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Development of surface finish during the polishing of porcelain ceramic tiles

I. M. HUTCHINGS*, Y. XU, E. SÁNCHEZ‡, M. J. IBÁÑEZ‡, M. F. QUEREDA‡
Institute for Manufacturing, Department of Engineering, University of Cambridge, Mill Lane, Cambridge CB2 1RX, UK
E-mail: imh2@cam.ac.uk

Polishing tests on a laboratory scale have been used to simulate and study the industrial polishing process for unglazed porcelain ceramic tiles. Tile surface quality was assessed in terms of roughness and optical gloss. Tests with a sequence of progressively smaller silicon carbide abrasive particles showed a general trend of decreasing roughness and increasing gloss during the process. The coarser abrasives (larger than 400 grit number) caused the major change in surface roughness, while the finer abrasives (smaller than 400 grit number) produced the major change in gloss. In these materials the maximum gloss achievable by polishing is limited by the porosity of the ceramic. The rate of material removal during polishing with a coarse abrasive obeyed an Archard-type wear law, being linearly proportional to applied load, although load had little effect on the surface roughness attained after different durations of polishing. In contrast, load had a significant effect on gloss, with higher loads leading to higher values of gloss. The development of both roughness and gloss with polishing time is well described by quantitative empirical models involving a simple exponential function. The same model for gloss evolution is also shown to apply to data reported from industrial-scale polishing experiments in previous work.

1. Introduction

Polished unglazed porcelain ceramic tiles show high mechanical strength and chemical, stain and frost resistance, and also offer aesthetic advantages over glazed ceramic tiles. They are therefore being increasingly used in high specification architectural applications. The polishing operation during manufacturing involves the use of a succession of polishing stages (typically twenty or more) with steadily decreasing abrasive particle size. The abrasive particles, usually silicon carbide, are embedded in a magnesium oxychloride cement matrix to produce composite tools which are mounted on a rotating polishing head which presses against the tile surface. Polishing typically accounts for more than 40% of the total cost of the product, and current industrial polishing processes involve high wear of the grinding/polishing tools, high energy consumption, the production of large amount of polishing waste, excessive numbers of rejected products and poor control of final product quality. Previous studies have been carried out to investigate the mechanisms of polishing by different sizes of abrasive particles, with emphasis on the influence of the polishing conditions and the mechanical properties of the tiles or polishing tools [1–5]. Studies have also been made of the related problem of the polishing of natural stone, such as granite [6]. However, these studies have not provided detailed quantitative information on the development of surface finish (as described by roughness and optical gloss) during the polishing process.

In this work, a complete sequence of polishing stages was carried out with a laboratory-scale polishing rig to determine the changes which occur in the tile surface. This experimental method has been shown in previous work to replicate the key features of the industrial-scale polishing process [7]. In addition, tests were carried out to investigate the influence of contact load and abrasive particle size. Polished tile surfaces were characterised in terms of their roughness and gloss, and were examined by SEM.

2. Experimental method

A laboratory-scale polishing rig has been designed to simulate, as far as possible, the important features of the industrial polishing conditions. A full description of the apparatus and the experimental conditions has been published elsewhere [7]. It uses an automatic metallographic polishing machine with sample drive head (Struers Ltd.: RotoForce 3 and RotoPol 35). Abrasive pins (made from the same cement-based composite material as the industrial polishing tools) were mounted in

* Author to whom all correspondence should be addressed.
‡ *Present address*: Instituto de Tecnologia Cerámica, Universitat Jaume I, Castellón, Spain.

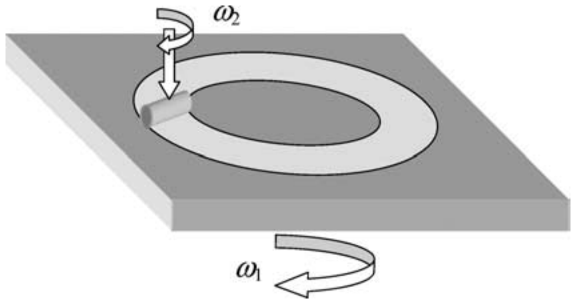


Figure 1 Schematic diagram showing the relative motion between the abrasive pin and tile sample.

