POLISHING MECHANISM AND ITS EFFECT ON THE MECHANICAL PROPERTIES OF CERAMIC RESTORATIONS - A REVIEW OF THE LITERATURE

R Ahmad, B.M. Wu, S.M. Morgano. Polishing mechanism and its effect on the mechanical properties of ceramic restorations – A review of the literature. Annal Dent Univ Malaya 2001; 8: 57–61.

Review Article

R. Ahmad[1], B.M. Wu[2] and S.M. Morgano[3]

[1] *Department of Conservative Dentistry*
Faculty of Dentistry
University of Malaya
50603 Kuala Lumpur, Malaysia

[2,3] *Department of Restorative Sciences and Biomaterials*
Boston University Goldman School of Dental Medicine
100 East Newton Street
Boston, Massachusetts 02118-2392

Corresponding author – Rohana Ahmad

ABSTRACT

Polishing of dental ceramics has become an increasingly important procedure in restorative dentistry as all-ceramic restorations, which require post-cementation occlusal adjustment, are gaining in popularity. There are numerous studies in both dental and ceramic literature on polishing of dental ceramics and the effects of polishing on their mechanical properties. However, lack of standardization in polishing parameters, precludes comparison among these studies. A clear understanding is lacking of the relative roles and interdependence of handpiece speed, abrasive characteristic, and polishing load. This paper will discuss the mechanism of polishing and review the literature on polishing and its effect on the mechanical properties of ceramic restorations.

Key words: polishing mechanism, polishing parameters, dental ceramic, mechanical properties.

INTRODUCTION

Minimization of surface roughness is important in controlling aesthetics, wear, mechanical properties, and plaque accumulation of dental ceramic restorations. For metal ceramic restorations, surface finish can be achieved by either glazing or polishing. For all ceramic restorations, however, polishing is the only viable option since occlusal adjustment is performed after cementation. This limitation has stimulated greater interest among researchers in the field of ceramic polishing. The quest for efficient and effective methods and materials for ceramic polishing is evidenced by the number of publications on the subject. In the past, glazing was always advocated as the last surface treatment before final cementation (1). A glazed surface was thought to produce smoother, more cleansable surfaces and stronger mechanical properties. Polishing was not done routinely for fear that it would introduce more surface flaws and weaken the material. With advances in polishing instruments, it became possible to achieve acceptable surface smoothness by using rotary equipment. Previous studies have established that in addition to producing smoother surfaces, polishing may also produce surfaces, which are less abrasive than glazed surfaces (2,3).

Since polishing is becoming an increasingly important procedure in aesthetic dentistry, a better understanding of polishing mechanisms will facilitate the search for an optimal polishing protocol that will serve as a guideline for dental practitioners to carry out a safe and effective polishing procedure. The effects of polishing on the mechanical properties of ceramic restorations must also be given due consideration.

Polishing Mechanism

Polishing is a chip-removal process and the cutting tool is an individual abrasive grain in the polishing wheel. This polishing process and its parameters (4) are illustrated in Figure 1.

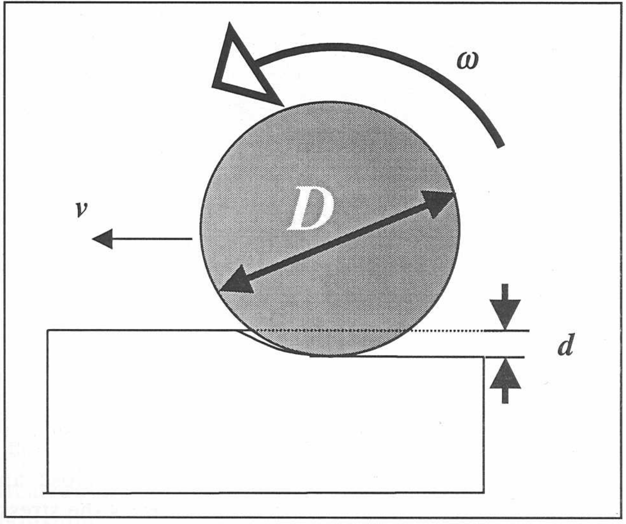

Figure 1. Schematic illustration of the polishing process, showing process variables. The figure depicts conventional (up) grinding. A straight grinding wheel of diameter *D* removes a layer of material to a depth *d*. An individual grain on the periphery of the wheel moves at an angular velocity ω, while the workpiece moves at a velocity *v*.

