Cracking of Porcelain Surfaces Arising from Abrasive Grinding with a Dental Air Turbine

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Abstract

Purpose: The purpose of this in vitro study was to evaluate porcelain cracking induced by abrasive grinding with a conventional dental air turbine and abrasive diamond burs.
Materials and Methods: Four commercially available porcelains were examined—Wieland ALLUX, Wieland ZIROX, IPS e.max Ceram, and IPS Empress Esthetic Veneering porcelain. Sixty discs of each porcelain type were fabricated according to manufacturer instructions, followed by an auto-glaze cycle. Abrasive grinding using fine, extra-fine, and ultra-fine diamond burs was carried out, using a conventional dental air turbine. The grinding parameters were standardized with regard to the magnitude of the force applied, rotational speed of the diamond bur, and flow rate of the water coolant. A testing apparatus was used to control the magnitude of force applied during the grinding procedure. The ground surfaces were then examined under scanning electron microscope.
Results: Cracking was seen for all porcelain types when ground with the fine bur. Cracking was not seen for specimens ground with the extra-fine or the ultra-fine bur.
Conclusion: Wet abrasive grinding with a conventional dental air turbine and fine grit diamond burs has the potential to cause cracking in the four porcelain types tested. Similar abrasive grinding with smaller grit size particles does not cause similar observable cracking.

All-ceramic restorations are a popular treatment modality in contemporary fixed prosthodontics. Occlusal interferences and/or areas where the restoration is overcontoured necessitate adjustment to establish proper form and function. Abrasive grinding using diamond burs in a dental air turbine is one method available for making such adjustments; however, the effects of this type of adjustment on all-ceramic restorations are not yet fully understood. Previous researchers have demonstrated that surface and subsurface damage can arise from diamond bur machining of ceramic under simulated dental operatory conditions.[1-4] To date, most of this damage has been characterized in terms of the mode of machining damage, specifically the brittle and ductile modes of material removal.[5]

Ceramics, with their low-thermal conductivity and inherent brittleness, are known to be susceptible to thermal shock damage.[6] It has been previously postulated that the heat from ultra-high-speed abrasive grinding with diamond burs and subsequent cooling under water irrigation has the potential to cause thermal stresses and cracking.[7] The presence of such cracks would further contribute to a weakening of the material structure, through the redistribution and amplification of any applied stresses at the crack tips.[8] Unstable cracking may be precipitated by the propagation of these cracks. Such chipping of the veneering porcelain in all-ceramic restorations remains problematic,[9,10] with the true causative factors remaining elusive.[11] Certainly, it would appear that the chipping and bulk fracture of all-ceramic restorations has a multifactorial origin, of which thermal shock damage has not been studied in depth in relation to the failure of veneered all-ceramic prostheses. This article, therefore, aims to elucidate if wet abrasive grinding with diamond burs using a conventional dental air turbine and grinding parameters simulating in vivo adjustment can give rise to cracking, which may be due to thermal shock.

Materials and methods

Four commercially available all-ceramic veneering porcelains were examined: an alumina ceramic core veneering porcelain, Wieland ALLUX (WA; Wieland Dental & Technik GmbH & Co. KG, Pforzheim, Germany), a zirconia ceramic core veneering porcelain, Wieland ZIROX (WZ; Wieland Dental & Technik GmbH & Co. KG), a zirconia and a lithium disilicate

Table 1 All-ceramic veneering porcelains used

Porcelain type	Coefficient of thermal expansion (CTE) (per K)	Glass transition temperature (T_g) (°C)
Wieland ALLUX	7.0×10^{-6}	585
Wieland ZIROX	9.3×10^{-6}	570
IPS e.max Ceram	9.5×10^{-6}	490
IPS esthetic veneering porcelain	15.5×10^{-6}	480

glass-ceramic core veneering porcelain, IPS e.max Ceram (EC; Ivoclar Vivadent AG, Schaan, Liechtenstein), and a leucite-reinforced press glass-ceramic core veneering porcelain, IPS Empress Esthetic Veneering porcelain (EV; Ivoclar Vivadent AG). The coefficient of thermal expansion (CTE) and glass transition temperatures (T_g) of these materials are listed in Table 1. Disc-shaped specimens of approximately 10 mm diameter and 2 mm thickness were fabricated using a stainless steel mold and fired according to manufacturer instructions. After firing, the discs were air cooled to room temperature, before being subject to a further auto-glaze firing, also following manufacturer specifications.

