POLISHING PROCESS OF CERAMIC TILES – INFLUENCE OF TOOL WEAR ON GLOSS

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ABSTRACT

In this work, the influence of tool-wear on the evolution of surface quality in terms of gloss and roughness of the polished ceramic tiles is researched. For this, three different curvatures were used to perform the experiments on a laboratory scale CNC-Tribometer with a sequence of progressively smaller silicon carbide abrasive particles embedded in a magnesium oxychloride matrix. To achieve and maintain the curvature of the tool during the tests, a new developed tool holder was used. This tool holder was exclusively devised for this purpose and it is currently under patent request. The radii of the curvature were set to 130 mm, 100 mm, and 70 mm. These values correspond to a new, half used and worn tool condition in the industrial polishing process. The used grit-size was from #320 to Lux.

Tile surface quality was evaluated in terms of roughness and optical gloss. Topography was used to evaluate the tile removal rate and tool wear. Also, the motor power was measured to evaluate the energy consumption. The measurements were done before and during the experiments, until a saturation of gloss for each grit number was achieved.

The used abrasives show a general trend of increasing gloss and decreasing roughness during the process. The used abrasives caused major gloss enhancement and had only a small effect on surface roughness. The results presented in this paper show the achieved roughness and gloss for each curvature as a function of used abrasive grit number, as well as the material removal rate of the tile, the polishing efficiency, the dissipated power in the contact, and the specific grinding energy.

1. INTRODUCTION

The porcelain stoneware tile industry successfully emerged in the 1980s and has been steadily growing, especially in the past decade [1]. Part of this success can be credited to the polished unglazed porcelain tile, which has good mechanical and chemical properties, such as abrasion, frost, and stain resistance. These attributes make it an excellent choice for a wide variety of applications [2]. Its main characteristic, the very low porosity, yields these important qualities and also leads to very low water absorption capacity (maximum of 0.5%) [3], distinguishing it from other ceramic tiles. As an example of current market growth, in the world's largest ceramic tile producer, consumer, and exporter, China, porcelain tile is estimated to stand for 80% of the total ceramic production. And considering that the annual Chinese ceramic tile production has been dramatically increasing in the past few years, surpassing 6500 Mm^2 in 2011 [4], more than 5200 Mm^2 would account only for porcelain tiles.

Among other properties, surface gloss is a very important criterion in the quality control of the product, it being able to reach up to 80 GU (gloss units) in highly finished surfaces. However, an onerous polishing step carried out by a sequence of polishing heads with decreasing abrasive particle sizes is needed to generate the commercially specified gloss levels; the low efficiency of the process leads to high costs due to large amounts of energy consumption and material waste. Consequently, the opportunity to reduce costs and improve the quality of the product is evident via the optimization of the polishing process. But in order to accomplish it, a better understanding of its characteristics through controlled experiments is needed; therefore, the influence of the main variables must be thoroughly analysed.

Some previous works on the subject utilized specially designed tribometers [5] and had already produced a little information over the past decade on the behaviour of gloss gain over polishing time and its important relation with the roughness of the surface. However, the literature does not provide detailed data on the influence of different values of contact pressure on the behaviour of either gloss or roughness.

The present work studied the evolution of gloss and roughness in porcelain tiles for three different tool wear states (represented by the curvature) for a wide set of abrasive particle sizes, as well as the consequent rate of material removal from the tile surface and the tool. For this purpose, a CNC tribometer was utilized, whose ability to properly simulate the kinematics of the industrial polishing process on a laboratory scale has been successfully verified in previous works [6].

2. METHODOLOGY

In a typical industrial polishing process, the tool curvature decreases due to wear from 130 mm to 70 mm. At the same time the contact pressure between the abrasive and the tile increases from 10 MPa to 15 MPa due to a constant linear tool load of 1.7 N/mm [5].

In this work, the development of surface quality in terms of gloss and roughness was investigated for a sequence of abrasive grain-sizes (from semi finish to super finish) and for three different wear states of the tool (new, 50% used and worn). The aim was to investigate the impact of tool wear on the surface quality for a sequence of abrasive grain sizes.

The customized CNC-Tribometer [7] (Figure 1), the tool used for the experiments [6], the applied methodology and all the equipment used to acquire and evaluate the process outcome variables are detailed below.

feedrate	0 - 12 m/min
lateral amplitude	120 mm
rotating speed	0 - 3000 1/min
load	0 - 200 N
positioning accuracy	< 10 µm
max. power	3.2 kW

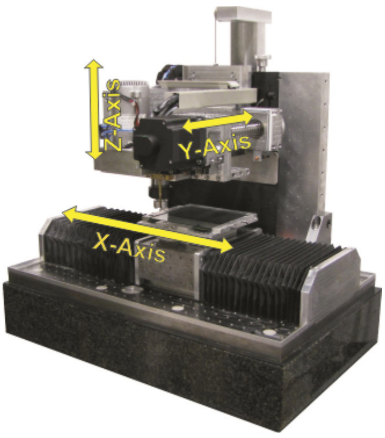

Figure 1. CNC-tribometer.