With the assumption that the cutting force on the grain is proportional to the cross-sectional area of the undeformed chip, it can be shown from first principle that the grain force (tangential force on the wheel) is proportional to the process variables:

$$\text{Grain force} \propto \frac{v}{\omega C}\sqrt{\frac{d}{D}}$$

Grain force increases with increasing workpiece velocity and depth of cut; and decreases with increasing wheel speed, number of cutting points per unit area of the periphery of the wheel and wheel diameter. It can be seen that the workpiece speed, number of cutting points per unit area and wheel speeds have greater influence on grain force than depth of cut and wheel diameter.

The energy dissipated in producing a chip consists of the energy required for (a) chip formation, (b) ploughing and (c) friction caused by rubbing of the grain along the surface. The grain develops a wear flat as a result of the polishing operation. The wear flat rubs along the polished surface and, because of friction, dissipates energy mainly in the form of heat. This temperature rise during polishing is an important consideration because it can adversely affect the surface properties by inducing residual stresses on the workpiece. Residual stresses are induced by non-uniform plastic deformation near the workpiece surface. Mechanical interactions of abrasive grains with the workpiece produce predominantly residual compressive stresses as a result of localized plastic flow (Figure 2).

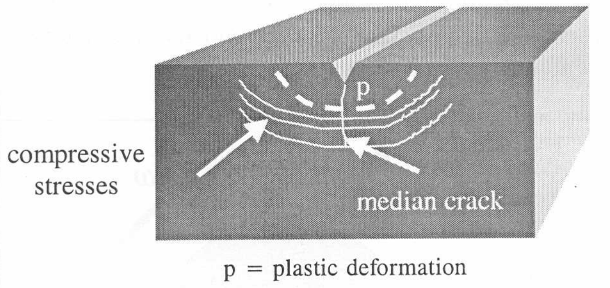

Figure 2. Schematic representation of compressive stresses as a result of mechanical interactions of abrasive grains with the workpiece. For cracks to propagate, energy must be consumed to overcome the compressive stresses.

The regions of compressive stress beneath each abrasive particle can overlap, producing a layer of compression. The compressive layer can act to partially close an existing surface crack. This in turn increases the stress required for crack propagation and effectively increases the strength of the material.

Residual tensile stresses are caused mainly by thermally induced stresses and deformation associated with the grinding temperature and its gradient from the surface into the workpiece. At the polishing zone, the thermal expansion of hotter material closer to the surface is partially constrained by cooler subsurface material. This thermal expansion generates compressive thermal stresses near the surface, which, if sufficiently large, cause plastic flow in compression. During subsequent cooling, the plastically deformed material tends to contract more than the subsurface material, but the requirement for material continuity causes tensile stresses to develop in a surface skin. To ensure mechanical equilibrium, residual compressive stresses must also arise deeper in the material, but these stresses are much smaller in magnitude than the residual tensile stresses. Since dental ceramics are much weaker in tension than in compression, residual compressive stresses are considered beneficial, whereas residual tensile stresses adversely affect strength (5). Therefore, depending on which type of stress predominates, the polishing procedure can either weaken or strengthen the workpiece.

