POLISHING OF PORCELAIN STONEWARE TILES: SURFACE ASPECTS

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ABSTRACT

Porcelain stoneware can be considered a material in which the synergy between production technology and physical-mechanical properties is excellent. These characteristics allow use of this type of tile both indoors and outdoors, where reliable behaviour and high performance are required. To improve the aesthetic characteristics of these products and make them more competitive with natural stone, polishing of the proper surface has become a very widespread industrial process.

Reported in the present paper are the results of Vickers hardness tests, roughness measurements and extensive microstructural observations using optical and scanning electron microscopy, of the proper surface of some commercial porcelain stoneware tiles: i) as fired and ii) polished. To study the evolution of the surface morphology, stage by stage, an interrupted laboratory machining procedure, starting with grinding and ending with polishing, was established. The improvement in the surface was evaluated on the basis of the reduction and/or complete removal of the grinding induced damage. Based on the results obtained, a model explaining the aspects related to the machining of the proper surface of porcelain stoneware tile is suggested, in which the microstructure of the material represents the limit condition.

1. INTRODUCTION

As compared with other classes of tiles, porcelain stoneware tile is characterised by a very high density which gives these tiles excellent characteristics of bending strength, resistance to surface abrasion, stains resistance, surface hardness and a relatively high fracture toughness [1].

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In the case of ceramic floor tiles, the proper surface is particularly subjected to various types of environmental stress and, contrary to glazed tiles, in unglazed products the ceramic body is in direct contact with the environment. Even though this difference does not eliminate the sensitivity of the proper surface to impacts and other stresses, it can be favourable, especially in dense, homogeneous products such as porcelain stoneware, with more uniform bulk material characteristics. Consequently, the practice of polishing these products has been favoured by the possibility of easily masking damage and the fact that after removal of the surface layer by machining, the appearance of the tile is close to the original appearance.

Machining ceramic material is a particular and very expensive process. Material removal, due mainly to brittle fracture processes, involves stress conditions [2] and crack systems that cause degradation of the surface layer [3], relating to the fundamental crack systems induced by a Vickers indenter: i) radial cracks, responsible for strength anisotropy and degradation, and ii) lateral cracks, responsible for material removal [4]. Since, after the various stages of grinding which are generally very severe, the material retains an undesired residual stress field and a complex system of cracks, it becomes necessary to extend the machining process in order to restore the starting surface conditions as much as possible. To achieve this result, even though grinding induced damages should be first removed as much as possible, lapping is probably the most widespread surface finishing process [5].

Although polishing of the proper surface of porcelain stoneware tiles has become a usual industrial surface treatment, it is based more upon individual expertise than on a rigorous analysis of the machining parameters and their correlation with the microstructural characteristics. Since such information is for the most part lacking, the industrial procedure gives rise to several drawbacks related to the machining itself and the microstructural features of the material [6]. Consequently, strength anisotropy and degradation of the mechanical characteristics of the new surfaces are often observed [7]. During service, this technological memory, held in the surface layer, becomes a dangerous source of material removal. The nature of this process is evolutionary and depends on both the characteristics of the material and the intensity of the various types of environmental stress. The same problems encountered in machining advanced technical ceramics are also encountered in the machining of porcelain stoneware tiles.

2. EXPERIMENTAL

Three different commercial porcelain stoneware tiles, as fired and industrially polished, were selected for the present study and are denominated throughout the text as products 1, 2 and 3. To eliminate the influence of the production parameters, the tiles examined, for each type of product, were all taken from the same production lot. Suitable samples cut from the as fired tiles were polished in wet conditions using a laboratory

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bench grinder-polisher (Leco Co., VP-150, USA), following a well established laboratory machining procedure including six stages in sequence. The number of revolutions was kept constant, 150 rpm, and the other machining parameters are specified stage by stage in Table 1.

Stage	Abrasive grit, µm	Machining time, min	Applied pressure, MPa
I	60	30*	103
II	22	1	124
III	14	3	138
IV	10	60	159
V	5	60	193
VI	2	60	193

*seconds

Table 1. *Machining parameters used during the laboratory polishing.*

In order to explain the morphological evolution of the proper surface during machining, at the end of each laboratory machining stage, the samples were observed using both the optical and scanning electron microscopes. This technique made it possible to recognise, starting from grinding, areas particularly damaged and to examine their evolution throughout the machining process, stage by stage. At the end of each stage, the surface roughness parameters, average roughness R_a and maximum roughness R_M, were measured using a roughnessmeter (Hommel Tester, T2000, Germany). These measurements were also carried out on the proper surface of the corresponding as fired and industrially polished tiles.

