutting [23].

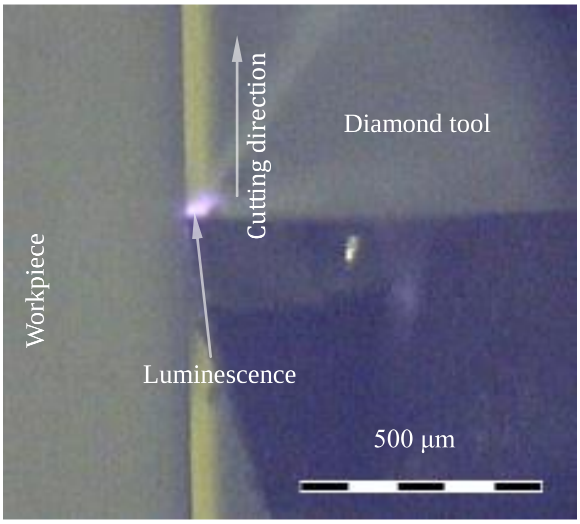


Figure 9. Light emission when diamond turning of PC [18]

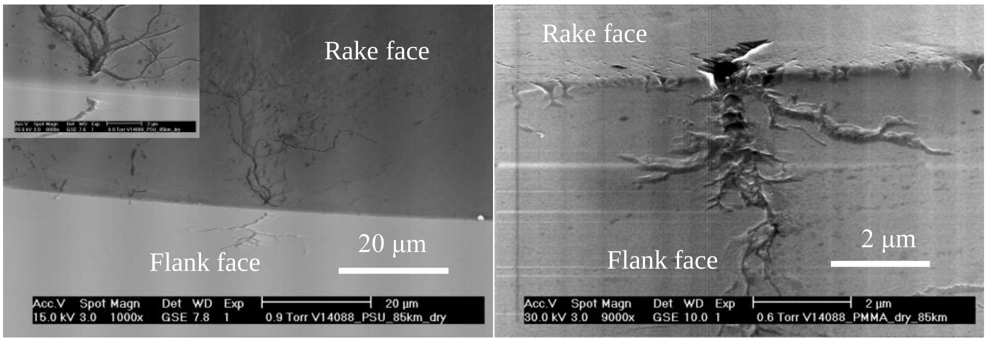


Figure 10. Tribo-electric wear of diamond tools when cutting polymers [83]

3.4.8 Electricity

Static electricity is a universal phenomenon in nature. During cutting the electric insulating materials, static electricity maybe takes place. The electric field can create electrostatic discharge between two surfaces, or induce lightning, plasma and luminescence. It causes or facilitates DTW, namely tribo-electric wear [83]. In industrial applications of UPDM of lens, tribo-electric wear might occur and may become a key problem.

Brezoczky and Seki [84] experimentally tested an electrostatic attractive force in diamond rubbing on hard amorphous carbon films, which creates tribo-electricity at a nanometric distance and leads to tribo-electric wear. Gubbels et al. [18, 83] measured electrostatic voltage between diamond tool and polymers (PC and PMMA) during machining and observed light emission induced by electrostatic discharge, as shown in Fig. 9. Fig. 10 presents tribo-electric wear of diamond tools when cutting polymers. It has been concluded that tribo-electric wear is one DTW mechanism but does not dominate in diamond turning of polymers. During wet cutting of PC, the wear is less without luminescence, but the wear pattern is the same as observed during dry cutting and cutting PMMA. The assertion that tribo-chemical wear is performed is in contrast to the work of Paul et al. [49], since PMMA and PC do not have unpaired d-electrons. Therefore, further research needs to be conducted for clarification.

3.4.9 Adhesion

Adhesion occurs by intermolecular attraction when diamond contacts and slides on the surface of materials [57, 59]. Adhesive wear proceeds at a low cutting temperature. Adhesion is totally different from abrasion in wear types as it looks as though some diamond materials are torn off from the tool surface, whose surface patterns are concavo-convex and rough.

Zong et al. [80] observed adhesion when lapped diamond tools with steel scaife. Adhesive wear has been experimentally verified in cutting hard nitride coatings (TiN_x, CrN_x and $TiAlN_x$) of electroless nickel [85] and silicon [22, 54]. In addition, adhesion has been observed in cutting titanium [86], steel and tungsten carbide [82] and PC [18]

Adhesion is a general process in cutting many materials, which will lead to adhesive wear. Importantly, the adhesive wear rate is different among different materials, which seems to follow the trend shown in Fig. 2. Paul et al. [49] concluded from experimental observations that adhesion and erosion of diamond surfaces are related to the ability of a metal in terms of available d electrons and accessible metal atoms.

4. DTW Measuring, DTW monitoring and DTW controlling

4.1 DTW Measuring

DTW can directly be measured by optical measurement, scanning electron microscope (SEM), atomic force microscope (AFM), as presented next. They are considered as an efficient means to estimate tool wear lands, tool wear features and tool wear mechanisms.

4.1.1 Optical microscope (OM)

OM is the most direct and simplest method for detecting DTW features. Currently, it is preferred to utilize in observing DTW, since it is convenient to measure DTW. The OM has tranditionally been used to observe tool wear features or measure tool wear lands simply through optical amplification [48]. However, imaging quality is greatly influenced by cutting fluid and chips. without a clear 3D distinction. Currently, a new OM, named differential interference contrast microscopy, has been employed to observe DTW features [23, 39, 82]. It provides impressive 3D-like images, which makes it much easier to observe DTW features and measure tool wear lands than a traditional OM.

A white light interferometer can also be utilized to provide true 3D wear lands for studying DTW [13]. However, OM is limited by its low resolution and small depth of field and offers only 2D measurement. Hence, although the OM is a rapid handy measurement tool, it cannot be used to detect very little wear but other microscopic methods such as AFM or SEM can.

4.1.2 Atomic force microscope (AFM)

Atomic force microscopy (AFM) is one kind of scanning probe microscope, with a sub-nanometric resolution for imaging, measuring and manipulating on a nanoscale. It has a wide range of applications covering almost every sciences. In the past, AFM was employed to measure diamond tool cutting edge [80, 87]. AFM is an efficient tool to measure the nanometric cutting edge.

AFM is also meaningfully employed to study DTW by mapping tool tip since it can capture a little wear [29, 73, 78, 82, 85]. In measuring DTW, AFM has several advantages over SEM. AFM shows a true 3D surface, but SEM only presents a 2D image. However, when the tip radius of AFM is close to the edge radius of a diamond tool, the measured edge profile is not true. The measurement accuracy will be influenced by the sharpness of the probe tip. In addition, it takes a long time scanning a sample and doing the experimental preparation.

4.1.3 Scanning electron microscope (SEM)

Scanning electron microscope (SEM) falls into the category of electron microscopy, providing high resolution imaging up to the order of 1 nm. Compared with OM, SEM has a larger depth of field and can provide a 3D image. In addition, it can be used to analyze the distribution of different elements or to identify the composition and measure the abundance of elements in a sample.

In studying DTW, SEM is mainly employed to observe tool wear mechanisms. The two reasons for this are that (1) it gives a high-resolution clear image with more 3D information for understanding the surface features of a diamond tool; and (2) it can determine chemical compositions produced after DTW takes place. The preparation for DTW measurement is gold coating.

SEM is preferentially extended to inspect diamond tools, such as tool cutting edge, tool wear lands and tool wear features. Although SEM shows 3D information of diamond tool cutting edge with a high resolution, but only a 2D image is qualitatively provided. Hence, it cannot directly be used to quantitatively study DTW. To overcome the 2D image problem, Asai et al. [88] developed a new method to measure tool cutting edge. In this method, two secondary electron detectors are used in SEM to obtain a 3D image. For this method, specialized equipment is required not commonly used in most SEMs.

Another technique is the electron beam induced deposition method (EBID), which has been developed by Drescher and Dow [89]. In this method, a hydrocarbon contamination stripe is deposited on a diamond and is then measured by SEM with a known angle; the stripe profile can then be calculated and hence the tool cutting edge profile is obtained. The EBID method has been used in studying DTW [14, 21, 89] but only distinguishes a semi-3D shape from 2D SEM image. A method similar to EBID is a focused ion beam (FIB) microscope, but it is not used for imaging since its resolution is inferior to that of EBID [14].

Other techniques have been employed to study DTW mechanisms, such as X-Ray photoelectron spectroscope (XPS) [27, 48], reflection electron microscopy [90], infrared spectroscopy [10, 42, 43, 90], transmission electron microscopy [91], electron energy loss spectroscopy [91], scanning tunneling microscope [92], scanning probe microscopy [93], Ramon spectroscopy [21, 25], X-ray diffractometry (XRD) [40], energy dispersive spectrometer (EDS) [27, 30] and laser scanning microscope [94]. Using XPS, Zong et al. [54] found that SiC and diamond-like particles are formed on and diamond carbon diffused into a silicon wafer during the nanometric cutting process. Ge et al. [40] used XRD and Ramon spectroscopy and found that the diamond-graphite transition takes place in UPDT of SiC_p/2009Al matric composite. Ikawa et al. [43] and Tanaka et al. [44] conducted a Hertzian fracture test with acoustic emission (AE) detection and an infrared absorption test to analyze the effects of impurity and fracture of diamond tools on wear mechanisms.

