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Measurement of Residual Stress in Porcelain Tiles with the Hole-Drilling Method

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Abstract

Residual stress in porcelain tiles affects the application of the tiles, and especially so in the case of large-format porcelain tiles. However, quantitative characterization of the residual stress in porcelain tiles presents a critical problem. In this study, the hole-drilling method, which is widely used for the measurement of residual stress in metal structures, was adopted to measure the residual stress in porcelain tiles. One flat and one curved porcelain tile were measured. The details of and precautions required for application of the hole-drilling method for porcelain tiles are described. The validity of the results has been analyzed, demonstrating that the hole-drilling method can be used to measure the surface residual stress in porcelain tiles.

Keywords: Residual stress, hole-drilling method, porcelain tile, strain

I. Introduction

In the past three years, large-format ceramic tiles have undergone rapid development in China. In 2019, there were only just over 20 production lines capable of producing large-format (1 200 × 2400 mm and larger) porcelain tiles in China, but this number increased to over 100 by 2022. The boom in large porcelain tiles led to many problems that had not been previously encountered. Uneven deformation is one of the common problems. This is because the porcelain tiles experience rapid sintering and uneven cooling during the manufacturing process. Some large porcelain tiles show bad cutting behaviour during installation, such as unexpected cracking during cutting [1]. Some porcelain tiles present delayed curvature several days or even weeks after sintering [2]. All of these problems seem to point to one thing: residual stress, especially surface residual stress. In fact, residual stresses are extremely important since they seriously affect tiles' mechanical properties and behaviour, such as cracks, breakage, and deformation, entailing severe economic losses [3].

Residual stresses are self-equilibrating stresses that exist in a material in the absence of externally applied forces. The residual stresses in porcelain tiles are mainly generated during sintering and rapid cooling process as the process usually takes less than an hour to complete on the production line. The allotropic transformation of quartz and body-glaze interaction can also lead to the generation of residual stress. Porcelain tile material usually contains a mixture of crystalline and non-crystalline materials, which makes it difficult to use commonly applied X-ray diffraction methods for the measurement of macroscopic residual stress [4]. Agenor De Noni Junior *et al.* have investigated the microscopic residual stress of porcelain tiles with the X-ray diffraction method. They have shown that micro residual stress on quartz particles is over 200 MPa [5], which is significantly higher than the macroscopic residual stress of the porcelain tile.

The most commonly used method for measuring residual stress in porcelain tiles is the crack compliance method, or strain relaxation slotting method (SRSM). This method is a destructive method for the measurement of residual stress. It consists of gluing a strain gauge on the bottom of the specimen, and then making increasingly deep cuts from the top surface, measuring the strain during cuts, and finally calculating the stresses over the thickness [6]. This method has been successfully used to measure residual stresses in porcelain tiles [7, 8]. But the sizes of the measured porcelain tiles were only 30 mm × 150 mm, or 20 mm × 70 mm, respectively, much smaller than the current large-format porcelain tiles. Large porcelain tiles usually experience an uneven sintering process, and the residual stress is obviously different from that of small tiles. The 3-point bending method can also be used to measure the residual stress on the tile surface, especially for glazed tiles [2]. But the method is not sensitive to the thickness of glaze layer, therefore, the thickness is doubled during the actual residual stress measurement [2]. The Stoney method can be used to estimate the residual stress in thin ceramic coatings [9, 10]. With the Stoney formula, the residual stress in the coating can be calculated based on the curvature and the thicknesses of the coatings and the substrate. But the large porcelain tile is almost flat and the curvature may be

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too small to be measured, which has limited the application of the Stoney method.

The hole-drilling method is the most widely used technique for measuring residual stresses in materials, not only metals but also ceramics. Brian Munn and Keyu Li have used the hole-drilling method to characterize residual stresses in monolithic silicon-carbide (SiC) tiles, and the results confirmed the viability and practicality of the method [11]. Amélie K. Mainjot *et al.* have investigated the residual stresses in dental ceramics. The results have shown that the hole-drilling method is a practical tool for residual stress measurement of veneering ceramic, though in the few cases where cracks had occurred during drilling [12]. Porcelain tile is generally made from clay, kaolin, feldspar, and quartz. The mixture composition develops mullite, glassy phase, crystalline phase and porosity during sintering. The highly complex microstructure and phase composition of porcelain tile increase the difficulty of its residual stress measurement. There are few studies that have investigated the measurement of porcelain tile residual stress using the hole-drilling method. In the present work, the residual stresses in porcelain tiles have been measured with the hole-drilling method. Two large-format porcelain tiles, one flat and one curved tile, were tested in compliance with the ASTM E837 standard [13]. The validity of the test was also discussed in the study.

