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The analysis of tool wear mechanisms in the machining of pre-sintered zirconia dental crowns

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Abstract

The growth of Digital Dentistry has opened new potentials in the dental restoration sector where personalised restorations could be made in a much shorter time than before. Zirconia has been widely used due to its excellent wear properties and biocompatibility. Zirconia is machined primarily in its pre-sintered state, using carbide tools. Even in its pre-sintered state, zirconia is abrasive and caused tool wear. Tool wear is affected by tool substrate used, cutting conditions used, machining method employed, etc. Tool substrates are such as tungsten carbide, steel, etc. Cutting conditions refer to speed, feed, depth of cut, etc. Machining methods refer to milling wet or dry. Understanding tool wear helps in better tool design. Tools that lasted longer would mean the end users i.e. dental technicians would have less unproductive downtime changing tools. In addition, worn tool would produce broken restorations, which is undesirable. With this in mind, the aim of this paper was to study tool wear by identifying the wear mechanism that occurred when carbide tools machined pre-sintered zirconia. Test was constructed using recommendations from ISO 8688:1989. Cutting conditions used were adapted from those used in desktop dental milling machines. Pre-defined stopping criterion was set and flank wear of tool was measured every 15 minutes using an optical microscope. When tools reached the stopping criterion, Scanning Electron Microscope (SEM) and Quadrant Backscatter Diffraction (QBSD) were used to analyse worn tool in details. Findings showed transgranular and intergranular fractures were the wear mechanisms on carbide tools when machining pre-sintered zirconia.

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Keywords: Digital dentistry; Tool Wear; Carbide; Pre-Sintered Zirconia

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1. Introduction

For decades, dental prosthesis has been a common method of restoration, but like many other medical sectors the method, material and technology used to create these restorations has evolved throughout the application of these procedures. The most recent of these evolutions is the shift in material to using zirconia for structural parts of these restorations, such as crowns and copings, due to its high strength, excellent wear properties and biocompatibility. To create these the generally implemented method is Computer Numerically Controlled (CNC) milling of zirconia in a pre-sintered state as it allows for access to this material and other along with the repeatable accuracy precision and high quality control[1]. This happens in the dental laboratories or in milling centres and has become known as dental CAD CAM. Pre-sintered zirconia is machined instead of its sintered counterpart, as the latter is high in hardness and poor in thermal conductivity giving it low machinability. Pre-sintered zirconia has a hardness around 66 Vickers hardness. Once the same block is fully sintered the hardness value increases to be above 1600 Vickers hardness. This increased hardness comes from the consolidation of grains. The pre-sintered zirconia also could sustain greater amounts of mechanical damage and absorb more energy [2]. This allows it to resist cracking induced damage during machining.

Dental restorations, such as copings and crowns, have the main purpose of repairing damaged teeth to a state where they can again be used for mastication. The ability for restorations to resist wear and impact comes from the material. The need for an aesthetic matching of the surrounding teeth leads to other parts of material selection. The dental material should be able to blend in with the natural colour of teeth or be semi-translucent. This has caused the shift to zirconia with the development of yttria-stabilized zirconia. The speed of generating restorations as well as the accuracy required on final restorations has led to the shift away from the classic hand tooling towards Computer-Aided-Design (CAD) and Computer-Aided-Manufacturing (CAM) in dentistry. The machining process in dental laboratories typically uses a small desktop 5-axis Computer Numerical Control (CNC) machines. These machines are usually set up for machining disc of pre-sintered zirconia (cf. Figure 1). The geometry and dimensions of the restoration are taken directly from the patient mouth using impression moulding or laser scanning this give a highly accurate model to work with that the CAM package can build.