These experimental investigations provide evidence at the nanoscale and give some insights into how diamond tools are worn. Generally, the research on DTW is based on the qualitative technique SEM or the quantitative system AFM. Currently, 3D SEM with more functions has been commercially available. New and more precise microscopies will show more information to study DTW mechanisms.

4.2 DTW Monitoring

It is necessary to develop a tool condition monitoring (TCM) system to detect tool wear, thereby avoiding undesirable consequences such as product failing, time consuming and cost losing. In conventional machining, many methods have been developed to monitor tool wear. In UPDM, some studies have been conducted to monitor DTW by acoustic emission (AE), cutting force, acceleration, optical measurement, SEM, chip formation etc., as presented next. Based on the real-time capacity of signal acquisition, TCM can be categorized into on-line measurement (AE, cutting force, acceleration etc.), in-situ measurement (optical measurement etc.) and off-line measurement (SEM, AFM etc.). According to the mode of tool wear estimation in TCM, it can be classified into direct method (optical measurement, SEM, AFM etc.) and indirect method (AE, cutting force, acceleration etc.).

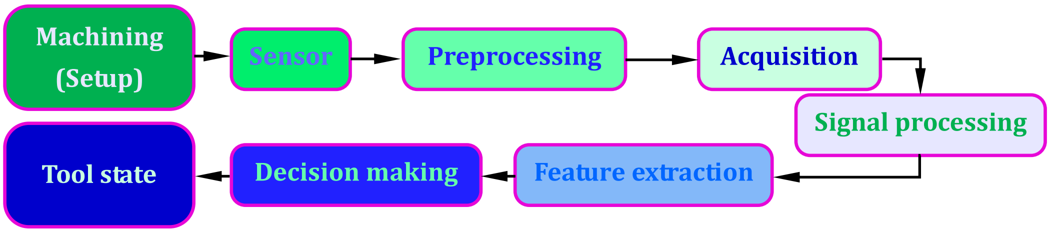


Figure 11. The framework of TCM [95]

As shown in Fig. 11, the TCM procedure generally includes signal acquisition, signal processing, feature extraction and decision making [95]. In UPDM, a little research work has been carried out on TCM, but it is still a big challenge to monitor a little DTW up to several nanometers, due to complex machining processes and micro-nano-scale size effects in UPDM.

4.2.1 Direction method

Direct method offers very direct tool wear parameters to compare with tool life criterion. On the other hand, its practical application is limited by the difficulty of accessing, use of cutting fluid, chips, illumination and fast real-time signal processing. Therefore, it is difficult to apply the method to on-line measurement, but it is possible to employ it in in-situ measurement.

Optical Measurement Significant results have been achieved with TCM in conventional machining by a CCD camera. In UPDM, as reviewed above, many scholars have employed OM to inspect DTW, analyze its features and discuss wear mechanisms. It mainly involves traditional OM, differential interference contrast microscopy, white-light profilometers. Little research has been conducted using OM to in-situ monitor DTW. Yan et al. [96] proposed nano precision on-machine profiling of curved cutting tools using a white-light interferometer. This method may be used to measure in-situ DTW. Shinozaki and Namba developed an on-machine measurement and observation system by a digital camera to detect tool wear in UPDM of large electroless nickel coated molding dies. Zhang et al. [98] proposed a new auto-regressive measurement method to reconstruct 3D topographic surfaces for DTW, using the in-process image of a diamond tool in UPRM. This is a possibility for in-situ/in-process 3D-wear measurement in UPRM.

SEM Due to the high resolution of SEM, it is widely used to observe and study DTW mechanisms and to estimate wear loss. It can detect nanometric wear. However, the method is not suitable to monitor DTW since a complicate experimental preparation should be provided every time for each sample. Not much work has been proposed using SEM to monitor DTW. It Zhang et al. [35] developed a novel method where the relationship between DTW and surface roughness and chip formation in UPRM is used to quantitatively estimate DTW. Significantly, it provides a possibility for on-line monitoring of DTW with a nanometric resolution by detecting chip formation. However, the detection is intermittent rather than continuous and the SEM measurement is a heavy and complicate work

AFM Due to its very high resolution, AFM has been employed to quantitatively analyze DTW with little loss. From the mapped diamond tool tip, the wear parameters can be quantitatively obtained. It is generally used to measure rather than monitor DTW possibly because the sample must be measured with time consuming. Notably, Gao et al. [99] developed a nanometric-resolution measuring instrument, consisting of an AFM and an optical alignment probe, to in-situ measure diamond tool tip for high precision positioning. More importantly, the method can be developed to in-situ monitor DTW.

From the above discussion, it can be summarized that among all direct methods the SEM and AFM methods are not suitable for practical application. The optical measurement method is more suitable for industrial applications even though the resolution is limited to several hundred nanometers by optical diffraction. In spite of the limitations such as interruption in machining, OM can provide reliable, actual and direct results. If the method can be successfully developed to detect DTW, it will have a promising future in industrial application of UPDM.

4.2.2 Indirection method

DTW will change cutting force, surface roughness, vibration, AE etc. These process parameters are indirect indicators correlating with DTW. Therefore, indirect method involving these process parameters can be developed to monitor DTW. Importantly, the signals are easily sensed to realize on-line monitoring. The cutting force and AE measurement techniques are the most commonly used in tool wear monitoring. The sensitivity is less than 10 nm. Some steps have been taken to develop an on-line monitoring system in UPDM, as presented next.

AE In machining, AE can detect most of the significant information with a wide bandwidth from 100 to 900 kHz due to high sensitivity and provide good signal quality. Fig. 12 presents the sources for AE sensors with different frequencies covering high frequency for UPM to low frequency for conventional machining [100]. In addition, metal cutting provide substantial AE signals owning to elastic and plastic deformation. It is commonly utilized to monitor tool wear [101].

In UPDM, AE has been used to monitor cutting processes of different materials [100, 102], such as surface defects and scratches, grain effect, chip formation and rubbing friction. In addition, AE has been applied to monitor DTW in UPDM. Abou-El-Hossein et al. [28, 30] used AE signals vs cutting distances to represent DTW. Yamaguchi et al. investigated DTW with and without chipping in UPDT of OFHC copper using AE signals [10] and used a wide-bandwidth AE sensor to measure AE signals during diamond turning electroless Ni-P in order to monitor DTW [17]. Marsh et al. [103]

fixed an AE sensor to monitor DTW in spin-turning single crystal silicon and mapped the AE signals vs resolutions as polar diagrams to discuss DTW.

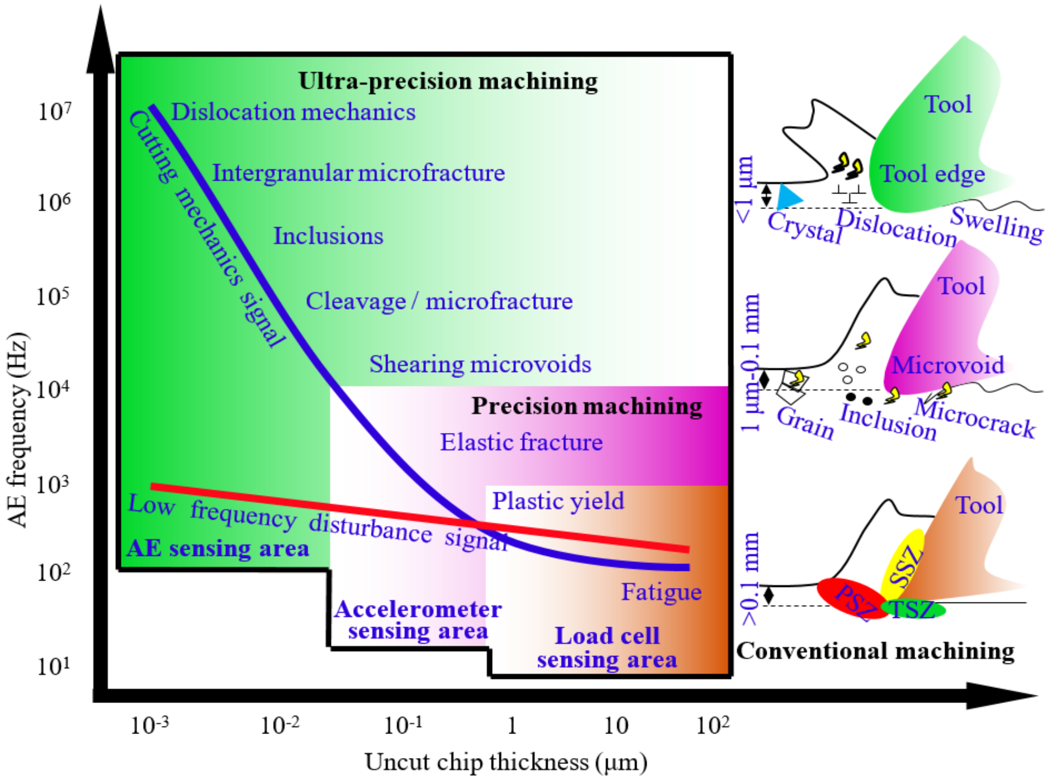


Figure 12. Sources of AE at different stages for material removal (PSZ: primary shear zone; SSZ: secondary shear zone; TSZ: tertiary shear zone) [100]

