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SIMULATION AND ANALYSIS OF AN ALTERNATIVE KINEMATICS FOR IMPROVING THE POLISHING UNIFORMITY OVER THE SURFACE OF POLISHED TILES

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ABSTRACT

The present work investigates the possibility of adopting a new kinematics at the industrial polishing lines of porcelain stoneware tile. An alternative motion of the transverse oscillation of the polishing heads is proposed, in which no radical changes in the industries facilities are required. The basic idea is to replace the purely sinus motion of the polishing heads by a rather trapezoid wavelike motion. In theory this could be achieved simply by adopting regular delays at the transverse oscillation motion. Consequences of this alternative kinematics were quantitatively analyzed considering the spatial homogeneity of polishing expected for tiles. Such homogeneity was represented by the coefficient of variation of the distribution of polishing time over the surface, which was in turn determined by means of computational simulations, taking into account the effect of multiple polishing heads.

Keywords: Polishing process, porcelain stoneware tiles, polishing kinematics, polishing simulations

1 NTRODUTION

Most porcelain stoneware tiles are polished after firing and in this case the final glossiness represents the most important criterion of quality [1,2,3]. High glossiness levels are appreciated by the costumer despite the extra costs due to the polishing process. Such costs arise mainly from the high demand for energy, water and abrasive tools [4,5], and implausibly also from the low efficiency levels, which are still considered being inherent to the industrial process [6,7].

In industries the polishing process is accomplished by a sequence of several tangential polishing heads with decreasing abrasive sizes, resulting in long polishing trains. Typically more than 30 polishing heads and up to 18 different abrasive sizes can be used to assure the production of tiles with the glossiness level required by the market [6,8].

The kinematics available in a given polishing train may be considered as a key feature in the final glossiness pattern to be expected over the surface of the polished tiles, as it determinates the uniformity of the number of abrasive contacts gathered during polishing. As results, the maximum homogeneity level offered by the polishing trains, which is purely governed by some kinematics and geometric preset parameters, ends up by limiting the overall efficiency of the polishing process.

Modern polishing trains possess a kinematics with basically three different components: the rotation W [$rad \cdot s^{-1}$] of abrasive blocks known as fickerts, around the center of each polishing head, the forward motion V [$mm \cdot s^{-1}$] of the conveyor belt, which defines the direction of the polishing process, and finally the oscillation of the polishing head, which is transverse to the polishing direction, has an amplitude A [mm] and a frequency f [s^{-1}].

Effectuation of both forward motion and transverse oscillation at the same time causes each polishing head to perform a sinusoidal trajectory relative to the tile's surface. As reported by Sousa et al.[9], according to the relation between forward motion and transverse oscillation frequency (V/f) a zigzag pattern of glossiness may be ascribed onto the polished surface. Furthermore, the most polished areas are found to be sensitively shifted from the tile center. This could be explained considering firstly the lack of abrasives in the center of the polishing heads, and secondly the overlapping of all those wavelike trajectories.

Regardless the frequency of transverse oscillation adopted at a polishing train, the center of the polishing heads containing no abrasives will be the close to the tile center most of the time. Bearing this concept in mind, the basic idea of the present work underlies in considering an increase of the time during which the region with less abrasive contacts remains far from the center. This idea was admitted to be feasible by causing a periodic delay at the transverse oscillation motion, during each peak and valley of the sinusoidal curve.

Figure 1 presents the trajectories of two adjacent polishing heads moving along the tile's surface. Figure 1a stands for the original sinusoidal trajectory, whereas Figures 1b and 1c exemplify some trajectories with the proposed delay. The distance undertaken during each delay was designed D/2 [mm].

