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The effect of pressure gradient and abrasive tool wear when polishing ceramic tiles

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ABSTRACT

A series of experimental investigations were conducted to develop and describe the distribution of the pressure gradient below and across the topological surface of laboratory grinding tools on a ceramic tile during the gloss gaining process. The possibility of controlling the pressure required for the industrial polishing ceramic tiles would prevent excessive wear, directly reducing energy and water consumption. The present research aims to determine the effect of incremental surface pressure distribution in the polishing of ceramic tiles with line contact. For this purpose, two grinding devices were mounted together as a polishing head and built from the machine's base coordinate system on a CNC tribometer with a deflection angle of 2.2°. The grinding pressure was distributed gradually underneath and across the polishing tools by implementing a new polishing tool composed of rotating shaft with pivot joint, helical springs and two abrasive blocks attached on it. Due to the configuration of polishing tools with preferred process parameters, the impact of the material removal and gloss production was found to be minimized or maximized according to the chosen kinematics. Results implied that the process outcome in terms of gloss level and fine surface finish is influenced by the surface pressure (maximum at approximately more than 15 MPa) as well as the abrasive tool surface wear. Furthermore, in the manufacturing line, higher wear rate is posed by the coarser abrasives but less wear rate on the finer abrasives with high gloss gaining.

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1. Introduction

Porcelain tiles are ceramic material made in a kiln (furnace) by heating materials such as clay, feldspar, and sand. The porcelain products were baked dry in the kiln at a very high temperature to obtain glossy translucence and low porosity characteristics [1]. Porcelain ceramic tiles come in both glazed and unglazed qualities. The unglazed ceramic tile as the most popular porcelain ceramic products are produced after being fired at a high temperature. The surface inspections are only carried out in unglazed porcelain tiles at the end of the production process, in which the glossiness level of the tile surface is relatively high. The finishing process of a ceramic tile to obtain the vitreous surface quality is commonly defined as polishing in the manufacturing units, although the most suitable designation is technically honing [2,3]. The consistency of ceramic material in its mechanical strength and the resistance to chemicals are the significant characteristics of the porcelain tiles with extremely low material porosity. They are highly impenetrable by chemical substances and cleaning agents which make them extremely useful in multiple environments for excellent outdoor flooring and wall cladding [4].

The strong mechanical strength as well as the resistance to scratch, chemical, stains and frost are the most captivating characteristics of the highly polished unglazed ceramic porcelain tiles. The surface finishing of ceramic tiles can be accomplished by the following processing: grinding, honing, lapping and polishing of geometrically undefined cutting edges in compliance with the DIN 8589 [5]. The biggest difference between these processes is the number of contacts over a time span between the abrasive particles and the machined surfaces [3,6]. The honing process is usually composed of a sequence of 14 to 18 polishing heads using

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various abrasive grain sizes, generally between 36 and 1500 mesh. At this point approximately 10 percent of the original tile thickness is removed [7,8] but there is no study supporting the need for an exact percentage of material removal. Because the upper surface of all the tiles on the conveyer belt must be placed consistently, the use of an excessive removal layer increases to prevent sudden breakage of the abrasive tools. The most effective technique for maintaining this coordination is to execute an active grinding process (leveling step) right before the honing process.

The honing process accounts for about 30 to 40 percent of all manufacturing costs from the entire porcelain production chain due to the heavy use of abrasive products, water and energy [7,9]. According to [10], China, the world's largest producer of ceramic floor tiles, produces more than seven million tons of waste on average from such wear and tear per year [11]. In this respect, a topographical study prior to the honing process would generate savings by promoting waste reduction from unwanted wear of the abrasive tool and the porcelain ceramic tile [12].

The aim of this work is to improve the previous research on the creation of the pressure gradient under and across the polishing tool's flat surface. The experiments were conducted in a custom-made tribometer that was designed to suit the industrial ceramic polishing processes at a laboratory scale. By retaining the same procedures and some parameter changes to achieve the same efficiency and performance, this work was carried out with two polishing tools being attached to the polishing head. During polishing the contact area between the abrasives and the ceramic tiles was found to be linear with a limited width of about 0.2 mm [9]. The linear uniform load is compared between uniformly distributed load (no springs attached) and triangular distributed load (the presence of helical springs) subjected on the tile surfaces during the tile polishing processes.