The hole-drilling method has some advantages over other methods for measuring porcelain tile residual stress. Compared to the crack compliance method or three-point bending method, the hole-drilling method can be regarded as a non-destructive or semi-destructive method as the hole is small, which is important for the measurement of large-size porcelain tiles. The X-ray diffraction method can only measure residual stress on the tile surface and the non-crystalline phases in the tile can have an impact on the accuracy of the measurements. Although various modified Stoney methods are still extensively used to evaluate the residual stress in a coating when it is adhered to a substrate [14, 15, 16, 17], the result of the Stoney‘s equation calculation is the average stress in the coating. The stress distribution over the coating thickness is difficult to obtain by means of the Stoney equation.

II. Materials and Methods

(1) Materials

Two large porcelain tiles supplied by MarcoPolo Holdings Company have been studied. One was a flat tile, and the other was a curved tile. The size of the flat tile was 1.2 m × 2.4 m while the curved tile measured 1.5 m × 0.68 m, both were 8 mm thick. Table 1 shows the chemical composition of the two porcelain tiles. Feldspar, kaolin clay and quartz sand are the three main raw materials for porcelain tiles. These raw materials go through a complex series of mixing, compressing, drying and sintering processes to form porcelain tiles. In order to obtain curved tiles, an arc mould was used for secondary sintering.

Table 1: Chemical composition of the two porcelain tiles in weight percentage (wt%)

Compound	wt %
SiO_2	67.80
Al_2O_3	24.27
Fe_2O_3	0.24
Na_2O	3.84
K_2O	2.03
MgO	0.92
others	0.90

(2) Method

The hole-drilling method consists of gluing a strain gauge on the surface of the porcelain tile, drilling a small blind hole at the centre of the gauge, and then measuring the relieved strain after drilling. Residual stress pre-existing in the hole region can be calculated based on the relieved strain. As the diameter and depth of the hole are usually less than 2 mm, the hole-drilling method causes relatively little damage and it can be considered a semi-destructive technique. The measurement procedure is well developed and now standardized as ASTM E837 – 20 or GB/T 31310 – 2014. It can be used to characterize the through-depth profile of the in-plane non-uniform residual stresses.

The hole-drilling method is the widely used relaxation method for measuring residual stresses of metal materials. But porcelain tile is very brittle and breaks easily during hole drilling. Some special processes and tools were used to solve the problem. A hole-drilling residual stress measurement system (SINT MTS 3000, Italy) was used for the hole-drilling procedure, see Fig. 1. The drill machine in the system had a high-speed air turbine (400 000 RPM) and drilled in step-by-step mode over the depth of the tiles. Drilling measurement was divided into 29 steps from the tile surface to a depth of about 1.4 mm. The initial depth interval was set to 16 microns to ensure the accuracy of the surface strain measurements. A strain acquisition instrument (MX440B, HBM, Germany) collected the strain values during the drilling process, which were used to calculate the value and direction of the original residual stress of the tiles.

Shown in the bottom left corner of Fig. 1 is the diamond burr used to ensure accurate drilling without causing tile breakage. The inverted cone head of the burr can ensure the quality of drilling. The thermal conductivity of porcelain tile material was lower than metal material, and drilling can easily cause the temperature of the tile to rise, affecting the strain measurement accuracy. At each hole step drilling interval, lubricant was added to lubricate the burr and reduce the local temperature at the measured point.

The MTS 3000 system can automatically and precisely determine the zero depth point based on electric contact when measuring metal materials. But porcelain tile is not a conductive material, only manual positioning is possible.

The strain gauge thickness is about 60 microns. When the burr head touches the strain gauge surface, it is manually lowered by 60 microns and the position can be assumed as the zero point.

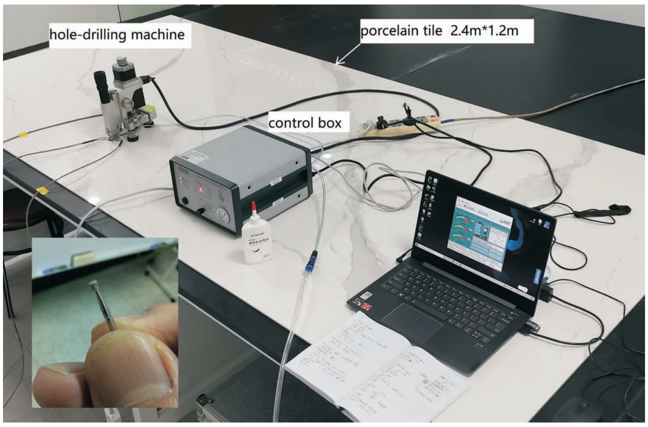

Fig. 1: The large flat porcelain tile measured with the hole-drilling method.