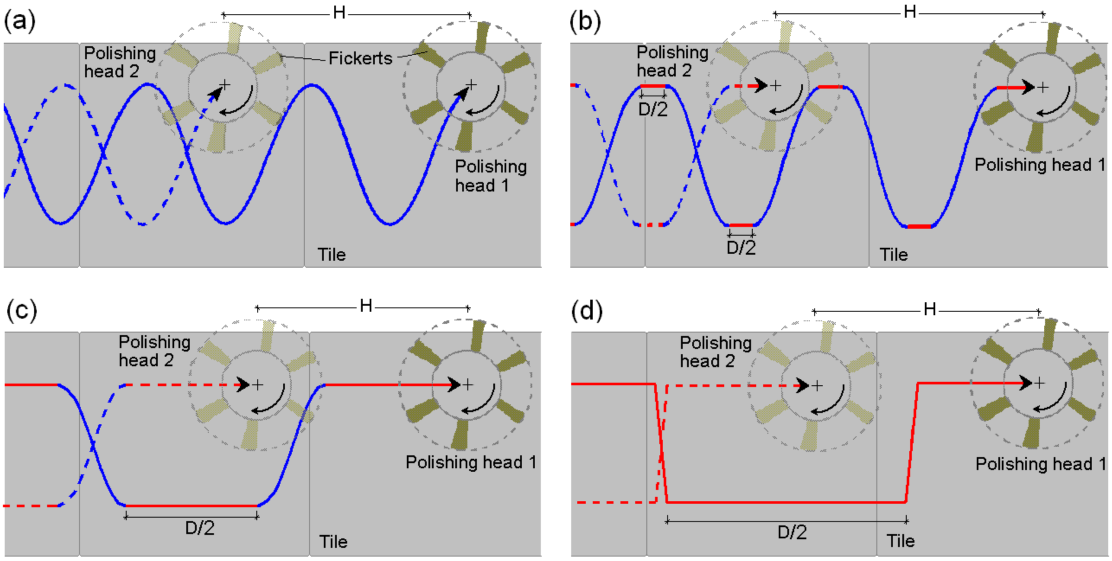

Figure 1 – Area under polishing and available motions in the polishing train

Figure 1 still includes the overlapping of trajectories from adjacent polishing heads. All the polishing heads are equally spaced by a distance H and perform the transverse oscillation at the same time. Similarly to the ratio V/f, this overlapping also plays an important role in the uniformity level of the polishing process over the tile surface[2,10].

Analogously to the sum of two coherent waves, an overlapping with a total constructive interference would only enhance the glossiness pattern already offered by a single polishing head. In contrast, an overlapping with destructive interference would lead to a better polishing coverage. The benefit of this better coverage was fully admitted in this work, since the new trajectories to be studied remain longer in asymmetry than the original sinusoidal waves. A useful criterion to distinguish between the destructive interference is given by the Equation 1, derived from literature[9]:

$$H = \lambda \cdot (n + \frac{1}{2}) \qquad (1)$$

Where $n \in N$ is the number of wave nodes, and λ [mm] represents the wavelength of the trajectory of the polishing heads, including the distance performed during the delays. After the introduction of distance D into the sinusoidal wave the polishing heads follow a trapezoid wavelike function, whose period is given by the sum of the time spent in sinusoidal motion, T_S [s], plus the time spent under delays, T_D [s]. Accordingly, the transverse oscillation frequency is then $f = 1/(T_S + T_D)$, and the wavelength λ of the function in turn depends on the forward speed V, so that $\lambda = V \cdot (T_S + T_D)$.

The of trapezoid character of the resulting function may be represented by the ratio between the delay distance D and the wavelength λ. Figure 1d illustrates a ratio D/λ of 100%, in which the polishing heads is supposed to move abruptly from one side to another at the polishing train. In contrast, Figure 1a represents the original sinusoidal wave, with a ratio D/λ of 0 %.

Regarding the cumulative polishing time, typical qualitative profiles for a single and for two adjacent polishing heads are explained in Figure 2a and 2b, respectively. The benefit of overlapping trajectories for the better polishing coverage may also be observed in Figure 2b. The inner radius r [mm] represents the centre of the polishing head, the outer radius R [mm] depends on the dimension of the fickerts (abrasive blocks).

