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Estimation of Ultrasound Velocity Spatial Distributions in Green Ceramic Tiles

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***Abstract*—From analysis of used and applicable quality control systems of ceramic tiles is clearly seen that the ultrasonic measurement systems have significant advantages. Each manufactured product in this case will be evaluated and the result will be obtained with a sufficient accuracy. Therefore, one of the applicable ultrasonic measurement systems for measurement of the density of ceramic tiles is analyzed in this article. In this case, ultrasound velocity measurements were performed in the sectors with a different thickness of the 0.105 m x 0.105 m size green ceramic tile using ultrasonic transducers developed in the Ultrasound Institute of Kaunas University of Technology with different acoustic contact zones. Such approach was necessary because the thickness of the tile in these zones is quite different.**

***Index Terms*—Ceramic tiles, ultrasound velocity measurements, the zero-crossing and the cross-correlation technique.**

I. INTRODUCTION

Currently quality control of ceramic tiles is based on statistical process control (SPC) of each step of the manufacturing process [1]. In the end each tile must meet certain specifications regarding physical properties, because it must be durable, stable reproducible and high temperature resistance. These properties are determined by standard tests established by the American Society of Testing and Materials (ASTM) [1]. In other words, each quality control test is standardized and described in the standards. The main quality requirements of manufactured ceramic tiles are established by International Organization for Standardization (ISO) standards for individual types of ceramic tiles [2] adopted also in Europe.

It is also known that the quality of ceramic tile mainly influences their physical properties, which depends on the selected composition mix and firing mode, after which the final product is obtained. Currently, a lot of various ceramic tiles are manufactured using different raw materials and manufacturing techniques. Each tile manufacturing process consists of a several steps, which are passed until the finished product is obtained. Since the tiles are manufactured from different raw materials, they are classified, mixed on various proportions, wet (or dry) grinded and spry-dried (or granulated), formed and dried, and finally fired.

Analysis of the tiles quality control results, using a variety quality control measurement systems, leads to the conclusion that it is difficult to write a typical standard for ceramic tiles quality control, because other physical factors (such as proper floor design and care) can make results meaningless [1]. Also there is a need to take into account the production process organization, because it also has important implications. However, such manufacturing process leads defective tiles that are recycled, but that represent a cost. Therefore, the tile quality control measurements using ultrasound are very promising, because this system can be installed in the tile manufacturing presses or immediately after it, and then all defective tiles will be removed and returned for recycling.

Such measurements are very important because mechanical properties of the tiles are not uniform across the whole surface and affect the ultrasound velocity [3]–[9], and after firing may lead to defective deformed or weakened tiles. Therefore main objective is ensuring the spatial density stability of the green ceramic tiles, which affects all other properties of the tile. So, elastic properties and density of tiles may be estimated by dynamic ultrasonic and vibration resonant frequency measurements [3], [10], [11].

Therefore, the aim of the research presented in this paper is investigation of the spatial variations of the ultrasound velocity in a green ceramic tile, in order to determine the optimum distance between neighboring transducers necessary for reconstruction of physical properties of the green ceramic tile.

II. SPECIMEN AND ITS MEASUREMENTS SETUP

The 105 x 105 mm size green ceramic tile was selected for ultrasound velocity measurements. This tile was manufactured by “Dvarcioniu Keramika”, Lithuania. The measurement points were marked by dots on the rear side of the tile and amounts a discrete measuring point (x_i, y_j) matrix, with the size is 31 x 9 (Fig. 1).

First of all, tested green ceramic tile was marked by dots for reconstruction of the spatial ultrasound velocity

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distribution (Fig. 1). Then its thickness h_m measurements were performed in each of these measuring points using micrometer ($h'_m = h_m$ mm ± 0.01 mm). Next step was the ultrasonic longitudinal wave velocity measurements in the same measurement points using the ultrasonic measurement system “ULTRALAB” developed by Ultrasound Institute of Kaunas University of Technology.