Cutting force Tool wear has a strong influence on cutting forces [22]. The cutting force measurement is commonly used to monitor tool wear. The cutting force is frequently measured to study cutting processes in UPM. It is also used to monitor DTW in UPDM [17, 21-23, 48, 53, 103] measured cutting forces to investigate DTW. The cutting force increases with the progress of DTW. Yan et al. [22] suggested the possibility of monitoring DTW using cutting force signals.

et al. [40], Jia and Zhou [21] studied surface roughness under different cutting distances influencing DTW in UPT. Zhang et al. [35] built a relationship model among DTW, surface roughness and chip formation in UPRM to quantitatively estimate DTW. Choi and Kim [53] employed a piezoelectric film accelerometer to monitor DTW.

Signal preprocessing In a cutting process, the measured signal contains many noises. It is difficult to decompose the part induced by DTW from the sensed signal and to eliminate noise. It involves analog preprocessing and digital preprocessing. In analog preprocessing, the analog signal is sensed by a sensor, gathered by digital acquisition card and then copied by a computer. In digital preprocessing, the digitized signal is compensated due to heat effects etc. and then is filtered using different methods such as low band pass filter. Finally, the signal is prepared for feature extraction.

Feature extraction During feature extraction, it is extremely important to obtain the most appropriate features well correlating with tool wear from the prepared signals. In addition, the feature extraction is crucial since DTW is very little and the corresponding change is easily disturbed or even hided by noise. Most of features are extracted from time, frequency, time-frequency or statistical domain, using signal magnitude, root mean square (RMS) level, fast Fourier transform (FFT), power spectral analysis and Wavelet transforms (WTs) [10, 17, 28, 30, 50, 103-105].

Usually, the features in the time domain are the signal magnitude, RMS level and ratio. In the frequency domain, the features are usually extracted from the vibration and sound signals by FFT or power spectral analysis. WTs are carried out in the time-frequency domain. WTs can effectively detect transient features such as sudden changes or discontinuities and largely reduce the signal processing time.

Decision making Tool wear recognition is vitally important to predict tool wear states, including neural networks, fuzzy logic, genetic algorithms and hybrid systems from the combination of various cognitive methods. Neural network seems to be frequently adopted. In UPDM, some cognitive methods have been applied in monitoring of DTW status, such as self-organizing map based neural network [105], fuzzy technique [104] and spectral and scaling exponents [17].

Computational efforts to build the relationship between the process parameters with DTW are high and laborious due to the amount of data processing and feature extraction is arduous since relative to noise the signal contribution from very little DTW resulting in poor surface roughness is not obvious enough. Furthermore, decision making for DTW is also challenging without wear calibration for feature extraction. The key problem is the relationship between feature extraction and DTW. Hence, more research should be carried out in UPDM to find a successful means of employing multi-sensors to monitor DTW and thereby enhance surface quality.

4.3 DTW Controlling

DTW is influenced by a wide variety of factors, such as cutting conditions, diamond tool performances, workpiece materials, cutting fluids and gaseous environment. The workpiece materials are the deterministic factors, associated with the dominant mechanism of DTW, namely chemical wear. Chemical wear is mainly governed by high temperatures produced at the interface between diamond tool and workpiece, pressures on the diamond surface, catalytic action of workpiece, gaseous environment, cooling/lubricating and activity of the clean surface, as presented next.

Relevant research has provided a valuable guidance for suppressing DTW and given an understanding of DTW mechanisms. Different approaches for DTW reduction have been developed, including cooling/lubricating, gaseous environment, intermittent cutting, electric field assistance, protective coatings, ion implantation, workpiece modification and a hybrid approach, as presented next. Table 7 lists the classification of DTW suppression.

4.3.1 Cooling/lubricating

Cooling plays a very important role in decreasing cutting temperatures and surface roughness and prolonging tool life [74]. In UPDM, coolant is frequently employed to lubricate diamond tools and dissipate cutting heat in order to improve cutting performance and prolong diamond tool life. However, Born and Goodman [29] proposed that cutting fluids (Polyalkaline Glycol (PAG), PAG with water and PAG with water and tri-potassium phosphate) in diamond turning of large single-crystal silicon optics do not significantly affect tool wear.

Yan et al. [22] found that kerosene and water as coolants can prolong the critical cutting distance in ductile-mode cutting of single crystal silicon and that tool life with water-based coolant is three times longer than that with oil-based coolant. The results support those of Durazo-Cardenas et al. [23]. Furthermore, lubricant with MoS_2 micro-particle contents can extend tool life better than the kerosene mist lubricant in cutting SiC [31] and 10%-Cu grease lubricant has the lowest tool wear in the nanoparticles MoS_2, GF, Cu and CuO [32]. Zhang et al. [34] used a carbon dioxide and carbon tetrachloride mixture lubricant to reduce DTW in ultra-sonic cutting of tungsten alloy, which has also been used to control DTW. Inada et al. [77] used ionized coolant carbon particles in cutting steel and observed a significant improvement of diamond tool life.

For easy-to-cut materials the lubricating effect is dominant, whereas for difficult-to-cut materials the cooling effect is prominent. The chemical reaction rate increases exponentially with temperature. Hence, chemical DTW may be retarded significantly in cryogenic machining. During machining steel in UPDM, different approaches for cryogenic cooling have been developed to control rapid DTW. Brinksmeier and Gläbe [73] sprayed liquid nitrogen in machining steel and found that DTW can be reduced by at least one order of magnitude.

Cryogenic cutting provides a certain capacity of machining steel in terms of DTW and surface roughness. Reducing temperature will reduce chemical wear. However, it is impractical since it is difficult to produce high-precision parts due to severe temperature gradients [49].

Table 7. Approaches to controlling DTW (References as presented next)

Modification type	Theoretical mechanism	Experimental realization
Process modifications	Reduction of reaction rate	Cryogenic cutting
	Inhibition of chemical reactions	Cutting in inert gas
	Reduction of contact time	Ultrasonic vibration cutting Vibration cutting Intermittent cutting
	Reduction of temperature	Coolant Vibration cutting Swivel
	Reduction of friction	Cutting fluid
Tool modifications	Build-up of a diffusion barrier	Protective coatings
	Modification of diamond lattice	Ion implantation
	Use of inert materials	Ceramic tools
	Modifying of tool geometry	Micro-/nano-textures
	Friction	Nitrogen cold plasma jet
Workpiece modifications	Suppression of chemical reactions	Ion implantation Workpiece substitution
	Thermal softening	Laser-assisted machining Local hot machining

4.3.2 Gaseous environment

In cutting steel, DTW is catastrophic and unacceptable since steel is chemically active with carbon. In cutting steel in a carbon-saturated atmosphere, the DTW rate can be considerably decreased in a gaseous environment. An Ar atmosphere results in decreased DTW compared to air, because the gaseous oxygen is prevented from reaching the cutting surface and catalyzing wear reaction [44, 61]. The result is in agreement with the finding that the reduced oxygen atmosphere effectively suppressed excessive DTW in cutting copper for large components [44, 61]. Further, at low cutting speed low wear is observed at high pressure and a sudden transition of air pressure occurs, for common industrial cutting speed the wear rate decreases with reduced air pressure and for high cutting speed the wear rate is independent of air pressure [26, 49, 106]. Fig. 13 presents the transition of wear rate vs air pressure at cutting speeds of 0.0133 mm/s and 0.13 mm/s, respectively. It shows that at the higher cutting speed the wear rate is higher and the transition of wear rate takes place in the higher air pressure.