the upper, rotating metallographic sample holder, and square tile samples were mounted on the lower, rotating disc normally used for the metallographic polishing cloth. Cylindrical abrasive pins 12 mm in diameter and 10 mm long were produced from a silicon carbide—cement composite with specifications conforming to normal industrial practice by Abrasivos de Castellón, Castellón, Spain. A single abrasive pin was used for each test. The tile samples 100 mm square were cut from a single batch of standard porcelain tiles supplied by Instituto de Tecnología Cerámica, Castellón, Spain. Fig. 1 shows a schematic diagram of the relative motion between the abrasive pin and the tile sample.

The abrasive pin was mounted with its axis parallel to the plane of the tile as shown in Fig. 1, and rotated about a vertical axis in the motorized head of the tribometer with angular velocity $\omega_2 = 150$ rpm. The pin was pressed against the tile surface under a pneumatically-controlled normal load, in the range from 17 to 50 N. A load of 17 N corresponds to the load per unit contact length (1.7 N mm^{-1}) typical of industrial practice [7]. The tile sample, fixed to the lower disc, also rotated about a vertical axis, with angular velocity $\omega_1 = 300$ rpm. The inner radius of the annular polishing track was 23 mm.

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. 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 the polishing experiments. This was 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 relative speed of the abrasive pin relative to the tile surface varied slightly across the wear track, from 0.8 to 0.96 m s^{-1}, but this did not cause any significant difference in the polishing effect on the tile surface.

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.

3. Laboratory polishing tests and discussion

3.1. Sequential polishing tests

Experiments were 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 porcelain tile was polished in sequence by the full range of grit sizes available from the largest grit size (number 36) to the smallest grit size (number 1500). The numbers describe the abrasive particle size using the standard FEPA mesh-size designation and the sequence employed was: 36; 46; 60; 80; 100; 120; 150; 180; 240; 320; 400; 600; 1000; 1500.

Before polishing, the tile surface was initially abraded with a diamond-impregnated fixed abrasive wheel (Struers Ltd., 250 μm particle size) in order to obtain a flat rough initial surface. All abrasion tests were performed with the contact region flooded with a copious supply of tap water. The tile was polished under the standard conditions described above (with a normal load of 17 N) using 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 give total polishing times of 180 and 300 s with this abrasive.

Fig. 2 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 grit size (1500) 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. For each grit size, the surface quality depended on the polishing time, with longer polishing times being

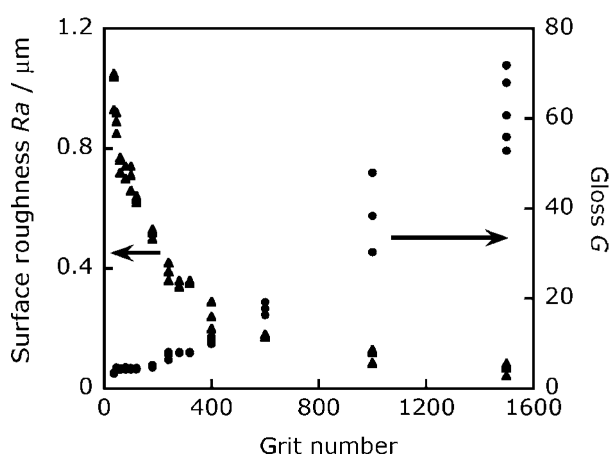


Figure 2 Surface roughness *Ra* and gloss *G* as a function of grit number of abrasive pin, for the full sequence of polishing steps. Polishing was carried out with each size for 15, 30 and 60 s; in the case of 1500 grit number, it was then continued for total periods of 180 and 300 s.

beneficial, especially for the smallest abrasive grit (numbers 600, 1000, and 1500). For the larger abrasive particles (small grit numbers) however, the effect of extending the polishing time from 30 to 60 s was not great.

In this test sequence the development of surface finish can be divided into two stages. For abrasive grit numbers below 400 (i.e., the larger grit particles), there was little improvement in gloss although the roughness was substantially reduced. The smaller abrasives, with grit numbers above 400, had a significant effect on the gloss but the corresponding change in roughness was small.

