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Unstable cracking (chipping) of veneering porcelain on all-ceramic dental crowns and fixed partial dentures

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Abstract

The central argument of this study is that residual stresses developed during the preparation of all-ceramic crowns and fixed partial dentures coupled with contact-induced cracking are the origin of the excessive chipping observed in clinical applications. The aim of this paper is to provide a simple basic analysis of the causes of residual stress development in ceramics and identify the key thermo-mechanical parameters responsible for these stresses and the resultant contact-induced failure. For simplicity, a bilayer planar geometry is considered. The key outcomes are the critical role of thermo-elastic properties and the thickness of the structures. The approach is then used to evaluate the propensity for unstable cracking of a range of crown structures, including substructures of a range of ceramics, and to show that two specific combinations are most prone to this behaviour, namely porcelain fused to glass ceramics and zirconia substrates. In addition, a simple approach for the minimization of the likelihood for such behaviour and chipping is proposed.

Keywords: Porcelain chipping; Dental crowns; Residual stresses

1. Introduction

All-ceramic crowns and fixed partial dental structures have become increasingly popular over the past decade [1]. The rapid take up of these intrinsically brittle materials has been hastened by advances in CAD/CAM technology that have enabled automated scanning of the complex shapes of teeth and the milling of such materials. Furthermore, the introduction of high-strength tetragonal yttria-partially stabilized zirconia (Y-TZP) as a framework material and the ability to rapidly machine this material in its partially sintered state has helped. This combination has very attractive aesthetic and biocompatibility properties in addition to its high strength and fracture toughness [2]. However, over the past 20 years there have been two other all-ceramic systems that have been widely available, namely In-ceram alumina and alumina onto which porcelain has been fired. These materials for single crown applications have had considerable success but, because of their inferior mechanical properties, they have been recently superseded by zirconia-based frameworks. Other materials that have been widely used for single crowns and short-span fixed partial dentures have been various glass ceramics containing leucite and lithium disilicate crystalline phases within a glass matrix [3].

During the last 3–5 years there has been an increasing number of clinical reports of failure of all-ceramic crowns and fixed partial dentures with an incidence much greater than porcelain fused to metal structures [2,4–10]. In addition, numerous local conferences (e.g., IADR, Toronto, August 2008; Zirconia, Zurich, November 2007) have been held to try to determine the origin of this problem, which is more pronounced with some laboratories than others even when the same materials of construction are used. There have also been reports of complete fracture of glass ceramic and glass-infiltrated porous ceramic-based crowns and bridges [11]. In general, the failure mechanisms of such

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materials have not been well documented as generally tests to evaluate and compare their behaviour have been based on "crunch the crown" tests, which are generally not able to be critically evaluated to understand the problem. More recently, observations of biaxial strength tests on bilayered materials have reported that crack propagation extends along the interface in porcelain bonded to zirconia whereas in other all-ceramic structures cracks had a tendency to run through the interface [12]. However, very recently there have been an increasing number of reports of clinical failures in porcelain fused to zirconia substrates that show crack extension throughout the porcelain. One example of such a failure in porcelain fused to a zirconia implant abutment is shown in Fig. 1. This shows a crack initiating within the porcelain and extending into the thicker part of the porcelain veneer before running to the surface. The present study investigates parameters that contribute to the latter failure problem.

The preparation of crowns and fixed partial dentures involves a series of thermal sintering cycles and associated cooling processes prior to the build-up of the next layer. It has been found that the matching of the thermal expansion between the porcelain and underlying framework, be it metal or ceramic, is critical for the avoidance of cracking after firing. Experimentally it has been found that a mismatch in coefficient of thermal expansion (CTE) of more than 10% results in such cracking, with the nature of the cracks dependent on whether the porcelain has a higher or lower CTE than the framework [34]. When the porcelain has a much higher CTE than the framework, cracks initiate normal to the surface because of the tensile stresses that develop in the porcelain on cooling. When the CTE of the framework is considerably higher than the porcelain, delamination of the porcelain may occur. DeHoff et al. [13] generated a finite element model of this behaviour and were able to predict the magnitude of the residual stresses as a function of the mismatch of CTE. These