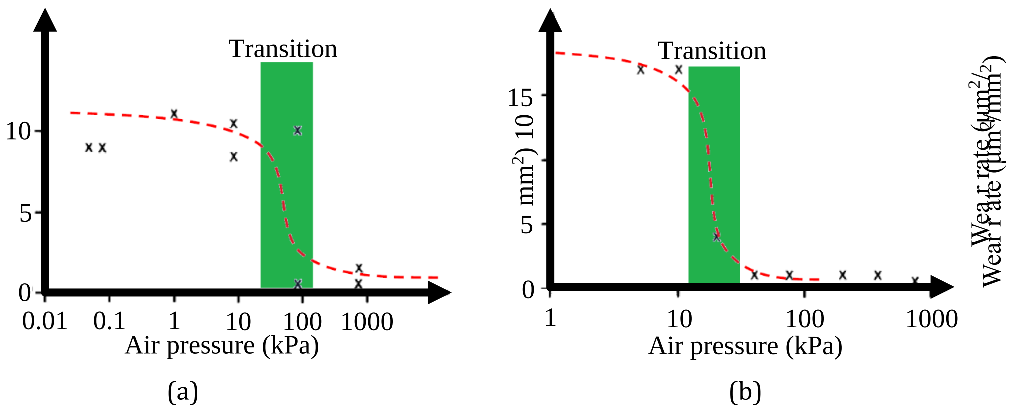


Figure 13. Wear rates (wear area/machined surface area) of single crystal diamond tools under different air pressures at cutting speed of (a) 0.0133 mm/s and (b) 0.13 mm/s [106]

Hitchiner and Wilks [107] stated that hydrogen (H_2) and methane (CH_4) give higher DTW than air due to their chemical reaction with C to produce gaseous hydrocarbon. Paul et al. [49] performed diamond turning of pure iron in air and helium and observed that DTW is catastrophic and indistinguishable in both cases. It is attributed to metal–carbon complexes still forming at the tool–workpiece interface.

In terms of DTW, cutting steel in a carbon-rich or oxygen-free atmosphere has been investigated. Due to the chemical affinity between Fe of steel and C of diamond, the atmosphere has not been proved practically to suppress DTW in cutting steel.

4.3.3 Vibration cutting

Vibration cutting, especially ultrasonic vibration cutting, has been utilized to study cutting mechanisms of various materials such as oxygen free copper, ferrous metals, glass, polysilicon, silicon, SiC, tungsten carbide, ceramics and calcium fluoride. It can reduce chemical DTW and extend diamond tool life significantly when cutting difficult-to-cut materials, like ferrous metals [108]. It has two functions in controlling DTW. One is heat dissipation with enough time to ensure low temperature and the other is short contact time between diamond and workpiece. The two functions together affect chemical wear in cutting difficult-to-cut metals.

Moriwaki and Shamoto [76] developed a 1D ultrasonic vibration-assisted system for UPDT of hardened steel, which extends tool life significantly with 4μm flank wear after a cutting distance of 1,600 m. They also carried out 2D ultrasonic vibration cutting during UPDT of steel [109] and found that (i) in normal cutting tool life is very short; (ii) in 2D ultrasonic vibration cutting forces and surface roughness increases slowly, indicating a low DTW rate, compared with 1D ultrasonic vibration cutting; and (iii) the critical cutting distance in 2D ultrasonic vibration cutting is up to 2,000 m, whereas in 1D ultrasonic cutting it is only about 1,000 m.

Brinksmeier and Gläbe [73] stated that ultrasonic vibration cutting yields a reduction of DTW of about two orders of magnitude and wear reduction does not scale linear with the reduction of effective cutting time. Wang et al. [39] proposed that DTW can be reduced by several orders of magnitude and mirror-quality surface can be obtained by using elliptical vibration cutting. Zhang [82] found that tool wear in elliptical vibration cutting was less than in ordinary cutting.

Zhang et al. [34] found that in ultrasonic vibration cutting tungsten-based alloy the higher the vibration frequency is, the less the tool wear. As the vibration amplitude increases, tool wear decreases. Generally, the used ultrasonic vibration frequencies used are 20, 40 and 60 kHz, although up to 80 kHz is commercially available. Ultrasonic vibration cutting has been successfully applied for controlling DTW. However, it is possibly limited by the restriction of vibration speed, self-excited chatter vibration and interference between tool tip and workpiece.

Most scholars speculate that in vibration cutting the intermittent contact between tool and workpeice shortens the time available for chemical wear and reduces cutting temperature further to slow DTW; effective chip thickness is also reduced to further decrease cutting forces that indirectly reduce tool wear. However, it is limited to relatively slow cutting speeds and relatively small vibration amplitudes, which reduce cutting efficiency and influence surface roughness, even for ultrasonic vibration cutting. Considering both cutting efficiency and surface quality, ultrasonic vibration cutting is an effective means of suppressing DTW.

4.3.4 Protective coatings

Coating is one means of improving tool performances. It has been used to prevent direct contact between diamond tool and workpiece in UPDM to extend diamond tool life. Brinksmeier and Gläbe [73] employed TiN and TiC coatings on diamond tools for the reduction of chemical wear in precision machining of steel. Zareena and Veldhuis [27] proposed a protective barrier made of perfluoropolyether polymer to protect diamond tools in UPM of titanium. Tool life is enhanced and surface quality is improved. It acts as an effective barrier delaying the diamond-graphitization transition.

However, the edge radius of diamond tools will become larger after coating, which is not suitable for high precision components by UPM. Also, the adhesive strength and abrasive resistance of coatings limit their application to protecting diamond tools for UPM.

4.3.5 Diamond tool modification

Coating on diamond tool surfaces is considered as one means of diamond tool modification preventing drastic DTW. Different diamond tool modification methods have been developed, such as ion implantation and tool geometry modification. Stock. et al. [110] carried out diamond wear tests with iron wheels and observed that diamond wear influenced by chromium implantation can be reduced significantly, due to low damage of the diamond lattice. Therefore, it provides a further potential to enhance the DTW resistance for machining of steel.

Brinksmeier and Gläbe [73] performed cutting Ck01N carbon steel with chromium-implanted diamond tools and found that the ion implantation does not improve tool wear. The wear land is equal or wider than that of un-implanted diamond tools. This is contrary to Stock et al.'sresult [110]. This may be due to lattice damages of ion implantation leading to amorphization, which reduces the strength of diamond crystal or other defects. Also, it is possible that insufficient abrasion resistance limits its cutting of ferrous metals. Further research into this form of diamond tool modification is clearly needed.

Tool geometry modification also falls into diamond tool modification. Yan et al. [22] turned the brittle material Si with a large feed using a straight-nosed diamond tool. This allows cutting the brittle material in ductile regime under a large feed further to reduce DTW. On the other branch, micro-/nano-structures on cutting tools can improve wear resistance. It gives a new idea that micro-/nano-textures will be applied to diamond tools.

4.3.6 Workpiece surface modification

This involves modifying the workpiece surface by changing physical and/or chemical characteristics. In UPDM, It brings down the original properties a little, but greatly improves diamond-machinability. Workpiece surface modification is successfully applied to retarding chemical DTW in cutting some difficult-to-cut materials.

Electroless nickel is comparable to pure nickel in its hardness and corrosion resistance. Significantly, it is diamond turnable. It can be prepared by chemical deposition or by electroplating methods. Much research has been carried out on cutting electroless nickel [16, 17, 79, 94]. Due to its easily-to-cut ability, it has been used as coating for molding dies. However, its mold life and product quality are still much lower than the steel mold. Additionally, during molding the amorphous layer will recrystallize at high temperatures and further degrade surface quality.

Nitrided steel can be diamond turned without excessive DTW. This has been first discovered by Brinksmeier et al. [111]. Fig. 14 presents DTW and surfaces after cutting of steel molds with thermo-chemical treatment. The compound layer after surface modification is composed of two phases, as shown in Fig. 14(a). After diamond milling of the compound layer, the optical surfaces have been obtained as shown in Fig. 14(b). In diamond milling of the unmodified steel after the cutting distance of 500 m the wear land width of VB is 36 μm, while for the modified steel the flank wear is not obvious. They took a breakthrough in machining steel with optical surface quality [111]. After modification, DTW is reduced by more than three orders of magnitude. Wang et al. [39] carried out plasma nitriding treatment in cutting AISI 4140 die steel, which reduce DTW by several orders of magnitude and produces mirror-quality surfaces.

Fang et al. [112] designed different thermo-chemical modifications, such as plasma nitriding, boronising, siliconising, boronitriding and compound boronising-aluminising, to bond the atoms of transition metal elements in steel with the chosen elements. It is found that nitrogen (N) improves the diamond tool life; N, silicon (Si) and aluminum (Al) helps to obtain a mirror-like surface; and B has a negative effect. Fig. 15 presents surface quality and DTW in turning NAK 80 with different surface modifications after a cutting distance of 150 m. They also found that plasma nitriding produces the best surface roughness and the smallest wear land ($VB<2.22$ μm and $Ra<33.78$ nm) in all thermochemical modifications for Stavax and NAK80 stainless steel after a cutting distance of 150 m [113]. No great difference on wear and surface roughness exists between the Stavax and NAK80 stainless steel by the same modification due to the same chemical compositions of compound layer. Moreover, mechanical wear is the dominant wear mechanism, which is obvious in boronitriding case due probably to the hard particles in the compound layers. Further, micro-chipping occurs in machining of complex boronizing-aluminized NAK80.

