CIRP Annals - Manufacturing Technology 68 (2019) 69–72

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Oxygen-shielded ultrasonic vibration cutting to suppress the chemical wear of diamond tools

XinQuan Zhang [a,*], Hui Deng [a,b], Kui Liu [a]

[a] *Singapore Institute of Manufacturing Technology, 73 Nanyang Drive, 637662, Singapore*
[b] *Southern University of Science and Technology, Shenzhen, 518055, China*

Submitted by Prof. Ekkard Brinksmeier (1), University of Bremen, Germany

ARTICLE INFO

Keywords:
Diamond tool
Wear
Ultrasonic

ABSTRACT

Ultrasonic vibration has been applied to reduce intense chemical tool wear in ultra-precision diamond cutting of steel and other alloys since a few decades ago. But still, its tool wear suppression mechanisms have not been fully understood. In this paper, the effect of oxygen in suppression of diamond tool wear for ultrasonic vibration cutting is investigated. Experimental results show that the wearing rate is reduced by applying oxygen shielding to the cutting zone in comparison with air and argon. Scientific explanations are also provided for the observed phenomenon through low-pressure metal oxidation experiments and X-ray photoelectron spectroscopy surface analyses.

1. Introduction

Diamond tools have various unique physical and mechanical properties compared to other cutting tools, but its intense chemical wear in direct cutting of many important metal alloys, particularly steel, has strongly limited its wider industrial application. The short tool life is considered to be mainly caused by the metal-catalysed graphitization, due to the intimate contact between carbon atoms on the diamond cutting edge and metal atoms on the freshly cut surface [1].

To reduce the chemical tool wear in diamond cutting, several approaches have been applied by researchers to lower the chemical reaction rate between carbon and metal atoms, including cryogenic cooling [2], surface modification of tool [3], surface modification of workpiece [4] as well as ultrasonic vibration cutting (UVC) [5]. Among these technologies, UVC is most thoroughly studied, and has already been successfully adopted by optics manufacturing industry to enable direct ultra-precision cutting of stainless steel molds for replacement of conventional nickel-phosphorus plating. However, its tool wear suppression mechanisms have still not been fully understood, due to the difficulty in studying the state of chemical reaction happening on the micron-scale interface at an ultrasonic frequency.

Chemical wear of diamond tools during mechanical removal of metal alloys is a complex chemical reaction process, which occurs on the metal-carbon interface with loaded abrasive friction and varying thermal gradient. In a conventional cutting process, due to the continuous plastic deformation of metal material resulting from the non-interrupted tool-workpiece motion, the reaction at the cutting zone is considered under near vacuum condition, where ambient air is restrained from getting into the interface between solids. In comparison, as a controlled high-frequency intermittent cutting process, UVC regularly forms a physical gap between tool and uncut workpiece material, which allows ambient air or mist to penetrate in and triggers its potential reaction with the exposed reactive metal atoms. Such reaction may lead to the formation of other chemical bonds besides metal-carbon complexes, which could pose significant effect on the catalytic efficiency of metals for graphitization.

As oxygen is the most reactive gas in the air and also makes up the second largest portion, to better understand the diamond tool wear suppression mechanisms in UVC, in this study the effect of gas shielding with different oxygen concentration is investigated for cutting of different metal alloys. Oxygen shielding is realized by using an oxygen concentrator that supplies concentrated oxygen to the cutting zone. Based on a group of oxidation experiments and subsequent quantitative analyses, scientific explanations are provided for the observed phenomena.

2. Existing theories for chemical wear suppression in UVC

Compared to continuous cutting, UVC, under properly selected cutting and vibration parameters, usually leads to intermittent tool-chip contacts, reduced cutting force, improved cutting dynamics as well as enhanced physical penetration of air or mist. As the chemical reaction rate between two solids could be affected by many environmental factors, like contact time and temperature, considering the unique characteristics of UVC, two theories have been proposed to explain the suppressed diamond tool wear. Moreover, several engineering approaches for further reduction of the tool wear rate by changing cutting and vibration conditions were also proposed, as shown in Fig. 1.