Contact conditions	Line load (N/mm)	1.7 (102 N/60 mm)
	Contact pressure (MPa)	10; 12.5; 15
	Lubrication (L/min)	1
Tool	Outer diameter (mm)	115
	Inner diameter (mm)	55
	Rotation speed (rpm)	1800
	Feed rate (mm/s)	100
Abrasives	Grit size (FEPA F #)	320;400; 600; 800; 1200; Lux
	Curvature radius (mm)	130; 100; 70

Table 1. Summary of operating conditions.

3. EXPERIMENTAL

3.1. PREPARATION OF SAMPLES

Industrially polished ceramic tiles (type Onix Pol.) from the Brazilian manufacturer Cecrisa were used to perform the tests. The tiles were cut in rectangular samples of 300 mm by 140 mm to fit in the Tribometer. Before the experiments the polished surfaces of the tiles were sandblasted to achieve a matt but still plane surface. To keep reference points for topography measurements the edges of each sample were covered with adhesive tape during sandblasting. The samples were carefully sandblasted so that the glossy surface was removed, but the topography was kept unchanged plane.

3.2. PREPARATION OF ABRASIVES

The abrasive tools used in these experiments were segments taken from commercial abrasive blocks colloquially known in the ceramic sector as fickerts, industrially produced by Abrasivi Theobald from St. Ingbert. Except for the finest grain size (Lux), which is resin bonded, all these segments are made from silicon carbide grains embedded in a magnesium oxychloride (MOC) matrix. The industrial segments were cut in smaller blocks of 30 mm length, 10 mm width and approximately 22 mm height to be usable with the tool holder in laboratory scale, which in turn was developed to provide a swing motion to the abrasives and ensure a pre-set curvature [6]. The blocks were bonded in the tool holder with a hot-melt adhesive. This procedure provides a very tight fix of the abrasives without damaging the brittle blocks.

Before performing the test, the abrasives were prepared in a two-step dressing process. In the first step, the shape of the abrasives contact surface was changed from a rectangular to a cylindrical curvature with a pre-set radius (130 mm, 100 mm or 70 mm). As the radius is a function of the tool holder properties [6], they were changed to achieve the radius. In the second step, the abrasives were dressed on one of the prepared tiles with the same linear movement as used later in the experiments. This tile was only used to dress the abrasives and was not measured during the tests. The purpose was to adjust the form of the abrasives to the profile created on the samples.

3.3. EXPERIMENTS

Figure 2 shows the test layout used to perform the experiments. Tool rotation and linear forward motion of the tile were used to machine the tiles. To perform one passage of polishing the tool was placed on the tile at the start position, the rotation in counter clockwise direction was activated and the tile was moved. At the end position the rotation was deactivated, the tool was lifted and moved to the start position. The next passage was done in the same way, rotating in the opposite direction. The number of passages was increased as an exponential function with a base of two until 64 passages.

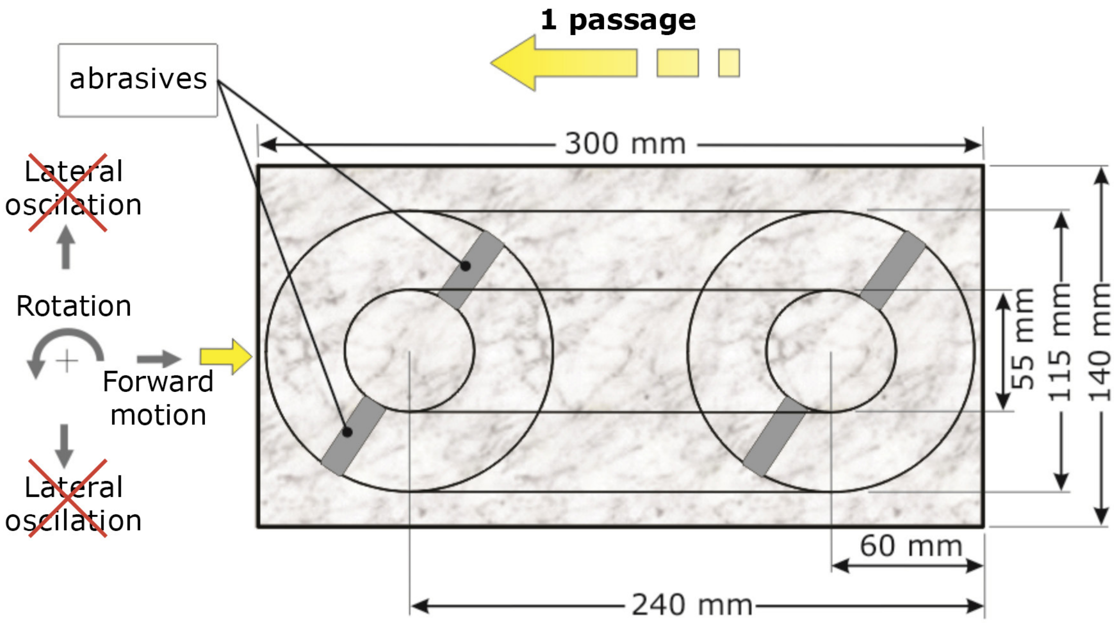

Figure 2. Test layout.

