G Model
CIRPJ-355; No. of Pages 9
ARTICLE IN PRESS
CIRP Journal of Manufacturing Science and Technology xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
CIRP Journal of Manufacturing Science and Technology
journal homepage: www.elsevier.com/locate/cirpj

Experimental evaluation of on-line discrete tile rotations in the polishing process of ceramic tiles

Fábio J.P. Sousa [a,*], Jan C. Aurich [a], Rubens Maribondo do Nascimento [b], Carlos Alberto Paskocimas [b], Danieli Tartas [c]

[a] FBK Department of Mechanical and Process Engineering, Institute for Manufacturing Technology and Production Systems, University of Kaiserslautern, TU-KL PO Box 3049, D-67653, Kaiserslautern, Germany
[b] Graduation Program in Materials Science and Engineering, PPGCEM Department of Materials Engineering, Federal University of Rio Grande do Norte, UFRN PO Box 1524, cCEP 59078-900, Natal, RN, Brazil
[c] Department of Production and Systems Engineering, EPS Federal University of Santa Catarina, UFSC, PO Box 476, CEP 88040-900, Florianópolis, SC, Brazil

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Polishing
Porcelain
Grinding
Simulation
Optical materials/properties

ABSTRACT

This work evaluates a new kinematics for the industrial polishing process of porcelain stoneware tile. In addition to the typical motions available in industrial polishing trains, each ceramic tile undergoes a discrete rotation during the polishing process, so that more uniform gloss distributions can be obtained without radical changes in the industries facilities. The consequences of this alternative were quantitatively analyzed. A customized computer numeric control (CNC)-machine was used for obtaining the corresponding experimental results. A reasonable linear correlation between theoretical and experimental gains in uniformity was verified, making viable the use of computational simulations to assist the on-line decisions during the tile production.

Introduction

The kinematics adopted in the polishing train is a key feature for defining the final glossiness pattern to be expected over the surface of the polished tiles [1]. Each polishing train offers a continuous spectrum of kinematic possibilities, according to the set of different available motions. Besides some geometric parameters, the option for a particular kinematics defines how often each region of the tile surface is subjected to the action of the abrasives during polishing [2].

Modern polishing trains possess a kinematics that basically results from different components [3], which are: (1) rotation W (rad s^{-1}) of the abrasive blocks (fickerts) around the center of each polishing head, (2) transverse oscillation of the polishing head, with amplitude A (mm) and frequency f (s^{-1}), and (3) forward motion V (mm s^{-1}) of the conveyer belt, which directly defines the productivity of the polishing process.

Both forward and transverse oscillation motions are accomplished at the same time, so that each polishing head performs a sinusoidal trajectory relative to the tile surface. As result, an undesired zigzag pattern of glossiness, known as "polishing shadows", are sometimes observed on the polished surfaces [1]. However, due to the fixed alignment of the tiles on the conveyer belt, the variability of gloss tends to be more intense along the polishing direction (defined by the forward motion). In addition, the lack of abrasives in the center of the polishing heads leads to further directional gradients [4].

According to previous works [6], the aforementioned defects can be partially mitigated by providing a convenient overlapping of those wavelike trajectories. As presented in Fig. 1, when adjacent tiles undergo a multiple of 90°-rotation inside the polishing train, several new alignments become possible. As consequence, a more uniform distribution of glossiness over the polished surface can be expected. Such increasing in polishing uniformity represents not only an advantage in terms of aesthetic effects, but also in terms of process efficiency.

The wavelike curves represent the sinusoidal trajectory of the center of the polishing heads over the tile surface. After being polished by the first polishing head, the tiles are ready to be conveniently rotated using discrete values of angles, so that next polishing heads can find different previous polishing patterns to overlap with. The term discrete is used to point out that the rotation motion can only assumed values multiples of 90°. Intermediary values are not allowed due to the underuse of the

* Corresponding author.
E-mail address: fabio.sousa@mv.uni-kl.de (Fábio J.P. Sousa).

http://dx.doi.org/10.1016/j.cirpj.2016.04.001
1755-5817/© 2016 CIRP.

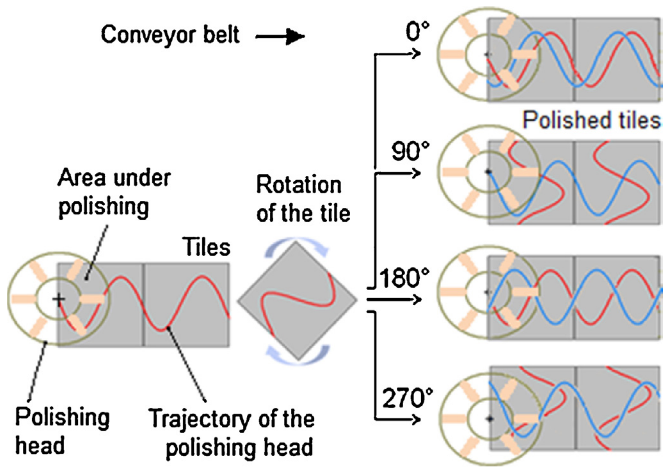

Fig. 1. Rotation of the tiles inside the polishing train and the resulting overlapping.

conveyer belt, as well as to avoid abrupt re-entrances of the fickerts on the tile surface.