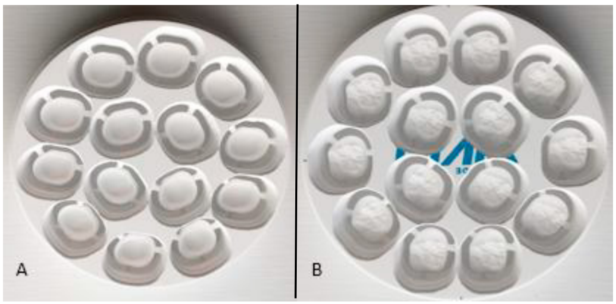

Figure 1: Machined zirconia dental crowns A) underside or fitting edge B) top side or visible surface

The process also uses extraction and air blasts to control the waste material for dry milling and coolant or water for wet milling. The pre-sintered zirconia discs that are used in the manufacture of restorations are formed by cold isostatically pressing powdered, or what is referred to as green state zirconia. From the dentists perspective, the actual process of machining is not a main priority in their working function, beyond the points that the process must be simple to operate and accurate in the final output. Tools wearing, changing the surface geometry of the crowns or even damaging the material are certainly unwanted and would be unwanted effects for both the dentist and the tooling manufacturer. As with any improvement strategy for processing operations, a fundamental understanding of the material-material interaction is vital [3]. To build this understanding of the tool wear that occurs during the prosthesis production, the remainder of the paper presents a modified ISO 8688:1989 test method for investigating tool wear in machining pre-sintered zirconia using carbide tools.

2. Tool life

Tool life is the measure of how long a tool can be used until it can no longer achieve its specified purpose. Much works have shown the direct effect that tool wear has on the surface finish of the machined surface and the stresses induced during the machining process [4, 5]. Both of these affect the end product of dental restorations especially at the high tolerance areas such as the marginal fitting edge, which is where failures occurs the most [6]. It is therefore important to understand the propagation of wear and the affect it has on both the tool and work surface. Tool wear has many specific classifications that have been set in stone by ISO 8688:1989 [7] these are: Flank wear, Face Wear, Chipping, Cracking and catastrophic failure. Flank Wear is the gradual loss of tool material from the tools flank or edge during cutting which leads to the progressive development of flank wear land. This flank wear land is a newly formed surface created from the worn away edge. Face wear is a gradual loss of material from the cutting tools leading face, or rake face, during cutting. This can result in one of two differing forms known as Crater wear and Stair Formed Wear, which form craters or a sloping land respectively on the face. Wear occurs due to friction and heat generated during cutting and of course the properties of material being machined. Zirconia, which is to be studied in the paper is known to be abrasive in nature [8].

3. Test Method

In order to analyse wear, three carbide grades with different properties as summarised in Table 1 were used to make the tools. The aim was to identify which carbide grades wear out the least when machining pre-sintered zirconia and what was the wear mechanism. Test were conducted on a 3-axis router. The cutting conditions used are summarised in Table 2. These conditions were adapted from those used in desktop milling machines in dental laboratories. Ø2mm ball nose end mills made from three different carbide grades were tested. These tools were uncoated. Each tool milled a circular pocket until it worn out. The stopping criterion used was when the flank wear of a tool reached 3.5% of the tool diameter. For a Ø2mm tool, this was 70 microns. Flank wear on the tool was checked at 15 minutes interval until the stopping criterion was reached. However, when tools broke halfway through the test or it caused margin of the milled pocket to crack, the tool would be considered as worn and no measurement would be taken on this tool for comparison purpose. Figure 2 shows pre-sintered zirconia discs in the CNC router that had a bed large to accommodate multiple discs at once. Vacuum extraction and air blasts were to control dusts that were formed from machining.

Table 1: The material properties of carbide grades

Carbide grade	CARBIDE A	CARBIDE B	CARBIDE C
Transverse Rupture Toughness (MPa)	3700	4000	4200
Fracture Toughness (MPa)	10	10.4	9
General Grain Size (µm)	Sub-micron	Sub-micron	Ultrafine

Table 2: Cutting Conditions

Process	X,Y Feed (mm/min)	Z Feed (mm/min)	Spindle Speed (rpm)	Step over (mm)
Roughing	2100	1200	25,000	0.8