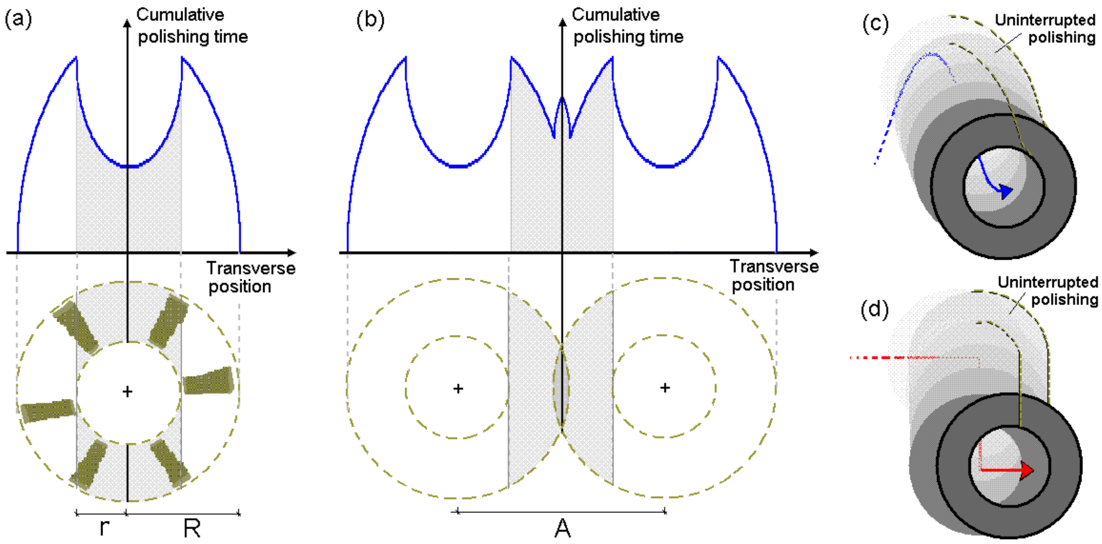

Figure 2 – Profiles of cumulative polishing time for a single (a) and for two overlapped polishing head (b). Regions with no polishing interruptions for sinusoidal (c) and for (d) trapezoid trajectories

Figure 2a still points out the biased occurrence of most polished regions, as consequence of the lack of abrasives in the centre of the polishing heads. Nevertheless, as can be seen in Figure 2b, this problem could be minimized by using an appropriate overlapping of two adjacent polishing heads. Moreover, as suggested in Figures 2c and 2d, this improvement seems to be more intense by the adopting the delayed wave rather than the original sinusoidal trajectory, and these assumptions were quantitatively analyzed in the next sections.

2 THEORETICAL CONSIDERATIONS

The trajectory and the geometry of the polishing head are presented in Figure 3, including the available motions. The hollow circle represents the effective work zone of the polishing heads, assuming that the rotation motion is much faster than the two others.