The dental air turbine used for the abrasive grinding was a KaVo Supertorque 630B (KaVo Dental, GmbH, Biberach, Germany), with three symmetrically spaced irrigant ports. Three different grit-sized diamond burs were used: fine, extra-fine, and ultra-fine (Komet Diamonds, Brasseler GmbH & Co. KG, Lemgo, Germany; Table 2). The head of these burs are ball shaped with a 2.3-mm diameter, whereas the shafts are friction grip and conform to ISO 1797 specifications. The air turbine was operated at 0.24 MPa air pressure to produce an unloaded speed of 340,000 rpm. The air pressure was confirmed using an air pressure gauge connected to the air and water line, whereas the rotational speed of the bur was confirmed using a magnetic tachometer (HPW-1, Micron Corp., Tokyo, Japan). Water coolant was delivered to the handpiece at a rate of 25 ml/min. The flow rate of the irrigant was confirmed using a gradated container and a stopwatch, before the abrasive-grinding procedures.

Porcelain discs were abrasively ground using a test apparatus that allowed for application of a constant load and 2 degrees of freedom (DOF) of movement of the handpiece (Fig 1). The design of the apparatus was based on a device similar to that used by Siegel and von Fraunhofer,[12-15] a design other researchers have also used as the basis for their grinding test apparatuses.[4,16] The bur was clamped to the ball-bearing mounted sleeve, and a 100 g weight, which has been cited as an appropriate load used

Table 2 Komet diamond burs used

Bur grade	Diamond grit size (μm)	Product code
Fine	46	#8801-023
Extra-fine	25	#801EF-023
Ultra-fine	8	#801UF-023

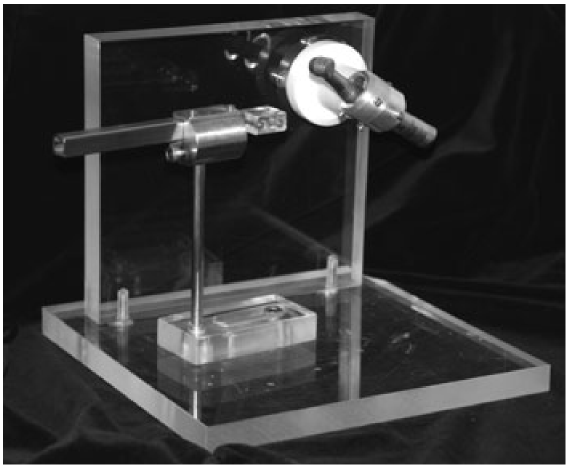

Figure 1 Grinding test apparatus used.

by clinicians, when carrying out abrasive machining with a dental handpiece[17,18] was applied to the head of the handpiece. To simulate clinical abrasive adjustment, the bur traversed the diameter of the disc twice, in a single direction (Fig 2). To eliminate bias, all grinding procedures were carried out by a single operator in a single session using the same air turbine. To maintain cutting efficiency, each bur was replaced after ten discs were ground.

Twenty discs of each porcelain type were ground using each grade of bur, resulting in 12 groups of 20 discs. Following abrasive grinding, the specimens were inspected under an optical light microscope to ensure the grinding response was similar and reproducible for all discs. One disc was selected at random from each group and subject to examination under scanning electron microscope (SEM; Cambridge Instruments S360, Cambridge Instruments, Cambridge, UK). The specimens were sputter-coated with gold-palladium alloy to a thickness of 10 to 15 nm, using the Emitech K575X Peltier-cooled high-resolution sputter coater (EM Technologies Ltd., Kent, UK). The used burs in this study were also examined under SEM and compared with

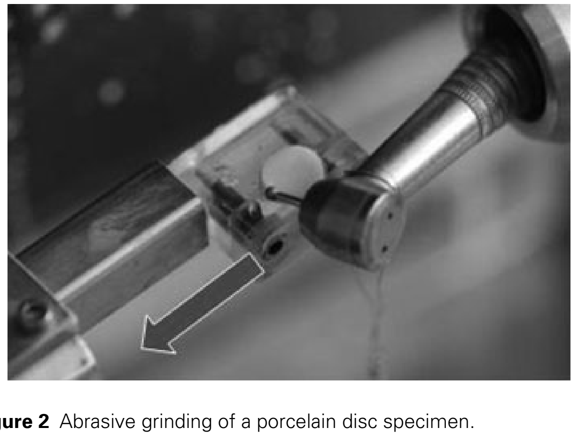

Figure 2 Abrasive grinding of a porcelain disc specimen.

