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ORIGINAL ARTICLE

Review of diamond-cutting ferrous metals

Z. J. Li · F. Z. Fang · Hu Gong · X. D. Zhang

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Abstract Machining of ferrous metals using diamond tools is one of the most important areas in ultra-precision machining as it is not possible to achieve a nanometric surface if one simply uses diamond tools to do the cutting. A review on the wear mechanism and existing approaches for the tool wear reduction discussed in literatures is conducted. By comparing the existing solutions in terms of tool wear and surface finish, publications have shown that ultrasonic vibration cutting and workpiece surface modification have better effects in improving tool life in diamond cutting of ferrous metals. However, the combination of the two solutions does not show a further improvement of either the surface finish or the tool wear reduction compared with that of ultrasonic vibration cutting alone. Studies show that substitutions of tools made of diamond with nano-grained CBN and development of novel suitable-for-diamond-cutting materials are potentials in prolonging the tool life.

Keywords Ultra-precision machining · Diamond · Ferrous metal · Tool wear · Surface quality

1 Introduction

Due to the characteristics such as high hardness, ability to form an extremely sharp cutting edge, high thermal conductivity, low friction, non-adhesion to most work materials, and high wear resistance [1], diamond is well-known as an ideal tool material for ultra-precision machining, which is generally regarded as a key technology of the twenty-first century [2, 3]. On the other hand, hardened steels are the most popular engineering material, especially in the molding industry. Some of them are required to have mirror surface finish and complex shape simultaneously. Ultra-precision cutting technology is generally useful to attain such mirror surfaces. By utilizing a sharp single crystal diamond tool and an ultra-precision machine tool, arbitrary micro- and macro-structures can be machined with mirror surface quality [4]. However, diamond tools are subject to catastrophic wear in conventionally machining ferrous metals, which subsequently can lead to surface deterioration [5–9]. Thus, the applicability of diamond cutting for the machining of ferrous materials is greatly restricted. With the increasing demand for complex and precise optical components, it is necessary to develop ferrous dies and molds owing to highly durable and low cost. Therefore, many studies were focused on wear mechanism of diamond tools and corresponding approaches for reducing the tool wear and surface roughness in machining ferrous metals.

This paper serves to review the wear mechanism and existing solutions in reducing the diamond tool wear in diamond cutting of ferrous metals. In the later part of the paper, potential approaches in prolonging the tool life in ultra-precision machining of ferrous metals are discussed.

2 Wear mechanism of diamond tool in machining ferrous metals

The catastrophic wear of diamond tools when machining ferrous metals cannot be explained alone by the differences in material properties like hardness, fracture toughness, crystal structure, and melting point. For extending applications of

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diamond tools in ultra-precision machining, it is essential to understand the wear mechanism and how to reduce the wear of diamond tools.

Ikawa and Tanaka [5] employed three different methods (simulated grinding test with single-grit technique, thermal etching test, and diffusion test) to investigate the wear of diamond grain in grinding. In another cutting test of mild steel [10], they reported that the diamond grain showed higher wear rate as the carbon content of the workpiece decreased, and the highest wear rate was observed in cutting of pure iron. Therefore, they concluded that the wear mechanism is divided into mechanical wear and thermochemical wear, and furthermore, the graphitization of diamond, which is especially sensitive to temperature and can be greatly accelerated due to contacting with iron, plays a dominant role in wear of diamond grains in grinding ferrous metals and subsequently diffused into the iron workpiece. Komanduri and Shaw [11, 12] proposed that diamond at room temperature is in a metastable state and would transform into graphite under the appropriate conditions of pressure and temperature. They detected the carbon diffused at the bottom of grooves scratched by diamond grain. Thornton and Wilks [7] compared wear rates at very low cutting speeds with the workpiece at the temperature of ambient and 220 °C and found that the wear process is not thermally activated due to the same wear rate in both cases. They also proposed that freshly generated surfaces have an enhanced reactivity which can further assist the graphitization process. By changing cutting speed and ambient gas pressure [8], they investigated diamond tool wear and solid state reactions and ascribed tool wear to graphitization of diamond which is accelerated by thermally activated catalytic reaction of clean surfaces of iron and ambient oxygen. Their explanation was that the diamond was worn away so that carbon atoms would be removed because of a linkage with the iron (or other) atoms in the steel. At least five types of bonds are involved in the wear process, as shown schematically in Fig. 1.

Bonds 1 and 5 are characteristics of the bulk materials (steel and diamond), bond 3 is the iron-carbon bond formed across the interface, and bonds 2 and 4 are those linking the uppermost iron and carbon atoms to the next lower layer under the conditions at this particular interface. Any chemical reaction at the interface is controlled by the form and strength of the bonds 2, 3, and 4 which are not fully determined by the behavior of the bulk material. Later, they reported much greater differences in the wear rates arise from differences in the chemical constitution of both the diamonds and the steels [9]. Hitchiner and Wilks [13, 14] investigated the effects of atmosphere on reaction rates and found that the wear of diamond turning mild steel was promoted by the presence of hydrogen and methane and was almost independent of the cutting speed. Extensive discussion of diamond tool wear mechanisms was presented by Evans and Bryan [15] who reckoned both fracture and chemical ones as dominant mechanisms and Paul et al. [16] who proposed a hypothesis that ascribes chemical wear of diamond tools to the presence of unpaired d electrons in the atoms of the workpiece material for breaking the diamond lattice and resulting in excessive chemical tool wear. Tanaka et al. [17] and Shimada et al. [18] explored thermochemical wear mechanism by means of an erosion test simulating wear process and ab initio molecular orbital calculation. They proposed two different mechanisms in terms of temperature, i.e., dissociation of carbon atoms on diamond surface due to the interaction with iron surface at the temperature higher than 1,000 K and removal of carbon atoms due to oxidization of diamond accompanied with deoxidization of iron oxide at the temperature lower than 900 K.

1 1 2 3 4 5 5

- Fe - Fe - Fe - Fe - C - C - C - C -

Fig. 1 Schematic of five types of bonds in wear process [8]

As diamond tool wear appears in a very small region, it is extremely difficult to monitor in real time with the currently existing experimental techniques. The problem is that the time scales over the cutting experiments are too long to permit direct observation of the diamond to graphite transformation, which occurs on a nanosecond to picosecond time scale, if it occurs at all. Molecular dynamics (MD) simulation has been found a powerful tool for understanding the machining process on the atomic and nanometer scales [19]. However, only a few publications of the MD simulations focused on tool wear of nanometric diamond cutting iron workpiece, partially due to the complexity of wear mechanisms.

