Tool wear analysis of multi-layer diamond coated tools for cutting white marble

F Lu ¹, H X Li ¹, C Gabor², Y Y Wang ¹ and J B Zhao¹

¹ School of Mechanical Engineering, Shenyang Jianzhu University, Shenyang, China
² Transilvania University of Brasov, Materials Science Department, Brasov, Romania

* lufeng72@126.com

Abstract. Study on the tool wear of cutting white marble by multi-layer diamond coated tool, and discussion of the wear characteristics and failure mechanism of the tool are presented in this paper. Multi-layer diamond coating was prepared by hot filament chemical vapor deposition (HFCVD). It was deposited on the surface of cemented carbide ball-end milling tool. The surface appearance of the tool was analyzed by an optical microscope. The grain state was analyzed by scanning electron microscopy. Comparing the surface morphology of the cutting for 1h, the area where the coating peeled off became larger when the cutting tool was cut for 2 hours, and the holding range was expanded along the cutting-edge direction while the flank surface was expanded, and the tool joint wear was severe. The composition of diamond grains was investigated by Raman spectroscopy. Comparing the surface morphology of the cutting for 1h, the area where the coating peeled off became larger when the cutting tool was cut for 2 hours, and the holding range was expanded along the cutting-edge direction while the flank surface was expanded, and the tool joint wear was severe.

1. Introduction

Natural stone is a typical brittle material. It is mainly composed of CaCO₃, MgCO₃ and SiO₂. It is basically insoluble in water and is a hard-white fine-grained marble. As one of the widely used stone materials in construction materials, natural stone is very easy to engrave because of its solid and delicate texture. In the course of stone processing, commonly used tools such as diamond sintered tools, electroplated diamond tools, often have shortcomings such as low processing precision, high manufacturing cost, high wear rate, easy peeling etc, which cannot meet daily needs [1-4].

The diamond coated tool is a new type of cutting tool that can effectively improve the wear resistance and surface hardness of the tool. To a certain extent it can extend the service life of the tool.

At present, the research on the cutting of diamond coated tools in the metal field is widely studied. However, there is less research on the application of diamond tools in the field of stone processing.

In this paper, hot filament chemical vapor deposition (HFCVD) was used to prepare a diamond coating on the surface of cemented carbide tools. The wear mechanism of multi-layer diamond coated tools during cutting process was studied, which provided a theoretical basis for the preparation of diamond-coated tools for brittle rigid materials [5-7].

2. Test

A WC-Co (YG6) cemented carbide milling cutter was used as a substrate material, and a multilayer diamond coating was prepared by the method of hot filament chemical vapor deposition.
Figure 1 shows the system of hot filament chemical vapor deposition. The vacuum unit of the system provides a good environment for diamond growth. The cooling device uses running water to remove excess heat from the substrate and the chamber wall to keep the surface temperature of the device constant. The gas supply system supplies the hydrogen and hydrocarbon gases required for diamond growth. It provides a gas-free, non-contaminating reaction environment. And the equipment can set the parameters required for the test such as gas flow ratio, chamber pressure and substrate temperature.

The test uses silk as a hot filament for heating. The distance between the hot filaments is 10mm, and the pressure in the reaction chamber is evacuated to 0.5 Pa. Subsequently, a mixed gas is introduced for carbonization. This process is to avoid wasting too much carbon source on the hot wire, which would result in producing graphite with insufficient carbon source. The substrate temperature is 800 °C, the hot filament temperature is 2400 °C, the gas pressure is maintained at 5 kPa, the H2 flow rate is 800 sccm, and the CH4 flow rate is 8.40 sccm, respectively. The ratio of methane to hydrogen is adjusted at two concentration values of 1% and 5% to prepare a composite film system in which two films are alternately stacked [8].

Multi-layer diamond coating was prepared by hot filament chemical vapor deposition method, and the film system with three layers was formed by alternately superposing the coating. This test kept the total thickness of the film uniform, about 7 μm. The adjusted carbon source concentration during deposition is 1% to form a bottom diamond film. The carbon source concentration is increased to 5% by changing the proportion of methane to hydrogen, and the diamond film is continuously deposited to cover the underlying diamond film. The top diamond film and the underlying diamond film grow at the same carbon source concentration, covering the second layer. Finally, a multilayer diamond coating having three layers is produced.

A diamond coating having a three-layer coating was prepared, and the carbon source concentration from the substrate was 1%, 5%, and 1%, successively. And the total thickness is 7μm. The surface state of diamond-coated tools of this structure without cutting is compared with the surface state after 1 hour and 2 hours after cutting white marble.