2. Methodology

In developing this experimental work, a custom laboratory scaled CNC controlled tribometer was used for the entire

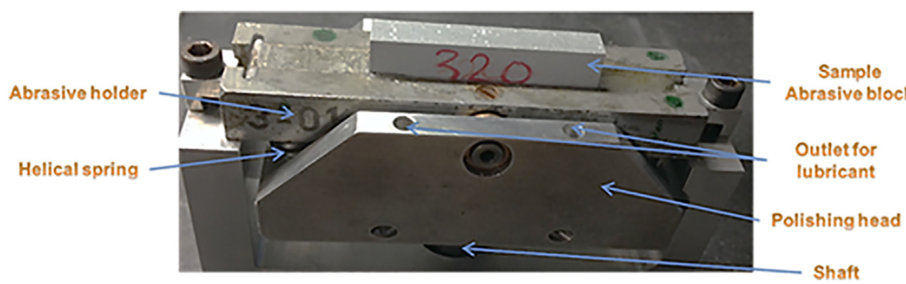

Fig. 1. A sample of abrasive block fixed on its holder as a polishing tool (fickerts).

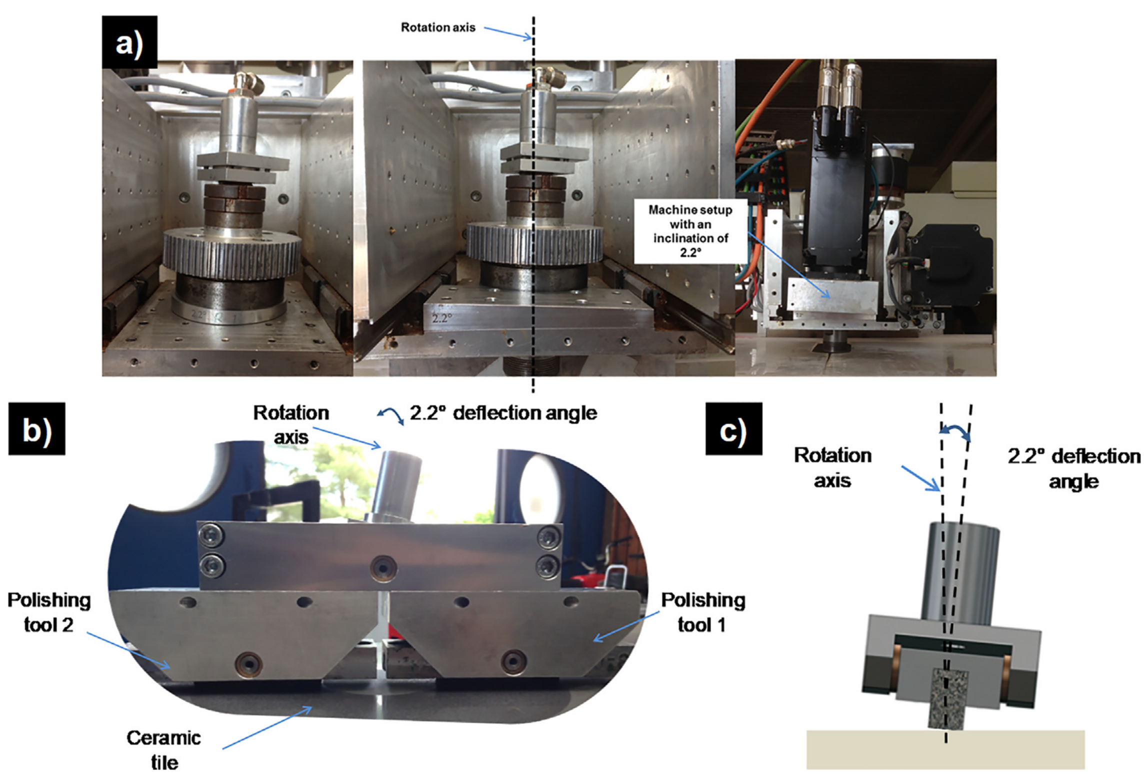

Fig. 2. Tribometer and polishing head with two polishing tools. (a) Installation of 2.2° inclined armatures on the tribometer; (b) Deflection of the polishing head; (c) Illustration of the deflected polishing tool.