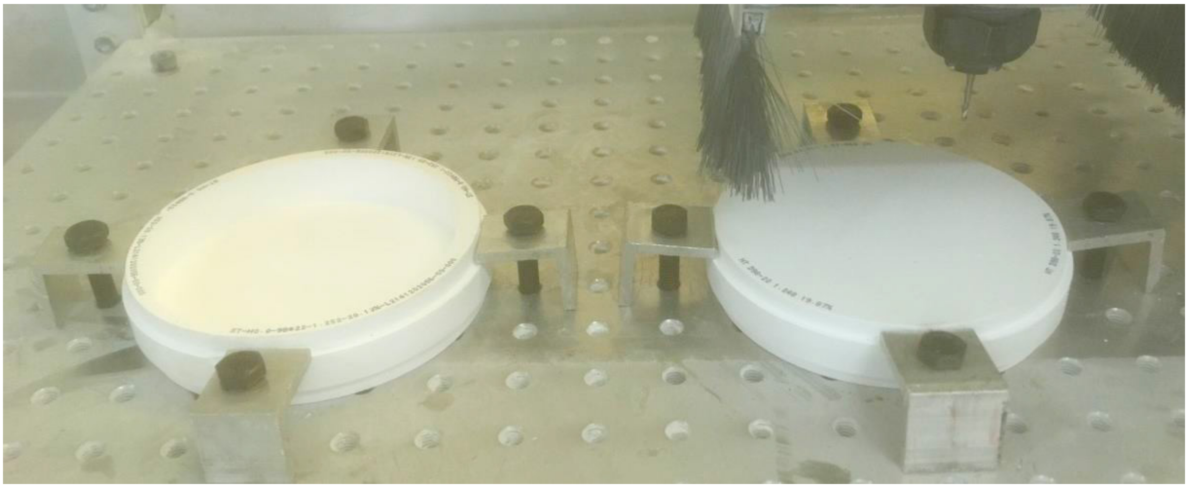

Figure 2: Pre-sintered zirconia disc inside the CNC router

Figure 3 show the flank wear of tools, which the left image showing flank wear after 15 minutes and the right showing flank wear after 310 minutes. The width of wear was measured using an Optical Microscope coupled with Stream, a measurement software from Olympus.

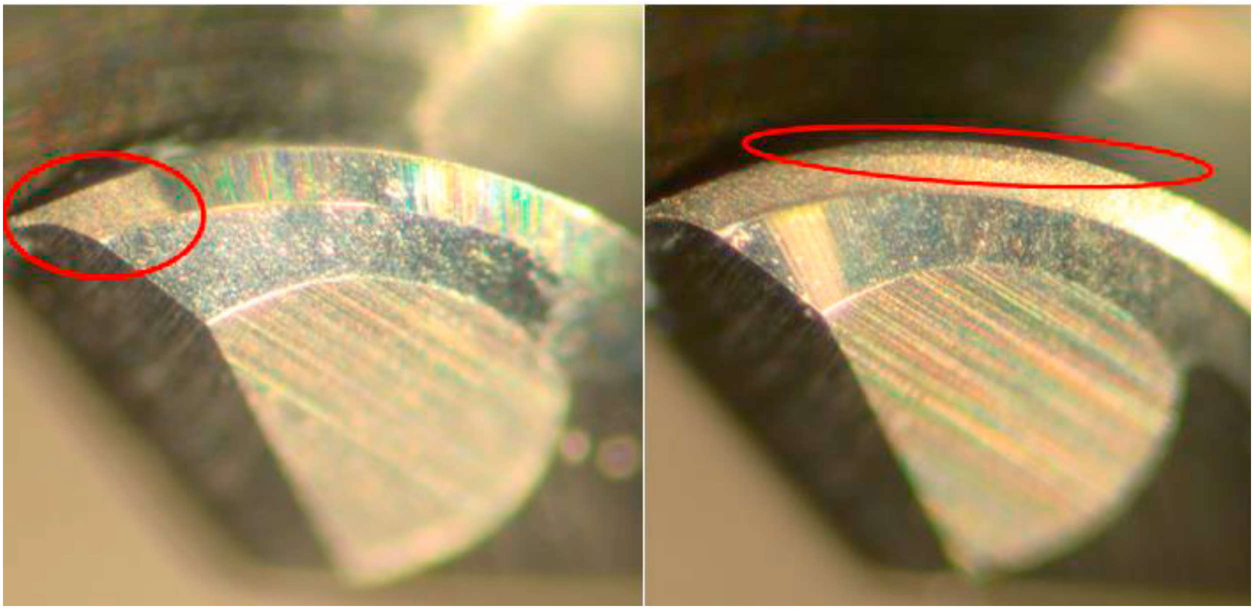

Figure 3: Tool wear progression on a ball nose end mill after 15 minute (left) and 310 minutes (right) at X8 magnification

4. Results and Analysis

The flank wear measured at the 15 minutes interval was plotted as shown in Figure 4, with the red line indicated, as Tool End Life was the stopping criterion of 70 microns used in the test. The final tool life in minutes is summarised in Table 3.

