原　　著

Stress Analysis of Dental Cast Investments: Calculation Model

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ABSTRACT

Stress calculation model was proposed to estimate stress and strain behaviours in dental cast investment which was composed of ethyl silicate (a bonding agent) and silica particle (a refractory material). Stress and strain curves were supposed for each material which constituted their composites to describe the stress and strain relation. The caluculation model which was considered originally by Wakasa and Yamaki was applied to dental cast investment as a composite of each material with respective stress and strain relations. The results showed that stress and strain relation in dental ethyl silicate-bonded investment had linear stress increment to strain during compression test, as supposed by the equation introduced in APPENDIX. The theoretical analysis proposed that the composite stress was achieved by an increase of stress in the bonding material, showing that stress increment was expressed by silica fraction and elastic modulus values of silica and bonding agent.

INTRODUCTION

The essential ingredients of dental inlay investment employed with gold casting alloys are a hemihydrate of gypsum and a form of silica[1]. The gypsum product serves as a binder to hold the silica refractory material to provide the rigidity and strength of investments which contain 25 to 45% of the gypsum. To develop new investments, the mixed investment powders with ethyl silicate solutions were examined for castable glass ceramic and titanium metal[2-5]. For the dental application, the property to need strengthened matrix of cast investments depends on the compositions of bonding and refractory materials. Thus, this study was to clarify the stress and strain relation of their materials and to apply it to new development of cast investments.

MATERIALS AND METHODS

The materials had the same compositions as the previous reports, which were composed of ethyl silicate and silica[6-9]. Two types of ethyl silcate solution used were E75 (75 wt% ethyl silicate/25 wt% mixture solution) and E50 (50 wt% ethyl silicate/50 wt% mixture solution) (wt% is described as % in this study). E75 and E50 had, respectively, 2.5 and 0.8 as a pH value. Ethyl silicate was $Si(OC_2H_5)_4$ (SiO_2 content=28%, pH=2.3) (Ethylsilicate 28; Colcoat Co, Tokyo). Mixture solutions were 1% 1N HCl, 14% ethanol and 10% distilled water (E75; 25% mixture solution) and 1% N HCl and 43% ethanol and 6% distilled water (E50; 50% mixture solution). Mixed ethyl silicate solutions were stored for 1 day at room temperature ($20\pm2^{\circ}C$), and ammonium carbonate (AC) solution as a catalyst (pH=8.1; Katayama Kagaku Kougyou Co, Osaka) was added to them before mixing with investment powders as described as 30/70, 50/50 and 70/30. As an example, the 30/70 powder was composed of 30% cristobalite/70% quartz silica as investment powder (Tatsumori Co, Tokyo). The cristobalite and quartz had 32 and 4 μm as a median particle size (SALD-2000, Shimadzu Co, Kyoto).

To propose a calculation model to have stress and strain relation of the mixed investment, first, stress and strain curves were measured for developed ethyl silicate—bonded investments, using a compression testing machine (AUTOGRAPH, Shimadzu Co, Kyoto) (crosshead speed =0.5 mm/min, chart speed ratio=100, full scale=250 kgf). Specimen size (cylinder) had a dimension of 6 mm

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diameter and 12 mm long, which was kept for 1 day at room temperature (20±2°C) after mixing it with mixture solution and setting. Secondly, the calculation model was given using stress and strain relation of each material of bonding agent (ethyl silicate) and refractory silica, because silica refractory and bonding agent had a difficulty to obtain their stress and strain relations. The equations were detailedly shown in APPENDIX. The main idea was based on the equations obtained in dentine bonding systems, which were supposed to be composed of two materials (dentine and composite resins) with different magnitudes of elasticity values[9].

RESULTS

Figure 1 shows stress-strain curves during compression test which were obtained for 30/70, 50/50 and 70/30 investments when mixed by E50 and E75 ethyl silicate solutions. The linear relation was found for stress and strain curves which showed a fracture after plastic deformation. Thus, a calculation model was shown schematically in Figure 2, which were expressed by ethyl silicate bonding and refractory silica materials. The stress and strain behaviour of the investment was considered to be that of composite material.