The surface temperature in polishing is related to process variables by the following expression:

$$\text{Temperature rise } \Delta T \propto D^{1/4} d^{3/4} \left(\frac{\omega}{v}\right)^{1/2}$$

Thus, temperature increases with increasing depth of cut, wheel diameter, and wheel speed; and decreases with increasing specimen speed. It can be seen that the depth of cut, *d* has the greatest influence on temperature. Because of the deleterious effect of residual tensile stresses on mechanical properties, the process variables should be carefully selected. Lowering wheel speed and increasing specimen speed (gentle grinding) can usually reduce residual tensile stresses (4). Gentle grinding however may prolong the polishing procedure and expose the ceramic surface to elevated temperature for a longer period of time. For example, reducing ω by ½ will double polishing time but reduce ΔT by only ~ 30%. This increase in time will allow more heat conduction to occur and therefore increase the thickness of the heat-affected zone.

Forces generated during polishing cause elastic deformation and deflection of the machine, the grinding wheel, and the workpiece. The normal deflection between the wheel and the workpiece may greatly exceed the depth of cut taken by the wheel. Periodic deflections associated with machine-tool vibrations cause chatter which adversely affects surface finish and wheel performance. The vibrations are usually classified into two types: forced vibrations and self-excited (regenerative) vibrations. Forced vibrations are caused by periodic disturbances external to the cutting process such as from an unbalanced wheel or spindle, electric motors, bearings, hydraulic systems, or even other nearby machines. Self-excited vibrations are generally associated with natural vibration modes of the machine-tool structure. The grinding instability is attributed to regenerative feedback effects on the workpiece and the wheel. Any irregularities in the cutting process cause variations in the cutting force which can dynamically excite the machine-tool structure and lead to variations in the local depth of cut during successive passes of the wheel, thereby regenerating undulations or lobes on the workpiece. Wheel regeneration can occur in a similar manner, with periodic wear-rate variations and lobes developing around the wheel periphery.

The particular wheel-workpiece combination influences the amount of chatter. Decreasing the wheel hardness, dressing the wheel frequently, reducing the depth of cut and supporting the workpiece rigidly reduce the tendency for chatter in polishing. It can be seen that many factors can influence polishing. In particular, the parameters *(v, ω, D, d)* are relevant and controllable experimentally. Numerous investigators have tried to propose an efficient and effective sequence for polishing of dental ceramics. However, in the earlier studies, the polishing parameters used, handpiece speed, abrasive characteristic, and polishing load were not controlled or standardized. Only more recently, some effort have been made by the researchers to control the handpiece speed and polishing load used.

Polishing studies comparing the efficacy of various polishing systems

Klausner et al. (6) quantitatively and qualitatively compared autoglazed surfaces and surfaces treated with four different polishing sequences by means of surface profilometry, scanning electron microscopy (SEM) and low power photography. No significant differences were found between the final polished surfaces and the initial autoglazed surfaces for all four polishing sequences. Sulik and Plekavich (7) also compared glazed surfaces and surfaces polished by using a rubber wheel, fine wet pumice, and wet tin oxide. They concluded that under SEM and clinical observation, the two groups appeared the same. Raimondo et al. (8) and Patterson et al.(9) reported poor performances for diamond polishing paste used alone, compared to oven glazing. Goldstein et al. (10) compared the polishing efficacy of various polishing systems on two feldspathic porcelains and reported that most systems were clinically acceptable for finishing ground porcelain. Hulterstrom and Bergman (11) compared the surface roughness of several polishing systems and techniques by means of a surface roughness analyzer. They concluded that Soflex (Soflex Polishing Discs, 3M Dental Products Division, St. Paul, MN) and Shofu (Shofu Polishing Kit, Shofu Dental Corp., Menlo Park, CA) polishing systems produced satisfactory surface finishes. Haywood et al. (12) reported that a polishing sequence of three diamond finishing points, then 30-fluted carbide bur followed by diamond polishing paste was a superior polishing technique.

None of these studies, however, identified the handpiece speed and load used to obtain the data. This lack of standardization precludes the comparison of the effectiveness of various polishing systems used in these studies.