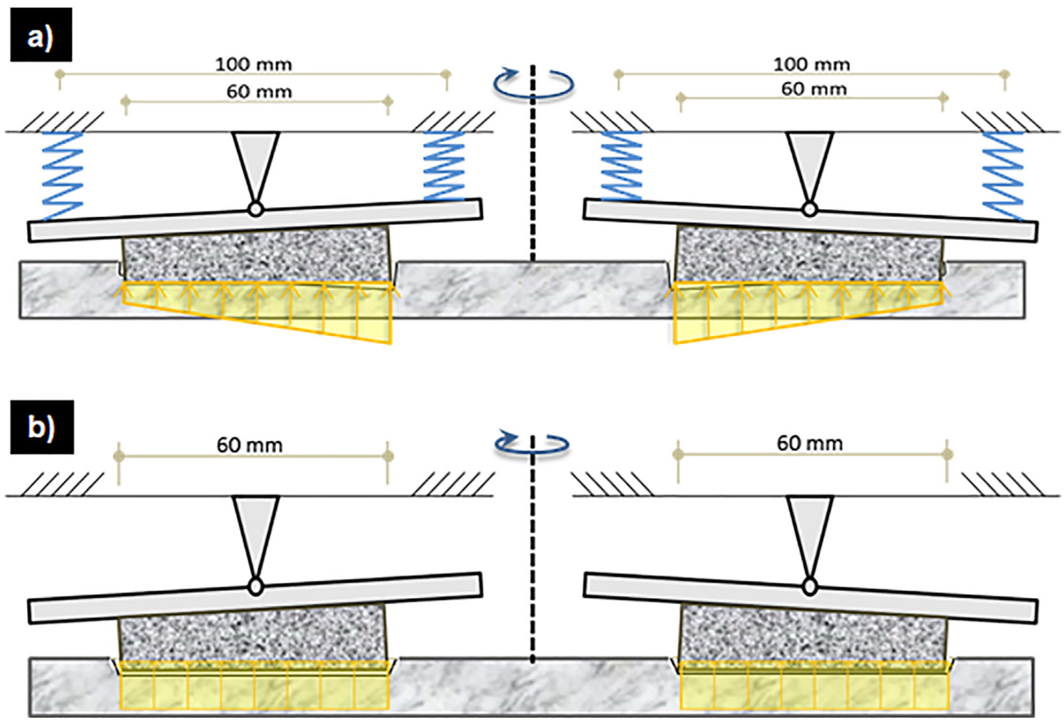

Fig. 3. Polishing head configuration against ceramic tile during the experiment (a) triangular distributed load (with helical springs attached) (b) uniform distributed load.

Table 1
Laboratory parameters for the polishing process.

RPM in min^{-1}	F_N in N	Angle of contact	Abrasive length in mm	Abrasive width in mm	Spring constant in N/mm	Linear load in N/mm	Maximum contact pressure in MPa
120	102	2.2°	60	10	20.25	1.7	10–15

