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Influence of macroscopic residual stresses on the mechanical behavior and microstructure of porcelain tile[☆]

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Abstract

The development of macroscopic residual stress, as in glass-tempering processes, was studied for porcelain tile. Mechanical strength was observed to increase less than might be theoretically expected, owing to deterioration of the sintered tile microstructure. A model has been developed, using linear elastic fracture mechanics, to estimate the natural flaw size in the tempered material. The study shows that as the cooling rate raises, the macroscopic residual stress and flaw size increase. This microstructural deterioration is mainly attributed to the allotropic transformation of quartz in the presence of thermal tensile stress at the porcelain tile surface.

Keywords: Firing; Defects; Mechanical properties; Porcelain; Traditional ceramics; Tiles

1. Introduction

1.1. Porcelain tile

Porcelain tile, which is characterized by a large quantity of glassy phase and low porosity, has excellent technical and aesthetic properties. The tile is basically made from clays, kaolins, feldspars, and quartz. Clays and kaolins provide plasticity and dry mechanical strength and form mullite and glassy phase during firing; feldspars are low-temperature glassy phase formers; and quartz contributes to thermal and dimensional stability, because it is the most refractory constituent.[1]

Porcelain tile compositions are formulated and processed to allow a rapid firing cycle of 40–60 min. The peak firing temperature, between 1180 and 1220 °C, is typically determined by establishing the temperature at which maximum densification is reached. Following densification, water absorption is less than 0.5% and closed porosity lies between 3 and 7%. Cooling is carried out as rapidly as possible in industrial practice, with little control over the variables of this firing cycle stage. Only the allotropic transformation temperature of quartz (573 °C) is taken into account by reducing the cooling rate to avoid tile breakage. Rapid cooling then immediately continues again and is maintained until the tile leaves the kiln.[1]

1.2. Mechanical properties of porcelain materials

There are basically three theories that explain the strengthening mechanism in triaxial porcelains,[2] which may be applied to porcelain tiles:[3] interconnection of acicular mullite crystals; dispersion of crystalline phases that limit the natural flaw size; and matrix strengthening as a result of the difference between the linear thermal expansion coefficients of the matrix and those of the disperse crystalline phases. These mechanisms act simultaneously, making it difficult to determine categorically which one contributes most.

In addition, the level of complexity of this system is further increased because porcelain tile may develop a macroscopic residual stress profile[4] resembling that typically found in glass-tempering processes.[5,6] This occurs as a result of the rapid

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cooling rate in industrial firing cycles and the large quantity of glassy phase (50–65%) that develops during firing in porcelain tile, as in other types of ceramic materials.[7–9]

A significant difference with respect to traditional glass tempering is that the quartz particles (which are not present in glass) give rise to peripheral cracks in the interfaces with the matrix to provide microscopic stress relaxation.[2] During rapid cooling, thermal tensile stresses develop at the surface. For this reason, starting at the allotropic transformation temperature of quartz, subcritical growth of peripheral cracks may lead to microstructural deterioration, which will severely affect the tile mechanical behavior.

This study analyses how the cooling stage of the firing cycle influences porcelain tile microstructure and mechanical behavior. A model has been developed for this purpose, based on linear elastic fracture mechanics, which allows estimation of the effect of the cooling rate on the variation of the natural flaw size in the material. The results have been corroborated by scanning electron microscopy (SEM) observation of the microstructures of some of the pieces obtained.

2. Mathematical modeling

2.1. Basic concepts

In accordance with linear elastic fracture mechanics, the mechanical strength of a material, σ_f, is given by the following equation[10]:

$$\sigma_f = \frac{K_{Ic}}{Ya^{1/2}} \quad (1)$$

where K_{Ic} is the fracture toughness; a, the natural flaw size; and Y, the calibration factor.

The presence of a macroscopic stress profile inside the piece will lead to a modification of toughness. The fracture toughness (K_r) associated with a residual stress profile throughout the thickness of the material $\sigma_r(x)$ is expressed by the following equation[10,11]:

$$K_r = \frac{Y}{\pi a^{1/2}} \int_0^a \sigma_r(x) g(x)\,dx \quad (2)$$

where $g(x)$ is the Green's function, which is dependent on the particular configuration of the stress application and crack propagation system. For the system described in Fig. 1, $g(x) = 2a/(a^2 - x^2)^{1/2}$, and $Y = 1.985$.

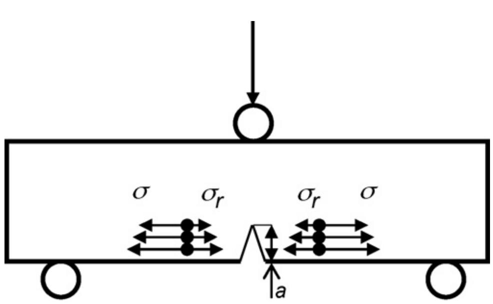

Fig. 1. Fracture propagation under a bending stress (adapted from Ref. 11).

The apparent toughness of a material with a macroscopic stress profile ($\bar{K}_{Ic}$) may be expressed by the following equation[11]:

$$\bar{K}_{Ic} = K_{Ic} - K_r \quad (3)$$

Thus, compressive residual stress raises apparent toughness, since K_r is negative. For typical tempering stress profiles, apparent toughness maximizes at the surface and decreases progressively inwards into the material. This can lead to unstable crack growth and subsequent catastrophic fracture of the material. However, these concepts are used to develop functional gradients in tempered glasses in order to produce stable fracture growth regions.[12,13]

2.2. Estimate of bending strength after tempering of porcelain tile

The mechanical strength of a material with a macroscopic residual stress profile may also be written as

$$\sigma_{ta} = \frac{\bar{K}_{Ic}}{Ya^{1/2}} \quad (4)$$

Combining Eqs. (3) and (4) gives:

$$\sigma_{ta} = \frac{K_{Ic}}{Ya^{1/2}} - \frac{K_r}{Ya^{1/2}} \quad (5)$$

If Eq. (2) is substituted for K_r it is necessary to consider a given residual stress profile in order to solve the integral. The residual stress profile may be considered as approximately proportional to the second-degree Legendre polynomial[14]:

$$\sigma_r(x') = \sigma_s(6x'^2 - 6x' + 1) \quad (6)$$

where σ_s is the residual stress at the surface; and $0 \le x' \le 1$, the domain of the function.

For small thickness values, $0 \le x' \le a$, x'^2 assumes such small values that these may be considered negligible compared with x'. Hence, in a plane near the surface, residual stress may be

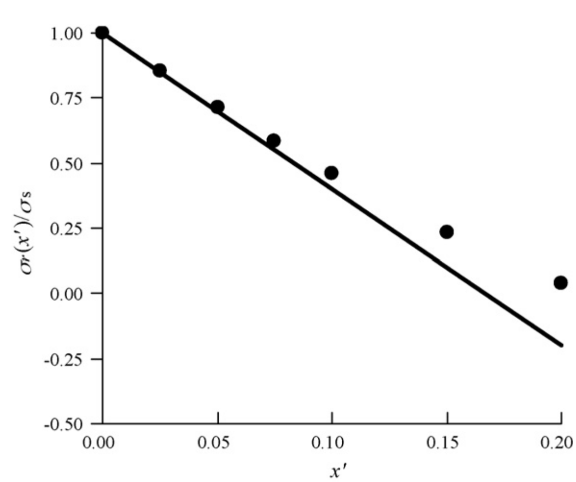

Fig. 2. Graphic representation of the linearization of the residual stress profile near the surface.