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# From Micro to Nanometric Grain Size CVD Diamond Tools

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## ABSTRACT

CVD diamond coated tools are developed for applications as different as turning of cemented carbides and bone drilling. The diamond films are deposited by Hot Filament Chemical Vapor Deposition (HFCVD), with grain sizes varying from conventional micrometric (12 μm) to nanometric (< 100 nm) and film thickness up to 50 μm. Silicon nitride ($Si_3N_4$) ceramics are chosen for the base material in order to guarantee maximal adhesion. Both the micrometric and nanometric CVD diamond grades endure the cemented carbide turning showing slight cratering, having flank wear as the main wear mode. However, nanocrystalline diamond present the best behavior regarding cutting forces (<150 N) and tool wear (KM=30 μm, KT=2 μm and VB=110 μm) and workpiece surface finishing (Ra=0.2 μm). In the case of the dental drilling experiments, a polymeric laminated test block is used to simulate the human mandible and maxilla. The temperature rise during drilling is monitored to prevent overheating above 42-47 °C that is known to cause tissue death and implant failure. It is possible to drill with a CVD diamond $Si_3N_4$ coated tool with significantly lower forces (fourfold smaller), lower rise in temperature (4°C less), lower spindle speeds (100 rpm) and higher infeed rates (30 mm/min), when compared to the commercial steel (AISI 420) drill bits.

## INTRODUCTION

### Microcrystalline CVD diamond cutting behaviour

The growth of diamond crystals by low pressure CVD technique was firstly documented in 1952, almost at the same time of the development of High Pressure High Temperature (HPHT) method of diamond manufacturing, by William Eversole of Union Carbide [1]. Nevertheless, the process was dismissed by most researches because the growth rate was very low, since graphite was co-deposited with the diamond leading to impure mixed phases [2]. In 1968, Angus and co-workers [3] were able to improve the diamond growth rate by including hydrogen in the carbon-containing gases. They discovered that the presence of atomic hydrogen during the deposition process lead to preferential etching of graphite, rather than of diamond.

The commercial availability of synthetic diamond cutting tools made by CVD route took place at the beginning of 1990s in two product forms: thick-film freestanding CVD diamond cutting tool tips and thin-film CVD diamond coatings [4,5]. The first form is produced by depositing a thick layer (from 150-1000 μm) of diamond on Si or Mo wafers, detached from the substrate and cleaned with acid solution. The next step is laser cutting of the free-standing diamond wafer in tool tips that are brazed onto a steel or cemented carbide body/insert tool. Finishing is made by grinding/polishing procedure of the tool cutting edge with the desired radius and edge angle.

With respect to thin-film coatings, these are made with fewer steps, by direct deposition of diamond films on a suitable substrate, as silicon nitride, silicon carbide and, the commercially more common, cemented carbide (WC-Co) with Co content lower than 6 wt.%. The thickness is generally in the range of 5 to 50 µm. Although this route is the simplest one, the problems with adhesion mainly on WC-Co substrates delayed the progress of the diamond direct coated tools. So, this kind of diamond cutting tool fabrication has been much investigated and is in continuous improvement. Some examples of the metallic and non-metallic materials along with their associated machining challenges that justify the use of the diamond tools are listed in Table 1.

Table 1. Examples of difficult-to-cut machine composite materials (adapted from [4])

| Material | Example | Example of use | Machining issues |
|---|---|---|---|
| Hypereutectic silicon-aluminum alloy | A390 (18 wt.% Si particles in Al matrix) | Reduced-weight, wear resistant, temperature-resistant pistons | Hard silicon particles are extremely abrasive |
| Metal matrix composites (MMC) | Duralcan (20wt.% SiC in Al matrix) | Brake rotors, light-weight structures | Hard SiC ceramic particles are extremely abrasive |
| Cemented tungsten carbide | WC- 25wt%Co (sintered WC grain in Co based alloy matrix) | High-fracture-toughness wear parts, mould industries | WC grains are very hard and strong bonded. The Co metal binder can react with the carbon in diamond |
| Structural aerospace composites | Carbon-epoxy (high density carbon fibers in epoxy polymer) | Stiff and light-weight support structures for commercial aircraft, strong and light-weight sporting goods | Carbon fibers are extremely abrasive |
| Glass fiber reinforced polymers (GFRP) | G10 (highly compressed fiber glass in epoxy polymer matrix | Light-weight, insulating circuit boards, low-cost structural composites | Glass fiber induce abrasive tool wear; polymer can cause corrosive (chemical) tool wear |
| Graphite | ISO 88 polycrystalline graphite | Electrodes to electrodischarge machining process (EDM) in mould industries | Abrasive aggregates of polycrystalline graphite are formed during machining and wears the cutting edge parts |