Narulkar et al. [20] utilized MD simulations of diffusion couple tests to investigate the chemical interaction between carbon (diamond/graphite) and iron. They found that diffusion of carbon into iron was observed only when a graphite interlayer was added to the diamond surface, while no diffusion was observed when diamond alone was used. Later, they [21] used realistic interaction potentials to provide a direct evidence that as cutting commences, the structure of diamond at the cutting edge begins to transform from diamond cubic into hexagonal graphite in the presence of iron, namely an initial graphitization of diamond. Graphitization takes place not atom by atom but simultaneously by groups of atoms via an intermediate activated state. And subsequent to this transformation, the graphitic carbon diffuses into the iron as shown in Fig. 2. They also observed that the diamond (1 0 0) plane is the most resistant and the (0 1 1) plane the least resistant to graphitization with the (1 1 1) plane showing intermediate propensity for transformation to a graphite structure. Furthermore, wear not only depends on the crystallographic plane but also on the direction of the cutting.

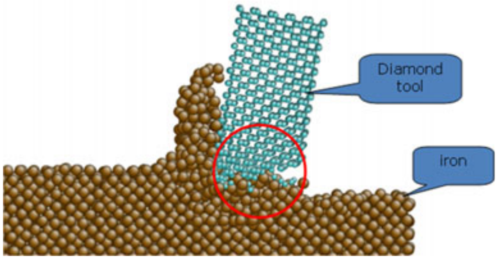


Fig. 2 MD simulations of nanometric cutting of pure iron [21, 22]

High temperature and intimate contact between diamond and iron not only transform diamond into graphite but also transform iron into hexagonal structure. The transformation of bcc iron to hcp iron plays an important role in the graphitization of diamond. This path is favorable energetically and geometrically for the subsequent diffusion of carbon into iron, or actual formation of chemical reaction to form iron carbide (Fe_3C) [22].

In order to establish more realistic models, further studies should be conducted on realistic interaction potentials, multi-scale simulations [23] for enlarging the simulation scales, and generalized potential energy surface [22]. Although researchers have taken great efforts to explore the wear mechanisms of diamond tool, it is necessary to have a further understanding in this important aspect. As a summary, wear mechanisms of diamond tool in machining ferrous metals can be divided into four groups [15, 16, 24]:

(a) Adhesion and formation of a built-up edge
(b) Abrasion, microchipping, fracture, and fatigue
(c) Tribothermal
(d) Tribochemical wear, which was further divided into graphitization, diffusion, carbide formation, and oxidation

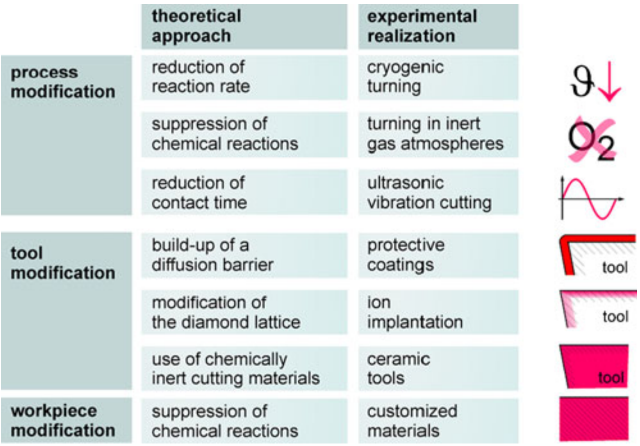
Chemical wear is generally considered as the dominant mechanism of diamond tool wear in machining ferrous materials, which is primarily due to diamond graphitization brought about by four factors [7–13, 15–18, 20–22, 25]:

(a) High temperatures at the interface
(b) Pressures below the diamond stable region
(c) The catalytic action of the iron and the atmosphere
(d) The enhanced activity of the clean surface generated during the machining process

These beneficial researches would give a valuable guidance for reducing diamond tool wear.

3 Approaches for tool wear reduction

In the past, surrounding the process system of machine tool–workpiece–tool, several methods for reducing tool wear in diamond cutting of steel have been proposed as shown in Fig. 3. Brinksmeier and Gläbe [26] revisited these solutions concentrating on identifying the mechanisms responsible for chemical and abrasive wear and quantifying tool wear [28]. Some of the approaches are further developed recently and several new methods arise at the same time.



	theoretical approach	experimental realization
process modification	reduction of reaction rate	cryogenic turning
	suppression of chemical reactions	turning in inert gas atmospheres
	reduction of contact time	ultrasonic vibration cutting
tool modification	build-up of a diffusion barrier	protective coatings
	modification of the diamond lattice	ion implantation
	use of chemically inert cutting materials	ceramic tools
workpiece modification	suppression of chemical reactions	customized materials

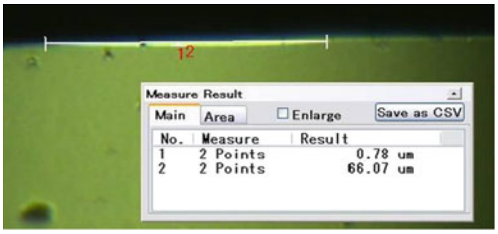
Fig. 3 Approaches to ultra-precision machining of steel [26, 27]

3.1 Machining process modification

3.1.1 Cryogenic turning

As mentioned above, temperature is one of the most important factors in causing chemical wear. Considering that lowering the temperature generally reduces chemical reaction rates and should decrease chemical wear, Li and Yuan [29] sprayed cryogenic coolants, such as liquid nitrogen, liquid CO_2, and alcohol cooled with dry ice, through a nozzle to the cutting zone and reported a substantial reduction in tool wear. Evans and Bryan [15] and Lundin et al. [30] studied the process by chilling tool and/or workpiece independently and achieved a surface roughness of less than 25 nm in Ra and no obvious tool wear with the edge radius r_β<40 nm after a cutting area of less than 1,000 mm^2 or a cutting distance of 928.93 m when cryogenic diamond turning 440 V′ stainless steel. Brinksmeier et al. [26, 31, 32] employed two types of heat sinks for cooling the diamond tools (liquid nitrogen cooling and Peltier element cooling) and observed a less than 40 nm radius of the worn cutting edge. Therefore, they assumed that chemical wear was becoming more important than abrasive wear when the diamond tool was cooled to cryogenic temperatures, which is in agreement with the results of Evans and Bryan [15].

After effective mitigation of chemical wear, other nonchemical wear processes still exist. Therefore, we explored a chilled air with minimal quantity lubrication system (CAMQL) [33–36] in a temperature ranged from 0 to −60 °C. The experimental conditions and flank wear are shown in Fig. 4. CAMQL system significantly reduced tool wear (the land width of flank wear VB 0.78 μm) and



No.	Measure	Result
1	2 Points	0.78 um
2	2 Points	66.07 um

Fig. 4 Tool wear of diamond cutting NAK80 using CAMQL system

improved surface quality (Ra 14.8 nm) compared to diamond cutting the as-received steel with mineral oil (VB 15.11 μm, Ra 233.69 nm) after a cutting distance of 150 m, but further improvement may need much lower temperature (rotational speed 1,500 rpm; feed rate 3 mm/min; depth of cut 3 μm; nose radius 0.5 mm; workpiece diameter 20 mm; temperature −40°C; pressure 0.28 MPa; oil amount 40 ml/h).

