ON-LINE DEFORMATION MONITORING OF THIN CERAMIC TILES

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ABSTRACT

In the ceramic industry, new scenarios have been recently opened by the development of new technologies for the production of thin tiles with large area (thickness lower than 6 mm and size larger than 1200x600 mm). Significant progress has been made on the subject in the last few years and most of the technological issues have been solved for large-scale production in compliance with current standards. However, an accurate analysis of the thin tile surface revealed the presence of small periodic deformations that can create, under specific lighting conditions, aesthetic problems. This phenomenon is due to pyroplastic deformations that occur during the firing process in roller kilns. This paper investigates this effect using a non-contact method, based on laser triangulation, for the on-line monitoring of tile shape. The developed technique combines short inspection time, compatible with typical tile production rates, with the high accuracy (±0.02 mm) required to detect such a small defect. Several tests have been performed analysing the tile deformation obtained under different firing conditions. The results have revealed a strong dependence of this phenomenon on roller circumference and firing temperature. This study provides a better understanding of the origin of periodic pyroplastic deformation for large thin tiles and proposes a measurement technique that allows an effective on-line control of this effect.

1. INTRODUCTION

In the ceramic tile industry, the realization of products with larger dimensions and reduced thickness is a topical industrial issue and many researchers are trying to develop innovative technical solutions for producing ceramic slabs with large dimensions (e.g. 60x60 cm, 120 x 60 cm or 120x120 cm) and reduced thickness (3-6 mm) [1-3]. Large-sized porcelain stoneware slabs are suitable for both outdoor and indoor building applications [1-3] and significantly simplify storage, packaging and installation. The low thickness reduces raw material consumption and transport efforts, resulting in a significant overall reduction of CO^2 emissions compared to traditional products. Innovative ceramic processes and new material compositions have been widely investigated (e.g. [4]) trying to obtain large thin tiles with high mechanical properties and morphological characteristics.

An accurate analysis of new production processes of thin tiles (performed in the context of the Italian Project "Grandi Superfici Ceramiche Leggere Riccamente Decorate") highlighted the presence of small periodic surface deformations that can compromise the shape and the aesthetics of the final product. To illustrate this phenomenon a tile has been placed on two planar steel frames and the interface separated the two bodies has been highlighted through a backlight. The Figure 1 shows a non-continuous contact on the edge of the tiles revealing the presence of this periodic deformation. Although this phenomenon is almost imperceptible on small samples or under normal lighting conditions, it becomes more evident on large surfaces (e.g. a building façade), especially with grazing light, generating light and dark bands.

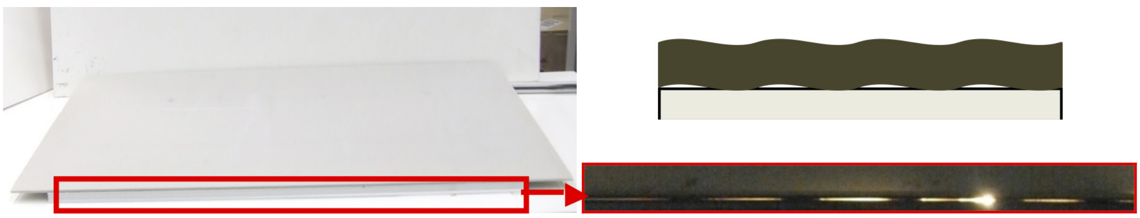

Figure 1. Left: front view of the tile; top-right: schematic representation of the periodic deformation; bottom-right: tile profile highlighted by using backlight.

The periodic deformations observed on new thin tiles are probably caused by pyroplastic phenomena that occur during the firing process and its morphology (spatial frequency and peak amplitude) depends on firing parameters. In fact, even considering the continuous technological evolution of roller kilns and the most recent solutions with rollers guaranteeing minimal deformation at high temperature, the pyroplastic effect can still represent an issue due to the thermal and mechanical interactions between rollers and tiles.

The pyroplastic effect has been widely investigated in the literature for the assessment of planarity in tiles produced in roller kilns [5]. Recent studies have been done to determine the correlation of this effect with the tile composition [6,7]. However, most of the work done in the past on ceramics only took into account typical shape defects (such as planarity), which are the most relevant for traditional thick tiles.