Although the existing two theories can well explain the results of enhanced tool wear suppression, both have not considered the

---

[*] Corresponding author.
E-mail address: zhangxinquan@sjtu.edu.cn (X. Zhang).

https://doi.org/10.1016/j.cirp.2019.04.026
0007-8506/© 2019 Published by Elsevier Ltd on behalf of CIRP.

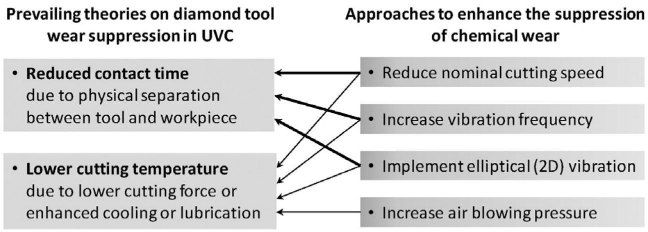

Fig. 1. Existing two theories of diamond tool wear suppression for UVC of steel and various engineering approaches to further extend the tool life.

graphitization process from the chemistry point of view. Besides affecting the contact time and cutting temperature, it is believed that the listed approaches shall also create different states of gas-metal-carbon interface and change the abrasive friction condition between the cutting edge and the metal material, which hence may influence its catalytic efficiency of graphitization accordingly. To understand the underlying chemical reaction mechanism, it is necessary to evaluate the effect of different ambient gases in such a manner that the contact time and the cutting temperature remain unchanged during the experimental investigation.

Oxygen is a highly reactive gas, but it is not a necessary element in catalysing the graphitization of diamond, because, with or without the involvement of oxygen, the metal-catalysed chemical wear still proceeds through the formation of a metal-carbon complex. For continuous diamond cutting of steel, although it is speculated that the presence of oxygen may accelerate the chemical tool wear [1], cutting tests reported in literature have given contradictory results [6,7]. In comparison, UVC provides physical access for ambient oxygen to enter the cutting zone, which could significantly strengthen its influence on the chemical reaction happening at the gas-metal-carbon interface. However, both theoretical and experimental studies on the effect of oxygen on diamond tool wear in UVC are still missing.

3. Experimental methods

In this study, gases with different oxygen concentration (concentrated oxygen, air and pure argon) were supplied through a gas flow meter and a customized laminar flow nozzle (see Fig. 2). Oxygen-shielded UVC is realized using an oxygen concentrator and an in-house developed vibration cutting attachment, which drives the tool to vibrate in ultrasonic frequency along the nominal cutting direction. Each tool was inspected using a microscope after a cutting test, and its flank wear was measured for five times to obtain the averaged value.

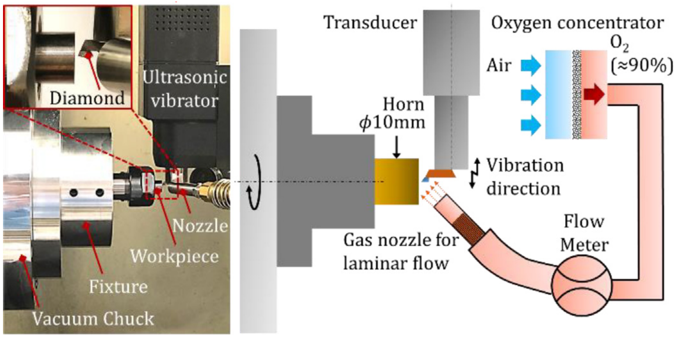

Fig. 2. Experimental setup for oxygen-shielded UVC.