Workpiece surface modification has significantly improved diamond tool life during cutting steel, by suppressing chemical tool wear. However, some problems should be considered and overcome: firstly, thermal deformation makes surface form deviant, secondly, mechanical wear of diamond tools obviously exists; thirdly, it affects optical performances; and fourthly, it has an impact on the performance of injection molding.

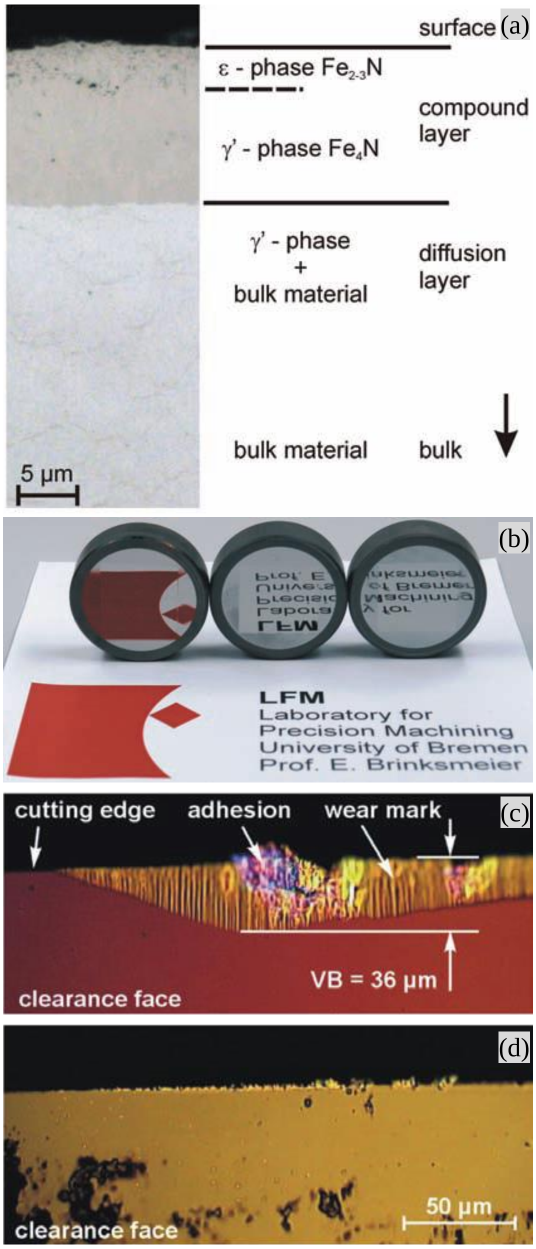


Figure 14. UPDM of steel molds: (a) cross section and dominant phases of steel after thermo-chemical treatment; (b) three diamond milled steel workpieces of 30 x 30 mm² with a 15 µm thick compound lRyer; Rnd DTW Rfter fRce-cutting of (c) unmodified steel and (d) a thermo-chemically treated carbon steel (0.45% C) with a cutting distance of 500 m [111]

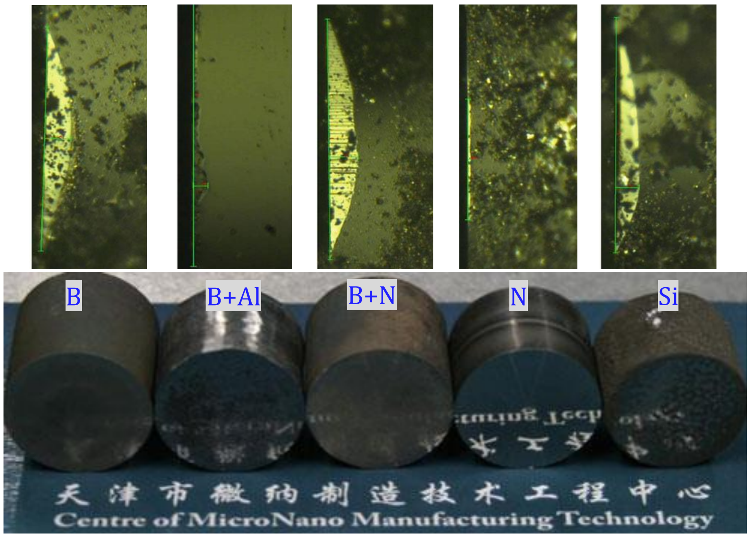


Figure 15. Surface quality and DTW of turning NAK 80 with different surface modification after a cutting distance of 150 m [113]

4.3.7 Substitution of diamond tools

Due to high DTW, diamond tools are unacceptable for cutting difficult-to-cut materials such as steel for molding dies. After all, diamond is expensive and the cutting process is not economic, efficient or practical. CBN is a potential tool that can be used instead of diamond tools due to its high chemical stability against steel.

A little research has been conducted to investigate cutting mechanisms of difficult-to-cut materials in UPM using pure CBN tools [114], PCBN [115], coated carbide tools [116], ultrafine-grain binderless CBN tools [117] and binderless CBN [118], ceramic tools [73] and tungsten carbide tools [119]. Results suggest that the tools can be used as promising substitutes for diamond tools in UPM of difficult-to-cut materials, but the surface roughness is not small enough to meet the optical demands and the cutting edge sharpness and the abrasion resistance needs to be further improved.

4.3.8 Hybrid approaches

Many unconventional methods have been invented to allow cutting difficult-to-cut materials, especially steel, with various levels of success in extending diamond tool life. These hybrid approaches may potentially further reduce DTW and improve surface quality.

Zhang et al. [34] incorporated carbon-rich gas-liquid cooling (CO_2 and CCl_4) with ultrasonic vibration cutting to reduce DTW in cutting of tungsten-based alloy. The cutting experiments show that ultra-sonic vibration with gas-liquid atomization cooling effectively reduces DTW. However, there exists a controversy over whether the carbon-rich atmosphere practically suppresses DTW or not. Wang et al. [39] employed elliptical vibration cutting in cutting plasma nitrided AISI 4140 die steel. The results are shown in Fig. 16. Although DTW is decreased by several orders of magnitude and mirror-quality surfaces are obtained by using either plasma nitriding treatment or elliptical vibration cutting, their combination does not yield a further improvement of diamond machinability.

