International Journal of Machine Tools & Manufacture 65 (2013) 99–106

Contents lists available at SciVerse ScienceDirect

International Journal of Machine Tools & Manufacture

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

Micro-cutting characteristics of EDM fabricated high-precision polycrystalline diamond tools

Zhiyu Zhang [a,b], Huanming Peng [b], Jiwang Yan [c,*]

[a] Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Science, Dongnanhu Road 3888, Changchun, Jilin 130025, China
[b] Department of Mechanical Systems and Design, Graduate School of Engineering, Tohoku University, Aramaki Aoba 6-6-01, Aoba-ku, Sendai 980-8579, Japan
[c] Department of Mechanical Engineering, Faculty of Science and Technology, Keio University, Hiyoshi 3-14-1, Kohoku-ku, Yokohama 223-8522, Japan

ARTICLE INFO

Article history:
Received 8 July 2012
Received in revised form
25 October 2012
Accepted 29 October 2012
Available online 6 November 2012

Keywords:
Micro cutting
Micro end mill
Polycrystalline diamond
Electro discharge machining
Structured surface
Mold fabrication

ABSTRACT

To fabricate three-dimensional microstructures, such as micro dimples, micro grooves and micro channels, on ceramic mold materials, tool fabrication with super hard materials is an essential step. In this work, micro electro discharge machining (EDM) was used to fabricate high-precision polycrystalline diamond end mills. Form accuracy and edge sharpness in one micron level were achieved by utilizing electro discharge induced graphitization of diamond grains under extremely low discharge energy conditions. The cutting performance of the fabricated tools was examined by machining micro dimples and micro grooves on tungsten carbide mold substrates. Results showed that using the EDM-fabricated tools, ductile mode machining of tungsten carbide was realized with a surface finish of 2 nm R_a, which is comparable to that produced by polishing.

1. Introduction

In recent years, there is an increasing demand for manufacturing large-area surface microstructures, such as micro groove arrays, micro pyramid arrays, and micro lens arrays. These microstructured surfaces can be used in optical communication devises, flat panel displays, light emitting diode applications, and so on [1,2]. For example, a micro lens array with lens diameter of several tens micrometers can increase 15% of luminance in the backlighting module of liquid crystal displays [3]. Micro lens array with lens diameter of several hundred micrometers is used in the Shack–Hartmann wavefront sensor to divide the wavefront surface into a number of beamlets [4].

Microstructures on semiconductor substrates can be manufactured by silicon-based micro machining methods such as photolithography and etching technology [5]. As for viscoelastic materials, replication techniques, such as plastic injection molding and glass molding press, are effective for microstructure fabrication. In the replication processes, the fabrication of precision molding dies is a crucial issue. Tungsten carbide (WC) is a commonly used die material for molding glass aspherical lenses, although the precision micro machining of WC is still challenging. Ultrasonic vibration assisted diamond cutting has been attempted to machine microstructures on WC, but there are a few limitations such as low machining speed and vibration-induced surface texture changes [6].

An alternative method is the use of micro end milling, which has been widely used in machining microstructures and curved surfaces on metals [7,8]. However, most of the previously used end mills were made of WC [9–11], which cannot be applied to the machining of WC molding dies. Single crystalline diamond end mill has been recently attempted for generating microstructures, but when machining super hard materials, like silicon carbide, cleavage-induced edge chippings and flank wear occur [12]. From this aspect, polycrystalline diamond (PCD) might be better than single crystalline diamond as the tool material for machining WC molds.

However, the fabrication of PCD micro end mills is extremely difficult due to the material's high strength and high hardness. Conventional tool fabrication methods, such as grinding and polishing, are not applicable because of extremely low material removal rate, long processing time, as well as rapid wear of the grinding wheels and polishing heads [13]. As a recently focused method, electro discharge machining (EDM) provides an effective way to micro tool fabrication. EDM is a noncontact process without problems of mechanical stress, tool bending/breaking and chattering [14,15]. EDM has been used for producing WC micro end mills [16–21]. For example, Fleischer et al. fabricated a WC end mill with a diameter of 100 μm by using wire EDM [19], and Yan et al. fabricated WC micro end mills with 50 μm

* Corresponding author. Tel.: +81 45 566 1445; fax: +81 45 566 1995.
E-mail address: yan@mech.keio.ac.jp (J. Yan).

0890-6955/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijmachtools.2012.10.007

diameter [20]. Egashira et al. reported the EDM fabrication of a WC tool with a diameter of 3 μm for micro drilling [21].

EDM fabrication of PCD tools has also been reported. For example, Masaki et al. fabricated a spherical PCD grinding tool (radius 800 μm) for glass micro grinding [22]. Minami et al. fabricated a semi-cylindrical PCD tool with a diameter of 60 μm by EDM [23]. These studies have demonstrated the feasibility of shaping PCD tools by using micro EDM. However, little attention has been paid on tool precision. Normally, an EDM fabricated tool has low form accuracy, a rough surface finish and a dull edge due to the electro discharge-induced crater generation. To date, the cutting performance of an EDM fabricated tool has not yet been experimentally confirmed.