3.2. Effects of abrasive size and applied load on material removal and surface finish

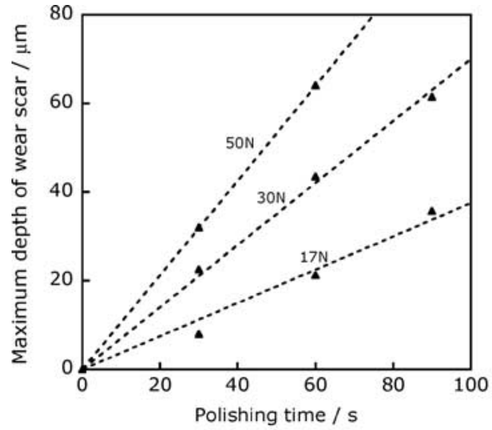
The applied load might be expected to affect both the rate of removal of material from the tile, and also the development of surface finish. Experiments were therefore carried out to investigate the influence of load, for abrasives of different sizes. Two abrasive particle sizes were used for this investigation: large (60 mesh), representative of the range of sizes where the major effect of polishing is on roughness, and small (1000 mesh), where the major effect is on gloss. Loads ranged from 17 to 50 N (i.e., 1.7 to 5 N mm^{-1} contact length) and the initial state of the tile was fully polished (i.e., as-received from an industrial polishing line). The other experimental conditions were as described in Section 2.

Material removal from the tiles was assessed in terms of the depth of the centre of the annular wear scar relative to the neighbouring unworn surface, measured by stylus profilometry. Fig. 3a shows the depth of the wear scar as a function of polishing time and load for the larger abrasive size (60 mesh). The relationship between depth and polishing time was essentially linear for each load, and the slopes of the lines also increased linearly with load as shown in Fig. 3b. This behaviour is consistent with a simple linear wear law of the Archard or Rabinowicz type [8]. The depth of the wear scar produced by the 1000 mesh abrasive was small compared with the grit size (ca. 5 μm) or the flatness of the surface, and could not therefore be measured accurately.

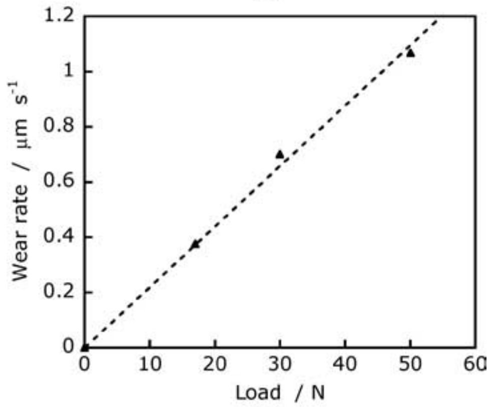
In experiments designed to study the effects of load and abrasive size on the development of surface finish, abrasive pins with mesh sizes 46 and 600 were used to polish the tile surfaces for 90 s in each test before the 60 or 1000 mesh abrasive was used, since these are the sizes used in the preceding steps in the industrial situation. The loads used on the pins were 17 or 30 N for both abrasives. The tiles were polished under the standard conditions described in Section 2 with each abrasive pin for 15 s, then for a further 15 s and then for two further steps of 30 s. After each increment of polishing, i.e., for a total of 15, 30, 60 and 90 s exposure to each size of abrasive, the surface roughness *Ra* and gloss *G* of the polished track surface were measured.

Fig. 4 shows the surface roughness *Ra* of the tile surfaces polished with 60 mesh abrasive under applied loads of 17 and 30 N. The roughness decreased with increasing polishing time for the two values of load. In both cases, the greatest reduction in roughness occurred over the first 30 s. of polishing. The roughness of the tile polished at the lower load was little different from that polished at the higher load. There was almost no change in the gloss of the tile surface after polishing with the 60 mesh abrasive, which is consistent with the results shown in Fig. 2 above.

Fig. 5 shows the gloss *G* of the tile surfaces polished with 1000 mesh abrasive at different applied loads. The



(a)



(b)

Figure 3 (a) Maximum depth of polishing track (wear scar) as a function of polishing time with 60 mesh abrasive, at three different loads. (b) Wear rate (expressed as mean rate of increase of depth of wear scar) plotted against applied load.