Cryogenic machining has shown its advantages in diamond machinability mainly in terms of tool wear and surface roughness. However, there exist some problems yielded by cryogenic machining, such as significant changes in atmosphere at the tool–workpiece interface and severe temperature gradients, which make it difficult to produce high-precision parts [16].

3.1.2 Turning in gaseous environment

Considering that gaseous hydrocarbon can eliminate the deterioration of the diamond tool by inhibiting or preventing the conversion of the diamond carbon to graphite carbon, Casstevens [37, 38] machined both mild and high-C steels in a carbon-rich atmosphere (CH_4, C_2H_2, CO_2, and CO, respectively) and found that there was no significant improvement in tool life as a result of turning under CO_2 but a significant decrease in tool wear with CH_4 (very slight deterioration or visible edge defects after machining an area of about 3 in^2 with peak-to-valley roughness of less than 12.5 nm). However, Hitchiner and Wilks [13] found that the presence of hydrogen and methane increased tool wear considerably far from reducing it because atomic hydrogen can react with the diamond to give a gaseous hydrocarbon. Paul et al. [16] machined pure iron samples in both air and in helium (oxygen-free atmosphere) and observed a rapid, large, and indistinguishable tool wear in both cases. They pointed out that machining iron in an inert atmosphere will generally not be worthwhile because the metal–carbon complexes would still form at the tool–workpiece interface. To prevent chemical reaction with ambient oxygen in the cutting zone, argon and nitrogen atmospheres were used in [26, 31], but no reduction in the wear and surface roughness was found and ambient oxygen has a negligible influence on the tool wear. Moreover, the carbon content of the workpiece did not affect the wear rate. Similar efforts were made in this regard by Tanaka and Yui [39].

In addition to turning in carbon-rich gas, cutting in carbon-rich coolants are also introduced (see Sections 3.4.2 and 3.4.4). Although diamond turning steels in a carbon saturated atmosphere showed some improvement in tool wear, both inert and carbon-rich atmospheres have not been proved practically in diamond machining steels due to the existence of continuous formation of metal–carbon complexes.

3.1.3 Intermittent cutting

Ultrasonic vibration-assisted machining has been used for cutting, grinding, tapping, and so on since 1960s. Kumabe [40] suggested that steel could be machined using diamond tool by applying ultrasonic vibration which was promising to reduce diamond tool wear. This was applied successfully for the first time by Moriwaki and Shamoto [41, 42] for ultra-precision machining purposes. They developed a linear (1D) ultrasonic vibration-assisted cutting system whose tool was vibrated along the cutting direction in spite of slightly vibration in the thrust direction. With this application, both the tool life and surface finish were improved significantly (0.03 μm $R_{\max}$ and flank wear of 4 μm after a cutting distance of 1,600 m [41]). Liu et al. [43] studied the machining mechanism and tool wear behaviors in terms of the flank wear, the characteristic of the chip formation, and the cutting forces. They also investigated the tool–chip gap and the lubrication at the cutting zone theoretically and experimentally during ultrasonic vibration-assisted cutting stainless steel and found that low vibration amplitude (<4 μm) and low cutting speeds (<20 m/min) are usually preferred to achieve mirror surface finish. Klocke and Rübenach [44] developed an ultrasonic-assisted diamond turning process to machine steel and glass and obtained optical surface quality. Klocke et al. [45] studied the kinematics of uniaxial ultrasonic-assisted diamond turning hardened steel and pointed out that by increasing the frequency from 40 to 60 kHz, high-quality surfaces and stable cutting process can be obtained. Later, they [46, 47] increased the frequency to 80 kHz and obtained optical surface roughness Ra< 10 nm and a shape accuracy below 300 nm with no clear tool wear. Shamoto and Moriwaki [48] and Moriwaki et al. [49] first proposed elliptical vibration cutting, i.e., vibrating the cutting tool in a plane including the cutting direction and the thrust direction (2D) in such a way that the cutting edge forms an elliptical locus in each cycle of the vibration as shown in Fig. 5.

In this method, the workpiece is fed at a nominal cutting speed, while the elliptical mode vibration is applied to the cutting edge. The cutting process starts at time t_1, and the tool reaches the lowest point of its elliptical path at time t_2. A tiny part left from the previous cycle is cut at a small depth until time t_3. After time t_3, the workpiece material is

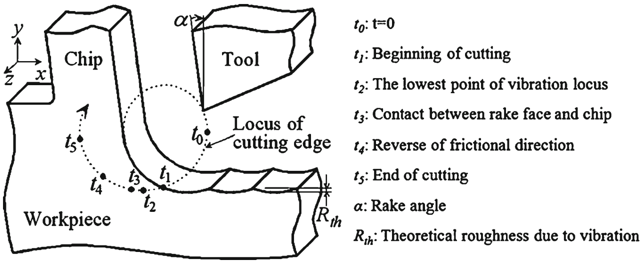


Fig. 5 Principle of elliptical vibration cutting [50]

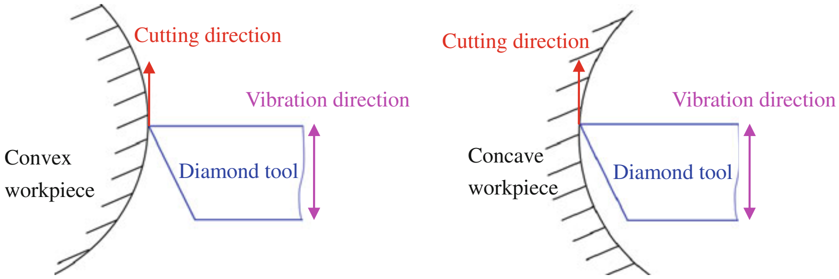
mainly sheared and removed as a chip at a large depth of cut. As the tangent of the cutting trajectory exceeds the shear direction at time t_4, the frictional direction on the rake face is reversed, which leads to an increment in shear angle and consequent reduction of the cutting force (virtual lubrication effect). Then, the tool disengages itself from the chip at time t_5, when the tangent is parallel to the rake face. As the tool and generated chips are basically in the same direction, when the vertical vibration speed of the tool exceeds the flow speed of the chips, the tool rake face assists in pulling the chips away from the workpiece, thus significantly reducing the cutting force, energy, and heat generation [48, 51–55].

