VIABILITY OF DISCRETE TILE ROTATIONS INSIDE THE POLISHING TRAIN

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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. The basic idea is to use a discrete rotation of the tiles during the polishing process, so that a more homogeneous polishing pattern can be obtained. All typical movements of the polishing heads are kept unchanged. No radical changes in the industries facilities are required, except by introducing a turntable conveyer at a given point inside the polishing train. Consequences of this alternative kinematics were quantitatively analysed considering four degrees of rotation: 0°, 90°, 180° and 270°, and three different kinematic conditions. The overlapping effect originating from assuming multiple polishing heads was also taking into account. The spatial uniformity of the polishing process expected for tiles was quantitatively represented by the standard deviation of the distribution of polishing time over the whole surface of six adjacent tiles. Such distributions in turn were determined by means of computational simulations. The simulated results revealed an important advantage for the posterior operation of tile setting, and also that improvements up to 10% in polishing uniformity may be achieved according to the polishing kinematic.

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1. INTRODUCTION

In the floor tile market the effect of glossiness is very appreciated by the customer. Despite the extra costs due to the required polishing process, 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].

The polishing costs arise mainly from the high demand for energy, water and abrasive tools[4,5], and implausibly also from the low efficiency of the polishing process[6,7]. In industries the polishing 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 currently required by the market[6,8].

The kinematics available at the polishing train may be considered as a key feature for defining the final glossiness pattern to be expected over the surface of the polished tiles. The distribution of abrasive contacts gathered during polishing is purely governed by kinematic and geometric preset parameters. As result, the maximum homogeneity level offered by the polishing train also restricts the overall efficiency of the polishing process.

Modern polishing trains possess a kinematics which consists basically of three different components: the rotation W [$rad \cdot s^{-1}$] of abrasive blocks (fickerts) around the centre of each polishing head, the transverse oscillation of the polishing head, with amplitude A [mm] and frequency f [s^{-1}], and finally the forward motion V [$mm \cdot s^{-1}$] of the conveyor belt. The latter defines not only the direction but also the productivity of the polishing process.

Performing both forward and transverse oscillation motion at the same time causes each polishing head to perform a sinusoidal trajectory relative to the tile surface. As reported by Cass[9], an undesired zigzag pattern of glossiness may be ascribed onto the polished surface. Furthermore, the lack of abrasives in the centre of the polishing heads shifts the most polished areas apart from the centre, causing directional gradients.

According to previous works[9], the aforementioned defects can be partially remedied by providing a convenient overlapping of those wavelike trajectories. However, due to the fixed alignment of the tiles on the conveyer belt, the distribution of polishing gradients tends to be more intense along the polishing direction (defined by the forward motion), regardless of the kinematics adopted.

Bearing this concept in mind, the main purpose of the present work is to consider a discrete rotation of the tiles inside the polishing train, so that different alignments between tiles and forward motion may become possible. As a consequence, a less directional distribution of polishing defects can be obtained. This in turn may lead to more uniform glossiness patterns over the polished surface, and thus improvements in aesthetic and in efficiency may be expected. An explanation of the basic idea is given in Figure 1.

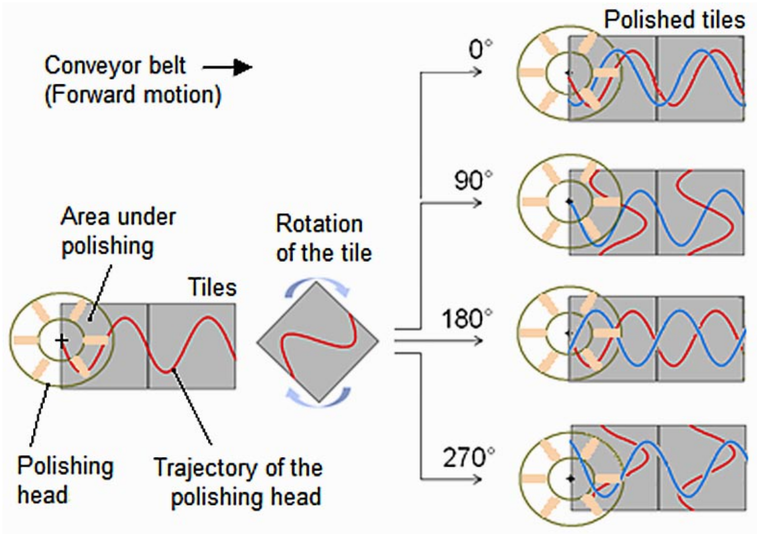

Figure 1 – Rotation of the tiles inside the polishing train and the resulting overlapping