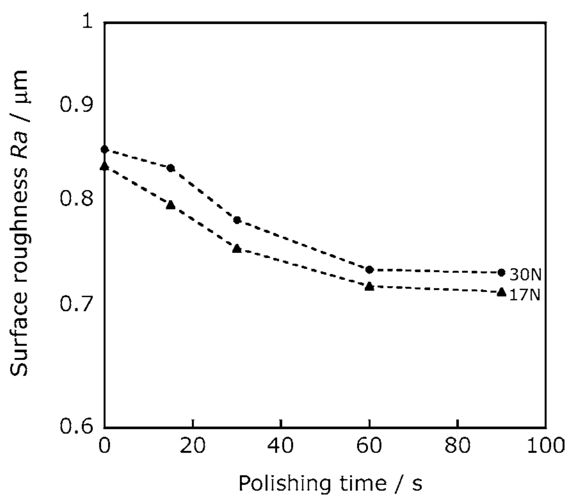


Figure 4 Evolution of surface roughness for tiles polished by 60 mesh abrasive, at two different loads.

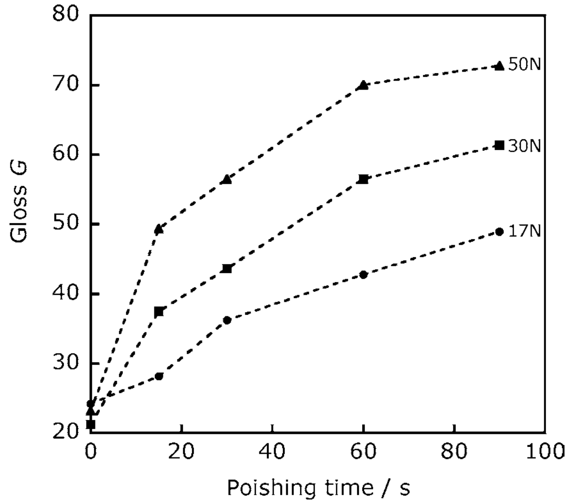
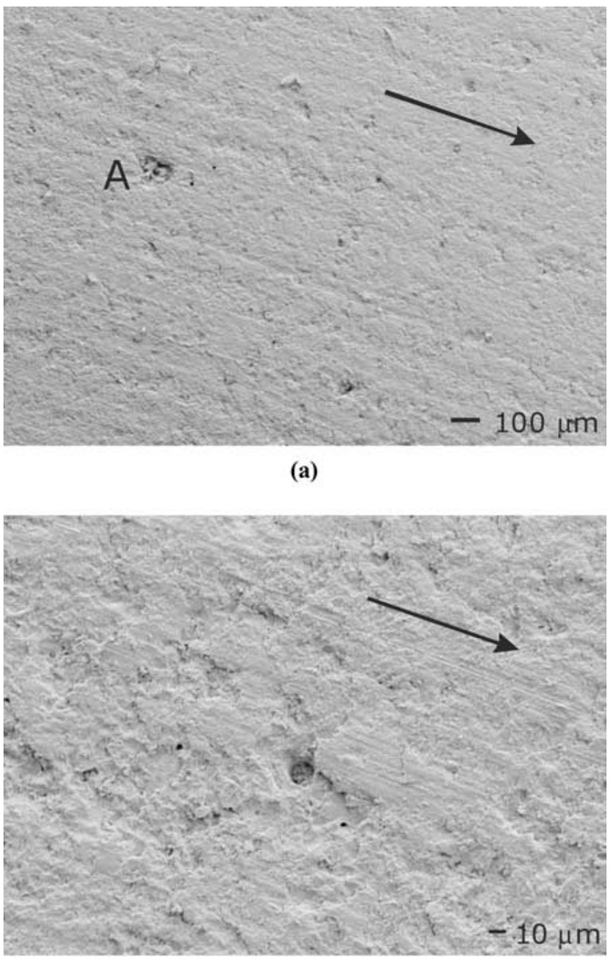


Figure 5 Evolution of gloss for tiles polished by 1000 mesh abrasive, at three different loads.