There is some divergence about the thin-film CVD diamond coating tool performance, which denotes the need for the improvement of this kind of tool. The tool life would span an order of magnitude in terms of cutting time, with some tools wearing at about the same rate as that of a PCD tool (PCD is the acronym of Polycrystalline Diamond, a sintered composite of HPHT diamond grains in a cobalt binder brazed onto a WC-Co substrate) [6]. Shen [6] tested thin film diamond coated indexable WC-Co and $Si_3N_4$ ceramic inserts from a large number of sources in dry machining of the hypereutectic A390 (18wt.% Si) aluminum alloy. He associated the different adhesion strengths with the reflected differences in the turning performance. Among the tools tested, two or three coatings sources were able to have good film-to-substrate adhesion and a machining performance comparable to that of the PCD inserts. When comparing the flank wear of these tools at the same cutting conditions, he found a great inconsistency even within a batch or among batches by the same coating source.

Uhlmann and co-workers [7] compared $Si_3N_4$ and WC-Co diamond coated tools in turning, milling and drilling of AlSi and AlCu alloys, and a fiber-reinforced polymer. They show that, in turning operations, the diamond coated silicon nitride tools provide the higher wear resistance, increasing the tool life and enlarging the usable cutting speed range. For milling, in some cases, and in all cases for drilling, the diamond coated WC-Co tools presented the best performance because of the high thermo-mechanical stress imposed to the tools in such operations.

In a study carried out by Uhlmann and Brucher [8] with thin film diamonds and thick brazed films tools in machining of the same AlSi alloy, the authors arrived to different conclusions. They found that the thick brazed films could be successfully used with a tool life of 7 min (wear criteria adopted of VB=0.2mm), while it was not possible to conduct tool life tests on both WC-Co and $Si_3N_4$ ceramic coated tools due to the occurrence of film delamination after cutting times of only 30s. These results contradict the previous, above cited, work of Uhlmann et al., which reports values of 50 min of tool life adopting the same wear criteria. The turning parameters were similar concerning to cutting speed, but differ on feed and depth-of-cut conditions. In the first work, these parameters were: 0.04 and 0.8mm for feed and depth, respectively, while in the second they were: 0.1 and 0.5mm.

D'Errico and Calzavarini [5] reported the turning of metal-matrix composites (MMC) based on SiC (20wt.%) reinforced Al matrix (Duralcan) with CVD thick diamond brazed (~500 μm) and thin-film coated WC-Co (20-50 μm) from different sources and compared with PCD tools. They concluded that the thick film can be considered as a competitor for PCD by its superior wear resistance (binder-free, pure diamond nature), reducing the tendency for diamond grain "pullout" when eroded by the SiC particles. On the other hand, the thin coated tools failed by coating delamination after a very short cutting time (the average was 10 s). More recently, Chou and Liu [9] demonstrated, in turning of the same MMC material with diamond coated WC-Co tools, that adjusting the cutting parameters (mainly diminishing the feed), the film could delay the onset of tool failure by film delamination from few seconds until almost 15 minutes, although all the tested tools failed by this way before reaching a tool life criteria by abrasion. Another problem addressed in that work was the adhesion of the work material on the asperities of the diamond film, which forms a built-up-edge (BUE) formation on the rake face. This can be very harmful to diamond coatings, since it can also cause chipping at the cutting edge of the tool when the adhesive junctions are broken [6].

