COMPUTATIONAL SIMULATION OF THE POLISHING PROCESS OF PORCELAIN STONEWARE TILES

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ABSTRACT

A high level of glossiness on the floor tile surface is highly appreciated by customers, despite the massive costs generated due to the polishing step. In the case of porcelain stoneware tiles, costs often stand for 30% of final cost. Nevertheless, this cost can be reduced by optimizing either the scratching phenomena or the polishing kinematics, which is the subject of the present work. Kinematics optimization deals with all the available motion of the polishing machine, which in turn governs the abrasive path over the tile surface. This path can be analytically determined so that a model was elaborated to predict the trajectory of the abrasive particles for each instant. The goal of this work is to understand the glossiness distribution over the tile surface as function of the polishing kinematics. A computational modelling of an industrial polishing line was carried out. Input variables were those parameters commonly available at industries. The polishing enhancement could be presented, in real time, by intensity colour graphics. Each pixel in those graphics corresponds to a small portion of the real tile surface. In order to check the model adequacy the values predicted were then compared with those attained in literature, as well as with some real values of glossiness, measured in an industrial polishing line. Good agreement with the literature was achieved so that the software developed can be surely used as guideline for further studies on gloss enhancement in ceramic tile industries.

1. INTRODUCTION

The polishing process has become quite common in stoneware floor tile production. This is due to the exceptional resulting aesthetic effect. Nevertheless, the industrial polishing process usually relies on trial and error, or, in spite of the systemic character inherent of abrasive process[1], on knowledge achieved from other materials such as natural stones, e.g. marble or granite[2,3,4].

The necessity of researches on polishing process, with either a scientific or technological point of view, is highlighted by considering the high operation costs involved. The polishing step stands for 30-40 % of final cost[5,7]. On the other hand, Hutchings et al[5,6] related the existence of several opportunities to reduce costs and to improve the final quality of the porcelain stoneware tile production. The cost rises from the high consumption of water (0,02-0,04 m^3), abrasive tools (0,5-0,6 kg) per m^2, and also considering the low energetic efficiency and poor capability of controlling the final quality actually associated with these industries[5].

Many fruitful works about simulating polishing process[2,3,5,6], or even on kinematics optimization of lapping machines[8,9], are available in literature for glassy materials. In view of this, the present work intends to analyze the kinematics involved in the porcelain stoneware tile polishing, attempting to furnish further data on this subject, including the development of a software that simulates the polishing process according to the operational parameters usually available by industries.

1.1. POLISHING PROCESS OF PORCELAIN STONEWARE TILES

The low level of water absorption, high hardness and high flexural modulus, allow porcelain stoneware tiles to be used under severe conditions even without the glaze protection. Nevertheless, a glossy proper surface seems to be very appreciated by the general customers, so that these tiles are often submitted to a polishing line.

Actually, polishing is a common term used in several ways, always with the connotation of increasing the gloss of a given surface. However, from a technical point of view, polishing is a machining process with almost no material removal, promoted by free abrasive particles, whose shapes are not individually defined. Besides, the material to support these particles must be quite soft, like cotton or leather, since the goal is to confer glossiness to the surface, instead of shaping it. The softness of the support causes the abrasives to scratch the surface with a minimal penetration, conferring hence the desired glossy appearance.

It must be mentioned that the highest glossiness that can be achieved by an industrial polishing line is limited by the stoneware tile microstructure[3]. Thus, even if an optimum polishing condition is adopted, the final level of gloss, as well as its spatial homogeneity, could be less than the expected.

In the industries more than thirty polishing heads can be arranged in sequence to comprise an industrial polishing line. In each polishing machine there is a disk made up of a horizontal spinning plate in which six abrasive blocks are coupled keeping a radial symmetry. These abrasive blocks, in turn, consist of silicon carbide particles embedded by a magnesium oxychloride cement matrix[7].

During polishing some regions over the tile surface are favoured on material removal. For simple polishing machines, whose available movements are the forward motion of the production line and the rotation of the abrasive disk, the tile centre undergoes a gentler polishing than the tile boundary[5].

For modern polishing machines, in addition to those two movements available at the simple polishing machines, there is also a lateral oscillation of the abrasive disk, so that the final movement can be exemplified in Figure 1. The favouring polishing for modern polishing machines was lacking in the literature surveyed. However, a zigzag overlapping was found to occur for such polishing machines, as indicated in Figure 2 for a single abrasive.