To understand the basic mechanics, Patten and Williams [56] developed a 2D finite element model, which is capable of simulating the amplitude and frequency independently of the tool in the cutting and thrust force directions over a wide range of values, to perform numerical simulations of vibration-assisted machining. They found that the cutting forces are directly and significantly affected by the vibration amplitude and the cutting speed, while the resultant temperatures are mostly affected by the cutting speed and not significantly affected by the vibration amplitude. Also, there appears not to be any significant thermal effects associated with the vibration amplitude alone that would contribute to a change in cutting force. Shamoto et al. [57, 58] developed various 3D elliptical vibration cutting models and revealed that the continuous chip formation process in the orthogonal and oblique types of elliptical vibration cutting is the unique cutting process with the reduced friction and the reduced thrust component of friction, respectively, while the practical elliptical vibration cutting can be understood as the intermediate process between the orthogonal and oblique types of elliptical vibration cutting.

With the development of ultrasonic elliptical vibrator whose resonant frequency is 20 kHz [59, 60], they found that 2D vibration cutting can significantly improve the cutting performance, i.e., lower cutting energy and cutting forces, higher machining accuracy, and surface finish and longer tool life [54, 60–64] (less than 0.05 μm in Ry and slight tool wear after a cutting distance of 2,250 m) than the conventional cutting including 1D vibration-assisted cutting [41] (0.03 μm in $R_{\max}$ and flank wear of 4 μm after a cutting distance of 1,600 m). Tool life strongly depends on the tool–workpiece effective contact time, and no wear reduction was detected for effective contact times larger than 54 % in [65]. The cutting distance on steel could be increased up to 1,500 m with a roughness of the machined surface of RMS<40 nm using optimized cutting conditions.

With the increasing demand for precision components with structured or micro-structured surface for optical or mechanical applications, various machining processes are also developed as follows. To realize ultra-precision machining over a relatively large area, Suzuki et al. [66] developed an ultra-precision elliptical vibration cutting system and obtained the maximum roughness of less than 0.04 μm in Ry both by ultra-precision planing (1,110 m) and grooving of hardened die steel. Moriwaki et al. [67] developed an elliptical vibration milling machine and applied it to elliptical vibration end milling and elliptical vibration planing as well as conventional milling and planing. They obtained a mirror surface on hardened steel with 0.11 μm in Ra by elliptical vibration planing with single crystal diamond tool. Song et al. [68] used fly-cutting or milling to control the contact time between the diamond tool and the steel in one cutting cycle by changing the cutting speed and cutting length in each cutting cycle and found that the wear of diamond tool was highly dependent on the tool–workpiece contact time regardless of the cutting speed and can be significantly reduced by decreasing the contact time to less than 0.3 ms. Shibasaka and Ishida [69] employed end milling to suppress wear on the single crystal diamond tool for cutting stainless steel and found that the utilization of mist was effective to reduce tool wear but not to improve surface roughness. Surface roughness of around 100 nm in Rz can be obtained under the conditions of clearance angle of 20° and swing radius of 2 mm. Macro-scale mirror surface sculpturing and micro/nano-scale ultra-precision sculpturing of steel materials with a depth of cut control as fast tool servo (FTS) function were realized by applying the elliptical vibration cutting with the developed 2 DOF and 3 DOF ultrasonic vibration systems [70–73]. To machine complex micro-structure surfaces, Chen et al. [74] developed a precision vibration-assisted micro-engraving system by the integration of FTS and ultrasonic elliptical vibration system, which can obtain a good quality of micro-V grooves and reduce cutting force by about 60 % compared with traditional removal process without ultrasonic vibration. Overcash and Cuttino [75–77] developed a tunable vibration turning device operating at ultrasonic frequencies and studied the dynamic tool–tip temperatures. Kim et al. [78] developed a programmable vibration cutting tool that can generate 2D vibration shapes without distortion by placing two piezoelectric actuators at right angles and

Fig. 6 Cutting sections of workpieces with different forms. **a** No interference occurs. **b** Interference occurs



a) No interference occurs b) Interference occurs

verified it by machining hardened mold steels. Similar efforts were also made by other researchers in [79–86].

In summary, intermittent cutting, especially ultrasonic vibration cutting, has become one of the most promising methods [2, 3, 87, 88] for ultra-precision diamond cutting of ferrous metals and has been practically utilized in industry. 1D vibration-assisted machining systems are used both in precision diamond machining of optical-quality surfaces and in traditional machining applications with depths of cut as large as 0.5 mm; 2D vibration-assisted machining systems tend to be used in precision machining applications only with depths of cut from about 1 μm to less than 50 μm [89]. However, in some cases, machining time is longer than that of the conventional methods due to the restriction of the vibration speed and self-excited chatter vibration occurs in elliptical vibration cutting [4], while concave workpiece as shown in Fig. 6 cannot be machined by 1D vibration-assisted cutting due to the interference between tool tip and workpiece.

3.1.4 Electric field-assisted machining

Zhang [90] has developed an electric field-assisted diamond machining method in which the surface electric potential of the workpiece is adjusted or tuned to be adequate by conduction charging or induction charging to inhibit the chemical reaction between the diamond tool and the workpiece. Therefore, the chemical wear rate of the diamond tool is reduced, and diamond tool life is extended. However, no experimental data were reported in the patent.

3.2 Tool modification

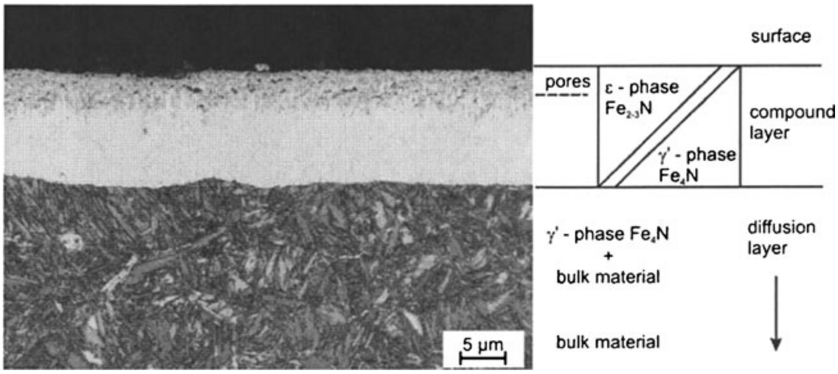
3.2.1 Protective coatings

To enhance tool performance, Klocke and Krieg [91] have discussed the systematic selection or development of a suitable tool coating based on the primary wear mechanisms. Although they mainly focused on conventional tool materials and the machining of non-ferrous materials, their report also provided a reference of applying tool coatings to diamond cutting of ferrous metals. To prevent direct contact between the diamond tool and work materials, TiN coating and TiC coating were used, respectively, on diamond tools to reduce chemical wear in machining steels [26, 92]. Both coatings protected the diamond tools but were worn abrasively during the cutting process. Dong et al. [93] compared the protective effects of TiN coating, TiAlN coating, and AlN coating. They reported that TiAlN coating had a better adhesive strength than the others and the wear of the TiAlN-coated diamond tools was reduced up to 50 % after a cutting distance of 1,130 mm. However, protective coatings, which are not suitable for machining ferrous metals economically, would also increase the edge radius of diamond tools, and their adhesive strength and abrasive resistance are relatively restricted.

