THE EFFECT OF SURFACE FINISHES ON FLEXURAL STRENGTH, FRACTURE TOUGHNESS OF FELDSPATHIC DENTAL PORCELAIN

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Statement of problems. Conventional feldspathic porcelain is used extensively as a restorative material and it is subjected to grinding and polishing during fabrication and delivery procedures. There is still considerable controversy concerning the best methods to achieve the strongest porcelain restorations after such adjustments.

Purpose. The objective of this study was to investigate the effects of (1) overglazing, (2) self-glazing, and (3) fine polishing on the flexural strength and fracture toughness of feldspathic dental porcelain.

Material and method. Ninety porcelain disks were prepared for flexural strength test and sixty porcelain disks were fabricated for fracture toughness test. Specimens were divided into three groups for each test as follows: 1) overglazed 2) self-glazed 3) polished. The flexural strength of feldspathic porcelains was determined by ring-on-ring biaxial flexural strength test. The fracture toughness values of three experimental groups were obtained by indentation fracture toughness test.

Results. The flexural strength of overglazed group was significantly higher than that of self-glazed and polished group ($P<0.05$), while the difference between self-glazed and polished group was not significant ($P>0.05$). The fracture toughness values of overglazed and polished group were significantly higher than that of self-glazed group ($P<0.05$), while the difference between overglazed and polished group was not significant ($P>0.05$).

Conclusions. This results supported the use of polishing as an alternative to glazing metal ceramic restorations, as it was not detrimental in flexural strength and fracture toughness. But, under the conditions of this study, overglazing was the ideal surface finishing method of feldspathic dental porcelain.

Key Words

Feldspathic dental porcelain, Surface finishing methods, Flexural strength, Fracture toughness

Dental materials must satisfy the various requirements such as proper strength, fit, biocompatibility, chemical stability and esthetics. Ceramic restorations are one of the most widely used types of restoration in dentistry because they can fulfill those requirements, and can provide the most natural replacements for teeth. However, the brittle nature of ceramics is a primary disadvantage of these restorative materials. Ceramics are thought to have low tensile strength because of the presence of flaws that initiate and propagate fractures. For this reason, improvements and new formulations to strengthen ceramics are continually being researched and developed. Although a great number of high-strength porcelain materials have been introduced,[1-8] it is generally believed that metal-ceramic restorations are stronger than all-ceramic materials and that they can withstand greater applied loads.[9] So, metal ceramic restorations are most widely used in prosthodontic treatment till now.

Conventional feldspathic porcelains used in metal ceramic restorations are composed primarily of SiO_2(silica, 64%) and Al_2O_3(alumina, 18%) with various amounts of K_2O(potash) and Na_2O(soda) to control expansion.[10] The flexural strength of feldspathic porcelains is quite low, generally in the range of 60 to 70㎫, which is one of the primary reason for the use of a metal substructure to reinforce the ceramic restoration.[11]

Considerable research efforts have been devoted to additional strengthening of feldspathic porcelain in metal ceramic restoration. These approaches involve generation of compressive stress, either internally or in the immediate subsurface layer.

Surface compressive stress can be generated through glazing, work hardening, or ion exchange.[12] In these methods, glazing and work hardening are most uncomplicated practical means of increasing the flexural strength of dental ceramic materials. A glaze placed on the surface of the porcelain will generate compressive stress if the underlying ceramic contracts more on cooling to place the surface glaze in compression.[13] This surface compressive stress can result in appreciable strengthening by inhibiting crack growth from the surface through the body of the porcelain. Work hardening of ceramics is also possible as a result of compressive stresses generated from fine grinding and polishing.[14]