In resume, direct comparisons and conclusions seems to be very difficult to be assumed since the properties of both diamond coatings and substrates, as well as their manufacturing process (substrate characteristics, surface pretreatments, diamond deposition conditions) certainly differs from producer to producer, affecting the overall quality of the final product. In addition, other factors as cutting parameters, cutting conditions (lathe stability, use and type of lubricant) and workpiece characteristics (mechanical properties, homogeneity, dimensions) will direct affect the machining performance of a tool.

## Nanocrystalline diamond

Friction between the tool/workpiece contact zones is influenced by the nature of the materials pairs, but also and in a great extent by the quality of the cutting edge, namely the tool surface roughness. A number of techniques were developed to polish the free surface of diamond films, as mechanical [10], thermo-mechanical [11], thermo-chemical [12] and laser [13]. But the stress imposed by some of these techniques as well as the time spent and the complexity of the equipments needed led to the development of diamond film growth with controllable grain texture and/or very small grain sizes, in order to diminish the inherent roughness created by columnar structure of the CVD growth [14].

To overcome this drawback, research efforts have started to focus on nanocrystalline diamond (NCD) coatings, due to its small grain size and very low surface smoothness [15-19]. One of the main advantages of these coatings is the almost constant crystallite size of the diamond through the entire film cross-section, contrarily to columnar growth observed in microcrystalline CVD diamond [15]. The control of CVD diamond film microstructure is achieved by changing the deposition parameters to growth or re-nucleation conditions of diamond. Such parameters are highly dependent on the technique used as well as geometric factors of the reactor chamber. NCD films can be produced in a microwave plasma CVD reactor from a variety of feed gas mixtures such as fullerenes/Ar, $CH_4$/Ar, $CH_4/N_2$, or $CO/H_2$ [19-22]. The diamond crystallite size typically varies from 3 to 30 nm and the intrinsic surface roughness from 15 to 40 nm [15]. The hot filament CVD technique can also be used to grow such coatings either by applying a bias current that can be used to enhance growth rate and minimize grain size and surface roughness [23] or by carefully adjusting deposition conditions under $H_2$/Ar/$CH_4$ gas mixtures [21,24,25]. The increase of $CH_4/H_2$ ratio also enhances the secondary diamond nucleation, but above a given ratio, graphite may form and prevents diamond nucleation [23].

NCD is normally described as nanocrystalline diamond grains embedded in a predominant tetrahedrally coordinated amorphous carbon network [15]. However, this kind of NCD film are often termed "cauliflower" or "ballas" diamond, because of the substantial amount of sp2-bonded nature of the grain boundaries [21,22]. The so-called "Ultra-Nanocrystalline" diamond (UNCD) is said to differ from NCD due to its much smaller grain sizes (3-5 nm) and have an abrupt grain boundaries with negligible sp2-bonded carbon [21].

## Silicon nitride ceramics as substrate material for CVD diamond

When considering tribological and mechanical applications, adhesion of the diamond film to the substrate determines the success of the component in service. This was the reason for the fairly slow progress of the thin-film CVD diamond coated tools, mainly because cemented carbides, the most common substrate for cutting tools [26,27], provided unsatisfactory and inconsistent adhesion between the diamond coating and the substrate. Nevertheless, great progress on different methods of mechanical and chemical substrate surface pretreatments have been made [28,29].

The CVD process ideally requires a substrate material with a thermal expansion coefficient similar to that of diamond ($\sim 1x10^{-6}K^{-1}$) in order to reduce the thermal induced stresses developed on the cooling step. Cemented carbide (cemented carbide) possesses a higher thermal expansion coefficient ($\sim 6x10^{-6}K^{-1}$), leading to a higher thermal mismatch. A promising solution was proposed by others, including our group, and consists on the use of silicon nitride ceramic ($\sim 2x10^{-6}K^{-1}$) cutting substrates. Furthermore, these ceramics do not induce graphite formation at the interface during deposition and enhance chemical bonding.