In the glass industry this phenomenon is known as "roller wave distortion" [8] and it occurs during the glass tempering process that makes use of roller kilns similar to those used for ceramic tiles. Several techniques have been developed for the on-line evaluation of roller wave distortion [9,10]. However, these techniques are mainly based on machine vision technologies capturing distortion of structured light patterns, methods that can be hardly applied on ceramics due to their particular surface characteristics (porous, matt, colour, etc.).

The paper shows the work done in analysing roller wave deformation (i.e. wave deformation generated in roller kilns) in thin ceramic tiles by developing a dedicated measurement system for on-line tile monitoring and by correlating the pyroplastic deformation to different process parameters (firing temperature, tile speed and roller pitch).

While in the glass manufacturing, roller wave distortion is already considered by ASTM C-1048 -04 for glass quality assessment, in the ceramic industry this topic has not yet been addressed. This study is one of the first attempts to characterize the roller wave deformation on tiles, paving the way to future standardization activities.

2. ON-LINE DEFORMATION MONITORING

The idea was to perform tests by monitoring thin tile production and to correlate the observed deformations with the process parameters. A dedicated measurement system has been developed for quality control of tile shape. The problem is to dynamically measure (i.e. at the exit of the kiln with tiles moving at about 1-4 m/min) surface deformations with a spatial resolution in the order of 1 mm and an accuracy of at least ± 0.05 mm. A flat bottom gauge can be used to measure the roller wave deformation off-line but, in addition to positioning error, the measurements are too slow to be compatible with production timing and they would not allow quality control on the total production.

In this work, among the potential optical techniques, a non-contact method based on laser triangulation sensors for the monitoring of the tiles exiting the kiln is proposed. At this stage, the prototype is installed near the kiln exit in order not to modify the production line, but in the future it may be installed directly on the line to measure at normal roller velocity, with dedicated solutions to minimize the tile vibration effects.

The test bench installed at the kiln exit at the Sacmi Imola S.C. plant is shown in figure 2. The test bench consists of a Cartesian robot that is able to move two triangulation lasers over the tile surface. One laser (linearity: ± 1.2 μm) is focused on the top surface while the other one (linearity ± 4 μm) is focused on the bottom surface (see figure 2) so that it is possible to analyse the shape variation of both surfaces and to calculate the thickness. In this study, in order to improve the understanding of this phenomenon, the shape is measured on a 2D area, but for future on-line monitoring a single line would be enough.

Figure 2. Non-contact measurement system installed at the kiln exit.

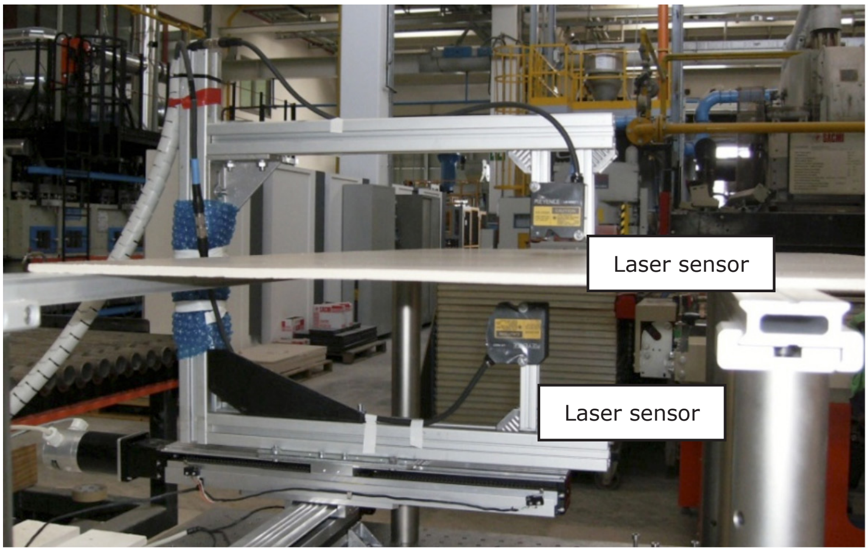

Figure 3. Laser sensors focused on the top and bottom surfaces of the tile.