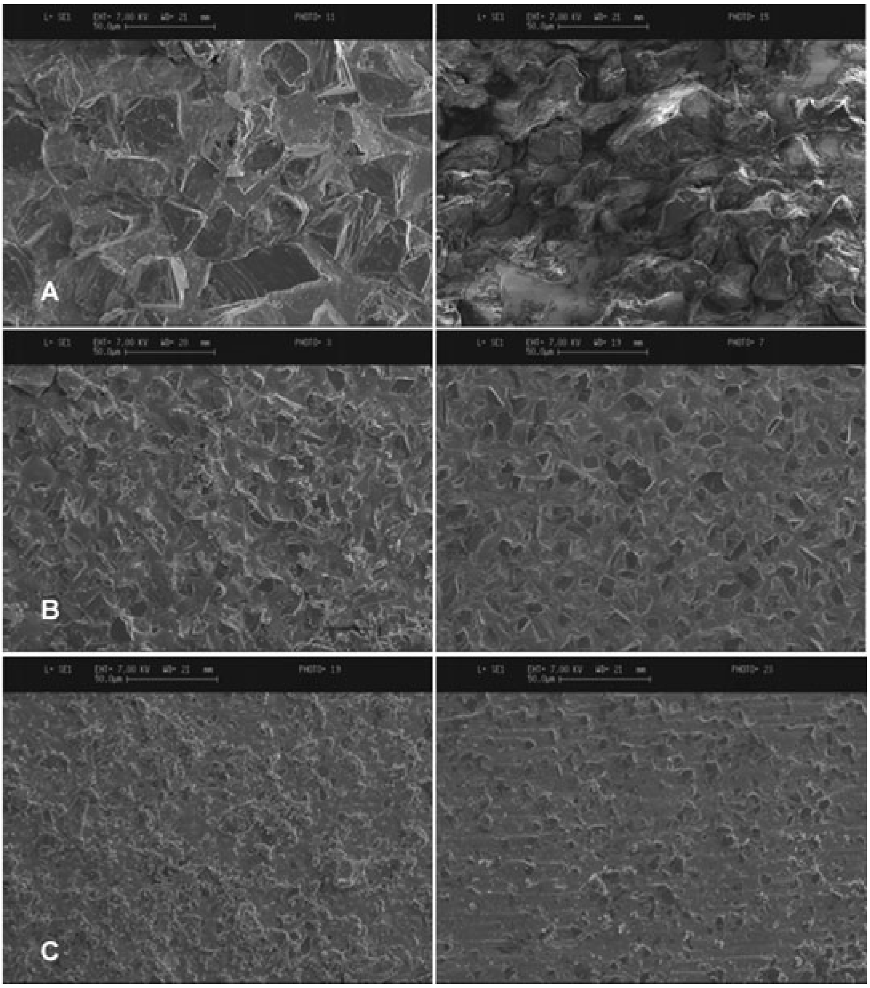

Figure 3 (A) Unused fine grit diamond bur (left) compared with used fine grit diamond bur (right)—note evidence of minor clogging in used bur, but with overall similar surface topography (500×) (B) Unused extra-fine grit diamond bur (left) compared with used extra-fine grit diamond bur (right; 500×) (C) Unused ultra-fine grit diamond bur (left) compared with used ultra-fine grit diamond bur (right; 500×)

unused controls to verify the lack of clogging and maintenance of cutting efficiency.