It is necessary to note that the method to implement oxygen shielding in this study may not guarantee identical oxygen concentration at the cutting point with that from the oxygen concentrator, because the supplied gas may mix with the ambient air with a different oxygen level (21%) once it has left the nozzle. Due to the relatively low shielding gas velocity (see Table 1) compared to the air blowing velocity of conventional spray mist (about 50 m/s and higher), the tool was installed facing downward, to allow formed chips to drop themselves as a result from gravity, instead of stacking on the rake face and affecting the cutting and vibration performance.

Table 1
Experimental conditions.

Parameters		Values
Tool	Polycrystalline Diamond	Nose radius 0.4 mm, rake 0°, clearance 7°
	Single Crystalline Diamond	Nose radius 0.2 mm, rake 0°, clearance 15°
Workpiece	Stainless steel (Hardened)	Iron 84%, chromium 14%, others 2%, 435 HV
	Iron	99.95%, 101 HV
	Chromium	99.95%, 145 HV
	Tungsten	99.97%, 440 HV
Depth of cut, a_p		4 μm
Feed per revolution, f_r		3, 15 μm/rev
Cutting distance, L_c		50, 100, 250, 500 m
Nominal cutting speed, v_c		1.25, 2.5 m/min
Spindle rotation speed (Varying), n		40–200, 80–400 rpm
Vibration frequency, f		40 kHz
Vibration amplitude, a		1, 1.25, 1.5 μm
Gas flow rate (Oxygen, air and argon)		10 L/min
Gas velocity at the nozzle outlet		2 m/s
Concentration of supplied oxygen		90 ± 3%
Concentration of supplied argon		99.9%

4. Experimental results

4.1. Effect of oxygen shielding in UVC of stainless steel

The initial cutting tests were conducted on Stavax stainless steel using Polycrystalline Diamond (PCD) tools under different gas shieldings. Stavax is a commonly used mold material by industry for injection molding of plastic optical lenses. Fig. 3 shows the comparative results of flank wear for the used cutting tools. As atmospheric argon plasma is well known for its capability of enhancing surface activation at room temperature due to the existence of high-energy ionized particles, its influence on the chemical tool wear is also investigated here by supplying the gas phase plasma to the cutting zone with the same flow rate. It can be observed that the diamond tool wear rate with oxygen shielding is significantly lower than the other three types of gases.

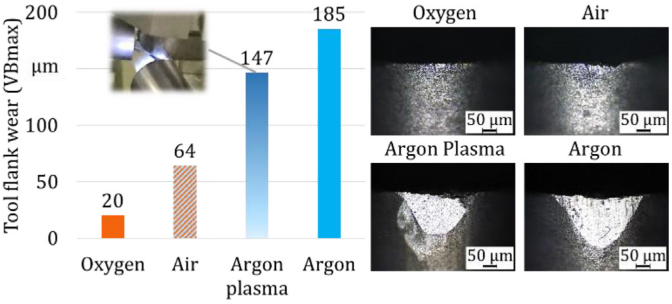

Fig. 3. PCD tool wear after UVC of stainless steel with different shielding gases. Cond.: $f_r = 3$ μm/rev, $L_c = 250$ m, $v_c = 2.5$ m/min, $a = 1$ μm.

Compared to Single Crystalline Diamond (SCD) with uniform cubic lattice structure, PCD is a composite fabricated by sintering micro diamond particles together with binder. Although its mechanical properties are dominated by diamond as the major constituent material, the tool wear mechanism is not exactly the same compared to that of SCD due to the involvement of metallic binder in the chemical and abrasive wear as well as the significant difference in edge radius. Hence, another group of cutting tests were conducted on the same steel but using SCD tools. The results are shown in Fig. 4. It can be observed that oxygen shielding consistently leads to a smaller diamond tool wear compared to air shielding, indicating that a higher oxygen concentration around the cutting zone is beneficial to the tool wear suppression in UVC of hardened stainless steel.

