Manufacturing Reliable Ceramic Crowns: The Role of Abrasive Machining in Digital Dentistry

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MANUFACTURING RELIABLE CERAMIC CROWNS – THE ROLE OF ABRASIVE MACHINING IN DIGITAL DENTISTRY

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ABSTRACT

Dental caries is a ubiquitous disease and nearly 100% of the population is affected worldwide. Consequently, the need for reliable dental restorations is highly demanded. As more and more patients expect and request esthetics and biosafety, thus, metal-free prostheses are desired. Both biocompatible and esthetic ceramics and digital processing of prostheses have been developed to meet these demands. This paper reviews the current status of abrasive machining involved in affordable digital dental ceramic restorations with respects to dental ceramic materials, dental CAD/CAM systems, and extra/intraoral dental handpiece adjustments. It highlights the importance and challenge of abrasive machining technologies in manufacturing of affordable and reliable dental restorations with cutting-edge materials.

1. INTRODUCTION

Tooth decay is the Australia's most common health problem. There are over 19 million decayed teeth in Australia and 11 million additional decayed teeth each year according to the data released by the Australian Dental Association (ADA) in 2012 [1]. Dental restorations are highly needed, and dental services cost approximately $2 billion/year [1]. Globally, dental caries and missing teeth are omnipresent and will remain one of the most ubiquitous diseases, eventually affecting nearly everyone in the world for decades to come [2, 3]. Currently, over 100 million crowns are needed; among them, biocompatible and aesthetic ceramic crowns cost $2 billion worldwide each year [4]. Worldwide, the demand for biocompatible, aesthetic, affordable and reliable ceramic restorations is increasing and the aging population will drive this demand even higher [5].

Porcelains were first introduced to dentistry in 1774 [6]. Since then, more and more ceramic materials such as polycrystalline and glass ceramics have been successfully applied as restorative materials. Processing of these materials is also evolved from traditional casting and forming to computer-assisted designed and manufacturing (CAD/CAM). In this article, we review the role of abrasive machining involved in ceramic restorations. We briefly discuss (1) the application of a wide range of dental ceramics based on their machinability, (2) the digital abrasive machining of dental ceramics for rapid production of prostheses, (3) the extraoral and intraoral final adjustments of ceramic prostheses, and (4) the challenges in production of reliable ceramic prostheses.

2. DENTAL CERAMICS

In dentistry, many dental restorative materials are available, including metals, ceramics, polymers and composites, but there are challenges about the future and long-term viability of these materials. Historically, metals are the oldest restorative materials that have been widely used as crowns, fixed partial dentures (FPFs), and removable partial dentures (RPDs). They are mechanically strong and durable, and have a long history of use in dentistry but are not esthetically pleasing because of their metallic color, and carry a risk of causing allergic or toxic reactions within the soft or hard tissues of the oral cavity. Meanwhile, the United Nations Environmental Programs (UNEP) and the World Health Organization (WHO) also concern on the use of mercury in dental amalgam, one of the heavy metals which pose a threat to human health [7].

To improve aesthetics, porcelains were first introduced to dentistry in 1774 [6], initially as veneers for porcelain-fused metal structures. Due to their high biocompatibility and aesthetics, more and more ceramics and porcelains are used as restorative materials in dentistry as ceramic-metal crowns. Over the last two decades, non-metallic bio/dental materials have become more and more popular. In particular, all-ceramic restorations consisting of short/long anterior/posterior bridges, crowns, onlays, inlays and veneers, and ceramic denture teeth have been developed [5, 8, 9]. These dental ceramics include porcelain-based feldspar, leucite, mica containing glass ceramics, glass-infiltrated alumina, spinell, or lithium disilicate glass ceramics, polycrystalline transformation-toughened tetragonal zirconia [8, 9].