Results

Optical observations under the light microscope indicated that the depth of the grinding groove created by the burs increased with the grit size, irrespective of the porcelain type. Further qualitative analysis of the ground surfaces under SEM revealed that for all bur grit sizes, the predominant mechanism of material removal was through ductile or metallic-like micromachining for WA, WZ, EC, and EV. A limited amount of brittle fracture and microcracking could be seen with all burs used. For all porcelain types, evidence of generalized chipping along the edge of the grinding groove could be seen, with more extensive chipping associated with the fine diamond bur compared with both the extra-fine and ultra-fine burs. Empirically, grinding with the fine bur produced visibly rougher surfaces than those created by grinding with either the extra-fine or ultra-fine burs. Plough marks or plastic deformation grooves were seen in the specimens abraded with the fine and extra-fine bur, corresponding to the traveling direction of the bur in relation to the grinding groove across the porcelain disc.

When compared under SEM with unused controls, the used burs did not demonstrate any discernable loss of diamond particles. The surface topographies were also very similar between the used and unused burs, indicating no significant dulling of the particles. For the fine burs, evidence of minor clogging could be seen in the used burs; however, the overall topography and protrusion of the diamond particles through the matrix was not dissimilar to the control burs. No clogging was seen with the extra-fine or ultra-fine burs (Fig 3).

Examination of the porcelain specimens ground with the fine bur revealed a series of cracks within the grinding groove generated across the discs. These cracks were distinct from the brittle-type machining damage arising from the diamond bur and were seen for WA, WZ, EC, and EV. These cracks were bi-directional, generating an almost orthogonal network

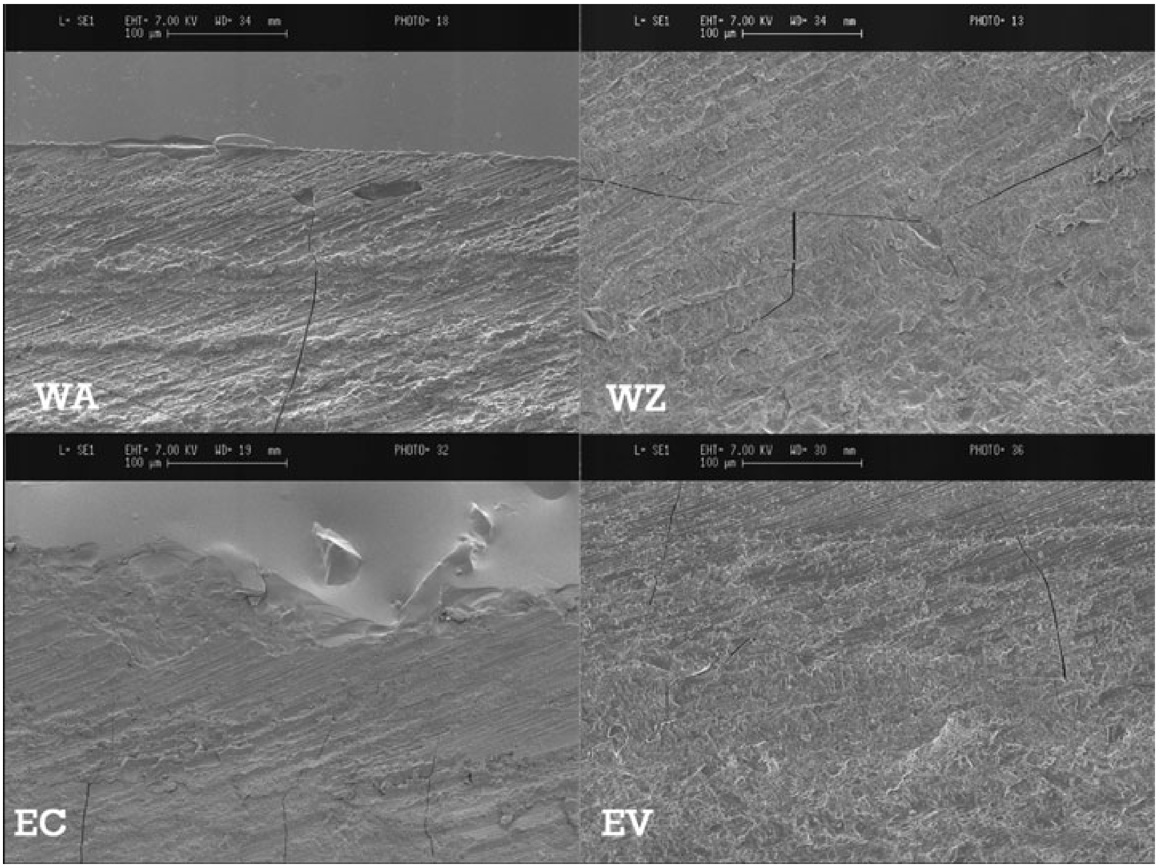

Figure 4 SEM images of the surfaces of the porcelain specimens ground with the fine bur demonstrating bi-directional cracking, indicative of thermal shock cracking (250×). WA, Wieland ALLUX; WZ, Wieland ZIROX; EC, IPS e.max Ceram; EV, IPS Esthetic Veneering.