The wavelike curves represent the sinusoidal trajectory of the centre of the polishing heads over the tile surface. After being polished by the first polishing head, the tiles are ready to be conveniently rotated, so that next polishing heads can find different previous polishing patterns to overlap with.

In the scope of this work, the rotation of the tiles was assumed to be feasible by employing a turntable somewhere between two adjacent polishing heads distributed along the conveyor belt. It must be mentioned that the implementation of such device requires an extra segment inside the polishing line, as no gap between the tiles can be allowed while they are being driven toward the next polishing heads. This is to avoid an abrupt re-entrance of the abrasive blocks onto the proper surface of the tile, which very often results in coarse scratches.

2. THEORETICAL CONSIDERATIONS

In typical polishing trains, the polishing heads oscillate together, so that the overlapping of adjacent polishing heads resembles to the interaction of classical coherent waves. Total constructive interference tends to enhance the glossiness pattern already offered by a single polishing head, whereas destructive interferences generally offer a better polishing coverage[9].

The wavelength λ of the polishing trajectory is defined by the ratio between the forward motion V and the transverse oscillation frequency f, namely $\lambda = V/f$. The final level of uniformity expected for the polishing process depends on both λ and the overlapping between successive polishing heads[2,11]. According to literature[10], when all the polishing heads are equally spaced by a distance H, and performing the transverse oscillation at the same time, the condition for the greatest overlapping (destructive interference) is given in Equation 1:

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

where n $\in N$ is the number of wave nodes, simultaneously representing the initial position where the polishing heads can be located at an initial time. In this work, it should be noted that a tile rotation of 180° also affects this interference criterion, as it usually promotes a sudden change in the distance H between the polishing heads.

A typical wavelike pattern left after the passage of a single polishing head is given in Figure 2a, based on simulated results for only two adjacent tiles. The pattern refers to the time during which each region over the tile surface has effectively suffered the polishing process. After the passage of successive polishing heads, such polishing gradients may fade away or even be enhanced according to the aforementioned overlapping degree. An example of the superposing process is presented in Figure 2c.

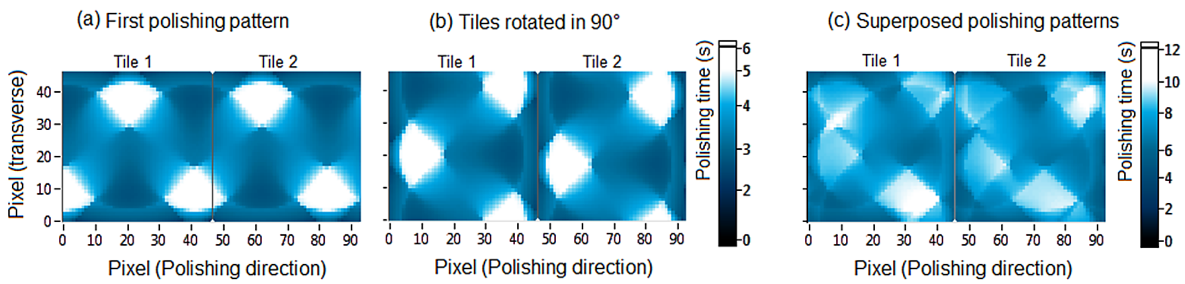

Figure 2 – Superposing of polishing pattern.

