# 歯科用陶材の研削における延性／脆性遷移条件

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## Ductile/Brittle Transition Conditions in Grinding of Dental Porcelain

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### Abstract

The functional surface of porcelain crowns are ground with diamond burs during occlusal adjustment in dental field. This procedure results in the introduction of surface and subsurface flaws (brittle-mode grinding), and can be accompanied by reduction in strength and fatigue lifetime. Recently, it was demonstrated that brittle ceramics can be ground without subsurface flaws (ductile-mode grinding). The aim of this study was to predict the ductile-brittle transition conditions in grinding of a dental porcelain material. By modeling the grinding process of an abrasive particle as an indentation of a spherical indenter, the elastic-plastic stress field under the indentation was calculated using Hill's spherical cavity expansion solution. The ductile-brittle transition conditions were predicted by comparing the fracture toughness of the material to the stress intensity factors of penny-shaped pre-existing cracks under the stress field, and represented by a critical radius of the spherical indenter. The calculations showed that the critical radius in grinding of the porcelain material is deduced to be 2.0 microns. By modeling the grinding process by an abrasive particle as a Vickers indentation, a critical depth of cut is deduced to be 1.3 microns. It was concluded that the dental porcelain can be ground

without subsurface cracks（ductile-mode grinding）by controlling either the radius of abrasive particles or the depth of cut.

## INTRODUCTION

In brittle materials like dental porcelain, the process of grinding is usually accompanied by an occurrence of Radial, Lateral, and Median cracks[1]. And, it is thought that these occurring cracks, especially the Median crack has decreased the strength and the fatigue lifetime of the brittle material ground[2]. On the other hand, the ductile-mode grinding without an occurrence of these cracks has been reported to be possible even in the brittle materials under the certain conditions[3]. However, the ductile-brittle transition conditions in grinding of dental porcelain have not been clarified. If this ductile-brittle transition conditions can be evaluated, the useful data concerning the possibility of the ductile-mode grinding in dental porcelains are obtained. Furthermore, it can be understood the influence of the grinding process on the mechanical properties of dental porcelain. The aim of this study, therefore, was to predict the ductile-brittle transition conditions in grinding of the dental porcelain.

## MATERIALS AND METHODS

Schematic representation of the process of the brittle-mode grinding, in which a dental porcelain material is ground by an abrasive particle, is shown in Fig. 1. In brittle-mode grinding, Radial, Lateral, and Median cracks are generated under the surface of the dental porcelain. Though the grinding process is thought to be complex phenomena, however, it can be simply thought that grinding by an abrasive particle consists of an indentation and a scratch of an abrasive particle to the surface of the material. Fig. 2 shows a schematic representation of an indentation model of the grinding with an abrasive particle. In this study, the grinding by an abrasive particle has been modeled as an indentation of an abrasive particle into the surface of the material. Moreover, the indentation process by an abrasive particle was assumed to be equivalent to a model by whom a spherical particle was indented to the surface of the material using the following assumptions. That is, first, a hemi-spherical plastic deformation zone is formed under the indentation regardless of the shape of indenter. The plastic zone with the same
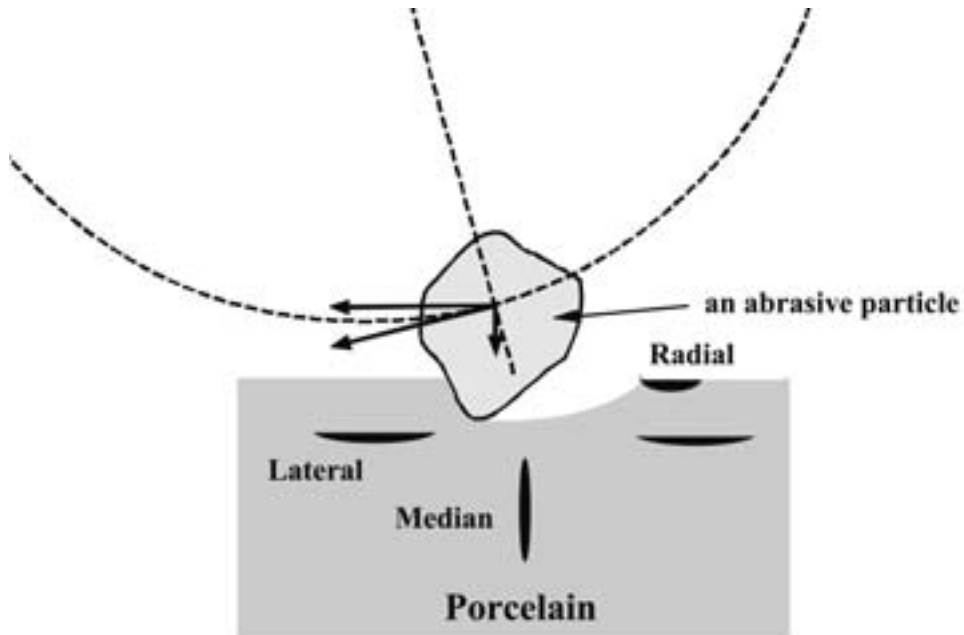
Fig. 1　Schematic of brittle-mode grinding of dental porcelain with an abrasive particle.