of cracking. Crack branching, where present, was limited (Fig 4). As demonstrated in these images, the cracks did not run parallel to the plough marks or the grinding groove made by the diamond bur machining processes. Evidence of chipping associated with these cracks was seen in certain areas (Fig 5), although this was generally isolated to only a few areas. Examination of the surfaces ground with the extra-fine and ultra-fine burs did not reveal these cracks (Fig 6) for any of the porcelain specimens.

Discussion

From the results of this study, the preliminary hypothesis for the origin of the cracks observed is from the heat generated by grinding with the larger grit burs followed by the quenching effect of the water coolant from the air turbine handpiece. These cracks have characteristics consistent with thermal shock damage,[19] and do not appear to be part of the brittle machining damage, that is, local chipping or cracking about the ductile grooves seen elsewhere along the abrading flaw, nor are they associated with ductile-type material removal processes. Given that this thermal shock cracking was not seen with the other bur types, and that the grinding parameters were otherwise identical for all specimens, it is reasonable to conclude that the 46 μm size abrasive diamond particles of the fine burs were able to generate larger amounts of heat through friction from the ploughing material removal processes than the 25 and 8 μm diamond particles of the extra-fine and ultra-fine burs.

Ceramics are well known to be susceptible to thermal shock, because of their poor thermal conductivity and brittleness.[6,20] The principle behind thermal shock cracking is similar to the development of isothermal residual stresses in ceramics, in that a temperature gradient is created, causing temperature-related dimensional changes within the ceramic body. These dimensional changes result in the formation of stresses within the body of the material. If these stresses are generated rapidly and are sufficiently large, they can cause crack propagation, which may be either stable or unstable, in the process known as thermal shock cracking.[19]

The resistance of ceramic to thermal shock damage is dependent on a number of factors, including the ceramic's strength, thermal conductivity, CTE, elastic modulus, and Poisson's ratio.[21,22] Kingery's approach is concerned primarily with the initiation of fracture by the thermal stresses. Materials with high strength, high-thermal conductivity, low CTE, and low-elastic modulus are, therefore, less likely to develop thermal shock fracture.[21] Hasselman's approach conversely ignored the question of fracture initiation, but rather concentrated on the

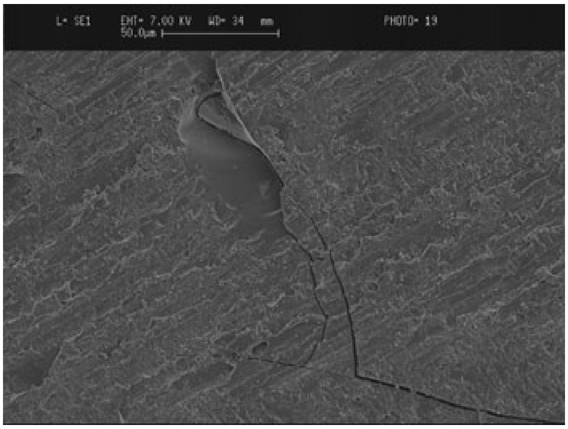

Figure 5 Evidence of chipping associated with thermal shock crack on a Wieland ALLUX specimen ground with the fine bur (500×).

issue of crack propagation with regard to a modification of the Griffith criterion.[22] Cracks would, therefore, propagate when the elastic strain energy associated with the thermal stresses, which is related to the CTE, elastic modulus, and temperature differences, is greater than the fracture toughness of the material considered.