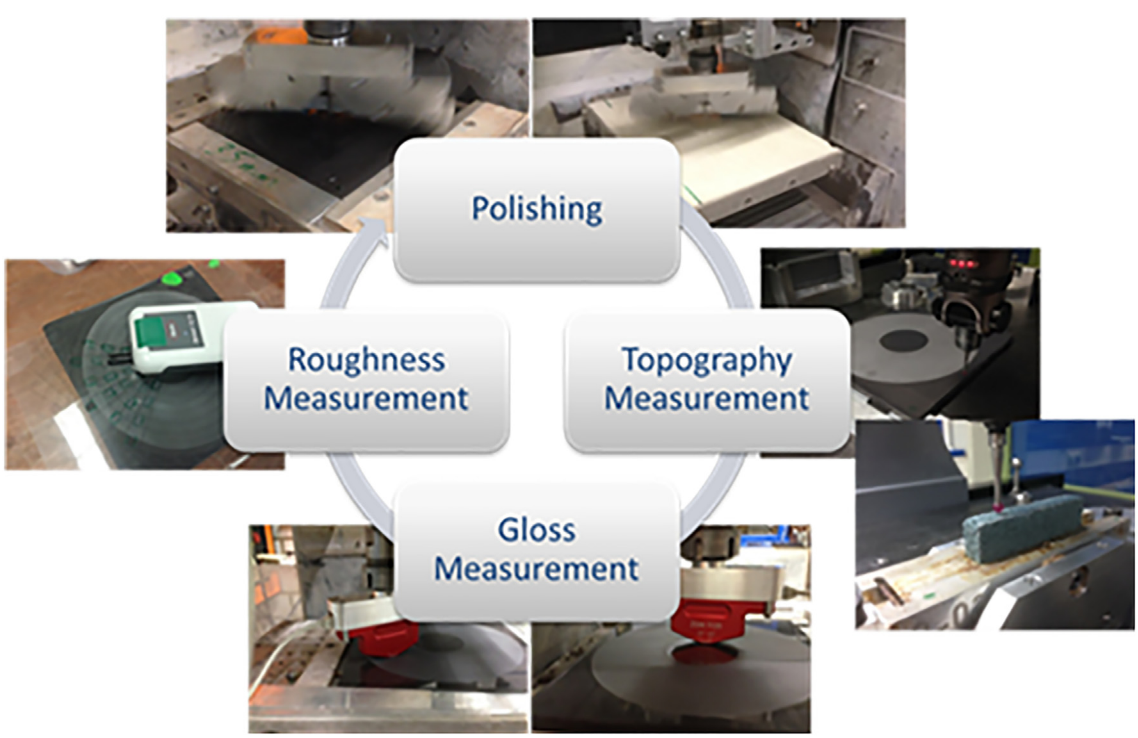

Fig. 4. Experimental sequence and cycle [6].

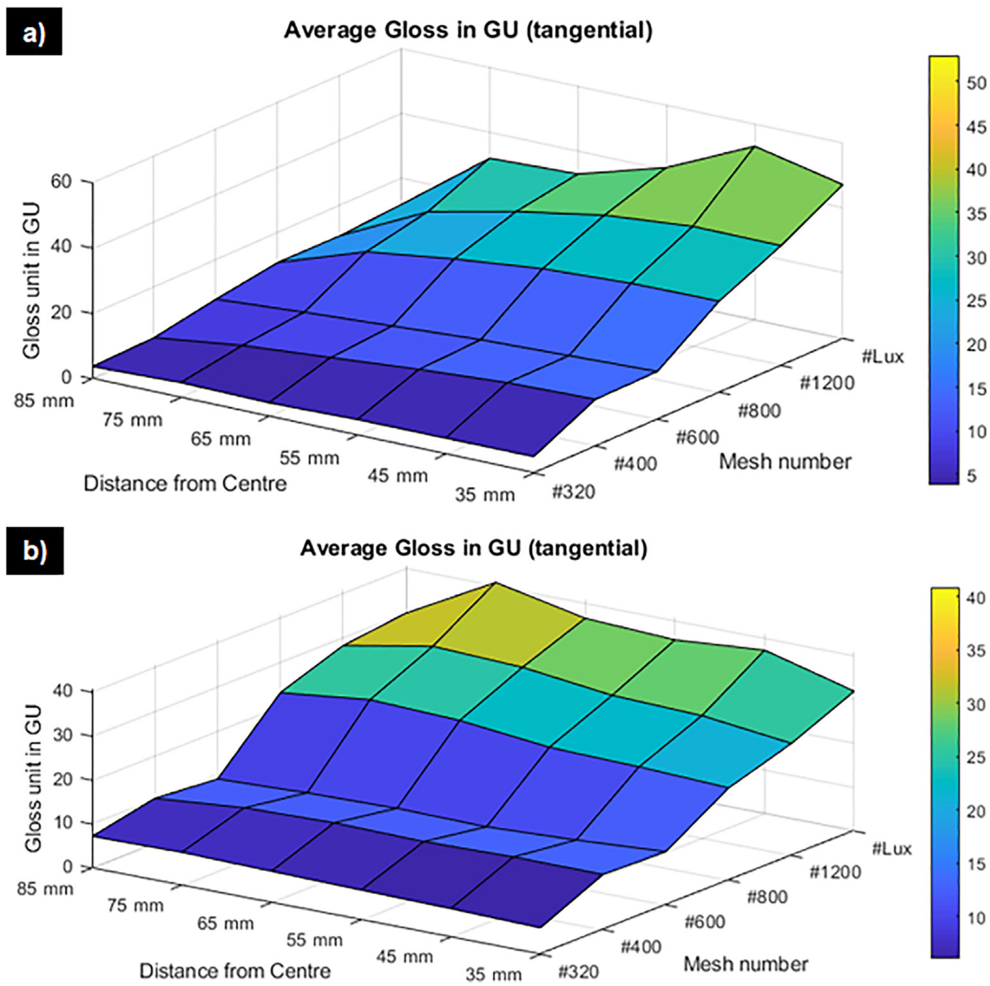

Fig. 5. Gloss Unit measured in direction tangential to the tile's radius subjected to a) triangular distributed load and b) uniform distributed load.

experiments [2,6,13]. The coordinate measuring machine, glossmeter and mobile roughness measuring device were other hardware tools involved in contributing to the development of virtual as well as mathematical analyses and displays. Raw data acquired from the tile polishing processes were successfully interpreted using LabVIEW programs and spreadsheets.