The Cartesian robot used for the tile scan has the following characteristics:

- Max scanning area: 600x400 mm (a scan area up to 1200x400 mm can be inspected thanks to a sliding support for the tiles).
- Scan speed: 0-300 mm/s.
- Min scan resolution: 0.01 mm.

System performances have been evaluated with lab tests considering the intrinsic uncertainty of the lasers and other sources of error affecting the measurement during the scanning: vibration, electromagnetic noise and variation of environmental conditions (air temperature, humidity…). Different measurements have been performed on a reference plane providing an accuracy of ± 0.02 mm on the displacement of each surface (with a coverage factor k=2) considering a scan speed of 100 mm/s and an acceleration of 100 mm/s^2. This uncertainty is mainly due to the vibration of the robot at relatively high frequency. Higher accuracy can be achieved by performing an analysis in the spatial frequency range of interest (around the central frequency of the roller wave deformation, 0.0074 mm^{-1}).

NI PXI 8109 is used to have real time data acquisition and to synchronize a high-speed acquisition board (2-channels, 14-Bit, 100 MHz, 100 MS/s) with the motion controller. The user interface (Figure 4) displays the 2D maps and average profiles of thickness and top and bottom surfaces.

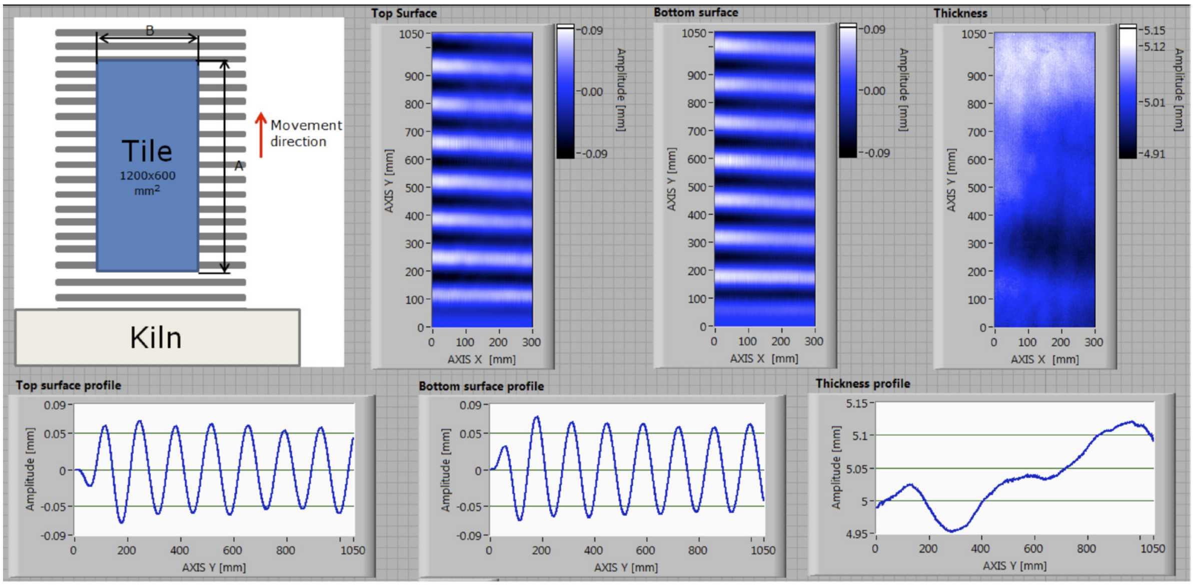

Figure 4. Software interface.

Real time signal processing algorithms have been implemented to analyse the deformations in time and spatial frequency domains. To highlight the roller wave deformation a band-pass filter (centred around the spatial frequency corresponding to the roller circumference) has been used for the top and bottom surfaces, highlighting periodic deformation and filtering out tile slope and planarity.

3. EXPERIMENTAL PROCEDURE

The purpose of this study is to characterize the pyroplastic effect and correlate this deformation with the process parameters using the developed measurement system. Tile firing process, during which the pyroplastic deformation occurs, is a complex phenomenon where different parameters (tile temperature and roller velocity) vary according to the firing curve (figure 5).