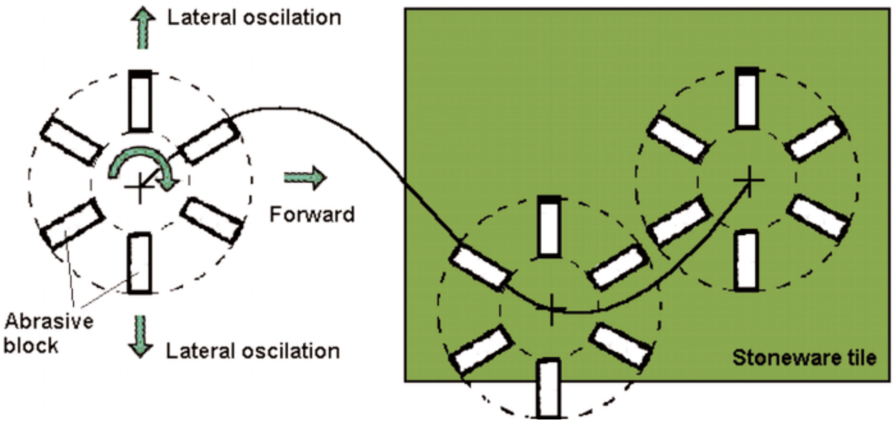

Figure 1. Plan view of the relative motion of the abrasive disk

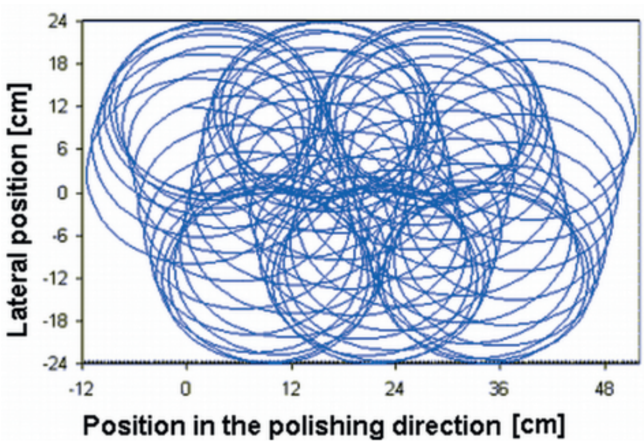

Figure 2. Trajectory of a single abrasive along the polishing line

Figure 2 actually presents the multiples scratches caused by a single abrasive during the porcelain stoneware polishing. This graphic was analytically determined using parameters typically used in the State of Santa Catarina - Brazil, which has a world level participation in the ceramic tiles market[10].

Kinematics optimization mainly deals with the available motion of the polishing machine, which in turn rules the abrasive trajectory over the tile surface. Since this trajectory can be analytically determined, the position of the abrasive particles for each instant (t [s]) can be hence predicted, depending on the following operational parameters: rotation of the abrasive disk (w [rad/s]), forwarding speed of the polishing line (V [m/s]), frequency of the lateral oscillation (f [s^{-1}]), lateral oscillation amplitude (A [m]), and the distance from the chosen particle to the centre of the abrasive disk (r [m]).

Admitting an axis reference system in which the unitary vector $\hat{\mathbf{i}}$ is parallel to the forward direction of the tile, and that the unitary vector $\hat{\mathbf{j}}$ stands for the direction of the lateral oscillation, i.e., perpendicular and belonging to the same plane that vector $\hat{\mathbf{i}}$, the displacement vector ($\vec{D}$) of the abrasive at instant t_0 results from the contribution of each source of motion: forwarding of the tile ($\vec{D}$E), rotation ($\vec{D}$R) and lateral oscillation of the abrasive disk ($\vec{D}$OL). As vectors this can be expressed as:

$$\vec{D} = f(\mathrm{w},\mathrm{r},\mathrm{A},\mathrm{f},\mathrm{V},\mathrm{t}) = \vec{D}E + \vec{D}R + \vec{D}OL \qquad (1)$$

This results in the following:

$$\vec{D} = \{\mathrm{V}\times\mathrm{t} + \mathrm{r}\times\cos(\mathrm{w}\times\mathrm{t})\}\hat{\mathrm{i}} + \left\{ \mathrm{r}\times\mathrm{sen}(\mathrm{w}\times\mathrm{t}) + \frac{\mathrm{A}}{2}\times sen(2\times\partial\times\mathrm{f}\times\mathrm{t})\right\}\hat{\mathrm{j}} \qquad (2)$$

Furthers details on the kinematic parameters involved in the polishing process, such as scratching speed and radii are available in the literature[11].