4.2. Effect of oxygen shielding in UVC of pure iron and chromium

Stainless steel is corrosion resistant due to the addition of a significant amount of chromium. As it is an alloy made from two major

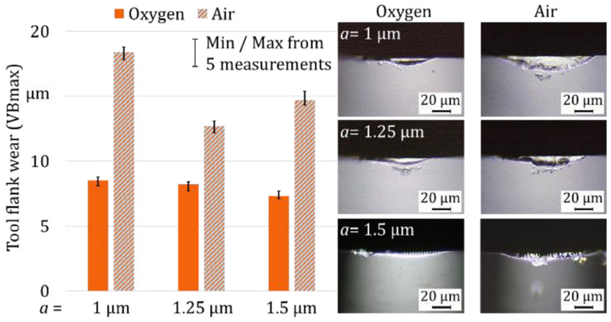

Fig. 4. SCD tool wear after UVC of stainless steel with oxygen shielding and air shielding. Cond.: $f_r = 3$ µm/rev, $L_c = 500$ m, $v_c = 2.5$ m/min.

constituting elements (iron and chromium), it is necessary to differentiate the effect of oxygen concentration on each element, because they may have different chemical affinity with oxygen and carbon atoms, which hence leads to a varying catalytic efficiency for graphitization.

Fig. 5 shows the comparison of tool flank wear under different gas shieldings and cutting conditions using SCD tools. The tool wear rate for UVC of chromium is found several times higher than that for iron. This phenomenon indicates that, although chromium constitutes a minor portion of the Stavax stainless steel (see Table 1), its contribution to the chemical tool wear in UVC of such iron-chromium alloy could be more significant. For UVC of iron, although argon shielding leads to a slightly larger tool wear than oxygen and air, the effect of varying oxygen concentration and cutting distance is less obvious. In comparison, the tool wear rate for cutting of chromium consistently increases with the decreasing oxygen concentration and increasing cutting distance.

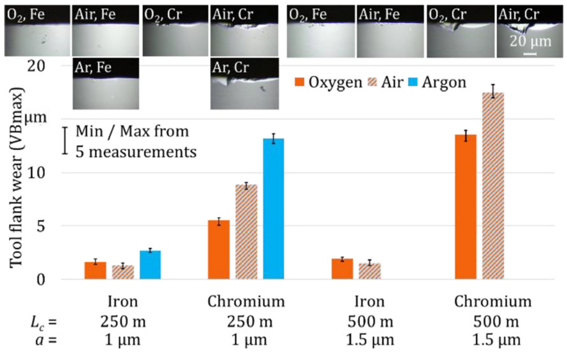

Fig. 5. SCD tool wear after UVC of pure iron and chromium with different shielding gases. Cond.: $f_r = 3$ µm/rev, $v_c = 2.5$ m/min.

4.3. Effect of oxygen shielding in UVC of pure tungsten

Tungsten is another important metal material for optics manufacturing industry, due to its superior mechanical properties at elevated temperature. UVC of tungsten alloys has been utilized as an alternative technique for replacement of conventional ultra-precision grinding of ceramics in precision glass molding [8]. Similar to iron and chromium, tungsten also has a strong chemical affinity with diamond, which accordingly causes intense chemical wear during cutting even with the assistance of ultrasonic vibration. To investigate the effectiveness of oxygen shielding in UVC of tungsten, different gas shielings and cutting conditions were tested. Due to the significantly faster tool wear rate in cutting of tungsten compared to the other metals, a relatively larger feed rate is used to reduce the cutting distance for each face turning operation, so as to prevent the cutting edge from wearing off before it reaches the centre of workpiece.

From the results shown in Fig. 6, the tool wear rate for UVC of tungsten is found several times higher than that for chromium and an order of magnitude higher than that for iron, respectively. Similar to stainless steel and chromium, an increased oxygen concentration is found apparently beneficial to the suppression of diamond tool wear for UVC of tungsten.