These strengthening methods are associated with surface finish of metal ceramic restoration. The surface finish of ceramic restorations is also important with respect to esthetics and wear of opposing restorations or dentition. Traditionally, glazing has always been advocated as the last surface treatment before final cementation. A glazed surface was thought to produce stronger and more cleansable surfaces. But, it is a common clinical practice to adjust ceramic restorations following luting and precluding reglazing. These modifications may be necessary to correct occlusal interferences, improve esthetic appearances, achieve more favorable contours, finish the margins of porcelain-bonded restorations, and improve surface smoothness.[15] Such adjustments break the glaze, resulting in a rougher surface and inferior surface properties. A rough surface may promote plaque formation and maturation[16,17] and increased abrasion of the opposing teeth.[18] Furthermore, such grinding may negate the strengthening effect of glazing procedure.[19] Polishing the final surface of ceramic restoration is very important for those reasons. Various polishing methods are available to improve the ceramic surface, but there has been no agreement on any superior method.

Meanwhile, there have been many controversial studies about strength between glazed and polished porcelain. Levy[20] tested the effect of polishing with pumice and etching on the flexural strength of dental ceramics after air and vacuum glaz-

ing and overglazing. Results showed no significant difference between treatments; however, polished glazed specimens had higher strength values. In a similar study, Brackett et al[21] reported that the flexural strength of specimens treated with an overglaze was significantly greater than specimens treated with self-glazing or self-glazing and polishing. Giordano et al[10] compared the strengthening effects of self-glazing, overglazing and polishing. They found that polishing and the application of an overglaze resulted in greater strength values. However, the increased flexural strength from overglazing is still significantly less than that obtained from polishing. In their other study, Giordano et al[12] also stated that overglazing with a specific glass powder and fine grinding and polishing could increase the flexural strength of feldspathic porcelains similarly. On the other hand, Rosenstiel et al[22] reported that a significant increase in fracture toughness was found in polished dental porcelain versus glazed porcelain. Fairhurst et al[23] also stated that the polished specimens showed significantly higher flexural strength than the glazed specimens. Griggs et al[24] reported that there was no statistically significant difference in mean strength between the glazed and non-glazed specimens. While, Williamson et al[25] reported the results of their study which was to determine how surface treatments and moisture affect the flexure strength of high-leucite feldspathic porcelain. In dry conditions, overglazed specimens were significantly stronger than polished specimens. But, in wet conditions, there was no significant difference between the flexure strength of overglazed and polished specimens.

These various and conflictive results are due to the difficulties of experiments. The difficulties of experiments include the difficulty of specimen fabrication, variables in porcelain firing procedure, methods of grinding and polishing, evaluation methods of surface characteristics, variable strength test methods and so on.

The objective of this study was to investigate the effects of (1) overglazing, (2) self-glazing, and (3) fine polishing on the flexural strength and fracture toughness of feldspathic dental porcelain.

MATERIALS AND METHODS

1. Specimen fabrication

Ninety porcelain disks measuring 12㎜ in diameter and 2㎜ in thickness were prepared for flexural strength test and sixty porcelain disk samples measuring 7㎜ in diameter and 5㎜ in thickness were fabricated for fracture toughness test in refractory molds by use of ultrasonic condensation and blotting techniques. Vita porcelain was selected for this investigation because it has been used in many previous studies.

For the preparation of refractory molds, machined aluminum molds were made at first. After the proper impression taking of the aluminum mold with polyvinylsiloxane impression material(Exafine, GC Co., Japan), refractory cast material was poured into the impression body for the completion of the refractory mold.

All specimens were fabricated by one technician who condensed the porcelain into the mold in a standardized manner. Specimens were fired in one furnace (Programmat P 95, Ivoclar, Schaan, Liechtenstein) according to the manufacturer's directions. The following firing schedule was applied: predrying temperature, 600℃ for 6min; rate of rise, 50℃/min for 6min; final temperature, approximate 900℃. Vacuum was initiated at 600 ℃ and released at just before final temperature. The specimens were arbitrarily numbered and surfaces were steam cleaned.

