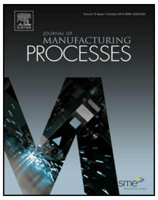
Journal of Manufacturing Processes 29 (2017) 320–331

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro



Research paper

Wear mechanisms and performance of abrasively ground polycrystalline diamond tools of different diamond grains in machining titanium alloy

Guangxian Li[a,*], Shuang Yi[a], Shoujin Sun[b], Songlin Ding[a]

[a] School of Engineering, RMIT University, Mill Park 3082, Victoria, Australia
[b] Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

ARTICLE INFO

Article history:
Received 13 February 2017
Received in revised form 19 July 2017
Accepted 22 August 2017

Keywords:
Polycrystalline diamond (PCD)
Abrasive grinding
Wear mechanism
Flank wear
Crater wear
Chip analysis

ABSTRACT

Abrasive grinding, electrical discharge machining and laser machining are the three approaches to manufacture polycrystalline diamond (PCD) tools. However, the performance of PCD tools made by the three methods was found different. Customized PCD tools made of three different PCD materials were fabricated by abrasive grinding in this paper. Through a series of cutting experiments, cutting forces, cutting temperatures, morphological characteristics of wear areas on tool surface, and the geometric parameters of chips were analysed to investigate the wear mechanisms, cutting performance, as well as the effects of material structure. It was found that adhesive-abrasive process and chemical diffusion were the main mechanism of wear of PCD tools. However, the wear processes of the three tools were different due to the difference in material structures. PCD tools made of uniformly sized diamond grains wear in a steady "spalling process". In contrast, PCD tools made of mix-size diamond grains suffered from large-scale fracture at the tool tip. The shapes of chips and the related geometric parameters reflected different wear processes. Chip shapes changed from spiral to strip with the growing of crater wear, segment chips were generated because of the change of tool geometry caused by the fracture of the tool tip.

1. Introduction

Titanium alloys are difficult to machine due to their low thermal conductivity (7 W/m.K) and high chemical reactivity [1]. Severe cutting conditions including high temperature and highly abrasive interaction at tool/chip and tool/workpiece interfaces significantly accelerate the rate of tool wear, which adversely affect tool life, cause premature tool failure, and eventually lead to very low cutting efficiency [2]. The cutting speed recommended in industry for the turning of Ti6Al4 V with tungsten carbide (WC) tools, which is 60 m/min, results in an extremely low material removal rate [3]. When applied in high speed cutting (larger than 100 m/min), the life of WC tools decreases dramatically to as short as a few minutes. Owing to the ultra-hardness and excellent thermal-conductivity, polycrystalline diamond (PCD) has been gradually used as an advanced tool material in cutting titanium alloys. The hardness of PCD which is about two times of that of polycrystalline cubic boron nitride (PCBN) ensures the high abrasive wear resistance of the tool. Its high thermal-conductivity which is five times of that of WC reduces the accumulation of heat around the cutting edge and makes it the most promising tool material for machining titanium alloys [4]. According to experimental results [5], PCD tools have much longer tool life in comparison with WC tools in machining Ti6Al4 V at high cutting speeds (over 200 m/min).

In machining titanium alloys with PCD tools, particularly in the milling process, chipping and fracture are often found on the cutting edges [6]. According to Amin et al. [7] the fracture of tool nose, abrasion on flank face and notching along the cutting edge were the main wear types found on the surface of PCD tools in milling Ti6Al4 V. Su et al. [8] conducted a milling experiment of TA15 using PCD end mills with the cutting speed of 350 m/min. They found that the reduced yield strength of PCD tool caused by high cutting temperature in combination with the dynamic shock on the cutting tools led to the acceleration of crater wear and flank wear. In the high speed milling of Ti6Al4 V conducted by Li et al. [9], the cutting speed was increased to 375 m/min, which is the upper limit of the speed a PCD tool can withstand. The large scale of spalling found on both flank face and rake face of the tools indicated that

---

* Corresponding author.
E-mail addresses: s3516088@student.rmit.edu.au (G. Li), s3516088@student.rmit.edu.au (S. Yi), ssun@swin.edu.au (S. Sun), songlin.ding@rmit.edu.au (S. Ding).

http://dx.doi.org/10.1016/j.jmapro.2017.08.010

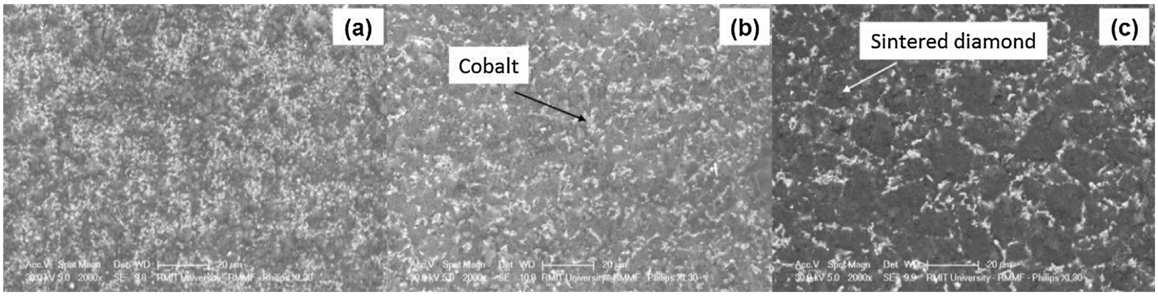


Fig. 1. Raw PCD materials (a) CTB002 (b) CTB010 (c) CTM302.