Based on the mechanical properties, dental ceramics can be classified as machinable and difficult-to-machine materials. Machinable dental ceramics include mica-containing, feldspar, and leucite glass ceramics with hardness of approximately 6 GPa or less, fracture toughness of approximately 1 MPa.m$^{1/2}$ or less and flexural strength of approximately 100 MPa or less [9 – 11]. Examples of these materials are Vita Mark II (Vita Zahnfabrik, Germany) and ProCAD (Ivoclar Vivadent, Liechtenstein). Due to the low strength of these materials, they are more often used in anterior restorations. Machinable dental ceramics can be directly machined using commercial dental CAD/CAM systems to form prosthetic profiles and relatively easier adjusted in the oral environment using clinical dental handpieces and abrasive burs although both processes induce surface and subsurface damage to the materials if course diamond grits are applied.

More recently, high-strength difficult-to-machine materials have been used for all-ceramic load-bearing restorations. These materials are lithium disilicate glass ceramics, zirconia and glass-infiltrated alumina and spinell with flexural strength of higher than 400 MPa [8,9,12,13]. Examples of these materials include IPS emax.CAD and IPS emax.Press (Ivoclar Vivadent, Liechtenstein), and IPS emax.ZirCAD (Ivoclar Vivadent, Liechtenstein) and ZenoStar (Wieland Dental, Germany). These materials are commonly used in bi-layered veneer-core ceramic crown structures as core materials [8, 13–16]. However, these bi-layered structures were found less durable because brittle fractures frequently occur in weak porcelain veneers and veneer-core interfaces [13,17,18]. To overcome this structural weakness, monolithic ceramic crowns made from strong zirconia and lithium disilicate glass ceramics have been developed [13]. In comparison of these two materials, zirconia crowns appear unnatural and do not mimic human tooth colours due to its opacity although zirconia has higher strength [9,13]. Lithium disilicate glass ceramics match tooth colours well and promise to overcome the obstacles encountered with zirconia [9,13].

High strength ceramics of zirconia and lithium disilicate glass ceramics are very difficult to machine. Dental zirconia is yttria-stabilized tetragonal zirconia polyscrystal (Y-TZP) with a high-fracture strength and toughness. Y-TZP ceramics are fully dense with a fine microstructure consisting of submicrometer tetragonal grains, which can be transformed to monoclinic grains with volume dilatation [8,14]. This phase transformation produces compressive stresses, making crack propagation more difficult and surface flaws less detrimental to fracture [19–21]. Lithium disilicate glass ceramics have the unique multi-phase structures consisting of highly interlocked needle-like and layered lithium disilicate crystals and glass matrix. Due to the different thermal expansion coefficients and elastic moduli between lithium disilicate crystals and the glass matrix, tangential compressive stresses are formed in the microstructure of lithium disilicate glass ceramics, enabling the deflection of crack propagation under loads [22–24]. In general, both zirconia and lithium disilicate glass ceramics cannot be directly machined in their sintered states using commonly used dental CAD/CAM systems. For zirconia, pre-sintered zirconia is often machined by dental CAD/CAM machines. They are then sintered for high strength at temperatures of approximately 1350–1500 °C [14]. Similarly, lithium metasilicate glass ceramics are firstly milled using dental CAD/CAM systems for dental prosthetic profile generation. They are then heat-treated to a temperature of 850 °C to form lithium disilicate glass ceramics [22]. Abrasive machining of both pre-sintered materials produces extensive machining damage and traces, which cannot be fully healed during sintering. These machining defects must be minimized by polishing because they result in the early failure of the ceramic crowns and the serious wear of mating teeth during chewing [4,5,11]. However, high strength of fully sintered zirconia and lithium disilicate glass ceramics make polishing and intra-oral adjusting with diamond abrasives very difficult.

