Diamond & Related Materials 54 (2015) 79–90

Contents lists available at ScienceDirect

Diamond & Related Materials

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

Optimization of diamond coated microdrills in aluminum alloy 7075 machining: A case study

Xuelin Lei, Bin Shen, Fanghong Sun *

School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China

ARTICLE INFO

Available online 12 November 2014

Keywords:
Aluminum alloy
NCD
Microdrill
Tribological property
Cutting performance

ABSTRACT

Aluminum alloy 7075 is widely used for producing micro-scale heat sinks, micro-fluidic devices, micro-propellers and so on. This paper deals with optimizing microstructure and thickness of diamond coatings on microdrills used in 7075 aluminum alloy machining. Firstly, the friction tests between microcrystalline diamond (MCD), nanocrystalline diamond (NCD) films and aluminum alloy reveal that the stable coefficient of friction (COF) of MCD–aluminum alloy working pair is 0.240, much higher than that of NCD–aluminum alloy working pair (0.072). The decrease of COF is mainly attributed to the lower roughness of NCD films and the presence of more graphite or the non-diamond phases in NCD coatings. Afterwards, comparative cutting tests involving MCD, NCD, diamond-like coating (DLC) and TiAlN coated microdrills show that after drilling 200 holes, NCD coated microdrills exhibit the best cutting performance. Furthermore, NCD coated microdrills with coating thicknesses of 1 μm, 2 μm, 4.5 μm and 7 μm are fabricated and their cutting performance is studied in aluminum alloy machining. The cutting experiments show that the NCD coated microdrill with coating thickness of 4.5 μm shows the best cutting performance, exhibiting not only lowest flank wear and no tool tipping or chipping on the main cutting edges but also the highest quality of drilled holes because of the outstanding adhesive strength and wear resistance of the NCD coating.

1. Introduction

Aluminum alloy 7075 is the typical Al–Zn–Mg–Cu series high-strength alloy, which is widely used for producing micro-scale heat sinks, micro-fluidic devices, micro-propellers and so on, due to its outstanding strength-to-density ratio, good chemical resistance, and relatively low densities. However, this aluminum alloy is difficult to be machined due to its unique adhesive and abrasive properties. Consequently, many researches have been focused on the cutting parameter and machining process optimization with the aim at high efficient machining of aluminum alloy 7075. Rao et al. have compared the cutting mechanisms of tungsten cemented carbide (WC–Co) and polycrystalline diamond (PCD) cutters in aluminum alloy 7075 machining by finite element method and cutting tests [1]. Then, Davim et al. found PCD cutters exhibit better cutting performance compared with WC–Co ones [2]. Bhushan and Anuar et al. have studied the effect of cutting speed, feed rate as well as cutting depth on the work piece surface roughness and tool wear during aluminum alloy machining, then these cutting parameters are optimized [3–5].

Besides optimizing cutting parameters, coating thin diamond films may be another effective way to enhance cutting performance of cutting tools in aluminum alloy machining due to the high hardness and excellent wear resistance of diamond films [6,7]. Furthermore, the diamond surface has intrinsically low affinity for aluminum at the atomic scale [8]. The low adhesion between diamond films and aluminum alloy is helpful for preventing chips from adhering to the flute surfaces and further postponing the formation of build-up edges on the cutting tools [9]. Previous studies have shown that the working life of diamond coated cutting tools indicates a several fold increase in aluminum work pieces when compared with uncoated ones [10,11].

Nevertheless, the cutting performance of diamond coated tools in aluminum alloy machining is far from satisfaction due to the detachment of diamond films [12,13]. Consequently, some researches have been focused on improving the substrate–diamond film adhesion in ways of optimizing substrate grain size, surface pretreatment, deposition parameters as well as cutting edge shapes [14,15]. Besides, the course diamond films are found to be not suitable for aluminum alloy machining due to the high cutting forces and accumulation of work piece material on the cutting tools [16]. Polishing the diamond films has been proved to be an effective way to improve the cutting performance of diamond coated inserts [13]. So it is supposed that for cutting tools with complicated shapes, directly depositing diamond films with low surface roughness may be helpful for the cutting performance improvement in aluminum alloy machining.

Meanwhile, the diamond film thickness should not be neglected as the coating thickness affects the characteristics of diamond coated cutting tools in different perspectives that may mutually impact the

* Corresponding author.
E-mail address: sunfanghong@sjtu.edu.cn (F. Sun).

http://dx.doi.org/10.1016/j.diamond.2014.11.003
0925-9635/

tool performance in machining in a complex way [17]. When machining the specific work piece, Haubner et al. show that there exists an optimized diamond coating thickness region on the cutting tools [18], while some researchers find that the life of diamond coated tools increases with the coating thickness [19,20]. For micro-cutting tools, the effect of coating thickness on their cutting performance may be more significant due to the small cutting edge radius of micro-cutting tools. Therefore, the diamond coating thickness on microdrills should be further investigated and understood.

In the present study, at first, in order to optimize the final performance of diamond coated tools during dry machining operations, the resulting tribological interface at the cutting edges between diamond films and aluminum alloy 7075 is studied by the friction tests to reveal the fundamental wear mechanisms. Thereafter, the microdrilling tests are conducted to optimize the diamond coated microdrills step by step in two aspects: the coating type and the coating thickness. The systematic comparison in terms of the wear of microdrills, the average feed force, and the quality of drilled holes is conducted to finally obtain the optimized diamond coating on microdrill in aluminum alloy 7075 machining.

