CIRP Annals - Manufacturing Technology 65 (2016) 105–108

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

The influences of pulsed-laser-ablation and electro-discharge-grinding processes on the cutting performances of polycrystalline diamond micro-drills

Paul Butler-Smith [a], Maximilian Warhanek [b], Dragos Axinte (1)[a,*], Michael Fay [a], Jean-Francois Bucourt [c], Raphael Ragueneau [c], Konrad Wegener (2)[b]

[a] Faculty of Engineering, Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, NG7 2RD, United Kingdom
[b] ETH Zürich, IWF, LEE L214, Leonhardstrasse 21, 8092 Zürich, Switzerland
[c] Diamoutils SAS, 32 Rue Adrastée, 74650 Chavanod, France Submitted by D. Axinte

ARTICLE INFO

Keywords:
Drilling
Laser-beam-machining
Electrical-discharge-machining

ABSTRACT

Geometrically complex micro-tools are manufactured via processes which can affect their cutting performances. This paper studies the effects pulsed-laser-ablation and electro-discharge-grinding on polycrystalline diamond matrices and their binder phases at nanometric scales, revealing distinct differences in the resulting substructures. The dissimilarities in micro-scale material removal phenomena of these manufacturing processes combined with their effects on the generated surface topographies and cutting-edge geometries can significantly influence the wear and cutting performance of micro-drills. A study on the micro-drilling of a ceramic matrix composite workpiece material confirms that pulsed-laser-ablation of composite diamond structures offers a step-change in the fabrication of micro-tools.

1. Introduction to PCD tools

Some critical performance components for aerospace and other high demanding applications frequently demand the machining of micro-features (holes, slots <2 mm) in difficult-to-cut materials such as Metal Matrix or Ceramic Matrix Composites (MMCs, CMCs). Such applications challenge the performance of the cutting tools employed in the machining processes to achieve geometric conformance of the required shapes/features while also needing to comply with the requirements on structural integrity of the workpiece material.

Polycrystalline diamond (PCD) has become well established as a cutting tool material for a wide range of applications, offering performance advantages and durability over most alternative tool materials [1]. The PCD structure principally consists of a sintered matrix of intergrown diamond grains supported by a carbon reactive catalyst/binder phase (e.g. Co, Fe, W) which enhances its fracture toughness up to 8.8 MN m$^{-3/2}$ [2] and provides electrical conductivity to support electro-discharge processing.

While conventional (diamond abrasive) grinding can readily be employed for the processing of larger tools with geometrically defined cutting edges, i.e. where sufficient material structure exists to support the produced grinding forces, this process is not normally suitable for the production of PCD micro tools. This is particularly the case for micro drills having long slender profiles that require alternative (non-contact) processing techniques [3]. Furthermore the mechanical grinding process can be limited in achieving complex geometries due to access restrictions defined by the overall tool geometries.

1.1. EDM and PLA manufacturing process

Electro-discharge machining (EDM) processes (cutting, drilling, grinding), utilise an electrically induced plasma which occurs in a gap between an electrode and an electrically conductive workpiece in the presence of a dielectric fluid [4,5]. In the case of PCD, the EDM processes rely on preferential conductive paths offered by the metallic binder phase, creating a plasma with sufficient energy to effect localised evaporation of the metal phase and a physical state change of neighbouring diamond to graphite (3652 °C) and an ensuing vapor phase (4200 °C) [6], thereby removing both the primary composite material components [7]. Micro EDM has been successfully employed for the generation of complex geometries for PCD micro tools. In particular, electro discharge grinding (EDG) offers the possibility of producing the required geometries (e.g. cutting edges, flutes) in rotary PCD micro-tools [8], within the geometric limitations of the electrode wheel.

Pulse laser ablation (PLA) offers an attractive alternative for micro tool fabrication with the benefit of being able to process both electrically non-electrically conductive diamond [9,10] as well as composite diamond structures. As a result of short-pulsed (nanosecond/picosecond) laser irradiation of PCD, a shallow heat affected zone is produced below the ablated surface, consisting of an amorphous carbon layer and a graphitic layer [11]. Within this

* Corresponding author.
E-mail address: dragos.axinte@nottingham.ac.uk (D. Axinte).

http://dx.doi.org/10.1016/j.cirp.2016.04.008
0007-8506/© 2016 CIRP.

zone, the binders produce thin elongated bands during evaporation as a result of a reaction with the surrounding carbon. Importantly the phase change from diamond to graphite is stable, which means that the graphitised layer in heat affected region forms a well defined boundary with unaffected diamond in the material substructure [12].

1.2. PCD cutting edge wear

Mechanical wear on the cutting edge of a polycrystalline structure of PCD for a given set of operating conditions, as would be experienced in drilling, primarily depends on factors such as the degree of diamond grain intergrowth and the support provided by the catalyst/binder. Specific fracture modes have been identified in PCD structures in cutting of silicon reinforced wood composites [13]; trans-granular fracture propagates through the diamond grains while inter-granular fracture propagates through the intergrowth boundaries between the diamond grains. In the former case some micro fracture of individual grains could precede macro fracture or chipping of the cutting edge whereas in the latter case, individual or multi grain loss could preferentially occur due to the weaker intergrowth boundaries. Such fracturing leads to increased drilling forces, hole edge degradation and material delamination in the drilling of composite materials [14].

The process by which the tool is prepared can also influence specific wear modes of the PCD. It is of the Authors' knowledge that no studies have been reported to date on the influences of EDG and PLA processes on the cutting edge wear of PCD micro drills, particularly relating to the material's substructure. This paper presents the effects of these processes on the PCD substructure at nanometric resolutions and the influence of drilling micro cutting edge performance and wear.