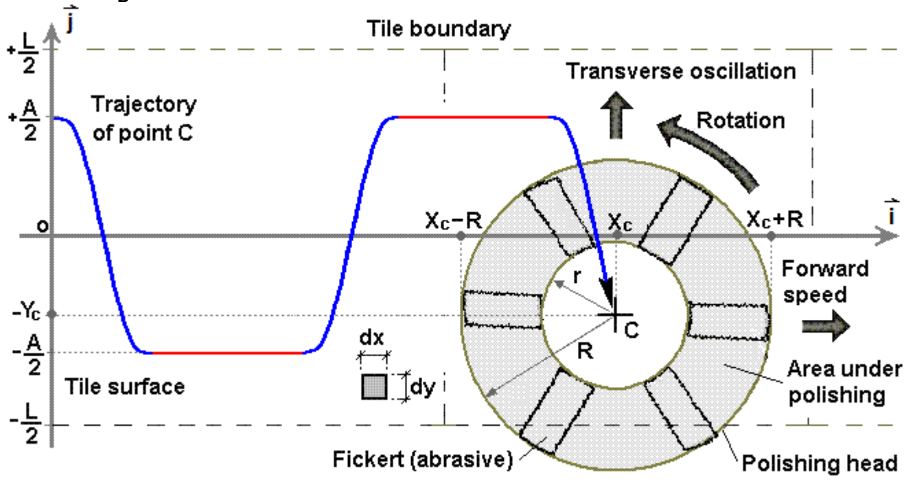

Figure 3 – Area under polishing and available motions in the polishing train

According to Sousa et al.[10], the effective polishing time for a given surface point with coordinates (X,Y), and dimensions dx and dy, can be analytically determined by the spatial function $S_T = f(X,Y)$, written in Equation 2. Function f_{TW} stands for the trapezoid wavelike function which should be performed by the center of the polishing head, designated as point C (X_C ; Y_C).

$$S_T = \frac{d}{dY_C}\left[\int_{Xc-R}^{Xc+R}\left| f_{TW} - f_{OCY}\right| \frac{dx}{2}\right] - \frac{d}{dY_C}\left[\int_{Xc-r}^{Xc+r}\left| f_{TW} - f_{ICY}\right| \frac{dx}{2}\right] -$$

$$\left\{\frac{d}{dY_C}\left[\int_{Xc-R}^{Xc+R}\left| f_{TW} - f_{OCI}\right| \frac{dx}{2}\right] - \frac{d}{dY_C}\left[\int_{Xc-r}^{Xc+r}\left| f_{TW} - f_{ICI}\right| \frac{dx}{2}\right]\right\} + (R - r); \qquad \text{if } Y_C \geq 0 \qquad (2a)$$

or:

$$S_T = \frac{d}{dY_C}\left[\int_{Xc-R}^{Xc+R}\left| f_{TW} - f_{OCI}\right| \frac{dx}{2}\right] - \frac{d}{dY_C}\left[\int_{Xc-r}^{Xc+r}\left| f_{TW} - f_{ICI}\right| \frac{dx}{2}\right] -$$

$$\left\{\frac{d}{dY_C}\left[\int_{Xc-R}^{Xc+R}\left| f_{TW} - f_{OCY}\right| \frac{dx}{2}\right] - \frac{d}{dY_C}\left[\int_{Xc-r}^{Xc+r}\left| f_{TW} - f_{ICY}\right| \frac{dx}{2}\right]\right\} - (R - r); \qquad \text{if } Y_C < 0 \qquad (2b)$$

Function $f_{OC\cap}$ represents the top half of the outer circle (radius R), hence defining the reach of the fickerts. Analogously, f_{ICU} is the function corresponding to the bottom half of the inner circle (radius r), which delimits the lack of abrasive in the center of the polishing head.

The design of the polishing head forbids the amplitude of the transverse oscillation to approach the lateral border of the tile. This is to avoid an abrupt re-entrance of the abrasive block (fickert) over the proper surface of the tile, which very often leads to coarse scratches.

For the same reason, no gap between the porcelain tiles can be admitted while they are being driven toward the polishing by the conveyer belt.
The following kinematic parameters were adopted for the polishing train: W = 47.12 $rad \cdot s^{-1}$ (450 rpm), V = 75 $mm \cdot s^{-1}$, R = 230 mm, r = 110 mm, and A = 120 mm. A nominal size of 450 x 450 mm was adopted for each tile. An extra value of oscillation amplitude A = 220 mm was also considered. This value, which corresponds to $2 \cdot r$, leads to a complete misalignment of regions with no abrasives particles, and since A < R, it is still inside the limit for a save re-entrance of the fickerts on the surface being polished.

Once the values of kinematic parameters were established, the corresponding polishing patterns were simulated considering several different trapezoid waves with a ratio D/λ ranging from 0 % up to 100 %. In case of overlapped patterns, adjacent polishing heads spaced by distance H = 550 mm were considered to overlap yielding the best polishing coverage possible.

The decision for all those values aforementioned was taken considering the results of a previous work on kinematic optimization[2,9,10,11]. The uniformity of polishing for each condition was then quantified by means of the spatial standard deviation of the corresponding distribution of polishing time, given by Equation 2.