3.2.2 Ion implantation

Nitrogen-implanted diamond tools have a higher abrasion resistance as reported by Hartley [94] and Zhang [95]. Stock

Fig. 7 Cross section and dominant phases of nitrided steel [116, 119]

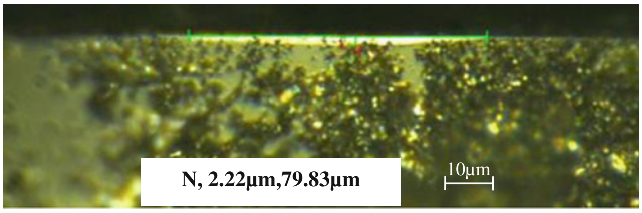


et al. [96] modified single crystal diamond surfaces by implantation of high energy nitrogen, chromium, and titanium ions and found that the wear of the zone influenced by chromium implantation with sacrificial layers can be reduced significantly, which offers further potential to enhance the wear resistance of diamond tools for steel machining. Chromium-implanted diamond tools were used for precision turning of Ck01N steel, but the widths of the wear lands were equal or larger than that of unprotected tools [26, 92]. Although ion implantation method showed some advantages in metastable materials formation [94] and diamond wire drawing dies [95], some defects are introduced [97] and insufficient abrasion resistance makes it impractical in diamond cutting ferrous metals.

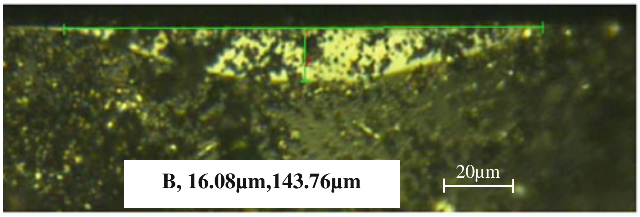
3.2.3 Substitution of diamond tool

Although many properties of diamond, such as high hardness, thermal conductivity, and so on, determine the major industrial application of diamond in cutting and polishing tools, diamonds are subject to chemical wear, rare, and expensive after all. Therefore, it is necessary to explore the substitution of diamond tool.

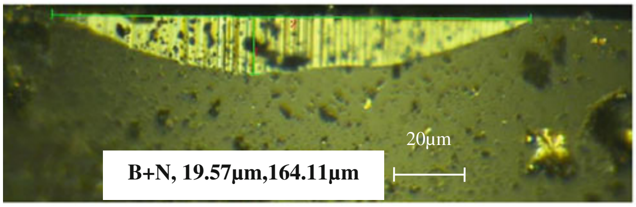
Polycrystalline diamond tools and chemical vapor deposition diamond tools (including thin film and thick film) are normally used for machining of non-ferrous metal alloys, plastics, and composites [98, 99]. Both of them are not recommended for machining ferrous metals due to high chemical wear [99, 100]. Single crystal and sintered CBN tools with higher chemical stability against steel were developed [101, 102], and mirror-like steel surfaces were obtained but with rapid tool wear. Chou and Evans [103] utilized CBN tools with different grain sizes (0.5–3 μm) for machining hardened tool steels and found that flank wears were less than 45 μm VB_{max} after 6.2 km cutting distance and surface finish was better than 80 nm in Ra. Knuefermann et al. [104] employed a nano-grained CBN tool for precision machining of hardened steel and achieved better than 40 nm in Ra. Faceted sapphire tool and sintered nano-grained alumina tool with the cutting edge radii of 120 nm were used for precision turning of Ck01N steel, but the flank wear was comparable to that of unprotected diamond tools [26, 92]. Neo et al. [105] employed binderless CBN or pure CBN tools for direct ultra-precision machining of alloy steel and attained a surface roughness of less than 30 nm in Ra. Oberschmidt and Kurz [106] investigated the performance of commercial binderless CBN tools (grain size <0.5 μm) for ultra-precision machining of steel and obtained roughness values of Ra<35 nm and peak to valley of P-V<200 nm after a cutting distance of approximately 80 m. To further reduce cost, Liew [107, 108] investigated the performance of coated carbide tool in ultra-precision machining of stainless steel, but the results are far from those of using CBN tools. Fujisaki et al. [109] developed ultra-fine-grain (<100 nm) binderless CBN tools with the sharp cutting edges and high hardness as next to those of single-crystal diamond tools but better characteristics in terms of heat and chemical resistance. They obtained tool wear of only on the order of 100 nm or less and less than 100 nm in Rz for a blade



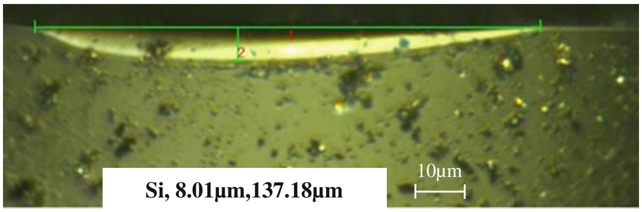
(a) Plasma nitriding



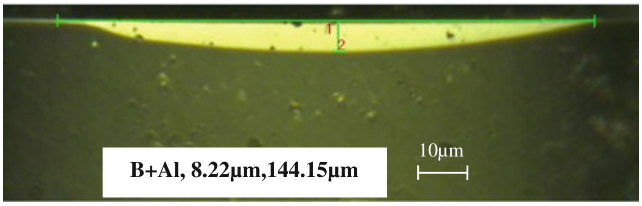
(b) Boronizing



(c) Pack boronitriding



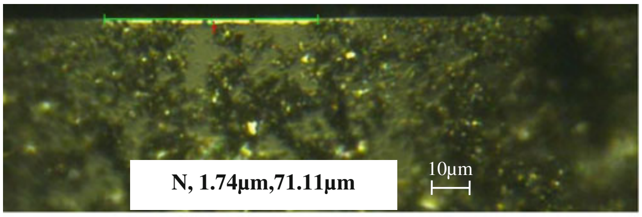
(d) Pack siliconizing



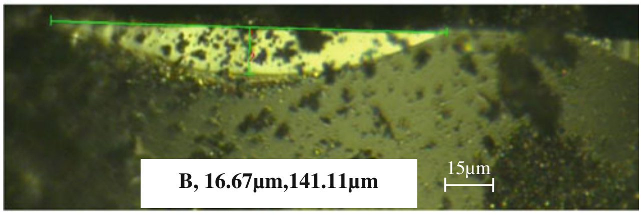
(e) Complex boronizing-aluminizing

Fig. 8 Tool wear of diamond turning Stavax stainless steel described by different surface modifications, land width, and length with cutting distance of 150 m. **a** Plasma nitriding. **b** Boronizing. **c** Pack boronitriding. **d** Pack siliconizing. **e** Complex boronizing–aluminizing lifetime of about 2 or 3 km for high-speed milling of stainless steels under dry conditions with air blowing.

