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Journal of the European Ceramic Society 25 (2005) 3151–3156

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Analysis and laboratory simulation of an industrial polishing process for porcelain ceramic tiles

I.M. Hutchings[a,*], K. Adachi[a], Y. Xu[a], E. Sánchez[b], M.J. Ibáñez[b], M.F. Quereda[b]

[a] *Department of Engineering, Institute for Manufacturing, University of Cambridge, Mill Lane, Cambridge CB21RX, UK*
[b] *Instituto de Tecnología Cerámica, Universitat Jaume I, Castellón, Spain*

Received 18 May 2004; received in revised form 2 July 2004; accepted 10 July 2004
Available online 11 September 2004

Abstract

This paper reports the design and initial tests of a laboratory-scale tribometer to simulate the development of surface finish (roughness and optical gloss) in the industrial polishing process for porcelain ceramic tiles. The mechanical conditions in a typical industrial polishing process have been analysed and the results used to define the conditions to be reproduced in a laboratory simulation. The tribometer allows the relative sliding speed and contact pressure between the abrasive tool and the tile to be controlled. Measurements can be made of changes in roughness and gloss, as well as of the rate of material removal from the tile and from the tool. The evolution of surface roughness and optical gloss of porcelain ceramic tiles has been studied, with a succession of different abrasive tools. These results have been compared with data gathered from an industrial polishing line with a similar sequence of abrasive sizes, and show that the tribometer reproduces the important features of the process well. Surface roughness and gloss are two important variables to assess the final tile properties and also represent the most useful measures of quality at different stages in the evolution of the final polished surface.

Keywords: Ceramic; Vitreous ceramic; Tile; Polishing

1. Introduction

Highly polished, unglazed porcelain ceramic tiles are being increasingly used in high-specification architectural applications as they show excellent performance, including good mechanical strength and chemical, stain and frost resistance, as well as aesthetic advantages over glazed ceramic tiles.[1] Polishing forms the final operation during manufacturing, following surface planing and flattening, and more than 40% of the total cost of the product is attributable to the grinding and polishing process. Typical commercial specifications require a final surface gloss level of 65–70%. Current industrial polishing processes are considered to be inefficient, with unnecessarily high wear of the grinding/polishing tools, high energy consumption, the production of large amounts of polishing waste, excessive numbers of rejected products and poor control of product quality. Typically 0.5 to 0.6 kg of cement-matrix polishing tool material is consumed per square metre of final polished product. There are thus clear opportunities to reduce the cost and improve the quality of the final product, through improved understanding of the polishing process. Previous studies of tile polishing have been carried out on an industrial scale, with the disadvantage of limited control of the test conditions,[2–5] or with a manually-controlled polishing machine with poor control of applied load.[6,7] Studies have also been made of the related problem of the polishing of natural stone, such as granite.[8] Apart from this earlier work, the optimisation of the polishing process has received little scientific attention. In order to develop our understanding of the polishing process further, there is a need for well-controlled experiments on a laboratory scale, in which the effects of the process variables can be carefully studied.

In the present work, a typical industrial polishing process for porcelain ceramic tiles was analysed to determine the

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[*] Corresponding author. Tel.: +44 1223 765217; fax: +44 1223 766142.
E-mail address: imh2@cam.ac.uk (I.M. Hutchings).

0955-2219/$ – see front matter © 2004 Published by Elsevier Ltd.
doi:10.1016/j.jeurceramsoc.2004.07.005

conditions to which both the tiles and the abrasive materials are exposed, and information from this study was then used to design a laboratory-scale polishing rig (tribometer), which could be used to investigate the polishing mechanisms and polishing rates. Profilometry and optical gloss measurements were the main tools used to study the evolution of the quality of the polished tile surfaces. The experimental results from the laboratory rig were then compared with data gathered from an industrial polishing line in order to validate the laboratory-scale simulation.

2. Analysis of a typical industrial polishing process for ceramic tiles

The information used in the following discussion was obtained from various industrial sources in Spain and Italy, and is considered to be typical of current European practice.

