Polishing of Porcelain Tiles in Industrial- and Laboratory-scale

Abstract: This work reports the design and use of a laboratory-scale tribometer and a new developed tool-holder to reproduce the industrial polishing process for ceramic tiles in laboratory-scale. The mechanical conditions in a typical industrial polishing process were used to execute the tests in industrial-scale on a single polishing head test-rig. The results of spatial glossiness and roughness distribution from the industrial-scale test were taken as reference. After adaption of parameters the tests were repeated on a tribometer in laboratory-scale. The custom-made CNC-tribometer allows all parameters and kinematics used in the industry to be controlled and provides additionally a very high position accuracy of the tool. The new developed tool-holder provides similar contact conditions as known from the industrial process. The results of the evolution of glossiness and roughness from laboratory-scale test are compared with the data obtained from the test in industrial-scale and show that the tribometer and the new tool-holder accurately reproduce the polishing process from industrial-scale in laboratory.
Keywords: polishing, vitreous ceramic, porcelain tiles, industrial and laboratory test

Introduction

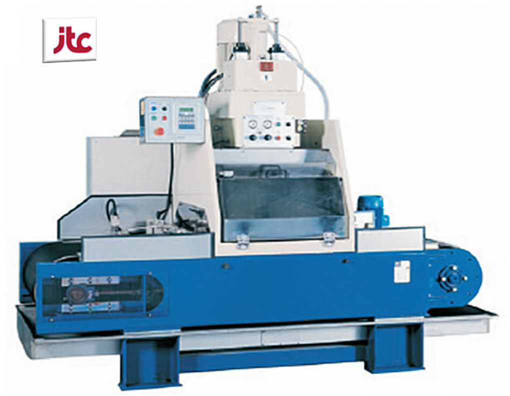
Polished unglazed porcelain ceramics with high gloss levels show excellent mechanical and chemical resistance, which combined with good aesthetical properties, has led to an increase in its demand in high-specification architectural applications [1]. This notable increase in both production and consumption of such product in the past decade has introduced many new players to the market [2, 3], creating a very competitive scenario that demands companies with higher productivity and also efficiency in the manufacturing process. That becomes even more significant taking into account that more than 40 % of the total product costs are involved with the final polishing process, due to the high energy consumption, excessive waste generation, high wear rate of the abrasive tools, poor controlled product quality and overall process inefficiency [1].
In this context, further investigations on the influence of kinematics and phenomenological parameters become even more relevant for the customization and also optimization of the polishing process, which can lead to products with better overall quality and also lower global costs. Previous studies have shown that it is possible to reproduce industrial conditions in a laboratory scale experiment with very good agreement in results, and that specifically designed tribometers are a very useful tool in order to investigate and understand the influence of each parameter in the polishing results [4]. This work presents the results obtained with a new designed CNC tribometer created in an international cooperation program between Germany and Brazil: The *Brazilian-German Collaborative Research Initiative on Manufacturing Technology – BRAGECRIM*. This tribometer enables the simulation of a wider and more complex range of process kinematics and phenomenological conditions, with precisely controlled parameters such as applied force, lubricant flow, rotating speed and direction of the polishing head, feed rate and direction of the conveyer belt and the position of the polishing head. This paper also compares the gloss values obtained in the laboratory experiment against the industrial scale tribometer of the *Instituto de Tecnología Cerámica (ITC)*, Castellón/ES, in order to validate the simulation results. With more complex and flexible process kinematics, the repeatability of the laboratory experiment must increase.

Experiments

In this section the machines used for carrying out the experiments in industrial- and laboratory-scale are presented. The experiments were first conducted at an industrial scale test bench. The parameters were adapted to the laboratory scale and the test was repeated on a self-made CNC-tribometer in laboratory scale. The applied methodologies and equipment used to acquire and evaluate the process outcome variables are also presented.