The hardness of the proper surface of the as fired, industrially polished and polished in laboratory products by a hardness tester (Zwick, 3212, Germany), equipped with a Vickers indenter was measured. A suitable indentation load range was selected (1.96, 4.91, 9.81 and 19.62N), and the average hardness values were calculated considering at least ten valid impressions for each load[8].

4. RESULTS AND DISCUSSION

The plots of Vickers hardness vs. indention load for the products tested are reported in Figures 1 a, b and c. The behaviour of the three products is different even though in all cases the machining process always causes a decrease in surface hardness which is more marked after the industrial treatment than after the laboratory procedure. This behaviour is particularly evident in products 1 and 2, in which the laboratory polishing procedure allows complete (product 1) and partial (product 2) recovery of the original surface hardness. Since the machining procedure and parameters are constant, the different behaviour shown by product 3 can be attributed to its microstructural characteristics. The hardness curve of the as fired product 3 also differs significantly from those of products 1 and 2. The higher porosity of product 3 and its interference with the indenter, at increasing indentation loads, explains the hardness behaviour. The possibility of restoring, after machining, the starting surface hardness depends on local parameters, in particular the degree of the lack of homogeneity between the surface layer and the bulk material [6,9].

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Reported in Figures 2 a and b are the surface roughness parameters, average roughness R_a and maximum roughness R_M, measured after each machining stage. Also reported in the same graphs are the R_a and R_M values of the proper surface of the as fired and industrially polished tiles. For the three different products, these values when referred to the as fired proper surfaces are significantly different, depending on the asperities produced by the geometry of the mould. Furthermore, some common important aspects can be emphasised: i) R_a and R_M decrease rather quickly during the grinding stages, while the variations due to the polishing stages (10, 5 and 2 μm) are almost negligible, ii) the roughness parameters of the industrially and laboratory polished surfaces are very close, and iii) after the first grinding stage (60 μm), an increase in R_M is observed for products 1 and 2.

Since machining removes the surface unevenness and asperities, these results were to be expected. In the as fired proper surfaces, the high values of R_M have to be attributed to the unevenness rather than to the open porosity, which is almost zero in porcelain stoneware tile. Although the laboratory polishing completely removes the damages induced by grinding, it does not always result in a considerable decrease in R_M.