Hasselman later unified these two theories of thermal shock fracture initiation and crack propagation and was able to predict the strength degradation in brittle ceramics with respect to the magnitude of thermal stress.[23] A critical temperature difference (ΔT_c) was elucidated based on the aforementioned properties, where fracture nucleation would arise, and an instantaneous decrease in fracture strength could be seen. Therefore, temperature differences smaller than the ΔT_c for a given material would not result in thermal shock cracking and strength degradation. In this study, the temperature differences arose from the heat generated during abrasive grinding, followed by rapid cooling from the air and water coolant. In accordance with this study, rapid cooling has been reported to be more likely to precipitate thermal shock cracking, because of the development of tensile stresses on the surface, whereas rapid heating is more likely to create compressive stresses on the surface, and is hence less likely to cause thermal cracking.[20]

Abrasive grinding requires a high expenditure of energy, in relation to the volume of material removed. Much of this energy is expended as heat, arising from friction between the tool and the workpiece.[24] The low thermal conductivity of ceramics can actually result in surface temperatures near the abrasive tool higher than similar machining conditions in metal workpieces.[7] The temperature increase on the surface of the substrate is directly related to the total grinding energy converted into heat

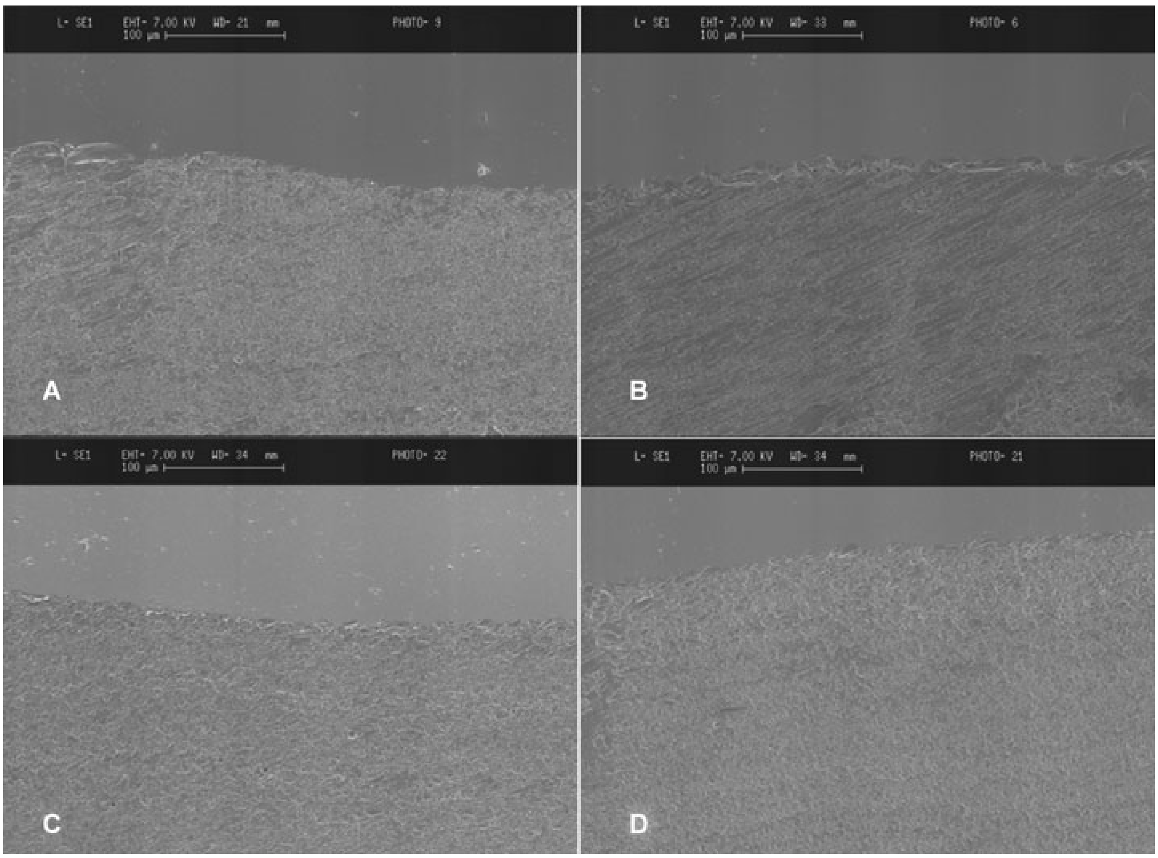

Figure 6 SEM images of the surfaces of (A) WA ground with the extra-fine bur, (B) WA ground with the ultra-fine bur, (C) WZ ground with the extra-fine bur, and (D) WZ ground with the ultra-fine bur—note absence of surface cracks (250×).