3. DENTAL CAD/CAM SYSTEMS

Conventional fabrication processes of dental crowns and bridges generally involve intraoral abutments, impression, working model, waxing up, casting of metal works, porcelain works, final restorations, luting to the abutments [15,16]. These processes are manually based, labor-intensive, and heavily depended on the art crafts of individual dental clinicians. Such methods are unlikely useful for the fabrication of crowns or bridges made of modern dental ceramics. Digital dentistry, represented by dental CAD/CAM technologies, has been introduced to restorative dentistry since 1980's. Since then, restorative processes have been digitized and computer-assisted. Similar to any other CAD/CAM systems applied in manufacturing engineering, dental CAD/CAM systems are also based on data acquisition, data processing and manufacturing. They consist of digital image generation and data acquisition, computer-assisted milling systems and tooling systems [15,16]. For instance, intraoral digitizing (optical impression) is used to replace conventional impression. CAD is applied for replacing of virtual model/waxup. CAM with NC machining/milling is utilized to generate final restorations. Now it is possible to create a 3D model of the oral cavity directly with advanced computer-aided scanning systems. The digital model can then be used to design the restoration, such as crowns, bridges and partial denture framework in less than 20 minutes [25].

Once the restoration solid model is established, abrasive machining using diamond tools is commonly involved in milling and grinding of ceramic blocks to generate dental restorative profiles. First, computer-aided process planning (CAPP) needs to be approved. Following is the CAM process in which a diamond milling toolpath needs to be designed to machine the ceramic block to generate the basic restorative profile. Details of these operations include the defining of machining boundaries, options of auto cut, cut single or cut all, selections of machining parameters for multi-axis solids or surface toolpaths, and toolpath capabilities of finishing.

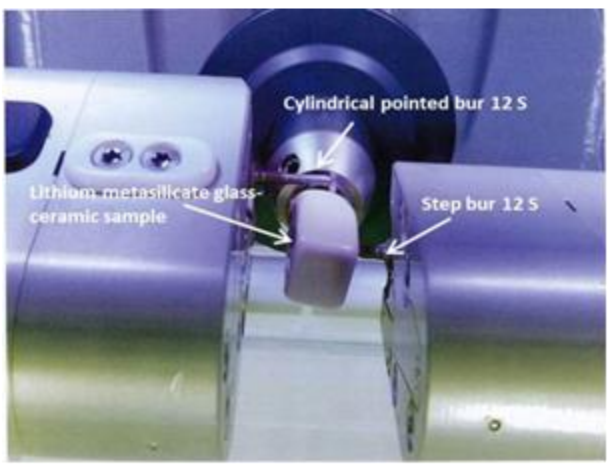

Fig. 1. CAD/CAM abrasive machining of a lithium metasilicate glass-ceramic (emax.CAD) block using a chairside CAD/CAM system (CERAC AC, Sirena) in which two milling units with diamond burs are used.

Fig. 2. Two diamond burs applied in the chairside CAD/CAM dental system in Fig. 1, (a) a step bur 12 S and (b) a cylindrical pointed bur 12 S.

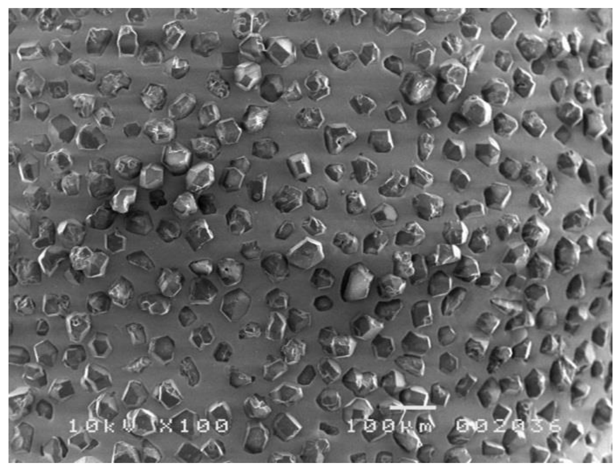

Fig. 3. Scanning electron micrograph of the detailed morphology of diamond abrasive grits on the diamond burs in Fig. 2, revealing of diamond grit size of approximately 60 µm.