The effective polishing time E_{PT} for each surface region centred at (X_C,Y_C) is determined according to the following equation:

$$E_{PT}(X_C, Y_C) \qquad (2)$$

Where V is the forward speed and S_T is the polishing distance which, as described elsewhere[11], is given by means of Equations 3 and 4:

$$S_T = \frac{d}{dY_C}\left[\int_{Xc-R}^{Xc+R} \left| f_S - f_{OC\cup} \right| \frac{dx}{2}\right] - \frac{d}{dY_C}\left[\int_{Xc-r}^{Xc+r} \left| f_S - f_{IC\cup} \right| \frac{dx}{2}\right] -$$

$$\frac{d}{dY_C}\left[\int_{Xc-R}^{Xc+R} \left| f_S - f_{OC\cap} \right| \frac{dx}{2}\right] + \frac{d}{dY_C}\left[\int_{Xc-r}^{Xc+r} \left| f_S - f_{IC\cap} \right| \frac{dx}{2}\right] + (R - r) \qquad (3)$$

; if $Y_C \geq 0$

and:

$$S_T = \frac{d}{dY_C}\left[\int_{Xc-R}^{Xc+R}\left| f_S - f_{OC\cap}\right|\frac{dx}{2}\right] - \frac{d}{dY_C}\left[\int_{Xc-r}^{Xc+r}\left| f_S - f_{IC\cap}\right|\frac{dx}{2}\right] -$$

$$\frac{d}{dY_C}\left[\int_{Xc-R}^{Xc+R}\left| f_S - f_{OC\cup}\right|\frac{dx}{2}\right] + \frac{d}{dY_C}\left[\int_{Xc-r}^{Xc+r}\left| f_S - f_{IC\cup}\right|\frac{dx}{2}\right] - (R - r) \qquad (4)$$

; if $Y_C < 0$

where f_S stands for the sine function of the polishing trajectory. Function f_{OCU} in turn 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 centre of the polishing head.

A computational algorithm was developed using the software *LabVIEW®*, version 2010, in order to carry out all the calculations and simulations needed. The algorithm solves and presents the numerical solutions of Equations 3 and 4 throughout the complete polished surface. Results of simulations were presented by colour scale surface graphics, in which the position of each pixel is directly and univocally associated with a square region at the tile surface, 8.75 mm wide.

In addition, the following parameters were taken as constant during all the simulations: W = 47.12 $rad \cdot s^{-1}$ (450 rpm), A = 60 mm, f = 0.20 Hz, R = 230 mm, r = 110 mm, and adjacent polishing heads spaced by distance H = 550 mm. To compute the effect of kinematics, three values of forward speed were considered: V = {25, 50, 75} mm/s, yielding the following possible values for the wavelength of the polishing trajectory λ = {125, 250, 375} mm. The decision for these kinematic conditions was due to the results of previous works on kinematic optimization[2,9,11,12].

Once the expected distribution of polishing time is achieved, the corresponding polishing uniformity can be quantitatively evaluated by means of the standard deviation σ accounting for the whole polished surface. In this work, six tiles were taken for this purpose. To assure the same packing along the conveyor belt, the tiles were assumed to be square, with a nominal width of 420 mm. As presented in Figure 1, the rotation level was limited to θ = {0°, 90°, 180°, 270°}, aiming to keep a rotational symmetry.

The values of wavelength adopted in this work are not a perfect multiple of the tile length. Moreover, due to the oscillatory nature of the wavelike polishing trajectory, its relative position regarding tile boundaries will vary in time. As consequence, the overlapping of polishing patterns before and after tile rotations will change in both intensity and final pattern. Such effects were taken into account by assuming the position of the polishing trajectory to be shifted, pixel by pixel, along all the polishing direction, as explained in Figure 3. The simulations are carried out for every single shifted position, so that the corresponding curves representing the variation of uniformity (σ) according to pixel position of the wave-front were assembled for each kinematic combination (λ) and rotation angle θ.