After initial flattening and rough grinding to correct the gross form and thickness of the product, often with diamond-impregnated fixed-abrasive tools, tiles are polished in a sequence of stages, most commonly with silicon carbide abrasive particles (ca. 10 wt.%) embedded in composite blocks formed with a magnesium oxychloride cement matrix.[2] The abrasive particle size in the composite is gradually reduced from each polishing stage to the next, progressing from an initial size of several hundred micrometres to a final size of a few micrometres, sometimes over more than 20 stages. A final, high quality polished tile surface typically has a surface roughness *Ra* of about 0.1 to 0.2 μm and optical gloss (measured at an angle of incidence β of 60°) up to about 80%.

Fig. 1 shows schematically the operation of a typical grinding tool in which six approximately rectangular composite blocks attached to a rotating head are pressed downwards against the tile surface. A swinging motion of each abrasive block is achieved by a mechanism inside the head. This swinging motion distributes the wear over a cylindrical surface on the block (with radius *R* indicated in Fig. 1b), and ensures that the local contact between the block and the tile occurs over a narrow strip along the surface of the block. The contact area is flooded with water, which removes heat and also flushes away the wear debris from both the block and the tile. The tool typically rotates about a vertical axis at a speed of 450 rpm (giving a mean peripheral speed of the blocks of ca. 8 m s^{-1}) while the tiles move linearly on a conveyor belt at a much slower speed (typically 75 mm s^{-1}) beneath the rotating tool. A normal load of 200 N is applied to each abrasive block, and the cylindrical radius *R* of the block surface (i.e. the radius of the swinging action) decreases from 130 mm (for a fresh block) to about 72 mm due to wear of the block during the polishing process.

During the industrial process, the contact length (in the direction of relative motion) between the abrasive block and the ceramic tile changes with the sliding time, and so does the contact pressure as wear causes the radius of the block surface to decrease. If, as a first approximation, it is assumed that the contact between the block and the tile is elastic, then these two parameters can be estimated from the standard Hertz equations for elastic contact between isotropic bodies. The contact length 2*b* (as defined in Fig. 1b) is given by:

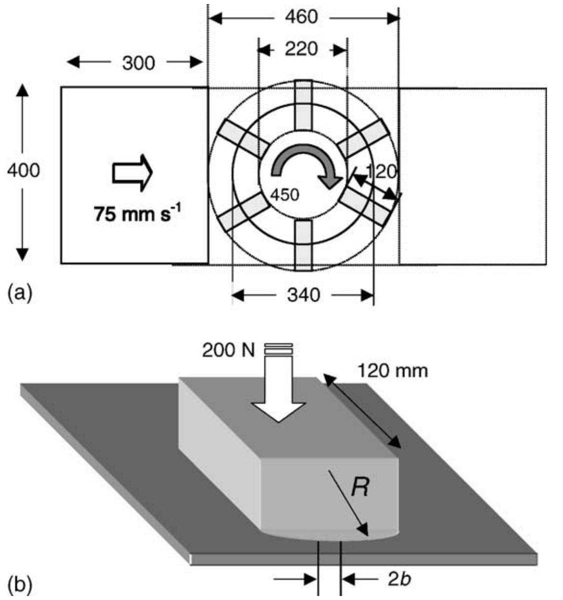

Fig. 1. Schematic diagrams of typical industrial polishing process: (a) a rotating head carries six abrasive blocks and the tiles are transported slowly beneath the head and (b) detail of a single abrasive block, which oscillates in a small arc with radius *R* about a horizontal axis while the whole polishing head rotates about a vertical axis.