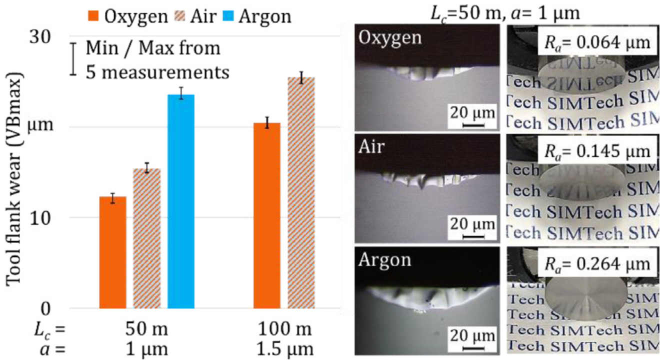

Fig. 6. SCD tool wear and machined surfaces after UVC of tungsten with different shielding gases. Cond.: $f_r = 15$ µm/rev, $v_c = 1.25$ m/min.

5. Discussion

5.1. Effect of oxygen pressure on growth of metal oxide

The oxygen concentration of the supplied shielding gas towards the cutting zone is in direct correlation with the oxygen partial pressure for the gas-carbon and gas-metal interfaces. Generally, diamond is relatively stable in gaseous oxygen at room temperature due to the high kinetic energy barrier for its oxidation, which only occurs when the temperature reaches 600 °C and above. Compared to diamond, most metals are more reactive with oxygen, and an oxide film will be formed on any metal surface after it is exposed to air, except some noble metals.

The initial oxide formation on a clean metal surface starts from initial adsorption of molecular oxygen by an electric field and its subsequent dissociation from molecule into chemisorbed atomic oxygen, which interacts with the metal atoms to form covalent bonds. The thickness of formed oxide film increases with time, until its gradually increasing work function is large enough to impede the emission of electrons. The growth rate of metal oxide can be illustrated by the following direct logarithmic model [9]:

$$\frac{dg}{dt} = Ae^{-\frac{E}{RT}}P^{0.6}e^{-\frac{\gamma g}{RT}} \tag{1}$$

where, g is the thickness of oxide, t is time, $Ae^{-\frac{E}{RT}}$ represents the reaction rate coefficient, A is a pre-exponential constant, E is the activation energy for oxidation reaction of specific metals, R is the molar gas constant, T is the absolute reaction temperature, P is the oxygen pressure, and γ is the increase of the free activation energy with coverage. As described in this equation, the rate of oxide growth is directly influenced by the activation energy and the oxygen pressure, which are determined by the substrate material and the ambient gas respectively. Hence, it can be predicted that both, metal element and oxygen concentration shall play important roles in the formation of metal oxides, in accordance with the results of diamond tool wear rate.

To investigate the effect of metal elements and oxygen pressure quantitatively, a group of low-pressure oxidation experiments using a custom designed X-ray photoelectron spectroscopy (XPS) at room temperature (20 °C) were conducted, as shown in Fig. 7(a). Thin plates with 1 mm thickness made of the same three pure metals (see Table 1) were polished to mirror surface and then cleaned with acetone. Before each oxidation step, the sample surfaces were cleaned by a few cycles of Ar^+ sputtering in the ultrahigh vacuum (UHV) analysis chamber until existing oxide was fully removed. Oxidation was performed sequentially under three different pure oxygen pressures for identical time (1000 s) in the reaction chamber, monitored by a vacuum gauge.

After each oxidation step, the samples were transferred back to the analysis chamber, and photoelectron spectra of the oxidized surfaces were obtained, as shown in Fig. 7(b). By analysing the spectra of each metal surface with different oxidation conditions, the thicknesses of formed oxide film were calculated using Thermo Avantage software, as shown Fig. 7(c). The oxide thickness is determined using the Beer's law equation, $I = I^{\infty}\exp[-g/(\lambda\cos\theta)]$. I/I^{∞}