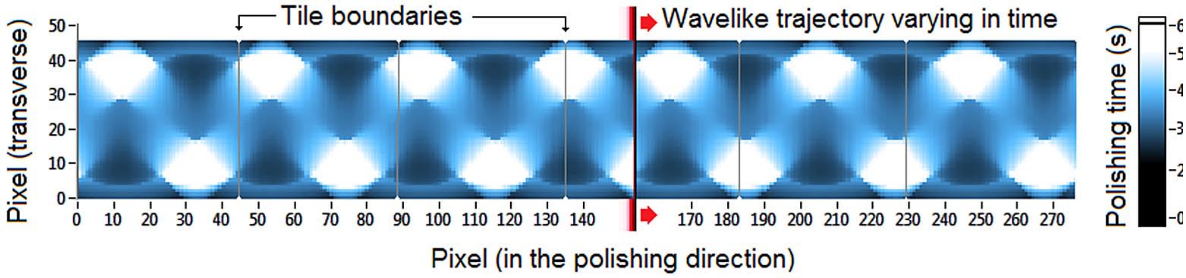

Figure 3–Wave-front varying along the polishing direction

3. SIMULATIONS

The simulated effect of a single polishing head regarding the distribution of polishing time over the surface of six tiles is presented in Figure 4a, considering at first the smallest value of the forward speed, V= 25 mm/s. The simulated results for the subsequent rotation and superposing processes are given in Figures 4b and 4c respectively. The last figure contains the work of two polishing heads, and therefore the corresponding scale of colours was set doubled.