A thin layer of surface glaze was applied to the specimens of overglazed group(Vita glaze powder and liquid). The specimens were placed on a platinum foil-lined sagger tray and allowed to dry for 6 minutes, then, glazing was accomplished

using an initial temperature of 600℃ raised at a rate of 75℃ per minute to approximate 900℃. The specimens were glazed using a rapid firing cycle without vacuum. The specimens were held at the final temperature for 1 minute. For the specimens in the self-glazed groups, the specimens were placed on a platinum foil-lined sagger tray and placed in a 600℃ oven without predrying. The self-glazed specimens were fired in the same schedule with overglazed samples without surface glaze. When the final temperature was reached, the specimens were also held for 1 minute. After firing, the reverse sides of glazed surfaces were ground with an abrasive wheel. Ninety biaxial flexural strength test specimens were ground to a thickness of 1.5±0.3㎜ and sixty fracture toughness test specimens were ground to a thickness of 4.5±0.3 ㎜. Distilled water was used as the lubricant.

Polishing consisted of using a series of wheels coated with a diamond paste from 15㎛, 9㎛, 6㎛, and 3㎛ to 1㎛. The paste was applied to the specimens for 20 seconds under a load of 15 pounds at a rate of 350rpm. The specimens were fixed with wax to a standard sample holder and leveled to create a flat surface relative to the polishing wheel. A lapping machine(Alpha Precision Ind. Co., Seoul, Korea) was used to ensure reproducible control of the polishing procedure. The specimens were cleaned between grits with an ultrasonicator in a soap solution followed by deionized water. Opposing faces were flat and parallel to within 0.05㎜. For the proper alignment of specimens in each test, the reverse sides of glazed surfaces were also polished like this. During these grinding and polishing procedure, glazed surfaces were not disturbed.

Specimens were divided into three groups in each test(n=30 in biaxial flexural strength test, n=20 in fracture toughness test) as follows: 1) overglazed 2) self-glazed 3) polished.

2. Biaxial flexural strength test

The biaxial flexure test has been used frequently for the determination of fracture characteristics of brittle materials. The measurement of the strength of brittle materials under biaxial flexure conditions rather than uniaxial flexure is often considered more reliable, because the maximum tensile stresses occur within the central loading area and spurious edge failures are eliminated. This allows slightly warped specimens to be tested and produces results unaffected by the edge condition of the specimen. This feature make the method suitable for assessment of the effects of surface conditions on strength.[26] In this study, the ring-on-ring test method was used and the tests were performed on a universal testing machine(Model 5584, Instron, Instron Co. Canton, MA., U.S.A.). The ring-on-ring bending apparatus was designed similarly to the one described by Wachtman et al[27] having a loading ring diameter of 1.41㎜ and a support ring diameter of 10.0㎜ with eight supporting balls. It has been shown that when more than six supporting points are used, the multiple points constitute a continuous ring support.[28] The specimen dimensions were measured by one investigator using a digital caliper. The thickness of each specimen was calculated as the mean of three measurements taken at random sites. The diameter of each specimen was calculated as the mean of the major and minor axes. The specimens were fractured in a ring-on-ring biaxial flexure fixture with the treated side under tension at a loading rate of 0.5㎜ per minute(as recommended by ISO/DIS 6872, 1994). The specimens were broken such that the greatest tensile force was applied to the treated surface. The load at failure was recorded and the biaxial flexure strength for each specimen was calculated with the following Shetty' s equation.[29]

$$M = \frac{3P}{4\pi t^2}\left[2(1+v) - \ln\frac{a}{b} + \frac{(1-v)(a^2-b^2)}{R^2}\right]$$

Where P is the load at fracture in newtons, t is the thickness of the specimen, a is the radius of the circle of support points, b is the radius of the loading ring, R is the radius of the specimen, all in meters, v =0.25 is Poisson' s ratio.