2. Experimental procedure

The cemented tungsten carbide balls (4 mm diameter) and microdrills (Tungaloy Inc.) are used as substrates for diamond deposition in this study. The detailed geometry parameters of microdrills are shown in Table 1. Before diamond film deposition process, two-step chemical pretreatments, using a combination of Murakami reagent ($KOH:K_3(Fe(CN)_6):H_2O = 1:1:10$) and acid etching in $HCl + H_2O_2$, are adopted to roughen the substrate surface and etch cobalt in order to facilitate the nucleation and growth of diamond films. Thereafter, MCD and NCD films are deposited on balls and microdrills in a homemade hot filament chemical vapor deposition (HFCVD) apparatus using acetone and hydrogen as the reactant sources under the deposition parameters as shown in Table 2 [21,22]. The liquid acetone is introduced into the reactor by part of the hydrogen. In order to obtain constant saturated vapor pressure of acetone in the hydrogen, the temperature of acetone is maintained at 0 °C by immersing the containers in the glacial-aqueous mixed solution. The flow rate of hydrogen is controlled by the mass flow meters. The saturated vapor pressure of the acetone is 8.9 kPa when the temperature is 0 °C. Then the acetone concentration can be calculated by the ideal gas law. During the diamond deposition procedure, the temperature of hot filaments is measured by Raytek MR1SCSF Double-color Integrated Infrared Thermometer (range: 600 °C–3000 °C) and set as 2200 °C. The substrate temperatures are about 800–900 °C, which are measured by K type thermocouples (range: −200 °C to 1300 °C) with a diameter of 1.1 mm.

The surface topographies of as-deposited MCD and NCD films are captured by field emission scanning electron microscopy (FESEM, Zeiss Ultra_55). The ingredients and phase characterization of diamond films are examined by Raman spectroscopy (SPEC14-03), using a He–Ne laser with an excitation wavelength of 632.8 nm.

The tribotests are carried out using a ball-on-flat geometry contact with reciprocating motion on a friction testing machine (UMT-2, CETR Inc.). The working pairs are MCD–Al alloy, NCD–Al alloy and WC–Co–Al alloy, respectively. The normal load is fixed at 4.0 N and the reciprocating frequency is 8 Hz, which can provide an average sliding velocity of 128 mm/s for a friction stroke of 8 mm. The sliding tests are conducted in ambient air (R.H. 35%). After the tribotests, the 3D surface topographies of wear tracks are characterized by Phase Shift MicroXAM-3D from a 900 × 600 μm^2 scanning region. The section contours obtained from 3D surface topography are used to calculate the specific wear rates (K) of the flat specimens. The detailed morphology of worn surfaces is captured by FESEM. Besides, FESEM is used to measure the average diameter of the ball wear scars, as well as to study the wear modes on balls. The specific wear rates of the ball specimens are evaluated from the equation: $(\pi \times d^4) / (64 \times r \times W \times L)$, in which d is the diameter of the near circular wear scars on balls, r is the ball radius, W is the applied normal load, and L is the sliding distance [23]. The specific wear rates of flat specimens are calculated from the equation: $(S \times F) / (W \times L)$, where S is the sectional area of wear track, obtained from the cross-sectional wear profiles on worn diamond films, F is the friction stroke (8 mm). Then, Energy Dispersive Spectrometer (EDS) is adopted to estimate the chemical composition in the wear tracks.

The cutting performance of diamond coated microdrills in aluminum alloy machining is evaluated on a micro-machining center. The radial runout of the spindle (Dake Inc.) used is less than 3 μm. For the sake of comparison, diamond-like coating (DLC) and TiAlN film are also deposited on microdrills by physical vapor deposition (PVD) methods. The detailed cutting parameters in the microdrilling tests are illustrated in Table 3. A Kistler 9272 dynamometer is mounted under the work piece to measure the feed forces at vertical direction after drilling every 20 or 50 holes. After drilling every 20 or 50 holes, the optical microscopy (Keyence VHX-500F) is applied to detect the delamination of diamond films, the quality of drilled holes as well as the flank wear of main cutting edges. After cutting experiments, the microdrills are ultrasonic cleaned to reveal the worn flank faces.

3. Results and discussion

3.1. Tribological properties between diamond films and aluminum alloy

Fig. 1 shows the surface morphologies of MCD and NCD coated and uncoated WC–Co balls. It is observed that MCD and NCD films are uniformly deposited on WC–Co balls. The diamond grain size in MCD

Table 1
The detailed geometry parameters of microdrills.

Tool geometry	Values
Diameter of drill body	0.4 mm
Body length	5 mm
Helix angle	35°
Number of flutes	2
Cutting edge radius	2 μm
Tool rake angle	10°
Flank angle	8°
Web thickness	0.15 mm
Tip angle	120°
Diameter of tool shank	3.175 mm
Length of drill	38 mm

Table 2
The detailed nucleation and growth parameters for MCD and NCD films.

	MCD		NCD	
	Nucleation	Growth	Nucleation	Growth
Hydrogen flow rate [sccm]	800	800	800	800
Acetone concentration [%]	3	2.7	3	0.9
Pressure [Pa]	1500	3500	1500	1000
Filament temperature [°C]	2200 ± 50	2200 ± 50	2200 ± 50	2200 ± 50
Substrate temperature [°C]	850–900	800–850	850–900	870–920
Filament diameter [mm]	0.4	0.4	0.4	0.4

Table 3
The detailed cutting parameters in the microdrilling tests.

Cutting parameters	Values
Spindle speed [r/min]	70,000
Feed rate [mm/s]	3.5
Cutting velocity [mm/s]	0–1465
Feed per tooth [μm]	15