STUDY OF THE RESIDUAL STRESSES ON QUARTZ PARTICLES IN PORCELAIN TILE

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ABSTRACT

The present study seeks to determine the influence of the cooling rate on the development of residual stresses on quartz particles. For this, porcelain tile test pieces were prepared from an industrial composition, and were subjected to different cooling conditions. The microscopic stresses in the quartz particles were measured by XRD. By means of a calculation procedure developed in this work, the equivalent residual stress in the entire particle was determined, values being obtained between 240 and 260 MPa. This result is coherent with the Selsing model, which postulates a relation between the residual stresses, the elastic properties and the difference in the coefficient of expansion of the matrix and the quartz particles independent of the cooling rate. However, the theoretical values range from 560 to 600 MPa, which is approximately twice the measured value. This discrepancy may be attributed to partial detachment of the quartz particles, or to the cracks that appear around or inside these particles.

1. INTRODUCTION

A spherical particle of a disperse phase in an infinite glassy matrix develops microscopic residual stresses whose magnitude may be calculated according to the Selsing model[1]:

$$\sigma_{rr} = \frac{\Delta\alpha \cdot \Delta T'}{\frac{1+\upsilon_m}{2\cdot E_m} + \frac{1-2\upsilon_c}{E_c}} \cdot \left(\frac{R}{R+l}\right)^3 \quad (1) \qquad \sigma_{\theta\theta} = \frac{-\sigma_{rr}}{2} \quad (2)$$

Where: σ_{rr} is radial stress; $\Delta\alpha$, the difference between the coefficients of linear thermal expansion of the particle and the matrix; $\Delta T'$, or range of cooling temperature (in the case of a glassy matrix, from the glass transformation temperature to ambient temperature is approximately considered); *R*, particle radius; *l*, the distance from the particle surface to a given point in the matrix; $\sigma_{\theta\theta}$, the tangential stress.

This study seeks to determine the influence of the firing cycle cooling rate on the development of microscopic residual stresses on quartz particles, the major crystalline phase in porcelain tile. This study is part of a work published by the authors[2].

2. EXPERIMENTAL PROCEDURE

In order to carry out the study, test pieces of 80x20x7 mm were prepared by pressing (40 MPa) from an industrial spray-dried powder. The firing temperature was 1190ºC, with a view to achieving maximum density. The test pieces were subjected to six different cooling conditions: combining coolings inside or outside the kiln and with or without the use of forced convection (variable rates between 0.1 and 8.5ºC/s). The microscopic stresses on quartz particles were analysed by XRD, and they were directly measured on whole test pieces.

The microscopic residual stress (σ_r) values were obtained from the interplanar distances (d_{hkl}) of the families of planes (112) and (211) calculated from the XRD measurements and Bragg's law, Equation (3). With this information it was possible to determine the volumetric strain of the quartz crystal unit cell (ε_v). An equivalent linear strain (ε) was then defined which finally allowed determination of the equivalent residual stress on the particles. The calculation procedure is represented by the following sequence of equations:

$$d_{hkl} = \frac{n\lambda}{2\cdot\sin\theta} \; (3) \rightarrow \quad \frac{1}{d^2_{[hkl]}} = \frac{4}{3}\cdot\left(\frac{h^2+h\cdot k+k^2}{a^2}\right)+\frac{l^2}{c^2} \; (4) \rightarrow \quad V = 0{,}866\cdot a^2\cdot c \; (5) \rightarrow$$

$$\rightarrow \varepsilon_v = \frac{V-V_o}{V_o} \; (6) \rightarrow \quad \varepsilon = (1+\varepsilon_V)^{1/3} - 1 \; (7) \rightarrow \quad \sigma_r = \varepsilon\cdot E \approx \sigma_{rr} \; (8)$$

Where: *h,k,l*, are the Miller indices; *a* and *c* are the quartz lattice parameters; V_o, is the volume of the non-stressed quartz unit cell; and E is the quartz modulus of elasticity.

3. RESULTS AND CONCLUSIONS

Table I gives the obtained experimental data. The residual stress values obtained on the quartz particles range from 240 to 260 MPa. This result is consistent with the Selsing model, which postulates a relation between the residual stresses, elastic properties and differences in the coefficient of expansion of the matrix and quartz particles independent of the cooling rate.

Ve* [ºC/s]	$D_{(112)}$ [nm]	$d_{(211)}$ [nm]	V [nm³]	σ_r (MPa)
**	1.8179	1.5416	113.00	0
0.1	1.8235	1.5476	114.15	264
0.6	1.8233	1.5473	114.10	252
3.2	1.8233	1.5478	114.13	259
4	1.8232	1.5468	114.05	241
6.6	1.8235	1.5476	114.15	264
8.6	1.8231	1.5475	114.08	248
*cooling rate, **standard quartz data (without residual stress).				

Table I. Experimental results of the residual stress measurements on the quartz particles

Using Equation (1), a residual stress would be expected in the quartz particles of 580 MPa (assuming: E_c = 78 GPa, E_m = 70 GPa, $\nu_c = \nu_m$ = 0,2, ΔT' = 730ºC, $\alpha_{c(20\text{-}750ºC)}$ = 203x10^{-7} ºC^{-1}, $\alpha_{m(20\text{-}750ºC)}$ = 74x10^{-7} ºC^{-1}). This theoretical value is approximately twice the experimentally determined values. This discrepancy may be attributed to partial quartz particle detachment, or to cracks that appear around or inside the particles, which are readily observable by electron microscopy. Finally, it may be noted that the methodology used, based on the determination of the volumetric strain undergone by the quartz unit cell, allowed obtainment of a residual stress value equivalent to the entire particle, and not just to a given crystalline plane.

REFERENCES

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