MODELLING OF THE INDUSTRIAL CERAMIC TILE POLISHING OPERATION

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ABSTRACT

The distribution of the grinding tools in an industrial ceramic tile polishing facility is established, generally, in an empirical form by trial and error, seeking to find a compromise between the productivity of the facility and product quality. A better understanding of the work done by each grinding tool on the piece to be polished in each section of the polishing train would undoubtedly facilitate design of faster and more efficient polishing cycles.

In this study a model has been developed that enables calculating the work done by the abrasive grinding tools at different points of the workpiece surface, establishing the existence of significant variations among the points, even in the case of a perfectly flat piece. Moreover, if the piece is not flat, the foregoing effect is compounded by curvature, which leads to more vigorous polishing at the points located highest above the mean plane of the piece. The grinding tools studied were trapezoidal prisms, known as 'fickerts', one of the most common geometries used in the industry. The model has been verified in a pilot polishing facility, measuring the transverse profile of the piece before and after polishing. The difference between both profiles was used to establish the wear produced by the grinding tools on the piece and, therefore, to evaluate indirectly the work performed during polishing at different points in the surface. Good agreement was found with the theoretical values.

The model developed enables readily foreseeing the effect that different operating variables, such as grinding tool geometry, the transverse oscillating movement of the polishing train, the relative dimensions of the head/piece, and the geometry of the polishing head itself have on final surface quality.

1. INTRODUCTION

Polishing is a key processing stage in porcelain tile manufacture, and can account for over 40% of product cost. This operation is carried out with long polishing trains, in which tile thickness is reduced by up to 10%[1-3]. Though the process is generally known as 'polishing', it actually involves several different operations. Thus, in the first process phase, rollers or other grinding tools with coarse diamond grain are used to dress and level the tile surface, removing a great volume of material.

However, this necessary step is traumatic for the tile surface, as it generates tracks and deep cracks that need to be completely eliminated in subsequent phases. The tools used in the next polishing step are generally trapezoidal prisms, known as 'fickerts', which contain SiC grains of highly varying size[4,5]. Figure 1 shows a photograph of an abrasive assembly (head) with six fickerts, used in the industrial polishing process. The rotation of the head at high velocity (450 rpm) assures a certain number of contacts between the abrasive surface and the workpiece surface. In addition, each grinding tool also has an oscillating movement, which contributes to keeping the fickert surface cylindrical and assures tile surface planarity[6].

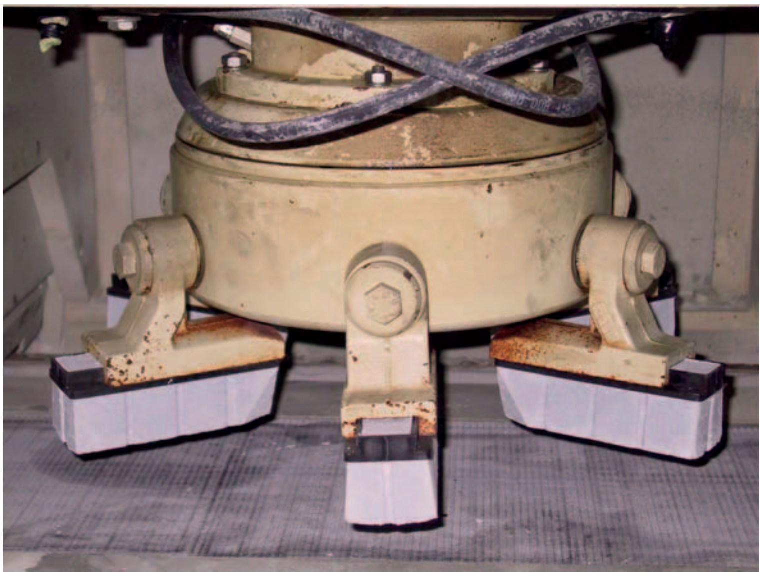

Figure 1. Photograph of an oscillating polishing head with 6 grinding tools of the fickert type

In an industrial polishing cycle it is very important that the abrasive grain size ('grit') of the grinding tools should follow a specific sequence, progressively from large to small. This is because each successive tool repairs the erosion caused by the foregoing grinding tool, which has a larger abrasive grain size[7,8]. The resulting defects thus become progressively less severe, until the smallest abrasive grain sizes are reached which actually polish the surface, without causing any appreciable damage. It is important, furthermore, that the pieces should undergo the action of each abrasive sufficiently long for it to do its work, since, if the piece passes on to the following, smaller size before it is convenient, the defects that have not been eliminated will remain in the surface, and the polishing operation will have been inappropriate[9].