Some attempts have been made to control selected polishing parameters. Haywood et al. (13) investigated the effects of water, speed, and experimental instrumentation on finishing and polishing porcelain intraorally. They reported that the best results were obtained when diamond instruments were used wet at moderate speed, and when carbide instruments were used dry at high speed. The relative speeds used were characterized by the amount of air pressure delivered to the handpiece. No effort to control polishing load was made. Scurria and Powers (14) compared the roughness produced by five different combinations of intraoral instrumentation on feldspathic porcelain and machinable glass ceramic. The relative speed used was reported as pounds per square inch of air pressure delivered to the handpiece. No attempt was made, however, to confirm the speed used. Force applied to the handpiece was measured by performing all polishing on samples stabilized on a special balance designed to weigh laboratory animals (Mettler Balance PM4600, Mettler Instrument AG, Hightstown, N.J). They found that feldspathic porcelain could be polished smoother than glazed, and Dicor (Dicor MGC, Dentsply, York, PA) ceramic could be polished smoother than Ceramco II (Ceramco Inc, Burlington N.J) ceramic. In this study the use of a 30-fluted carbide bur did not improve smoothness as reported by Haywood et al (12).

Despite numerous reports on polishing methods and systems, a clear understanding is lacking of the relative roles and interdependence of handpiece speed, abrasive characteristic, and polishing load. Subsequently, it is very difficult to draw a meaningful conclusion when comparing studies done to evaluate the effect of polishing on ceramic. Since the polishing parameters used were not quantified, the contradicting results (increased or degradation in strength as a result of polishing) reported in these studies may in fact be due to the polishing process itself.

Polishing effects on mechanical properties of dental ceramics

There are a number of studies in the dental and ceramic literature on the strengthening effects of grinding and polishing, as well as heat treatment of ceramics. The effectiveness of these strengthening mechanisms is not well established and may not be applicable to clinical dentistry. Previous studies both support and refute the strengthening effect of surface and heat treatments. Levy (15) evaluated the effect of polishing with pumice and etching on the flexural strength of dental ceramics after air, and vacuum glazing, and overglazing. He reported no significant difference among treatments; however, polished glazed specimens had higher strength values. Brackett et al. (16) tested the effects of autoglaze, overglaze, and autoglaze plus polish on the strength of five dental ceramics. Polishing was done with a Shofu Polishing Kit. The authors reported that the flexural strength of the specimens tested with an overglaze was significantly greater than specimens treated with autoglaze and those treated with autoglaze and polish. Unfortunately, the polishing parameters used in these studies were not quantified and the difference in polishing may have affected the results.

Results that contradicted these studies were reported by Fairhurst et al (17). He investigated the strengthening of feldspathic porcelain by analyzing the effects of various polishing and firing procedures on four groups (n = 50) of Jelenko body porcelains (Jelenko Gingival, Jelenko Dental Health Products, Armonk, NY). Group one was fired, glazed – no hold, and polished; group two was fired, polished, and glazed – no hold; group three was fired, polished and glazed – 1 min. hold; and group four was fired, polished and not glazed. All specimens were fired in a programmable furnace (Sunfire 10, The J.M. Ney Company, Bloomfield, CT) at a pressure of 0.01 MPa from 593°C to 927°C at 56°C / min. The pressure was returned to 1 atm at a temperature of 927°C, firing continued, and the specimens were removed from the furnace when the temperature reached 968°C. Glaze-firing consisted of an additional firing at 1 atm pressure at 56°C / min. from 593°C to 946°C, the temperature at which the specimens were removed from the furnace. Grinding of all specimens was carried out on an industrial polisher (Buehler Ecomet III, Buehler Ltd, Lake Bluff, Ill.) through 15-mm diamond paste and the polished surface to be tested through 1 mm. No mention was made of polishing load and duration. The specimens that were fired, polished to 1-mm surface finish, and not glazed were significantly higher in flexural strength compared to the other groups. The other three groups that received additional firing recorded a significant decrease in strength. The study concluded that self-glazing did not increase flexural strength and that some glazing techniques can be detrimental to the fracture properties of leucite-containing porcelains.