3. Fracture toughness test

Flexural strength testing has been an effective method for comparing the strength of ideal, relatively flaw free, samples. However, in artificial crowns, samples rarely have polished flat surfaces, and notches and large flaws may be present. Tests for fracture toughness determine a material' s sensitivity to flaws and notches. Various methods can be used to determine fracture toughness, but most of these methods require intricately shaped specimens. Production of sufficient numbers of these specimens with accurate shape control is often difficult with ceramic materials. Because of the difficulty in producing accurately shaped specimens, the Vickers indentation technique was used in this study with a protocol closely following that described by Rosenstiel and Porter.[30]

Vickers hardness tester(AVK-CO Mitutoyo Co., Japan) was used to determine the fracture toughness(Kc) and the hardness of the porcelain tested. The value of the modulus of elasticity for these feldspathic porcelain specimens was obtained from the literature(70㎬).[31] Five indentations on each specimen were made with a Vickers diamond using a load of 5㎏ or a force of 49N for 15 seconds. This load was sufficiently high that the radial cracks were approximately equal to or greater than the diagonal of the indentation, but not so high that lateral chipping occurred. Crack length was measured within 1 minute of indentation by using the traveling microscope on the hardness tester. Two readings were made for each indentation, and the average of the ten readings used to derive the Kc for each specimen. The Kc and the hardness were calculated by using the length of the cracks that appear to emanate from the Vickers indentation according to the following equations.[32]

$$H = 1.8544\ \frac{P}{(2a)^2}$$

$$Kc = 0.016\left(\frac{E}{H}\right)^{1/2}\left(\frac{P}{c^{3/2}}\right)$$

Where Kc = fracture toughness, H = Vickers hardness, P = applied indenter load, a = half diagonal of the indentation, c = crack length(measured from the center of the indentation), and E = elastic modulus.

4. Statistical analysis

Analysis of variance(ANOVA) with Tukey honest significant difference(HSD) test was performed to analyze the data at a significance level of 0.05.

RESULTS

The mean and standard deviation of flexural strength of the porcelain specimen groups are presented in Table Ⅰ. Fractured specimens could be grouped according to a two-segment or three-segment fracture pattern. However, no relationship between the fracture mode and the strength was observed. Table Ⅰ shows that the overglazed group is strongest(64.43±24.85㎫), followed by the polished group(52.08±11.90㎫), while the self-glazed group is the weakest(47.02±12.56㎫). One-way ANOVA(Table Ⅱ) reveals a significant difference in flexural strength between the groups($P<0.05$). This result is presented graphi-

Table I. Mean and standard deviation of the flexural strength of three experimental groups

	N	Mean(㎫)	S. D.
Overglazed	30	64.43	24.85
Self-glazed	30	47.02	12.56
Polished	30	52.08	11.90

Table II. Summary of one-way ANOVA for biaxial flexural strength

	Sum of squares	df	Mean square	F	Sig.
Between groups	4811.81	2	2405.93	7.87	0.001
Within groups	26602.02	87	305.77		
Total	31413.82	89			

Table III. Tukey HSD test for flexural strength test

	N	Subset for alpha=0.05	
		1	2
Overglazed	30		64.43
Self-glazed	30	47.02	
Polished	30	52.08	

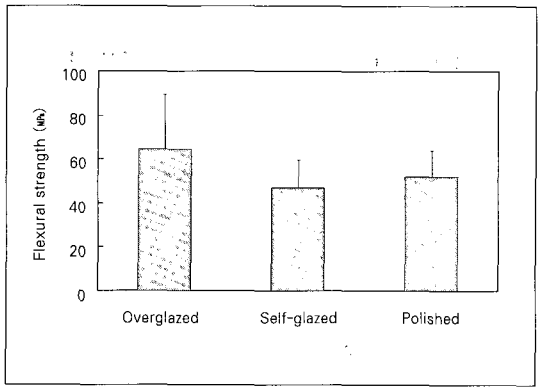

Fig. 1. Biaxial flexural strength and standard deviation bars for three experimental groups.