There were six different mesh sizes of abrasive blocks used in the current work (#320, #400, #600, #800, #1200 and #Lux) [14]. Each abrasive block was prepared into a smaller block having the size of 60 mm length by 10 mm width and approximately 22 mm height. Fig. 1 shows a single abrasive block attached on the polishing tool for the experiment.

In this study, two abrasive blocks (known as fickerts) were used as the polishing tools. The abrasive block is inclined at 2.2° to allow the swinging motion of the grinding tools during polishing. As shown in Fig. 2(b), helical springs were installed in each holder. With the pivot joint in place, the inclination of the rotating axis with the drive axis is enabled for the tribometer to imitate the swinging motion of the rotating polishing heads in industrial production line. All the configuration mentioned above were carried out to produce a linear line contact between the grinding tools and the ceramic tiles. The line contact of the abrasive block has a radius with a theoretical value of 130 mm [9]. As reported by Hutchings et al. [9] the theoretical radius length of the abrasive block, which is according to the approximated operating conditions in the ceramic tile industry, could be determined prior to conducting the laboratory experiments. In this study, the arc circumference length, s and the theoretical radius length, R of the abrasive block is set to be 5 mm and 130 mm respectively, thus, a deflection angle, θ of 2.2° is obtained using the equation of circle arc length [6]. The tile polishing processes are repeated with the absence of the helical springs for data comparison. The effect of uniform load distribution on gloss gaining will be presented against the effect of linearly distributed load on the surface of the polishing tools. Fig. 3 illustrates the configuration of the polishing head consisting of two abrasive blocks (polishing tools) with and without the helical springs during the machining processes.

Prior to the laboratory work, the flat surface of the abrasive block (also known as fickert) is prepared to have an inclined surface or line contact between the block and the tile surfaces. The preparation of the fickerts follow the use of the common ceramic tiles similar to the previous work [6]. After achieving the line contact surfaces between both fickert and the tile surfaces, an unglazed ceramic tile with codename 'Black Onix' made by the Brazilian ceramic tile industry CECRISA was used for the gloss gaining experiments. The tile with a default height of 9 mm was resize into a square shape of 200 mm width by 200 mm length.

All polishing tests were carried out with the use of tap water as the flood coolant. The water is neutral with a pH number of approximately 7. The coolant flow rate was controlled by the CNC tribometer and set constant at 1 L/min during the polishing work. The process parameters selected for the entire experiments were tabulated in Table 1. The parameter was selected in accordance to the approximated operating conditions from the industrial polishing process as being reported by Hutchings et al. [9]. According to the equations derived from [6], the maximum