A computational algorithm was developed in order to carry out all the calculations and simulations needed. This algorithm solves and presents the analytical solutions of Equation 2 for throughout the entire polished surface, and considering each kinematic condition under investigation. Results of simulations were exhibited in the next section by means of either 3D or gray scale surface graphics, in which the position of each pixel is directly and univocally associated with a region at the tile surface.

With the intention of achieving the evolution of the cumulative number of abrasive contacts during any extend of the polishing process a second algorithm was also developed. This algorithm simply counts the number of abrasive contacts undergone by each region over the tile surface, caused by any one of the available fickerts. Both algorithms were written in G language, using the software *LabVIEW®*, version 8.5.

3 SIMULATIONS

The effect of a single polishing head was analysed at first. Figure 4 exemplifies the polishing pattern simulated considering four different kinematic condition with the same ratio D/λ = 10 %. A good perception of the effect of adopting an oscillation amplitude $A = 2 \cdot r$ can be seen by comparing Figure 4a with 4c, or also by comparing Figure 4b with 4d. The oscillation frequencies were fixed at f = 0.12 s^{-1} and f = 0.34 s^{-1}, respectively.

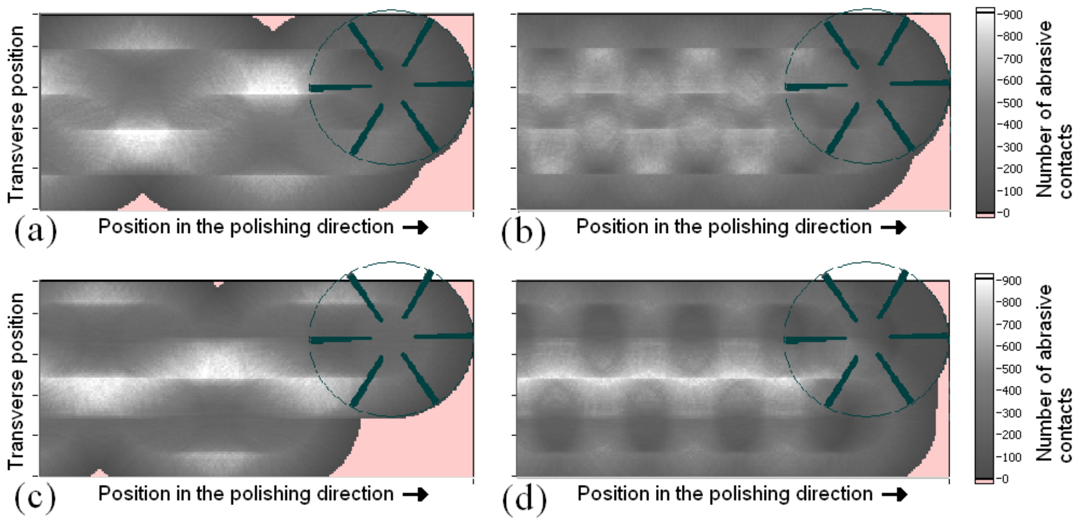

Figure 4 – Spatial distribution of cumulative abrasive contacts considering D/λ = 10%, transverse amplitude A =120 mm with oscillation frequency (a) f = 0.12 s^{-1} and (b) f = 0.34 s^{-1}, and also A = 220 mm with (c) f = 0.12 s^{-1} and (d) f = 0.34 s^{-1}.

For both oscillation frequencies the use of A = 2·r has caused a slightly higher accumulation of polishing time at the tile centre. Nevertheless, the longer override of fickerts outside the tile surface must also be taken into account. Such overrides were admitted to decrease the efficiency of the process, as no polishing effect results therefrom.

The positive effect of the oscillation frequency over the distribution of polishing time can be clearly seen by comparing the pairs of Figures 4a-4c against Figures 4b-d. Besides the improvement in the uniformity of the polishing pattern, the higher frequency has lead to different polishing patterns. More details of Figure 4b regarding the number of abrasive contacts and polishing boundaries can be seen in Figure 5.