Table 1 indicates $(-q/E_B)$ value at each elasticity value of bonding area, 10^2, 10^3 and 10^4 MPa for strain=0.005 to 0.10 (E_B; elasticity value of bonding agent as a bonding area). This value was the value in the equation (A6) in APPENDIX. Using this values, Table 2 indicates $(1-(q/E_S))$ value at each strain value (0.005 to 0.10) for Es=

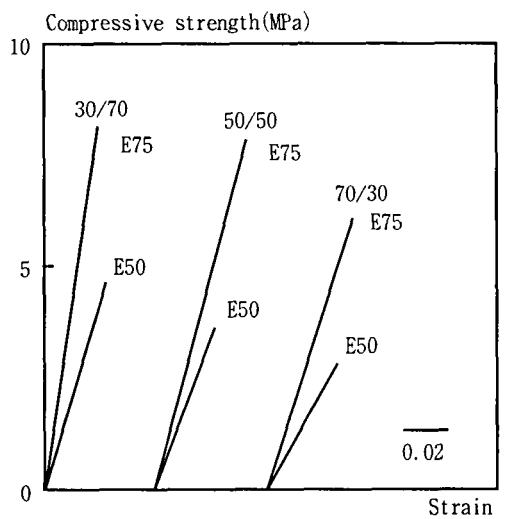

Figure 1 Stress-strain curves of 30/70, 50/50 and 70/30 investments during compression test. The bonding agents used were E75 and E50. See text for key.

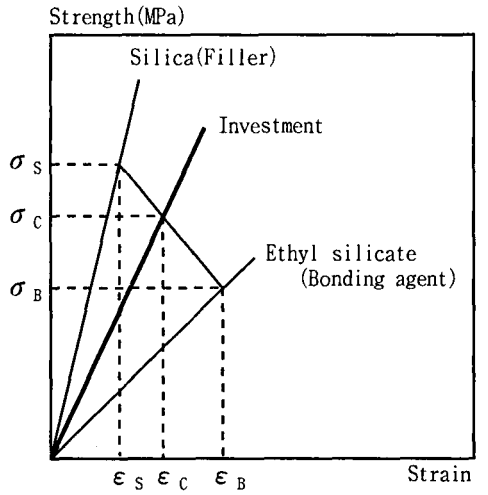

Figure 2 Schematic diagram of stress-strain curves of the composite (silica/bonding agent). Composite stress=σ_C, strength of silica=σ_S, strength of bonding agent=σ_B. Strain corresponding to each strength was described as ε_C, ε_S and ε_B.

Table 1 The value of $(-q/E_B)$ at each value of elasticity, 10^2, 10^3 and 10^4 MPa for each strain of 0.005, 0.01, 0.05 and 0.10.

Strain	$(-q/E_B)$ Elasticity of bonding area (MPa)		
	10^2	10^3	10^4
0.005	3.3×10^3	3.3×10^2	33
0.01	1.7×10^3	1.7×10^2	17
0.05	3.3×10^2	33	3.3
0.10	1.7×10^2	16.5	1.7

Table 2 The value of $1-(q/E_S)$ at strain=0.005, 0.01, 0.05 and 0.10.

Strain	$1-(q/E_S)$
0.005	5.7
0.01	3.4
0.05	1.5
0.10	1.2

$E_S=7\times10^4$ MPa

Table 3 The value of $d\sigma_C/d\varepsilon_C$ ($\times E_B$) for volume fraction of 0.10 to 0.75 at strain=0.005, 0.01, 0.05 and 0.10.

Strain	$d\sigma_C/d\varepsilon_C$ ($\times E_B$) Fraction (v/v %)				
	0.10	0.25	0.50	0.625	0.75
0.005	7.4	20.1	58.9	97.7	174.7
0.01	6.5	17.5	51.0	84.5	151.0
0.05	3.5	8.5	23.7	38.9	69.1
0.10	2.6	5.8	15.0	25.3	44.9

$E_B=10^3$ MPa

7×10^4 MPa (Es; elasticity of refractory silica material), which was the value to caluculate the value in the equation (A6), that is, $d\sigma_c/d\varepsilon_c$. Table 3 indicates work-hardening rate, that is, $d\sigma_c/d\varepsilon_c$ value at each strain value (0.005 to 0.10) for each volume fraction of silica filler (0.10 to 0.75) ($E_B=10^3$ MPa). The range of value was 2.6 to $174.7\times E_B$, which was selected to satisfy a range of experimental results.