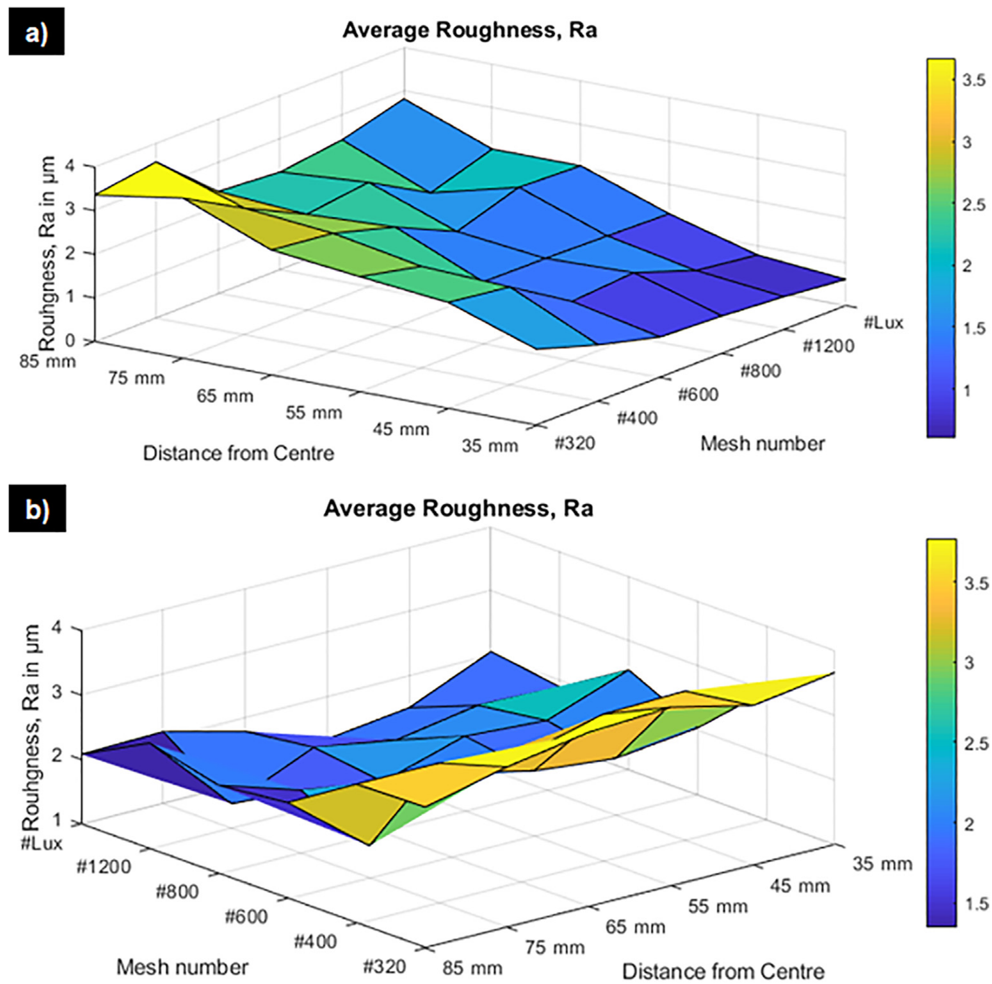

Fig. 6. Surface roughness measured from inner to outer side of the tile surface subjected to a) triangular distributed load and b) uniform distributed load.

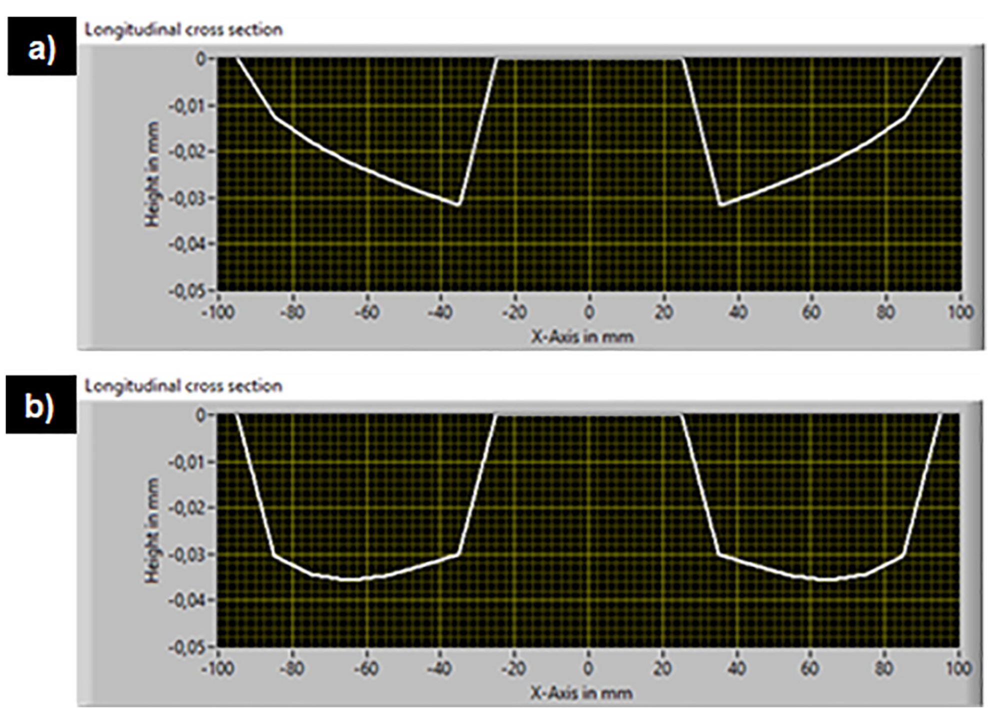

Fig. 7. Wear depth of the polished surfaces measured from the tile center after being subjected to a) triangular distributed load and b) uniform distributed load.