Grinding tool distribution in the industrial polishing facility is generally established empirically, by trial and error, in a compromise between productivity and product quality[10]. A better understanding of the work done by each grinding tool on the piece to be polished, in each section of the polishing train, could favour the design of faster and more efficient polishing cycles, and improve polished surface quality. The importance of predicting the distribution of the polishing work performed on the pieces is evidenced by the appearance of certain surface defects in the polished pieces, causing breaks in surface gloss or texture, which originate in the lack of uniformity in the path travelled by the grinding tools across the tile surface.

In view of the above, the present study has addressed the development of a model that enables calculating the work that abrasive tools (fickerts) do on different points in the tile surface, establishing a polishing work profile across the surface. The model allows foreseeing the effect that different operating variables, such as grinding tool geometry or the transverse oscillating movement of the polishing train have on surface end quality. The model has been verified in a pilot polishing facility, by measuring the dimensional profile of the piece before and after polishing.

2. DESCRIPTION OF THE PROPOSED MODEL

The work done by the head during the polishing process is put into:

a) grinding tool wear

b) tile abrasion

c) other processes (heating of the cooling water, noise, energy dissipation in the polishing machine itself, etc.)

To develop the model, the simplest case has been used first, in which the piece is assumed to remain static. Figure 2 schematically illustrates an oscillating head with 6 fickerts, and some of the key parameters. It is reasonable to assume that the polishing work done on an element of the tile surface, dA, in the period of time [t, t+dt] (dW_p) is proportional to the work done on the element of the grinding tool in contact with this surface dW_m (Figure 2). Moreover, the work dissipated by other processes (aside from grinding tool abrasion and tile wear) dW_{ex}, can also be considered proportional to dW_m. Mathematically:

$$dW_p = \gamma_p dW_m \qquad 1a$$

where γ_p and γ_{ex} are the corresponding coefficients of proportionality.

The previous expression enables relating *total work put into polishing* (dW) to *work put into grinding tool wear* (dW_m) and *into removal of material from the tile* (dW_p):

$$dW_m = \frac{dW}{1 + \gamma_p + \gamma_{ex}} \qquad 2a$$

$$dW_p = \frac{\gamma_p dW}{1 + \gamma_p + \gamma_{ex}} \qquad 2b$$

As γ_p and γ_{ex} only depend on the type of grinding tool used and material to be polished, to calculate the polishing work done at different points of the same piece, both parameters may be assumed constant.

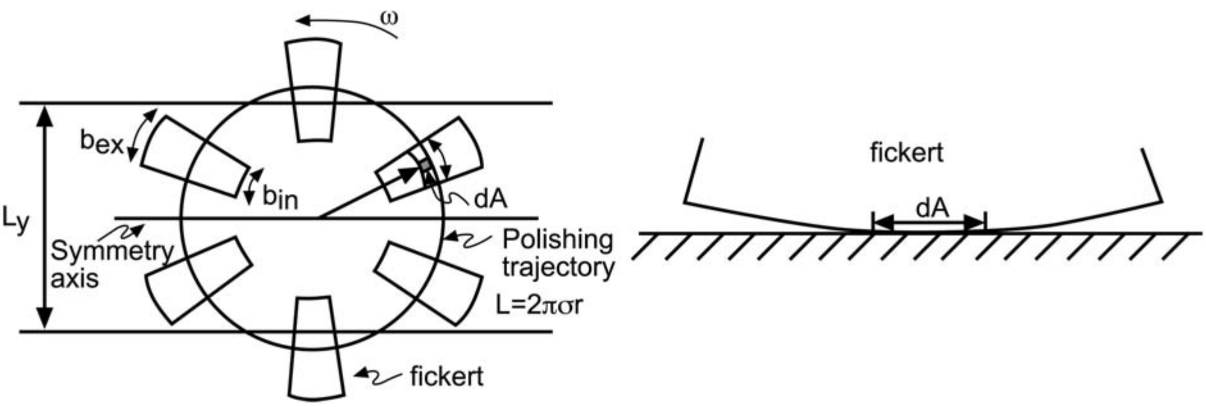

Figure 2. Schematic illustration of an oscillating polishing head (a) with the fickert in contact with the piece (b).