radius is formed when the indentation volume is equal. Secondly, the elastic-plastic stress field developed is depend on the radius of the plastic zone. And the elastic-plastic stress field under indentation is calculated using Hill' spherical cavity expansion solution[4]. In addition, penny-shaped pre-existing cracks with various sizes are introduced into this stress field, and the condition that the Median crack occurs, that is, the ductile-brittle transition condition, is evaluated by calculating the stress intensity factor at the crack surface, and comparing it with the fracture toughness of the dental porcelain material. The Young's modulus, Poisson's ratio, Vickers hardness, and the fracture toughness of the dental porcelain material are assumed to be $E=57.3$ GPa, $\nu=0.26$, $Hv=6.93$ GPa, and $K_{IC}=0.84$ MPam$^{1/2}$, respectively[5].

## RESULTS and DISCUSSION

Fig. 3 shows the result of the stress analysis when a hemispherical indenter with radius of 50 microns is indented. In this case, a hemispherical plastic deformation zone formed under the indentation has the radius of 1.92 times the radius of the indenter.
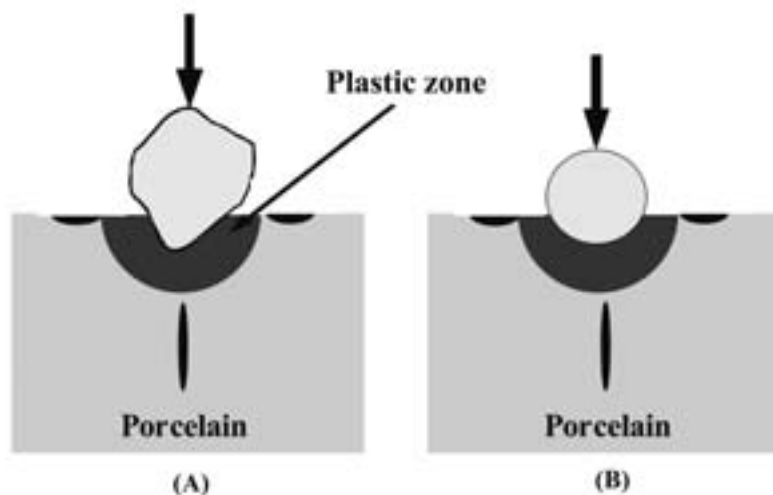
Fig. 2　Schematic of a indentation model of the grinding with an abrasive particle. We assumed that the plastic zone exhibits spherical symmetry regardless of indenter, and identical plastic zone boundaries develop for indentations of equal volume.