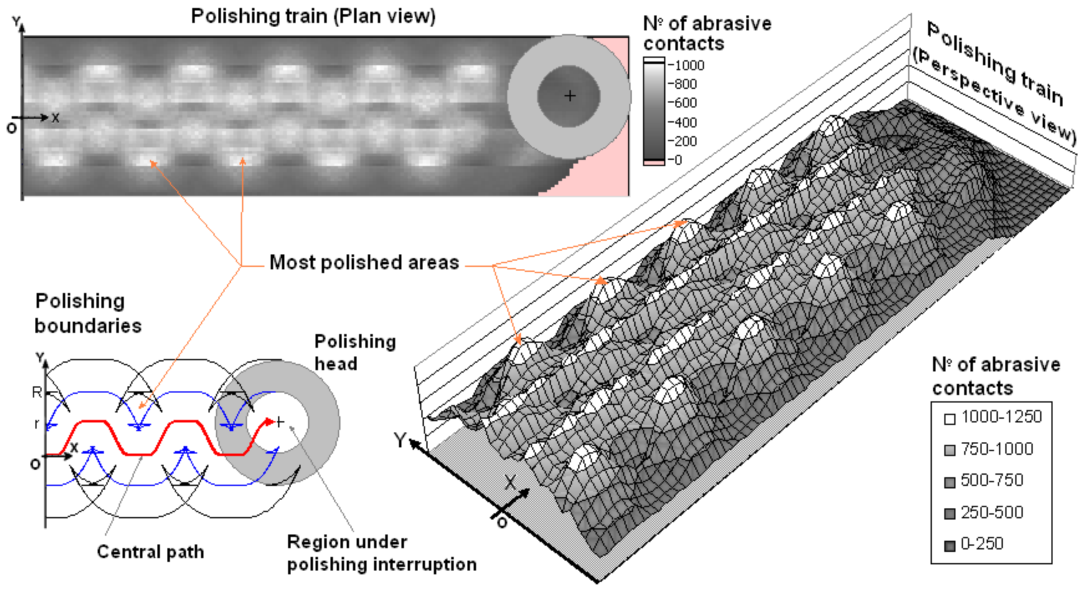

Figure 5 – Spatial distribution of polishing time over the surface of three adjacent tiles

Still considering a single polishing head, the simulated results regarding the distribution of effective polishing time were assembled in the response track plots presented in Figure 7. In this figure, mean values of effective polishing time (Fig. 7a) and the respective coefficient of variations (Fig. 7b) are given for different combinations of transverse oscillation frequency and ratio D/λ. The smaller is the coefficient of variation found for a particular combination, the more uniform is the corresponding distribution of polishing time all over the tile surface.

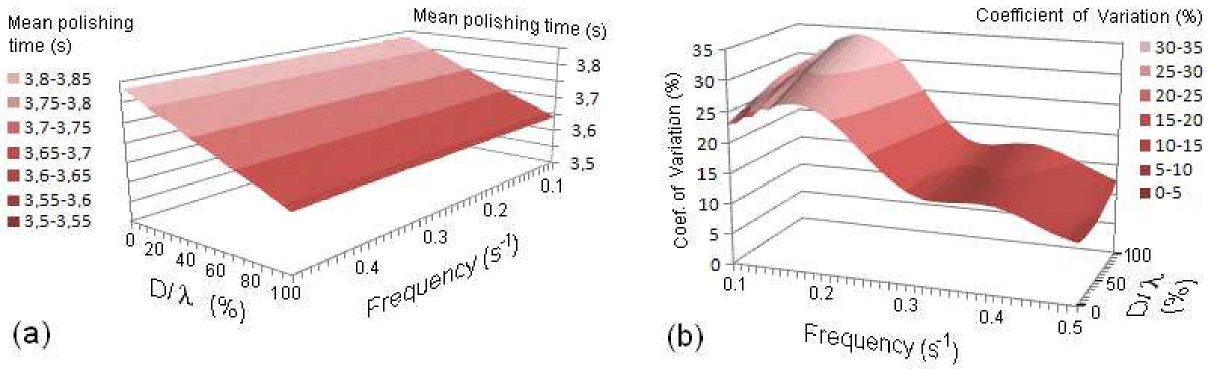

Figure 6 – Response track plot estimated regarding (a) mean value of effective polishing time and (b) the respective coefficient of variation, for different kinematic combinations