In this investigation, the total time in seconds during which a given region of the tile surface effectively remains exposed to abrasive contacts under the polishing heads is referred as time of effective polishing (TEP) to be distinguished from the time required for the polishing process. The latter simply represents the time during which a particular region remains being driven along the conveyer belt, whereas the former takes into account that the polishing heads cannot cover the entire tile surface incessantly, because of the transverse oscillation motion, its circular shape, and the lack of abrasives in its center. Therefore, the TEP can be seen as the effective part of the total polishing time. Fig. 2 provides a better understanding of these two terms, including a typical gloss-gaining curve found in literature [7]. An abrasive contact is considered to occur every time an abrasive particle scratches a given region of the tile surface.

In a microscopic point of view, the evolution of gloss results from the multiple abrasive contacts accumulated during the polishing time. As seen in Fig. 2, the resulting evolution of glossiness has an asymptotic behavior, which is very well described and modeled by Hutchings [8]. In contrast, the relationships among polishing time, TEP, and number of abrasive contacts are all linear.

In quantitative terms, significant improvements in polishing uniformity could be provided by such extra rotation motion, specially using rotation levels of either 90° or 270° (or 90° clockwise). According to some simulated results, the improvements in uniformity were supposed to vary from 10% up to no remarkable improvements at all [6], depending on the kinematics and on the tile position along the polishing train.

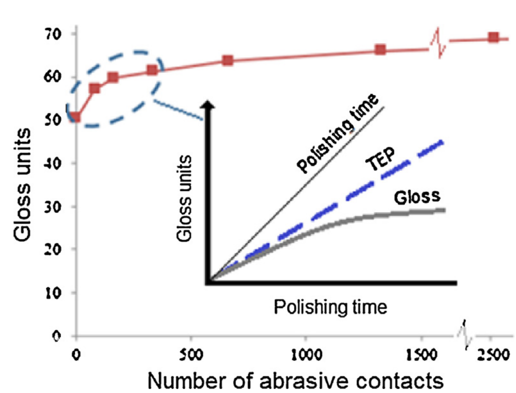

Fig. 2. Evolution of TEP and gloss during the polishing process. Adapted from Matsunaga et al. [7].

However, the simulations previously performed were exclusively focused on theoretical limits, so that no experimental results were presented. Such lack of experiments becomes more pronounced when considering the well-known nonlinearity observed between the polishing time and the evolution of gloss during the polishing process [7–10], previously exemplified in Fig. 2.

Bearing the aforementioned concepts in mind, the main purpose of this work is to provide an experimental evaluation of the effect of using discrete tile rotations during the polishing process of porcelain stoneware tiles. Besides encouraging the implementation of this extra rotation motion in new polishing trains, this evaluation is also devised to check applicability of kinematic simulations in estimating the final polishing patterns based on TEP distributions.

Theoretical considerations

A typical wavelike polishing pattern left after the passage of a single polishing head is given in Fig. 3aa, based on simulated results for only two adjacent tiles [6]. The scale of color used in the graphs refers to the TEP, which as explained previously, is the time in seconds during which each region over the tile surface has effectively suffered the polishing process. The value of TEP for each single surface region is described in detail elsewhere [2]. After the passage of successive polishing heads, such polishing gradients may fade away or even be enhanced according to the overlapping degree. An example of such overlapping is presented in Fig. 3.

Still in Fig. 3, it is essential to notice that the wavelengths of the polishing trajectory are only rarely a perfect multiple of the tile length. As consequence, the overlapping of polishing patterns before and after tile rotations will continuously vary between adjacent tiles and also along the time, as detailed in Fig. 3d and 3e. Each picture element (pixel) of the graph represents a defined region of 5×5 mm^2 on the tile surface.

The effect of such continuous variation was simulated by admitting the polishing trajectories to be shifted, pixel by pixel, and considering arbitrary origins, along the polishing direction (Fig. 4). The shifted distances were termed α and β. The former is the shift distance right before the tile rotation, whereas the latter is the distance right after it. In other words, α and β are mathematical artifacts devised to enable the simulation of all possible overlapping conditions between two consecutive polishing heads.

By considering all possible combinations of α and β, a quantitative analysis of the resulting polishing patterns were carried out and graphically presented as a function of these two variables. The homogeneity of each polishing pattern was quantified by the standard deviation of the spatial distribution of TEP, taking into account the entire region of the tile surface. Such standard deviation was represented by σ. The resulting 3D surface plot is presented in Fig. 5. Noteworthy is that the scale of color in graphs of Figs. 3 and 4 represents the TEP, whereas in Fig. 5, it represents the degree of polishing homogeneity. The smaller is σ, the higher is the polishing uniformity.

Due to the periodicity of the wavelike polishing trajectory, the same level of uniformity can be achieved by periodical combinations of α and β, as observed in the figure. As described in the next section, results from this 3D surface plot were used to identify the most promising polishing patterns to be experimentally investigated.

Method

To evaluate the impact of introducing a discrete tile rotation inside industrial polishing trains, the difference of uniformity between tiles processed with and without the tile rotation motion