$$b^2 = \frac{4PR}{\pi E'} \tag{1}$$

where

$$\frac{1}{E'} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \tag{2}$$

Here $P = W/L$, where W is the applied load and L is the length of the abrasive block; R is the radius of curvature of the abrasive block; and ν_1, E_1, ν_2 and E_2 are Poisson's ratio and Young's modulus respectively of the abrasive block and ceramic tile. The maximum contact pressure p is given by:

$$p = \frac{2P}{\pi b} \tag{3}$$

Fig. 2 shows the change in contact length 2*b* (according to Eq. (1)) and contact pressure *p* (from Eq. (3)) during the polishing process as a function of the radius *R* of the abrasive block. The broken vertical lines show the upper and lower limits of radius corresponding to the values for a fresh block and a fully worn block. As the radius of the abrasive block decreases from 130 to 72 mm due to wear, the contact pressure increases from 10 to 15 MPa, and the contact length decreases from 0.2 to 0.15 mm. These values, based on an elastic deformation model, should be treated as minimum values for contact length, and hence maximum values for pressure, since wear of the abrasive block occurring during

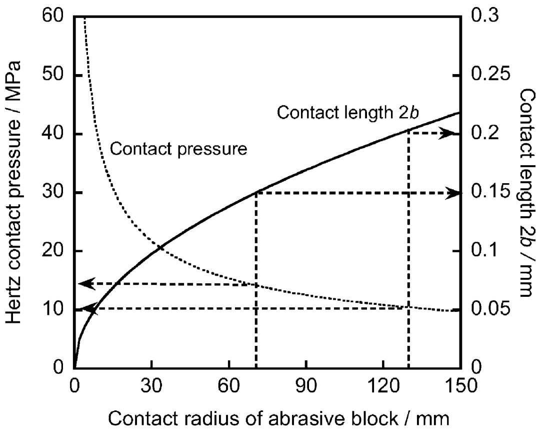

Fig. 2. Change in elastic contact pressure and contact length 2*b* (as defined in Fig. 1b) during the industrial polishing process, as a function of the radius of curvature *R* of the abrasive block.

the sliding process will tend to increase the contact length and so decrease the pressure.

Other relevant parameters can also be calculated from the geometry and information on polishing conditions shown in Fig. 1. The polishing action experienced by the tile will be different at different distances from the centre-line of the polishing head. Fig. 3 shows the total sliding distance (based on the estimate of *b* derived above) and the corresponding number of block-tile contact cycles experienced by the different regions of a tile as it passes under the polishing head, as a function of lateral position relative to the centre-line. The maximum and minimum numbers of contact cycles which regions of the tile experience during the polishing process, for the conditions assumed here, are 250 and 130. The total sliding distance experienced by the blocks can also be calculated. Fig. 4 shows the sliding distance (relative to the tile) of each point along the contact line on the abrasive block, as a function of radial position relative to the axis of rotation of the block, although the motion is distributed over the whole cylindrical surface of the block generated by the swinging motion. The range is from about 20 to 45 m for the passage of a single tile under the polishing head. The sliding histories of different regions of both the abrasive block and the ceramic tile cannot be described simply. The operating conditions in a typical industrial polishing line, derived from this analysis, are summarised in Table 1.

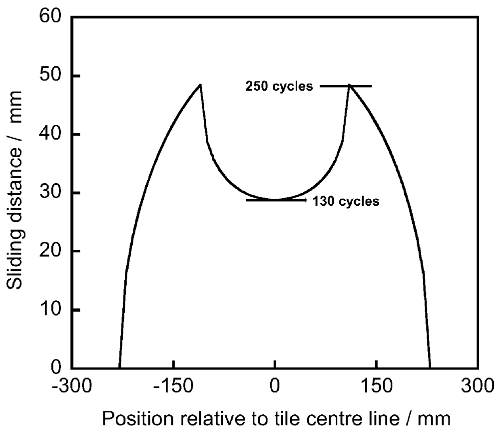

Fig. 3. The number of contact cycles and sliding distance experienced by points on a ceramic tile in the industrial process, as a function of position relative to the centre-line of the tile.