Industrial-scale test

All experiments in industrial scale were done at ITC in Castellón on a single-head polishing machine shown in Fig. 1. This equipment is a custom design of the Italian polishing machine manufacturer *Ancora spa*. It was constructed with the same components as the industrial polishing lines. Thus the same industrial polishing tools, called *Fickert*, could be used. The use of industrial components enables to investigate the industrial polishing process in the laboratory without the influence of possible scale effects. To offer a



feedrate	1 - 18 m/min
lateral amplitude	470 mm
rotating speed	450 1/min
load	0 - 1200 N

Fig. 1 Test bench for the industrial-scale polishing tests

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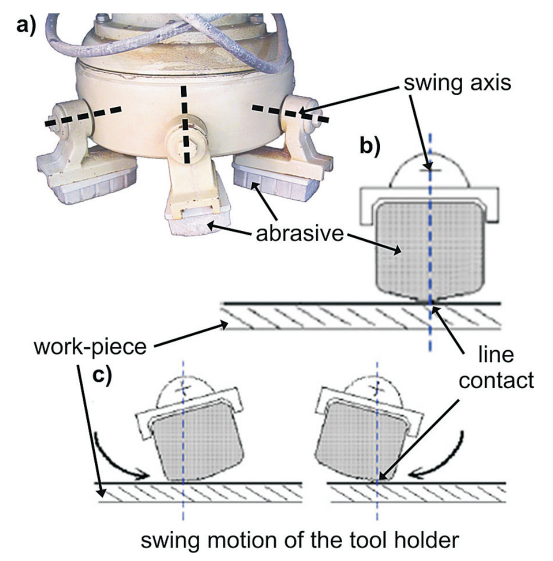
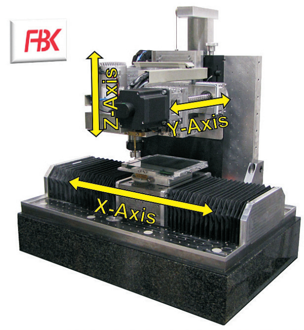


Fig. 2 Tool for industrial-scale polishing



feedrate	0 - 12 m/min
lateral amplitude	120 mm
rotating speed	0 - 3000 1/min
load	0 - 200 N
positioning accuracy	< 10 µm

Fig. 3 CNC-tribometer

better control of the process parameters than that commonly present in industrial polishing lines, this polishing machine was equipped with additional controls to adjust the polishing head rotation speed, the speed variation and the direction of the conveyer belt. The number of passages could be set using reverse direction.

The used polishing head is representative of the industrial machinery usually employed as polishing heads and is shown in Fig. 2a. These have generally six tool holders for abrasives. The tool holders are attached firmly to the swing axles which are radially arranged inside the polishing head. These axes are rotated by an internal mechanism consisting of gears, springs, levers and a cam plate. The individual tool holders are tilted synchronous but phase shifted by 60° to each other. This pivotal movement is shown in Fig. 2b–c. It provides a cylindrical curvature to the tool surface which ensures a line contact between the tool and the work piece.

Laboratory-scale CNC-tribometer

The implementation of the experiments in laboratory scale was performed on a self-made CNC-tribometer [5]. The description and the main machine parameters are shown in Fig. 3. The construction of the tribometer with the three linear axes perpendicular to each other and the rotating work spindle is similar to a milling machine. The control of the tribometer is also the same as with conventional CNC milling machines with G-codes according to DIN 66025, and is therefore highly versatile. The Z-axis of the tribometer was designed deviating from the usual position control in milling machines as a force controlled axis. This way it is possible to use the normal load as a setting parameter of the process. The adjustment of the contact pressure is achieved with a balancing system with dead weights and can be set to 0 N for static tests. The accuracy and repeatability of each linear axis is less than 10 µm. This allows performing experiments on a laboratory scale with any kinematics in a very simple and fast way, with good accuracy and repeatability.

In order to keep the laboratory scale tests comparable to the industrial polishing process, the contact between the tool and the work piece has to be the same. A simple miniaturization of an industrial polishing head with all the mechanism was impossible due to the high effort needed. For these reasons a tool holder had to be developed, which meets the following requirements:

- small enough to be used in laboratory scale
- provides a linear contact between the abrasive and work piece
- simple to manufacture.