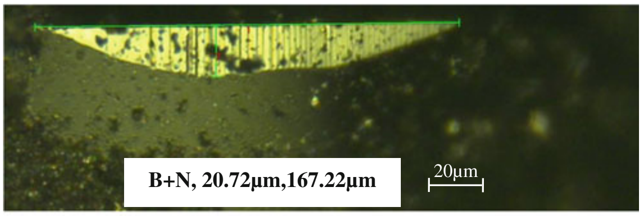
The above-mentioned cutters, such as nano-grained CBN and ceramic tools which are generally used in hard cutting, are very promising substitutions of the diamond tools in ultra-precision cutting of ferrous materials at least from economic aspect. However, the reported surface finish cannot meet the demands for optical mold inserts yet. Further investigation is required to improve the cutting edge sharpness and abrasion resistance of substitute tools and combine with minimum quantity lubrication [110–112].



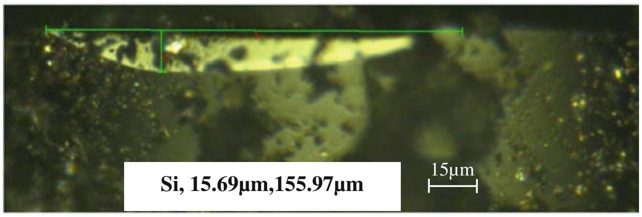
(a) Plasma nitriding



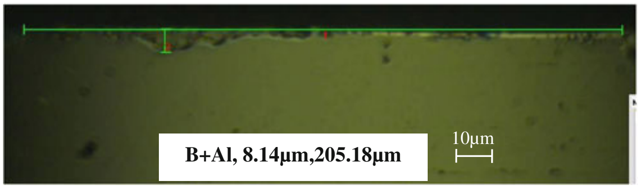
(b) Boronizing



(c) Pack boronitriding



(d) Pack siliconizing



(e) Complex boronizing-aluminizing

Fig. 9 Tool wear of diamond turning NAK80 described by different surface modifications, land width, and length with cutting distance of 150 m. **a** Plasma nitriding. **b** Boronizing. **c** Pack boronitriding. **d** Pack siliconizing. **e** Complex boronizing–aluminizing

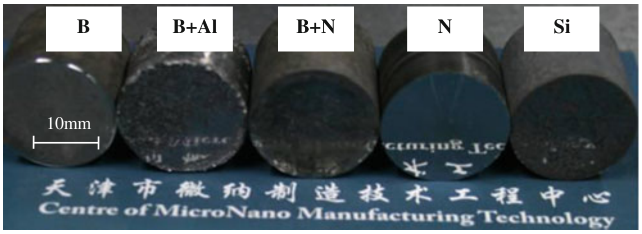


Fig. 10 Surface quality of diamond turned Stavax by different surface modifications

3.3 Workpiece surface modification

Surface modification is the act of modifying the surface of a material by bringing physical, chemical, or biological characteristics different from the ones originally found on the surface of a material. On the other hand, transition metal elements, such as iron, cobalt, nickel, etc. in transition groups IV–VIII of periodic table, are generally considered to be non-diamond turnable [16] due to their catalysis on the wear of diamonds [8, 113]. Therefore, surface modification techniques can be used to seize those elements and do not change the properties of original workpiece materials at the same time, which can produce a compound layer to be diamond machined.

Initial point of this approach is a special characteristic of nickel. Arnold et al. [114] diamond turned nickel-phosphorus alloy that is prepared by chemical deposition or by DC plating methods and observed that tool wear was decreased with increasing phosphorus content and crystallinity, which correlates well with the presence of unpaired d electrons. Similarly, Brinksmeier and Gläbe [27, 115], Osmer et al. [116], and Brinksmeier et al. [117–119] diamond machined the compound layers (shown in Fig. 7) of plasma nitrided steel molds [120] and reported a reduction of diamond tool wear more than two orders of magnitude (VB 36 μm→no significant wear (r_β 40 nm→120 nm)) and surface roughness of 8–10 nm in Ra after a cutting distance of 500 m. Dai et al. [121] investigated the effects of different

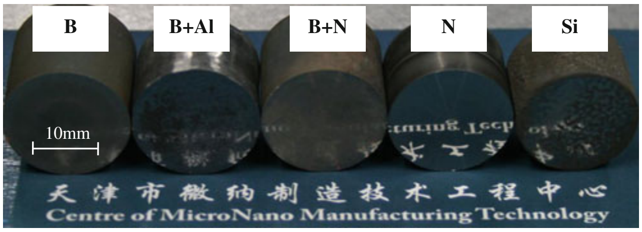


Fig. 11 Surface quality of diamond turned NAK80 by different surface modifications

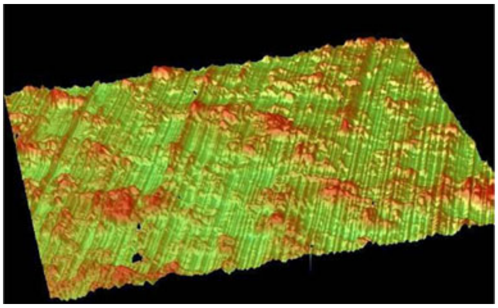


Fig. 12 Surface morphology and roughness of plasma nitrided Stavax measured by white light interferometer (6.72–16.90 nm in Ra)

chemical elements in nitrided steels on tool wear and obtained surface roughness of 12.7–17.5 nm in Ra and 1.57 μm in VB after diamond turning a polished and plasma nitrided NAK80 for 80 m while surface roughness of 4.2–7.5 nm in Ra and 5.30 μm in VB after diamond turning a polished and plasma nitrided Stavax for 60 m. It is also found that Ni, Cu, Si, and Al are beneficial to improve the tool life, while Mn, Cr, and Mo play the negative role. Similar efforts were followed by the researchers in [122–124].