Due to the fixed speed of the conveyor belt, the oscillation frequency does not affect the mean values of the effective polishing time (Fig. 7a). However, changes in the frequency have a noticeable effect on the homogeneity of the spatial distribution of polishing time (Fig. 7b). These results are in accordance with previous studies[2,10,11].

If on one hand the use of high frequencies leads to a more homogeneous polishing process, on the other hand the criteria of energy consumption and the lifetime of the polishing machines might be damaged[11]. In case of using trapezoidal waves, the exposition to such criteria becomes more important, since the polishing heads are required to move more rapidly than sinusoidal waves with the same wavelength.

Figure 7 also made evident the disadvantage of introducing the delay D when admitting only a single polishing head. Regarding the mean polishing time (Fig. 7a), the negative effect of the ratio D/λ results from the longer time during which abrasives located in the peripherical region of the polishing head remain outside the tile surface. Furthermore, during the delay the polishing pattern promoted by a single polishing heads is enhanced, and therefore a more heterogeneous polishing is produced (Fig. 7b).

Finally, the benefits of admitting multiples polishing heads effect of using multiples polishing heads oscillating in a coherent fashion could be then evaluated by the response track plots presented in Figure 8.

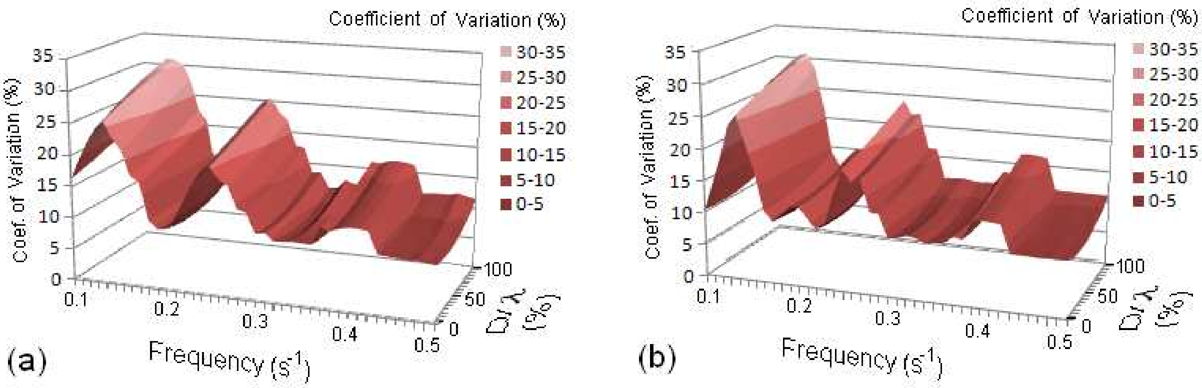

Figure 7 – Coefficient of variation simulated for distributions of effective polishing time considering (a) two and (b) three adjacent polishing heads.

Recalling Equation 1, adopting a number of wave nodes of n = 0, 1, and 2, a convenient interference condition occurs for the wavelengths λ = 157, 220, 367 mm. Taking into account the forward speed adopted (V= 75 mms^{-1}), such values respectively yield the following oscillation frequencies f = 0.48, 0.34 and 0.20 s^{-1}. This in turn explains the position of the smallest values of coefficient of variations observed in the figure.

In contrast to Figure 7b, the higher predominance of regions with small coefficient of variation found in Figure 8 highlights the improvement in polishing uniformity that may expected by adopting multiple polishing heads.