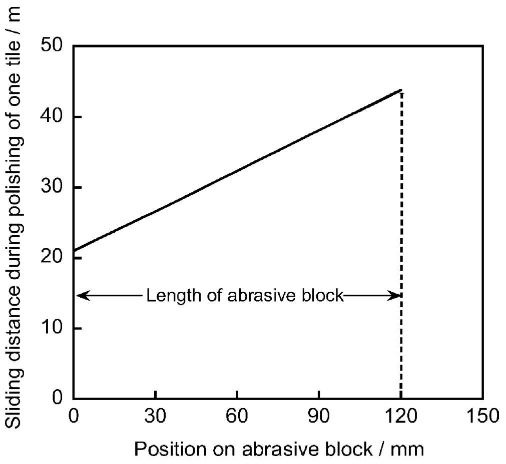

Fig. 4. Sliding distance on abrasive block as a function of distance from the inner end of the block.

In order to simulate the essential features of this process on a laboratory scale, it is desirable to replicate the contact conditions and relative motion, and also preferable to use comparatively simple specimens. However, in reducing the size scale of the process it is not possible to reproduce its complexity and the values of all the operating parameters correctly. It was assumed that the contact loading between the abrasive block and the tile, and the total sliding distance of each relative to the other, are the most important parameters which affect the removal of material from both the block and the tile, and also the final surface quality of the tile.

3. Design of the laboratory test rig (tribometer)

The laboratory tribometer was designed to reproduce, as far as possible, the important features of the industrial conditions listed in Table 1. An automatic metallographic polishing machine with sample drive head (Struers Ltd., RotoForce 3 and RotoPol 35) was adapted for this purpose. Abrasive pins

Table 1
Summary of approximate operating conditions in the industrial polishing process

Contact conditions	Line load on abrasive block ($\mathrm{N\,mm^{-1}}$)	1.7
	Contact pressure (MPa)	10–15
	Elastic contact length in direction of sliding (mm)	0.2
Ceramic tile	Number of interactions with block (cycles)	130–250
	Relative sliding distance at each point on tile (mm)	30–50
Abrasive block	Sliding distance (m per tile)	20–45

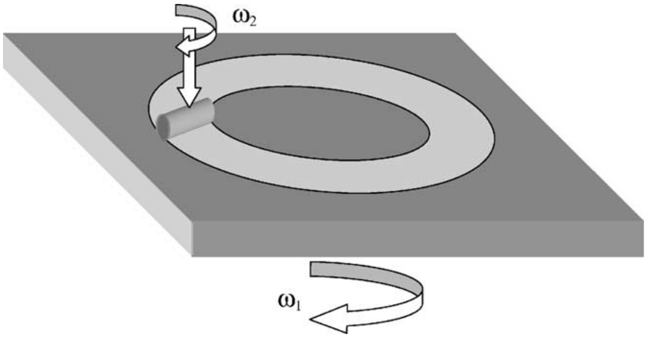

Fig. 5. Schematic diagram showing the motion of the tile sample and abrasive pin in the laboratory test rig (tribometer).

(made from the same material as the industrial blocks) were mounted in the upper, rotating metallographic sample holder, and square tile pieces were mounted on the lower, rotating disc normally used for the polishing cloth. Fig. 5 shows a schematic diagram of the relative positions and motion of the abrasive pin and tile sample in this test.

The cylindrical abrasive pins were 12 mm in diameter and 10 mm long, and commercial porcelain ceramic tiles were cut into samples 100 mm square. The pins and tile samples were firmly held in specially designed holders, which fitted into the polishing machine. A single abrasive pin was used in each test, mounted with its axis parallel to the plane of the tile, rotating about a vertical axis in the motorized head of the tribometer with angular velocity ω_2 as shown in Fig. 5, and pressed against the tile surface under a pneumatically-controlled normal load. The tile sample, fixed to the lower disc, also rotates about a vertical axis, with angular velocity ω_1. By adjusting the operating conditions of the tribometer (the normal load and the rotational speeds of the abrasive pin and tile), the important features of the relative motion between the abrasive block and ceramic tile were replicated.