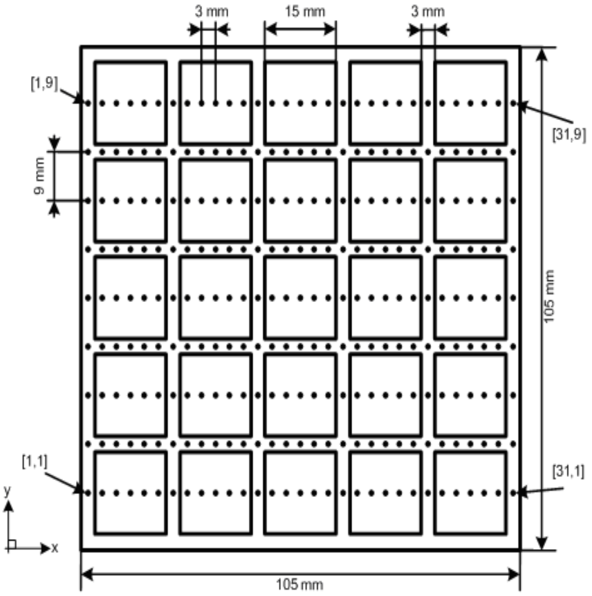

Fig. 1. Green ceramic sample used for ultrasonic longitudinal wave velocity measurements.

Ultrasonic pulse through-transmission measurements were performed as in the previous article, using a dry acoustic contact between ultrasonic transducers and the ceramic sample [3].

In this case, for the ultrasonic signals propagation time measurements the zero-crossing and the cross-correlation techniques were used at the laboratory conditions [3]. The width of the rectangular time window of the measured signal was chosen such that to minimize the spectrum distortions [12]–[16]. So, the ultrasound velocity obtained using the zero-crossing technique is $c_{zc}(x_i, y_j)$ and the ultrasound velocity obtained using the cross-correlation technique is $c_{cc}(x_i, y_j)$. The x_i, y_j are the coordinates of the measurements points; $i = 1 \div M$; $j = 1 \div N$; $M = 31$; $N = 9$ are the total numbers of measurements positions along x and y axis correspondingly. Fig. 1 clearly shows, that the distance between the neighboring measurement points along x-axis is 3 mm and the distance between the neighboring measurement points along y-axis is 9 mm.

Taking into account, that the average thickness differences of the tiles is 0.5 mm and the width of the pattern is 0.3 mm, the different diameter transducers were selected for ultrasound velocity measurements.

Therefore, in this investigation were used two 1.0 MHz transducers (developed in Ultrasound Institute of Kaunas University of Technology) which were placed along one axis on both sides of the ceramic sample. The algorithm of these measurements was presented in the previous paper [3].

During measurements the single period signal with a 1.0 MHz frequency, with the excitation voltage 50 V was generated and the gain was 24.5 dB, while the averaging level was 8. Also the received signals at each measurement were stored in a computer memory for analysis and future studies.

As can be observed in Fig. 2 the central frequency of the signal propagated through the sample corresponds to the reference signal frequency and causes a minimum of signal losses. The losses of the measured signals were determined during each measurement. The obtained losses are clearly seen in Fig. 2, which contains the spectra of the reference (1) and on the tile measured signals (2).

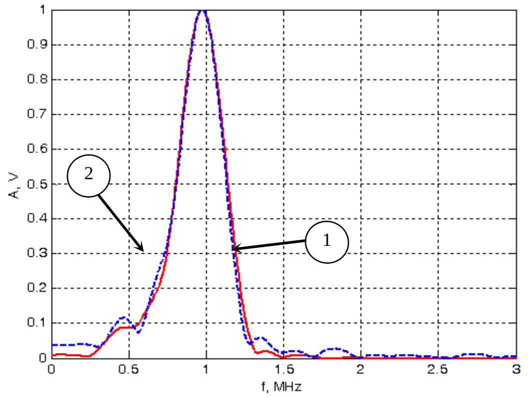

Fig. 2. Normalized spectrum of the reference signal (1) and the signal measured on the sample of the green ceramic tile (2).

The acoustic contact stability and the measurements results repeatability were verified by 16 measurements in the 0.9355 cm PMMA plastic in the same point and the obtained standard deviation of the ultrasound velocity was 1 m/s.

Influence of humidity on the object ultrasound propagation velocity is not significant, because measurements are made with dried tiles at the constant humidity level.