Commercial dental CAD/CAM systems are classified as chairside or office-based and laboratory-based. Chairside dental CAD/CAM systems provide in-office design and milling, allowing one-appointment restoration fabrication using prefabricated ceramic monoblocks. Today, the most popular chairside system is the CEREC AC (Sirona Dental Systems GmbH, Bensheim, Germany), which was introduced in 1987 by Mormann and the first dental system to combine digital scanning with a milling unit [26]. Over the thirty years, the CEREC systems have been significantly evolved. The current version is capable of taking half-arch or full arch impressions and creating crowns, veneers and multiple unit bridges. It is equipped with an advanced intraoral 3D scanning device (digitizer) using intense blue light from blue light-emitting diodes and powerful software to create 3D restorative models, this system enables the milling of a very wide spectrum of all machinable dental ceramics, lithium metasilicate glass ceramics, and pre-sintered zirconia blocks [26,27]. The twin milling units with the two axes of four degrees of freedom for each one are installed for simultaneous processing of restorations with two diamond burs. Fig. 1 shows the CAD/CAM abrasive machining of a lithium metasilicate glass-ceramic (emax.CAD) block using a chairside CAD/CAM system (CERAC AC, Sirena) in which two milling units with diamond burs are used. The milling units have the function of digital closed-loop feed control for extremely sensitive processing of ceramic materials. Two burs have cylindrical and step shapes, as shown in Fig. 2, rotate at a rotational speed of 60,000 rpm. Scanning electron micrograph in Fig. 3 shows that both diamond burs are single-layered and electroplated with diamond grit morphology and size of approximately 60 μm [26,27].

Laboratory-based dental CAD/CAM systems are much large, more expensive, and have more integrated and precise functions in comparison with chairside systems [28–30]. These systems are particularly useful for direct grinding or milling of fully sintered, completely dense zirconia or alumina ceramic restorations with high strength. Thus, sintered-induced shrinkage can be avoided to obtain high precision of restorations. More advanced laboratory-based CAD/CAM systems are centralized production using machining centers and network systems [15,28,29]. Satellite scanners in the dental laboratory can be connected with a production center via the Internet. Data sets of restorative models produced in the dental laboratory are sent to the machining center for the manufacture of the restoration. These laboratory-based devices or machining centers use 3-axis, 4-axis or 5-axis milling systems using tungsten carbide end milling tools or single-layered electroplated diamond tools [15,16,30]. For pre-sintered ceramic blocks, dry-milling is generally used to reduce the machining cost and avoid moisture absorption by the highly porous ceramic [29]. For fully sintered high-strength ceramics, wet milling with diamond tools is conducted to reduce the machining heat and machining-induced damage to the ceramic workpiece. Tool wear in machining of these fully sintered ceramics is very severe. Examples of laboratory-based dental CAD/CAM systems include DECSY (DIPRO, Tokyo, Japan), inLab (Sirona Dental Systems GmbH, Bensheim, Germany), Lava (3M ESPE, Saint Paul, Minnesota, USA) [15,16,29–31].

4. DENTAL HANDPIECE ADJUSTMENT

Although dental CAD/CAM systems produce reasonably accepted profile precision of restorations, manual adjustments must be operated by clinicians to meet marginal and occlusal fits before restorations are finally fixed in a patient's mouth. This process includes extraoral and intraoral operations using dental handpieces and dental abrasive burs. Fig. 4 demonstrates two clinically applied high-speed dental handpieces with inserted diamond burs with cylindrical and flame shapes. Both air-turbine and electric dental pieces are very popularly used in clinics, rotating at speeds of 300–400 krpm. Diamond burs are made from natural or synthetic diamond grits with a wide range of grit sizes from super coarse to ultrafine grains [32–34]. Fig. 5 shows a scanning electron micrograph of diamond grits of approximately 100 μm.

Fig. 4. Clinically applied high-speed dental handpieces with diamond burs of cylindrical and flame shapes.