3.4. MEASUREMENTS

The surface quality was evaluated in terms of surface gloss, roughness and topography. The marked areas in Figure 3 indicate the reference surfaces used to measure surface gloss, roughness and tile topography.

The **glossiness** was measured parallel to the feed direction by a Zehntner ZGM 1120 gloss meter with an incident angle of 60°. This angle is seen as most appropriate for middle gloss surfaces and gloss values approximately from 10 to 70 G.U. [8]. The gloss distribution was measured automatically with the CNC-Tribometer along a grid of 51x3 measurement points. The distance between two points was set to 20 mm longitudinal and 2 mm lateral, and the maximum spot size of the gloss meter was approximately 2 mm by 5 mm. The area measured by the gloss meter was smaller than the machined area. However, as the gloss meter had a contact surface of 20 mm by 15 mm, this approach allowed the gloss meter to be positioned directly on the machined surface independently of the wear depth.

The **roughness** was also measured parallel to the feed direction by a portable roughness measurement device MarSurf M 300, Mark Mahr, with 5.6 mm traverse length per DIN EN ISO 4288. The roughness was measured in the middle of the reference surface in a column of 9 points with a distance of 10 mm.

The **topography** was measured by a TESA Micro-Hite DCC NS coordinate measurement system. To measure the tile topography two different approaches were used: one was designed to measure the whole sample surface which was used to calculate the absolute removed volume. Therefore, a curse grit pattern of 42x9 points with a distance of 30 mm longitudinal and 3 mm lateral, respectively was used. The other one used a finer grit pattern of 61x3 points with a distance of 20 mm longitudinal and 2 mm lateral, respectively. It measured the depth of the removed layer in the centre part of the tile where constant feed rate and rotating speed was assured.

The sample topography was measured before the machining with the respective grit size and after it underwent 64 passages. The reference surface was selected bigger than the machined area. By this approach some topography measurement points were taken from an unmachined area. They were used as references to calculate the removed volume and the thickness of the removed layer.

The tool topography was also measured before machining and after 64 passages. The aluminium tool holder was used as reference to measure the high of the abrasives in a pattern of 9x10 measurement points. The tool wear was calculated as the mean height of the tool multiplied by its cross section.

The dissipated **power** in the contact between tool and tile was calculated as the difference in power of engaged tool and no-load power measured at the same speed. The mechanical power of the motor was measured by the ESR Pollmeier MidiDrive D/AS BN 6747 motor controller.

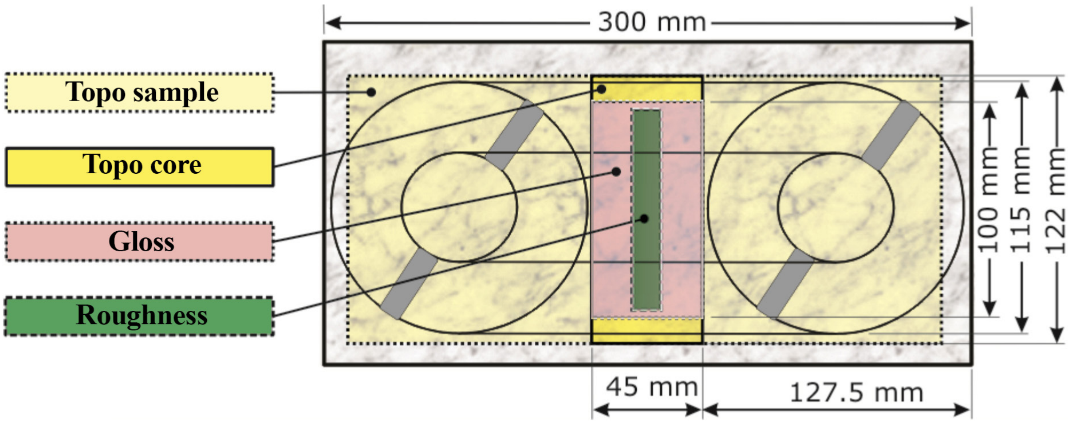

Figure 3. Reference areas.

4. RESULTS AND DISCUSSIONS

4.1. GLOSS ENHANCEMENT

To reduce the quantity of data and to improve the visibility of the figures, only the values of gloss and roughness, achieved with the particular grain size after 64 passages, were plotted as a function of the used abrasive. The results are shown in Figure 4 and Figure 5.

Figure 4 shows the evolution of gloss as a function of used curvature and grit sizes. Each value represents the average of 153 measurements and the standard deviation.