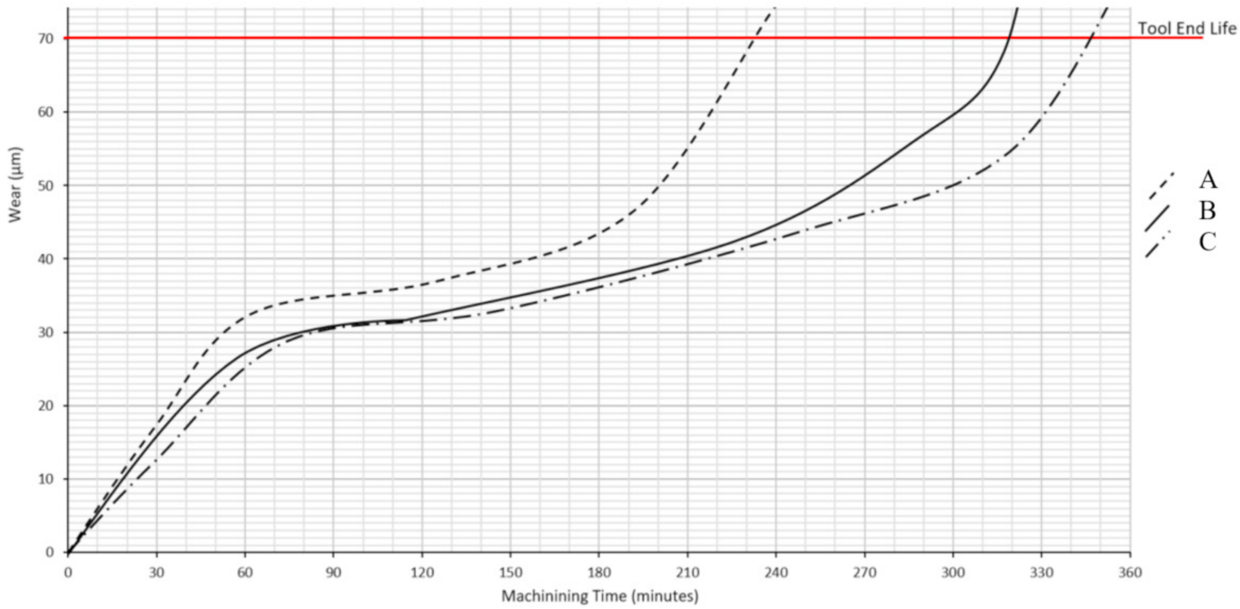

Figure 4: Tool wear curve

Table 3: Average tool life for Carbide grades and material properties of Carbide grades

Carbide grade	CARBIDE A	CARBIDE B	CARBIDE C
Average Tool Life (minutes)	240	315	350

After testing was completed, the tools were prepped for observation under SEM and more specifically Electron Backscatter Diffraction (EBSD). The purpose of this was to observe the affect the three body abrasive wear has on the microstructure of the cemented carbide to determine which properties might be causing the failure of the tool. This was done by mounting the tested tools in the resin, polishing, and etching the worn area the samples so that a decent image can be taken of the grain structure around the worn faces and tool tips. These samples were then observed under the SEM at the optical research centre (ORC) in Southampton. From these images observations of how the grain has deformed after the tool life has been reached. Figure 5 shows the images taken of the three carbide grades when unworn by the machining process. These images were used as a reference point to make observation and a series of initial observations, such as the gran density and grain size. As can be seen in Figure 5C, carbide C has a very fine grain structure that is fairly tightly packed were as the other two are medium and mixed grain carbide for A and B respectively.