3. Test results and analysis

The surface morphology of the film system and the wear surface of the tool surface were observed by Zeiss Super 55 field emission scanning electron microscope. The surface composition of the diamond coating was analyzed by using a Horiba, Lab Ram HR laser Raman spectrometer.
3.1. Raman spectroscopy of diamond coating

Figure 2 represents a Raman spectrum analysis of diamond film. The diamond film has obvious characteristic peaks at 1337 cm\(^{-1}\), which means that there are much sp\(^3\) hybrid components in the nano-diamond film. The characteristic peak of diamond is shifted from 1332 cm\(^{-1}\) to 1337 cm\(^{-1}\) due to the existence of residual stress, and its residual stress is expressed as compressive stress [9]. The scattering peak of the amorphous carbon component is generally between 1350 cm\(^{-1}\) and 1600 cm\(^{-1}\) [10]. In the figure 2, the diamond film exhibits a broad scattering peak at 1491 cm\(^{-1}\), indicating that there are some crystal defects such as dense grain boundaries and grain defects in the film. It may be derived from the C-H bond in trans-polyacetylene, which has a greater impact on the quality of the diamond film [11].

![Raman spectroscopy of diamond coating](image)

Figure 2. Raman spectroscopy of diamond coating.

This paper explores the changes of the cutter head and the cutting edge of the diamond coated tool during the cutting test. The cutting material is white marble stone with a cutting speed of 3000r/min, a feed rate of 300mm/min and a cutting depth of 1mm. During the cutting process, the stone and the tool flank surface impact and friction, and the failure mode is mainly abrasive wear. It is generally believed that the abrasive wear morphology of diamond is divided into five forms: complete, smooth, microscopic, macroscopic, and shedding [12].

3.2. Analysis of surface morphology of diamond coated tools

Figure 3 shows the macroscopic morphology of the blade tip of the diamond coated tool under the optical microscope, and figure 4 shows the macroscopic morphology of the blade of the diamond coated tool under the optical microscope. Figure 3 (a) and figure 4 (a) show the surface topography of the diamond-coated tool when it is not cut, from which it can be seen that the coating at the tip is completely and evenly coated on the surface of the tool, and the surface of the tool is intact.

![Optical microscopy of the surface wear profile of the tip of diamond coated tool](image)

Figure 3. Optical microscopy of the surface wear profile of the tip of diamond coated tool.
From the figure of the diamond-coated tool for 1h, it is obvious that there is trace of coating peeling off. And the position of falling off is mainly at the flank along the cutting edge. Comparing the surface topography of 1h cutting, it can be seen that after the diamond coating tool is cut for 2h, the area of the coating falling off becomes larger, and the falling range extends in the flank surface along the cutting-edge direction. The reason for this phenomenon is that the high-speed rotation of the milling cutter and the continuous collision and wear of the stone eventually lead to the coating falling off. As the cutting time increases, the amount of wear increases and the coating falls off [13-15].

3.3. Microscopic topography of diamond coated tool surface

Figure 5 is a scanning electron micrograph of the wear state at the blade edge. Figure 5(a) shows the diamond coated tool without cutting, the grain size is evenly covered on the tool base, and the surface is flat. Figure 5(b) is a topographical view after 1h cutting.

It can be seen that the diamond coating covered by the surface of the substrate has a large area of grain detachment and the side flank is bonded. There are two main reasons for the large area of the coating to fall off. First, the effect of the Co removal treatment is not obvious during the preparation of the coating tool [16-17]. The time to remove cobalt is too short, and the graphitization is serious during the growth of the diamond particles. If the time is too long, the strength of the base material is lowered. The mechanical occlusion effect of the surface of the substrate and the diamond particles is not good, and the bonding force is not strong. When subjected to large impact and friction, large-area peeling occurs. Second, the diamond coating is constantly subjected to large impact forces during the cutting process. And the expansion coefficients of diamond and tool differ greatly. High thermal stress and cutting force reduce the fatigue strength of the coating, resulting in large area shedding. Figure 5(c) shows the morphology after 2h cutting, and the bond wear is severe. The main cause of bond wear is high-speed extrusion and friction between the tool and the substrate, resulting in very high heat of cutting. High cutting temperature, the more severe the bond wear. High cutting temperatures cause the fatigue strength of the diamond film to decrease, and micro cracks also appear.
When the micro cracks continue to expand to a limit, the coating will fall off. Micro pits appear during the cutting process [18]. As the cutting progresses, fine chips and abrasive particles enter the pit. This makes the larger diameter micro-pit structure cause secondary cutting, resulting in greater cutting force. The impurities accumulated in the pits are constantly increasing.

3.4. Diamond coating tool blade surface topography
Figure 6 shows a scanning electron micrograph of the cutting edge of a diamond coated tool for 2h. Obvious detachment and notch at the blade edge were observed under the microscope, and the damage area was large. In addition to cutting force and cutting temperature, there is a reason that Acid-base etching removes surface Co, which has a certain influence on the hardness and toughness of the tool itself during the preparation of the coating [19-20].