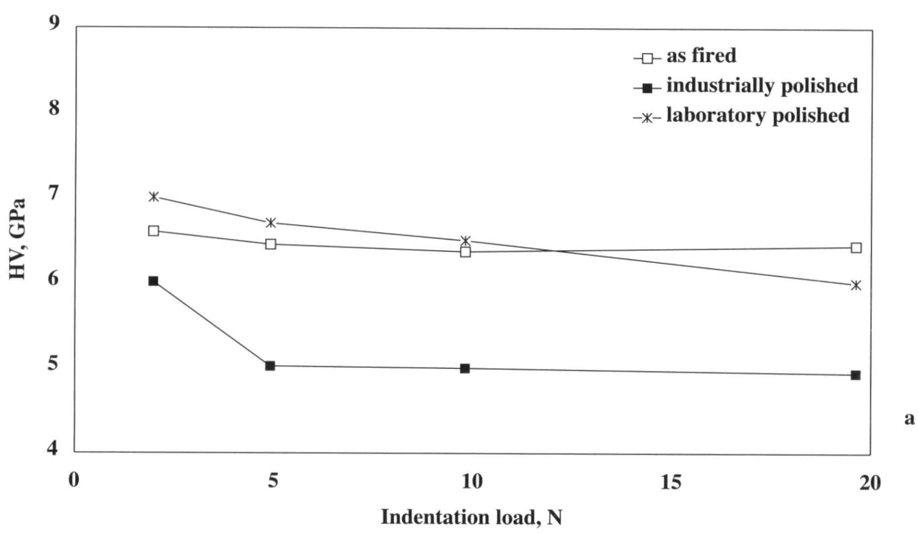


FIGURE 1-A

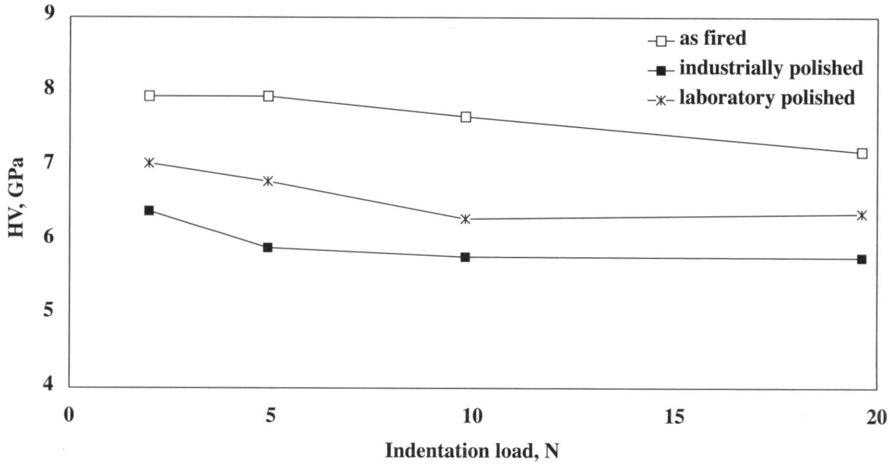


FIGURE 1-B

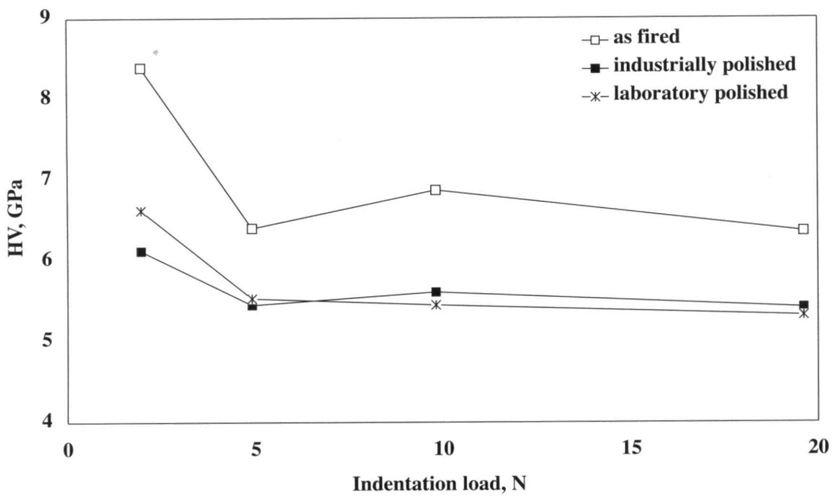


FIGURE 1-C

Figure 1. *Vickers hardness of the surface of the products as a function of the indentation load: a) product 1, b) product 2, c) product 3.*