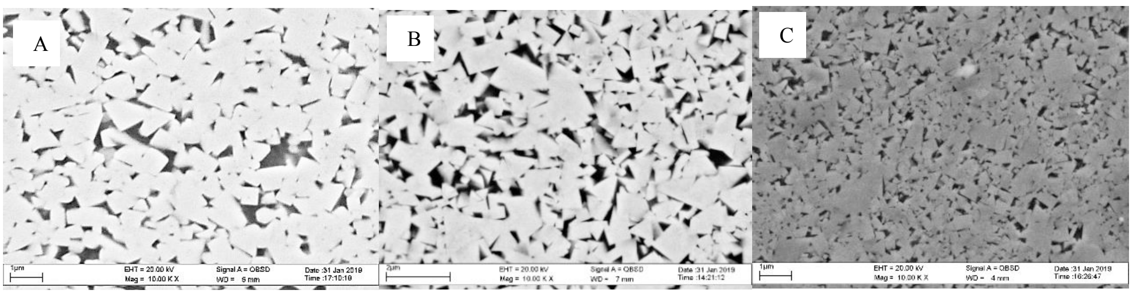

Figure 5: Unworn Carbide grades left to right A, B & C

This disparity in grain size is very common for cemented carbide due to the sintering forming process, which allows it to be such a tailorable tool material. The crystal structure of cemented is also very variable, however this due more the nature of material. This inconsistent structure is what leads to poor grain tessellation especially at larger grain sizes; which in turn causes the brittle nature of the material. The images Figure 6 shows how the first grade of carbide resisted the tool wear. This tool shows the most transgranular fracturing having entire rows of crystals sheared in a straight line ignoring the grain boundaries, as shown in Figure 6B toward the top of the image.

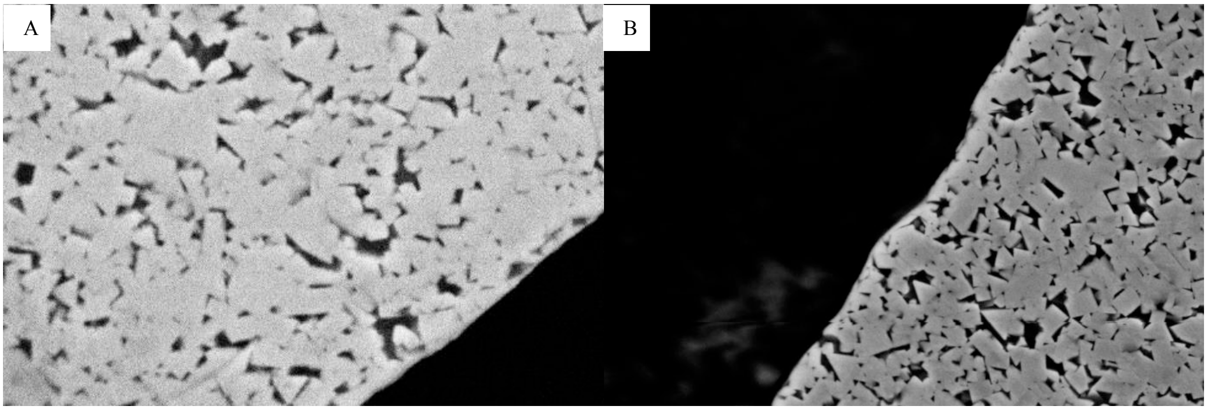

Figure 6: QBSD images of Carbide A worn edges at 10 kX magnification

This grade of Carbide also had the shortest tool life by more than an hour. This form of fracturing happens in place of intergranular fracturing were the fracture follows roughly the grain boundaries of each crystal. This can be seen to be happening in some cases in both Figure 6 and Figure 7. This tends to happen more in materials were the grains align or the intergranular interactions are much weaker than the grains themselves or when the material removal mechanism provokes such a reaction such as hard particle abrasion. The images of the tool edges reveal how the edge deteriorates and resist the forces of the machining process such as in carbide B shown in Figure 7. This deformation is typical of abrasive wear causing the grain to round in some places. It also causes grains to break away but where the grain breaks. Some of the grains break through their own boundaries. This again is transgranular fracturing and can be seen in the highlighted in Figure 7A.