2. Micro drill assessments

2.1. Drill fabrication by EDG/PLA and performance evaluations

The PCD grade selected for the tools was the Element Six A3DP consisting of a 5 μm nominal grain size and binder/catalyst of predominantly Cobalt (circa 7% vol.), This material is supplied as a 5 mm thick PCD layer sintered directly onto a tungsten carbide substrate, allowing the drill's cutting edge and full flute geometry (point angle 137°, notched centre, helix angle 30°, primary clearance angle 13°, secondary clearance angle 30°) of the considered design to be produced in the PCD material and providing a sufficient thickness of tungsten carbide backing for the drill stem. Round blanks were initially EDM wire cut from a PCD disc and mechanically ground to achieve a blank diameter of 1.78 mm. The blanks were subsequently vacuum brazed into a drill shank for spindle mounting.

Several PCD micro drills were produced using an EDG process on a Vollmer QXD200 machine employing the following parameters; pulse energy 10 mWs, pulse frequency 5 kHz, voltage 180 V, electrode wheel Cu25%/W75% using a multi pass process.

A modified EWAG Laser Line ULTRA machine was used to generate the equivalent PCD micro drill geometries to those produced with the EDG process. The following parameters are applied with a tangential laser process: wavelength 1064 nm, fluence 6.7 J cm^{-2}, pulse frequency 800 kHz, pulse duration <12 ps.

Comparative drilling tests were carried out using a Hurco BMC30 CNC milling/drilling machine. Drilling feed force was measured periodically using a SPIKE Promicron spindle mounted wireless cutting tool dynamometer (sampling rate: 1.6 kHz, axial force resolution: 0.5 N). The selected workpiece material was an aerospace grade development CMC flat plate of 3.2 mm thick containing silicon fibres (nominal diameter 8 μm) in a silicon matrix impregnated with iron particles (nominal size 20 μm). Drilling test parameters were selected (cutting speed: $V_c = 45$ m min^{-1}, feed speed: $V_f = 480$ mm min^{-1}) to produce defined hole edges and uniform hole surface quality. The PCD micro drills were inspected after every 50 holes produced and the tests terminated after cutting edge wear was detected. All drilling was carried out in dry conditions.

SEM micrographs (Philips XL30) were taken of the tools' cutting edges and measurements were made of the profiles (Alicona G5) of unused EDG and PLA produced PCD drills and after drilling 300 holes in the CMC test material. Using a 20× lens objective, the average cutting edge radius was measured employing Alicona's robust least square fitting algorithm with a vertical resolution: 0.1 μm, and a lateral sampling resolution: 0.5 μm for a measured length of 0.2 mm along each cutting edge (Table 1).

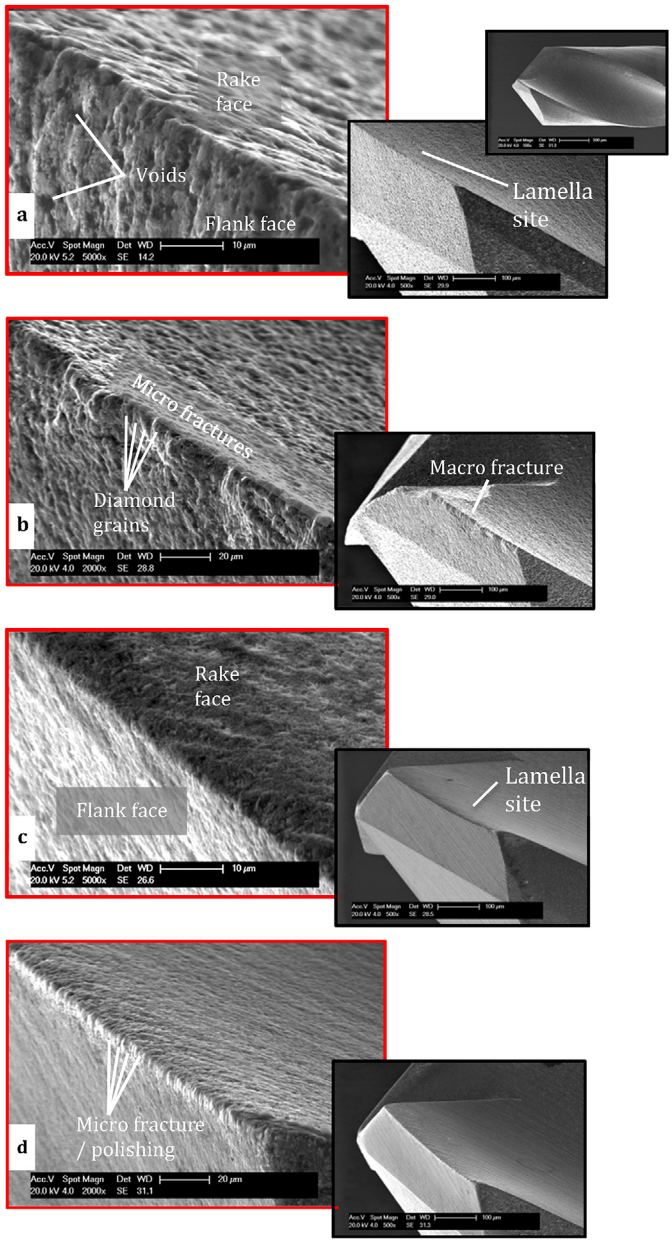

Fig. 1. Drill cutting edges of (a) unused EDG produced, (b) worn EDG produced, (c) unused PLA produced and (d) worn PLA produced PCD drills.

Table 1
PLA and EDG generated drill flute surface finishes and cutting edge radii.

Drill generation processes – edge condition	Flute surface roughness Ra (μm)	Average cutting edge radius (μm)
EDG – new	0.72	5.5
EDG – worn		10.8
PLA – new	0.16	9.5
PLA – worn		10.2