On the other hand, the *total work put into polishing per unit time (power),* $d\dot{W}$ can be calculated from the friction force between the head and the tile in the following form:

$$d\dot{W} = \alpha r \omega \mu \sigma dA_m \tag{3}$$

where:

- α: fraction of the travel of the grinding tool element in which there is contact with the tile
- r: distance from the centre of the head to the grinding tool element (m)
- ω: polishing head rotation speed (rad/s)
- μ: coefficient of friction between the grinding tool and the tile surface
- σ: contact pressure between the surfaces (Pa)
- dA_m: grinding tool surface in contact with the tile (m^2). dA_m = bdr, where b is grinding tool width (b is constant in the case of parallelepiped grinding tools, whereas it varies linearly with r if the grinding tool is trapezoidal)

Deriving Equation (2a) in respect of time and subsequently combining it with Equation (3) allows deducing the *power per unit grinding tool area* ($\dot{W}_{sm}$):

$$\dot{W}_{sm} = \frac{d\dot{W}_m}{dA_m} = \frac{\alpha r \omega \mu \sigma}{1 + \gamma_p + \gamma_{ex}} \tag{4}$$

$\dot{W}_{sm}$ is independent of r, because all the points of the grinding tool wear equally. This means that the pressure applied by the grinding tool (σ) is not constant through the grinding tool, but that it varies in accordance with an expression directly deducible from Equation (4):

$$\sigma = \frac{k_1(1 + \gamma_p + \gamma_{ex})}{\omega \mu} \frac{1}{\alpha r} \tag{5}$$

where $\dot{W}_{sm}$ has been expressed as k_1 to highlight the fact that it remains constant.

The polishing work on the piece can be calculated from Equation (2b). This work takes place on piece surface area $dA_p = 2\pi\alpha r dr$. Therefore, combining Equations 2b and 3 and using the definition of dA_m and dA_p, *polishing work per unit time and area on the piece* can be obtained in the following form:

$$\dot{W}_{sp} = \frac{k_1}{2\pi(1+\gamma_p+\gamma_{ex})}\frac{b}{\alpha r} \tag{6}$$

The situation represented by Equation (6) corresponds to a configuration in which there is no relative movement between the tile and the polishing head. However, during the polishing process, the pieces advance, with which the relative position of a point P of the piece and the head changes. Integrating this for all the period of time in which there is contact between P and some point of the grinding tool gives *total polishing work* at P, W_L; this can be calculated by integrating (6):

$$W_L = \frac{k_1}{2\pi(1+\gamma_p+\gamma_{ex})}\int_t \frac{b}{\alpha r}dt \tag{7}$$

As the objective of the model is to evaluate relative variations in the polishing work, in the foregoing expression we can eliminate the independent parameters of position and, by changing a variable, obtain a simpler equation to calculate total polishing work, W_L^+:

$$W_L^+ = \int_x \frac{b}{\alpha r}dx \tag{8}$$

In certain cases, in particular when the tiles are large, in addition to their advancing movement, polishing trains can display an oscillating movement transverse to that of tile advance. In this case, it is more appropriate to speak of *mean work per oscillation cycle,* ($\overline{W}_L^+$):

$$\overline{W}_L^+ = \frac{1}{\pi}\int_{-1}^{1} \frac{W_L^+(A_T y'_C)}{\sqrt{1-y'^2_C}}dy'_C \tag{9}$$

where:

A_T: transverse oscillation amplitude

y'_C = y_C/A_T, where y_C is the distance between the centre of the head and the tile symmetry axis.