2. EXPERIMENTAL

The equations presented above were used in a simulation software, made in *LabVIEW* 5.1®, in order to aid the understanding of the glossiness enhancement during the polishing process. In the software the cumulative number of times that any abrasive had touched each portion of the stoneware surface is recorded along time and then presented by a colour intensity chart.

The friendly interface of the simulation software can be seen in Figure 3. Five polishing heads can be seen in the graphic. Users must act on the proper knobs to select values for those operational parameters, inside a range commonly adopted in industries. Afterwards, some input boxes must be filled with the tile size, lateral oscillation amplitude, inner and outer abrasive disk radii, and even the graphic resolution.

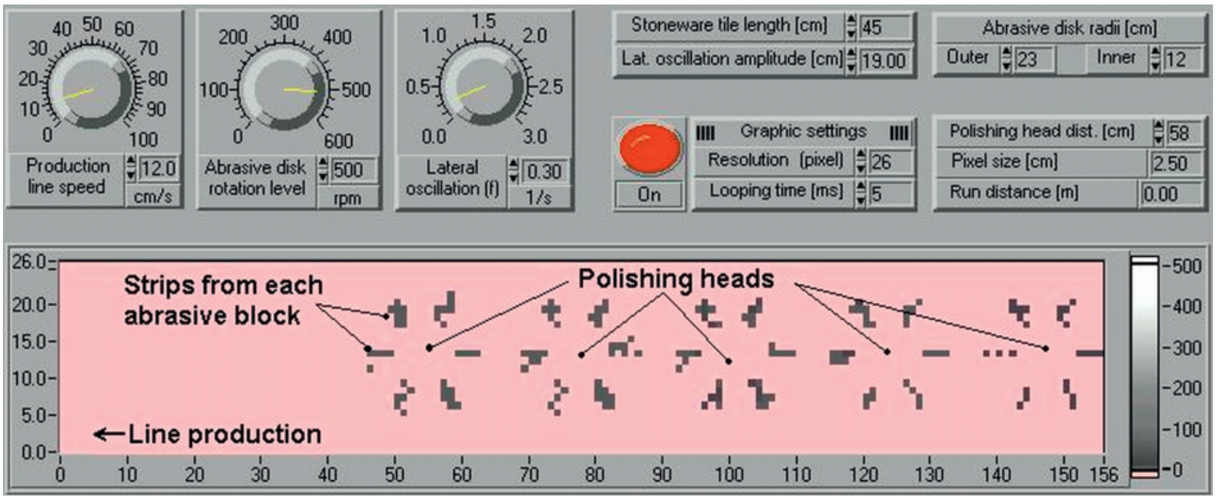

Figure 3. Software interface: simulations according to the operational parameters set by the user

The graphic resolution means the number of pixels to fit the graphic. Each pixel in the intensity graphic is univocally associated with a small real area at the tile surface. As consequence, the higher the resolution, the smaller is the corresponded real area.

In this work a resolution of 26 was picked so that each pixel stands for a square region of about 25 x 25 mm^2 of the tile surface. Figure shows the pixel mapping along the porcelain stoneware tile surface.

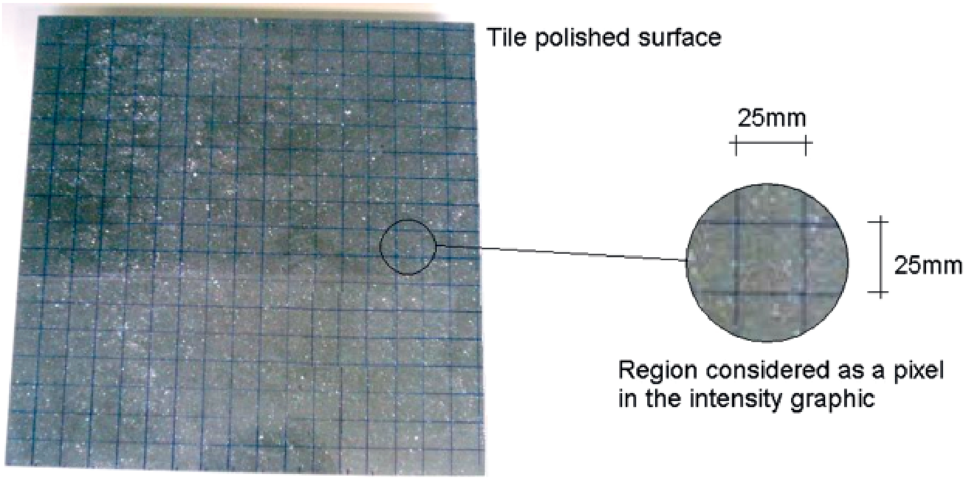

Figure 4. Pixel mapping

Thus, while the program is running, the graphic background undergoes a continuous colour change throughout the abrasive path. This enhancement of the number of times that abrasives had touched a given region was used by Hutchings et al to explain the gloss distribution found in stoneware tiles polished with simple polishing machines, i.e., using no lateral oscillation[5,6].

