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# Micro- and nano-crystalline CVD diamond coated tools in the turning of EDM graphite

F.A. Almeida [a,*], J. Sacramento [b,c], F.J. Oliveira [a], R.F. Silva [a]

[a] Ceramics Eng. Department, CICECO, University of Aveiro, 3810-193, Aveiro, Portugal
[b] High School of Technology and Management, Apartado 473, 3754-909, Águeda, Portugal
[c] Durit S.A., Albergaria-a-Velha, Portugal

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ABSTRACT

Electrical discharge machining is a widely used technique, namely in metal mould shaping. High quality EDM graphite is the foremost choice as electrode material but the random oriented graphite aggregates cause an abrasive action over the tools used in its machining. Wear-resistant diamond tools were then chosen as an adequate option to guarantee tight tolerances and good surface finishing. In this work, microcrystalline and nanocrystalline CVD diamond coated inserts are used in turning operations. Cutting forces were always very low (<20 N) as also was the tool wear. An important result is the absence of diamond film delamination showing the high adhesion level offered by the silicon nitride ceramic substrates for CVD diamond coating. The smoother nanocrystalline coatings allowed to obtain a better workpiece surface roughness than the microcrystalline ones.



## 1. Introduction

Electrical discharge machining (EDM) is used to shape high-performance, intricate and accurate parts in leading aeronautical, automotive and moulds manufacturing companies. Graphite is the most widely used material for EDM electrodes due to its low cost and especially because of its high temperature resistance in the spark arc when compared, for instance, with copper [1]. High quality EDM graphite is fine grained and has low porosity content. The different C–C bond strength in the basal planes and between adjacent layers confers to graphite anisotropic mechanical and electrical properties, namely a considerable high strength and electrical conductivity in the basal plane [2]. An important consequence of the strong variation of mechanical strength with direction is the difficult machinability of graphite. In graphite machining, the random oriented graphite aggregates lead to a very abrasive powdery chip. This feature explains why diamond tools became the best solution for this application. The first option was the polycrystalline diamond (PCD) grade: the benefits of using PCD inserts comparing to conventional cemented carbide ones in turning of graphite were proved at high cutting speeds, such as 500 $m\cdot min^{-1}$, where the tool life increased almost three-fold [3]. However, the graphite debris created by machining abrade the cobalt binding phase of the PCD tools, leading to diamond particles loosening and, consequently, tool wear. An advanced solution is the use of binderless CVD diamond coatings. A tool-life gain of more than 10 times was reported in milling operations with CVD diamond cemented carbide coated tools, compared to uncoated ones [4]. An EDM graphite producer reported an improved life of 25 to 30 times of diamond coated cemented carbides tools comparing to TiN-coated ones in turning operations [5]. An impressive gain of 242% in cost per graphite part produced is estimated by Myers [6] in an economic comparison projection between CVD diamond coated and uncoated cemented carbide end mills. In the same work, a few examples of parts machining, like EDM electrodes milling for making injection molds, attested the real benefit of CVD diamond showing 15 times gains in tool life and tight accuracies.

This work consists of the evaluation of the cutting performance of hot filament CVD diamond coated silicon nitride ($Si_3N_4$) ceramic tools in turning of EDM graphite. This substrate is potentially one of the most suitable substrate materials for diamond deposition owing to their close thermal expansion coefficients and chemical compatibility [7]. The influence of cutting parameters (cutting speed: 200 to 800 m $min^{-1}$ and feed: up to 0.2 mm $rev^{-1}$) on the cutting forces and tool wear were evaluated for different cutting tool geometries (round and triangle cutting tips) and different CVD diamond coatings (micro- and nano-crystallite sizes).

## 2. Experimental procedure

The $Si_3N_4$ ceramic cutting tools were fully densified by pressureless sintering at a dwelling temperature of 1750 °C; for 2 h, in an atmosphere of 0.1 MPa $N_2$, using aluminium and yttrium oxides as densification additives. The weight percentages were: 89.3% $\alpha$–$Si_3N_4$ (Starck grade M11), 7.0% $Y_2O_3$ (Starck grade C) and 3.7% $Al_2O_3$ (CT-3000SG, Alcoa). The

* Corresponding author. Fax: +351 234 425300.
*E-mail address:* falmeida@ua.pt (F.A. Almeida).