The solution of integrals 8 and 9 will need to be performed by numerical methods.

3. EXPERIMENTAL

With a view to verifying the validity of the model, polishing experiments were conducted using the pilot polishing facility shown in Figure 3. This machine is fitted with a single oscillating head, identical to those used in industrial polishing facilities. The feeding belt has a to-and-fro movement to provide a certain residence time of the abrasives (fickerts) on the tile surface. Thus, in each cycle, the piece crosses the head twice (forward and back). When industrial polishing cycles (in which over 20 heads can take part) are to be reproduced, it is only necessary to replace the group of fickerts with others of different grit, as many times as required.

In our case, only a single set of grinding tools with a large grain size (grit 46) was used, since the purpose was to remove a sufficient amount of material from the ceramic tile and to evaluate the variation in the surface profile. In order to assure attainment of this last objective, 10 cycles were performed, which corresponded to 20 passages of the tile under the abrasives, which is much longer than the residence time used in industrial practice. The tests with the pilot polishing facility were conducted on porcelain tiles of two different sizes: 300x300 mm and 400x400 mm. The tiles had been polished beforehand in an industrial polishing facility to assure a flat starting surface without any defects. The operating conditions set in the pilot polishing facility (head rotation speed and pressure, and feeding belt advance speed) matched the usual operating conditions in an industrial polishing installation.

The experimental evaluation of the polishing work was performed indirectly, measuring the dimensional profile over the length of the tile surface, before and after testing in the pilot polishing facility. The difference between both profiles enables establishing the wear produced by the grinding tools on the piece and, therefore, allows determining the abrading work done at different points in the surface. The dimensional measurements before and after polishing were made in a three-coordinate measuring machine, with an uncertainty of 10 μm.

Figure 3. Photograph of the pilot polishing facility

4. RESULTS AND DISCUSSION

4.1. DETERMINATION OF THE POLISHING WORK PROFILE ON THE TILE FROM THE DEVELOPED MODEL

The integration of Equation 6 for a parallelepiped grinding tool geometry (b_{in} = b_{ex} in Figure 2) leads us to the polishing work profile (W_L^+) on a tile of 400x400 mm, represented in Figure 4. As may be observed, a clearly non-linear, albeit symmetrical profile is obtained with respect to the centre axis of the tile (axis parallel to the direction of advance of the feeding belt). The regions in which the polishing work is less intense, i.e. in which the sliding distance travelled by the fickerts is smaller, are located on the tile symmetry axis, as well as on the tile edges. In contrast, the polishing work intensifies (reaches its maximum value) in the areas equidistant between the symmetry axis and the tile edges. As the figure shows, this difference would mean reaching 250 abrasive–tile contact cycles in the region with the maximum polishing work and, for example, hardly 130 cycles on the tile symmetry axis. The reason for this characteristic profile is related to the design and constitution of the oscillating head itself, which has, as can readily be observed, a large circular inner area that contains no abrasive elements, which is crossed by the tile.

The implications of this profile in the unfolding of the polishing operation are very important, since material elimination will obviously be less effective in the areas of the tile surface in which the polishing work is less intense and vice versa. This uneven material removal will need to be repaired in the course of the polishing operation, in which grinding tools containing progressively smaller abrasive grain sizes are used in industrial practice, until the desired roughness and gloss are achieved. However, if the distribution and sequence of the abrasives are inappropriate, the polishing cycle is too fast, or the dimensional characteristics of the tiles are not uniform, this irregularity may remain throughout the polishing cycle and give rise to a poor quality finish.