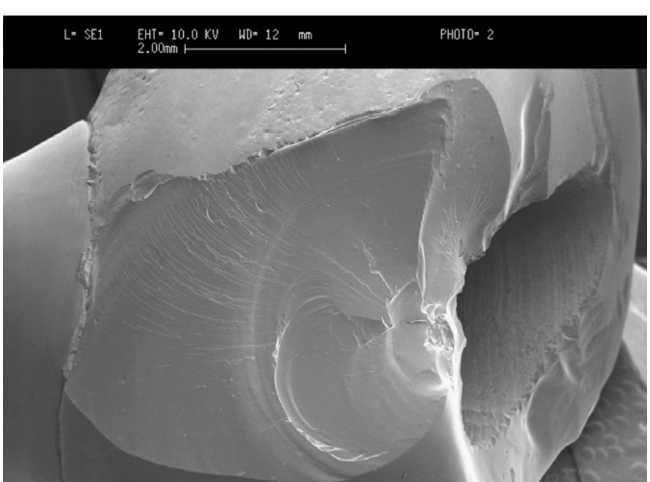

Fig. 1. Scanning electron microscopy image of chipped porcelain on porcelain fused to a zirconia coping abutment. Image courtesy of Neil Waddell, University of Otago, Dunedin, New Zealand.

authors have also been able to quantify the magnitude of the residual stresses by comparing the size of indentation-induced cracking in porcelain in the presence and absence of residual stresses using an approach developed by Marshall and Lawn [14]. Lenz et al. [15] also investigated the thermal expansion mismatch-induced stresses in ceramo-metallic crowns and found that the radius of curvature at the transition from the occlusal to the wall section of the crown also increased the residual thermal expansion mismatch stresses.

The other source of residual stresses in crowns and fixed partial dentures is associated with the possibility of thermal gradients being developed in these structures during cooling. If such a temperature gradient is present and part of the material has a temperature in excess of the glass transition point, then residual thermal "tempering" stresses become locked into a material [16]. These stresses scale with the temperature gradient and the thermal and elastic properties of the materials considered. The resultant stress distribution is such that compressive stresses develop at the surface and compensating tensile stresses develop internally. In the case of a plate cooled at the same rate on both surfaces, a parabolic stress develops, with the surface compressive stress double the magnitude of the internal tensile stresses. However, the compressive stresses are only within the external 16% of the thickness, with the bulk of the internal structure experiencing tension.

The consequence of residual thermal tempering stresses developed during preparation is that the apparent strength of the material is increased. This arises because the bending or applied tensile stresses have to initially exceed the surface compressive stresses. Typically the strength of such tempered materials may be double that of annealed materials and forms the basis of the widespread and safe application of glass construction materials. However, once a crack develops in such a material it can spontaneously shatter, as the internal tensile stresses rapidly accelerate and bifurcate cracks.

The presence of tempering residual stresses as a consequence of cooling for porcelain fused to metal was appreciated by Bertolotti [17], who found the curvature of a bilayer plate to be much greater than that anticipated from thermal expansion mismatch and was dependent upon cooling rate. In a series of studies, Asaoka and Tesk [18,19] analysed the magnitude of the residual and transient stresses that developed in porcelain fused to metal and porcelain as a function of cooling rate. They showed for a three-layer system, comprising metal, opaque and body porcelain, that the magnitude of the stresses through the plate increased with cooling rate. In a follow-up study they investigated the influence of thickness and cooling rate on the tempering stresses developed in a porcelain body.

The contact-induced response of such thermally tempered materials has been a topic of concern as such materials include car windscreens and television screens. A pioneering analysis of this topic was developed by Lawn and Marshall [20]. They showed that two regimes develop