Griggs et al. (18) repeated the study by Fairhurst et al.(17) with a larger average flaw size and a wider distribution in flaw sizes. It was thought that the effects of glazing might be more obvious if the initial flaw size were bigger. The same type of Jelenko body porcelain was used in their study. The firing schedules used were different, however, and so was the type of furnace used. Firing consisted of drying at 593°C outside the muffle for 10 min, drying at 593°C inside the muffle for 10 min, increasing the temperature at 100°C / min from 593°C to 968°C under a pressure of 0.09 MPa, and increasing the temperature at 100°C / min from 968°C to 996°C under a pressure of 0.10 MPa (1 atm). The specimens were then held at 996°C for 15 seconds and bench-cooled. The glazing process consisted of preheating at 593°C outside the muffle for 5 min, preheating at 593°C inside the muffle for 5 min, and increasing the temperature at 100°C / min from 593°C to 996°C under a pressure of 0.10 MPa with no hold time. All specimens were fired in a programmable vacuum furnace (Ney Mark IV Digital Furnace, The J.M Ney Company). Specimens were ground with 240-grit SiC abrasive paper on a steel-back wheel, and one side of each specimen was polished through 600-grit SiC abrasive. Again, load and duration of grinding and polishing of the specimens were not reported. Flaws were induced by means of a Vickers indenter under different loads for each group. Following indentation, half of the specimens from each group were re-fired. The results indicated that re-firing of porcelain did not significantly increase the flexural strength regardless of the size of the surface flaws. The flaw sizes induced by the indenter ranged from 37 mm wide and 16 mm deep to as large as 118 mm wide and 87 mm deep. In this study the degradation in strength after additional firing did not occur. This result is probably due to the different firing schedules. The sample size used in this study was too small, however, and included only 6 samples per group.

Giordano et al. (19) reported that overglazing, grinding, and polishing all significantly increased the flexural strength of dental ceramics by 15% to 30%, and re-firing of the ground and polished samples decreased the flexural strength significantly from 11% to 18%. Re-firing of the as-fired group did not affect the flexural strength. The flexural strength of the overglazed group was not significantly different from both annealed groups. Grinding and polishing of each specimen was performed on an industrial polisher (Buehler Ecomet III) at a rate of 350 rpm under a 15-lb (6818 g) load that was 50 times the average clinical polishing load of a prosthodontist for a fine-grit polisher (129 g, based on the authors' unpublished pilot study). Grinding consisted of subjecting the material to a 30-mm diamond wheel for 15 seconds, and polishing consisted of using a series of wheels coated with a diamond paste in series from 15 mm, 9 mm, and 6 mm to 3 mm. The paste was applied to the specimens for 20 seconds. The amount of materials removed was not mentioned.

Chen (20) conducted a study comparing the flexural strength of dental ceramics polished manually and by a machine (Buehler Ecomet III). Manual polishing was performed by using a constant load of 130 g and was applied to the handpiece by using a loading device. The same force was used for all wheels of different grit sizes for 30 seconds each at a speed of 10,500 rpm. Polishing on the industrial polisher consisted of subjecting the material to a 15-mm diamond wheel under a 2-lb load at a speed of 120 rpm for three minutes, followed by 6-mm diamond paste under a 12-lb load at a speed of 360 rpm for three minutes and finally followed by a 1-mm diamond paste under a 16-lb load at a speed of 360 rpm for another three minutes. This nine-minute-polishing procedure reduced the sample thickness by 500 mm. The results indicated that the flexural strength of machine-polished samples was higher but not statistically significantly higher compared to manually polished and control (self-glaze) groups. Surface roughness was evaluated quantitatively by surface profilometry, and specimens polished with the Buehler machine had the best surface finish.