However, along the whole domain of oscillation frequency investigated in this work, the coefficient of variation was found to increase with the ratio D/λ. This reveals that, concerning polishing uniformity, no benefits may be expected by the introduction of any delay in the wavelike trajectory of the polishing heads.

4 CONCLUSIONS

From the evaluation of the several polishing conditions quantitatively simulated in this work, the following conclusions can be drawn:

- The transverse oscillation frequency f seems not to affect the mean value of the spatial distribution of polishing time over the polished surface. However, the homogeneity of this distribution was found to vary noticeably with changes in the oscillation frequency;

- Regarding a single polishing head, both the effective polishing time and the uniformity of the polishing process was found to decrease with the ratio D/λ, as results of the longer time during which abrasives remain outside the tile surface;

- An improvement in the polishing uniformity may expected by adopting multiple polishing heads, especially by adopting oscillation frequencies of f = 0.48, 0.34 and 0.20 s^{-1}, where a convenient interference takes place between trajectories of adjacent polishing heads;

- No benefits regarding the uniformity of the polishing process may be expected by the introduction of any delay in the wavelike trajectory of the polishing heads.

Finally, the response track plots offered in this work might be helpful as a guideline for a conscientious kinematic selection. However, more investigations on the phenomenology involved in the polishing process are still needed so that an optimum polishing process could be intended, for any kind of kinematic configuration.

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5 REFERENCES

[1] C. Y. Wang, T. C. Kuang, Z. Qin, X. Wei, "How abrasive machining affects surface characteristics of vitreous ceramic tile", American Society Ceramic Bulletin, 9201-9208 (2003).

[2] F. J. P. Sousa, N. V. Júnior, W. L. Weingärtner, O. E. Alarcon, "Glossiness distribution over the surface of stoneware floor tiles due to the polishing process", Journal of Material Science, 10124-10132 (2007).

[3] A. Tucci, L. Espósito, "Polishing of porcelain stoneware tile: surface aspects", World Congress on Ceramic Tile Quality - QUALICER, Castelón – Spain (2000).

[4] M. Hutchings, K. Adachi, Y. Xu, E. Sánchez, M. J. Ibáñez, M. F. Quereda, "Analysis and laboratory simulation of an industrial polishing process for porcelain ceramic tiles", Journal of the European Ceramic Society, 3151-3156 (2005).

[5] M. Hutchings, K. Adachi, Y. Xu, E. Sánches, M. J. Ibáñez, "Laboratory Simulation of the industrial ceramic tile polishing process", World Congress on Ceramic Tile Quality - QUALICER, Castelón – Spain, 19-30 (2004).

[6] I. M. Hutchings, Y. Xu, E. Sánchez, M. J. Ibáñez, M. F. Quereda, "Optimización del processo de pulido para piezas de gres porcelânico", World Congress on Ceramic Tile Quality - QUALICER, Castelón – Spain (2006).

[7] L. Espósito, A. Tucci, D. Naldi, "The reability of polished porcelain stoneware tiles", Journal of the European Ceramic Society, 785-793 (2005).

[8] M.J. Ibáñez, E. Sánchez, J. García-Ten, M. J. Orts, V. Cantavella, J. Sánchez, C. Soler, J. Portolés, J. Sales, World Congress on Ceramic Tile Quality - QUALICER, Castelón – Spain (2002).

[9] F. J. P. Sousa, J. C. Aurich, W. L. Weingaertner, O. E. Alarcon, "Kinematics of a single abrasive particle during the industrial polishing process of porcelain stoneware tiles", Journal of the European Ceramic Society, 3183-3190 (2007).

[10] F. J. P. Sousa, J. C. Aurich, W. L. Weingaertner, O. E. Alarcon, "Analytical determination of the Distribution of Polishing Time over the Surface of Polished Tiles", Journal of the American Ceramic Society, 3468-3477 (2007).

[11] F. J. P. Sousa, J. C. Aurich, W. L. Weingaertner, O. E. Alarcon, "Optimization of the Kinematics Available in the Polishing Process of Ceramic Tiles by Computational Simulations", V. 92, 41 – 48 (2009).