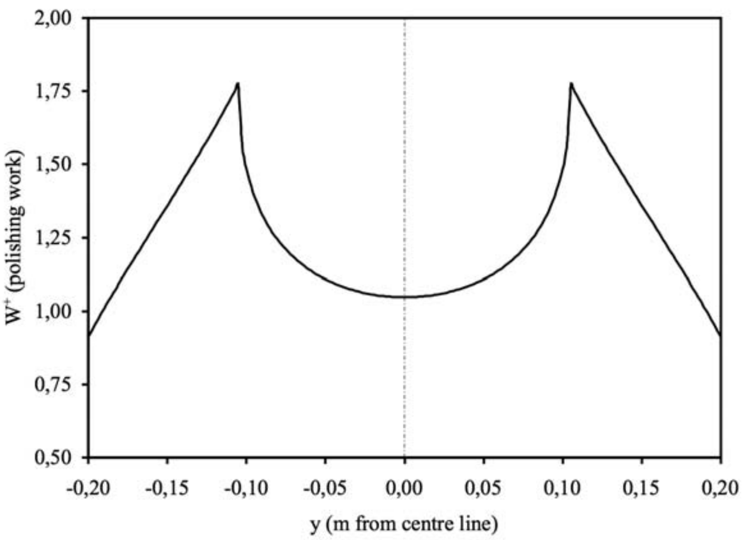

Figure 4. Polishing work profile obtained by developing Equation (6) on a 400x400 mm tile in a direction perpendicular to tile advance in the polishing facility

4.2. EXPERIMENTAL EVIDENCE RELATED TO THE IRREGULAR DISTRIBUTION OF THE POLISHING WORK

In order to verify the possible incidence of an irregular distribution of the polishing work predicted by the model, a thorough inspection was made of the polished surface of the porcelain tiles of different size, polished in different industrial facilities, which all operated with oscillating heads fitted with fickerts. Although the extent of the study does not allow establishing categorical conclusions, certain tendencies relating to the behaviour of the inspected materials were repeatedly observed:

- The large-sized tiles (>300x300 mm) all displayed a region with less gloss located in the centre of the surface, which crossed the tile lengthwise, parallel to the direction of travel through the polishing facility. As an optical effect was involved, the pieces needed to be observed in a place with great luminosity to enable appreciating the defect.
- The defect became more pronounced as the polished surface gloss and/or tile size increased.
- The defect was mitigated when, in the case of rectangular tiles, these were polished with their longer side perpendicular to the direction of tile advance in the polishing facility. With this arrangement, the polishing facility operated, moreover, with a transverse oscillating movement of the heads (see section 4.4). In industrial practice, however, this polishing direction is not normally used, since it can lead to other problems in the final finish.

With a view to quantifying the defect, two 300x600 mm pieces were chosen, which had been polished in different ways: one had been polished according to the standard procedure, i.e. with its longer side parallel to the direction of advance in the industrial polishing facility; the other, at right angles to the foregoing situation. As already mentioned, the first piece showed the defect clearly, whereas the second did not. In both tiles we determined the dimensional profile transverse to the defect, i.e. along the shorter side, using a coordinate measuring apparatus. Figure 5 shows the results obtained, in which the arrows indicate the polishing direction in each case. It can be observed that the surface with defect exhibits a discreet concave curvature with an inflection or change of slope in the area between 100 and 150 mm, right on the centre axis of the tile. The depth of the concavity is approximately 0.06 mm. The piece polished in a 'sideways' arrangement, which did not display the defect, exhibited a profile with a much greater concavity (0.12 mm). This suggests, therefore, that the less intense polishing work in the centre of the piece is responsible for the change in the dimensional profile of the surface and, hence, for the change in gloss noted. However, the fact that the 'sideways' polished piece shows a continuous progressive curvature, while in the piece polished in standard conditions an inflection point in the profile is detected, indicates that the defect is also related to the lack of homogeneity in tile curvature, which contributes further to the polishing work gradients.