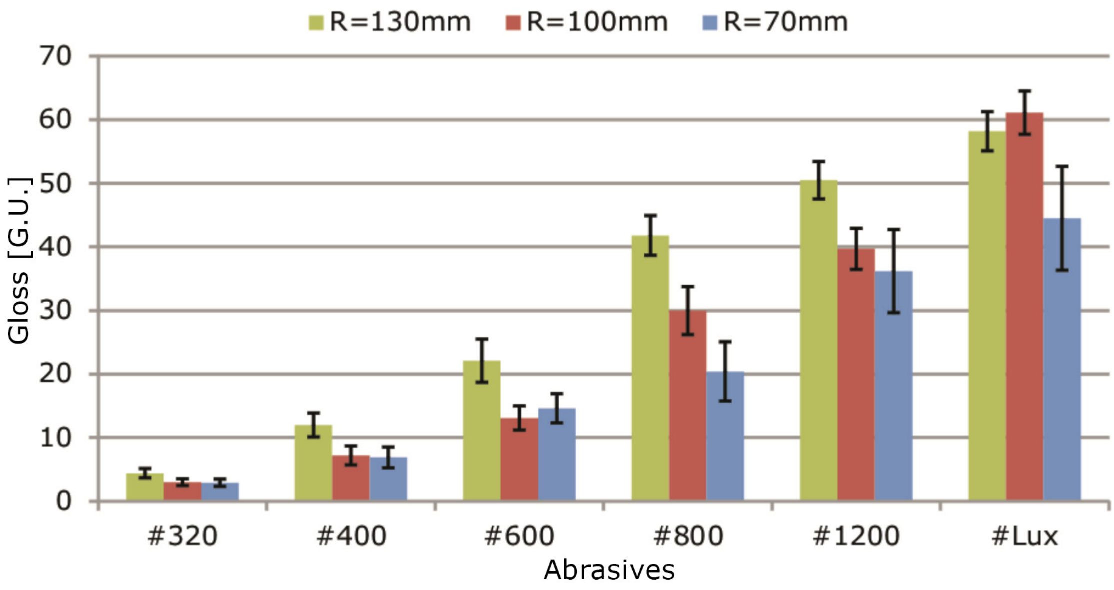

Figure 4. Gloss after 64 passes for each grain size.

It can be seen that the gloss gain is steady for each curvature and rises with finer abrasives. According to Wang the gloss gain is based on the visualization of the crystalline facets of the ceramic and the polished surface consists of small plastically deformed groves in ductile-mode machining, pores and craters [9]. To achieve ductile-mode machining on ceramics, small depths of cuts are preferable [9], [11]. This can be achieved by one of the following options: reducing the protrusion of the abrasive grains; reducing the grain size; or reducing the grain load. By increasing the tool curvature, the contact width of the linear contact also increases which on the other hand with a constant load results in a decreased contact pressure [5]. By using an abrasive with the same concentration of abrasive grains, it leads to a smaller cutting depth due to smaller grain loads [11].

With exception of the #600 abrasives (where the middle tool curvature resulted in the smallest gloss) and #Lux (which is resin bonded and partly showed the opposite behaviour to the MOC bonded abrasives [12]), following the correlation described above, higher radii of curvature resulted in higher gloss values. One possible explanation for the different behaviour of #Lux can be given by the different properties of the bonding material. These are brittle with a high Young module for the MOC binder and very elastic with a high impact resistance for the resin binder. Together with the fact that worn and blunt grains result in higher grain cutting forces [9], it leads to the assumption that the resin binder is able to hold the dull grains longer than the MOC binder. In addition, dull grains have a smaller protrusion and are preferred for ductile mode removal.

The value of the standard deviation of the 153 measured gloss values is a good indicator of the surface gloss homogeneity of the generated surface (the lower the standard deviation the better the homogeneity). Except for the #600 abrasive, higher radii of curvature resulted in a smaller standard deviation of surface gloss. Smaller standard deviation, despite the uneven distribution of polishing contacts known from literature [5] and higher gloss values, means a further advance on the gloss gaining curve known from literature [13].

4.2. ROUGHNESS DEVELOPMENT

Figure 5 shows the achieved mean values of roughness and the standard deviation of the 9 measurements for each curvature and grain size, respectively. It can be seen that roughness decreases steadily with finer abrasives but apparently there is no strong correlation of roughness or its standard deviation with the tool curvature. For example, the achieved roughness with the finest abrasive (#Lux) shows the smallest values with the smallest standard deviation at the smallest curvature. Whereas for #1200 it is almost the opposite only that here the highest roughness was achieved with the middle curvature.

Wang already described that for finer abrasives (semi finish to polish) surface roughness is not appropriate to evaluate the surface quality and that surface gloss should be used instead [9]. On the other hand, it can be seen that the biggest tool curvature resulted in the smallest roughness values with exception of grit #320 and #Lux. However, only the measured roughness for the #800 behaves according to the model of Hecker where higher tool curvature resulted in lower surface roughness [14].