and transferred into the workpiece at the grinding zone.[25] The remainder of the heat generated during wet grinding (such as in this study) is transferred to the material chip(s), the diamond bur, and the irrigant or coolant.[26]

Xie and Huang demonstrated, using thermocouples embedded in partially stabilized zirconia, a temperature rise of 800°C on the surface when the grinding wheel velocity was 160 m/s, whereas a temperature rise of only 100 to 300°C was seen when the wheel velocity dropped below this.[27] In this study, given that the unloaded velocity of the handpiece, the load applied to the handpiece, and the rate of irrigant flow were consistent throughout the experiment, the different grit sizes of the burs must, therefore, have the biggest influence on the specific grinding energies and subsequent energy partition to the porcelain disc specimens.

From the empirical optical microscopic observations, the specimens ground with the fine bur showed deeper grinding grooves than the specimens ground with the extra-fine and ultra-fine burs, indicating a larger volume of material removed. This increased material removal, therefore, suggests that more friction-generated heat (or work done) would be seen with the fine burs than the other grades of burs.[28]

Hahn's grain-rubbing hypothesis provides further elucidation for the higher temperature differences seen with fine bur abrasive grinding. In this model, heat generation is examined at the individual grain (abrasive diamond particle) level, and can be attributed to three sources—the grain/workpiece interface, the chip shear plane, and the grain/chip interface. Of the three heat sources, the grain/workpiece interface where the abrasive particle makes contact with the workpiece is cited as being of the greatest importance. As an abrasive wheel or bur contains many abrasive particles traveling across the workpiece, the combined effect from the friction of all the contacting particles can be regarded as a continuous band source of heat, also known as the workpiece background temperature.[28] However, localized temperature spikes are also generated at the workpiece/grain tip contact zone, momentarily raising the temperature at a given point to multiple magnitudes above the background temperature.[29]

Given that these temperature spikes are dependent on the abrasive grain-to-workpiece contact friction, it can be inferred that the fine grit burs produced higher flash temperatures in this study because of the larger abrasive particle surface areas. This hypothesis seems to be supported in the literature, with one group of researchers testing the thermal effects of cavity preparation with diamond burs on extracted teeth, using thermocouples placed in pulp chambers.[30] These researchers found that under constant loading conditions, coarser diamond burs equated to larger increases in intrapulpal temperatures when compared to finer burs.[30]

Throughout the grinding procedure in this study, water irrigation at a rate of 25 ml/min was used. The water was at room temperature, approximately 23.5°C, and was responsible for the cooling and resultant ΔT causing the thermal shock cracking. In industrial wet grinding involving abrasive wheels and other grinding implements, water irrigation is successfully employed to prevent thermal damage from arising on the workpiece.[26] In these processes, the coolant flow rate and delivery nozzle position are noted by various researchers to be of significant importance in the prevention of thermal damage and residual stress creation.[31]

The handpiece used in this study, the KaVo Supertorque 630B (KaVo Dental GmbH) consists of three irrigant ports evenly distributed around the bur-chucking mechanism. Other dental air turbines may consist of one, two, or four ports.[15] Research has shown that varying the number of irrigant ports has an effect on the distribution and maximum flow rate of the water coolant.[32] It is, therefore, theorized that the rise in temperature from abrasive grinding is exacerbated through inefficient cooling and irrigation, stemming from the inability of the coolant to access beneath the abrasive-grinding contact zone. This hypothesis seems to be supported in the literature, where large temperature spikes arising from high-speed abrasive grinding of zirconia were demonstrated experimentally with thermocouples, despite the use of water cooling.[27]