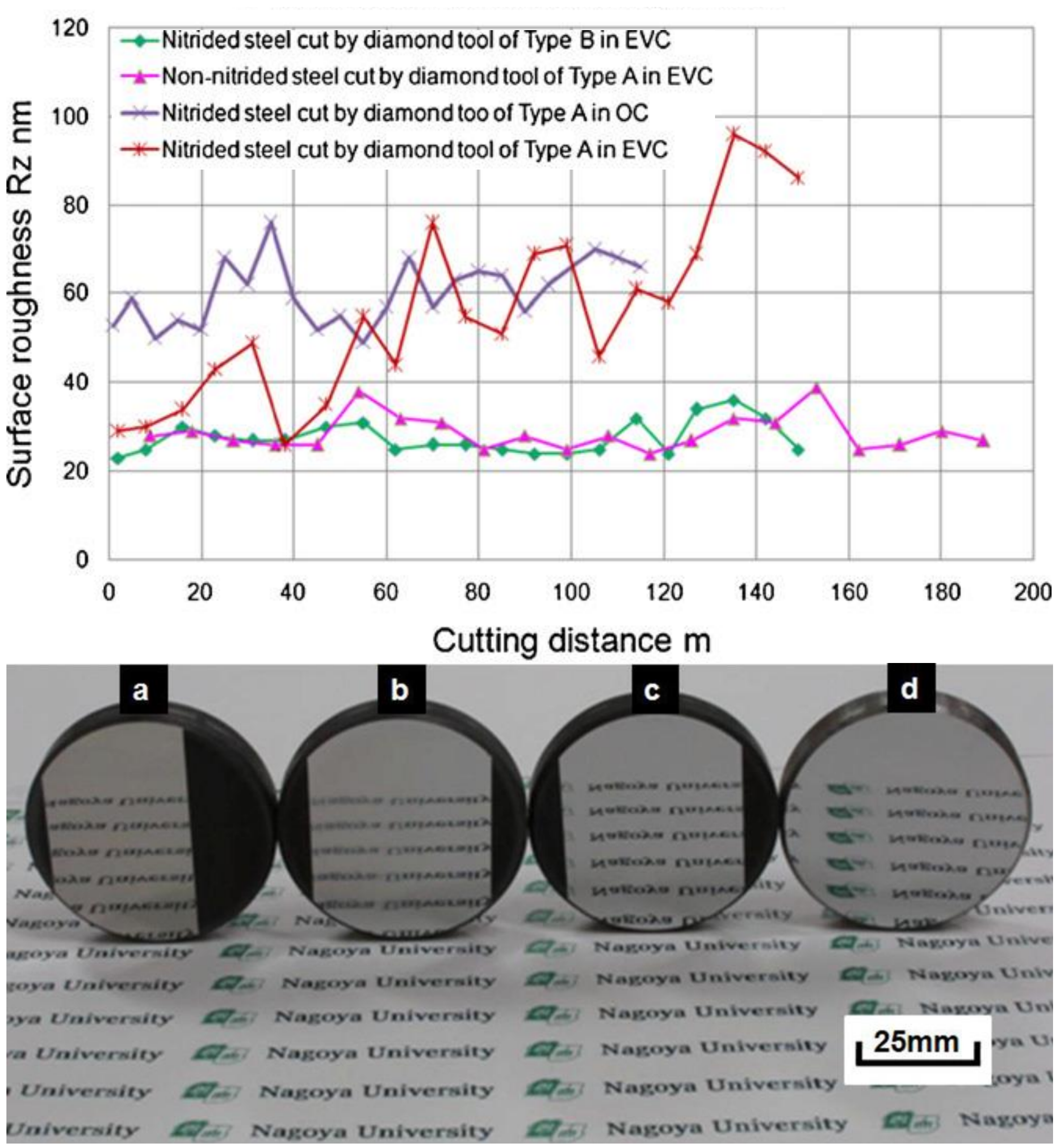


Figure 16. Surface roughness variation and photograph surfaces with single crystal diamond tools in cutting Steel AISI 4140 with (a) OC+PNT+Type A; (b) EVC+PNT+Type A; (c) EVC+PNT+Type B; and (d) EVC+Type A (PNT: plasma nitriding treatment; OC: ordinary cutting; EVC: elliptical vibration cutting; Type A: R(100)F(100); Type B: R(110)F(100) [39]

Inada et al. [77] developed an ionized coolant system in cutting ferrous materials. The coolant was mixed with nano-carbon particles and electrolyzed through carbon poles. It not only softens the workpiece surfaces, but also creates a protective layer on the diamond tool surfaces, thus reducing surface roughness and DTW. However, the cutting mechanism has been not fully discussed. The combination of plasma nitriding and cryogenic cutting was employed by Li et al. [113] to further reduce DTW and improve surface quality in cutting ferrous metals. Compared with cutting the as-received steel with mineral oil (VB 15.11 μm, Ra 233.69 nm) after a cutting distance of 150 m, the hybrid method significantly reduces DTW (VB 0.78 μm) and surface roughness (Ra 8.81 nm). However, the results are not superior to that with only workpiece surface modification after a cutting distance of 500 m [111].

In terms of retarding DTW, hybrid methods do not give a better result than one method alone. The chemical reaction is sufficiently hindered up to a saturation point, so no more chemical reaction can be reduced by more methods. Additionally, abrasion wear may be dominant and is not further reduced. The abrasion wear may be dominant.

4.3.9 Other methods

Some other different methods have been proposed to restrain DTW during cutting of difficult-to-cut materials. Yan et al. [31] proposed a tool-swinging method to control tool wear in diamond turning of SiC and observed that DTW is significantly reduced compared to ordinary cutting. Fig. 17 shows the effects of tool swinging and lubricants [31]. Tool-swinging and grease can reduce DTW. Song et al. [37] used fly-cutting to control the tool-workpiece contact time in cutting steel and found that it can be successfully cut by controlling the contact time and DTW strongly depends on the contact time. Thus, the ultra-intermittent cutting process can reduce DTW. This can be classed as process modification.

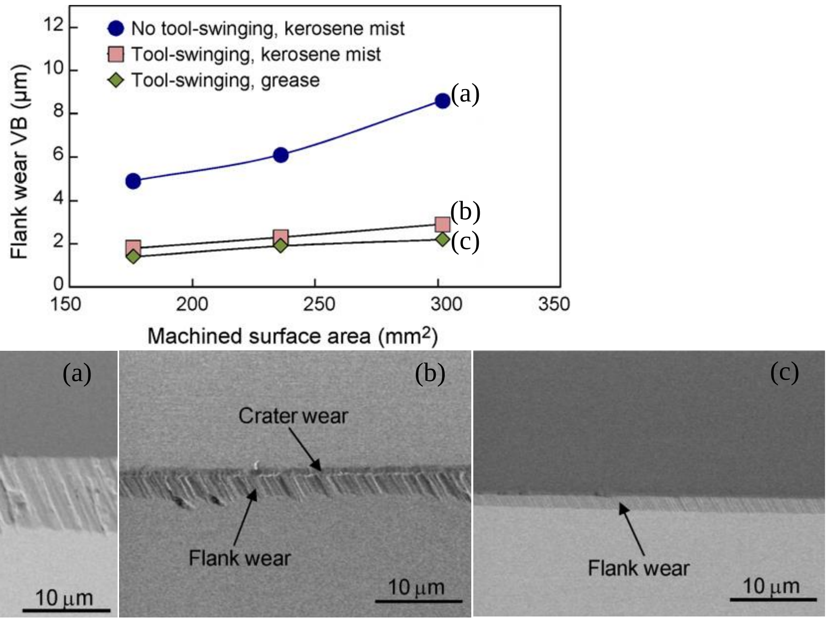


Figure 17. Flank wear influenced by tool-swinging and lubricants with respect to the machined surface area [31]

Laser assisted machining has been carried out in conventional machining of difficult-to-cut materials to assist cutting. Ravindra et al. [120] used micro-laser assisted machining (μ-LAM) to cutting SiC in UPDT. The workpiece is preferentially heated and thermally softened at the local tool-workpiece interface by the laser device, which minimizes DTW. Brehm et al. [121] applied local hot machining to reduce tool wear rate in cutting glass. Other external energy assisted machining is possible in UPDM for reducing DTW.

As discussed above, chemical wear in cutting difficult-to-cut materials can be retarded to an extent using different methods. Some significant contributions have been made to DTW suppression. However, mechanical or physical tool wear is not discussed enough in depth, since it becomes dominant after reducing chemical wear. Therefore, a combination of multiple different methods provides the possibility of further decreasing DTW and extending diamond tool life during cutting difficult-to-cut materials.

5. DTW Modeling

DTW has been ascribed to mechanical, chemical and/or physical interactions. Some theoretical studies have looked into DTW mechanisms and some attempts have been made to predict DTW. These theoretical methods generally include analytical modeling (AM), finite element modelling (FEM) and molecular dynamics simulation (MD), as presented next.

5.1 Analytical model

AM is a mathematical model, providing a powerful tool to predict tool wear, tool life and a suitable time for tool replacement to avoid compromising surface quality. Many AMs have been successfully developed for conventional cutting. It is developed according to wear mechanisms and principles. In the classification of DTW mechanisms, abrasive wear is dominant in cutting easy-to-cut materials, whilst in cutting difficult-to-cut materials chemical wear governs. It obeys the wear laws. Several attempts have been made to develop suitable methods for predicting DTW over the past several decades. The methods are presented next.

5.1.1 Tailor model

In conventional cutting, Taylor's equation and its modified/extended equation have been successfully used to predict tool wear/tool life [122]. In UPDM, it has been employed to predict DTW [29]. In the Taylor equation, the coefficients can be calculated and obtained based on a series of experiments. This empirical method is simple and easy to perform and predict tool wear before machining.

5.1.2 Archard model

Archard [123] derived Archard's wear law representing contact and rubbing of flat surfaces. Then, Crompton et al. [15] rubbed diamond on various materials and found that diamond wear follows the Archard's wear law. Further, Wilks and Wilks [47] reviewed the properties and applications of diamond and found an indirect relationship between DTW and Archard's wear law. Furthermore, the Archard wear law has been promoted by Lane [14] to predict abrasive wear.

5.1.3 Arrhenius/Fick model

Relating DTW to a chemical interaction, Paul et al. [47] noted that diffusion follows Fick's law and graphitization follows Arrhenius law. The model has been successfully applied to predicting conventional tool wear. Based on Fick's law, Uemura [71] deduced a quantitative equation to predict tool wear volumes during cutting Ni and Fe. The calculated wear amount is in agreement with the experimental data, where the temperatures are under the assumption of 560^{o}C for Fe and 600^{o}C for Ni. Lane's experimental results [14, 63] well support the law to predict DTW in cutting steel. Since the temperature is difficult to measure in the practical machining process, it is not easy to model tool wear. The temperature can be obtained by FEM.

5.1.4 Other models

Other models have been proposed to predict DTW in UPDM. DTW affects surface roughness, chip formation and cutting force. The relationship can be used to predict tool wear. Zhang et al. [35]

proposed a chip formation model related to DTW. A cutting force model has been developed to predict DTW [124]. The predicted results are in good agreement with the experimental results.