Adhesive chips are distributed at the edge of the blade because the cutting tape tends to form a high temperature region, and the abrasive grains of the diamond coating die are easily affected by the high temperature during the falling process. This situation will affect the waste generated by the cutting stone cannot be discharged, and will reduce the surface quality of the processed stone, processing accuracy and efficiency have also been greatly affected.

4. Conclusions
When the diamond coated tool is cutting for 1h, the position where the coating falls off is mainly at the flank surface along the cutting edge direction. Comparing the surface topography of 1h cutting, it can be seen that when it is cutting for 2h, the area of the coating falling off becomes larger, and the falling range extends in the flank surface along the cutting edge direction.

A large area of the diamond coating covered by the surface of the tool substrate cut for 1h is peeled off, and the side surface is bonded. When it is cutting for 2h, the increase of tool bond wear is mainly due to the high cutting pressure and friction between the tool and the base to generate high cutting heat. The higher the cutting temperature, the more severe the bond wear. The high temperature region formed by cutting tends to adhere the abrasive particles and also reduces the fatigue strength of the coating.

Cutting force is reduced, cutting environment is bad, resulting in a decrease cutting efficiency. During the pre-treatment process, the acid-base etching method will affect the hardness and toughness of the tool itself. The etching time is too long, the tool quality is degraded, and large gaps are prone to occur. If the etching time is too short, Co cannot be removed, which promotes the formation of graphite impurities and reduces the quality of the tool.

Sintered diamond tools and electroplated diamond tool are common cutting tools. Electroplated diamond tool is more severely worn on the bottom than the frank when cutting marble. So, the frank is the main cutting surface. It is a limitation for cutting process. Sintered diamond tool needs to choose pre-alloy powder with good wear resistance.
At the same time, it needs to match type, concentration, materials of diamond. This can lead limitation in the choice of materials. In order to reduce the limitation of work, the CVD diamond-coated tool is studied in this article.

Acknowledgments
This study was supported by the Liaoning Natural Science Foundation (20170540757), Program for Science and Technology Innovation Talents of Young and middle-aged of Liaoning (SYSCXRC2017002).

References
[1] Wu Y H, Yan G Y and Zhao D H 2018 J. Machine Tools and Automated Machining Technology 5 p144
[2] Skordaris G, Bouzakis K D, Charalampous P, Kotsanis T, Bouzakis E and Lemmer O 2016 J. CIRP Annals 65 p101
[3] Kun Z and Gyurika I 2013 J. International Review of Applied Sciences and engineering 4 p63
[4] Huang Q, Yu D, Xu B, Hu W, Ma Y, Wang Y and Tian Y 2014 J. Nature 510 p250
[5] Wu Y H, Yan G Y and Zhao D H 2017 J. Lubrication & Sealing 42 p54
[6] Dampala R, Kumar N, Kumaran C R, Dash S, Ramamooorthy B and Ramachandra Rao M S 2014 J. Diamond and Related Materials 44 p71
[7] Sein H, Ahmed W, Jackson M, Woodwards R and Polini R 2004 J. Thin Solid Films 447 p455
[8] Suzuki H, Okada M, Asai W, Sumiya H, Harano K, Yamagata Y and Miura K 2017 J. CIRP Annals 66 p93
[9] Salgueiredo E, Amaral M and Almeida F A 2013 J. Surface and Coatings Technology 236 p380
[10] Zhang S Q, Wang Tand Tang Y B 2017 J. Integrated Technology 6 p10
[11] Tang Y, Li Y S, Yang Q and Hirose A 2010 J. Diamond and Related Materials 19 p496
[12] Bolshakov A P, Ralchenko V G, Yurov V Y, Popovich A F, Antonova I A, Khomich A A, Ashkinazi E E, Ryzhkov S G, Vlasov A V and Khomich A V 2016 J. Diamond and Related Materials 62 p49
[13] Wang C C, Wang X C and Sun F H 2018 J. Surface and Coatings Technology 353 p49
[14] Cheng C, Xue P and Xue F 2018 J. Carbon 130 p215
[15] Çalışkan H, Kurbanoğlu C, Panjan P, Čekada M and Kramar D 2013 J. Tribology International 62 p215
[16] Lü F X, Tang W Z and Song J H 2004 J. Metal Processing: Thermal Processing 6 p62
[17] Park K H, Beal A, Kwon P and Lantrip J 2011 J. Wear 271 p2826
[18] Nakamura M, Sumomogi T and Endo T 2003 J. Surface and Coatings Technology 169 p743
[19] Chen N, Shen B, Yang G and Sun F 2013 J. Applied Surface Science 265 p850
[20] Aslantas K, Onur O, Ismail U and Büyüksaş I S 2009 J. Advanced Manufacturing Processes 24 p1423