A tool holder that satisfies all of the requirements was developed and applied for a patent request [6]. The

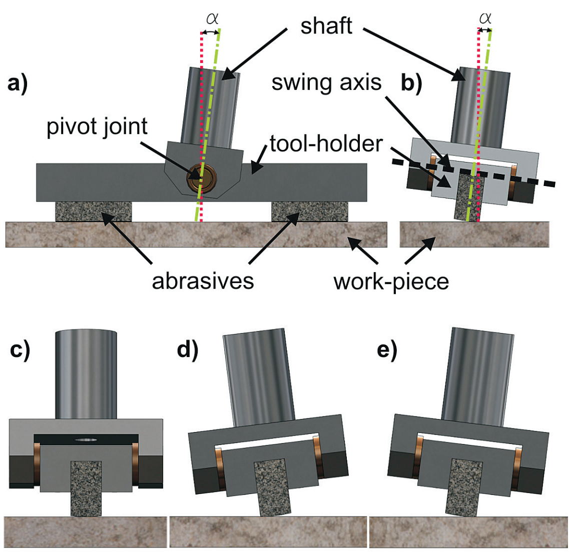


Fig. 4 Tool holder in laboratory scale

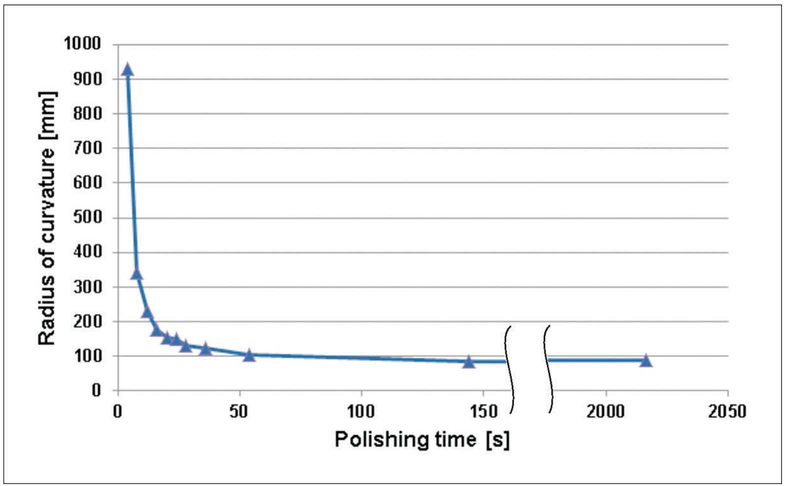


Fig. 5 Development of abrasive curvature

Tab. 1 Process parameters in industrial-scale and adaption to the laboratory-scale

Process Parameter	Industry		Tribometer
Outer diameter D [mm]	540		115
Inner diameter d [mm]	250		55
Number of abrasives	6		2
RPM (D) [min⁻¹]	450	$V_{c(D)}$ = 12,72 m/s	2,113
Feed rate [mm/s]	75	f_z = 1,667 mm/abrasive	117,38
Load [N]	1166	F_{lin} = 1,34 N/mm	80
Abrasive contacts per passage	199,5	–	41,4