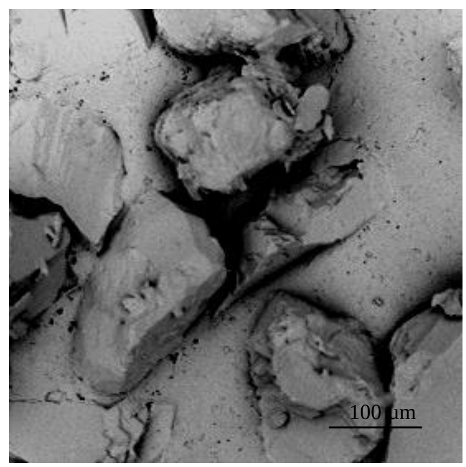

Fig. 5. Scanning electron micrograph of a medium dental bur with diamond grits of approximately 100 μm.

Fig. 6 demonstrates the extraoral adjusting of a porcelain-fused-to-metal (PFM) dental crown. A dental handpeice, manually controlled by a clinician, drives the diamond bur with morphology shown in Fig. 5 to grind the porcelain surface of the crown. Fig. 7 shows a 3D scanning electron micrograph with surface roughness measurement of the adjusted porcelain surface using the diamond bur shown in Fig. 5. It reveals machining scratches and traces, and average and maximum surface roughness values of *Ra* and *Rz* of 2.29 μm and 12.41 μm, respectively. Polishing must be conducted using fine diamond abrasives to remove theses scratches and roughness for high quality restorations.

Fig. 6. Extraoral adjusting of a porcelain-fused metal (PFM) dental crown using a clinical dental handpiece and the dental bur with diamond abrasives shown in Fig. 5.

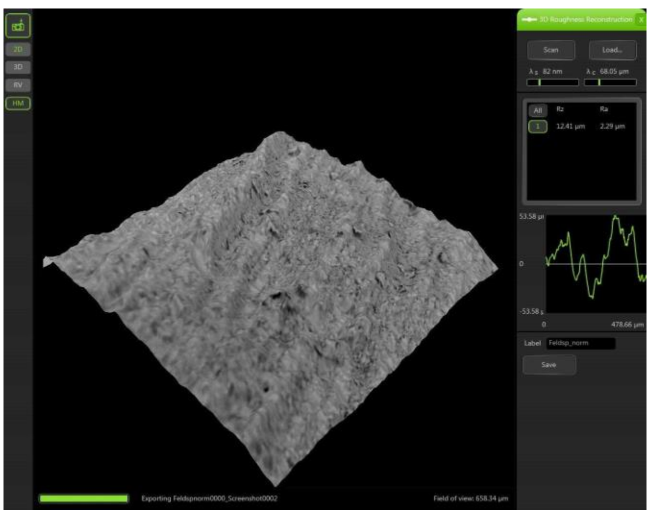

Fig. 7. 3D scanning electron micrograph of the adjusted porcelain surface using the diamond bur in Fig. 5, with the measured average and maximum surface roughness values of 2.21 µm and 12.41 µm, respectively.

Intraoral adjusting is a very routine practice in clinical dentistry for final adjustment of prostheses with high-speed handpieces. In this process, cautions must be taken as many patients suffer from dental phobia. Simulated studies on dental adjustment of a wide range of dental ceramics and porcelains have shown that surface quality of ceramic restorations and cutting processes depended on the operational parameters using either air-turbine or electric handpieces [35,36]. In particular, surface roughness and surface/subsurface damage are significantly controlled by diamond grit sizes [37–39]. Due to the coolant volume limitation in the oral environment, intraoral abrasive machining-induced heat can cause phase transformations in some glass ceramics, which likely results in phase-transformation induced cracks to the ceramic restorations [37].