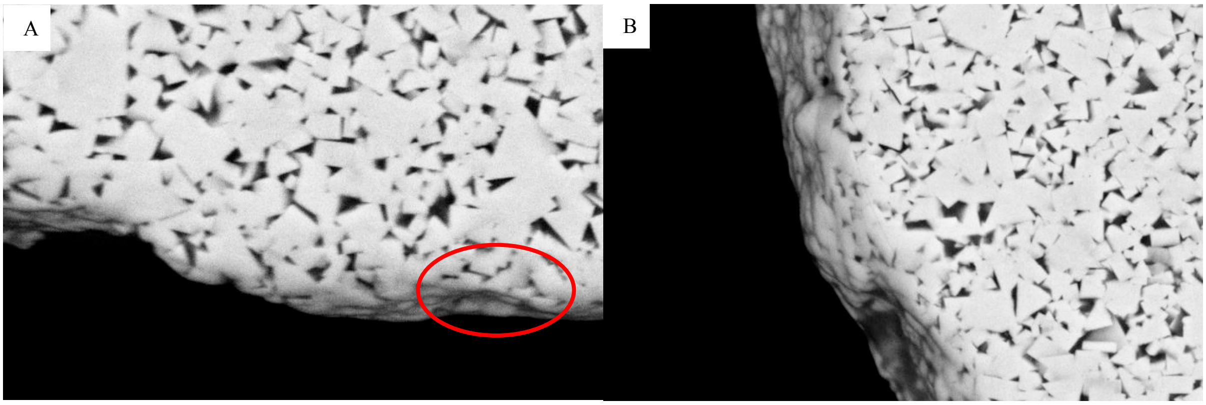

Figure 7: QBSD images of Carbide B worn tool edges at 10 kX magnification

This is a product of poor transgranular fracture toughness. However, most of the fracturing happens around the some of the grains unlike the wear that occurs in carbide C. As can be seen in Figure 8B the grains are compressed at the tool edge increasing the crystal density drastically. This is part of the forming process of the tool to harden the tool. This tool did also have the longest tool life and highest transgranular fracture toughness. This is more than likely due to the hardened surface grain. In the area where the tool wear is more concentrated, the edge looks like Figure 8A. This show much more intergranular fracturing along the edge than previously. The tools made from this grade Carbide failed due to localised chipping quite rapidly toward the end of its tool life were as the other tools gradually developed a flank land slowly.

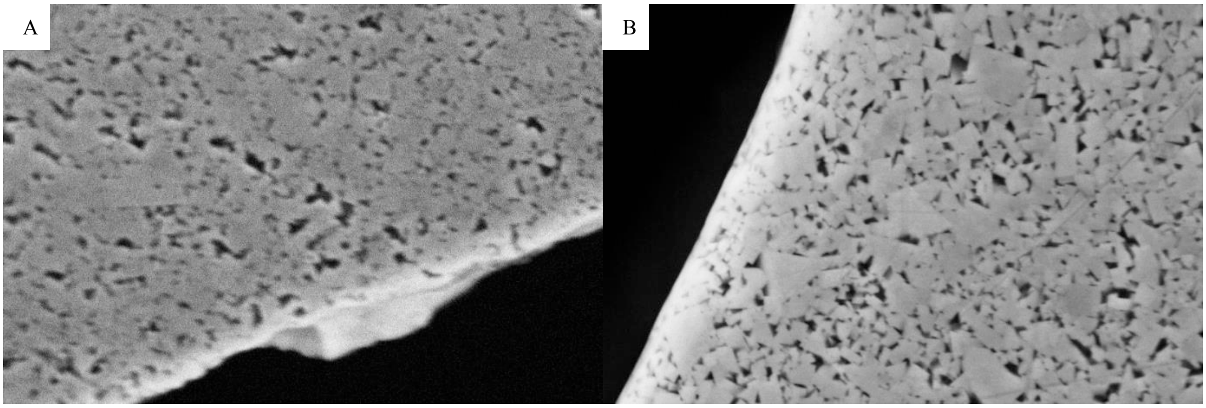

Figure 8: QBSD images of carbide C worn edges 10 kX magnification

This shows that transgranular fracture toughness is key to resisting the three-body abrasion that occurs during the machining of pre-sintered zirconia. This is more than likely due to the individual crystals of zirconia still be hard especially in comparison to the hardness of a whole disc of pre-sintered zirconia.