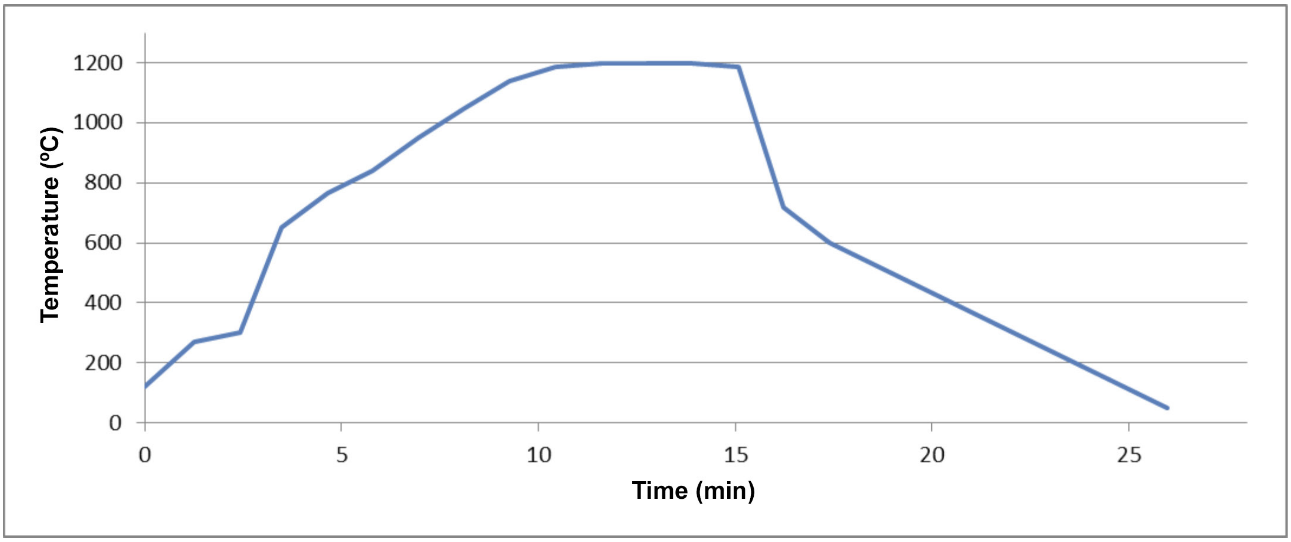

Figure 5. Example of firing curve used in the tests performed.

In the analysis of the firing process, two variables have been considered: max firing temperature and tile speed. Two series of 12 tiles (A1 and A2 in Table 1) have been realized with two replicate samples for each firing condition. A standard porcelain stoneware composition (35-45 wt% kaolin clays, 45-55 wt% feldspars; 5-10 wt% quartz) has been used. The tile speed is fixed at 0.78 m/min for the A1 series and 2 m/min for the A2 series. These values have been defined considering a length of the kiln of about 40 m, while for an industrial kiln higher tile speeds of up to 4 m/min can be reached. The temperature has been varied from 950°C to 1230°C with larger steps on low temperature and finer steps around the typical firing temperatures (about 1200°C) as shown in Table 1.

An additional analysis has been then performed to determine the effect of the kiln on the roller wave deformation by doubling the roller pitch (from 60.5 mm to 121 mm) in the high firing module of the kiln (series A3 of Table 1).

Series	Number of samples	Firing speed (m/min)	Max Temperature (°C)	Kiln system
A1	12	0.78	900-1000-1100-1180-1230	Roller distance 60.5 mm (standard roller pitch)
A2	12	2	900-1000-1100-1180-1230	
A3	6	2	100-1180-1210	Roller distance 121 mm (double roller pitch)

Table 1. Process parameters varied during the test.