Table IV. Mean and standard deviation of the fracture toughness of three experimental groups

	N	Mean (㎫ · $m^{1/2}$)	S. D.
Overglazed	20	1.90	0.37
Self-glazed	20	1.13	0.16
Polished	20	1.63	0.52

Table V. Summary of one-way ANOVA for indentation fracture toughness

	Sum of squares	df	Mean square	F	Sig.
Between groups	6.14	2	3.07	21.15	0.000
Within groups	8.27	57	0.14		
Total	14.41	59			

cally in Fig.1 for easier comparison. Tukey HSD multiple comparison test(Table Ⅲ) shows that the overglazed group is significantly stronger than the self-glazed and the polished group($P<0.05$), while the difference between self-glazed and polished group is not significant($P>0.05$).

Table Ⅳ shows the mean values and standard deviation of fracture toughness of the porcelain specimen groups. The highest value of fracture toughness is found in the overglazed group(1.90

Table VI. Tukey HSD test for flexural strength test

	N	Subset for alpha=0.05	
		1	2
Overglazed	30		1.90
Self-glazed	30	1.13	
Polished	30		1.63

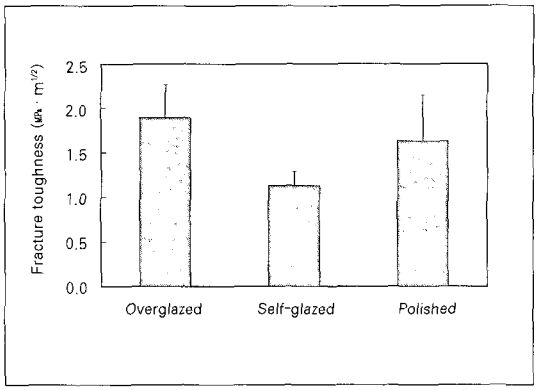

Fig. 2. Indentation fracture toughness and standard deviation bars for three experimental groups.

± 0.37MPa · $m^{1/2}$), followed by the polished(1.63 ± 0.52MPa · $m^{1/2}$), and then the self-glazed group(1.13± 0.16MPa · $m^{1/2}$). This result is also presented graphically in Fig. 2 for easier comparison. One-way ANOVA of fracture toughness test(Table V) also shows significant difference in fracture toughness between the groups($P<0.05$). Tukey HSD multiple comparison test for fracture toughness test(Table VI) shows that both the fracture toughness values of overglazed and polished group are significantly higher than that of self-glazed group($P<0.05$), while the difference between overglazed and polished group is not significant($P>0.05$).

DISCUSSION

Conventional feldspathic porcelain was chosen in this study because it is used extensively as a restorative material and it is subjected to grinding and polishing during fabrication and delivery procedures. The change in surface roughness after different surface finishing techniques has attracted the attention of prosthodontists regarding wear of the opposing teeth or restorative material,[33] and the strength,[10] plaque retention,[34] stainability[22] and appearance[35] of the restoration. There is still considerable controversy concerning the best methods to achieve the most practical porcelain restorations after such adjustments. Contrasting opinions and results have been reported by different groups of researchers when testing different ceramic materials and surface finishing techniques, e.g. overglazing, self-glazing and polishing with a variety of instruments.[15,20-36]

Feldspathic porcelains, which are used in the construction of porcelain-fused-to-metal restorations, have an inherent weakness because of their brittle nature and processing flaws. Although long term clinical studies are the only bases for reliable predictions of longevity and functionability of dental restorations, various physical properties of the materials are also important for their potentials as successful restorations. Mechanical strength is one of the important factors that control the clinical success of dental restorations. Usually, complex stress distributions that are induced by compressive, tensile, and shear stresses are present in most specimens under practical conditions. But, in general, tensile strength is considered as the more meaningful property for the brittle material, compared with compressive strength, for assessment of the failure potential of dental restorations, especially in the presence of critical surface flaws. The strengths of brittle materials are usually measured in flexure test because this test is generally easier to perform than a pure tensile test. Recently, the bi-axial flexure test

