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Performances of AlCrN coating for micro-ball-end milling of pre-sintered 5Y-TZP

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Abstract

This study deals with micro-ball-end milling of a pre-sintered ceramic material. The aim is to underline the reliability of a classical AlCrN coating while machining the material for dental and luxury applications. A particular tool configuration – which is identified as critical by the targeted sectors – is tested in common stable cutting conditions, previously determined. Cutting forces, tool reliability and surface integrity data is obtained by green machining of a 5Y-TZP (tetragonal zirconia polycrystal stabilized by 5%mol of yttrium) with 1 mm diameter tungsten carbide micro-tools coated with AlCrN PVD (Physical Vapour Deposition). The links between tool wear and their consequences on machined surfaces are mainly discussed. The coatings performances are then briefly underlined and compared to the reference in that field, diamond coating. The results highlight that the choice of an appropriate coating is mandatory for this type of abrasive ceramics, even if they are partially sintered, and depends on the targeted parameter: tool life or surface integrity.

1. Introduction

The increasing demand for micro-components leads to an improvement of control and development for dedicated methods in the concerned manufacturing fields. Regarding the other processes, micro-milling seems to be one of the most versatile. From a down-scaling approach of conventional machining, the term "micro-milling" is used when the concerned tools are less or equal than one millimetre in diameter [1]. This process is applicable to a wide range of materials and allows to produce three dimensional complex geometry with relatively high shape ratio parts (until details presenting few tens of microns in thickness) [2]. Nonetheless, by decreasing the scale, some phenomena – generally neglected on macro-scale in conventional machining – see their impacts increase. The material removal rate is very low in front of classical machining applications [3]. In this context, new mechanisms of cutting that affect tools performance [4] and surface integrity [5] are involved. Pre-sintered ceramics have particular mechanical behaviour in front of metallic materials. For example, S. Mohanty et al [6] underlined the brittle behaviour of green alumina. Most of existing papers aim to bring out the influence of cutting conditions, grain size of the machined material, type of mill coating and tool integrity after a short machining length [7]. This paper provides an experimental study that gives elements concerning the machining behaviour of AlCrN coating after long lengths. It crosses data extracted from surface integrity, in-time force measurements and qualitative tool wear analysis. For the experiments, one-millimetre-diameter ball-end mills coated with AlCrN are used. The local geometry of the tool results of the conclusions of B. Escolle works [8].
This study is divided in three main parts. Firstly, the experimental setup and methodology are exposed. Secondly, the experimental data are presented and analysed. Finally, the conclusion presents pros and cons of AlCrN-coating in front of diamond coating.

2. Experimental setup

2.1. Workpiece material & tools

The machined material is a pre-sintered 5Y-TZP presenting a low hardness of 41 HV10 (±1), a low Young modulus (11 GPa), no plastic domain and a high abrasiveness. This material is commonly used in dental industry to produce dental prostheses. Its green state comes from a hot isostatic pressing at 800°C which permits a partial densification of the particles within the ceramic [9]. The repartition of particles size of the machined material is relatively uniform and its granular dimension is inferior to 300 nm in diameter.
Concerning the tested tools, a classical type of pre-finishing/finishing tool – adapted to the targeted field – is taken: 1 mm diameter micro-grain tungsten carbide ball-end mill with two flutes. Moreover, AlCrN is a classical coating to machine for hardened steel milling. Its low friction properties and abrasion resistance distinguished it in front of other coatings, which explains this coating choice.

2.2. Experimental plan

A Meyrat MHF-25 electric turning spindle – able to turn from 5,000 to 80,000 rpm – is used. The machine tool used is a Willemin-Macodel W418 5-axis milling centre.
A simple machining operation is performed for this study: the particular configuration of flat machining for slotting in climb milling with half of the tool immerged. This choice permits to simplify the study and to single out tool behaviour in the most problematic configuration based on standard uses in the dental prostheses manufacturing. A spindle speed of N = 35,000 rpm is taken according to industrial standard. The theoretical depth of cut (d_n) is fixed to an optimum of 150 µm and the feed per tooth (f_t) is fixed at 18 µm/tooth according to preliminary tests. Finally, a maximum length of machining (L) is set at 17,760 mm in accordance with tool life industrial needs.

