Research Article

Siwen Tang*, Pengfei Liu, Zhen Su, Yu Lei, Qian Liu, and Deshun Liu

Preparation and cutting performance of nano-scaled Al_2O_3 -coated micro-textured cutting tool prepared by atomic layer deposition

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Abstract: Al_2O_3 nano-scaled coating was prepared on micro-textured YT5 cemented carbide cutting tools by atomic layer deposition ALD. The effect of Al_2O_3 nano-scaled coating, with and without combined action of texture, on the cutting performance was studied by orthogonal cutting test. The results were compared with micro-textured cutting tool and YT5 cutting tool. They show that the micro-texture and nano-scaled Al_2O_3 coated on the micro-texture both can reduce the cutting force and friction coefficient of the tool, and the tools with nano-scaled Al_2O_3 coated on the micro-texture are more efficient. Furthermore, the friction coefficient of the 100 nm Al_2O_3 -coated micro-texture tool is relatively low. When the distance of the micro-pits is 0.15 mm, the friction coefficient is lowest among the four kinds of pit textured nanometer coating tools. The friction coefficient is the lowest when the direction of the groove in strip textured nanometer coating tool is perpendicular to the main cutting edge.

The main mechanism of the nanometer Al_2O_3 on the micro-textured tool to reduction in cutting force and the friction coefficient is discussed. These results show that the developed tools effectively decrease the cutting force and friction coefficient of tool–chip interface.

Keywords: atomic layer deposition, nano-meter coating, Al_2O_3 , cutting tool, friction coefficient micro-texture

1 Introduction

Dry cutting technology, as an environment-friendly and cost-saving machining technology [1–4], is getting more attention because people keep a watchful eye on the environment problem. However, severe friction occurs between tool and chips during dry cutting process, which generate a large amount of heat, and then causes the tool to fail prematurely. Moreover, the oxidation of tools can reduce its mechanical properties and significantly affect its service performance [5]. To improve machining accuracy and efficiency, the coated cemented carbide tools have been more and more applied to the machining [6]. Among the coating materials, Al_2O_3 offers great chemical inertness and oxidation resistance and enhances the wear resistance [7–9]. Al_2O_3 retained hardness at elevated temperature, showing a high chemical and thermal stability, even at temperatures above 1,000°C, at which most nitride coatings suffer from severe and rapid oxidation [10,11]. Al_2O_3 coating is used as thermal barriers to protect the cemented carbide substrates from the high temperatures at the cutting edge [12]. The Al_2O_3 coating obtains higher hardness compared with ZrO_2 , and the modest hardness of ZrO_2 limits their use for wear applications [13]. Numerous investigations carried out by various authors showed that the textured tools exhibited better performance than conventional non-textured tools during different machining conditions [14–26]. More recently, researches show that the micro-texture and coating on the tool surface are better than non-textured coating tool

* **Corresponding author: Siwen Tang**, Hunan Provincial Key Laboratory of Health Maintenance for Mechanical Equipment, Hunan University of Science and Technology, Xiangtan 411201, China, e-mail: siw_tang@hnust.edu.cn

Pengfei Liu: Hunan Provincial Key Laboratory of Health Maintenance for Mechanical Equipment, Hunan University of Science and Technology, Xiangtan 411201, China, e-mail: 1432982610@qq.com

Zhen Su: Advanced Technology Generalization Institute of China North Industries Group, Beijing 100089, China, e-mail: 444053262@qq.com

Yu Lei: Department of Chemical and Materials Engineering, University of Alabama in Huntsville, Huntsville, AL 35899, United States of America, e-mail: yu.lei@uah.edu

Qian Liu: Hunan Provincial Key Defense Laboratory of High Temperature Wear Materials and Preparation Technology, Hunan University of Science and Technology, Xiangtan 411201, China, e-mail: 26121895@qq.com

Deshun Liu: Hunan Provincial Key Laboratory of Health Maintenance for Mechanical Equipment, Hunan University of Science and Technology, Xiangtan 411201, China, e-mail: 1432982610@qq.com

and the textured tool without coating [27–30]. Applying nano-scaled coating has better performance than traditional micro-crystalline coating [31], and nano-scale coatings are isotropic, can be applied to three-dimensional objects having similar properties, this indicates that combination of the nano-scale coating and micro-texture has a good prospective in improving the performance of the cutting tool. However, Neves *et al.* [32] show defects in the coating may work as crack initiation points and lead to coating failure, thus it is very important to improve coating integrity and reduce coating defects.