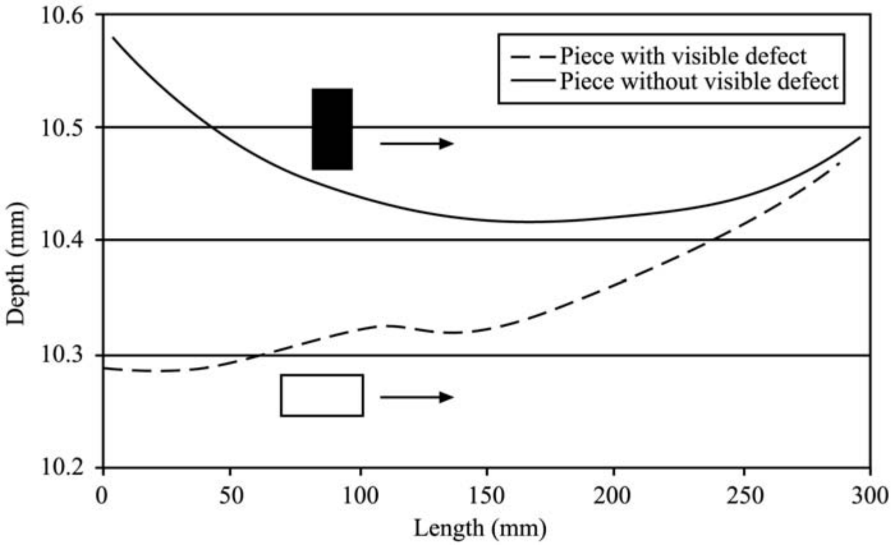

Figure 5. Surface profile of two polished porcelain tiles with and without visible defect of gloss change (300x600 mm tiles)

4.3. EFFECT OF FICKERT GEOMETRY

In industrial practice it is usual to modify fickert geometry in order to mitigate, as far as possible, the contact cycle gradients that develop between the grinding tools and the tile surface. From the model it is possible to simulate the effect of grinding tool geometry on the polishing work profile. Figure 6 shows the result of the model for four fickert geometries, represented by parameter $r_b = b_{in}/b_{ex}$ (Figure 2), in a 400x400 mm tile. As the value of r_b decreases, the fickerts go from a parallelepiped ($r_b = 1$) to an increasingly trapezoidal geometry.

As this figure shows, diminishing the value of r_b enables reducing the height of the polishing work peaks, while simultaneously increasing the polishing work on the tile edges, yielding a more favourable profile, although the centre region of the piece, where the polishing work is minimum, hardly undergoes any change. However, although the reduction of r_b is beneficial, this must be done within certain limits, fixed by fickert design itself, since an excessively low value of r_b can lead to a loss of abrasive surface and, in an extreme case, to the interaction of the grinding tools in the course of the actual polishing process.

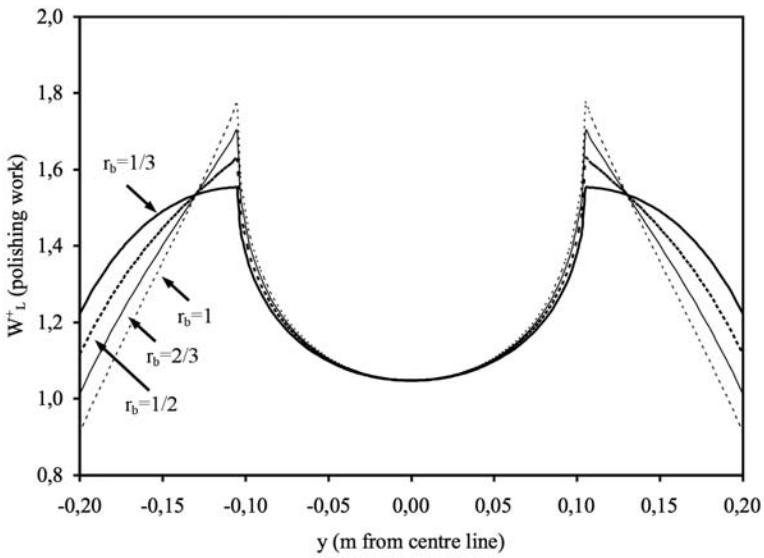

Figure 6. Effect of fickert geometry (value of r_b) on the polishing work profile (400x400 mm tile)

4.4. EFFECT OF THE TRANSVERSE OSCILLATING MOVEMENT OF THE POLISHING HEADS

When large-sized tiles are to be polished, many industrial facilities allow moving the bridge in which the oscillating heads are lodged by a transverse oscillating movement, in order to relieve, as far as possible, the polishing work gradients described previously. The amplitude of the oscillating movement (A_T) quantifies the displacement of the head rotation axis to both sides (left and right) in the polishing train.