2.3. Measure and data processing

The force signals, in-time measured with a high sensitivity three components Kistler dynamometer (Minidyn 9256C1), permit to distinguish maximum, minimum and average machining forces. The first and second parameters are obtained by averaging the local maxima and minima in order to plot two least squares constant functions. This method permits to circumvent the problem of chaotic local signals, essentially due to the brittle nature of the used work piece material. We consider that force amplitude tends to give an image of dynamical forces because the force amplitude is directly linked with the extreme configurations of the tool during machining, which is due to its dynamical behaviour. Force average represents basically static forces. Each obtained force value is an average of ten trials performed on the same machining conditions in order to avoid dispersion problems and to verify the stability of measurement.
Concerning the surface analysis, this study relies on Sq* parameter – measured with an Alicona Infinite Focus confocal microscope. It is defined like Sq parameter – as established in the standard 25,178 – but omitting the separation between second and third order defaults. This choice is justified by two main points: the industrial validation based on aesthetic criteria, including crimping defects, and the current lack of knowledge concerning the filters values to separate second and third orders defects.
Tool observations are done with a FEI Quanta 450W SEM (Scanning Electron Microscope). It permits to highlight qualitatively defects of the micro-mills at different steps of their using thanks to the high depth of focus of this hardware.

3. Experimental results

3.1. Forces observations and tool wear analysis

Rxyz (resultant of machining forces) amplitude Fig. 1 is taken as reference because being similar to the other results concerning Rx (resultant of forces applied on the orthogonal direction to the feed rate X), Ry (resultant of forces applied on the feed direction Y) and Rz (resultant of forces applied on the tool axis Z) plotting. Consequently, SEM observations were done for characteristic points: 4,960, 11,360 and 17,760 mm.
Erreur ! Source du renvoi introuvable. 2a shows an overview of the mill at the end of the first wear phase (for L = 4,960 mm). The wear mechanism has affected the coating but also the tool carbide itself due to a high degradation of the cutting edge and the flank face. Nonetheless, after this step, a more sharpened cutting edge appears, which explains the brutal forces decrease for a machined length greater than 4,960 mm. The cutting edge underwent an abrasion wear that – from a rake face view – ironed out its shape defects (Fig. 3ab). The first high level of forces is mostly due to the degraded shape of this cutting edge that does not promote a cutting but a ploughing behaviour (confirmed by a relatively high level of dynamic forces on the feed direction Y in the first phase). This resistance versus the machined material is quickly annihilated by the abrasion of this local zone, letting discovered a sharpest cutting edge without coating. At the end of this first phase, pull-outs are detected at different scale levels. Droplets are torn from the tool surface, creating holes in the coating and so weaknesses in front of 5Y-TZP abrasion. Coating around the tool tip is gradually chipped (Fig. 2a).

Observing the tool tip at the end of the second phase (L = 11,360 mm), the abrasion in this area continues to extend until the second flank face (Fig. 2b). Besides, abrasion channels are more numerous and within a larger diameter comparing to the first phase. Wear mechanisms go on and deform the global shape of the tool. A high abrasion takes place during this second phase, which can be attested by the inclusions of 5Y-TZP on the tool material. Considering the brittle nature of the material, the ceramic residues on machined surfaces and the high velocity flow of zirconia during milling, a third body wear seems to be the most appropriate dominant behaviour on the tool tip. It partially explains the brutal decrease of all forces within this second phase. The machining is promoted by a sharpest edge of cut and an abrasion behaviour takes place via an indirect contact between the tool and the machined surface on the tool tip. It is worthwhile to underline that abrasion ironed out once again the shape defects of the cutting edge (Fig. 3c).

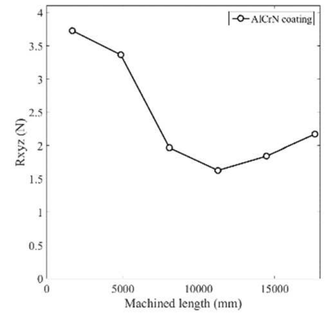

Fig. 1 Force amplitude of the resultant Rxyz applied on the tool

The last phase – between 11,360 and 17,760 mm – is a progressive amplification of the phenomena observed on the second phase. The coating on the first flank face is almost totally worn (Fig. 2c). Inclusions of 5Y-TZP on the tool carbide are pervasive everywhere within the abraded area on the flank faces. Wear of these faces clearly modifies the initial shape of the mill and of the cutting edge. At this point, the cutting edge wear is not acceptable because the degradation of the first flank face begins to affect the rake geometry and totally modifies the initial tool geometry.