has been used frequently for the determination of fracture characteristics and the tensile strength of brittle material. Strength testing of brittle materials in biaxial rather than uniaxial flexure offers useful advantages. First, because the maximum tensile stresses occur within the central loading area, spurious edge failures are eliminated. Second, the biaxial stress state represents the more severe of the two stress configurations and is accordingly better suited to conservative strength design. Besides, Wachtman et al[27] reported that a coefficient of variation of about 7% can be achieved by biaxial flexural strength test and that different laboratories generally obtain good agreement on strength values. Essentially, the biaxial test involves loading a circular plate on opposite sides with radially symmetrical bending forces. The magnitude of the stresses thus produced may then be calculated from standard formulas for thin plates in flexure.[37]

Probably the most attractive biaxial test arrangement is that which uses two opposing coaxial loading rings of unequal diameters; apart from its simplicity, this arrangement ideally should generate uniform tensile stress in the specimen surface opposite the smaller loading ring.[38]

Several previous studies[44,37,39] advocated the placement of a polyethylene film between the specimen and support to improve the uniformity of load distribution. Such a film was found to be unnecessary in the present study because all specimens tested had intimate contact with the ring after glazing or polishing.

In this study, the relative flexural strength of feldspathic porcelain was slight lower than those of similar previous reports.[40,41] This result may be attributed to the difference of fabrication method of specimens. Condensation method in this study was not for the test of physical property of material itself, but for the simulation of the clinical conditions.

In the present study, the flexural strength data of the overglazed group was significantly higher than that of the polished group and the self-glazed group. This result was in good agreement with those of some previous studies.[21,25]

The application of an overglaze in which the thermal coefficient of expansion is slightly less than that of the underlying porcelain could significantly improve the flexural strength of feldspathic dental porcelains. The strengthening could result from two possible mechanisms. First, when the restoration is heated with such an overglaze, the overglaze layer fills in surface flaws, reducing their depth and blunting the flaw tips. This should provide a strength increase, because, for a given ceramic material, strength increases with decreasing flaw depth and sharpness.[42] Second, for feldspathic porcelains, the overglaze layer has a lower thermal expansion coefficient than the leucite-rich interior. This places the outer surface in compression when cooled. The compressive stress state diminishes the local tensile stress produced from applied loading at surface flaws, thereby necessitating the need for increased applied loading to initiate flaw propagation from the external surface.[43] Thus, a more appropriate glaze involves the application of a thin uniform layer of glass that fuses with the underlying ceramic to form a smooth homogeneous coating that provides resistance to chemical erosion and generates compressive stresses while filling surface defects. The application of an overglaze as the final finish may be the most practical method of increasing the strength of feldspathic porcelain and could be performed after staining or repeated if additional occlusal adjustments were required.

In this study, no significant difference of flexural strength was found between the self-glazed and the polished group. This result was in accord with that of Sherill and O' Brien' s study.[44] But, it

was not in agreement with those of the other studies.[12,23] In those studies, a feldspathic porcelain' s strength was found to be higher after fine polishing than after self-glazing. On the other hand, Chu et al[45] reported the higher flexural strength in self-glazed group than in polished group. These contrasting results may be originated from so many variables in the polishing procedure. In the polishing procedure, a number of parameters were able to interact with each other and the ceramic microstructure to alter polishing effects-cooling and debris removal from a lubricant, polishing tool coarseness and wear, abrasive particle type and fineness, polishing process and feed rate. Thus, the polishing process was quite complex, involving numerous material and parameters. In addition, these controversial results may be caused by the intrinsic flaw distribution which could be altered during the surface finishing procedures. This alteration of intrinsic flaw distribution was a result of the locations and nature of the leucite particles surrounded by a lower thermal expansion glass matrix which formed microcracks upon cooling, due to differences in thermal expansion coefficients.[46] However, it was not clear whether with increasing microcrack density there was an accompanying increase in strength due to crack stopping or a decrease in strength due to the higher probability of producing a large critical flaw, as might have occurred in self-glazed group. It was also possible that certain thermal effects might blunt microcracks.