The model developed also allows simulating this movement, in this case from Equation (7), which enables calculating the dimensionless work per oscillating cycle ($\overline{W_L^+}$). Figure 7 plots the results of the work profile on a 400x400 mm tile, for three different oscillating movement amplitude values (A_T): without oscillating movement ($A_T = 0$), $2A_T = 40$ mm and $2A_T = 80$ mm, values which encompass the values used in industrial operation. It can be observed that the oscillating movement is efficient in eliminating the polishing work peaks and, consequently, improving the variation profile of this parameter across the tile surface. As with fickert geometry, the effect is much less pronounced in the centre region of the piece, where the minimum work values accumulate. When the amplitude value is increased (A_T) its levelling effect also rises; however, in industrial practice, facility design makes it difficult to establish values of A_T much higher than those evaluated in the study.

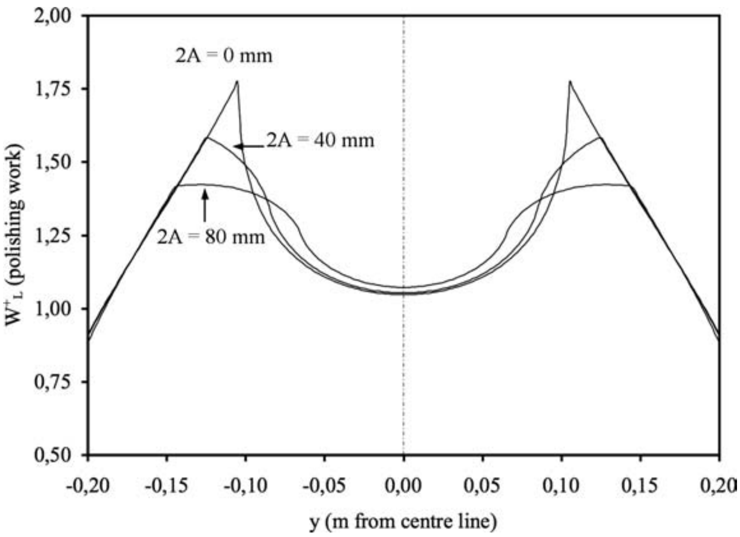

Figure 7. Effect of transverse oscillating movement amplitude (A_T) on the polishing work profile (400x400 mm tile)

4.5. VERIFICATION OF THE VALIDITY OF THE MODEL

Assuming that more polishing work means greater material removal from the piece, this parameter could be evaluated experimentally, in an indirect form, from the dimensional profiles of the tiles before and after polishing, subsequently plotting the difference between both (Δz). When the amount of material removed during polishing increases, the value of Δz will rise, which, taking into account the foregoing, must also be related to more intense polishing work.

In order to perform this experimental verification, two porcelain tiles which had been polished industrially, measuring 300x300 mm and 400x400 mm, were tested in the pilot facility according to the conditions described in section 3. The value of Δz was determined across the piece in the direction perpendicular to its advance in the polishing train. Figure 8 plots the experimental values of Δz (as points) and the polishing work, W_L^+, calculated from Equation 6 (continuous solid line) as a function of the distance from the tile centre axis, for the 300x300 mm and 400x400 mm tiles. It can be observed that the profiles of the pieces follow, qualitatively, the tendency predicted by the model: in the centre region, the polishing work is less and two areas appear at the two sides on which the work maximises. However, in the 300x300 mm tile, the maximum wear values are located at a smaller distance from the centre in regard to that predicted by the model, whereas for the 400x400 mm tile the opposite occurs.