Since these measurements, performed at different points (x_i, y_j) according to Fig. 1, two-dimensional spatial distributions of its values are presented in Fig. 3 and Fig. 4.

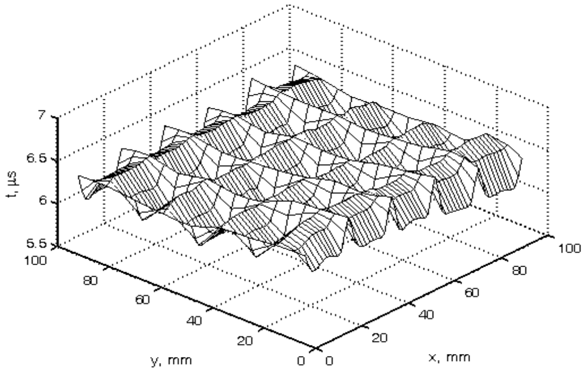

Fig. 3. The delay time distribution across ceramic sample using zero-crossing measurement method.

The results of the delay time measurements using the zero-crossing technique are presented in Fig. 3, which shows that the measured time delay corresponds to the tile thickness distribution. Then, the ultrasonic velocity was calculated using the distribution of thickness of the tile and the ultrasonic propagation delay time at the same measurements points (Fig. 3) and presented in Fig. 4. The ultrasound speed distribution shows that its velocity values are inversely proportional to the tile local thickness and indicate that these values on the tile pattern are lower.

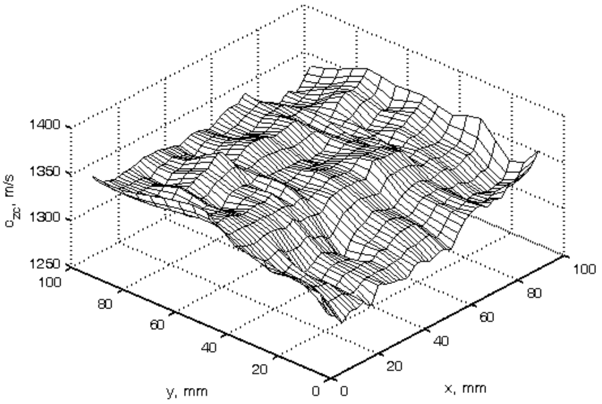

Fig. 4. Spatial ultrasound velocity czc variations across ceramic sample using zero-crossing measurement method, which is in the range (1290 - 1380) m/s.

The spatial density variations of the tile influence its quality and after firing they may cause deformation of the tile. Since the measured ultrasound velocity directly depends on the density of the tile, it has been studied in more detail.

The ultrasound velocity is measured in discreet points on a tile surface. The main question is what should be the distance between the measurement points, e.g., ultrasonic transducers, in order the spatial distribution of ultrasound velocity $c_{zc}(x, y)$ would be reconstructed with a necessary accuracy. The original field $c(x, y)$ can be restored by summing the measured discreet spatial field values at each field (x_i, y_j) point multiplied by the interpolation function [3]

$$c(x,y)=\sum_{i,j} c(x_i,y_j)\cdot\frac{\sin(\omega_x\cdot(x-i\cdot\Delta x))\,\sin(\omega_y\cdot(y-j\cdot\Delta y))}{(\omega_x\cdot(x-i\cdot\Delta x))(\omega_y\cdot(y-j\cdot\Delta y))}, \quad (1)$$

where ω_x and ω_y are the highest spatial frequencies of the spatial frequency spectrum of the field $c(x, y)$, which correspond to the field components with shortest periods. In order this reconstruction would be accurate, the sampling intervals, or in other words, the distances between the measurement points must fulfill the following requirements: $\Delta x \le \pi / \omega_x$ and $\Delta y \le \pi / \omega_y$ [3].

The main problem is to determine the spatial frequencies ω_x and ω_y, which are used to reconstruct the original field $c(x, y)$.