The bottom right corner of Fig. 2 shows one three-element type A strain gauge rosette (BE120 – 1.6CD, ZEMIC, China) glued on the porcelain tile surface after hole drilling. In the top left corner of Fig. 2 is the hole profile measured with laser confocal microscope. It shows the diameter of the hole as about 1.9 mm, with a vertical edge and a flat bottom. The hole-bottom filled radius (r in Fig. 2) was less than 0.2 mm which was suitable for correction algorithms of strain calculation [18].

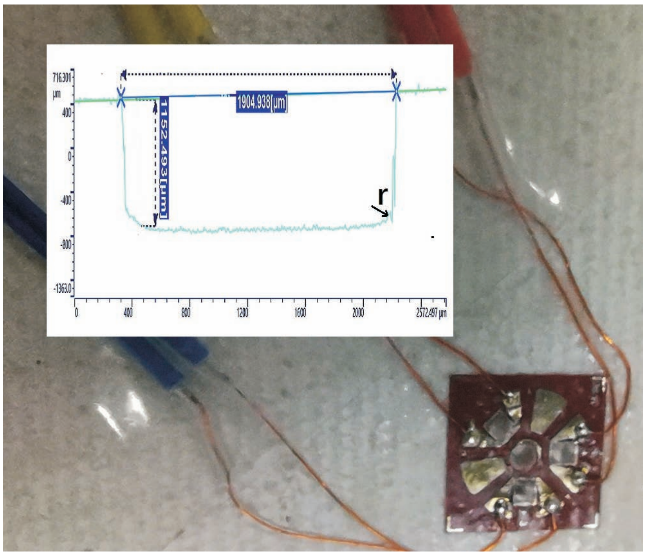

Fig. 2: The strain gauge on the porcelain tile and the hole profile.

Because of rapid heating and cooling, porcelain tiles generally have non-uniform residual stress fields over their thickness. The hole-drilling strain data were input into MTS3000 EVAL software to calculate the residual stresses σ_x,σ_y and τ_{xy} within each step. From these stresses, the corresponding principal stresses σ_{max} and σ_{min} and their orientation can be calculated.

The integral method was adopted to calculate the residual stress through the thickness of the porcelain tile. The combination strains of each drilling step (p_j, q_j, t_j) can be calculated with following equations.

$$p_j = \frac{(\varepsilon_3+\varepsilon_1)_j}{2} \quad (1)$$

$$q_j = \frac{(\varepsilon_3-\varepsilon_1)_j}{2} \quad (2)$$

$$t_j = \frac{(\varepsilon_3+\varepsilon_1-2\varepsilon_2)_j}{2} \quad (3)$$

the subscript j refers to the hole-drilling depth steps corresponding to the successive sets of measured strains ε_1, ε_2, ε_3. For each of the hole drilling steps, the combination stresses (P, Q, T)can be computed from the corresponding combination strains based on solving of the matrix equations:

$$\bar{\alpha}P = \frac{E}{1+v}p \quad (4)$$

$$\bar{b}Q = Eq \quad (5)$$

$$\bar{b}T = Et \quad (6)$$

$\bar{\alpha}$, $\bar{b}$ are the matrix of the calibration constants defined in the ASTM E837 standard [13]. The in-plane Cartesian stresses σ_x, σ_y and τ_{xy} using:

$$\sigma_x = P\text{-}Q \quad (7)$$

$$\sigma_y = P+Q \quad (8)$$

$$\tau_{xy} = T \quad (9)$$

The X and Y axes were set in the direction parallel to the 0 °and 90°grid of the strain gage rosette.

III. Results and Discussion

(1) Flat porcelain tile

A 1.2 m × 2.4 m flat tile was measured on the no-glaze side using the hole-drilling method (Fig. 1). Residual stresses at several points about 26 cm from the edge of the tile were measured. Fig. 3 showed the hole drilling relieved strains of one point in three directions.

As mentioned earlier, porcelain tile contains many phases, such as mullite, quartz and feldspar. Scanning electron microscopy also shows that the tile body contains a few small, isolated pores [3]. The fluctuation of strain data along the tile depth may be related to the structure.