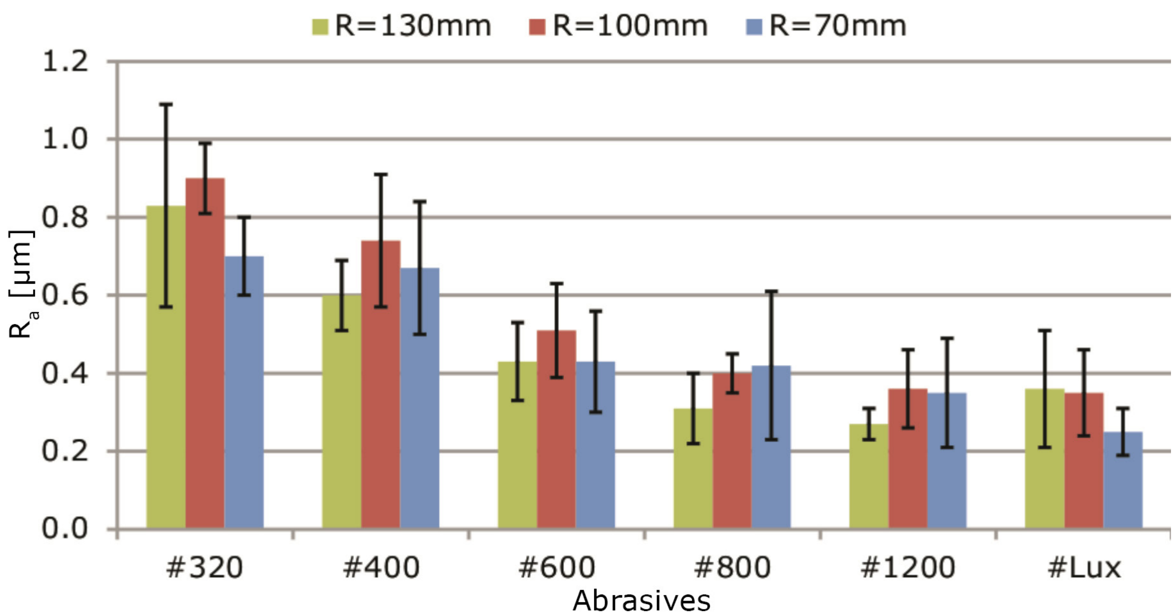

Figure 5. Roughness.

4.3. REMOVAL RATE

Figure 6 shows the calculated material removal per contact of the tile for particularly used grain sizes and the used curvature after an accumulated machining of 64 passages, respectively. The thickness of the removed material layer was calculated as the difference between tile topography before and after the machining with the particular grain size. The removal rate is defined as the mean thickness removed from the tile surface by a single tool contact. The number of contacts is a function of the process parameters and tool dimensions and was calculated according to literature [6]. By this approach, it is possible to compare the removal rate from tools with different dimensions and process parameters.

The removal rates achieved with grit #320 are by far the highest values and indicate a change in removal modes from brittle with grit #320 to ductile with #400 and finer. According to Sánchez the transition from brittle mode to ductile mode removal is characterized by very small removal rates and a rapid increase of surface gloss [15]. Taking only the abrasives with ductile removal it can be seen that the removal rate decreases with finer abrasives. This is a result of decreasing the cutting depths which leads to a shift of the predominant material-removing mechanism from micro ploughing to micro scratching [11], [14].

Except for grit #600 and #800 no strong correlation between the used tool curvature and the removal rate is observed. For grit #600 and #800 it corroborates the Preston hypothesis and the research of Klocke. According to them, higher pressure caused by the smaller tool curvatures results in higher removal rates of the ceramic [16].

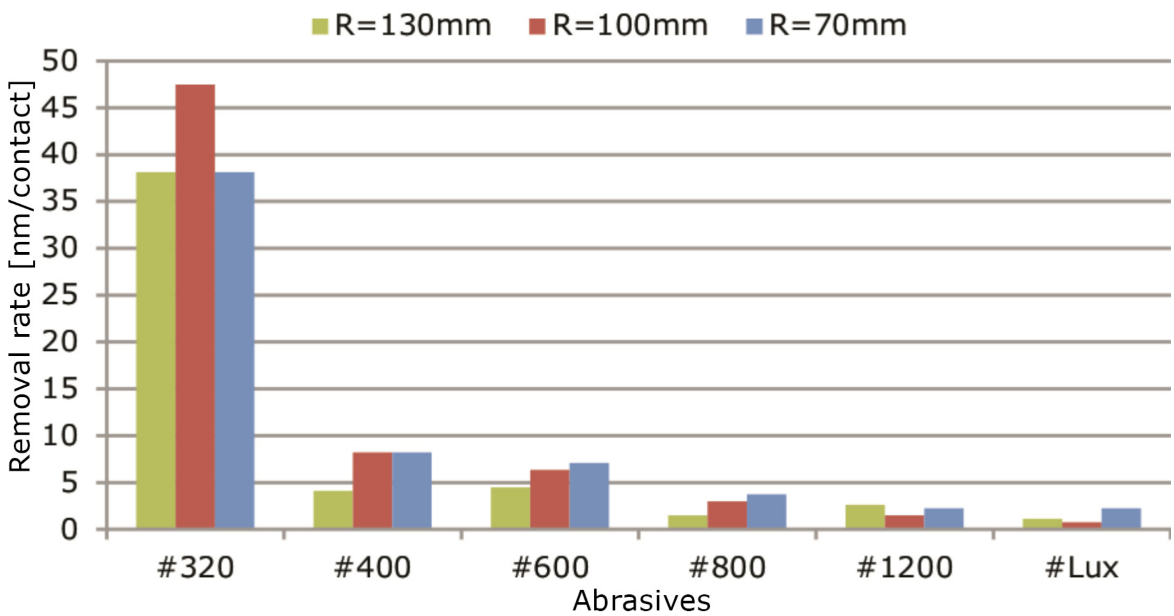

Figure 6. Removal rate

4.4. POLISHING EFFICIENCY

Figure 7 shows the polishing efficiency of particularly used grit size and tool curvature. According to the literature, the polishing efficiency is defined as the ratio of tile wear rate to tool wear rate [17]. The polishing efficiency decreases with smaller grit sizes until minimizes at grit #800 and increases again with finer abrasives.