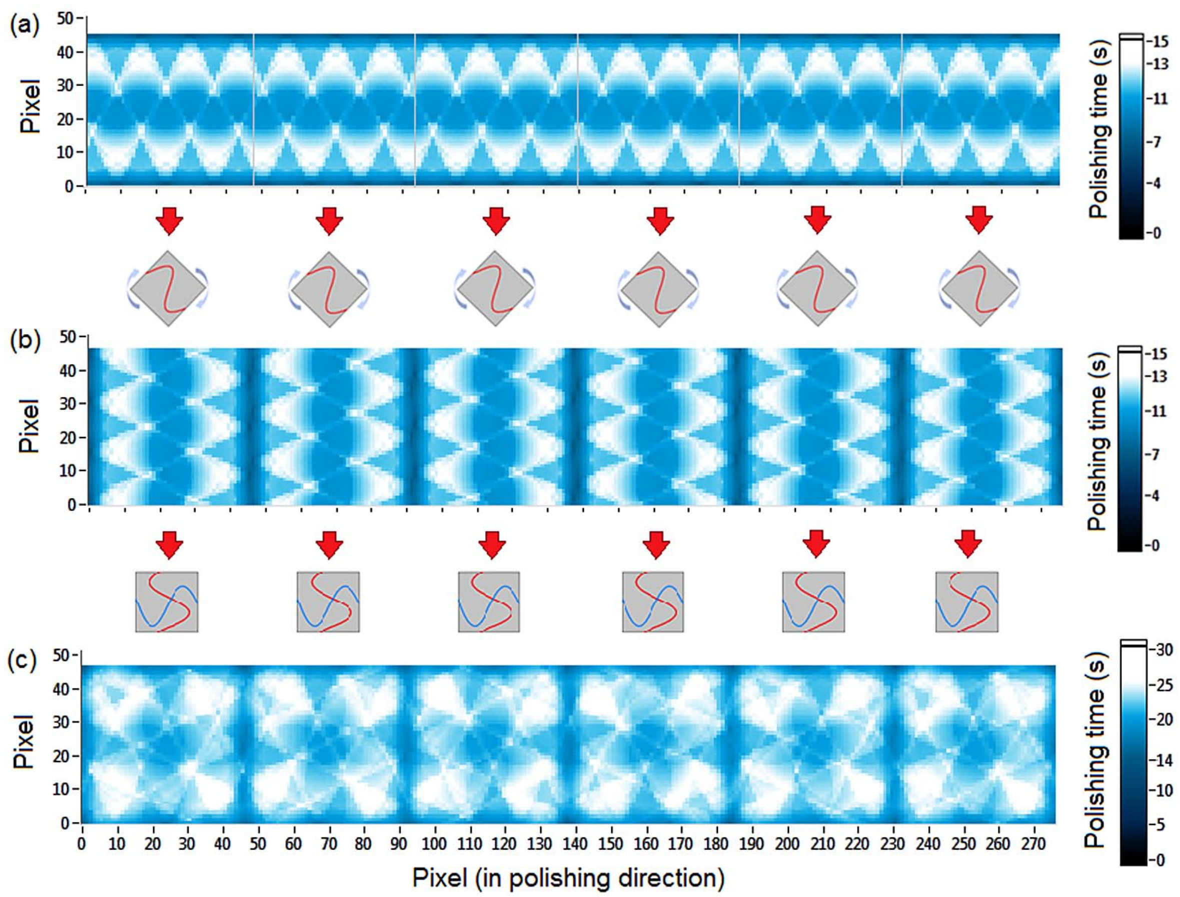

Figure 4 – Simulated polishing patterns for V= 25 mm/s. (a) Before and (b) after the tile rotation of θ = 90°, and (c) the resulting superposing of patterns.

By observing the resulting superposed pattern obtained from the simulations, an improvement in polishing uniformity seems to be achievable introducing a discrete rotation of tiles in 90°. At least in qualitative terms, the option for such extra rotation motion was able to provide a polishing pattern with less directional polishing gradients, which alone offers an important practical advantage for the posterior operation of tile setting. Nevertheless, it must be recalled that the sequence in Figure 4 refers to a stationary position of the transverse oscillation motion. As explained above, those polishing patterns vary as the wave-front advances along the polishing line.

In this sense, Figure 5 presents a quantitative analysis of the simulated polishing patterns computing all the possible wave-front positions along the polishing direction. As explained above, the polishing uniformity was represented by the standard deviation σ of the spatial distribution of polishing time, considering the surfaces of all the six tiles. The smaller is σ, the better is the polishing uniformity. Each curve included in the graph stands for a different rotation level. It should be borne in mind that the curve $\theta = 0°$ must be taken as reference for comparison purposes, as it represents a typical polishing line, in which there is no tile rotation available. Therefore, the technical viability of adopting a particular rotation level to improve the polishing pattern expected for the polished tiles becomes detectable when the corresponding curve remains long enough under the reference curve.

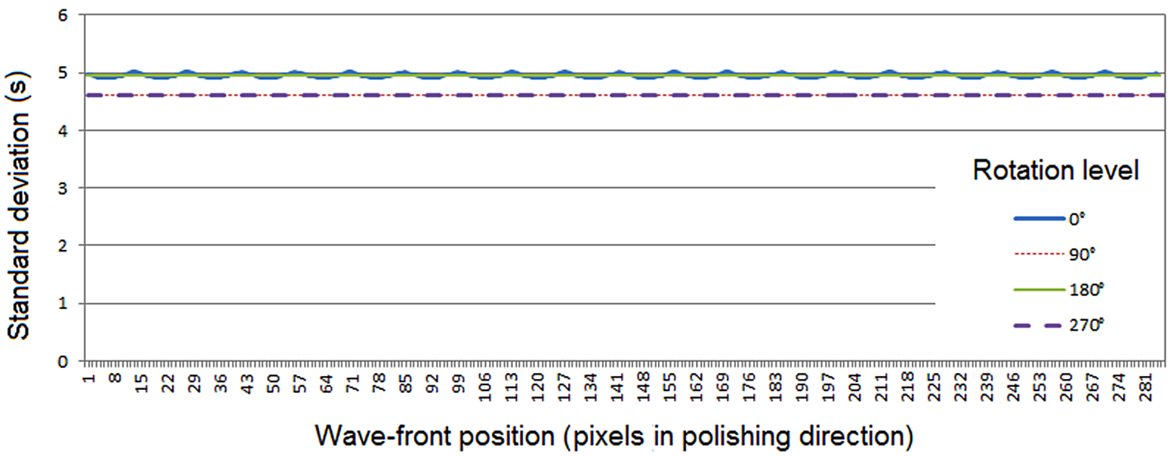

Figure 5 – Variation of polishing uniformity during the process for V = 25 mm/s

According to the graph in Figure 5, and considering the polishing parameters aforementioned, the standard deviation σ of polishing time offered by a typical polishing line varies smoothly and periodically within the range of 4.9-5.1 seconds. As could be expected, this variation has the wavelength λ defined by the ratio V/f = 125 mm (ca. 14 pixels). A tile rotation of $\theta = 180°$ may offer less variability, but no significant improvement in uniformity. In contrast, a steady value of $\sigma = 4.6$ s was calculated for a tile rotation of $\theta = 90°$ and also for $\theta = 270°$. Hence an improvement of about 8% in the polishing uniformity may be expected by adopting a rotation level of either 90° or 270°. The coincidence of both later curves means that, on average, the final pattern is the same for both counter- and clockwise rotations, as the amount of polishing time is the same above and beneath the tile centre.