In a preliminary test, a scan on a large area (300x1050 mm) of the tile has been performed and the resulting maps have been shown in figure 4. From the test it was possible to conclude that the peak to peak variations are periodic and constant on most of the tile surface so that a drastic time saving can be obtained inspecting a smaller area of the tile (18x1000 mm), obtaining the same information. Considering as main requirement the total inspection time, a continuous scan along the tile motion direction, where the periodic deformations occur (Y axis), has been performed (with a max velocity of 100 mm/s and acceleration of 100 m/s^2). A resolution of 0.1 mm has been chosen along this direction while a larger step (2 mm) has been selected for the X direction. Using this setup three maps (thickness, top and bottom surfaces) of 90000 points have been obtained for each tile in less than 3 minutes. The scan speed, if the system is used to measure on a single line, is clearly compatible with the on-line speed of the tiles.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The tests have been realized, reproducing on a real production line the different firing conditions described in Table 1 (varying tile speed, firing temperature and roller pitch).

The graphs in figure 6 show that the pyroplastic effect generates a periodic deformation on the top and bottom surfaces with a constant spatial period of 135 mm. This same period has been obtained for all the firing conditions analysed and has been found to correspond exactly to the roller circumference (the roller diameter was 43 mm). Since no significant variation was noted on doubling the roller pitch or varying the firing curve (maximum temperature and tile speed), it was also concluded that none of these parameters affect the spatial period of roller wave deformation.

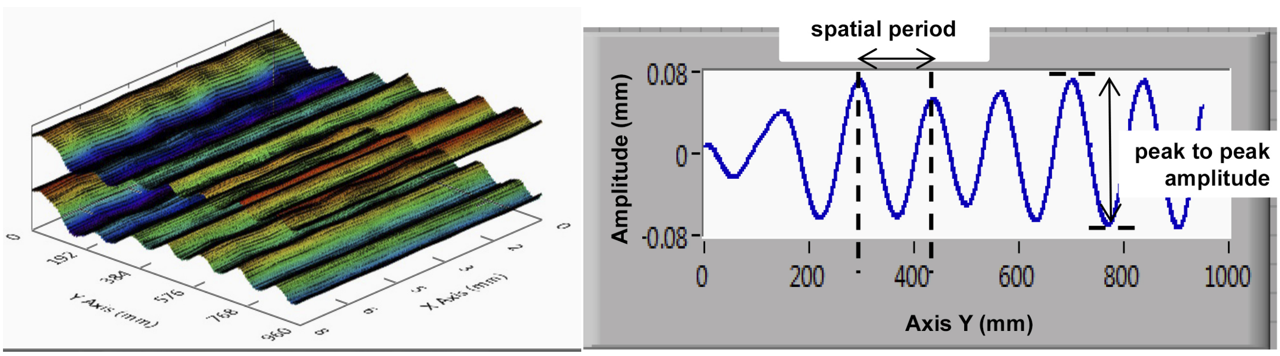

Figure 6. Left: 3D map of top and bottom tile surfaces; right: average profile of top surface.

While the spatial period was the same for all the series analysed, a correlation between the magnitude of the roller wave and the firing temperature was observed. Figure 7 and Figure 8 show that the amplitude of the roller deformation on the top and bottom surfaces can be considered irrelevant up to 1100°C (peak to peak amplitude inferior to 0.02 mm), while an increase is noted from 1100°C to the highest temperature tested (1230°C) with a maximum peak to peak amplitude of 0.30 mm. Another interesting piece of information can be derived from the thickness measurement. From a first visual assessment it seemed that the deformation only occurred on the surfaces, while a more accurate analysis revealed a roller imprint also in the thickness (see figure 9), albeit to a lesser extent (below 0.04 mm). Figure 7 and Figure 8 showed no clear dependence of roller wave amplitude on tile speed (i.e. firing duration) and roller pitch.