Table 1
Basic properties of PCD tool materials [21].

Material	CTB002	CTB010	CTB302
Grain size (μm)	2	10	2 to 30
Binder material	cobalt	cobalt	cobalt
Diamond fraction (%)	84.8/68.6	89.7/77.4	91.4/80.6
Density (g/mm^3)	4.35	4.08	3.99
Young's modulus (GPa)	883	1000	901
Poisson's ratio	0.1	0.1	0.11
Hardness (GPa)	50	50	50

Table 2
Sharpness and roughness after grinding.

Material	CTB002	CTB010	CTM302
Sharpness (μm)	5.42	5.92	6.48
Roughness (nm)	111	121	129

the structure of PCD became extremely unstable under such a high cutting speed and the high frequency change of cutting forces. As for the turning process, its main difference from milling is that the influence of heat generated by the continuous cutting is more significant although the dynamic force exerted on tool surfaces are not as severe as those in the interrupted cutting (milling) processes. Results of relevant experiments showed that, in addition to flank wear caused by the abrasion at tool/workpiece interface, thermal activated wear including chemical diffusion and build-up edge also existed [10]. Based on the experiments on turning Ti6Al4 V with different cutting parameters, Silva et al. [11] concluded that severe crater wear and adhesion in the worn area could be attributed to the combination of attrition and diffusion-adhesion mechanism.

So far the research on wear mechanism of PCD material had been carried out in micro-scale. D. McNamara et al. conducted a series of experiments [12] to investigate the fracture toughness of PCD structure. Their results showed that the fracture toughness of PCD was affected by the size of diamond grains, status of secondary phase (binding material) and the residual stress after the sintering process. Cheng et al. [13] found that high cutting temperature reduced the cohesive energy of carbon and weakened the C-C bond of diamond, which reduced the strength of the microstructure within diamond grains. Some experiments have been conducted with the aim to investigate the stability of PCD microstructure in certain environments. Based on the results of a sliding wear test, Deng et al. [14] found that the friction behaviour of PCD changed with the increase of ambient temperature. The friction coefficient decreased and the development of micro-cracks along grain boundaries increased with the increase of temperature in the environment. According to the experiments conducted by Jaworska et al. [15], the thermal resistance of different PCD structures was influenced by the materials of secondary phase. Westraadt et al. investigated the thermal degradation of PCD properties when the temperature was up to 800 °C [16], and found that the conversion from diamond to graphite resulted in the formation of internal cracks. This was different from the hypothesis Deng et al. proposed that cracking was solely caused by thermal expansion and the extrusion of cobalt.

Abrasive grinding with diamond wheels, laser machining and electrical discharge machining are the three processes currently utilized in industry to machine PCD tools [17]. The core challenge in abrasive grinding is the hardness of diamond particles sintered in its structure which results in low machining efficiency. Laser machining of PCD is a new technology emerged in the last decade. Due to the large heat affect zone and large scale dislodgement of diamond particles caused by laser energy, its industrial application is constrained. Compared to laser machining, the area of heat affected zone in EDM can be much smaller because of the use of dielectric fluid and more importantly, the ability to control discharge energy in each single pulse in the machining process [18]. However, owing to the different machining theories, the quality, performance and wear mechanisms of PCD tools manufactured by these three methods are different [19,20].

The in-depth understanding of wear behaviour and mechanisms of PCD tools under different machining conditions is critical for the wide application of PCD tools in industry. In addition to residual stress and surface roughness, it is known that grain size and volume fraction of diamond in the PCD may have influences on the properties of PCD tools, which, in turn, will affect the wear mechanism of PCD tools. However, it is far from clear how these factors, or the structure of different PCD materials, will affect the development of tool wear, and to what extend the affection will be. The fundamental knowledge of the wear mechanism is critical for the wide application of PCD tools. In this paper, three types of tools made of different commercial PCD materials were machined by abrasive grinding. The wear resistance of PCD tools was investigated through turning titanium alloy Ti6Al4 V. Optimal grinding parameters were used to ensure the high quality of tool surfaces. Tool materials and turning parameters were selected according to the industry practice for turning titanium alloy. Different mechanisms of tool wear as well as the performance of PCD tools made of different materials were investigated by analysing the variation of cutting force, roughness of machined surface, morphology of worn areas, and geometric characteristics of the chips.

2. Experiment

2.1. Preparation of cutting tools

Three types of PCD materials (CTB002 (Fig. 1a), CTB010 (Fig. 1b) and CTM302 (Fig. 1c)), manufactured by Element Six were used. These PCD materials were sintered with different-sized diamond grains and pre-defined volume percentages of cobalt powder, the basic physical and mechanical properties of each material are listed in Table 1.