JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 65 (2017) 102–116

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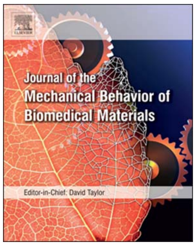

Research Paper

# Surface quality of yttria-stabilized tetragonal zirconia polycrystal in CAD/CAM milling, sintering, polishing and sandblasting processes

*Abdur-Rasheed Alao*[a], *Richard Stoll*[b], *Xiao-Fei Song*[c], *Takashi Miyazaki*[d], *Yasuhiro Hotta*[d], *Yo Shibata*[d], *Ling Yin*[a,*]

[a]*Mechanical Engineering, College of Science & Engineering, James Cook University, Townsville, QLD 4811, Australia*
[b]*Restorative Dentistry, College of Medicine and Dentistry, James Cook University, Cairns, QLD 4870, Australia*
[c]*Key Laboratory of Advanced Ceramics and Machining Technology of Ministry of Education,*
*School of Mechanical Engineering, Tianjin University, Tianjin 300072, China*
[d]*Division of Biomaterials and Engineering, Department of Conservative Dentistry, Showa University School of Dentistry,*
*Tokyo 142-8555, Japan*

ARTICLE INFO

*Article history:*
Received 22 June 2016
Received in revised form
11 August 2016
Accepted 13 August 2016
Available online 20 August 2016

*Keywords:*
CAD/CAM milling
Material removal mechanisms
Phase transformation
Surface damage & morphology
Surface treatments
Yttria-stabilized tetragonal zirconia polycrystal

ABSTRACT

This paper studied the surface quality (damage, morphology, and phase transformation) of yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) in CAD/CAM milling, and subsequent polishing, sintering and sandblasting processes applied in dental restorations. X-ray diffraction and scanning electron microscopy (SEM) were used to scan all processed surfaces to determine phase transformations and analyse surface damage morphology, respectively. The average surface roughness ($R_a$) and maximum roughness ($R_z$) for all processed surfaces were measured using desk-top SEM-assisted morphology analytical software. X-ray diffraction patterns prove the sintering-induced monoclinic-tetragonal phase transformation while the sandblasting-induced phase transformation was not detected. The CAD/CAM milling of pre-sintered Y-TZP produced very rough surfaces with extensive fractures and cracks. Simply polishing or sintering of milled pre-sintered surfaces did not significantly improve their surface roughness (ANOVA, $p > 0.05$). Neither sintering-polishing of the milled surfaces could effectively improve the surface roughness (ANOVA, $p > 0.05$). The best surface morphology was produced in the milling-polishing-sintering process, achieving $R_a = 0.21 \pm 0.03\ \mu m$ and $R_z = 1.73 \pm 0.04\ \mu m$, which meets the threshold for bacterial retention. Sandblasting of intaglios with smaller abrasives was recommended as larger abrasive produced visible surface defects. This study provides technical insights into process selection for Y-TZP to achieve the improved restorative quality.

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*Corresponding author.
E-mail address: ling.yin@jcu.edu.au (L. Yin).

http://dx.doi.org/10.1016/j.jmbbm.2016.08.021
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## 1. Introduction

Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) has high strength and fracture toughness, good biocompatibility, low radioactivity, which make it suitable for applications as load-bearing core structures in crowns and bridges in restorative dentistry (Denry and Kelly, 2008; Manicone et al., 2007; Miyazaki et al., 2013). Recent progress in the processing of Y-TZP materials with high translucency could significantly widen the clinical indications of monolithic zirconia restorations to avoid interface fractures in veneer-core structures (Tong et al., 2016). Generally, pre-sintered or sintered Y-TZP blocks or discs can be shaped to restoration profiles using CAD/CAM technologies (Andersson and Odén, 1993; Beuer et al., 2008; Miyazaki et al., 2009; Mörmann, 2006; Rekow, 2006; Strub et al., 2006; Yin et al., 2006). These digital manufacturing technologies assure the standardization and the uniform material quality of the restorations, reducing their fabrication time and manufacturing cost (Rekow and Thompson, 2005; Wittneben et al., 2009). However, CAD/CAM milling of fully sintered Y-TZP requires machining systems to be extremely strong, robust and stiff because of the high strength, high hardness and low machinability of the material (Alao and Yin, 2014b, Denry and Kelly, 2008; Rekow et al., 2011). Further, machining-induced mechanical stresses in sintered Y-TZP can cause the martensitic tetragonal to monoclinic phase transformation, resulting to low temperature degradation of the restorations and making them susceptible to catastrophic fracture (Silva et al., 2010; Zarone et al., 2011).