Predicted tool wear is not real tool wear as it only provides a reference. In these models, tool wear and inputs are mutually affected. For example, tool wear increases cutting temperature and cutting force, which enlarge tool wear as calculated from the models. Hence, these models fail to represent an evolutionary wear process. Theoretically, they lose accuracy at a certain level. More importantly, AM can be easily used to optimize cutting parameters to improve cutting performance if DTW is correctly predicted before machining.

5.2 Finite element modeling

FEM is a useful tool to provide some insights into the material removal process in UPDM such as cutting force, chip formation, cutting temperature etc. Some scholars have studied DTW mechanisms in order to predict DTW.

Lane et al. [14, 63] proposed a FEM method to simulate cutting temperature. The simulated temperature has been put into an analytical model to predict DTW during cutting of ferrous metals. Yan et al. [125] simulated cutting silicon using a FEM method. When the cutting edge radius r is beyond a critical value (below 200 nm), the high temperature zone will transit from the tool rake face to the tool flank face, which causes the transition of the wear pattern from crater to flank wear. The result is supported well by SEM photographs of the DTW.

FEM has also been employed to simulate ultrasonic assisted cutting ferrous metals to predict cutting temperature and cutting force and explore why ultrasonic assisted cutting can reduce DTW [126]. The simulated cutting temperature and cutting force in ultrasonic assisted cutting is less than that in ordinary cutting [126]. Additionally, the reduced cutting temperature and cutting force will result in diffusive wear reduction [126]. It is consequently theorized that vibration cutting reduces tool wear by reducing cutting temperatures and cutting force.

FEM can explain some cutting mechanisms in cutting. However, it is limited by the scale effect to simulate all cutting mechanisms. Until now, DTW cannot be directly simulated by FEM, since there is a lack of a suitable constitutive equation for wear mechanisms and computing time is too costly and long. Wear commonly occurs at an atomic, molecular and/or nanometric scale.

5.3 Molecular dynamics simulation

In UPDM, diamond tools undergo different kinds of tool wear mechanisms, such as diffusion wear, abrasive wear, oxidation wear, fatigue wear and adhesive wear. To theorize the DTW mechanisms, MD is considered as an efficient tool. Until now, it has enhanced some physical understandings of nanometric cutting mechanisms of materials such as silicon, silicon carbide, copper, aluminum and pure iron.

Pastewka et al. [45] carried out MD and found that the polished diamond undergoes a sp^3-sp^2 order-disorder transition resulting in an amorphous adlayer (sp^2 and sp) strongly influenced by the crystal orientation and polishing direction. The simulation is shown in Fig. 18. The tribo-chemistry governs the DTW. The MD studies that have been conducted to investigate DTW in machining are summarized in Table 8. These MD results well support the reported observations.

In UPDT of single crystal silicon, the MD results show that silicon carbide forms at the interface and the simultaneous mechanism of sp^3–sp^2 disorder of diamond tool takes place [132].

The silicon carbide and carbon-like particles have been observed in experiments [54]. The temperature gradient between the tool rake and flank faces leads to relatively higher flank wear. The thrust forces with the cubic orientation of the diamond tool are lower than the dodecahedral orientation, which signifies that the cubic orientation is highly wear resistant [39].

The performed MD reveals some convincing understandings of DTW mechanisms in machining of some materials. The chemical reaction of diamond such as graphitization and amorphization is a natural feature of DTW. For some machined materials, additional chemical reaction, such as SiC formation, between diamond carbon and the machined material occurs. However, the simulations are governed by the developed potential functions that describe the tool-workpiece interactions and the cutting speed is further higher than that is selected in practical operations. Therefore, more research needs to be carried out on the growing hot topic of DTW mechanisms.

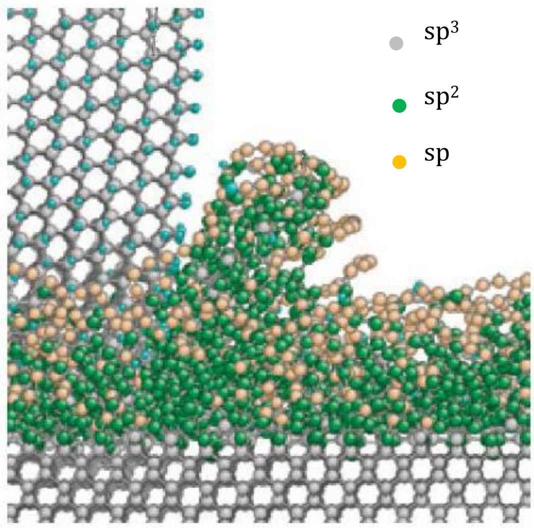


Figure 18. MD of polishing for diamond with sp^3-sp^2 transition [45]

Table 8. DTW mechanisms by MD (EAM=embedded-atom method, PF=potential function, SC=single crystal)

Ref.	PF	Workpiece	Mechanism
[127]	Morse PF	SC copper	Inter-diffusion; Re-adhesion
[128]	EAM PF	SC copper	Adhesion
[129]	EAM PF	Iron	Diffusion; Graphitization
[130]	Tersoff PF for C Modified EAM PF for Fe	Iron	Graphitization; Diffusion
[55]	Tersoff PF	SiC	sp^3–sp^2–sp transition
[78]	MEAM PF	Silicon	Thermo-chemical wear
[131]	Tersoff PF	Silicon	Dynamic hard particles
[132]	Tersoff PF	Silicon	SiC formation; sp^3–sp^2
[75]	Ab-initio molecular orbital calculation	Iron	Diffusion over 1,000K Oxidization down 900K

6. Future research opportunities for DTW

With regard to DTW in UPDM, a great deal of research has been carried out. Many significant advances of DTW have been made over the last few decades, covering wear characteristics, wear mechanisms, wear monitoring, wear controlling and wear modeling. However, some DTW mechanisms are still not fully understood in terms of improving cutting performance, reducing DTW and prolonging diamond tool life. Developments in the capability of computers and sensors provide new opportunities for advancing our understanding of DTW.

6.1 Development of DTW mechanisms

Diamond tools undergo different wear mechanisms in machining, covering from mechanical to chemical. DTW is mainly determined by cutting temperature, cutting pressures, catalytic action of elements and the activity of the machined materials. Mechanical wear is a natural feature of diamond tools due to the direct tool-workpiece contact in cutting of any materials, regardless of whether they are easy-to-cut materials or difficult-to-cut materials.

Chemical wear is relevant to machined materials but chemical activity has not been studied. It is dominant during cutting of difficult-to-cut materials, which induces high cutting temperature and high cutting pressure to catalyze chemical reaction. However, the cutting temperature and pressure are not high enough to lead to a chemical reaction between the carbon of the diamond and the atoms of the workpiece and the practical regional temperature and pressure cannot be measured accurately. Graphitization is considered as a precursor to DTW and subsequently the graphitized diamond diffuses into the machined materials. Unfortunately, there is still a lack of a understanding of graphitization, amorphization and diffusion in cutting.

Physical wear is relative to fracture, defects, impurity etc. The selection of raw diamonds is very important for tool life. It is an internal feature of DTW. In industry, raw diamonds can be efficiently classified into different ranks in accordance with the absorption of diamonds in the infrared, visible light and ultraviolet. Tribo-electric wear falls into the realm of physical wear and takes place in cutting electric insulating materials, such as PC and PMMA for lenses. There is controversy over electric wear, which lacks convincing evidence. Further research is needed on this topic to improve cutting performance of polymers and to prolong diamond tool life.

Adhesion can be categorized as physical wear, which takes place generally in machining nonspecific materials. It can be usually observed through cutting tests, but the wear rate is individual. The tool wear decreases from difficult-to-cut materials to easy-to-cut materials related to the affinity ability of the machined materials, although the physical laws are not clear. More studies on the subject of adhesion are needed.

6.2 Development of DTW monitoring

In UPDM, a little DTW will be reproduced on a machined surface and deteriorates nanometric surface roughness and sub-micrometric form accuracy. DTW monitoring plays a crucial role in cutting. It provides a suitable tool replacement time to ensure surface quality. To efficiently monitor DTW, different methods have been developed, such as acoustic emission (AE), cutting force, acceleration, optical measurement and chip formation. They can be classified into on-line monitoring, in-situ measurement and off-line measurement, which can also be categorized into direct method and indirect method. Each method has its own disadvantage.

In off-line measurement, DTW can be measured by high-resolution equipment. However, it is not suitable for DTW monitoring in UPDM, since nanometric tool repositioning is extremely difficult or even impossible if the diamond tool is removed from the tool fixture and the measurement time takes too long. Hence, on-line or in-situ measurement is a feasible alternative, although a little DTW causes slight changes in signals, which makes feature extraction very difficult. Decision making is also more challenging. In in-situ measurement, the measurement resolution is very low and monitoring is not real-time and is intermittent. It will be possible to efficiently monitor DTW in real-time if a multi-sensor measurement method can be developed. Accordingly, more effort should be made to study DTW monitoring in order to enhance surface quality.