However, strength is more of a conditional than an inherent material property, and strength data alone cannot be directly extrapolated to predict structural performance. Strength data are meaningful when placed into context via knowledge of material microstructure, processing history, testing methodology, testing environment and failure mechanism.[47] In other words, strength alone will not provide sufficient information to decide whether or not a treatment process has enhanced the resistance to fast fracture. Since strength is dependent on crack size, it can vary with the handling procedure, finishing procedure or with random processing flaws. In various strength tests, the crack or flaw size at the fracture origin is not controlled or measured. The results of those tests are subjected to statistical scatter due to the distribution of crack sizes.[48] Fracture surface analysis of test specimens will be necessary in further study, because it can be used to characterize defects and to validate that flexural data accurately presents appropriate information.[49,50]

Dental ceramics, like all brittle materials, suffer from an inability to absorb appreciable quantities of elastic strain energy prior to fracture.[51] This liability is manifested in such behavior as flaw sensitivity, low tensile strength, and a tendency to catastrophic failure. One measure of the strain-energy absorbing ability of a brittle material is the critical stress intensity factor, fracture toughness, or Kc. The fracture toughness of a material is a measure of its strain-absorbing properties and relates to the level of tensile stress which must be exceeded at the tip of a crack before catastrophic fracture process is initiated. Unlike fracture strength, Kc is an intrinsic characterization of mechanical response because it is not sensitive to variables such as the size and density of surface flaws, which are controlled by the manner in which test specimens are prepared. Namely, apparent fracture toughness values are sensitive to the type of porcelain used and to the magnitude of residual stresses in the specimen.[52]

Several techniques have been proposed to assess the fracture toughness of brittle materials.[53] These methods include the double cantilever beam, double torsion, notch bend, and indentation techniques. The introduction of the indentation technique, first described by Parmqvist

in 1962,[54] enabled Kc testing to be performed on a number of brittle dental materials. The indentation technique is particularly suitable for study of dental ceramics because the dimensional requirements of the specimens are relatively small, and crack growth parameters are determined by use of cracks that are approximately the same size as those expected at clinical evaluation. Also, it is attractive for dental ceramics because the technique allows actual restorations to be studied and the small size of the indenter tip enables multiple measurements to be made on the same specimen.

The indentation-derived fracture toughness value for feldspathic porcelain in this study, regardless of surface finishing methods, was in good agreement with similar values reported previously,[31,52,55] which indicated that this method is reproducible.

Although several empirical equations have been proposed for calculation of Kc, one obtained by Anstis et al[32] was adopted for use in this study, on account of its simplicity and reliability.

For the determination of Kc of dental feldspathic porcelains by the indentation technique, Morena et al[52] used a small indentation load of 4.9N(500g). They chemically etched the post-indented surface with dilute HF solution to widen and accentuate the radial cracks. We initially adopted their technique, but failed to achieve similar results: visible cracks were not produced by such a small load. We therefore increased the indentation loads, ranging from 9.8N(1kg) to 49N(5kg). It then became apparent that, for the dental feldspathic porcelains, larger loads of 49N were needed to induce the clearly visible radial(median) cracks.

Slow growth of cracks from stress corrosion subsequent to indentation was demonstrated by Anusavice and Lee[55] and by Gupta and Jubb.[56] In this study, We measured only immediate effects of stress application on fracture characteristics of feldspathic porcelains. Evaluation of stress corrosion susceptibility may provide more useful insight for long-term performance characteristics of these differently finished feldspathic porcelains, but further investigation is needed.