To avoid these problems, CAD/CAM milling is more often conducted on pre-sintered Y-TZP in enlarged frameworks to compensate for sintering shrinkages (Filser et al., 2003; Klocke et al., 1998). Then, sintering is performed for full crystallization to ensure the diffusion of ions across Y-TZP grain boundaries without the involvement of a liquid phase, achieving the increased mechanical strength (Hallman et al., 2012). In addition, the fabrication process of pre-sintered Y-TZP can decrease the milling time and reduce the cutting tool wear (Al-Amleh et al., 2010; Alao and Yin, 2014b, 2016; Denry, 2013; Filser et al., 2003; Klocke et al., 1998; Luthardt et al., 2004; Ritzberger et al., 2010). However, surface and subsurface damages can easily occur in CAD/CAM milled pre-sintered Y-TZP surfaces (Rekow and Thompson, 2005) because of its low damage tolerance and stiffness (Alao and Yin, 2014b, 2016). These damages cannot be healed in the subsequent sintering process. Therefore, they compromise the strength of the restorations and shorten their lifetimes (Rekow et al., 2011).

To minimize the milling-induced damage and understand the material behaviour of zirconia in diamond abrasive processes, indentation studies simulating the abrasive machining behaviour (Komanduri et al., 1997; Malkin and Hwang, 1996) have been conducted on pre-sintered Y-TZP (Alao and Yin, 2014b, 2016). These studies have detailed the microstructural compaction (pore closure and opening), and kink band formation in porous Y-TZP during the penetration processes by a diamond indenter (Alao and Yin, 2014b). Meanwhile, the machinability of pre-sintered Y-TZP was also determined in terms of its elasticity, plasticity and resistance to machining-induced damage (Alao and Yin, 2016). High deformation rates in indentation corresponding to high cutting speeds in abrasive machining were found to be favourable for the ductile material removal mode for minimization of the machining-induced damage in porous pre-sintered Y-TZP (Alao and Yin, 2014b, 2016). However, indentation mechanics do not cover all aspects of the machining behaviour (Komanduri et al., 1997; Malkin and Hwang, 1996). Therefore, it is essential to conduct machining science studies for the understanding of the fundamental responses of pre-sintered Y-TZP to CAD/CAM milling process for high quality of restorations.

Following the sintering process of the CAD/CAM-milled Y-TZP materials, the restorations generally require further surface treatments for improved or roughened surface finishes depending on surface orientations (Denry and Kelly, 2008; Miyazaki et al., 2009; Rekow et al., 2011). In general, exterior surfaces, i.e., occlusal, buccal and lingual surfaces, must be intra/extra-orally polished to obtain occlusal fitness, adequate surface textures and roughness for aesthetic light reflection and bacterial plaque retention (Bollen et al., 1997). Highly polished-sintered Y-TZP surfaces were reported to exhibit bio-tribological properties similar to natural teeth which lowered the antagonist enamel wear (Mitov et al., 2012; Miyazaki et al., 2013; Passos et al., 2014; Preis et al., 2012). Interior intaglio surfaces are normally roughened by chemical etching or sandblasting for strong adhesion of ceramic restorations in the oral environment (Denry and Kelly, 2008; Miyazaki et al., 2009; Rekow et al., 2011). Chemical etching of sintered Y-TZP in hydrofluoric acid is impossible due to the absence of the glassy phase in the materials, which makes adequate roughness and micromechanical bonding possible (Hallmann et al., 2016; Kern, 2009; Monaco, 2013). Therefore, chemical activation for roughening of intaglio surfaces of sintered Y-TZP has to be replaced by mechanical actions, such as sandblasting. Pure alumina particles (Chintapalli et al., 2013; Kosmač et al., 1999, 2000; Monaco, 2013), silica coated alumina particles (Kern, 2009) or zirconia particles (Hallman et al., 2016) are all used for the blasting processes. Studies have investigated the sandblasting effect on the strength of Y-TZP (Chintapalli et al., 2014; Curtis et al., 2006; Guazzato et al., 2005; Hallmann et al., 2016; Kosmač et al., 1999, 2000; Passos et al., 2015; Zhang et al., 2004). However, little has been done towards systematic studies of the characteristics of CAD/CAM-milled pre-sintered Y-TZP surfaces under different pre- and post-mechanical and thermal treatments.

Surface quality plays an important role in the mechanical behaviour such as wear and fatigue of dental restorations (Denry, 2013, Rekow and Thompson, 2005; Rekow et al., 2011). The quality measures include surface roughness and morphology, phase transformation, mechanical properties of processed surfaces (Ulutan and Ozel, 2011). The surface quality of sintered Y-TZP has been investigated in conventional and high-speed grinding processes (Luthardt et al., 2004; Xu et al., 1997; Yin and Huang, 2004; Yin et al., 2003). However, there lacks comprehensive and systematic examinations of the surface integrity of CAD/CAM-milled pre-sintered Y-TZP surfaces subjected to different sintering, polishing and sandblasting conditions.