The standard conditions used in the experiments are listed in Table 2. The normal load on the abrasive pin (17 N on a pin 10 mm long) was selected to produce the same load per unit distance along the pin (1.7 N mm^{-1}) as in the industrial process. The main source of the relative motion between the abrasive material and the tile (corresponding to the rotation of the polishing head in the industrial process) was the rotation of the tile. For the rotational speed used in the laboratory experiments, the typical polishing history to which a tile is exposed in a single polishing stage in the industrial process (130 to 250 passes of the polishing block) is achieved in a period of 26 to 50 s. The rotation of the abrasive pin was introduced to achieve a relatively even distribution of abrasive particle contacts across the annular polished track on the tile during a polishing experiment. This was found to be necessary since for the small contact area on the pin, only a small number of individual abrasive particles were exposed and active at any one time. The speed of the abrasive pin relative to the tile surface inevitably varied slightly across the wear track, between 0.96 and 0.80 m s^{-1}, but this did not cause any significant difference of the polishing effect on the tile surface.

Table 2
Polishing conditions used in the laboratory tests

Line load (N mm^{-1})	1.7 (=17 N/10 mm)
Rotational speed of tile specimen (rpm)	300 ($\omega_1 = 10\pi$ s^{-1})
Rotational speed of abrasive pin (rpm)	150 ($\omega_2 = 5\pi$ s^{-1})
Outer radius of wear scar r_1 (mm)	33
Inner radius of wear scar r_2 (mm)	23
Outer edge speed of abrasive pin (m s^{-1})	0.96
Inner edge speed of abrasive pin (m s^{-1})	0.80
Average speed of abrasive pin (m s^{-1})	0.88

4. Laboratory polishing tests

4.1. Materials, experimental method and procedure

Standard SiC composite abrasive pins were produced with specifications conforming to normal industrial practice by Abrasivos de Castellón, Castellón, Spain, in small moulds by the same process, and from the same cement-based composite material, as the much larger industrial blocks. A single cylindrical abrasive pin was used in each test.

The tile samples were cut from a single batch of standard porcelain tiles supplied by Instituto de Tecnología Cerámica, Castellón, Spain. These tiles had been fired at 1210 °C and had a microstructure consisting of a glassy matrix with composition SiO_2–Al_2O_3–$(Na,K)_2O$, undissolved quartz, and mullite, in approximate proportions 55 wt.%:35 wt.%:10 wt.%. Fig. 6 shows an SEM image of the typical microstructure revealed on a fracture surface after acid etching. The tiles had a bulk density of 2.40 g cm^{-3}, Vickers hardness of 5.7 ± 0.1 GPa, Young's modulus of 68 ± 3 GPa and fracture toughness of 1.50 ± 0.02 MPa m$^{1/2}$.

Surface roughness *Ra* and gloss *G* were measured with a stylus profilometer (Taylor Hobson Talysurf 10) and optical glossmeter (Rhopoint Novo-curve, 60° measuring angle) at four evenly spaced positions around the annular polishing track after each test to evaluate the polished surface quality. Each value quoted is the mean of the four measurements. Variability in the results associated with the tile and pin materials, experimental procedure and measurement methods was small, typically amounting to about 5% of the measured value for both roughness and gloss.

A test sequence was performed to simulate as closely as possible on a laboratory scale the development of the tile surface in an industrial polishing line. A single sample of ceramic tile was polished in sequence by abrasive pins with the full range of grit sizes available, from the largest grit number (36) to the smallest grit number (1500). The grit numbers describe the abrasive particle size using the standard FEPA designation and the sequence employed was: 36, 46, 60, 80, 100, 120, 150, 180, 240, 320, 400, 600, 1000, and 1500.