DISCUSSION

The stress and strain behaviour was estimated by calculation model which represented stress increment with respect to strain as indicated in APPENDIX. The composite which was investment powder and bonding agent had composite stress during plastic deformation. The stress and strain change was schematically a linear relation between strain and stress (Fig. 2). According to the equations, the stress was determined and was compared with experimental stress and strain change (Fig. 1). From this theoretical and experimental stress increments, experimental cast investment is chosen with an appropriate combination of investment powder and bonding agent.

A spinel investment composed of $MgO/Al_2O_3/ZrO_2$ was developed for titanium casting[10-14], because a remaining expansion was equivalent to the casting shrinkage of titanium and the compression strength was 8.8 to 19.6 MPa. In this study, to apply their mixed investments to casting moulds of titanium or castable glass ceramics, investment powders investigated were 30/70, 50/50 and 70/30 as cristobalite/quartz ratio (wt%), and two bonding agents E50 and E75. In dental ethyl silicate-bonded investment, an aqueous suspension of colloidal silica was made to gel by the addition of a catalyst (an accelerator). Ethyl silicate was used as another system for binder formation (matrix). As reported by Wakasa et al[2,3], ethyl silicate hydrolyzed in the presence of hydrochloric acid, ethyl silicate and distilled water. The sol which was accelerated by ammonium carbonate was mixed with α cristobalite and α quartz investment powders in this study. Thus, binder formation (sol to gel) and refractory silica material were respectively considered as an investment matrix and investment silica filler in the investment (composite).

As shown in greater stress increment values in 30/70 and 50/50 investments than in 70/30 investment, the mixture of quartz to cristobalite was important with the increased strength. The cause that the theoretical stress increment had an increased value for the former two might be due to the interfacial strength between the matrix (bonding material) and filler (refractory material). The calculation model is considered in near future to clarify the formation of interfacial stress. To develop dental cast investments which are composed of refractory material (silica) and bonding agent (ethyl silicate, or hemihydrate of gypsum, or phosphate compound), theoretical analysis of stress and strain behaviour is needed.

SUMMARY

It is summarized that theoretical analysis of ethyl silicate-bonded investment (composite material) composed of ethyl silicate (bonding agent) and silica filler (refractory material) was proposed by a calculation model to represent stress and strain relation. The equation described the stress increment to strain or ($d\sigma_c/d\varepsilon_c$), supposing the investment as the composite of their ingredients (ethyl silicate and silica) in the investment.

APPENDIX

The equations were introduced by the idea which was given by Wakasa and Yamaki for dentine bonding systems composed of dentine and composite resins[9]. The equation was given as the differential of the composite stress, because ethyl silicate-bonded investment was constituted by ethyl silicate (bonding agrent) and silica filler (a refractory material). The diffrential of the composite stress, σ_C, gives

$$d\sigma_C=\frac{\partial\sigma_C}{\partial\sigma_S}\frac{\partial\sigma_S}{\partial\varepsilon_S}d\varepsilon_S+\frac{\partial\sigma_C}{\partial\sigma_B}\frac{\partial\sigma_B}{\partial\varepsilon_B}d\varepsilon_B \qquad (A1)$$

where σ_S=strength of silica, σ_B=strength of bonding agent. Here, the silica and bonding agent are assumed to represent the following equation, as indicated in Fig. 2,

$$\sigma_S = E_S \varepsilon_S \quad \text{(A2)}$$

$$\sigma_B = E_B \varepsilon_B \quad \text{(A3)}$$

$$q = (\sigma_S - \sigma_B)/(\varepsilon_S - \varepsilon_B) \quad \text{(A4)}$$

Thus, the work-hardening rate is calculated as follows,

$$\frac{d\sigma_C}{d\varepsilon_C} = \frac{f}{1-f} \frac{E_B - q}{1-(q/E_S)} + E_B \quad \text{(A5)}$$

$$\frac{d\sigma_C}{d\varepsilon_C} = E_B \left\{ \frac{f}{1-f} \frac{1-(q/E_B)}{1-(q/E_S)} + 1 \right\} \quad \text{(A6)}$$

where f is a fraction of silica in the investment.

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