For the brittle removal mode with grit #320 the polishing efficiency is the maximum for the highest tool curvature (lowest contact pressure) and decreases with smaller curvatures (increasing contact pressure). This behaviour is consistent with the literature where smaller grit loads are preferable in the last tools [9].

For abrasives working at the ductile removal mode no correlation between tool curvature and polishing efficiency can be observed. At this fine grit sizes, the grain load is too low to result in a failure of the MOC bonder. The very high calculated values and their high variation for the resin bonded #Lux abrasives result from the very low removal rate of the tile and the tool.

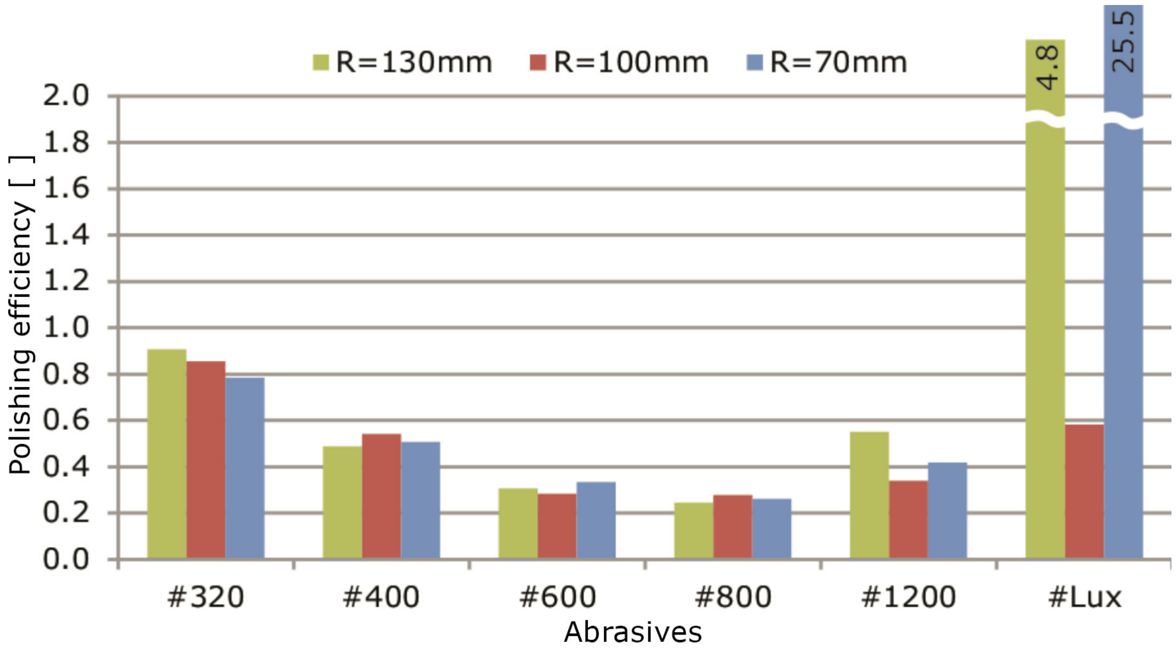

Figure 7. Polishing efficiency

4.5. POWER

Figure 8 shows the dissipated power in the tool-tile contact for a particularly used grain size and tool curvature. It can be seen that with finer abrasives the dissipated power in the contact for each curvature is steadily decreasing. However there is no strong correlation between the used curvature and the power. For MOC bonded abrasives (#320 to #1200) the middle curvature of R=100 mm needed the lowest power. The #Lux abrasive shows by far the lowest dissipated power in the contact which can be explained by the change of the tribological system properties due to the use of the resin bonder.