Some researchers used atomic layer deposition (ALD) technology to prepare coating tools for processing and obtained good results. Mohseni and Scharf [33] reported the improvement of the wear resistance of carbon–carbon composites by ALD of ZnO/Al₂O₃/ZrO₂ coatings. A study by Giorleo *et al.* [34] showed that the life of micro-drill bit was significantly improved when drilling the Ti-plates by ALD-coated Al₂O₃. ALD is able to meet the needs for atomic layer control and conformal deposition [35]; more importantly, ALD can fabricate pinhole-free nanometer coating. The basis of ALD thin film coating growth is the alternating saturated gas–solid phase reaction. When the chemical adsorption of the surface is saturated, the number of surface-reactive precursors no longer increases with time, so there is only one layer film grown per cycle. ALD can obtain coatings of nanometer or even atomic thickness. The self-limiting growth mechanism of ALD has many characteristics: good bonding strength, layer-by-layer deposition, uniform film thickness, good composition uniformity, step coverage, conformality, repeatability, and accuracy at the atomic scale. In addition, reaction temperature of ALD temperature is around 200°C, largely lower than physical and general chemical vapor deposition (PVD and CVD), and this will be beneficial to the mechanical properties of the tool matrix material. ALD technology can improve coating adhesion to the substrate [36] and get better surface integrity [34] compared to PVD technology. Unlike CVD, ALD keeps the precursors strictly separated from each other in sequenced deposition cycles, thus preventing gas phase reactions and allowing atomic layer-by-layer deposition with nearly 100% step coverage [37]. The surface-controlled nature of ALD enables extremely uniform and conformal films on virtually any complex substrates [38]; thus, the ALD technology is suitable for micro-textured surface coatings.

Based on the above analysis, this paper prepared nanometer coating on the micro-textured tools using ALD deposition method and studied their cutting performance, expecting to provide a new way for the development of new cutting tools. In this article, the nano-scaled Al₂O₃-coated micro-textured cutting tool is prepared to improve the wear resistance and friction reduction performance of the tool.

2 Experimental process

2.1 Preparation of micro-texted tool with nanometer coating

Two textures of stripe and pit were designed (named as ST and PT), and the micro-texture was prepared on the rake face of commercial YT5 (WC-10Co-5%TiC) tool by a laser marking machine. The stripe textures are parallel and vertical cutting edges, and 45° and 135° with the cutting edge (named as strip texture 1–4, respectively). The pit pitch of the micro-texture pit is 0.2, 0.15, 0.1, and 0.05 mm, respectively (named as pit texture 1–4, respectively).

Nanometer-Al₂O₃ coating was prepared on YT5 textured tool by ALD. First, YT5 tool was cleaned by an ultrasonic cleaner with acetone for 15 min and dried with high purity nitrogen. The stop/exposure mode was used for the ALD process, and each ALD cycle considers pulse, exposure, and purge times for each of the precursors. Thus, the pulse times of TMA and H₂O in the cycle were 30 and 100 μ s, respectively, while the exposure and purge times were both 10 μ s. The thicknesses of the alumina thin films were 50, 100, and 200 nm measure by ellipsometer (named as FNST, HNFT, and TNFT correspond to 50, 100, and 200 nm coated stripe textured tools. Named FNPT, HNPT, and TNPT correspond to 50, 100, and 200 nm coated pit textured tools.). The morphology of the tools after coating is shown in Figure 1. Figure 2 shows the micro-morphology of textured tools surface obtained by AFM.