To find out more suitable permeated elements for workpiece surface modifications, we have tried various thermochemical treatments, such as pack boronizing, pack siliconizing, pack boronitriding, and complex boronizing–aluminizing in contrast to plasma nitriding. Figures 8, 9, 10, 11, and 12 show the experimental results of diamond machinability (evaluated especially in terms of tool wear and surface quality) of different compound layers. It can be seen that:

(a) There exist remarkable differences on diamond machinability among different thermochemical modifications due to different chemical compositions of compound layers. At the same cutting conditions, compound layers obtained by plasma nitriding have the best diamond machinability (VB<2.22 μm and Ra< 33.78 nm) than other mentioned thermochemical modifications (VB>8.01 μm and non-mirrorlike surface) in both cases of Stavax and NAK80 stainless steels after a cutting distance of 150 m.

(b) There is no great difference on diamond machinability between the same modified Stavax and NAK80 stainless steels due to the same chemical compositions of compound layers.

(c) Mechanical wear is presumably the dominant wear mechanism which is obvious in boronitriding case due probably to the hard particles in compound layers and also supported by the textures of machined surfaces observed by a white light interferometer which accord with tool wear marks. Micro-chippings also appear in machining of complex boronizing-aluminized NAK80.

So far, workpiece surface modification mainly focused on chemical aspect by producing a compound layer, i.e., a new diamond-machinable material. Thermochemical treatment, which is fast and cheap, can not only effectively improve the diamond machinability of steels but also increase corrosion stability of the machined surface. However, form deviation of the modified steels comes up due to thermal deformation and mechanical wear of diamond tool still exists. Therefore, to overcome the problems, physical aspect and the combination with chemical aspect should be considered in future work. In addition, the influence of the machined compound layer on optical performance and the behavior of the machined compound layer in injection molding of plastics have to be investigated in mass production [116].

3.4 Combination of the above-mentioned approaches

As mentioned above, several approaches showed some improvements in prolonging the diamond tool life. Therefore, the combination of them may be a potential for further reduction of diamond tool wear and surface roughness.

3.4.1 Cryogenic turning and elliptical vibration cutting

The combination of cryogenic cutting (liquid nitrogen cooling and Peltier element cooling) and elliptical vibration cutting was investigated in [32]. Comparison of the wear land width of monocrystalline diamond tools and the surface roughness after a cutting distance of 1,000 m at ambient and cryogenic temperatures with and without tool vibration is shown in Table 1. The combination improved surface quality, but there was no significant difference in reduction of tool wear compared with cryogenic cutting alone.

3.4.2 Ultrasonic vibration cutting in a carbon-rich atmosphere

Zhang et al. [125, 126] and Zhou [127] tried ultrasonic vibration cutting stainless steel in CO_2 and the combination of CO_2 and cutting fluid of vegetable oil and CCl_4. Cutting forces and temperature in the cutting zone are greatly reduced compared with the conventional machining method, and the affinity between diamond tool and the iron atom of workpiece is also minimized as gas shield application. They

Table 1 Comparison of tool wear and surface finish [32]

	Temperature	Wear land width VB (μm)	Roughness Ra (nm)
Without tool vibration	Ambient	≈40	≈350
With tool vibration	Ambient	≈20	≈80
Without tool vibration	−130 °C	≈0.6	≈140
With tool vibration	−120 °C	< 0.5	≈30

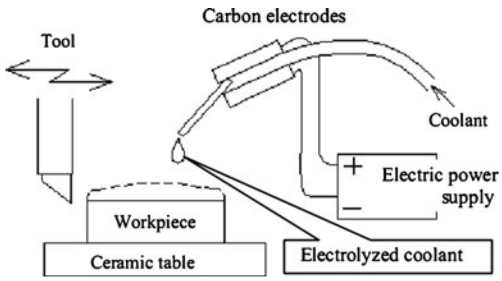


Fig. 13 Schematic of the ion-shot coolant system [128, 129]

reported that the amplitude is the most important factor affecting tool wear and surface roughness and attained a surface roughness Ra of less than 0.15 μm and flank wear of less than 5 μm when cutting distance is up to 2,000 m in CO_2. However, the results are not better than those of ultrasonic vibration cutting alone (0.03 μm in $R_{\max}$ and flank wear of 4 μm after a cutting distance of 1,600 m in 1D vibration cutting [41], or less than 0.05 μm in Ry and slight tool wear after a cutting distance of 2250 m in 2D vibration cutting [54]).

3.4.3 Workpiece surface modification and ultrasonic vibration cutting

In the light of effects of plasma nitriding alone and elliptical vibration cutting alone on diamond tool wear and surface roughness, Wang et al. [123] explored an approach by combining the two solutions. However, the combined solution did not present any further improvement either on the surface finish or on reduction of tool wear (obvious wear and 30 nm in Rz after a cumulative cutting distance of about 150 m) compared with that of elliptical vibration cutting alone (no serious wear and 30 nm in Rz after a cumulative cutting distance of about 190 m). Being dependent on the crystal orientation of the diamond, micro-chipping was observed on both the rake face and the flank face in accordance with the (1 0 0) plane due to the significant increase in hardness and inclusions in the steel after plasma nitriding treatment, while micro-chipping was almost completely suppressed when using the diamond tool with a rake face and flank face in accordance with the (1 1 0) plane and (1 0 0) plane, respectively, owing to their resistance to damage.

3.4.4 Workpiece surface modification and tool modification

To prevent chemical reactions, Inada et al. [128–131] proposed an ion-shot coolant system as shown in Fig. 13, i.e., a coolant mixed with nano-carbon particles and supplied through carbon poles for electrolyzation. On one hand, they reported that the ion-shot coolant modified the workpiece surface softer down to 200 nm which enabled ductile mode cutting with smooth cheap generation. On the other hand, proper combination of cutting parameters and carbon density of the ion-shot coolant can create a protective layer on the tool surface that can prevent from a direct contact between the tool and the work material and thus reduce surface roughness and tool wear as shown in Table 2.

However, the softening mechanism and wear mechanism are not fully understood. In addition, the direct and continuous contact between tool tip and bulk material is inevitable in the proposed method.

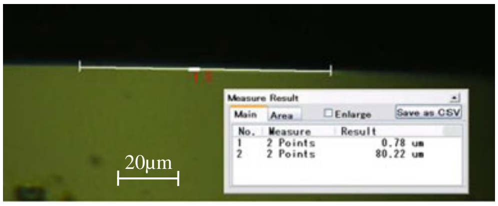
3.4.5 Workpiece surface modification and cryogenic turning

To reduce the catalysis of Fe in the workpiece and the temperature in the cutting zone as well as abrasive wear at the same time, we tried the combination of plasma nitriding of NAK80 steel and CAMQL with the same experimental conditions as mentioned in Sections 3.3 and 3.1.1. The flank wear is shown in Fig. 14.