2.1. GLOSS AND NUMBER OF CONTACTS CORRELATION

The gloss value announced by the software underlies on the premise that the gloss level of a small enough surface portion is somehow proportional to the number of time abrasives had touched this portion. Actually such premise was already used to explain the gloss distribution found in stoneware tiles polished with simple polishing machines, i.e., using no lateral oscillation[5,6].

However, for modern polishing machines such proportionality becomes greatly difficult to assess. In the present work this difficulty was bypassed using the gloss-gaining curve along the polishing steps, which was furnished by literature[12].

Figure 5 summarizes the gloss-gaining curve, as well as the data assessing. Hutchings et al[6] and Sánchez et al[12] reported that the gloss gaining really happens at the ending steps of the polishing process. Actually the gloss gaining can be ascribed to an even more reduced number of polishing steps. In this works only the five steps depicted in Figure 5 were considered in order to decrease the computational work. Such steps were picked due to their highest average inclination, which was measured by the graphics points captured with the aid of the software AutoCAD 2000®.

The highest number of contacts found in the polishing simulation was stated as the upper limit of 80% of gloss. An initial gloss was adopted so that the range of gloss could vary from 20% up to 80% according to the number of abrasive contacts the pixel had undergone. The importance of steps I, II, III, IV and V can be highlighted considering that the gloss increases from about 20% to almost 80% while inside of them.

Tile Number	Grit size D_{50}	Estimated* gloss [%]	Average* inclination
44	38.5 - 44.5	9	1.29
52	17.3	19	6.85
54	9.3	33	9.9
56	9.3	53	4.55
58	8.5	62	2.7
60	8,5	67	1.41
68	< 8	79	0.38
72	-	80	-

* Withdrawn from the adjacent graphic

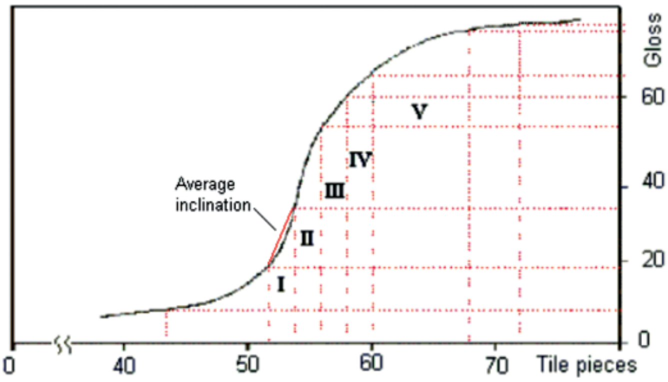

Figure 5. Gloss-gaining of the porcelain stone tile presented by Sanchez et al[12]

In order to follow the experimental tendency, the average inclinations of the gloss-gaining curve for each polishing heads were used as guideline for establishing the correlation between the number of abrasive contacts and the final gloss of a given stoneware tile.

2.2. MODEL CHECKING

The validity of the developed software was firstly tested for simple polishing machines. Since the number of contacts for a cross section of a polished tile was promptly furnished by literature[5,6], the model checking was made by comparing the behaviour of both model and literature curve.

In addition, the software was checked by comparing the predicted gloss with the measured values of four real tiles taken in the polishing line of the Cerâmica Portobello S.A. Company. These four samples were polished with known condition and collected just in sequence.

Gloss measurement was carried out for each 25x25mm^2 of the tile surface, for each sample. All the measures were made by the same operator, using a gloss checker Horiba model IG-320.

3. RESULTS AND DISCUSSION

The software results for a null value of lateral oscillation frequency, i.e. for a simple polishing line, are exposed in Figure 6. Uncoloured pixels are just due to the numeric rounding process, and it can be reduced either by increasing the graphic resolution or decreasing the time increment. Obviously in both cases more computational resources would be required.