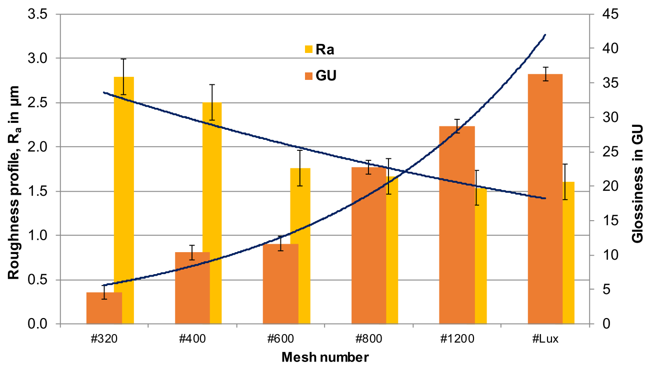

Fig. 8. The correlation of glossiness values and roughness profiles.

pressure exerted by the presence of the helical spring is governed by the spring constant, *c*, the deflection angle, as well as the geometrical size of the abrasive block, thus a concentrated pressure of approximately more than 15 MPa on the inner region of the machined surface can be obtained. The maximum pressure is applied on the inner region of the machined ceramic tile's surface compared to the outer region due to the elongation and compression of the spring during the polishing kinematics.

The 'Black Onix' tile sample was honed with all the six different abrasive grit sizes of the abrasive tools from #320 until #Lux subsequently after each other. This includes honing with defined period and measuring the surface topography of the ceramic tile and the abrasive blocks, the glossiness level as well as the roughness profiles. The kinematics of the ceramic polishing process consists of circular clockwise rotations about the tile center. During this experiment, each honing cycle of the fickert lasts for 125 s. The changes of the tile's glossy surface were recorded. After each honing process, the topography of the grinding tools was measured. Subsequently, glossiness and surface roughness of the polished ceramic tiles were measured using the instruments. The tile was clean and dried prior to each measurement of process output. Fig. 4 depicts the complete logical approach of the current project methodology as a circular process.

3. Results and discussion

The experimental evidence on gloss gaining and evolution of surface roughness by polishing the tile sample against two abrasive tools with uniform and with triangular distributed load provides an overview of the development of wear on the ceramic tile surfaces. A significance effect to the development of glossiness and finer surface roughness could be seen from the results as illustrated in Fig. 5.

It is interesting to note that the findings in both Figs. 5 and 6 are consistent with the effect of pressure gradient studied in previous work [6]. According to both figures, the glossiness level (GU) measured in the tangential direction on the tile surface, is inversely proportional to the surface roughness, R_a. A finer surface finish means a high value of gloss as the gloss is seen as the reflection of light due to the incident angle on the surface structure [15]. Lowest surface roughness depicts the highest gloss level of the ceramic tile's surface.

It was reported in literatures [7,9,16] that surface roughness attained after a duration of polishing was affected only a little by the applied load. Load had a noteworthy effect on gloss, in contrast to surface roughness, higher load leads to higher value of gloss. As for pressure that was exerted on the machined surface subjected by the polishing tools fitted with the helical springs, it is recognized that the inner region of the polished tile suffers much pressure than the outer region and can be calculated by the equations given in [6]. The triangular distributed uniform pressure that exerted on the abrasive surfaces is affected by the helical spring stiffness value [6]. The two springs created force moments with the line of action is passing through the abrasive holder pivot joint. Thus, focusing the pressure more on the area where the spring is compressed, and less on the side where the spring is elongated during the polishing process.

It can be concluded from the diagrams illustrated in Figs. 5, 6 and 7 that the relationship between gloss level, surface roughness and the tile wear depth, suggested that the highest gloss value measured in gloss units (GU) is found at the highest depth of the machined surface with the lowest value of R_a and where the highest load was exerted (approximately more than 15 MPa). According to literatures [2,7,9], the machining mode influences the surface quality of the machined samples. With smaller grain sizes, a higher load cannot cause the abrasive grains to penetrate the ceramic deeper than the critical cutting depth due to the grain projection being lower than the critical cutting depth, which will then maintain the machining process in ductile-mode rather than brittle-mode [17,18]. Hutchings et al. [9] stated that, coarse abrasives do not enhance the surface gloss. It was reported that the gloss started to improve and increase steadily only after the abrasives with mesh number 400 and above. The gloss increased substantially over time during the experiments, which indicates that the applied loads were distributed evenly across the machined