The strain data depend on the residual stresses that exist in the tile inside the hole. The residual stresses over the tile depth were calculated from the strain data using mathematical relations based on linear elasticity theory. The elastic modulus and Poisson ratio of the tiles provided by MarcoPolo Holdings Company are 70 GPa and 0.2, respectively. Fig. 4 shows the maximum principal stress mean and standard deviation of five measurement points on the tile. The results show a compressive stress on the surface of approximately 200 micro meters. The maximum value of the compressive stress was about – 20 MPa. With increasing depth, the residual stress gradually became tensile stress. The compressive stress on the tile surface is related to its rapid cooling process. During cooling process, the surface of the tile becomes rigid first, impeding its interior contract later, and eventually leading to the compressive stress on the surface.

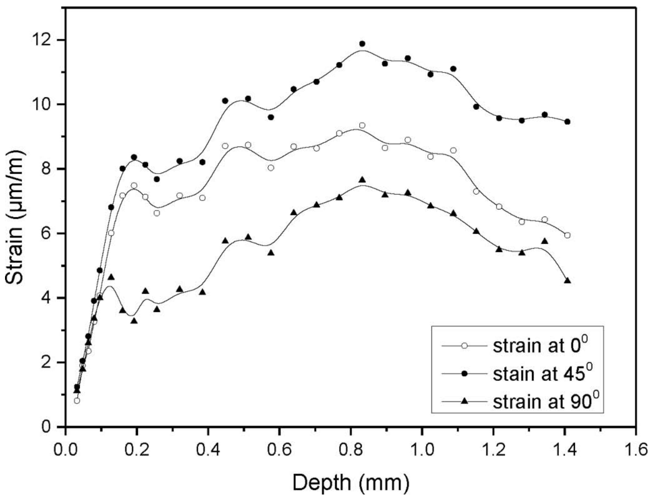

Fig. 3: Hole-drilling strain curves for one point on the tile.

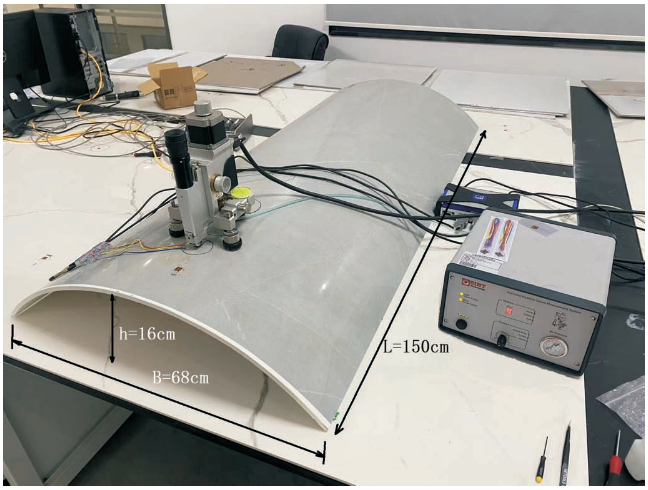

Fig. 5: The size and shape of the curved porcelain tile.

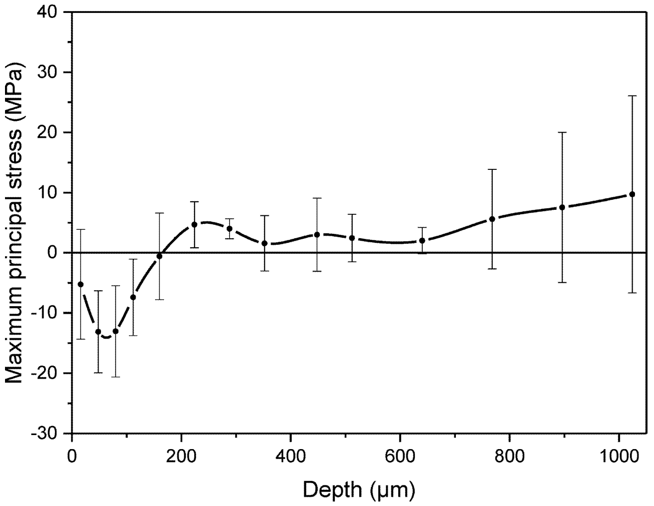

Fig. 4: The mean and standard error for the residual stress on the tile.