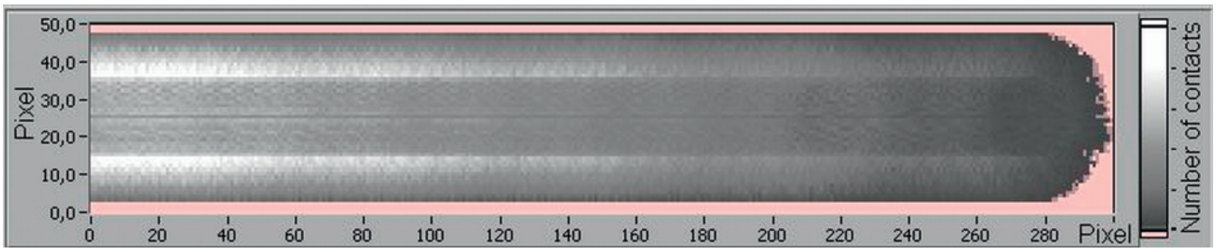

Figure 6. Polishing simulation for a simple polishing machine

Contacts generation can be seen as slightly circular shadows in the position of each polishing head, especially for the first ones. The contact distribution was promptly revealed after the first polishing head. The pattern was enhanced thereafter by the four others polishing heads. The darker pixels in the tile centre are due to the lacking of abrasives in the most inner region of the abrasive disk. The pattern presented by the intensity graphic was quite close to those available in literature[5,6], as suggested by comparing both typical contact profiles presented in Figure 7. The comparison was made directly with the number of contacts, and for one polishing head only.

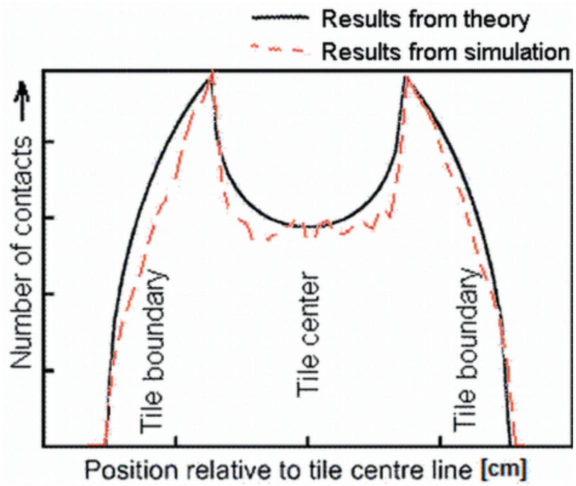

Figure 7. Contacts profiles for simple polishing machines from simulated and literature data[6]

The relative minimum offered by the simple polishing machines is undesirable since it requires extra polishing resources for leading the tile centre to a minimum gloss level, whereas some other regions are overworked, which in fact lead to the extra abrasive consumption rather than aesthetic value.

In view of this, lateral oscillation can be seen as an extra device designed to reduce such biased gloss enhancement. The polishing favouring becomes gentler as the disk regions without abrasive are no longer fixed. However, on the other hand two others operational parameters are introduced, making the polishing kinematics more complicated to optimize, especially by trial and error. Besides, another kind of overworking starts to occur, as presented in Figure 8.

The wave movement accomplished by the abrasive disk leads to the zigzag pattern previously mentioned for a single abrasive. The typical contact profiles found for the modern polishing machines are presented in Figures 8 a-c, taken from different positions of the production line, in order to prove the zigzag pattern. It was considered a lateral oscillation amplitude and frequency of 0.12 m and 0.34 s^{-1} and a forward speed of 6 cms^{-1}.

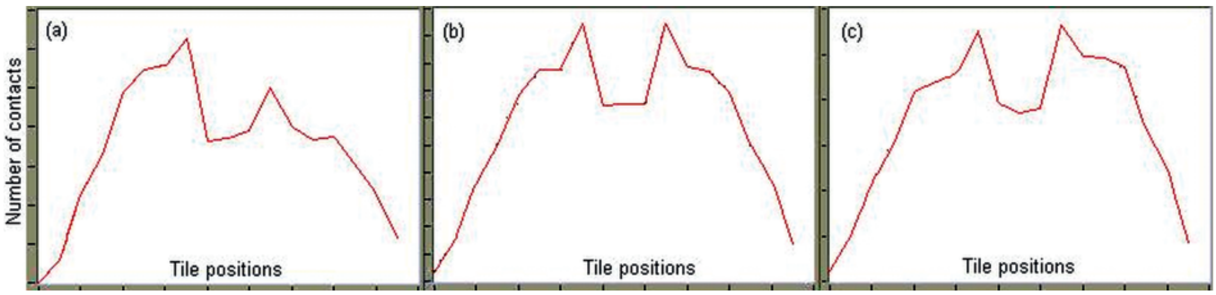

Figure 8. Contact profiles simulation using modern polishing machines at three successive polishing times

Regarding the distribution of abrasive contacts, one might notice that in this case the polishing profiles from modern polishing machines were found to be quite better than those produced by simple polishing heads, despite the zigzag favouring.