CAMQL system combined with workpiece surface modification significantly reduced tool wear (VB 0.78 μm) and improved surface quality (Ra 8.81 nm) compared to diamond cutting the as-received steel with mineral oil (VB 15.11 μm, Ra 233.69 nm) after a cutting distance of 150 m, but the results are not better than those of workpiece surface modification alone [115] (no obvious wear with r_β 40 nm→120 nm, Ra 8–12 nm after a cutting distance of 500 m) or cryogenic turning alone [15] (no obvious wear

Table 2 Surface roughness and tool wear by using ion-shot coolant system [128–131]

Work material	Surface roughness	Tool wear	Cutting area	Type of machining
SUJ-2	3.6 nm $R_{\max}$ (NCEC)	–	Cutting width 1 mm, depth of cut about 6 μm	2D orthogonal cutting (cutting speed 150 mm/min)
	9.9 nm $R_{\max}$ (KM)	Approx. 130 μm^3		
SUS420J-2	15.3 nm Ra (NCEC) (0.0015 wt.%)	Approx. 65 μm^3	-	Turning (cutting speed 3,000 mm/min, depth of cut 2 μm, pick feed 50 μm)
	700 nm Ra (NCEC) (0.0015 wt.%)	–	-	
	About 60 nm Ra (NCEC) (0.0015 wt.%)	–	37.5 mm^2	Turning (cutting speed 3,000 mm/min, cutting width 5 μm, cutting length 10 mm, cutting depth 2 μm)
	<12.5 nm Ra (NCEC) (0.0035 wt.%)	–	37.5 mm^2	



```
No.  Measure    Result
1    2 Points        0.78 um
2    2 Points       80.22 um
```

Fig. 14 Tool wear of diamond cutting plasma nitrided NAK80 using CAMQL system after a cutting distance of 150 m [36]

with $r_\beta < 40$ nm, Ra<25 nm after a cutting area of less than 1,000 mm^2 or a cutting distance of 928.93 m), which shows lubrication is not dominant in this case.

4 Discussion

Some tool wears are eventually observed during diamond turning of ferrous metals because the higher temperatures induced by extended rubbing of hard objects provide enough kinetic energy to break carbon–carbon bonds on the surface of the tool [16]. As mentioned in Section 2, wear mechanisms of diamond tool in machining ferrous metals, which may take place simultaneously and interactively, are divided into mechanical–abrasive wear and chemical–reactive wear. However, the diamond is so much harder than mild steel that any abrasive component of wear should be negligible. Therefore, chemical–reactive wear could be the principal mechanism of wear of single point diamond tools in the machining of ferrous materials. Furthermore, graphitization is considered as a precursor to wear of diamond and subsequently diffuses into the iron. The transformation of tetrahedral diamond into hcp graphite due to metastable state at room temperature as internal cause could be reduced by controlling the external causes, such as temperature, catalysis of iron, pressure, and so on, below the threshold values.

Table 3 shows the comparison of several representative solutions to diamond cutting of ferrous metals in terms of tool wear or tool life, surface finish, as well as the underlying problems. Although the different effects of the enumerated approaches cannot be completely reflected by the reported values due to different indexes (e.g., Ra, Ry, Rz, etc.) or conditions of workpiece, cutting parameters, and geometry of diamond tool, intermittent cutting especially ultrasonic vibration cutting alone and workpiece surface modification alone has been proved practically in industry for significantly reducing tool wear and consequently improving surface finish by short contact time and elimination of catalysis of transition metal elements like iron, respectively. Interestingly, the combinations of the solutions do not yield further improvement. Ultra-fine-grain binderless CBN

Table 3 Comparison of several representative solutions to diamond cutting of ferrous metals

Solution	Tool wear	Cutting distance/area	Surface roughness	Underlying problems
Cryogenic turning	No obvious wear ($r_\beta < 40$ nm)	<1,000 mm^2	<25 nm Ra	Severe temperature gradients
Turning in gaseous environment	Very slight deterioration	3 in^2	<12.5 nm P-V	Metal–carbon complexes would still form
Ultrasonic vibration cutting	Slight	2250 m	<0.05 µm Ry	Machining efficiency is low or self-excited chatter vibration occurs
Electric field-assisted machining	–	–	–	No experimental data were reported
Protective coatings	3 µm	1,130 mm	–	Insufficient abrasion resistance
Ion implantation	6 µm	1,130 mm	–	Insufficient abrasion resistance
Substitution of diamond tool (nano-grained CBN or ceramic tools)	Only on the order of 100 nm or less	2–3 km	<100 nm Rz	Insufficient abrasion resistance and cutting edge sharpness
Workpiece surface modification	No significant wear (r_β 40 nm→120 nm)	500 m	8–12 nm Ra	Thermal deformation and mechanical wear still exists
Cryogenic turning and elliptical vibration cutting	<0.5 µm	1,000 m	30 nm Ra	No significant reduction of tool wear compared with cryogenic cutting alone
Ultrasonic vibration cutting in a carbon-rich atmosphere	<5 µm	2,000 m	<0.15 µm Ra	No improvement compared with elliptical vibration cutting alone
Workpiece surface modification and ultrasonic vibration cutting	Obvious wear	150 m	30 nm Rz	No improvement compared with elliptical vibration cutting alone
Workpiece surface modification and tool modification	Approx. 65 µm^3	–	15.3 nm Ra	Tool tip will still directly contact workpiece
Workpiece surface modification and cryogenic turning (CAMQL)	0.78 µm	150 m	8.81 nm Ra	No improvement compared with workpiece surface modification alone or cryogenic turning alone

tools with the sharp cutting edges and high hardness as next to those of single-crystal diamond tools but better characteristics in terms of heat and chemical resistance are promising at least from economic aspect.

In all the above-mentioned cases, mechanical–abrasive wear is inevitable due to direct tool–workpiece contact and could be dominant when chemical–reactive wear is suppressed. Any wear of the diamond tool will increase tool forces and hence temperature, which in turn will increase rates of dissolution, diffusion, and catalyzed graphitization [15]. Therefore, further study is necessary to conduct for reducing abrasive wear by lubrication. On the other hand, Ikawa et al. [2] pointed out that the material removal process is not governed solely by cutting tool but also critically by the work material. Work materials must be chosen [132] or developed [133–135] which give an acceptable machinability on which nanometric surface finish can be achieved.

5 Conclusions

Diamond tools are subject to catastrophic wear in machining ferrous metals. It has been intensively reviewed in the wear mechanisms and existing approaches for reducing the tool wear and analyzed the characteristics of each solution in terms of tool wear or tool life, surface finish, as well as the underlying problems. According to the literature survey, ultrasonic vibration cutting and workpiece surface modification have better effects in improving tool life in diamond cutting of ferrous metals, but the combination of the two solutions does not yield further improvement of either the surface finish or the reduction of tool wear compared with that of ultrasonic vibration cutting alone. Studies show that substitutions of tools made of diamond with nano-grained CBN and development of novel suitable-for-diamond-cutting materials are potentials in prolonging the tool life.

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