prototype of the developed tool holder and its functionality is shown in Fig. 4. In its simplest form the tool is made of a rotating shaft and an abrasive holder with the abrasives.
The shaft and the abrasive holder are interconnected with a one-dimensional pivot joint. In the plane build by the shaft-axis and the axis of the pivot joint as shown in Fig. 4b, the abrasive holder is fixed perpendicular to the shaft. Around the pivot joint the abrasive holder can rotate freely. The rotation axis of the shaft is deflected by an angle with respect to the surface normal of the work piece.
This deflection and the one-dimensional pivot joint cause a cyclical migration of the tool-work piece contact from one side to the other side of the surface of the abrasive blocks during the rotation of the shaft. Fig. 4a shows the tool in a Position where the joint compensates the inclination of the shaft axis. The line contact with the work piece is in the geometric center of the abrasive blocks (Fig. 4c). In Figure 4b the tool is rotated by 90°, the joint no longer compensate the inclination of the shaft axis. This obliges the line contact between abrasive blocks and the surface of the work piece to move toward the edge of the abrasive blocks as shown in Fig. 4d (the point of view rotates with the tool holder). With a further rotation of the tool by 180°, the line of contact moves to the opposite edge (Fig. 4e). After further rotation of 90° the line contact is again at the center of the tool. The result of this cyclical migration of the contact is a curvature on the abrasive surface. The radius of this curvature is a function of the deflection angle. With a defined deflection of the shaft axis the desired tool radius can be easily set to that known from the industry scale, which varies according to their lifetime (new R = 130 mm, 50 % R = 100 mm and worn R = 70 mm [1]). In Fig. 5 the development of the surface curvature of the abrasive blocks in laboratory-scale is shown as a function of polishing time. The shape of the abrasive blocks starts with a rectangular form and reaches after 60 s of polishing time the desired curvature, keeping it constant for a long period of time. For α = 2,85° the curvature radius is R ≈ 100 mm.

Adaption of the parameters

The parameters used at the industrial scale test bench are typical in industrial practice. The geometric values of the tool were given by the layouts of the test bench. The rotating speed, the feed rate and the load were taken from literature (*Hutchings et al.* [4]). These parameters were adapted to the laboratory scale and are shown together with the geometric values in Tab. 1.
The rotating speed was adapted so that the same cutting speed at the peripheral abrasive particle could be achieved.
The feed rate was adapted so that the sliding distance in feed direction between two adjacent abrasive blocks will be the same. The load was set to have the same linear load of the abrasive block. The contact number of abrasive contacts for each test is a function of geometrical dimensions of the tool and process parameters. It represents the intensity of contacts during each passage and can be calculated with the following formula:

$$N_c = \frac{\pi \cdot (D^2 - d^2) \cdot n_{abr} \cdot rpm}{4 \cdot v_f \cdot D} \quad (1)$$

Here D and d are the outer and inner diameter of the tool, respectively, n_{abr} is the number of abrasive blocks, rpm is the rotating speed of the tool and v_f is the feed rate of the work piece.
Due to the high difference in the number of contact per passage for the both tools, the work piece in laboratory scale has to undergo almost five times more passages to get the same contact number as in industrial scale.

Methodology

To validate the CNC-tribometer five tiles were polished with a #400 abrasive tool (silicon carbide particles embedded in a magnesium oxychloride cement matrix) in industrial and laboratory scale. Process-outputs were the surface roughness and the distribution of gloss.
The roughness was measured parallel to the feed direction by a portable roughness measurement device MarSurf M 300, mark Mahr, with 5,6 mm traversing length according to DIN EN ISO 4288. The glossiness was also measured parallel to the feed direction by a glossmeter ZGM 1120, mark Zehntner, with an incident angle of 60°. The layout of the tests can be seen in Fig. 6. For both tests the lateral oscillation of the polishing head were disabled.
In industrial scale three tiles with the dimension of 400 mm × 300 mm were used. The first and the third tiles were only used to support the polishing head at reversal point of the feed direction. With this approach the second tile was pol-