In this work, we explore the feasibility of fabricating high-precision micro PCD end mills by minimizing the crater size in micro EDM. In previous works, electro discharge pulse duration has been used as a controlling parameter for improving tool surface quality [23]. In this work, we use electro discharge energy to control material removal mechanism of PCD and to achieve high tool accuracy and edge sharpness. The cutting performance of the EDM fabricated PCD end mill was then examined by generating micro dimples and micro grooves on WC mold substrates.

2. Experiments

2.1. EDM fabrication of PCD end mills

2.1.1. Tool shape

To generate micro dimples for lens array applications, in the present work, single flute spherical micro end mill was considered. The rake face of the end mill is a flat surface (nominal rake angle 0°), and flank face is a hemispherical surface (nominal relief angle 0°). When using the tool for machining, hybrid effects maybe expected: one is cutting effect by the rake face, and the other is grinding effect by the diamond grains on the flank face. The former takes place at a large depth of cut (for rough machining) while the latter is dominant at a small depth of cut (for fine finishing).

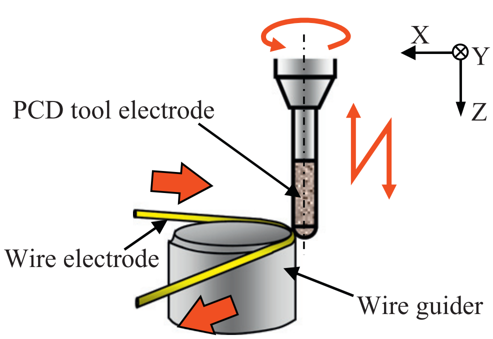

Fig. 1. Schematic of tool shape generation.

Fig. 1 schematically shows shape generation method for end mills by wire EDM. The wire electrode is fed continuously by a wire guider, while the PCD tool electrode is kept rotating and feeding along the *X* and *Z* directions. As electro discharges occur at an extremely small area between the wire and the PCD tool, high-precision shape formation can be realized.

2.1.2. EDM machine

Tool fabrication was performed by using a precision micro EDM machine, Panasonic MG-ED82W, which enables wire electro discharge grinding (WEDG) [17]. Fig. 2 shows a photograph of the main part of the machine. A PCD rod is clamped by a cylindrical mandrel which is supported by two V-type ceramic bearings on *Z*-axis table. This clamping mechanism is designed to minimize decentering errors caused by mounting and detaching of the tool electrode. The mandrel is driven by a DC motor at a rotation rate of 3000 rpm. A steel ball, rather than a motor brush, is used for providing an electrical connection between the mandrel and the electro discharge circuit.

Resistor-capacitor (RC) discharge circuit, as schematically shown in Fig. 3, is used in the machine. The discharging energy

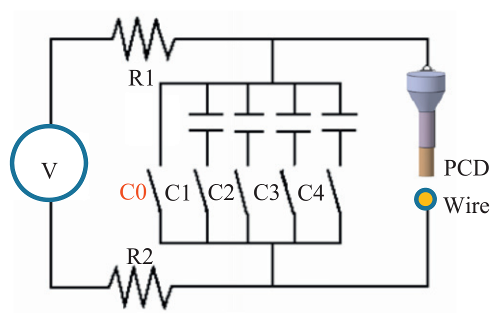

Fig. 3. Schematic of RC circuit for micro EDM.

Table 1
Experimental conditions for fabrication of PCD end mill.

Tool electrode material	Poly crystalline diamond		
Tool electrode rotation [rpm]	3000		
Wire electrode material	Brass		
Wire electrode diameter [μm]	100		
Voltage [V]	−110	−80	−70
Condenser capacitance [pF]	3300	10	1

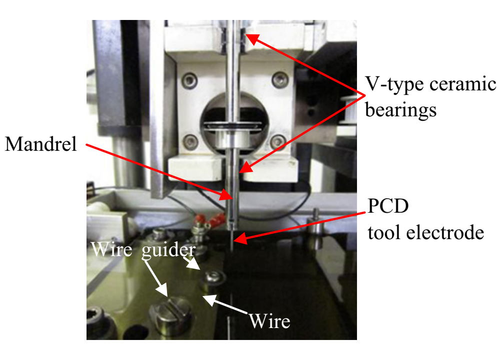

Fig. 2. Photograph of EDM setup.

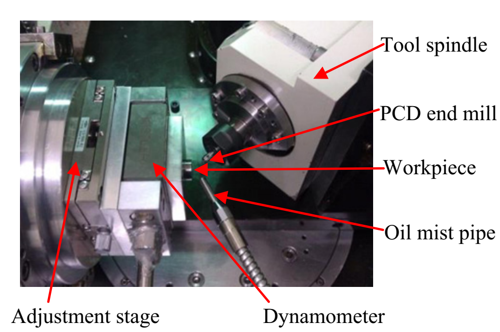

Fig. 4. Experimental setups used for micro end milling.