Figure 9 a presents a simulation of a polishing line under the same polishing conditions mentioned previously. Still in Figure 9 a comparison between results from the (b) simulation software and (c) measured values collect over the surface of four real tiles right after the polishing process can also be seen.

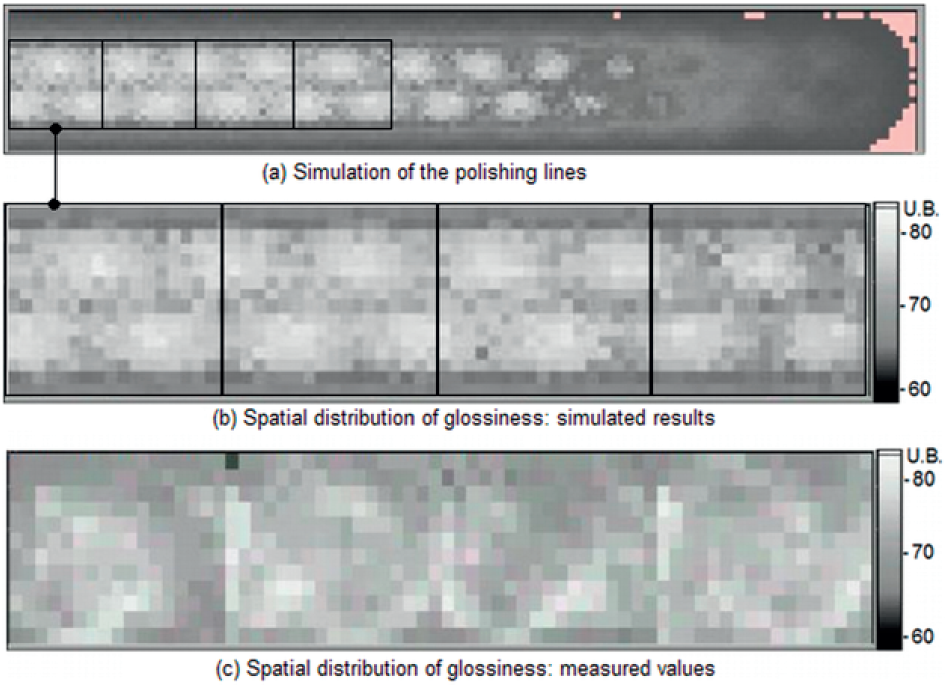

Figure 9. Comparison between simulated and measured values of glossiness

As can be seen in Figure 9b, the simulated results have promptly revealed a zigzag pattern to represent the final glossiness pattern of the polished tiles. Regarding the empirical results, a coarse zigzag pattern can be recognized at some extend in the Figure 9c. This fact can suggest a reasonable agreement between the simulated and measured values. However, the likeness between both results was limited to this. This can be explained considering the limited source of variable adopted, as well as the simplified model to relate abrasive contacts with gloss-gaining during polishing. In both cases, further studies are needed so that a better comprehensive agreement between simulated and measured values could be reached.

4. CONCLUSIONS

The kinematics involved in the polishing process can simulated using the isoparametric equations exposed. As consequence, a computational simulation of porcelain stoneware tile polishing could be developed and had exhibited good agreement with the literature surveyed regarding the number of abrasive contacts.

For simple polishing heads, were no lateral oscillation is available, the polishing simulation carried out using the operational parameters typically adopted in industries reaffirmed the biased gloss enhancement due to the fixed position of the polishing head and to the lacking of abrasives in its centre.

For modern polishing machines the profile of abrasive contacts furnished by the software suggests a more efficient availability of kinematics, in which a much gentler favouring tends to occur. On the other hand, a zigzag overlapping was revealed. The model had some credits since it displayed a reasonable agreement with the empirical values. The lacking of a strong agreement does not invalidate to program but only indicates that the inputs variables were not enough. It also indicates that the simplified model to convert abrasive contacts into gloss-gaining must be improved.

In view of this, further studies are needed either to compute others inputs variables or to provide new underlying for the correlation between the abrasive contacts and gloss gaining.

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