Before polishing, the tile surface was initially abraded with a diamond-impregnated fixed-abrasive wheel (Struers

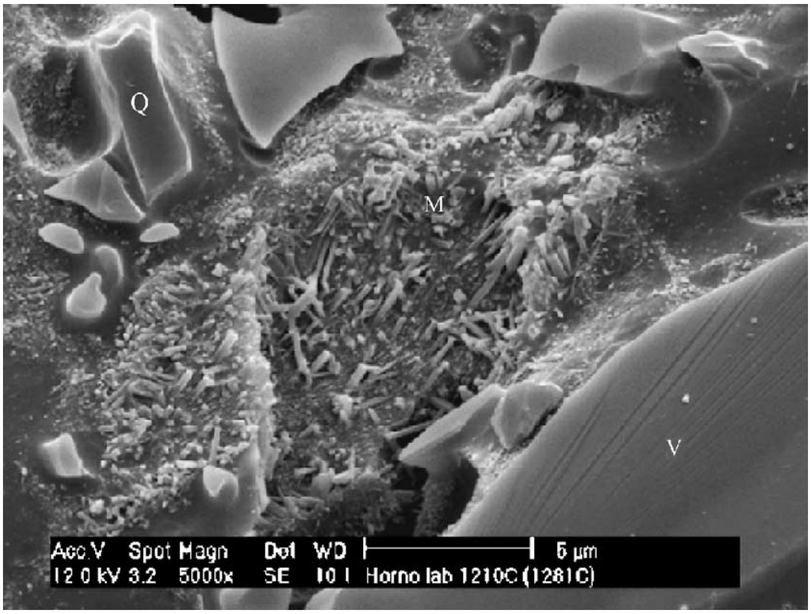

Fig. 6. SEM image of a fracture surface after acid etching, showing the typical microstructure of the tile body. Letters indicate the glassy matrix (V), undissolved quartz (Q) and mullite crystals (M).

Ltd., 250 μm particle size) in order to obtain a flat rough initial surface. This surface had a mean roughness *Ra* of 1.2 ± 0.1 μm, and a very low gloss value *G* of 2.8 ± 0.2%.

All abrasion tests were performed under the conditions shown in Table 2, with the contact region flooded with copious supplies of tap water. The tile was polished under the standard conditions with each abrasive pin for 15 s, then for a further 15 s and then for a further 30 s. After each increment of polishing, i.e. for a total of 15, 30 and 60 s exposure to each size of abrasive, the surface roughness *Ra* and gloss *G* of the tile surface were measured as described above. The polishing steps were then repeated with the next smaller size of abrasive. For the finest size (grit number 1500) additional tests were performed to total polishing times of 180 and 300 s.

4.2. Experimental results

Fig. 7 shows the roughness and gloss of the tile surface after each polishing step for each abrasive sample. For each grit size there are three points plotted, corresponding to the data after 15, 30 and 60 s exposure to each abrasive pin. The data for the final, 1500 grit size are an exception to this; five data points are shown, corresponding to 15, 30, 60, 180 and 300 s total polishing time with this abrasive.

The results show a clear trend of decreasing surface roughness and increasing gloss as the polishing process proceeded from large abrasives to small abrasives. These trends are much greater than the relevant measurement errors. For each grit size, the surface quality depended on the polishing time, with longer polishing times being beneficial, especially for the smallest abrasive grits (numbers 600, 1000 and 1500). For the larger abrasive particles (smaller grit numbers) however, the effect of extending the polishing time from 30 to 60 s was not great.

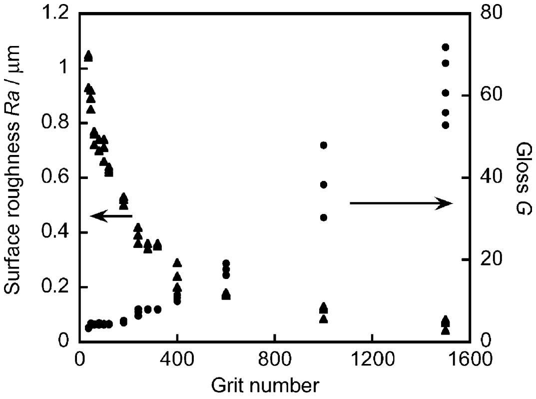

Fig. 7. Surface roughness *Ra* and gloss *G* of the tile surface as a function of grit number of abrasive pin for the full sequence of polishing steps (described in the text) in the laboratory tests.