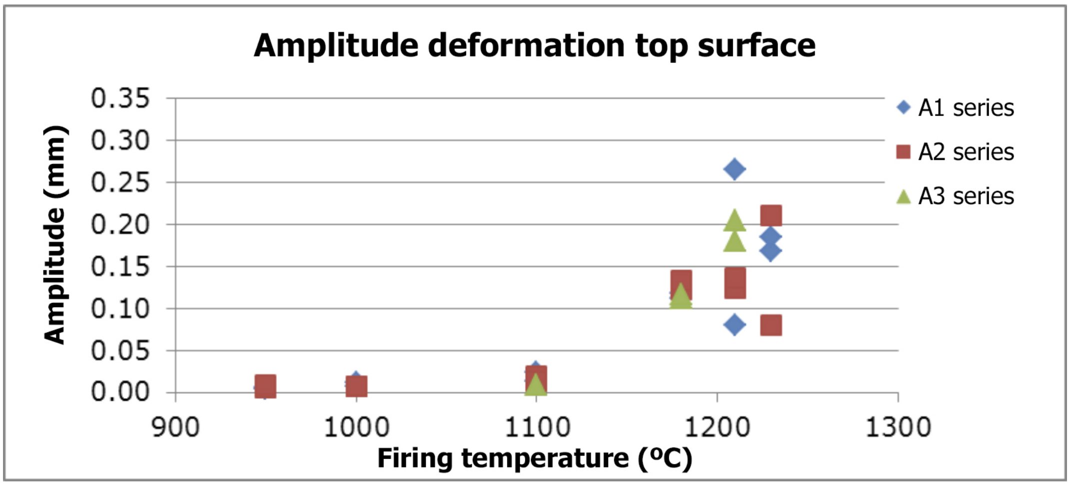

Figure 7. Correlation between roller wave deformation and firing temperature on the top surface (A1 series: tile speed 0.78 m/min; A2 series: tile speed 2 m/min; A3 series: tile speed 2 m/min and double roller pitch).

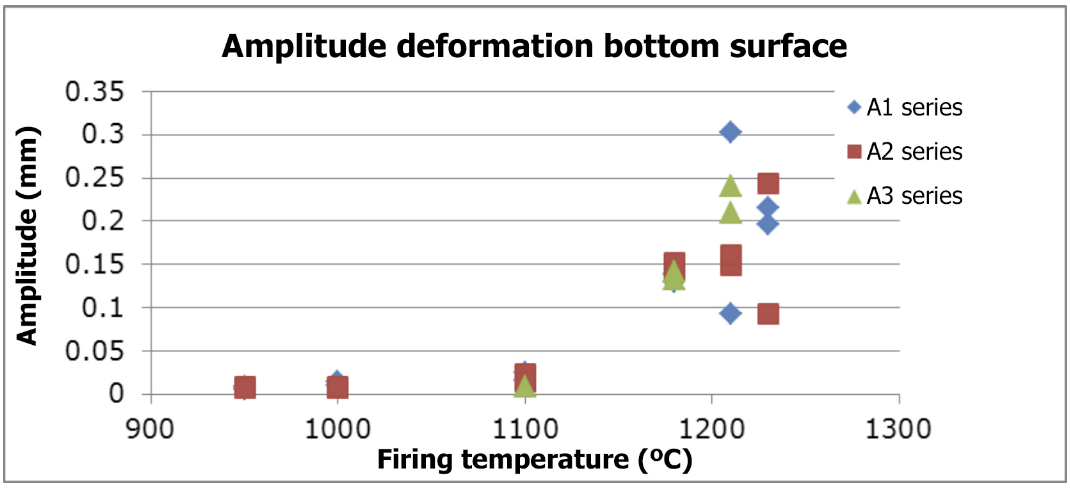

Figure 8. Correlation between roller wave deformation and firing temperature on the bottom surface (A1 series: tile speed 0.78 m/min; A2 series: tile speed 2 m/min; A3 series: tile speed 2 m/min and double roller pitch).