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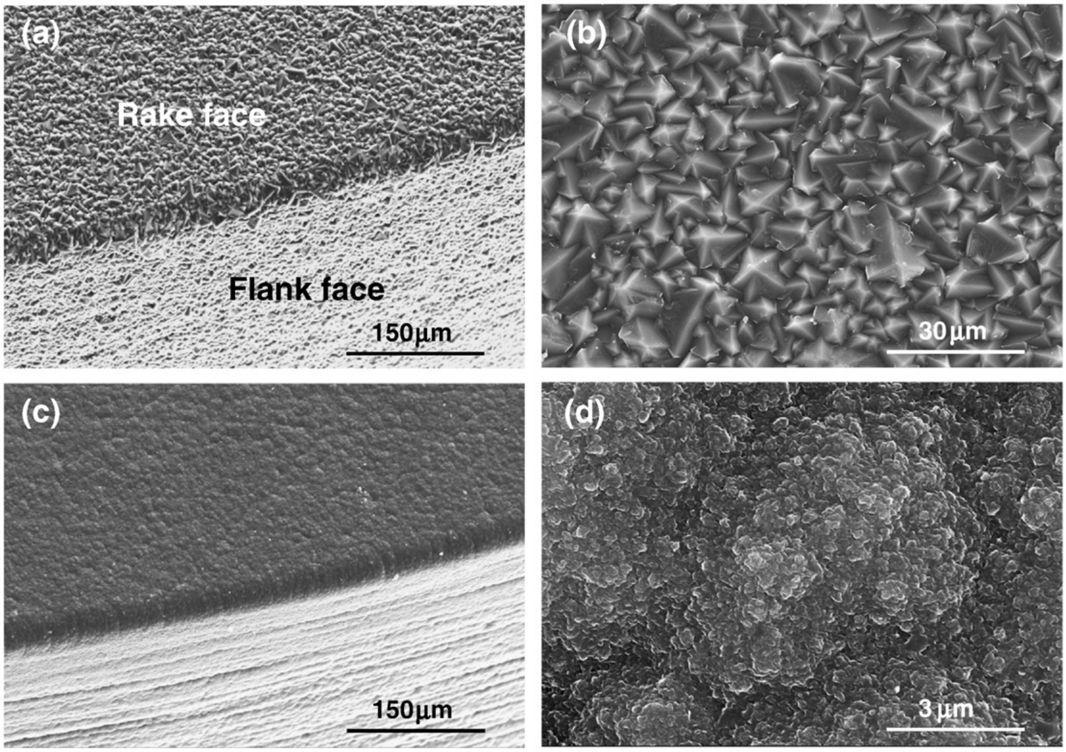


**Fig. 1.** (a) and (c) SEM micrographs of the cutting edge of the MCD and NCD diamond coated tools, respectively; (b) and (d) respective microstructure of the diamond film at the rake face.

sintered ceramic parts were ground to standard normalized geometries of round (RNMN1003 M0FN) and triangle (TNMN160308FN) shaped inserts. The rake face was lapped with 15 µm diamond slurry in an iron/polymer plate, followed by dry etching with $CF_4$ plasma for a controlled micro-roughening purpose. Before diamond deposition, the ceramic inserts were ultrasonically seeded in a *n*-hexane suspension of diamond powder (0.5–1 µm).