## Machining of cemented carbide by chip removal

Cemented carbide parts are used in a wide branch of industries, including chemical, medical, automotive, packaging, textiles, mining, oil and gas, siderurgy, and for shaping and drawing technologies. The machining of cemented carbide by chip removal using superhard cutting inserts is a recent technology, due to the high hardness and abrasive nature of cemented carbide. The option for turning process instead of grinding brings several advantages as: better

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surface quality, reduction of production steps, reduction of product time delivery, shortening the manufacture cycles, higher geometry flexibility (corners, radius and grooves) and finally less energy consumption.

A tenfold decrease on the machining time compared with the conventional diamond wheel grinding method was achieved by thick CVD diamond brazed tools in facing WC-27wt%Co [30]. In such applications, polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN) are the most established market options, together with thick CVD diamond brazed films. Just a few works are devoted to this issue [7,30-36], despite some of them are about micro-machining, where the depth-of-cut is only of a few micrometers (3 μm) [33,34]. There is a technical guide on the use of PCD or PCBN tools associated to the binder phase content, typically cobalt, of the cemented carbide workpiece [32]. Accordingly, PCD is used when the binder content is below 18wt%, due to its superior abrasion resistance. However, PCBN should be used when the binder content is above this value, regarding its higher thermal and chemical stability. This is due to the chemical affinity between carbon and cobalt, and so, binder contents higher than 18wt% increases considerably the carbon solubility, leading to detrimental effects in its wear resistance properties [32].

The use of thin film CVD direct coated diamond tools in cemented carbide machining is a first example of a novel application of this material and it will be discussed further. It may configure an excellent alternative for PCBN and PCD tools, considering that CVD diamond higher hardness and absence of cobalt binder allows its use for machining a wider range of cemented carbide's cobalt content without need to have several types of cutting tools. Also, the technology of direct coating allows the manufacturing of diverse cutting insert shapes, including chip-breakers.

### Bone drilling with CVD diamond tools

Dental implant surgery significantly moved forward in 1965 when Branemark introduced the first titanium dental implant [37]. For the implant threading, the bone must be previously drilled. Here, the main problem is overheating that may rise the bone temperature above the necrosis threshold range, 42°C to 47°C [38-41], resulting in the implant failure [42-46]. Materials with higher thermal conductivity and increased cutting efficiency compared to conventional metallic drills may be a very good alternative. Those are precisely excelling properties of CVD diamond, moreover if the drill body is made of Si3N4 ceramic to ensure adhesion of the coating to the tool substrate, as stated above.

Diamond tools are also biocompatible [47] and possess very high chemical stability, i.e., diamond wear debris, if present, are harmless when compared to metallic ones [47]. Moreover, CVD diamond in its nanocrystalline grade was demonstrated to exhibit a higher resistance to bacterial colonization than medical steel and titanium [48], avoiding bacterial infection from such foreign particles. The performance of NCD coated $Si_3N_4$ ceramic drills in bone drilling is a second novel application for CVD diamond tools that will be further discussed.

## EXPERIMENTAL

Fully dense $Si_3N_4$ ceramic discs are produced by powder technology including pressureless sintering at 1750°C for 2 hours in $N_2$ atmosphere [34]. For the cutting tests, the ceramic parts are ground to standard normalized geometries of round shaped indexable inserts, accordingly to ISO

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5608 insert identification system. For bone drilling experiments, the $Si_3N_4$ ceramics are machined to the shape of a commercial steel (AISI 420) drill bit. Surface treatments before CVD diamond deposition included: flank face grinding with diamond wheel, rake face polishing with 15 µm diamond slurry, etching by CF4 plasma (1 h), and scratching/seeding in a diamond suspension in n-hexane by ultrasonification (1 h).

Diamond growth is conducted by hot filament chemical vapor deposition (HFCVD). For the cutting inserts, three types of diamond films are produced, which are labeled in Table 2 as: MCD, for microcrystalline diamond; NCD1, for nanocrystalline diamond type 1; and NCD2, for a finest nanometric grade. Film thickness is evaluated from SEM cross-section micrographs. The surface roughness is determined using AFM microscopy from 50 µm×50 µm scan areas. Diamond crystallite sizes are estimated by the broadening of the XRD diffraction peak at 2θ~44°, corresponding to the diamond (111) plane. In the case of MCD films, the crystals average size is calculated from SEM views.