In this study, the fracture toughness data of the self-glazed group was significantly lower than that of the overglazed group and polished group. This result, presumably, may be associated with the annealing effect that occurred during self-glazing procedure.[22] Also, it may be originated from spontaneous microcracking, occurred upon cooling in self-glaze treatment. In feldspathic porcelains, the leucite particles contract more than the surrounding glass upon cooling. Above a critical particle size, the stresses created during cooling can induce microcracks circumferential to the leucite particles.[46] Previous studies have indicated that the size of leucite particles in feldspathic porcelain increases during heat treatment within the normal porcelain firing range.[57,58] This can increase the probability of microcracking.[59,60] It is possible that microcracking occurred during the self-glaze treatment.

Meanwhile, the relatively lower fracture toughness value in self-glazed group demonstrates reduced compressive stresses in the specimens. Generally, for slow-cooled porcelains, porcelains that have not been tempered,[61] self-glazing is unlikely to induce residual compressive stresses in the porcelain' s surface. The glassy surface formed during self-glazing does not contract at a greatly different rate than the underlying porcelain from which the glaze is produced. Consequently, residual compressive stresses were not induced in self-glazed surfaces, and the fracture toughness result of the self-glazed group was not increased.

The higher fracture toughness value in polished group than in self-glazed group was in

good agreement with the study of Rosenstiel et al.[22] This result may be obtained from a combination of compressive residual stress and the removal of larger surface flaws formed during processing. Larger defects that are generated during fabrication may be removed during grinding and polishing procedures, so some of the flaws that may become cracks are eliminated to increase fracture resistance. On the other hand, polishing of ceramic materials typically involves contact with a rotating wheel, producing multipoint surface grinding. The abrasive material impacts the surface, producing contact forces that cause crushing, plastic flow, and elastic recovery. This contact generates residual stress and forms a radial-lateral crack network. The presence of these cracks has been confirmed in fractographic studies by Rice and Mecholsky.[62] As the abrasive contacts the surface of the material, compressive stresses can be generated that affect flaws oriented perpendicular and parallel to the surface,[22] but depend upon the parameters of the polishing process. The area of compressive stress beneath each abrasive particle can overlap, producing a layer of compression. The resulting surface finish and stress state will have a major influence on the mechanical properties of the material. Residual compressive stresses have been found to occur in a wide range of ceramic materials following polishing.[63]

The results of this study support the use of polishing as an alternative to glazing metal ceramic restorations, because it was not detrimental in flexural strength and it resulted in higher value of fracture toughness.

Further quantitative investigation is indicated, and the results of this laboratory study with nonclinical specimen geometry and smooth surface texture should not be overinterpreted insofar as application to the clinical situation is concerned.

In other words, the relationship between strength, fracture toughness, and clinical performance has not been established, and further clinical investigations are imperative to substantiate such claims.

Therefore, further detailed investigations on the relationship between surface characteristics and clinical performance of feldspathic porcelains are required to elicit the closest result to truth.

CONCLUSION

Ninety porcelain disks were prepared for flexural strength test and sixty porcelain disk samples were fabricated for fracture toughness test. The flexural strength of feldspathic porcelains, which were differently finished(overglazed, self-glazed and polished), was determined by ring-on-ring biaxial flexural strength test. The fracture toughness values of three experimental groups were obtained by indentation fracture toughness test.

Under the conditions of this study, the following conclusions were made:

1. The flexural strength of overglazed group was significantly higher than that of self-glazed and polished group ($P<0.05$), while the difference between self-glazed and polished group was not significant ($P>0.05$).
2. The fracture toughness values of overglazed and polished group were significantly higher than that of self-glazed group ($P<0.05$), while the difference between overglazed and polished group was not significant ($P>0.05$).
3. The results of this study supported the use of polishing as an alternative to glazing metal ceramic restorations, as it was not detrimental in flexural strength and fracture toughness.

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