Higher values of forward speeds are very attractive to the industries, as they provide a direct increase in the productivity of the polishing line. Considering then a forward speed of V = 50 mm/s, the simulated polishing pattern after the passage of a single polishing head is presented in Figure 6a. Figure 6b presents the superposed pattern assuming a tile rotation of 90°.

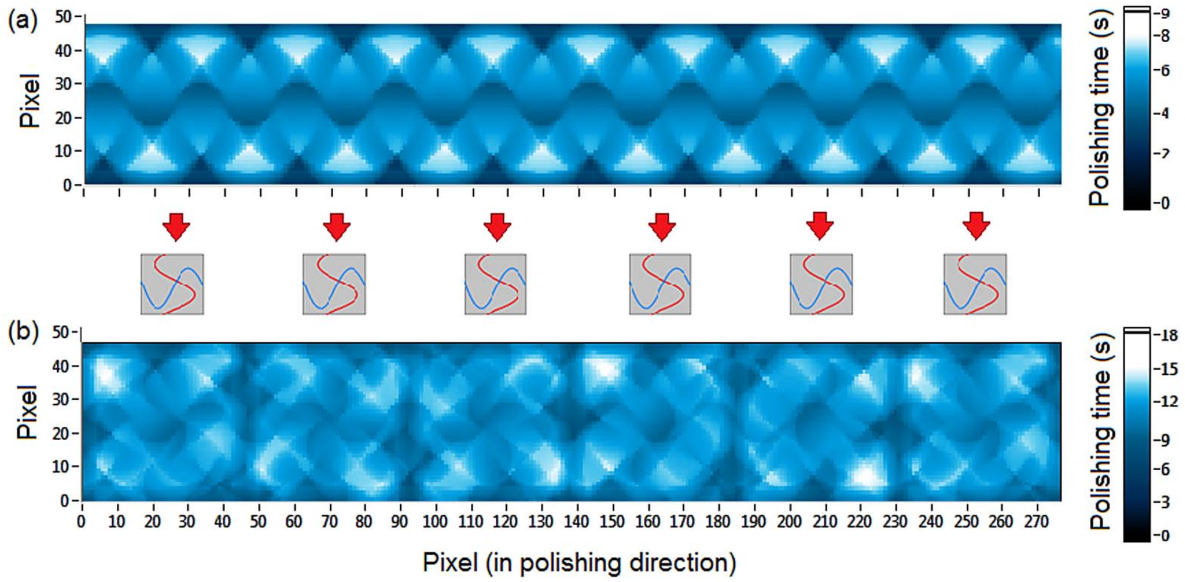

Figure 6 – Simulated polishing patterns for V= 50 mm/s, assuming (a) the passage of a single polishing head, and (b) the superposing after a rotation of 90°

As occurred at the previous graphs, the adoption of tile rotation seems to provide polishing patterns with less directional gradients. The reduction of polishing time seen in the legend highlights the trade-off existing between the increase of productivity and the decrease of time during which tiles are exposed to polishing along the conveyer belt. Moreover, with the increase of forward speed the difference in polishing patterns among the six tiles became evident. As explained before, such differences arise as the wave-front moves. Figure 7 offers a quantitative analysis regarding the behaviour of the polishing uniformity, as well as the final effect of the four levels of tile rotation considered.

