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Research Paper

Property–process relations in simulated clinical abrasive adjusting of dental ceramics

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ABSTRACT

This paper reports on property–process correlations in simulated clinical abrasive adjusting of a wide range of dental restorative ceramics using a dental handpiece and diamond burs. The seven materials studied included four mica-containing glass ceramics, a feldspathic porcelain, a glass-infiltrated alumina, and a yttria-stabilized tetragonal zirconia. The abrasive adjusting process was conducted under simulated clinical conditions using diamond burs and a clinical dental handpiece. An attempt was made to establish correlations between process characteristics in terms of removal rate, chipping damage, and surface finish and material mechanical properties of hardness, fracture toughness and Young's modulus. The results show that the removal rate is mainly a function of hardness, which decreases nonlinearly with hardness. No correlations were noted between the removal rates and the complex relations of hardness, Young's modulus and fracture toughness. Surface roughness was primarily a linear function of diamond grit size and was relatively independent of materials. Chipping damage in terms of the average chipping width decreased with fracture toughness except for glass-infiltrated alumina. It also had higher linear correlations with critical strain energy release rates ($R^2=0.66$) and brittleness ($R^2=0.62$) and a lower linear correlation with indices of brittleness ($R^2=0.32$). Implications of these results can provide guidance for the microstructural design of dental ceramics, optimize performance, and guide the proper selection of technical parameters in clinical abrasive adjusting conducted by dental practitioners.

1. Introduction

Polycrystalline and glass ceramics are extensively used in dental restorations as veneers, crowns, bridges, inlays and onlays due to their desirable aesthetics and inherent biocompatibility (Denry and Holloway, 2010; Kelly, 2004; Rekow et al., 2011). Depending on the mechanical and aesthetic requirements in clinical applications, a variety of materials are available. These dental ceramics include porcelain-based materials, glass-infiltrated alumina, spinell, or lithium disilicate, polycrystalline transformation-toughened tetragonal zirconia, and mica glass ceramics (MGC) (Denry and Holloway, 2010; Kelly, 2004; Kelly and Benetti, 2010). In restorative dentistry, the principal means of shaping and fitting ceramic restorations is by abrasive machining with rotational diamond tools with multiple cutting grits applied in two different environments (von Fraunhofer and Siegel, 2003; Rekow et al., 2011). In dental laboratories or clinics,

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deterministic computer-aided design and manufacture (CAD/CAM) systems with diamond milling tools are commonly used to prepare restorations from bulk materials (Bindl and Mörmann, 2005; Guess et al., 2010; Miyazaki et al., 2009; Rekow, 2006; Schmitter et al., 2012). The CAD/CAM milling process of bulk materials is deterministically operated under computer control using diamond milling tools of 64 μm grit size at 45 m/s milling speed and is supplied with sufficient coolant to removal milling chips (Sindel et al., 1998). In the oral environments, manual adjustments and finishing with diamond dental burs and dental handpieces are required during the placement of the restoration (Stappert et al., 2006). Dental burs of approximately 1 mm diameter, driven by air-turbine or electric handpieces, rotate at 260 K–400 K rpm at a water coolant rate of 15–30 ml/min and are manually manipulated by dentists (Choi et al., 2010; von Fraunhofer and Siegel, 2003).

High hardness and strength of dental ceramics, as well as their inherent brittleness and associated susceptibility to fracture, make abrasive machining response an important issue in both fabrication and adjustments of dental ceramics using diamond milling tools or dental burs (Chang et al., 2011; Schmitter et al., 2012). In particular, any residual damage induced during clinical adjusting in the oral environments can endanger the durability of a ceramic prosthesis, because clinical adjusting is the final machining process for controlling the quality of the prosthesis. Chipping damage at an edge during abrasive adjusting may impair the fit or appearance of a restoration and render it unacceptable for placement (Chang et al., 2011; Swain, 2009). Moreover, edge chipping is a manifestation of the introduction of surface and subsurface cracks (Song and Yin, 2009, 2010). Under appropriately applied stresses such cracks may result in fracture failure, seriously degrading the performance and reliability of restorations (Rekow et al., 2011; Song and Yin, 2010).