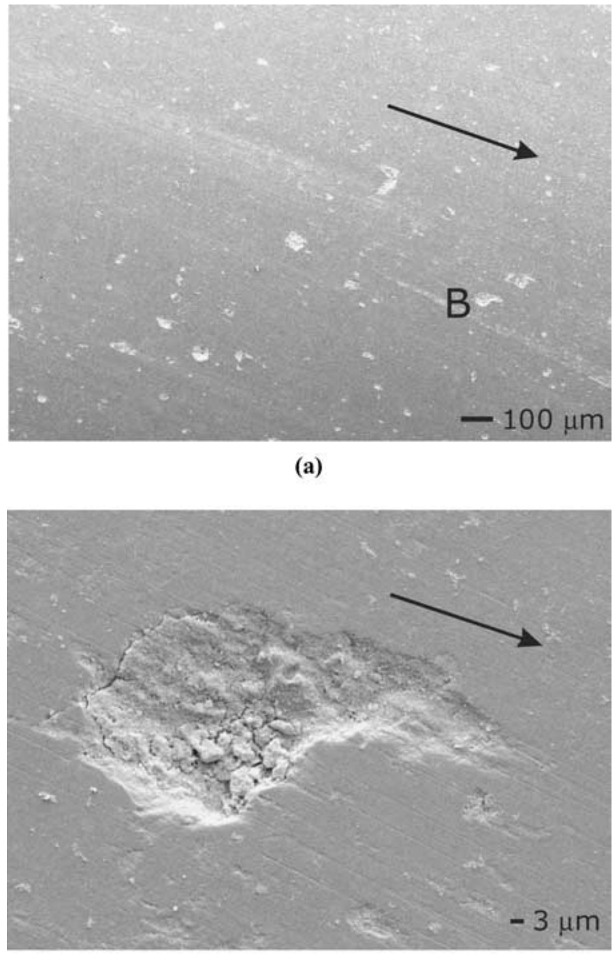
(a)

(b)

Figure 6 SEM images of tile surfaces polished by the 60 mesh abrasive grit, showing grooves in the polishing direction (arrows) and porosity (A).

gloss increased substantially over time during each test, and the maximum gloss was much higher at the higher loads. As in the sequential polishing tests reported in Section 3.1, the surface roughness did not change significantly with these small abrasive particles.

Figs 6 and 7 show representative SEM images (with secondary electron imaging) of tile surfaces polished at loads of 17 N by 60 mesh and 1000 mesh abrasives, respectively. The rougher surface associated with the coarser abrasive in Fig. 6 is characterised by linear grooves in the polishing direction (shown by the arrow). Pores are present, for example marked A in Fig. 6a, but do not contribute significantly to the overall roughness of the surface, which is dominated by surface features caused by the polishing process. In contrast the tile polished with the 1000 mesh abrasive (Fig. 7) shows a much smoother surface, but still with evident pores, as seen at higher magnification in Fig. 7b. Localised material removal is evident around the edges of this pore. Polishing tracks are not so evident as in Fig. 6, but examination at high magnification shows them to be about 0.1 to 0.3 μm wide, significantly smaller than the wavelength of the green light (about 0.5 μm) used in the optical glossmeter. For tile samples polished with the small abrasive particles, it is therefore likely that the pores in the surface play a major role in determining the limiting value of surface gloss which can be achieved; in these porcelain ceramics the porosity is typically 5–8% by volume [5].



(a)

(b)

Figure 7 SEM images of tile surfaces polished by the 1000 mesh abrasive grit, showing very fine grooves in the polishing direction (arrows) and significant porosity (B).

3.3. Quantitative models for the evolution of surface roughness and gloss

The results presented in Fig. 2 show that while some of the polishing stages had significant influence on both gloss and roughness, others apparently had little effect. It is possible that the relatively loose commercial tolerances in neighbouring abrasive particle size distributions may have been responsible for this. Among the larger abrasive sizes, grit numbers 36, 60, 180, 240 and 400 had the most significant effect on the surface roughness *Ra*, and among the smaller abrasives, grit numbers 400, 600, 1000 and 1500 had the greatest influence on the gloss G. The major change in surface roughness occurred in all cases over polishing periods of 15 to 30 s, and while the major change in gloss took place over a similar time-scale for the larger abrasives (400 and 600), for the smaller abrasives (1000 and 1500) there were significant changes over longer periods.