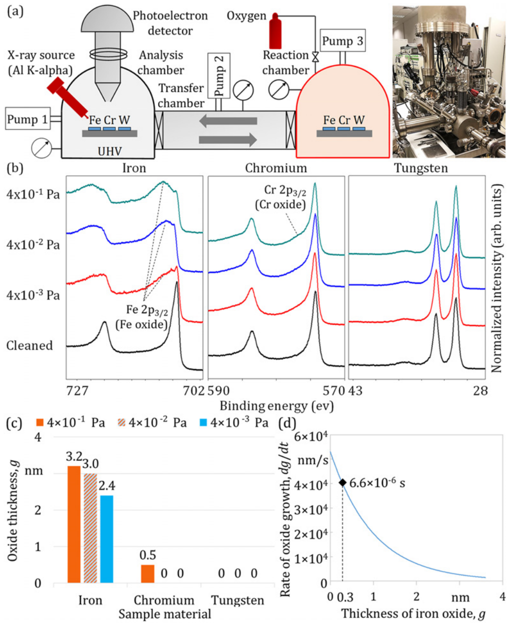

Fig. 7. (a) Setup of the oxidation and XPS analysis experiment; (b) photoelectron spectra of cleaned and oxidized metal surfaces; (c) thickness of oxide film formed under the three specified oxygen pressures; and (d) calculated growth rate of iron oxide with respect to its thickness at the atmospheric oxygen pressure (2.1×10^4 Pa).

represents the intensity ratio of metallic $2p_{3/2}$ signal from the metal substrate with and without an oxide layer, λ is the inelastic mean free path of electrons, and θ is the emission angle with respect to the sample surface normal (0° in this study). It can be observed that, even at the lowest oxygen pressure, a significant amount of iron oxide can be formed. Moreover, with the increasing pressure, the growth rate of iron oxide increases accordingly and is also significantly higher than that of chromium oxide. No tungsten oxide was detected even after oxidation with the highest oxygen pressure, indicating that tungsten may have the highest activation energy for oxidation. With the given thicknesses of iron oxide formed at the three oxygen pressures, a relationship between its growth rate and thickness can be derived according to Eq. (1). As shown in Fig. 7(d), in the atmosphere, the time required to form the first monolayer of iron oxide (0.3 nm thickness) is comparable with one period of ultrasonic vibration used in the UVC test (2.5×10^{-5} s).

5.2. Proposed tool wear suppression theory for oxygen-shielded UVC

Compared to metal, metal oxide is not an effective catalyst in synthesis of diamond. In fact, researchers have found that iron oxide covering iron catalyst will lower the catalytic efficiency for diamond growth by limiting the direct contact between graphite and iron, and such restraining effect becomes stronger with an increasing oxide thickness [10]. As catalysts enhance both, the forward and backward reactions of diamond-graphite transition by drastically lowering the activation energy, the formation of metal oxide on clean metal surface shall also restrain the graphitization of diamond. An increased oxygen pressure that accelerates the oxide growth could strengthen such influence. Although it is theoretically possible for carbon to extract oxygen from metal oxide, such reduction reaction usually requires the elevated temperature, similar to the oxidation of diamond.

It is apparent to note that the effect of oxygen shielding on diamond tool wear cannot be explained by the two theories mentioned in Fig. 1, because neither contact time nor cutting temperatures are changed here. Based on the above-described results and analyses, it is reasonable to state that the suppressed chemical wear of diamond tools in UVC with increasing oxygen concentration can be traced back to the enhanced oxide growth, which is resulting from an increased oxygen pressure at the cutting zone (see Fig. 8). The catalytic efficiency of a freshly cut metal surface for graphitization is weakened by the accelerated oxide growth or the increased oxide thickness.

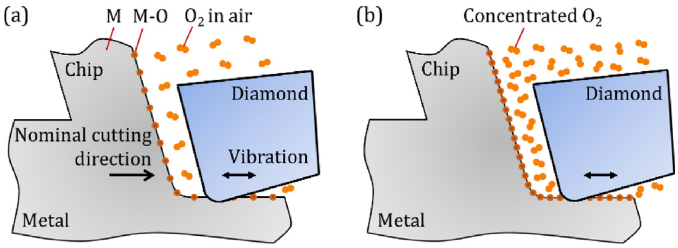

Fig. 8. Schematic illustration for the growth rate of oxide on a freshly cut metal surface in UVC with (a) air shielding and (b) oxygen shielding.