In future, a novel machine-tool system will be developed and implemented with multiple smart sensors like MEMS. The sensors will be used to monitor the machine-tool system, which will become robust, reconfigurable, reliable, intelligent and inexpensive. The techniques and methods of signal processing and decision making developed in the lab will eventually be commercially available.

6.3 Development of DTW controlling

Some tool wear controlling methods, such as process modification, tool modification and workpiece modification, have been developed for UPDM of difficult-to-cut materials to suppress DTW. For example, due to catastrophic DTW it is impossible to obtain a nanometric surface roughness if diamond tools are simply and directly used to cut steel. In general, the goal is to retard drastic DTW for cutting steel. The essential reasons are that (1) diamond tools suffer from outrageously rapid DTW; (2) diamond tools and UPM can be combined together to achieve complex and precise optical steel molds; and (3) steel molds are highly durable and low cost.

Vibration cutting, like ultrasonic vibration cutting, in UPDM of difficult-to-cut materials, especially steel, has proven to be more effective than other methods for mitigating tool wear and prolonging tool life. The major reason is that vibration cutting reduces cutting force and cutting temperature due to cyclic cooling and reduced contact time. Industrial applications of ultrasonic vibration cutting into UPDM have already been realized successfully to fabricate steel molds for the replication of optical freeform components. However, vibration cutting limits the nominal cutting speed resulting in the reduction of cutting efficiency. Improving cutting efficiency by increasing vibration frequency is one possible way of overcoming this.

Ultrasonic vibration cutting and workpiece surface modification alone have better effects in prolonging diamond tool life and improving cutting performance in machining ferrous metals. They alone have provided a practical industry application for significantly extending tool life with optical surface roughness. However, combination of the two methods does not further improve cutting performance or extend diamond tool life as compared to each being used alone. Furthermore, although DTW can be significantly decreased, no one proposed method can mitigate DTW to the extent found during cutting easy-to-cut materials such as copper.

In cutting ferrous materials, DTW mechanisms include mechanical-abrasive wear and tribo-/thermo-chemical wear, which may take place interactively and simultaneously. Chemical wear is the dominant wear mechanism, i.e. diamond graphitizes and then diffuses into iron. Regarding suppressing DTW, the hybrid method does not give a better solution than one method used alone, since chemical action is sufficiently isolated to a saturation point. Additionally, although mechanical-abrasive wear is inevitable it is not exacerbated and so there is a potential to reduce abrasive wear.

Micro/nano-structures formed on diamond tools can efficiently reduce mechanical-abrasive wear due to their excellent lubricant effect, which provides a novel means for further suppressing DTW. Ultra-fine-grain binderless CBN tools with sharp cutting edges and high hardness may be developed further as the next generation of cutting tools instead of single crystal diamond tools. However, more research should be undertaken to improve their cutting performance to bring out nanometric surface roughness. Furthermore, if workpiece materials could be developed that are suitable for diamond cutting, this would be one way of potentially extending diamond tool life.

Laser assisted machining in UPDM can minimize DTW in cutting brittle materials. In addition, other thermal assisted machining methods provide the possibility of mitigating DTW in UPDM for mitigating DTW. However, as only a few attempts have been made to study their cutting mechanisms in UPDM, there is a potential for further research in this area.

More studies need to be undertaken with the aim of providing a significant breakthrough in controlling DTW. As hybrid methods provide the best possibility of further prolonging diamond tool life and suppressing DTW, more attempts should be made to develop them.

6.4 Development of DTW modelling

Due to capricious DTW, UPM of especially difficult-to-cut materials becomes a challenging task. Significantly, MD provides a non-trial method to understand DTW mechanisms in depth. Some worthy contributions have been made to exploring DTW mechanisms.

Currently available MD software is not capable of simulating real nanoscale machining since MD needs huge computing time and space. In MD, the tool-workpiece size is limited in the range of several dozens of nanometers and software that can be designed to be more user-friendly is not suitable for other cutting tools.

MD provides an understanding of DTW mechanisms in machining of some materials. However, the simulations are determined by the developed potential functions to describe the tool-workpiece interaction. There is still a need to have a robust realistic potential function to accurately describe all phases of diamond carbon and the interactions of atoms from carbon, workpiece materials and even coolants and coatings. DTW mechanisms in MD are a hot topic. A more realistic potential function might be developed to give thorough insights into wear mechanisms in cutting with other tool wear controlling methods.

FEM is a powerful tool for simulating ultra-precision cutting processes, which is only limited by its constitutive equation. Although it has provided an understanding of some cutting mechanisms in cutting, a more powerful constitutive equation similar to the thermal-mechanical-chemical model should be developed. However, as in UPDM the cutting size is generally on a micrometric scale, the workpiece size on a millimetric scale and the tool cutting edge radius r on a nanometric scale, the size effects have to be considered. Some attempts have been made to develop multiscale FEM but as DTW takes place on an atomic scale it is not suitable for studying DTW mechanisms. Another drawback is that FEM also needs huge computing source so that it cannot be employed to predict diamond tool wear/life. Overall, although multiscale FEM is a potential means for studying DTW, but it can be only considered as an aid tool.

AM is a useful tool in industry to predict diamond tool wear/life. It can provide the tool replacement time in order to ensure surface quality. The conspicuous advantages of this empirically developed model are that there is no need for a thorough understanding of physical laws and it is especially effective for a complex process. The obvious disadvantages are that it needs a lot of time-consuming and costly cutting tests and it is difficult to be sufficiently accurate. The physical model requires a comprehensive knowledge pertaining to all physical laws.

Several attempts have been made to develop a prediction model for diamond tool wear/life over the past several decades. However, in these models the predicted tool wear affects inputs such as cutting temperature and cutting force. Conversely, the inputs influence also the predicted tool wear. Therefore, the mutual relationships are not taken into account in these models. Further studies should be carried out to make the models more precise and accurate for predicting diamond tool wear/life and to optimize cutting processes further to improve cutting performance and prolong diamond tool life. Additionally, the models could be combined with DTW monitoring to improve monitoring capability and prediction accuracy.

7. Concluding remarks

In ultra-precision machining (UPM), diamond tool wear (DTW) is a key factor directly and indirectly influencing surface quality regardless of machining easy-to-cut materials or difficult-to-cut materials. This review makes significant contributions to the understandings of several aspects of DTW in UPM, involving DTW characteristics, DTW mechanisms, DTW monitoring, DTW controlling and DTW modelling. Key information concerning DTW is as follows:

(1) DTW takes place inevitably in a UPM process. Many factors affect DTW, such as diamond crystal orientation, cutting parameters, tool geometries, cutting fluids and workpiece materials. Workpiece material is a fundamental factor.

(2) DTW is a gradual process, affecting surface quality either directly or indirectly by other factors. Some with DTW in a mutual promotion degrade surface quality. For example, DTW increases cutting forces, which promote vibration to further degrade surface quality and the increased cutting forces raise cutting temperature and pressure to accelerate DTW. For cutting of brittle materials, DTW leads to an undesirable ductile-brittle transition, which further shortens tool life and downgrades surface quality.

(3) DTW mechanisms can be classified into mechanical, physical and chemical wear. Mechanical wear covers abrasive wear, adhesive wear and fatigue. Physical wear involves thermo-chemical wear, tribo-electric wear, anisotropy and defect. Chemical wear covers chemical reaction, graphitization, amorphization and diffusion.

(4) For difficult-to-cut materials like steel, DTW is drastic and chemical wear is a major wear mechanism. Different approaches have been proposed to retard DTW, which can be classified into process modifications, tool modifications and workpiece modifications. Until now, vibration assisted cutting and workpiece modification provide the best solution to DTW suppression. A combination of multiple different methods, which reduces chemical wear and mechanical wear, provides the possibility of further reducing DTW.

(5) DTW monitoring is a crucial process to enhance surface quality. Different methods have been developed to monitor tool conditions, such as on-line, off-line and in-situ approaches, covering acoustic emission, cutting force, acceleration, optical measurement and chip formation. Until now, no efficient method has been used to monitor DTW, since it is too weak to easily detect. More research needs to be conducted on DTW monitoring.

(6) DTW modelling is a theoretical means by which its mechanisms are understood. Analytical modeling (AM) can be employed to predict diamond tool wear/life, but it is not real time and

is time consuming and very high costly due to the great number of cutting tests, or it lacks a full understanding of all physical laws. Finite element modelling (FEM) is a powerful tool for simulating ultra-precision cutting processes, but it is not suitable for studying DTW mechanisms due to its constitutive equation, size effects and the requirement for enormous computing source. Importantly, it can be used as an aid tool. Molecular dynamics simulation (MD) has offered convincing evidence of DTW mechanisms for some materials, but it is limited by its functionality. However, it has the potential for providing a deeper understanding of DTW mechanisms.

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