2.2 Cutting experiment

Orthogonal cutting experiments were carried out on a CNC lathe (Okuma Corp., Japanese). No cutting fluid was used in the machining processes. The cutting tool working geometry angle: rake angle $\gamma_0 = 0^\circ$, back angle $\alpha_0 = 11^\circ$, main angle $K_r = 75^\circ$, blade inclination $\lambda_0 = 0^\circ$, tip radius $r_e = 0.5$ mm. The cutting parameters were as

Figure 1: Macro-morphology of the coated textured tools.

Figure 2: Micro-morphology of textured tools surface (100 nm).

follows: $v_c = 100$ m/min, $a_p = 1$ mm, and $f = 0.1$ mm/r, and the work piece material was an AISI1045 steel sample with a hardness of 190 HB. The tools were made of cemented carbide (YT5) and textured using a laser maker and coated by ALD. A non-textured tool and textured tools were also tested to compare the machinability. Cutting force is measured by a three-way piezoelectric dynamometer and a charge amplifier, and the cutting forces in the three directions of X , Y , and Z are collected by a data collector and data acquisition software (Kistler Corp., Switzerland). Friction coefficient between tool and chips was calculated by the following equation [39,40]:

$$\mu = \tan \left[\gamma_0 + \arctan \left(\frac{F_y}{F_x} \right) \right], \quad (1)$$

where γ_0 is the rake angle, and F_x and F_y are the principle force and radial force, respectively.

A super depth of field microscope (Keyence Corp., Japan) and an electron microscope (SEM, JEOL Corp., Japan) were used to observe tool surface morphology and tool wear.

3 Results and discussion

3.1 Cutting force of cutting tools

The curve shown in Figure 3 is the change of YT5, PT4, and HNPT4 three-direction cutting forces with cutting time. The comparison in the figure shows that the principle force and radial force fluctuation amplitude of YT5, PT4, and HNPT4 decreased in turn under the same cutting conditions, which indicate that HNPT4 formed good sliding-rolling composite friction in the cutting process; thus, the vibration is smaller, and the cutting process is more stable.

Figure 4 shows the comparison of the cutting forces of the conventional tool, the micro-textured tool, and the nano-coated micro-textured tool at a cutting speed of 100 m/min. We use the pit textured tool, and the pit pitch is 0.05 mm. Compared with traditional tools (YT5), the cutting force of micro-textured tools (PT4) has been reduced to a certain extent, which has been confirmed by many researchers [41,42]. The main cutting force and radial force of the nano-scaled Al_2O_3 -coated micro-textured tool (HNPT4) are greatly reduced. All the axial force of the three is almost zero because it is an orthogonal cut.

3.2 Friction coefficient of cutting tools

3.2.1 Effect of nanometer coating thickness

Figure 5 shows the effect of different thickness nano-coating on the tool-chip friction coefficient of the tool rake face. For comparison, the friction coefficients of the conventional tool and the corresponding micro-textured tool are given together. It shows that 50, 100, and 200 nm nano- Al_2O_3 coating can further reduce the

Figure 3: Comparison of three-direction cutting forces. (a) YT5, (b) PT4, (c) HNPT4.

Figure 4: Cutting force of different tools.

tool–chip friction coefficient compared to the micro-texture tool, and the 100 nm nano-coating has the best reduction effect.

3.2.2 Effect of micro-texture morphology

The tool–chip friction coefficient of the four nano-coating tools with different shapes and texture is shown in Figure 6. For comparison, the friction coefficient of the corresponding uncoated textured tool is also given. The change in the stripe texture morphology has little effect on the friction coefficient between the tool and chip. Different stripe textures morphology and coating combinations have different effects on the friction coefficient of the tool–chip (Figure 6a). When the coating thickness is

Figure 5: Friction coefficient of different tools (FNT-50 nm coated textured tool, HNT-100 nm coated textured tool, and TNT 200 nm coated textured tool).