CONCLUSION

A better understanding of polishing mechanisms and the relative roles and interdependence of handpiece speed, abrasive characteristic, and polishing load will facilitate the search for an optimal polishing protocol. Until such protocol is established, it may be recommended that polishing procedures be done gently with a well maintained handpiece and polishing wheels.

Also, there exists a need to standardize the polishing parameters that are applicable to clinical dentistry so that future comparisons of the effectiveness of various polishing systems could be made and comparisons among studies on polishing and its effect on flexural strength become more meaningful.

REFERENCES

1. McLean JW. The nature of dental ceramics and their clinical use: Science and art of dental ceramics. Volume 1. Chicago Quintessence 1979; 61-114.

2. Jagger DC, Harrison A. An in vitro investigation into the wear effects of unglazed, glazed, and polished porcelain on human enamel. J Prosthet Dent 1994; 72: 320-323.

3. Jacobi R, Shillingburg HT, Duncanson MG. A comparison of the abrasiveness of six ceramic surfaces and gold. J Prosthet Dent 1991; 66: 303-309.

4. Malkin S. Theory and applications of machining with abrasives. Grinding Technology. Chichester, England. Ellis Horwood Limited 1989; 107-245.

5. Kalpakjian S. Manufacturing Engineering and Technology. Third Edition. Reading, Mass. Addison-Wesley Publishing Company Inc. 1995; 781-824.

6. Klausner LH, Cartwright CB, Charbeneau GT. Polished versus autoglazed porcelain surfaces. J Prosthet Dent 1982; 47: 157-162.

7. Sulik WD, Plekavich EJ. Surface finishing of dental porcelain. J Prosthet Dent 1981; 46: 217-221.

8. Raimondo RL, Richardson JT, Wiedner B. Polished versus autoglazed dental porcelain. J Prosthet Dent 1990; 64: 553-557.

9. Patterson CJW, McLundie AC, Stirrups DR, Taylor WG. Efficacy of a porcelain refinishing system in restoring surface finish after grinding with fine and extra fine diamond burs. J Prosthet Dent 1992; 68: 402-406.

10. Goldstein GR, Barnhard BR, Penugonda B. Profilometer, SEM, and visual assessment of porcelain polishing methods. J Prosthet Dent 1991; 65: 627-634.

11. Hulterstrom AK, Bergman M. Polishing systems for dental ceramics. Acta Odontol Scand 1993; 51: 229-234.

12. Haywood VB, Heymann HO, Kusy RP, Whitley JQ, Andreaus SB. Polishing porcelain veneers: an SEM and specular reflectance analysis. Dent Mater 1988; 4: 116-121.

13. Haywood VB, Heymann HO, Scurria MS. Effects of water, speed, and experimental instrumentation on finishing and polishing porcelain intra-orally. Dent Mater 1989; 5: 185-188.

14. Scurria MS, Powers JM. Surface roughness of two polished ceramic materials. J Prosthet Dent 1994; 71:174-177.

15. Levy H. Effects of laboratory finishing techniques on the mechanical properties of dental ceramics. Int Dent J 1987; 69: 1039-1045.

16. Brackett S, Leary J, Turner K, Jordan RD. An evaluation of porcelain strength and the effect of surface treatment. J Prosthet Dent 1989; 61: 446-451.

17. Fairhurst CW, Lockwood PE, Ringle RD, Thompson WO. The effect of glaze on porcelain strength. Dent Mater 1992; 8: 203-207.

18. Griggs JA, Thompson JY, Anusavice KJ. Effects of flaw size and auto-glaze treatment on porcelain strength. J Dent Res 1996; 75: 1414-1417.

19. Giordano R, Cima M, Pober R. Effects of surface finish on the flexural strength of feldspathic and aluminous dental ceramics. Int J Prosthodont 1995; 8: 311-319.

20. Chen YC. Evaluation of the effect among different surface polish on the flexural strength of dental ceramics. Boston University School of Dental Medicine, Boston, Mass., 1996. Master's thesis.