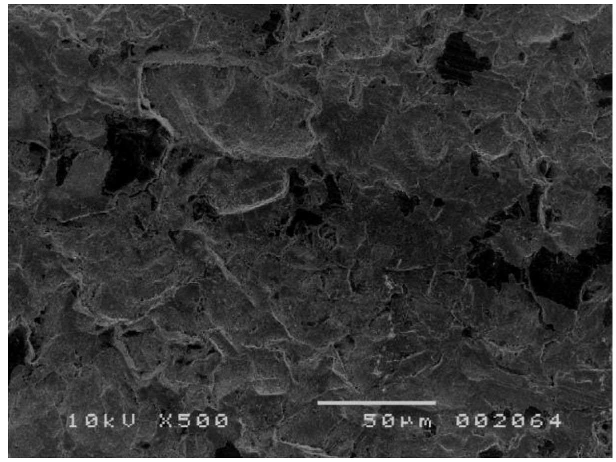

Fig. 8. Scanning electron micrograph of CAD/CAM machined lithium metasilicate glass ceramic (emax.CAD) showing brittle fracture on the surface.

5. CHALLENGES AND FUTURE OUTLOOK

All current chairside or laboratory-based CAD/CAM systems apply exclusively cutting restorations from a prefabricated block using diamond abrasive burs. This subtractive approach can create complete restorative shapes effectively, but at the expense of material being wasted. Studies have found that approximately 90% of a prefabricated block is removed to create a typical dental restoration [28]. The additive manufacturing or 3D printing approach is beginning to be explored in dental CAD/CAM systems [12,25,28]. In this approach, selective laser sintering is used for fabrication of ceramic and metal restorations [28]. In contract to the subtractive approach, additive manufacturing produces a restoration by building up a restoration in layers by depositing material based on the digital 3D design data [25]. However, new challenges have arisen, which include how to diminish the laser-sintering induced thermal cracks in ceramics and how to reduce the high production cost.

Due to the brittle nature of ceramics, machining-induced surface and subsurface damage has been a persistent problem in ceramic crowns obtained by digital manufacturing processes, which lead to catastrophic failure of the crowns [4,5,27,40]. Fig. 8 shows a scanning electron micrograph of CAD/CAM machined lithium metasilicate glass ceramic (emax.CAD) using chairside CERAC AC, in which brittle fracture occurred on the ceramic surface. Extraoral and intraoral adjustment of ceramic restorations using dental handpeices and diamond burs also undergoes indenting, scratching, cutting, removing and polishing processes by harder abrasives. These material removal activities inevitably induce surface and subsurface damage deep down to over 100 μm in restorations [39]. Studies have found that machining-induced surface flaws are the primary cause of failure in ceramic restorations [36,37]. Clinical studies have shown that brittle fracture causes the failure of ceramic crowns with a high failure rate of 21% over three years for high-load bearing layered ceramic molars [5]. High-strength ceramics, such as lithium disilicate glass ceramics and zirconia, have enabled monolithic crown designs with improved lifetime [13]. Despite the promising mechanical properties of these materials, they share the fabrication limitations of established dental ceramic materials, including (a) they are brittle and difficult to machine; (b) machining in the CAD/CAM fabrication process produces poor surface quality due to machining traces, surface and subsurface damage; (c) efficient polishing techniques need to be developed to minimize machining traces, surface and subsurface damage; (d) the influence of surface quality of engineered crowns on their wear and fatigue behaviour is poorly understood. Thus, there is an urgent need to improve the reliability of advanced ceramic crowns which relies on their manufacturing quality to obtain optimal wear and fatigue performance.

6. CONCLUSIONS

Digital manufacturing of ceramic restorations using dental CAD/CAM systems and extraoral/intraoral adjustment using dental handpieces have provided rapid restorative services to dental patients. All these processes involve abrasive machining, in which diamond or tungsten carbide tools play a key role in subtractive material removal. These processes create complex profiles of restorations, resulting in extensive material waste and surface/subsurface damage in restorations. High-strength and esthetic ceramics are expected to have prolonged life span. However, failures of these restorations applied in load-bearing posterior regions are found due to surface flaws produced in abrasive machining processes, which are stress concentration and crack origins. Emerging technologies such as 3D printing and high-quality abrasive machining techniques may significantly enhance the capabilities of digital dentistry to ensure that these cutting-edge materials are used to their fullest potential.

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