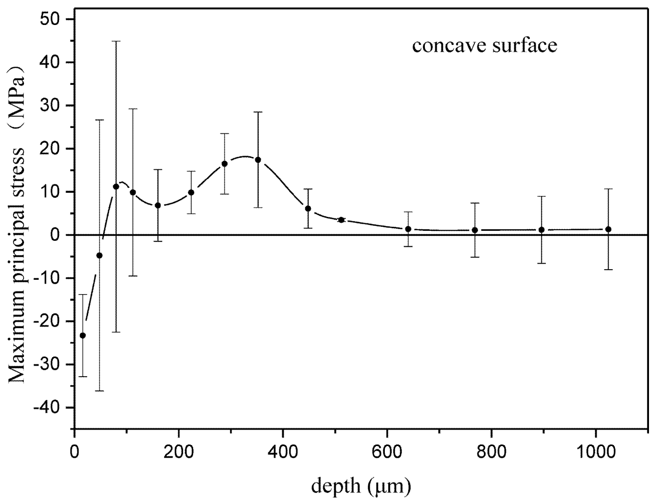

Fig. 6: Residual stresses at concave surface of the curved tile.

E. Sánchez measured the residual stress of porcelain tile with the strain relaxation slotting method (SRSM) and the results showed that residual stress of tile surface was about - 5 MPa to – 15 MPa depending on different cooling rates [7]. The compressive stress values obtained from the hole-drilling measurements showed a good agreement with the SRSM results.

(2) Curved porcelain tile

The manufacturing of curved tiles is a more complex process, entailing a second sintering stage to make the flat tile curved. Fig. 5 shows the size and shape of the curved porcelain tile. Residual stress measurement points were located in the middle of the concave and convex surfaces of the tile. Fig. 6 shows the result of four points mean value and standard error of maximum principal stresses measured at the concave surface.

The concave surface is squeezed during the second sintering process, resulting in a compressive surface stress. As can be seen from Fig. 6, despite some scattered stress data, the compressive stress on the surface was quite obvious. The results showed the concave surface of the curved tile had greater compressive stress compared to the flat tiles.

Fig. 7 shows the maximum principal stress at three points measured on the convex surface of the tile. The data from the three measurement points had good repeatability and as well as very small scattering. The larger tensile stress of convex surface and compressive stress of convex surface had good correspondence with the manufacturing process of the porcelain tile. The residual stresses of the curved tile were mainly affected by the bending procedure during the second sintering. The results of hole-drilling method of the curved tile proved the rationality of the method

It should be noted that the convex surface had tensile stresses above 100 MPa, which is much greater than the bending strength of porcelain tile. Fig. 7 showed the high tensile stresses were only within 100 micro meters of the surface, which was about the thickness of the glaze. There may be two reasons for the high surface tensile stress. First, the integration algorithm enabled that a small error in surface strain measurement led to large stress deviations. Second, the main precondition for the hole-drilling method is that material is isotropic, and linearly elastic. The stress calculation of the glaze uses the same material data as the body, while in fact the two are different.

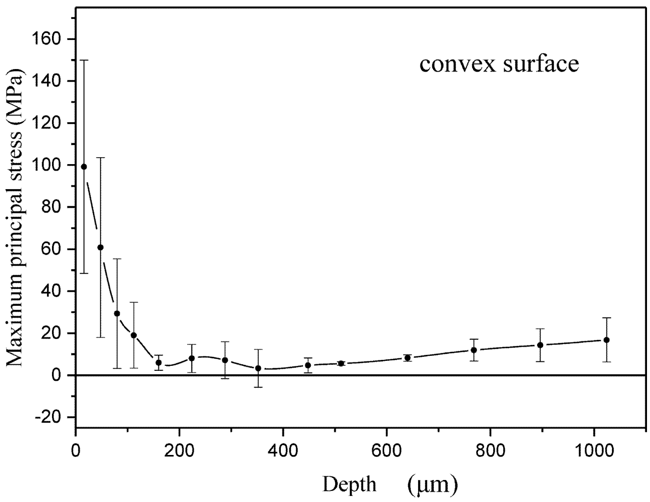

Fig. 7: Residual stresses at convex surface of the curved tile.

IV. Conclusions

The surface residual stresses of porcelain tiles have been measured with the hole-drilling method in compliance with the ASTM E837 and GB/T 31310 standards. As the thermal and mechanical properties of porcelain tiles are very different from that of metal materials, a special procedure is required before and during hole drilling. The compressive residual stress values measured on the flat tile surface are in good agreement with the results obtained in other literature, which indicates the feasibility and reliability of the method for porcelain tile measurement.

The surface residual stresses of the concave and convex surface of a curved tile were also measured with the hole-drilling method. The concave surface has compressive stresses while convex surface has tensile stresses, the result is relatively consistent with that expected. The excessive tensile stress measured on the convex surface may be related to the glaze layer. The influence of the glaze layer on the residual stress distribution requires further investigation.

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