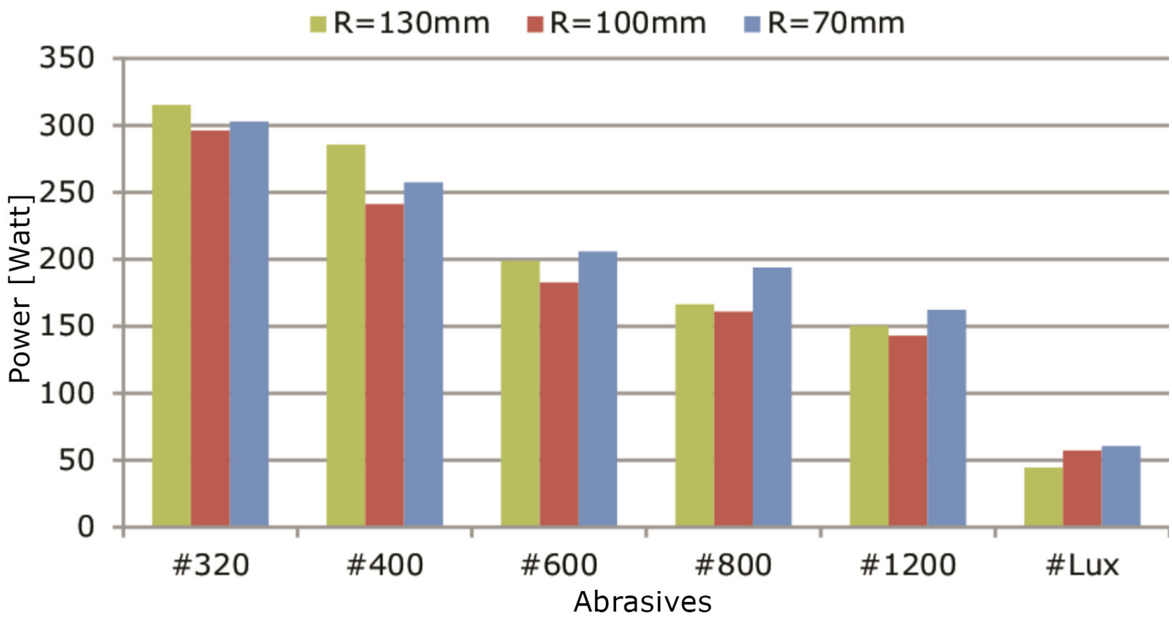

Figure 8. Dissipated power in tool-tile contact

4.6. SPECIFIC GRINDING ENERGY

The specific grinding energy was calculated from the following three values: the dissipated power; the removed material; and the accumulated tool working time for the observed tile area. Figure 9 presents the specific grinding energy for particularly used grain size and tool curvature, respectively. The specific grinding energy (e) is defined as the energy which is needed to remove one mm^3 of material [18]. In spite of the steady decreasing dissipated power (Figure 8) the values of e show an increasing tendency for finer MOC bonded abrasives due to decreasing removal rates. The resin bonded #Lux shows again a different behaviour and a decreased e to grit #1200.

The very low values of e for grit #320 result from the brittle mode removal with depths of cut higher than the critical depth of cut [9] which results in an efficient material removal dominated by micro chipping [9], [14], [18]. For the grit sizes #400, #600 and #800 there is a significant increase in e for the biggest curvature (R=130 mm) resulting in the highest surface gloss (Figure 4), whereas both the other curvatures are at a comparable level of e for all three abrasives. Using the grit #Lux, the maximum e is with the middle tool curvature (R=100) resulting in the highest surface gloss.

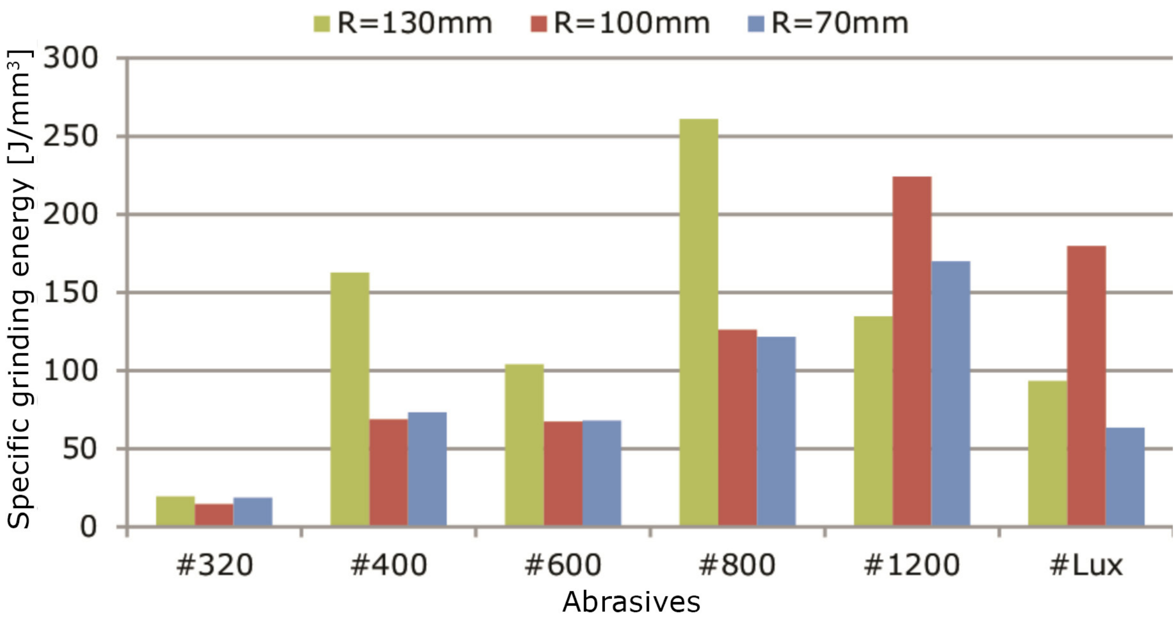

Figure 9. Specific grinding energy

5. SUMARY

Polishing tests with a sequence of progressively smaller silicon carbide abrasive particles (#320 to #Lux) were done for three different tool curvatures representing a new, half used and worn tool state from the industry. The following conclusions were obtained:

- change of the predominant removal mode was observed from brittle removal mode with grit #320 to ductile removal mode with #400 and finer;
- steady gloss gain was observed with the use of finer abrasives;
- strong correlations between the tool curvature and gloss gain was observed for MOC bonded abrasives working in ductile removal mode;
- bonding material of the tool was found to have a big influence on the tribological system;
- strong correlation between the tool curvature and the polishing efficiency was found for brittle mode removal for grit #320, but no correlation was found for ductile mode;
- dissipated power in the tool-tile contact decreased steadily with finer abrasives, however a correlation of tool curvature and dissipated power could only be seen for grit #Lux;
- specific grinding energy showed a tendency of increasing values for finer MOC abrasives.

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REFERENCES

[1] M.G. Junior; J.F.M. Motta; L.C. Tanno; A.Sintoni; J.M. Coelho; M. Caridade: Panorama e Perspectivas da Indústria de RevestimentosCerâmicos no Brasil. In: Ceramica Industrial 15 (2010), Nr. 3, p. 7-18.

[2] ISO 10545-3:1995. Ceramic tiles -- Part 3: Determination of Water Absorption, Apparent Porosity, Apparent Relative Density and Bulk Density. 1995.

[3] E. Sánchez: Technical considerations on porcelain tile products and their manufacturing process, Proceedings of Qualicer: VII World congress on ceramic tile quality Vol. I. Castellón: Cámara Oficial de Comercio, Industria y Navegación, 2002, p. 57-84.

[4] Anfacer - Brazilian Association of Ceramic Tile Manufacturers, The World Market [on line], <http://www.anfacer.org.br/site/default.aspx?idConteudo=160&n=Mundo>. [Visited: 16-05-2013]

[5] I.M. Hutchings; K. Adachi; Y. Xu; E. Sánchez; M.J. Ibánez: Laboratory Simulation of the Industrial Ceramic Tile Polishing Process, Congress: QUALICER (2004) Castellón (Spain), p.GI 19-30.

[6] A. Olenburg; F.J.P. Sousa;J.C. Aurich; E. Sánchez: Polishing of Porcelain Tiles in Industrial- and Laboratory-scale, cfi/DKG 90 (2013) No. 3, p.E39-E43.

[7] R.G. Souza; et al.: Influence of scratching angle on brittle machining of porcelain stoneware tiles, 21st Brazilian Congr. of Mechan. Engin. – COBEM 2011, 24–28 October, Natal, RN, Brazil

[8] Zehntner GmbH Testing Instruments, Glossmeter ZGM-1120, Equipment datasheet.

[9] C.Y. Wang; T.C. Kuang; Z. Qin; X. Wei: How abrasive machining affects surface characteristics of vitreous ceramic tile, American Ceramic Society Bulletin, October 2003, p. 9201-9208.

[10] F. Klocke; W. König: Fertigungstechnik 2: Schleifen Honen Läppen, Springer-Verlag Berlin Heidelberg 2005

[11] H. Huang; Y. Li; H.M. Zhu; X.P. Xu: Micro-structure detection of a glossy granite surface machined by the grinding process, Journal of Materials Processing Technology 129 (2002) p.403-407.

[12] A. Olenburg; M.R. Salati; F. Sant´Ana; F.J.P. Sousa: Polishing process of ceramic tiles – Variation of contact pressure, Advanced Materials Research Vol. 769 (2013) p. 124-130.

[13] I.M. Hutchings, Y. Xu, E. Sánchez, M.J. Ibánez, M.F. Quereda: Development of surface finish during the polishing of porcelain ceramic tiles, Journal of Materials Science 40 (2005), p. 37-42.

[14] R.L. Hecker; S.Y. Liang: Predictive modelling of surface roughness in grinding, International Journal of Machine Tools & Manufacture, 43 (2003) p. 755-761.

[15] E. Sánchez; J. García-Ten; M.J. Ibánez; M.J. Orts; V. Cantavella: Polishing porcelain tile – Part 1: wear mechanism, American Ceramic Society Bulletin, September 2002, Vol. 81, No. 9, p. 50-54.

[16] F. Klocke; R. Zunke: Removal mechanisms in polishing of silicon based advanced ceramics, CIRP Annals – Manufacturing Technology 58 (2009) p. 491-494.

[17] I.M. Hutchings, Y. Xu, E. Sánchez, M.J. Ibánez, M.F. Quereda.: Porcelain tile microstructure: implications for polishability, Journal of the European Ceramic Society 26 (2006), p. 1035-1042.

[18] E. Brinksmeier; A. Giwerzew: Chip formation Mechanisms in Grinding at Low Speeds, CIRP Annals 52 (2003) p. 253-258.