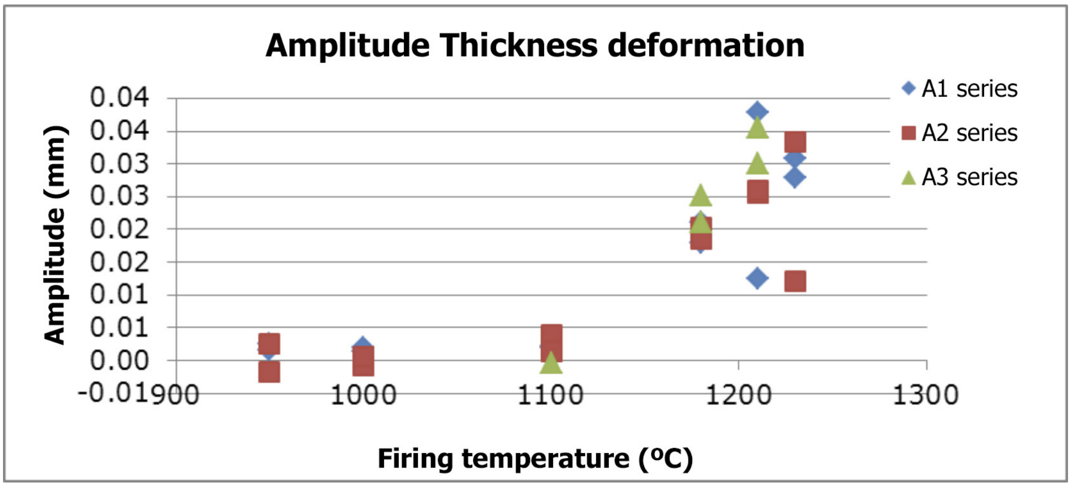

Figure 9. Correlation between roller wave deformation and firing temperature on thickness (A1 series: tile speed 0.78 m/min; A2 series: tile speed 2 m/min;A3 series: tile speed 2 m/min and double roller pitch).

The origins of the pyroplastic periodical deformation have to be sought in the sintering process of porcelain stoneware tiles. Most of the reactions occurring during firing are kinetically governed processes [11,12] that do not reach thermodynamic equilibrium in porcelain stoneware production, since the industrial cycles are shorter than 1 hour [13]. The pyroplastic effect is determined by the force and moments applied on the tiles due to its weight and to roller constraints. This deformation depends on tile composition and firing temperature [14,15].

The rollers act as an important barrier to heat transmission and generate a thermal gradient between the tile surface in contact with the roller and the opposite surface. Moreover, the rollers generate the translational motion by applying shear forces to the base of the tile while the phases in the material are changing. The pyroplastic deformation appears during this kinetic stage and is consolidated after cooling. The permanent pyroplastic effects are already described by [7] as the bending of a ceramic specimen caused by gravity during heat treatment or as the loss of shape of a product during its firing. Pyroplasticity is related to excess liquid phases forming during firing or to a reduced viscosity of these phases. Specifically for ceramic tiles fired in roller kilns, while the tile is carried by the rollers, it can partly bend to accomplish the roller rotation because it is subjected to vertical forces due its own weight.

The roller wave deformation has also been demonstrated to match the shrinkage measured in the same samples. In fact linear and thickness shrinkage (Figure 10 and Figure 11) were shown to be almost negligible below 1100°C and drastically increased beyond this value.

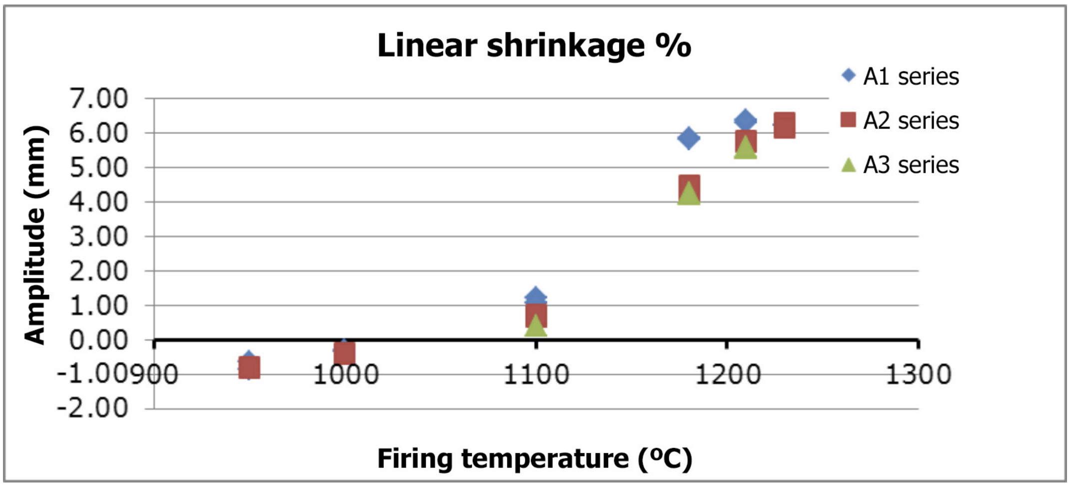

Figure 10. Correlation between linear shrinkage and firing temperature (A1 series: tile speed 0.78 m/min; A2 series: tile speed 2 m/min; A3 series: tile speed 2 m/min and double roller pitch).