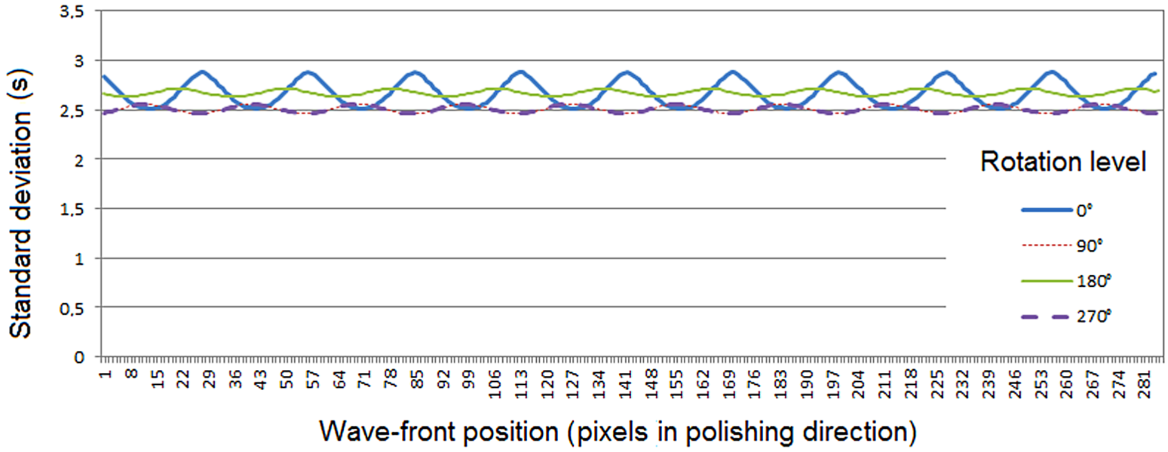

Figure 7 – Variation of polishing uniformity during the process for V = 50 mm/s

A periodical variation of polishing uniformity (σ) was also found to occur for V = 50 mm/s, but this time within a broader range of 2.5-2.9 seconds. As before, all variations followed the same wavelength λ given by V/f = 250 mm (ca. 28 pixels), and a smaller variation range could be achieved by adopting θ= 180°, but still with only point improvements in polishing uniformity. A slight variation has also occurred in both curves θ = 90° and 270°, with σ of about 2.5 s. In view of all those variations, the improvement in uniformity is not constant along the production line, but varies from 0% up to 10%. The simulated polishing patterns considering the forward speed V = 75 mm/s are presented in Figure 8.

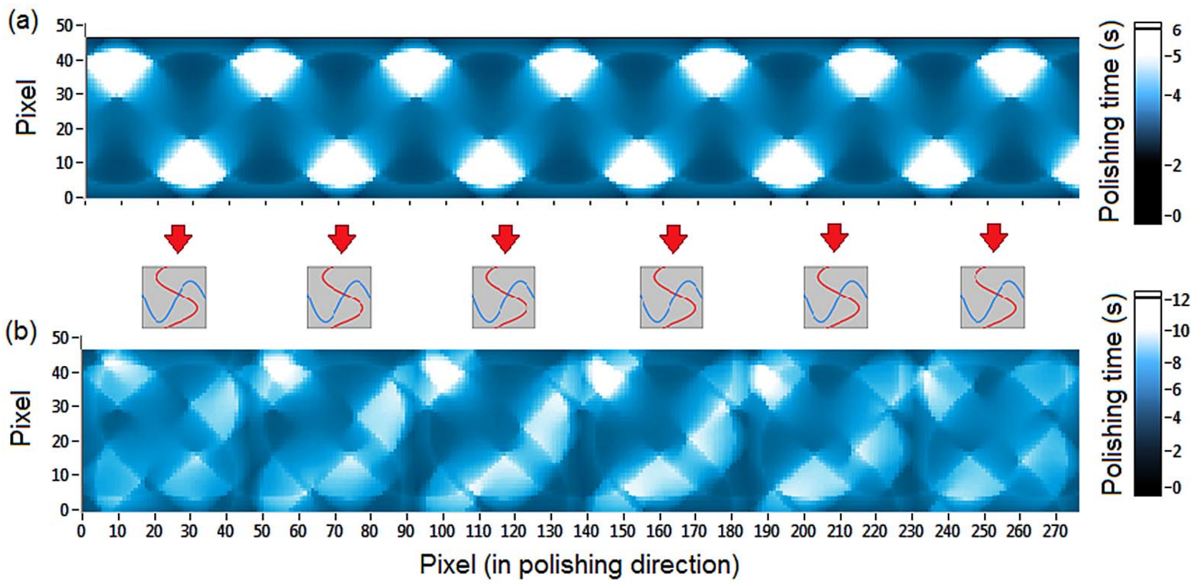

Figure 8 – Simulated polishing patterns for V= 75 mm/s, assuming (a) the passage of a single polishing head, and (b) the superposing after a rotation of 90°