5. Comparison of data between the laboratory polishing test and industrial polishing line

In order to validate the experiments performed with the laboratory rig, values of gloss were measured on tile samples taken from an operating industrial polishing line. The line was stopped to enable tiles to be withdrawn at a number of points. The abrasive particle sizes used in the line ranged in mesh number from 36 to 1800. As there were some duplicated or even triplicated polishing heads in the line operating with the

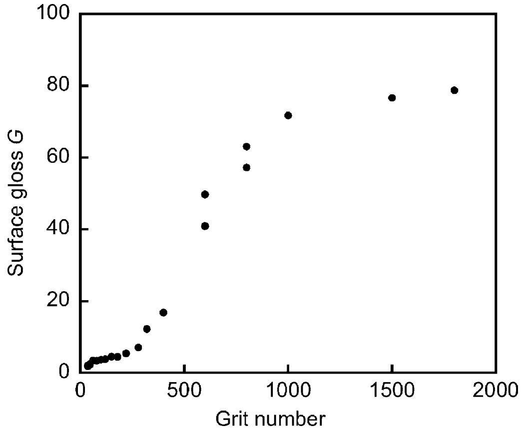

Fig. 8. Gloss values for samples withdrawn from the industrial polishing line after polishing with the grit size shown.

same size of abrasive, the data for some samples may relate to different polishing times.

Fig. 8 shows the gloss values measured on the samples from the industrial polishing line; surface gloss is a more important and sensitive parameter than the surface roughness in the evaluation of surface quality in the later polishing stages. It can be seen that the evolution of the tile surface in the industrial polishing line is very similar to that of the tile specimens polished by the laboratory tribometer, leading to similar values of final gloss (78% for the industrial process and 72% for the laboratory sequence).

For both the polishing sequences, the process can be divided into two periods. For abrasive grit numbers below 400 (i.e. larger grit particles), there was little apparent improvement in gloss although the roughness was reduced substantially. The smaller abrasives, with grit numbers above 400, had a significant effect on the gloss but the corresponding change in roughness was small. The final values of roughness and of gloss will tend to be limited by the porosity of the tile material, typically 5–8% by volume in such porcelain ceramics.[5,9]

The surfaces polished industrially had a somewhat higher final gloss than the surfaces polished in the laboratory. The values for the tiles from the industrial line showed some scatter at certain grit numbers, e.g. 600 and 800, since these values were measured from tile samples which had been polished for different times. These results are consistent with those in Fig. 7 and show that polishing time is a very important factor in improving gloss, for the smaller grit particles. The differences in final gloss values between the two polishing sequences can be accounted for by the differences in polishing times and also in the abrasive size used in the final stages.

Further tests with the laboratory rig are planned to study the evolution of surface quality in more detail, with the aim of modelling and optimising the overall polishing sequence; the apparatus can also be used to study the relative wear rates of both the tile and the abrasive pin, in order to optimise the efficiency of the polishing process.

6. Conclusions

Conditions in an industrial polishing line have been analysed and found to be complex; the histories of different regions of the tile differ significantly, as do the histories of different regions of the polishing blocks. Essential features of the process can be quantified and used to design a laboratory-scale polishing rig (tribometer). Preliminary tests with the tribometer have shown that the final polished surface quality (in terms of optical gloss and roughness) and its evolution were comparable with those observed in an industrial polishing line. Both the industrial polishing trials and laboratory testing showed little effect of polishing on gloss for the larger abrasive particles (grit numbers below 400), but a major effect for the smaller particles (grit numbers above 400).

Acknowledgement

The work was supported by the European Commission under Framework V, Competitive and Sustainable Growth Programme, Project number CRAFT-1999-70904, contract number GIST-CT-2002-50190.

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