In this study, the water flow rate was calibrated to a constant 25 ml/min; however, the results from Cavalcanti et al suggest that reducing the number of ports increases the pressure and velocity of water irrigation from each individual port, resulting in improved water distribution.[32] Other researchers have also found that the water spray emanating from the irrigant ports differs according to the pattern of port distribution.[15] These patterns, in turn, were found to have an effect on the cutting efficiency of diamond burs on a ceramic test substrate, depending on the type of cutting or machining employed; however, these researchers found evidence that for edge cutting (similar to the type of abrasive grinding used in the present experiment) the presence of one, three, or four ports did not produce any significant differences in the cutting rates.[15] This would suggest an even distribution of the irrigant on the workpiece for all three tested port patterns. Therefore, it would appear that the three-port design of the KaVo Supertorque 630B air turbine would be sufficient for effective irrigation and material removal; however, as demonstrated by Xie and Huang, temperature spikes can still arise from abrasive grinding, even in the presence of water irrigation.[27] These researchers report that in their study, the coolant supply into the grinding zone at ultra-high grinding speeds was insufficient to cool the workpiece to prevent thermal damage, because of an air barrier that formed around the rapidly rotating implement. Ramesh et al supported this finding in their investigation into coolant velocity during high-speed grinding,[33] which suggested that a higher coolant velocity enables the coolant to better lubricate and cool the grinding zone, thereby leading to less surface damage. A distinction is made between the coolant flow and the coolant velocity, with the coolant velocity related to the size of the delivery nozzle and the pressure at which the coolant is delivered. Smaller nozzles and higher pressures tend to equate to higher velocities. Given the three-port design of the KaVo 630B air turbine, it can be assumed that the coolant velocity from each individual port would be lower than a handpiece with a single port design, in agreement with Cavalcanti et al.[32]

Therefore, in this study, the relatively low coolant velocity might not have been sufficient to effectively distribute the water to and beneath the grinding zone, particularly given the high speeds and likelihood of an air barrier around the rotating bur. As a result, the effectiveness of the coolant at the grinding zone at a given point in time might be low, thereby having a negligible effect on any high temperatures that may develop as a result of the abrasive particle-to-workpiece friction; however, as the bur moves across the surface of the porcelain disc, the coolant then becomes able to contact the workpiece, causing a rapid decrease in the temperature leading to thermal shock damage. As mentioned earlier, the larger grit size with the fine burs is likely to cause an increased surface temperature by virtue of an increased surface area and, hence, increased friction.

Unfortunately, within the limitations of the experiment, the amount of the thermal shock damage was not able to be quantified. Qualitative observation of the specimens under SEM, however, demonstrated a higher density of the observed cracks for the EV specimen. This can be attributed to it having the largest CTE of all the porcelains tested in this study (Table 1), resulting in greater temperature-related dimensional changes and/or greater tensile strains developed upon cooling. Nonetheless, by virtue of the presence of the thermal shock cracks, it can be concluded that the ΔT created for all the porcelains investigated reached the ΔT_c threshold; however, because of the limitations of this study, it is not possible to empirically quantify the factors related to the thermal shock cracking, indicating an area suitable for further research. The effects on the mechanical properties arising from this thermal shock cracking and the associated damage caused by the abrasive grinding are the basis of a further study.

The findings of this study have significant implications for clinicians wishing to adjust all-ceramic restorations in vivo. In addition, they are important where abrasive grinding is used in the fabrication process of indirect ceramic restorations, such as with CAD/CAM technology. They suggest that thermal shock-induced damage arising from such grinding, especially with coarser burs, may significantly weaken the veneering porcelains and facilitate premature failure through chipping or fracture. This topic and the specific response of different veneering porcelains, bur grit size, and coolant delivery are areas for further research into this phenomenon.

Conclusions

This study has identified that cracking of veneering porcelain occurs during abrasive grinding with dental air turbines. Because of the poor thermal conductivity of porcelain, abrasive grinding of this material can induce the formation of large temperature spikes at the point of contact between the diamond bur and the porcelain surface—a phenomenon more pronounced with larger particle grit sizes. The water irrigant commonly used in dental air turbines acts to quench this heated surface, resulting in a large temperature difference. Should this temperature difference exceed the critical temperature difference, observable cracking will occur, which may cause a decrease in the strength properties of the porcelains. This article suggests that cracking of veneering porcelain can occur with abrasive grinding of veneering porcelain. This has implications for clinicians wishing to adjust all-ceramic restorations in vivo, or where abrasive grinding is used in indirect ceramic restoration fabrication, such as with CAD/CAM technology. Any thermal damage arising from such grinding may thereby facilitate premature failure through chipping or fracture. Further research into this phenomenon is indicated.

Acknowledgments

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