In the case of the $Si_3N_4$ drill bits, these are coated with a bi-layer of MCD/NCD2, following the respective deposition parameters, except the filament temperature that is lowered to 2050°C due to the vertical alignment around the drill. The final thickness is about 1.5 µm and 2.5 µm, respectively for the MCD layer and the NCD2 one.

Table 2. Hot filament deposition parameters and CVD diamond characteristics.

| Tool Type | $CH_4/H_2$ | $Ar/H_2$ | Gas flow (sccm) | Total pressure (mbar) | Filament temperature (°C) | Substrate temperature (°C) | Growth rate (µm·h$^{-1}$) | Thickness (µm) | RMS (µm) | Grain size |
|---|---|---|---|---|---|---|---|---|---|---|
| MCD | 0.02 | - | 100 | 25 | 2300 | 850 | 2.7 | 42 | 0.78 | 12µm |
| NCD1 | 0.03 | - | 100 | 25 | 2300 | 850 | 3.1 | 50 | 0.23 | 43nm |
| NCD2 | 0.04 | 0.1 | 50 | 50 | 2300 | 750 | 1.3 | 23 | 0.26 | 27nm |

SEM cross-sections of the three CVD diamond grades used for the cutting inserts coating are given in Figure 1. The respective insets show the respective top view morphologies. The MCD film has a columnar structure, originating large diamond grains at the free surface (Figure 1a). On the contrary, the nanocrystalline NCD1 and NCD2 films present a very flat surface. The relatively high RMS surface roughnesses given in Table 1 are mainly the result of the nominal RMS value of the $Si_3N_4$ substrate, which is about 0.4 µm. Good surface finishing can be achieved by the lower diamond crystallites sizes, NCD1 and NCD2, reaching the accepted industrial surface roughness parameter of about 0.2 µm.

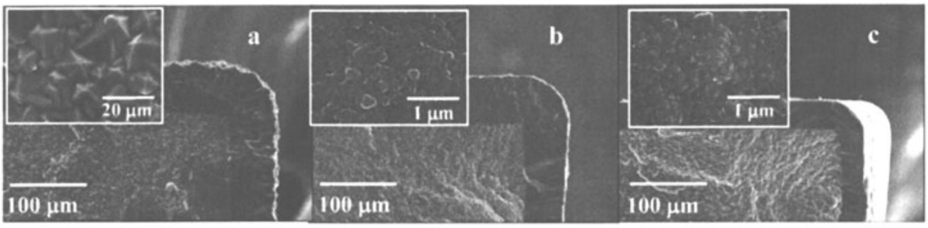


Figure 1. SEM cross-sections and top view insets of MCD(a); NCD1 (b) and NCD2 (c) tools. [36]

The turning tests are done using a CNC lathe equipped with a three-axis piezoelectric dynamometer platform. The workpiece surface quality is determined using a portable profilometer. The turning tests are conducted under dry cutting conditions. The workpiece material is a WC–25 wt.% Co cylinder (Ø=32 mm, length=60 mm). The cutting performance of the three types of diamond coated tools is evaluated at fixed conditions: speed=15 m $min^{-1}$, depth-of-cut=0.1 mm and feed=0.1 mm $rev^{-1}$. The resultant wear modes are measured accordingly with the ISO 3685 standard using optical and SEM microscopes.

The drilling tests are performed in a universal mechanical testing machine equipped with a variable speed drill. The human mandible bone is simulated using a laminated test block formed by a solid rigid polyurethane foam (trabecular bone) with a 2mm thick upperlayer of E-Glass-filled epoxy sheet (cortical bone). Spindle speed varied in the range of 50 to 1400 rpm (cutting speed of 0.5 to 13.2 m/min) and the infeed rate between 7.5 to 30 mm/min. Local temperature is monitored by two thermocouples placed in the polymer at different levels (TC1 placed immediately after the epoxy sheet at 3 mm depth, and TC2 is placed at the end of drilling hole at 15 mm).