Abrasive adjusting of dental materials was investigated using disposable, single layer diamond burs and high-speed, air-turbine dental handpieces operated under conditions that simulated those employed in a clinical setting (Chang et al., 2011; Dong et al., 2000; Siegel and von Fraunhofer, 1997a; Yin et al., 2001, 2003, 2004). The primary adjusting variable evaluated was bur grit size. The main machining characteristics measured were removal rate, surface roughness and degree of edge chipping. The influences of coolant chemistry and bur loading (accumulation of machining chips on the bur) on removal processes were also studied (Dong et al., 2000; von Fraunhofer and Siegle, 2003; Yin et al., 2004). Not surprisingly, the machining characteristics varied considerably for different materials. For a series of MGC, the diamond bur grit size and the load applied to the bur during machining had significant effects on the machining behavior (Dong et al., 2000). By increasing the size of mica platelets in glass ceramics, or by increasing the load on burs, the material removal rate increased. The chipping damage for MGC materials increased as either the load was increased or as the size of mica platelets decreased (Dong et al., 2000). It was also found that for a MGC containing coarse mica crystals, improved material removal rates and less machining fracture damage were obtained by an appropriate selection of coolant chemistry (Yin et al., 2004). For zirconia, no cracks and chipping damage could be detected for diamond burs of any grit size (Yin et al., 2003).

All previous studies have focused on individual materials or materials groups in clinical abrasive adjusting. In view of the complexity and importance of the clinical adjusting process, the question arises whether there is any mechanical property or combination of mechanical properties, which can be related to process characteristics, namely removal rate, surface roughness and chipping damage. These property–process relations in clinical adjusting of dental ceramics using handpieces have not been established. These relations lie at the heart of materials and process selections for restorative design in clinical dentistry. In ceramic grinding using large diamond wheels, property–process relations for a number of polycrystalline ceramics including alumina, silicon carbide, zirconia and silicon nitride have been established based on indentation fracture theories (Evans and Marshall, 1980; Jahanmir et al., 1999; Lawn, 1995; Marshall and Lawn, 1986; Yin and Huang, 2004). Whether these theories can be directly applied to clinical adjusting processes for dental ceramics is questionable. Therefore, this paper aimed to study the role of the mechanical properties in clinical abrasive adjusting of a wide spectrum of dental ceramics and to examine the relationship between material properties and abrasive adjusting process. The investigation attempted to establish correlations by examining the effects of seven dental ceramic properties on process characteristics, utilizing some previously published data (Dong et al., 2000; Yin et al., 2001, 2003). It was hoped that clear correlations would establish the predominant mechanism of material removal and adjusting quality under clinical conditions. Correlations were attempted between the removal rates, surface roughness and edge chipping and material mechanical properties to determine, at least, what properties most affect the outcomes of clinical adjusting process.

2. Experimental procedure

2.1. *Materials*

Seven dental ceramics were selected in this investigation, including four mica glass ceramic (MGC) materials, a feldspathic porcelain, a glass-infiltrated alumina, and an yttria-stabilized tetragonal zirconia (Y-TZP). The MGC materials consisted of a K_2O–MgF_2–MaO–Si_2O based glass matrix in which tetrasilicic mica platelets were precipitated. The three MGC materials (Corning, New York, USA) had average mica platelet diameters of 1.1 μm (MGC-Fine), 3.7 μm (MGC-Medium), and 10.0 μm (MGC-Coarse), respectively (Peterson et al., 1998b; Quinn et al., 2000). The forth MGC was a MGC-Dicor (Dentsply/Caulk, Milford, Delaware, USA) and had a mica platelet diameter of approximately 2 μm. The porcelain was Vita Mark II (Vita Zahnfabrik, Bad Säckingen, Germany), used for inlay/onlay/veneer restorations in the CAD/CAM Cerec system (Siemens, Bensheim, Germany). It consisted of a glass matrix containing approximately 30 vol% of sanidine, nepheline and anothoclase crystals of 1–7 μm in size (Peterson et al., 1998a; Yin et al., 2006). The alumina was an In-Ceram Celay alumina (Vita Zahnfabrik, Bad Säckingen, Germany),