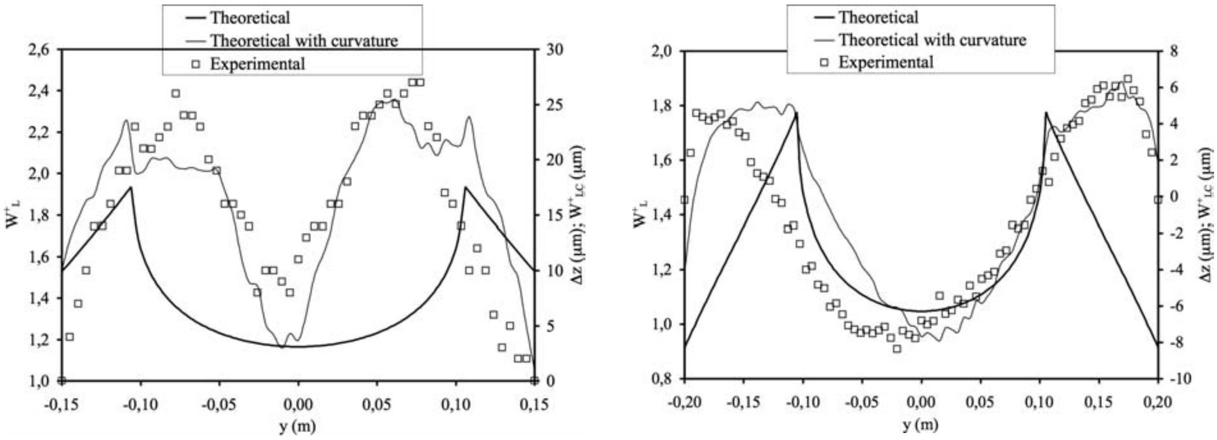

Figure 8. Comparison between the dimensional profile and the polishing work profiles with and without the contribution of tile curvature (left: 300x300 mm tile, right: 400x400 mm tile)

The explanation for this apparent discrepancy could be related to the contribution to the polishing work of tile curvature when the tile is being abraded, as already noted in section 4.2. Although the industrially polished pieces are much less curved than the equivalent unpolished pieces, they are not perfectly flat, and exhibit a certain curvature. When a tile with a regular curvature is subjected to the pressure of the polishing head, it is levelled. However, when the curvature is irregular, the levelling is incomplete, and the resulting slightly higher parts of the surface undergo greater polishing work. Figure 9 clearly shows this last behaviour.

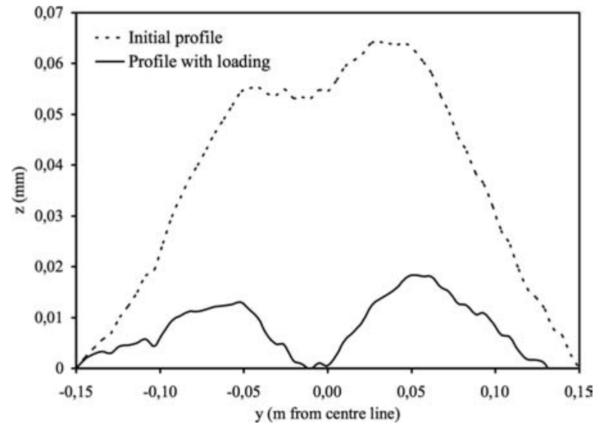

Figure 9. Modification of tile initial curvature under polishing head pressure (300x300 mm tile)

By combining tile curvature during polishing (estimated from the initial curvature according to Figure 9) with the profile deduced from the polishing work (Equation 8) it is possible to obtain a polishing work distribution closer to that found in reality. In effect, as Figure 8 shows, the curves corresponding to the contribution of both effects (designated the theoretical curve with curvature, W^{+}_{LC}) reproduce the experimental profiles much more faithfully.

5. CONCLUSIONS

A model has been developed that enables predicting the polishing work in different points of a porcelain tile surface. The results show that the polishing work is less in the centre and near the edges of the tile, with less material removal in these areas. In contrast, the polishing work peaks are located in the regions equidistant between the tile centre axis and its edges. This lack of uniformity, which is a direct consequence of the configuration of the oscillating head, can lead to defects associated with breaks in the texture and gloss of the polished surface.

In addition to the previous effect, tile curvature plays a very important role, particularly when this is irregular. In this last case, there are thus higher areas which are subjected to more intense wear than the rest of the piece, while the opposite occurs in the lower areas.

The model has allowed simulating the effect of different design and operating parameters, such as the trapezoidal geometry of the grinding tools and the transverse oscillation of the polishing train, for tiles of different sizes. It has been verified that, acting judiciously with both factors, it is possible partly, to mitigate the polishing work gradients on the tile surface.

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