## RESULTS AND DISCUSSION

### Machining of cemented carbide with micro and nanocrystalline CVD diamond

The force components during cemented carbide turning are given in Figure 2a: depth-of-cut ($F_d$), main ($F_c$) and feed ($F_f$) forces. The surface roughness of the MCD coated insert leads to excessive friction between the tool and the workpiece materials and thus high forces are generated during the cutting operation. On the contrary, cutting forces for both the two NCD grades are very similar, being relatively low. As the inserts are circular shaped, the contact area with the workpiece is high and thus the $F_d$ component is the highest in all grades.

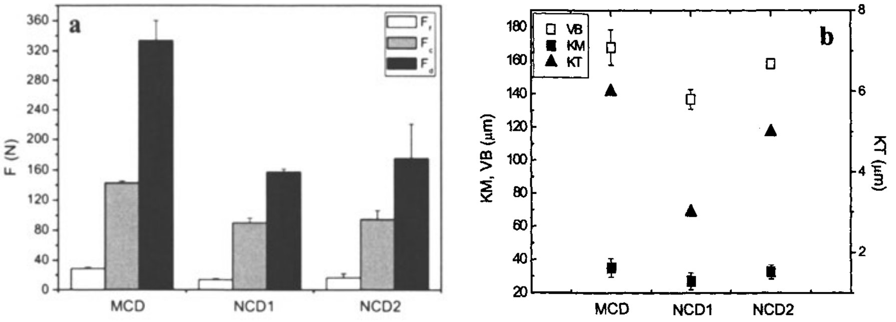


Figure 2. Cutting forces (a) and wear values at rake and flank faces (b) of the distinct diamond grades after one turning pass (~60 m cutting length, 4 min of cutting time).

Figure 2b summarizes the set of values of the crater centre distance (KM), average flank wear width (VB) and crater depth (KT). The lowest values occur for the NCD1 grade and the largest ones for the MCD coated inserts. For all grades, flank wear is the predominant kind of tool wear, as VB values denote. According to the ISO Standard 3685, a VB value of 300 µm is adopted for tool life criterion. This value of VB limit is not achieved after 4 min of cutting time by any of the tools. A remarkable feature of all the turning experiments is the absence of film delamination demonstrating that the adhesion strength to the $Si_3N_4$ substrates is adequate.

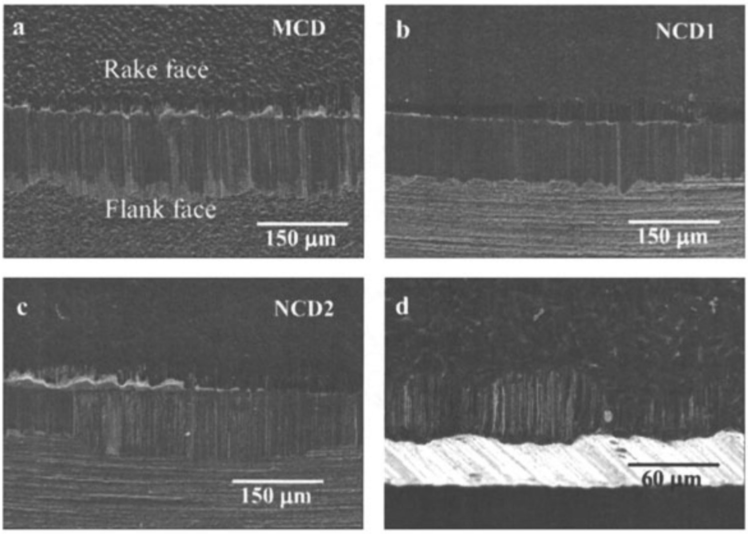


Figure 3. SEM micrographs of rake and flank faces of the distinct CVD diamond tools. (a) to (c) correspond to MCD, NCD1 and NCD2 coatings, respectively. Micrograph (d) is a top view of the MCD cutting tool after three machining passes (12 min of cutting time) [36].