Micro- (MCD) and nano-(NCD) crystalline diamond depositions were made in a hot filament chemical vapour deposition (HFCVD) reactor, using 4 straight and parallel tungsten wires as gas activators. The deposition parameters were: filament temperature ~2300 °C; substrate temperature = 850 °C; total pressure = 2.5 kPa; total gas flow = 100 sccm. To deposit MCD diamond, a volume ratio of 0.02 ($CH_4/H_2$) was used, while in the case of NCD, this ratio was 0.03. SEM micrograph on Fig. 1(a) and (c) show the edges of MCD and NCD diamond coated tools, respectively, while Fig. 1b and d are the respective microstructure of the film at the rake face. The two diamond grades are easily discernible due to distinct diamond grain sizes. The film thickness of both diamond grades was 22 ± 2 µm and the rake face surface roughness Rq values were 0.55 µm, for the MCD grade, and 0.18 µm, for the NCD one.

Dry turning tests were performed in an industry facility, using a CNC lathe (Mori Seiki). The ISO code of the tool holders were as follows: CRSNR2525 M 06 and CTGNR2525 M 16. A three-axis piezoelectric dynamometer platform (Kistler 9257BA) was coupled into the lathe, where the tool holder is fixed. In this way, the signals were amplified in a Kistler 5011 apparatus and connected to a PC by coaxial cables and an acquisition board (PCMCIA, Keithley). The analogical signals of the main cutting force (Fc, in tangential direction to the bar), feed force (Ff, in axial direction) and depth-of-cut force (Fd, in radial direction) were converted and filtered in real time using dedicated software. The variable cutting parameters were the cutting speed (200–800 m $min^{-1}$) and feed (0.02–0.2 mm $rev^{-1}$), while the depth-of-cut was fixed to 0.5 mm. The overall set of performed tests is given in Table 1. The main resultant wear types, crater depth wear (KT) and flank wear (VB), were measured accordingly with the ISO 3685 standard [8]. KT was estimated by focus/de-focus procedure in an optical microscope, VB was measured from SEM micrographs.

The initial dimension of the EDM graphite cylindrical bar used in the turning tests was ∅85.46 mm × 113 mm. The density of the graphite workpiece was 1.88 g $cm^{-3}$, as measured by immersion in ethylene-glycol, and falls in the upper limit of the densities range available in the market (1.6–1.9 g $cm^{-3}$) [9,10]. Nominal mechanical characteristics are: shore hardness = 62; flexural strength = 80 MPa; compressive strength = 112.6 MPa. The grain size is about 10 µm. The ASTM D1762-84 standard [11] was used to determine moisture, volatile matter, ash content, and so the fixed carbon. The analysis of carbon content revealed the high purity of the workpiece, with a value

**Table 1**
Overall set parameters used in the graphite turning

| Coating | Geometry | $v$ (m $min^{-1}$) | $f$ (mm $rev^{-1}$) | $L$ (m) | $t$ (min) | $n$ (rpm) |
|---|---|---|---|---|---|---|
| MCD | | 200 | 0.02 | 1499 | 7.5 | 754 |
| | | 400 | | 1481 | 3.7 | 1526 |
| | | 600 | | 1464 | 2.4 | 2316 |
| | | 800 | | 1446 | 1.8 | 3126 |
| NCD | | 200 | | 1375 | 6.9 | 822 |
| | | 400 | | 1393 | 3.5 | 1623 |
| | Round | 600 | | 1410 | 2.4 | 2404 |
| | | 800 | | 1428 | 1.8 | 3165 |
| MCD | | | 0.05 | 394 | 1.0 | 2297 |
| | | | 0.1 | 193 | 0.5 | 2339 |
| | | 400 | 0.2 | 95 | 0.2 | 2383 |
| NCD | | | 0.05 | 415 | 1.0 | 2179 |
| | | | 0.1 | 204 | 0.5 | 2217 |
| | | | 0.2 | 100 | 0.2 | 2256 |
| MCD | | | | 1357 | 2.3 | 2498 |
| | Triangle | 600 | 0.02 | 10075[a] | 17.8[a] | 2832[a] |
| NCD | | | | 1339 | 2.2 | 2531 |
| | | | | 8936[a] | 14.9[a] | 3214[a] |

[a] Values corresponding to the long cutting tests after 8 passes. The spindle speed ($n$) is at the last pass.