50 nm and 200 nm, the micro-texture morphology has little effect on the tool–chip friction coefficient. The texture morphology has a great influence on the friction coefficient when the coating thickness is 100 nm. When the stripe micro-texture is perpendicular to the cutting edge, the friction coefficient of the coating tool is the smallest, 0.43, which is reduced by about 25% than that of the stripe texture parallel to the cutting edge. For pit-textured tools (Figure 6b), the lowest coefficient of friction is obtained when the distance between points is 0.15 mm, variation in the tool–chip friction coefficient of the coated pit textured tool is similar to that of the coated stripe textured tool (Figure 6b), and the 100 nm pit textured coating also has a small coefficient of friction. When the pit texture pitch is 0.15 mm, the tool–chip friction coefficient is the smallest and is 0.31, which is lower than that of the stripe textured tool.

Figure 7 shows the micrograph of the 100 nm Al_2O_3 -coated stripe-textured tool after cutting when the stripe parallel and perpendicular to the major cutting edge. It can be seen that there is a certain adhesion on the tool rake face, and the stripe parallel to the main cutting edge has a significantly higher adhesion than that of tool with stripe perpendicular to the main cutting edge. The microscopic picture of the 100 nm Al_2O_3 -coated pit-textured tool with different texture spacing is shown in Figure 8. It can be seen that when the pit texture spacing is 0.15 mm, the adhesion of the tool is obviously lower than the pit texture pitch of 0.05 mm. From the magnified view of the 100 nm Al_2O_3 -coated pit micro-texture tool (pit texture pitch is 0.05), it can be seen that the chip is deposited in the micro-texture, and the micro-texture plays the role of collecting chips. At the same time, the energy spectrum analysis of Figure 9 shows that there is less adhesion (Figure 8c) on the surface of the coated tool, indicating that the coating has the function of reducing adhesion.

3.2.3 Effect of cutting speed

The effect of cutting speed on the tool–chip friction coefficient is shown in Figure 10. When the speed is increased from 100 to 200 m/min, the friction coefficient of stripe and pit micro-textured coating tools increases from 0.31 to 0.47 and from 0.43 to 0.60, respectively. It can be seen that as the cutting speed increases, the friction coefficient of the stripe textured and the pit textured nano-coating tool increases to some extent. It shows that the effect of nano-coating is more obvious at lower speeds.

Figure 6: Tool-chip friction coefficient of nano-coating textured tools: (a) stripe texture, (b) pit texture.

3.3 Discussion on the anti-friction mechanism of nano-coating on micro-texture

The friction coefficient of Al_2O_3 and steel is about 0.66 [43], while the friction coefficient of WC-Co-TiC cemented carbide and steel is about 0.2–0.4 [44], which indicates that the application of nano-alumina on the surface of cemented carbide does not reduce the friction coefficient of cemented carbide cutting tools, and it is also impossible to lower the friction coefficient of micro-textured tools and steel. However, our experimental results are the opposite. This implies that the application of the nano-alumina coating to the surface of the micro-textured tool causes a fundamental change in the friction mechanism between the tool and chip during the cutting process.

The micro-texture form and direction have a certain influence on the friction between the tool and chip. The main friction reduction mechanism of micro-textured tools is mainly the reduction in the contact area between

the tool and chips on the tool rake face [45]. When the nano-coating is applied to the micro-textured tool, on one hand, the high-strength, high-hardness, and heat-resistance properties of the coating protect the micro-texture of the tool rake face. On the contrary, the micro-texture collects the Fe_2O_3 particles and nano- Al_2O_3 particles formed by the chipping and nano-coating detachment, and the nano- Al_2O_3 coating particles in the micro-texture are squeezed and infiltrated into the actual chip contact interface under the action of cutting force and cutting heat. Because of the high hardness of the Al_2O_3 particles, it formed a similar rolling element between the tool and chips, so that the direct contact between the two dies is transformed into a two-body–three-body compound contact, so that the friction between the tool–chip interfaces changes from sliding to sliding-rolling, as shown in Figure 11. We know that the friction coefficient of rolling friction is much lower than the sliding friction, and this change will effectively reduce the friction coefficient between the chips.

Figure 7: Micromorphology of stripe micro-textured tool after cutting: (a) parallel, (b) perpendicular.

Figure 8: Micromorphology of pit micro-textured tool after cutting: (a) parallel, (b) perpendicular, (c) magnified view of (b).