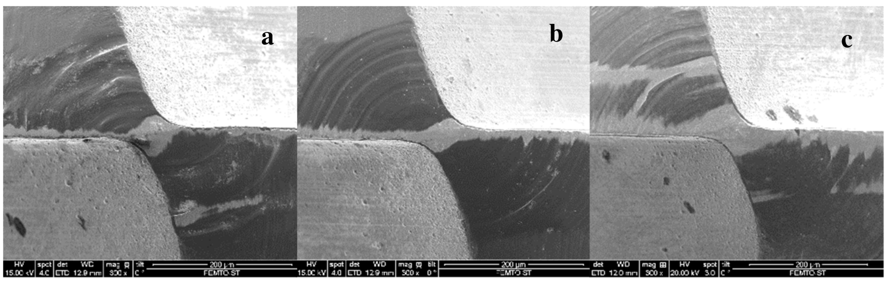

Fig. 2 Overview of the tool tip after 4,960 (a), 11,360 (b) and 17,760 mm (c) of machining

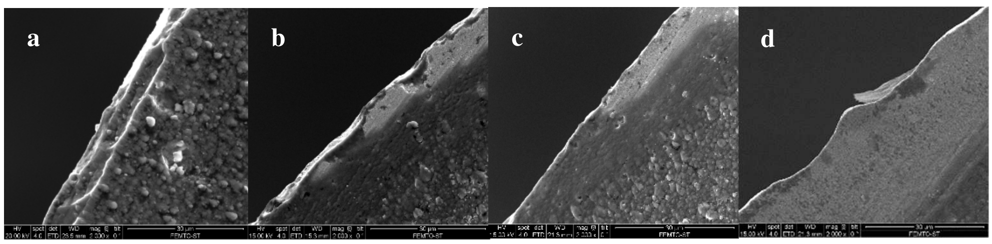

Fig. 3 Overview of a new cutting edge (a) and after 4,960 (b), 11,360 (c) and 17,760 mm (d) of machining

3.2. Surface integrity evolution

More the machining length rises for an AlCrN-coating more surface integrity improves. Indeed, more the tool is used, more the ploughing effect gradually disappears at the bottom of the machined surface. This evolution confirms the progressive installation of a third body wear mechanism. Indeed, on the tool tip, there is no major changes in the local tool geometry between L = 4,960 mm and 11,360 mm while ploughing at the bottom of the slot almost disappears in this range of length. Therefore, machining is not carried out by the tool geometry but by an intermediary that grind the material: the material itself. On the contrary, this third body effect is detrimental to the diamond coating because the material entirely covers the coating grains during machining without affecting it, which creates ploughing at the bottom of the machined slot.

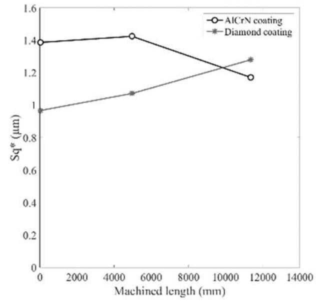

Fig. 4 Surface integrity of AlCrN and diamond-coated tool

4. Conclusions and perspectives

The AlCrN-coated tool wears relatively quickly. The machining behaviour of this tool varies a lot as forces data can underline it. However, wear of this tool provokes a surface integrity improvement. Nonetheless, it is highly detrimental for the mill. Indeed, after 17,760 mm of milling, the cutting edge geometry highly changes due to a pronounced abrasion of the flank faces. It indicates that this amelioration, regarding the surface integrity, should probably achieve a critical point where the tool would have undergone too much wear to be still reliable. This sort of coating is not suitable for the targeted uses because of its instability and relatively quick obsolescence. In front of this coating, the diamond coating is very reliable concerning his tool life but presents a significant degradation of its machined surface integrity by ploughing effect. According to these atypical results, it would be interesting to investigate more in details these coatings with at least another one to bring out their influence on the different studied parameters.

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