Besides oxygen-shielded UVC, the proposed theory is also able to explain the various approaches listed in Fig. 1. For example, the three methods to achieve reduction of the tool-workpiece contact time actually improve physical contact (in terms of time, frequency or area) of the clean metal surface with the surrounding air or mist per unit cutting distance, which will accordingly enhance the oxide formation and hence the tool wear suppression. Moreover, the approach of increasing air blowing pressure for lowering the cutting temperature in fact leads to a higher oxygen partial pressure around the cutting zone and acts in a similar way like the gas shielding with concentrated oxygen.

6. Summary

Oxygen-shielded ultrasonic vibration cutting is proposed in this paper to suppress the chemical wear of diamond tools. The effect of varying oxygen concentration is investigated through cutting of stainless steel and three pure metals (Fe, Cr and W) with different gas shieldings. The results show that oxygen shielding generally leads to a reduced tool wear rate compared to air and argon shielding. Low-pressure oxidation experiments and subsequent X-ray photoelectron spectroscopy analyses for the three metal elements show that a higher oxygen pressure increases the growth rate and thickness of metal oxides. Their tendency to form oxides is found different for each material but in accordance with the corresponding diamond tool wear rate observed in the cutting tests. Enhanced oxide formation caused by the increased oxygen pressure around the cutting zone is proposed to explain the suppressed chemical wear in oxygen-shielded UVC. This theory is found also capable to reasonably explain the other existing tool wear suppression approaches associated with UVC. To conclude, this study provides a new view from surface science into the chemical tool wear suppression in ultra-precision diamond cutting for applications in optics and other fields, and may also help science and industry to invent more techniques for enabling direct diamond cutting of various metal alloys or enhancing the performance of existing methods.

References

[1] Paul E, Evans CJ, Mangamelli A, McGlauflin ML, Polvani RS (1996) Chemical Aspects of Tool Wear in Single Point Diamond Turning. *Precision Engineering* 18:4–19.
[2] Evans C, Bryan JB (1991) Cryogenic Diamond Turning of Stainless Steel. *CIRP Annals* 40(1):571–575.
[3] Brinksmeier E, Gläbe R (2001) Advances in Precision Machining of Steel. *CIRP Annals* 50(1):385–388.
[4] Brinksmeier E, Gläbe R, Osmer J (2006) Ultra-precision Diamond Cutting of Steel Molds. *CIRP Annals* 55(1):551–554.
[5] Moriwaki T, Shamoto E (1991) Ultraprecision Diamond Turning of Stainless Steel by Applying Ultrasonic Vibration. *CIRP Annals* 40(1):559–562.
[6] Casstevens JM (1983) Diamond Turning of Steel in Carbon-saturated Atmospheres. *Precision Engineering* 5:9–15.
[7] Hitchiner MP, Wilks J (1984) Factors Affecting Chemical Wear during Machining. *Wear* 93:63–80.
[8] Suzuki N, Haritani M, Yang J, Hino R, Shamoto E (2007) Elliptical Vibration Cutting of Tungsten Alloy Molds for Optical Glass Parts. *CIRP Annals* 56(1):127–130.
[9] Eley DD, Wilkinson PR (1960) Adsorption and Oxide Formation on Aluminium Films, Proceedings of the Royal Society A: Mathematical. *Physical and Engineering Sciences* 254:327–342.
[10] Qin JM, Ma HA, Chen LX, Tian Y, Zang CY, Ren GZ, Guan QF, Jia X (2006) The Effect of an Iron Powder Catalyst Clad with a Fe2O3 Layer on the Nucleation of Diamonds. *Diamond and Related Materials* 15:1369–1373.