The dominant wear mechanism in cemented carbide cutting by diamond coated tools is abrasion caused by loose diamond debris and WC hard particles from the sliding action of the chip and workpiece rubbing on the rake and flank faces, respectively [35]. This can be seen in Figure 3, in general. In the MCD insert, the higher surface roughness leads to a higher probability of diamond microchipping and transgranular fracture, explaining the higher wear values. Nevertheless, the MCD tool is tested for longer times, reaching the VB limit after 12 min (Figure 3d). The different behavior of the two NCD grades can be explained by the higher amount of adherent material in NCD2 tool, that is characterized by a relatively higher surface roughness (Table 2), as a consequence of the nanocrystalline clustered morphology (Figure 1c). An further advantage of the NCD tools comparing to the MCD one is the better workpiece surface finishing being kept below the industrial accepted level of Ra=0.2 μm.

**Bone drilling behavior of bi-layered CVD diamond coated $Si_3N_4$ bits**

Figure 4a shows typical plots of the feed force evolution during the drilling tests. For each drill type (steel and CVD diamond bi-layer coated $Si_3N_4$), two different curves are given, corresponding to the maximum spindle speed (1400 rpm) and the minimum admissible spindle speed for the steel drill (350 rpm). In all cases, the feed force increases to a maximum when the drill tip is still cutting the denser upper layer of the polymer (that mimics the cortical bone) [44]. After that, a new cutting regime takes place, with nearly steady low force values when the mild polymeric foam (that emulates the trabecular bone) is drilled.

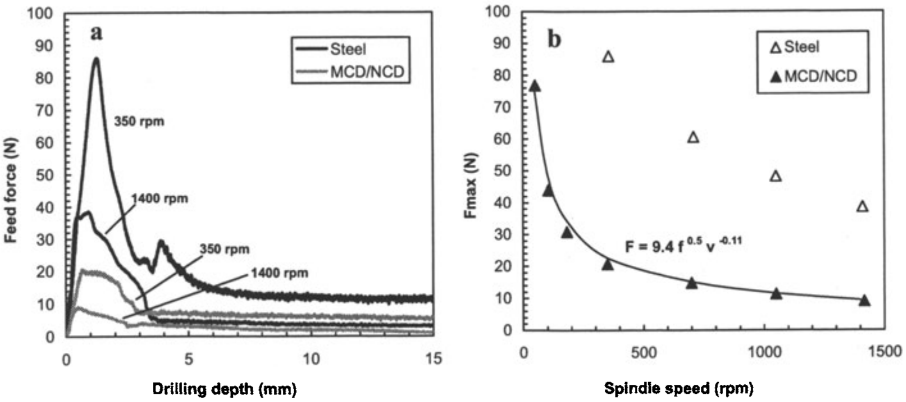


Figure 4. Feed force evolution as a function of the drilling depth (a) and maximum feed force values [49].

Although the force evolution in both drill types is similar, the values attained by the bi-layered CVD diamond coated drills are remarkably lower than those of the steel drill bit. This is the result of the more abrasive action of the diamond coated tool that sums to the shearing action of the tool edge leading to a lower cutting effort. The spindle speed has a net effect on the drilling action by decreasing the maximal feed force required for the task (Figure 4b). Again, the diamond tool is much better, for which an expression on the dependence of feed (f) and spindle speed is given in Figure 4b, denoting the prevailing importance of feed. Of noteworthy importance is the potential of the MCD/NCD2 coated tool to cut at very low spindle speeds (100-180 rpm), contrarily to the commercial steel drill. Bearing in mind that a threshold of 45N [38] is considered to be the uppermost value for normal loading in odontological drilling, the steel drill cannot operate below 1200 rpm in the absence of liquid cooling, while the diamond coated tool can be used from 100 rpm onwards. This ability reduces local heating, and thus bone damaging, while it allows collecting of bone debris for self-regeneration purposes.