Figure 9: Energy spectrum analysis.

Different coating thicknesses have different chances of forming sliding-rolling friction between the chips. When the nano-coating thickness is 100 nm, the friction coefficient of the four micro-textured coating tools is significantly lower than that of the uncoated micro-textured tool and the 50 nm and 200 nm coated micro-texturing tool. The possible reason is that the particles formed by the 100 nm coating during the cutting process enter well

between the tool and the chips, forming rolling friction. When the thickness of Al_2O_3 coating is 50 nm, the amount of nano- Al_2O_3 coating particles involved in the formation of three-body contact between the chips during cutting is too small to form a rolling friction state, which cannot achieve the effect of changing the friction mechanism; when the coated Al_2O_3 thickness is 200 nm, although the number of nano- Al_2O_3 coating particles generated

Figure 10: Effect of cutting speed on the tool–chip friction coefficient.

during the cutting process increases, too many coating particles will appear to be stacked, and the friction coefficient between Al_2O_3 and Al_2O_3 particles is larger than

that of Al_2O_3 and cemented carbides, so that the friction coefficient of the chip interface increases.

The probability of this transition in different micro-textured tool is also different. When the stripe texture is perpendicular to the main cutting edge, the nano-coated micro-textured tool has the lowest friction coefficient. This result is different from the pure micro-textured tool [6]. Under this condition, when the chip is perpendicular to the micro-texture direction and the nanoparticles are more easy to enter into micro-texture, coated particles are more likely to form a roll between the tool and the chip. At this time, the stripe-like micro-texture direction is parallel to the chip flow direction during the cutting process, so that the coating particles in the micro-texture can penetrate with the chip flow to enter into the actual chip contact portion, so that more nano-coating particles participate in the formed rolling friction. In the case of pit texture, the distance between the pit has an important effect on the friction form. The change in the pitch of the pit micro-texture causes a change in the micro-textured area occupancy of the rake face contact area. When the

Figure 11: Anti-friction mechanism of nanometer-coated textured tools: (a) tool–chip interface contact of different tools, (b) magnified view of point A and B in (a).

pit texture spacing is 0.15 mm, the nano-coating particles are more likely to exist in the micro-texture, forming rolling friction, and obtaining a lower tool–chip friction coefficient. Larger pit texture spacing cannot form effective rolling friction, and the smaller point texture spacing will obviously weaken the strength of the tool surface, which is easy to break, resulting in increased cutting force, which is not conducive to cutting.

As the cutting speed increases, the friction coefficient of the tool–chip interface increases during the cutting process of the nano-coated micro-textured tool. Low speed (100 m/min) is conducive to the formation of sliding friction during cutting. At high speed (200 m/min), because of the faster drag speed of the chips, the amount of chips generated per unit time increases, and the wear of the tool rake face is intensified, reducing the micro-texture anti-friction effect. At the same time, the increase in the chip removal speed removes the nano- Al_2O_3 coating particles formed by the coating peeling off, so that the rolling friction effect formed by the nano- Al_2O_3 particles between the chips during the cutting process becomes weak.

4 Conclusion

Surface texturing was made on the rake face of the WC-Co-TiC carbide tools, and then, nanometer Al_2O_3 was coated on the surface texturing by ALD. Dry cutting tests were carried out with these tools, and the friction coefficient is mainly analyzed. The following conclusions were obtained:

- (1) The micro-texture and nano-scaled Al_2O_3 coated on the micro-texture both can reduce the friction coefficient of the tool, and the tools with nano-scaled Al_2O_3 coated on the micro-texture are more efficient.
- (2) The friction coefficient of the 100 nm Al_2O_3 -coated micro-texture tool is relatively low. When the distance of the micro-pits is 0.15 mm, the friction coefficient is lowest among the four kinds of pit-textured tools. The friction coefficient is the lowest when the direction of the groove in stripe texture tool is perpendicular to the main cutting edge.
- (3) The main mechanism of the nano-scaled Al_2O_3 on the micro-textured tool to reduction in friction coefficient is that the nano-scaled Al_2O_3 form sliding friction between the tool and chip.

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