The normal stress to Z axis, which causes an occurrence of a Median crack, changes from compression to tension in the plastic deformation zone, and shows the maximum tensile stress at the elastic-plastic stress boundary, and the tensile stress has decreased gradually with an increase of the depth. The plastic deformation zone remains on the surface of the material as a residual compressive stress layer after polishing, and therefore, contributes to an increase in strength of the material. For the case that the radius of spherical indenter is 1, 2, and 3 microns, respectively, the stress intensity factors of the pre-existing cracks as a function of the crack length are shown in Fig. 4. The pre-existing cracks were introduced into the elastic-plastic boundary where the maximum tensile stress was generated. It was found that for the pre-existing crack with the length of 2 microns or less, the stress intensity factors do not exceed the fracture toughness value of the dental porcelain material. In another expression, it can be say that the dental porcelain is ground with the brittle-mode, where the Median crack occurs, for the condition of 3 microns or more in the radius of the indenter. Fig. 5 shows
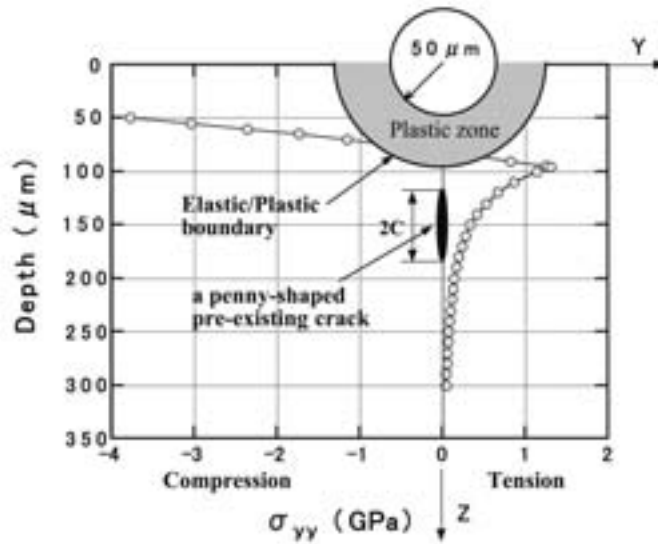
Fig. 3　Distribution of tangential stresss along the Z-axis when a hemispherical indenter with radius of 50 microns is indented.

the relationship between Median crack length and spherical indenter radius. It is predicted that a Median crack with the length of about 50 microns occurs when the indenter with the radius of 10 microns is indented. It is thought that this crack that occurs under the surface causes the decrease in strength of the material because it cannot remove by polishing. However, because the residual compressive stress layer exists above the crack, the extension of the crack to the upper side will be obstructed as long as this compressive residual stress layer is not removed by the polishing. Fig. 6 shows the relationship between Median crack length and depth of cut when the shape of an abrasive particle was assumed to be a Vickers indenter. It has been found that the Median crack can not occur when the depth of cut is 1.3 microns or less, and even the dental porcelain can be ground with the ductile-mode by controlling the depth of cut in grinding.
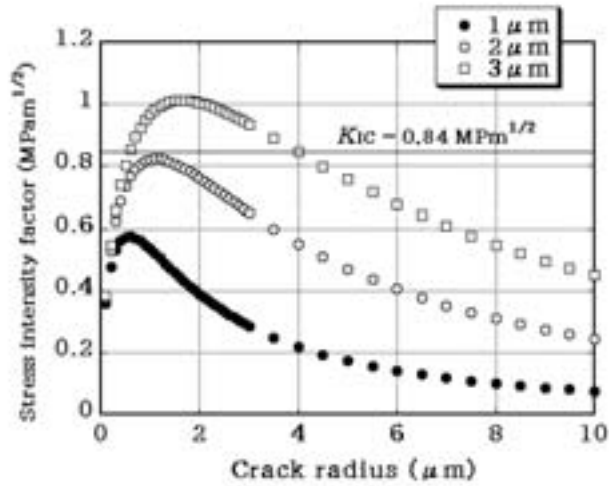
Fig. 4  Stress intensity factors of the pre-existing cracks as a function of crack length for the case that the radius of spherical indenter is 1, 2, and 3 microns, respectively.
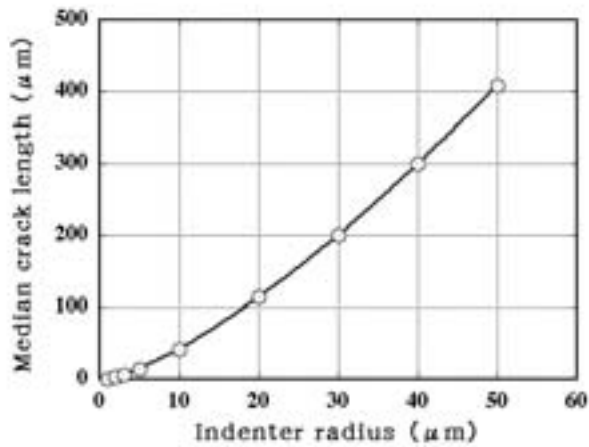