5. Discussion

The three carbide grades show less and less signs of transgranular fracturing from carbide A to carbide B to carbide C (left to right of Table 3). This points toward transgranular fracturing being the leading cause of tool failure. This further highlights that when machining pre-sintered zirconia three body abrasion is the primary wear mechanism as these go hand in hand. Zirconia has a very high transgranular fracture toughness allowing it to resist three-body abrasion itself [9]. This resistance comes from the fine grain size of the carbide C. As Carbide is a brittle failure material with in consistent grain structure is minimalizes the amount of material that is removed with each removal of the tool edge. Carbide C grade tools failed in a slightly different way to the other tools. Most of the tools had a progressive increase in flank wear land growth to point of failure like shown in Figure 3. Carbide C tools did this but much slower, then a small chip formed that rapidly propagated to point of failure as shown in Figure 9. This rapid propagation pointed towards this occurring due to the upper surface of this grade of carbide being harder; therefore, once a chink had been made in this layer the abrasion had two things going for it the increase surface area and the softer material.

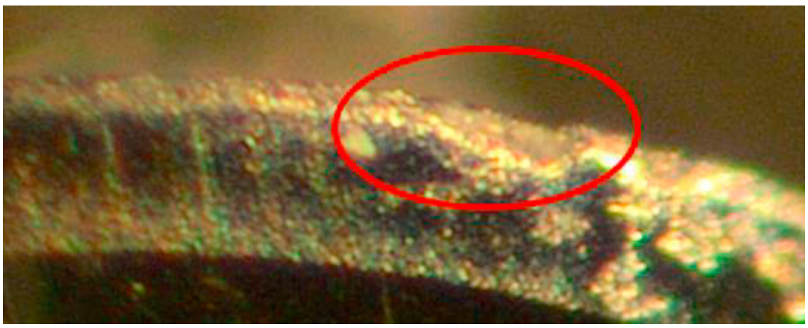

Figure 9: Chipping on tool edge of carbide C

This information will be especially useful to tool manufacturers when selecting carbide for creating tools to machine pre-sintered zirconia and materials that cause the same wear mechanism. Also in many dental laboratories, technicians are typically not from an engineering background meaning that tool wear is not something greatly understood in the sector. This has led to many parts failing inspection as the worn tool fails to create an accurate fitting edge.

During machining, zirconia dusts could become entrapped between the tool and the zirconia surface to create a three-body abrasion effect. Such effect had caused two types of material fracture on carbide, namely transgranular and intergranular fractures. Carbide A and B with submicron grain exhibited higher transgranular fracture as compared to the ultrafine grain, Carbide C. While Carbide C exhibited lower transgranular fracture, it also experienced intergranular fracture. Carbide C with finer grains had a higher hardness value was able to withstand abrasion caused by machining longer than any other carbide grades.

6. Conclusions

With the increased application of zirconia in digital dentistry, there is a need to have an in-depth understanding of the mechanisms of wear that are likely to happen as crowns etc. are manufactured. This is important from two perspectives, the manufacturer of the cutting tools needs to provide a product that does not fail in operation. The other player in this process is the dentist, they need to have confidence that the tools will remain intact and that the final crown is to the geometry they expect. Through SEM analysis and pattern of tool wear it was observed that the wear is three body abrasion as theorised by other works. Potentially problematic as only tooling with diamond coatings are likely to have the abrasive properties to withstand hard particle three body abrasion. However, further analysis of fracture including mean free path between grains need to be studied to make the analysis complete.

6.1 Future works

Now the groundwork of tool wear is understood, other parts of tooling need to be investigated so that the process can be more automated or tools can be put in place so that technician know when to change tools before parts start failing inspection. Further research should start with the reducing the sudden chipping that was shown to occur in carbide C.

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