The local polymer temperature during drilling is represented in Figures 5a and 5b, respectively for the steel drill and the diamond coated one. The temperature evolution on thermocouples TC1 and TC2 is firstly plotted as a function of the drilling depth, until removal at the end of cut (15 mm), and from that instant as a function of time. Taking the data from the TC1 thermocouple, four regions (I-IV) can be identified: I, when no variation of the initial temperature is detected until the drill crosses the TC1 placement; II, characterized by steep heating which comes from the locally generated heat at the contact between the drill tip and the polymer; III, when the increment of the distance between the heat source (the drill tip) and the TC1 positioning exceeds the temperature rising on the drill and on the polymer by heat accumulation; IV, corresponding to the polymer natural cooling after the drill removal. Concerning the TC2 thermocouple placed near the hole end at 15 mm, heating starts to be

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detected before the drill tip approaches this level; after the drill removal, this thermocouple still registers an increase in temperature as a result of the polymer thermal inertia.

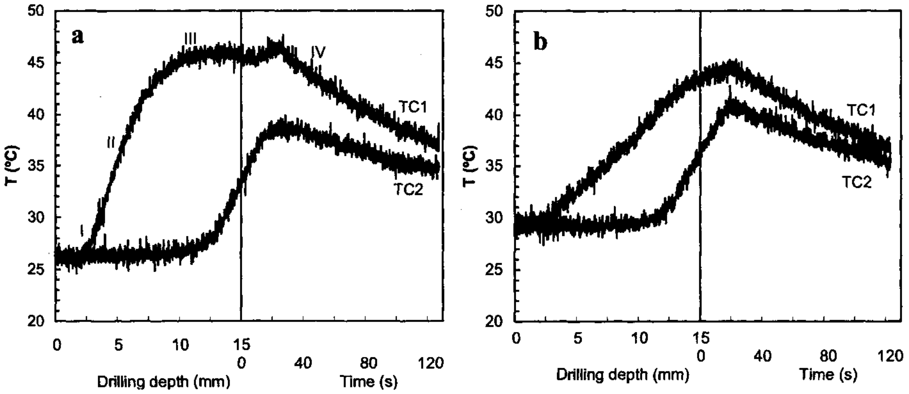


Figure 5. Temperature evolution as a function of the drilling depth and of the time after the drill bit removal, acquired by thermocouples TC1 and TC2, in drilling at a spindle speed of 1050 rpm with the steel drill bit (a). The same but for the bi-layered CVD diamond coated drill bit (b). [49]

The temperature evolution on the MCD/NCD2 coated $Si_3N_4$ drill test shows a net difference on the TC1 thermocouple data, Figure 5b, comparing to the steel tool, Figure 5a: the temperature gradient is less steep, the maximum temperature is lower, with a reduction of about 4°C. These are expected results taking into account that the drilling forces are much lower as before discussed. For the diamond coated drill the maximum temperature is always below 45°C at of 1050 rpm of spindle speed, below the threshold temperature for heat induced bone injury (47°C for 1 minute [39]).

Both types of drill bits are observed by SEM after testing [49]: the cutting edge of the commercial steel drill becomes chamfered as a result of the wear process, leading to higher drilling forces and excessive heating; on the contrary, the bi-layered MCD/NCD2 coated drill bit presented no signs of delamination or edge deterioration keeping intact the initial roundness of the coated edge.

## CONCLUSIONS

Silicon nitride inserts are successfully coated by CVD hot filament method with continuous and highly adherent diamond films of nano- (27 and 43 nm) and conventional 12 μm micrometric grain size types. The 43nm nanocrystalline grade presented the best behavior in machining of WC–25wt.% Co cemented carbide regarding cutting forces, tool wear and workpiece surface finishing. The conventional micrometric grade, featured by the presence of high asperities originated by the large crystals, suffered a higher abrasive action from the loose hard particles carried by the chip flow and from rubbing at the contact with the workpiece.

A dense and homogeneous bi-layer of microcrystalline/nanocrystalline diamond is also successfully deposited by HFCVD on $Si_3N_4$ drill bits for odontological purposes. After drilling