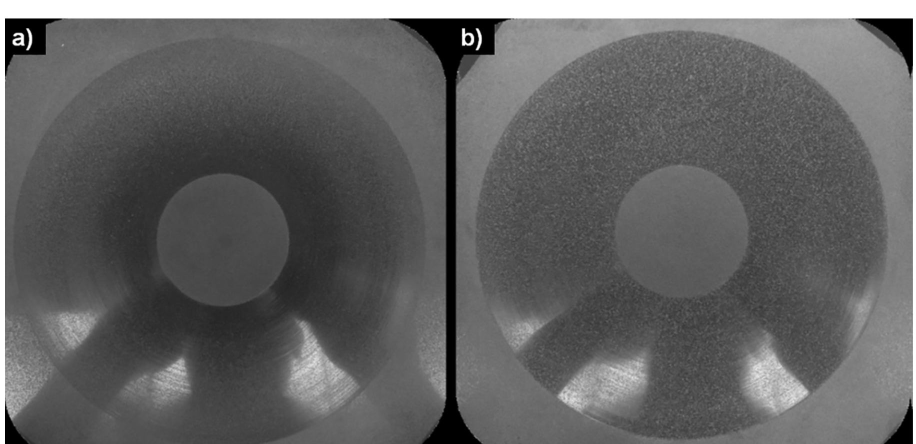

Fig. 9. Scratching score and the development of gloss on the ceramic tile being subjected to a) triangular distributed load and b) uniform distributed load.

surface of both abrasives and tile. The wear of the ceramic tile was also evenly distributed as shown in Fig. 7 and therefore, confirms the standard law of wear by Archard's and Rabinowicz which agreed that, by keeping all other parameters to be constant, the tile's surface wear is proportional to the applied contact load [2].

The average highest gloss level on the polished tile surface subjected by the triangular distributed load is presented in Figs. 8 and 9 and can reach up to approximately 36 GU with average roughness profile of about 1.7 μm. The effect of gloss gaining due to the maximum surface pressure exerted by the presence of the helical springs can be seen in the inner region of the machined surface as shown in Fig. 9(a). There is a significant correlation between the development of gloss and surface roughness profiles as shown in the diagrams. The gloss rises exponentially with the exponential decrease of the roughness. Except for #600, the gloss gaining effect shows a smooth exponential increase, while roughness profile decreases subsequently. This phenomenon can be explained by the predominant brittle-mode machining which is indicated by the high material removal indicated in Fig. 7(b). According to Hutchings et al. [9,19], the surface quality of the ceramic tiles being polished with increased mesh number of abrasives was depended on the polishing time. It was especially significant for the finer grit sizes (here: #400 until #Lux) and less beneficial for larger abrasive particles (here: #320). Surface gloss is a more sensitive parameter when determining surface quality than surface roughness and therefore, is more important in the final polishing stages. Different from literatures [2,6,8,11], there were more than six abrasive meshes used, thus, a better surface finish was achieved as compared to the results shown in present study.

A possible explanation on the wear development of the machined porcelain ceramic tiles surfaces in the present experiments as compared to other studies is the larger cumulative number of contacts and the polishing period as well as the number of polishing tools used. The chosen kinematics played a huge influence on the distribution of abrasive contacts over the surface under polishing and as a result, on the surface profiles [20–23]. The influence of the abrasive structure and geometric properties, such as scratch distribution and overlapping degree between the successive scratches; e.g. flat surface versus line contact surface, could be another reason for these differences [24].

4. Conclusion

In this study, the effect of pressure gradient during polishing process of ceramic tiles with line contacts has been successfully investigated. The highest concentrated surface pressure exerted on the inner region of the tile's surface is approximately more than 15 MPa due to the deflection of the helical springs and the geometrical variation of the polishing tools. The results of this study also supported the idea that pressure caused an influence on the gloss gaining and fine surface roughness but also higher surface wear. The high surface pressure on small contact area (line contact) does not necessarily imply on a good surface finish of the ceramic tiles with the increasing sequence of abrasives, which is shown by the result from the polishing process without the presence of the helical springs. However, the gloss development is dependent on the polishing time as well as the increased abrasives' mesh number. The results also suggested that the polishing line in the manufacturing of ceramic tiles will produce higher wear rate on coarse abrasives and higher gloss gaining as well as less wear rate of the finer abrasives being subjected to a multiple scratched ceramic tile. Increasing the number of the polishing machine especially for the finest grain sizes of the fickerts could produce high glossiness level in the ceramic tiles production line thus, cutting manufacturing costs and reducing waste altogether. The current findings add to a growing body of literature on manufacturing technology of honing process in describing the importance of process functions such as grinding speed, feed rate, scratching angle, number of contacts, process kinematics and geometrical changes of the mechanical and physical arrangement of the polishing tools.

CRediT authorship contribution statement

Amiril Sahab Abdul Sani: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Fábio José Pinheiro Sousa:** Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Software, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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