The results shown in Figs 4 and 5 suggest that the roughness and gloss may follow an exponential trend with increasing polishing time for any individual abrasive size, and empirical models for the evolution of the surface properties were therefore developed. It was assumed that when a tile surface with initial roughness R_o and initial gloss G_o is polished, the surface roughness will decrease with increasing polishing time towards an asymptotic value R_∞, with a characteristic time τ_1. The gloss will increase with polishing time, tending asymptotically to a value G_∞ with a characteristic time τ_2. For any abrasive grit size and polishing conditions, the values of τ_1 and τ_2 might in principle be different. G_o and R_o would be expected to be the gloss level and roughness resulting from the preceding polishing step, while G_∞ and R_∞ are the gloss level and roughness which would be developed after an extended period of polishing with a given grit size.

Equations 1 and 2 show simple relationships between surface roughness, gloss and polishing time t implied by the above models:

$$R(t) = R_\infty + (R_o - R_\infty)\exp(-t/\tau_1) \qquad (1)$$

where R = roughness of the polished tile at time t during the polishing process; R_o = roughness of the initial tile surface; R_∞ = asymptotic surface roughness; τ_1 = characteristic polishing time for roughness evolution.

$$G(t) = G_\infty - (G_\infty - G_o)\exp(-t/\tau_2) \qquad (2)$$

where G = gloss of the polished tile at time t during the polishing process; G_o = gloss of the initial tile surface; G_∞ = asymptotic value of gloss; τ_2 = characteristic polishing time for gloss evolution.

The experimental data for the abrasive sizes with significant effects on surface roughness or gloss are plotted in Figs 8 and 9. The broken lines show the predictions from Equations 1 and 2 fitted to the data for each grit size. Tables I and II list the corresponding values of R_o, R_∞, τ_1, G_o, G_∞ and τ_2. While the data were fitted well by assuming the same characteristic time of 20 s for the evolution of roughness with all the abrasives, and for the evolution of gloss with grit sizes 400 and 600, a much longer time of 60 s was found to be appropriate for the finest abrasives (1000 and 1500 mesh). This is consistent with the observation from Fig. 2 that

TABLE I Empirically determined values of the constants in Equation 1 for different abrasive sizes

Grit number	R_o	R_∞	τ_1 (s)
60	1.20	0.94	20
180	0.85	0.72	20
240	0.61	0.49	20
400	0.36	0.20	20

TABLE II Empirically determined values of the constants in Equation 2 for different abrasive sizes

Grit number	G_o (μm)	G_∞ (μm)	τ_2 (s)
400	8.0	11.7	20
600	11.7	19.7	20
1000	19.7	65.3	60
1500	48.1	68.1	60

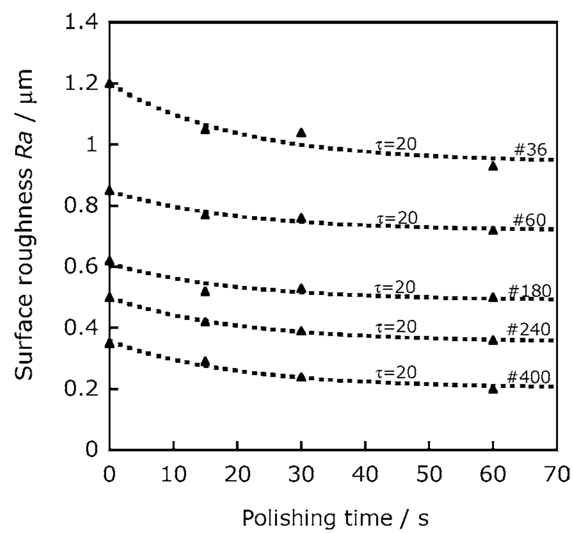


Figure 8 Evolution of surface roughness for polishing with different grit sizes. The broken lines show the predictions from the empirical model of Equation 1 and Table I.

prolonged polishing with these sizes led to significant improvement in gloss.