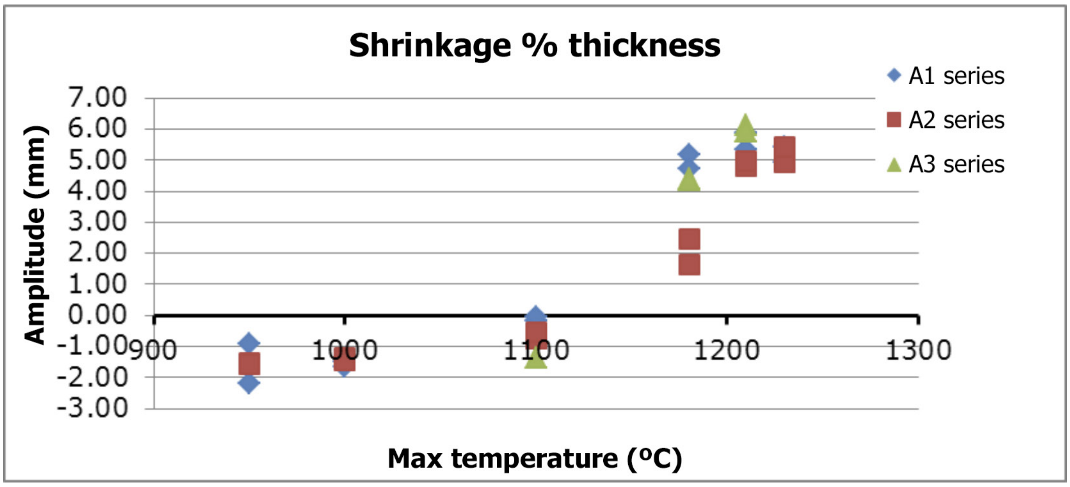

Figure 11. Correlation between thickness shrinkage and firing temperature (A1 series: tile speed 0.78 m/min; A2 series: tile speed 2 m/min; A3 series: tile speed 2 m/min and double roller pitch).

The results of Figures 10 and 11 agree with the sintered curves obtained by dilatometric measurements [16] on small specimens of stoneware. From the qualitative point of view all the ceramics undergo a first thermal expansion and then, when they reach the activation temperature of the sintering process, they undergo a quick contraction up to the maximum shrinkage [17].Under these conditions an abundant vitreous phase is generated with a sufficiently low viscosity to cause rapid deformation of the material (pyroplastic effect).

Both the shrinkage and roller wave deformation are critical issues especially for large thin tiles and it is difficult to keep them completely under control by only working on kiln parameters. The online monitoring system can provide a continuous feedback on the effective tile shape and can significantly improve the control of firing process maintaining high quality in production.

5. CONCLUSIONS

The roller wave deformation has been found to be a relevant issue for the production of thin tiles with large area. In this paper, the correlation between this particular pyroplastic effect and production parameters has been investigated using a non-contact method based on laser triangulation. This technique allows on-line measurement of the tile shape after the firing process with ± 0.02 mm accuracy. The system can be integrated into the roller line at the kiln exit and is able to measure the roller wave deformation on the tile at the typical roller velocity.

From the analysis of roller wave deformation induced on different tile samples it was found that this phenomenon can be correlated with the firing temperature, while no significant dependence on the tile speed was observed in the range from 0.78 m/min to 2 m/min. A clear correspondence between the periodic deformation and the roller circumference (135 mm) has been found for all the tiles inspected. The analysis also highlights that roller distance has no significant effect on this periodic pyroplastic deformation while thermal and mechanical stress combined with rolling are at the origin of this phenomenon. Even if the pyroplastic roller deformation is intrinsic in roller kiln technology, its effect can be minimized by working on tile and process parameters.

This paper proposes a methodology to characterize the roller wave deformation on thin tiles, providing quantitative information on the magnitude of this phenomenon, which may be used in the future as a reference for the definition of new deformation acceptance limits in the ceramic industry.

6. ACKNOWLEDGMENT

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