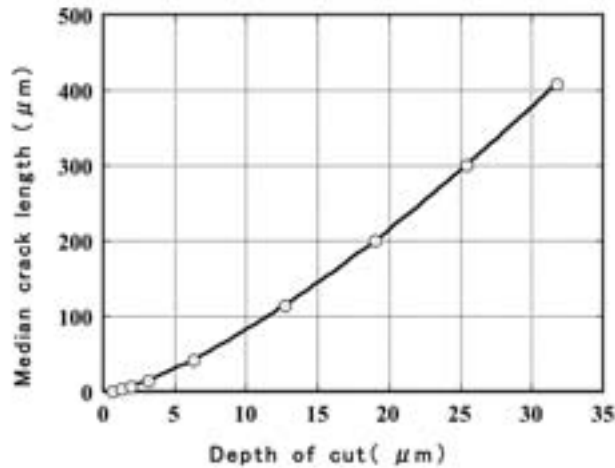Fig. 5  Relationship between Median crack length and spherical indenter radius.

Fig. 6  Relationship between Median crack length and depth of cut when the shape of an abrasive particle was assumed to be a Vickers indenter.

## CONCLUSION

It has been found that the stress intensity factors of pre-existing cracks do not exceed the fracture toughness of the dental porcelain material when a spherical indenter with the radius of 2 microns or less is indented. Therefore, the dental porcelain can be ground with the ductile-mode by controlling the radius of abrasive particles. When the shape of an abrasive particle was assumed to be a Vickers indenter, the ductile-brittle transition condition of the dental material was calculated to be 1.3 micron in the depth of cut. The fact means that regardless of the grain size of the diamond bur, dental porcelain can be ground with the ductile-mode by controlling the depth of cut.

## REFERENCES

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## 和　文　要　旨

　歯科領域においてオールセラミッククラウンのようなセラミックス修復物では、咬合調整のために、ダイヤモンドポイントなどにより咬合面を研削する必要がある場合がある。しかしこの咬合調整のための研削はセラミックスの表面あるいは表層下に亀裂を発生させ（脆性モード研削）、発生した亀裂はセラミックスの強さや疲労寿命の低下の要因となり得る。近年、脆性材料であるセラミックスにおいても、研削中に表層下の亀裂が発生しない延性モード研削が可能であることが示された。そこで本研究では、歯科用陶材の研削における延性モードと脆性モードの遷移条件を明らかにすることを目的とした。そのために、１個の研削砥粒による研削プロセスを球状圧子の圧子圧入としてモデル化し、圧子圧入時に陶材表層下に発生する弾塑性応力場を Hill の球殻押拡げの解を用いて計算した。そして延性モードと脆性モードの遷移条件は表層下に導入した円盤状の亀裂端の応力拡大係数と陶材の破壊靱性を比較することで予測し、球状圧子の臨界半径として表わした。その結果、陶材の研削における臨界半径は２μm であると推測された。また、研削砥粒の形状をビッカース圧子と仮定して求めた切り込み深さと研削により発生するメジアン亀裂長さとの関係から、切り込み深さが1.3 μm 以下であれば、延性モード研削が可能であることが分かった。すなわち、歯科用陶材は研削砥粒の半径あるいは切り込み深さを制御すれば、延性モード研削が可能であることが分かった。