For this purpose the spatial spectrum of ultrasound velocity variations (Fig. 5) was calculated using the 2D Fourier transform

$$S(\omega_x,\omega_y)=FFT\left[c(x_i,y_j)-\frac{1}{N\cdot M}\sum_{j=1}^{N}\sum_{i=1}^{M}c(x_i,y_j)\right], \quad (2)$$

where FFT denotes the fast Fourier transform, $c(x_i, y_j)$ is the ultrasound velocity values obtained in measurements positions along x and y axis across the tile using the zero-crossing technique and N is the number of measurements points.

The normalized spatial spectrum of the ultrasound velocity variations across a green ceramic tile enables to determine the most significant components of influencing the spatial distribution.

For example along the y-axis they are found in the following way

$$S_{\max}(f_y)=\max_x\left[S(f_x,f_y)\right]. \quad (3)$$

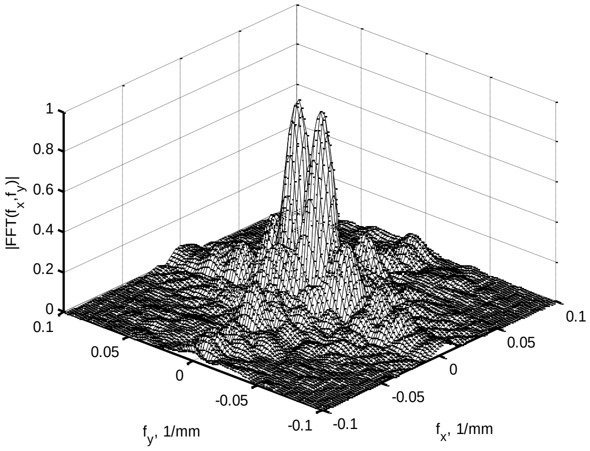

Fig. 5. Normalized spatial spectrum of the ultrasound velocity f(czc) variations across a ceramic tile.

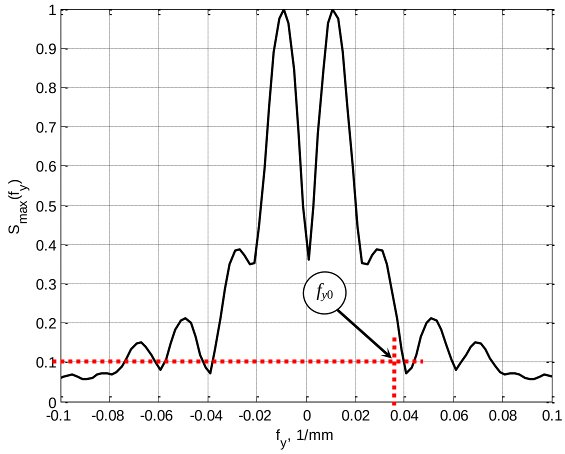

Fig. 6. Normalized spatial spectrum of the ultrasound velocity f(czc) variations across a ceramic tile.

The 1D spatial spectrum along y-axis is shown in Fig. 6. From the result presented follows that this spectrum is not band-limited, what means that highest frequencies $\omega_x = 2\cdot\pi\cdot f_x$ and $\omega_y = 2\cdot\pi\cdot f_y$ determining the distances between the measurement points (e.g., ultrasonic transducers), must be selected according to some criterion.

If the criterion is the required reconstruction error, then the frequency ω_y can be found as the frequency f_{y0} (Fig.6) at which rest of the spectral components is

$$\left|S(f_{y0})\right| < 0.1 S_{\max}(f_y). \quad (4)$$

In this case the ultrasonic velocity reconstruction error will be minimized. In our case the distance between measurement points determined in this way should be $\Delta y = 1\big/2 f_{y0}$ e.g., 12.5 mm.

III. CONCLUSIONS

Spatial distribution of the ultrasound propagation time in the tile corresponds to its pattern, but ultrasound velocity distribution is inversely proportional to the local tile thickness.

Spatial variations of ultrasound velocity in the tile allow determine its spatial spectrum, which can be used for the design of the layout of ultrasonic transducers, necessary to obtain the necessary accuracy of the spatial ultrasound velocity distribution.

Spatial density variations in a tile may be determined by exploiting a known relationship between the ultrasound velocity and the density of the tile.

However, the results obtained show that it is necessary to perform more detailed measurements of various tiles with various thickness and patterns.

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