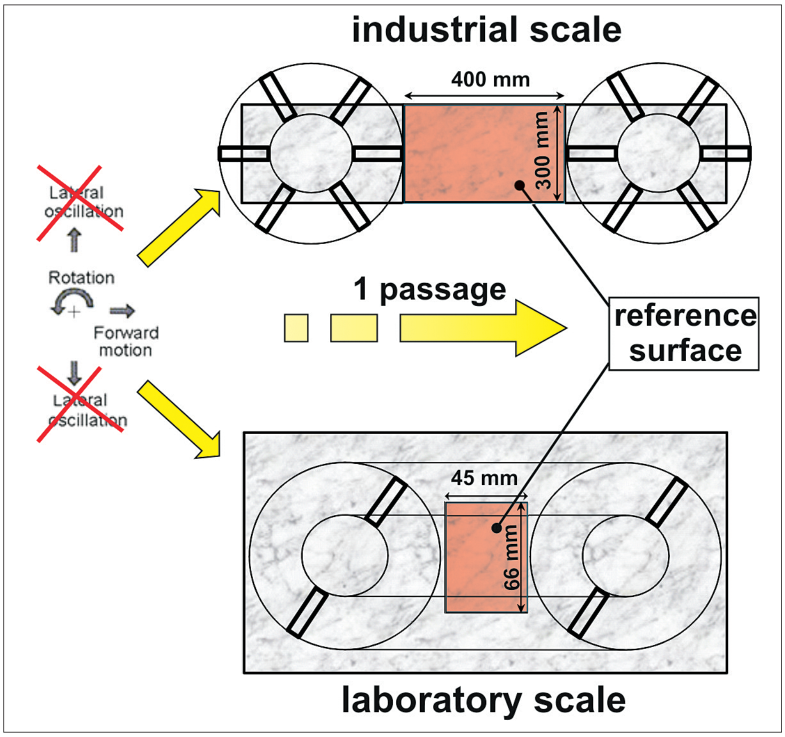


Fig. 6 Layout of the test industrial scale

ished with a constant feed rate in both directions. As reference surface the whole second tile was taken. The surface was marked with a mesh of 20 points × 26 points with a size of 15 mm × 15 mm and the gloss was measured manually for each square. The roughness was measured only in one column. These measurements were made after 0, 1, 3, 9, 19 and 29 passages respectively of the polishing head in the industrial-scale.

In laboratory scale, due to the smaller tool, it was possible to use only one tile of 300 mm × 150 mm. As reference surface only the area of 45 mm × 66 mm between the both reversal points was taken into account.

The gloss was measured automatically with the tribometer in a pattern of 34 × 9 measurement points. The distance between two points was 5 mm longitudinal and 2 mm lateral, which is the maximum spot size of the glossmeter. The roughness was measured in a column of 7 points with a distance of 10 mm. Due to the different contact numbers per passage in the laboratory scale the measured condition of the tile was 0, 1, 5, 9, and 19 passages respectively of the tool, so that an equal number of contacts in both scales could be provided.

Results and discussion

With the data obtained from the different stages during the polishing process it is possible to visualize the changes of gloss and roughness. Fig. 7 presents the data of surface glossiness and roughness obtained from the test in industrial scale as a function of the number of contacts. For glossiness each value represents the mean of 520 measurement points, and for roughness it represents the mean of 20 measurements. The broken lines show the prediction of empirical model from literature [7]. The good fit of the curves shows that the polishing process on the test bench in industrial scale was the same as in industry.

The gloss in industrial scale increases continuously during the whole polishing process.

The roughness in industrial test shows no changes after the first 200 contacts (1 passage), although the gloss increased remarkably. With further polishing process the roughness keeps decreasing until the contact number 3800, where it increases lightly although the gloss keeps increasing continuously.

The inversely proportional dependence between glossiness and roughness is very strong; it is due to the fact that an abrasive #400 was used. This grain size indicates the limit were its reasonable to change from roughness to gloss as the criterion to describe the surface quality [4]. In industrial polishing lines there are maximum three polishing heads with the same grid size used in sequence [8].

This equates to three passages in the industrial-scale test and is equivalent to 600 contacts. For this reason the range from 0 to 600 contacts for industrial-scale and 0 to 780 contacts for laboratory-scale, respectively, is taken into account and is displayed in Fig. 8.

Fig. 8 shows the development of surface gloss and roughness for both tests as function of the number of contacts. In laboratory scale each value represents the mean of 297 measurement points for gloss and 7 measurement points for roughness, respectively.