A comparison between Figures 8a and 8b do not indicate any remarkable improvements regarding polishing uniformity. The quantitative evaluation of the final effect can be seen in Figure 9. At a first glance, no permanent gain of uniformity can be expected by rotating the tiles in any one of the levels considered. On average, no significant improvement could be achieved either.

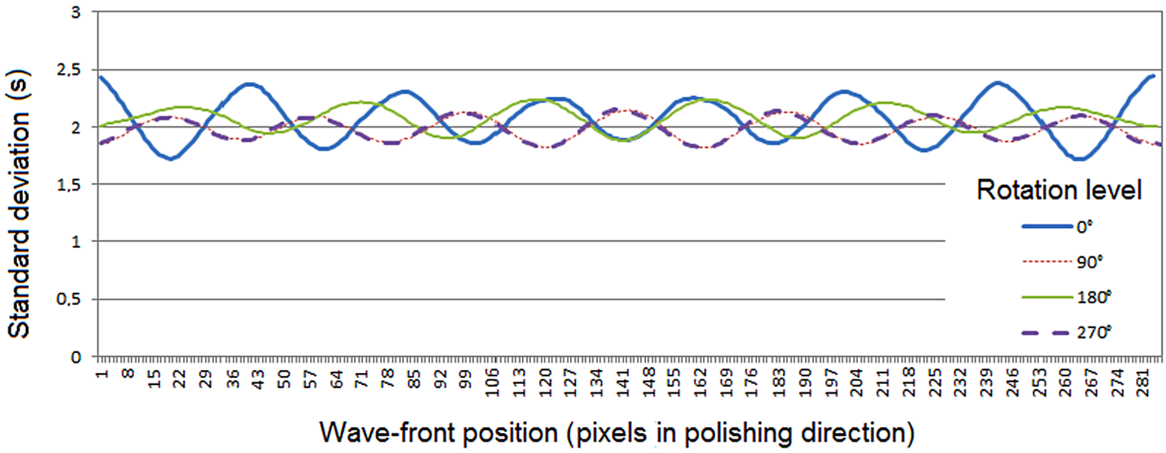

Figure 9 – Variation of polishing uniformity during the process for V = 75 mm/s

The corresponding polishing trajectory has a wavelength λ = 375 mm. This value may cause the polishing patterns to vary more intensively along the process, but as can be observed in Figure 8b, such variations will only become evident by confronting tiles from much spaced positions, and not within adjacent tiles. Despite causing higher productivities, speeding up the forward motion of the conveyer belt restrains the viability of adopting the extra rotation motion proposed in this work.

4. CONCLUSIONS

By observing all the resulting polishing patterns presented by the simulations, significant improvements in polishing uniformity can be achieved by introducing a discrete rotation of tiles in either 90° or 270°. In qualitative terms, such extra rotation motion was able to provided polishing pattern with less directional polishing gradients.

The polishing uniformity offered by a typical polishing line was found to vary smoothly and periodically as the wave-front advances along the polishing line. For tile rotations of 90° and 270°, an improvement of about 8% in the final polishing uniformity may be expected by adopting a forward speed of 25 mm/s. This level of improvement was stable during the polishing process, and as the amount of polishing time is the same above and beneath the tile centre, the effect was the same for both counter- and clockwise rotations.

Despite the convenience of using higher values of forward speeds, as they provide a direct increase in the productivity, the reduction of polishing time during which tiles are exposed to polishing along the conveyer belt revealed a trade-off existing between productivity and polishing uniformity, as the differences in polishing patterns among the six tiles became evident.

Thus, considering higher forward speeds, only point improvements in polishing uniformity were found to occur. The improvement in uniformity is not constant along the production line, but varies from 10% up to no remarkable improvements at all.

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