In order to examine the validity of the empirical model further, Equation 2 was also used to fit the data reported from another study of ceramic tile polishing. Wang *et al.* [4] carried out industrial-scale experiments on porcelain tiles using polishing wheels with a range of silicon carbide and alumina abrasives. Their tile samples were different in size, composition and mechanical properties from those used in the present work, but the trends in the development of surface quality were similar to those reported above, with surface roughness decreasing and gloss increasing as the polishing process proceeded. Fig. 10 shows their measurements for a tile sample polished with 600 grit size silicon carbide for 240 s and then polished with finer alumina abrasive, of unspecified size, for a further 240 s. It is evident that for the larger particles, there was little change in gloss after about 150 s, while for the finer abrasive improvement in gloss continued for a significantly longer period of polishing. This result is similar to the observations reported above. The broken lines in Fig. 10 show the

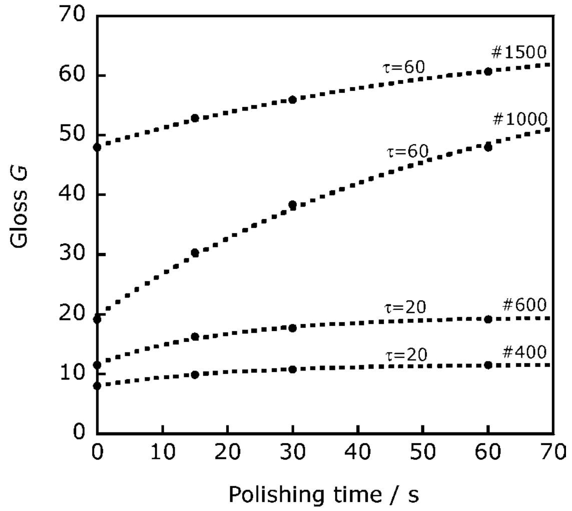


Figure 9 Evolution of gloss for polishing with different grit sizes. The broken lines show the predictions from the empirical model of Equation 2 and Table II.

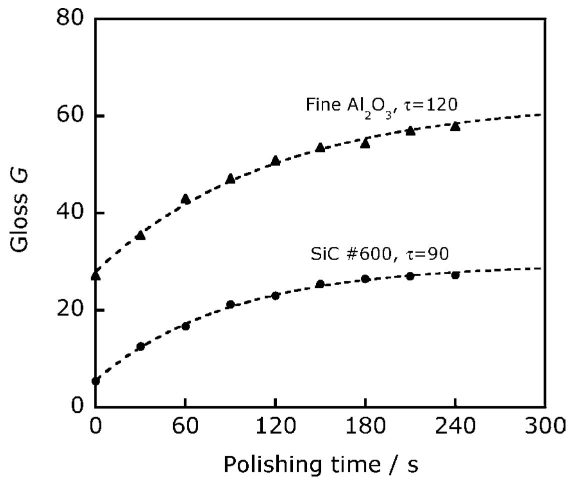


Figure 10 Experiment results reported by Wang *et al.* [4], for a tile sample polished with a grinding wheel with 600 grit size silicon carbide abrasive for 240 s, followed by fine alumina abrasive for another 240 s. The broken lines show the predictions from the empirical model of Equation 2.

predictions from Equation 2 with characteristic times of 90 and 120 s for the two sizes of abrasive. As for the results presented earlier, the model provides a good fit to these data.

4. Conclusions

Polishing tests with a sequence of progressively smaller silicon carbide abrasive particles showed a general trend of decreasing roughness and increasing gloss during the process. The coarser abrasives (larger than 400 grit number) caused the major change in surface roughness, while the finer abrasives (smaller than 400 grit number) produced the major change in gloss. In these materials the maximum gloss achievable by polishing is limited by the porosity of the ceramic.

The rate of material removal during polishing with a coarse abrasive obeyed an Archard-type wear law, being linearly proportional to applied load, although load had little effect on the surface roughness attained after different durations of polishing. In contrast, load had a significant effect on gloss, with higher loads leading to higher values of gloss.

The development of both roughness and gloss with polishing time is well described by quantitative empirical models involving simple exponential functions. The same model for gloss evolution has also been shown to apply to data reported from industrial-scale polishing experiments in previous work.

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