The gloss enhancement for the laboratory-test is steady and is similar to the curve obtained from the test in industrial-scale. The curve for roughness from both scales matches

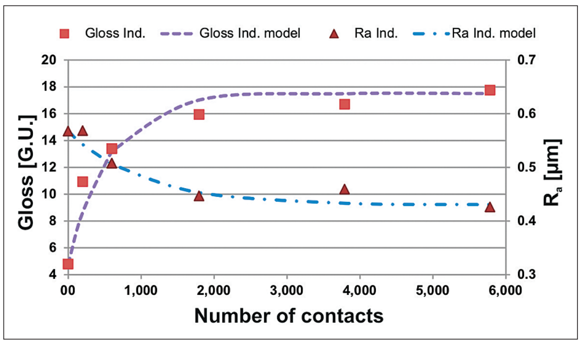


Fig. 7 Gloss enhancement in industrial scale for #400

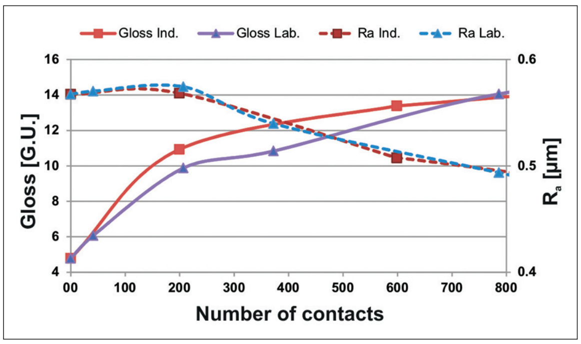


Fig. 8 Gloss and roughness development #400

each other perfectly. In both tests the roughness shows no significant changes after the first 200 contacts of the abrasive although the gloss increases. After the contact number of 200 the roughness is steady decreasing.
Fig. 9 shows the gloss distribution along the cross section of the tile for 600 contacts in industrial scale and for 780 contacts for laboratory scale, respectively. Here each value represents the mean of 26 measurement points in industry scale and 9 measurement points in laboratory scale, respectively. The absolute positions of the measurements were converted into relative positions of the width. The smallest value of the gloss indicates the rotating axis of the tool. The rotating axis of the laboratory test was exact in the middle of the referenced area.
This is due to the good positioning of the CNC-tribometer. The curve from industrial test was a little eccentric and was rearranged so that both rotating axis will match each other at the zero position of the graph. Now it can be seen that the curve from the laboratory test matches the curve from the test in industrial scale very good. The form of the curve comes from the addiction of the number of contacts to the radial distance to the center point of the tool [4].

Conclusions and implications

The design and construction of a laboratory-scale polishing tool has been completed and tests were executed on a CNC-tribometer in laboratorial-scale.
The results from this apparatus suggest a high reproducibility for gloss- and roughness-distribution regarding the results obtained from a test bench in industrial-scale.
The following conclusions were obtained:
• the linear contact condition between the abrasive and work piece in the industrial polishing line were reproduced with the new developed tool-holder in laboratory-scale;
• with the tool-holder developed it is possible to adjust different radius for the curvature of the abrasives in laboratorial-scale in a very simple and stable fashion;
• the benefit of the high accuracy and the good positioning of the CNC-tribometer were confirmed;
• preliminary polishing test with the new tool-holder and the CNC-tribometer have shown that not only the surface quality was comparable with that obtained from test in industrial-scale, but also the spatial distribution of the gloss was very similar;
• the CNC-tribometer developed is capable to reproduce the industrial polishing process of ceramic tiles, so that it can be used for scientific investigations on the evolution of glossiness and roughness along that process.

Acknowledgement

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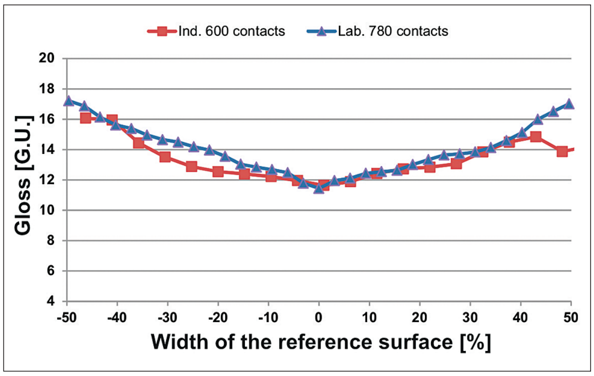

Fig. 9 Comparison of gloss distribution #400

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