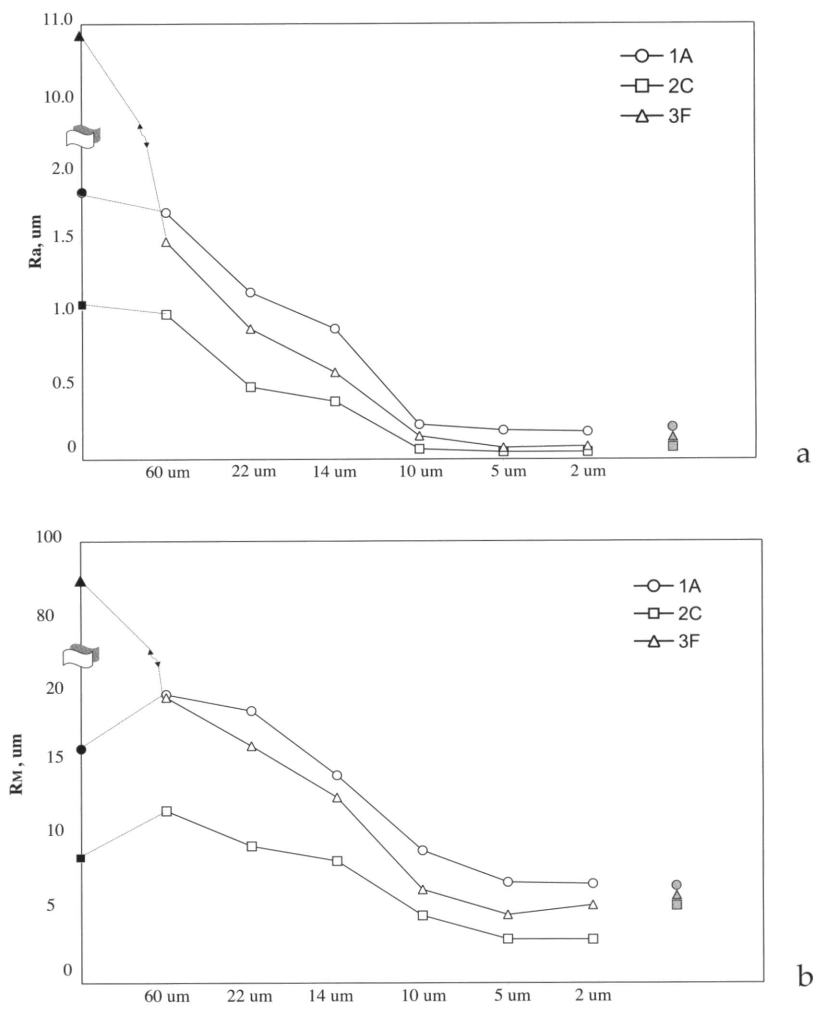
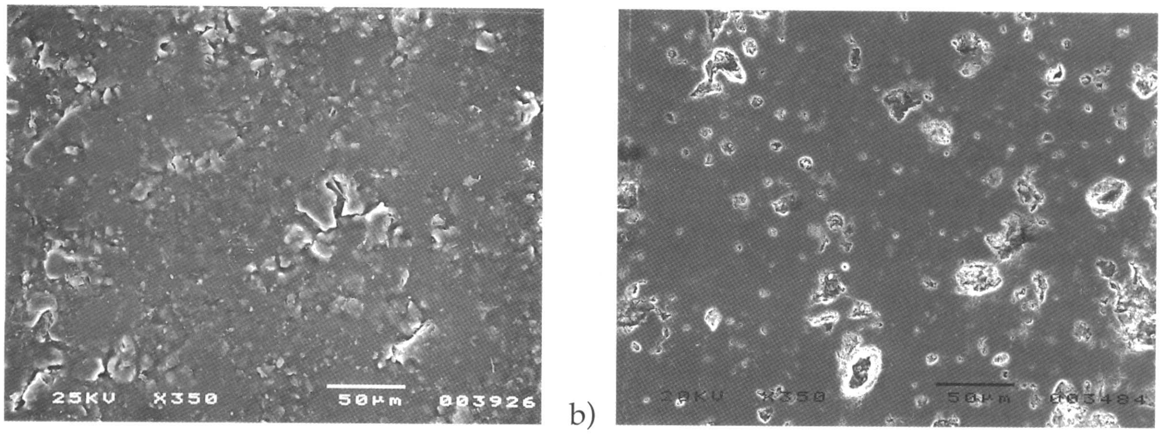
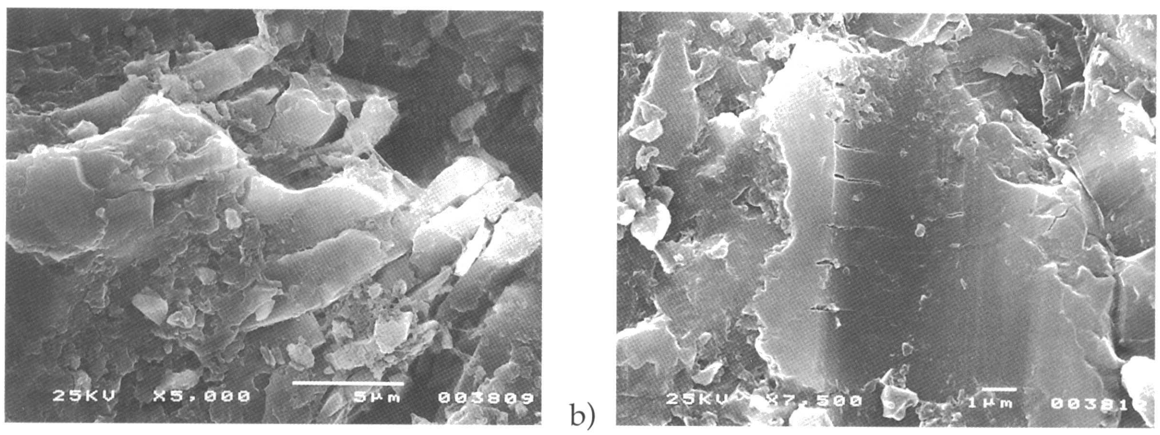


Figure 2. *a) Average roughness, R_a, and b) maximum roughness, R_M,), of the as fired samples (black symbols), and the polished samples after the different laboratory machining steps (dashed symbols) and after the industrially machining procedure (grey symbols).*



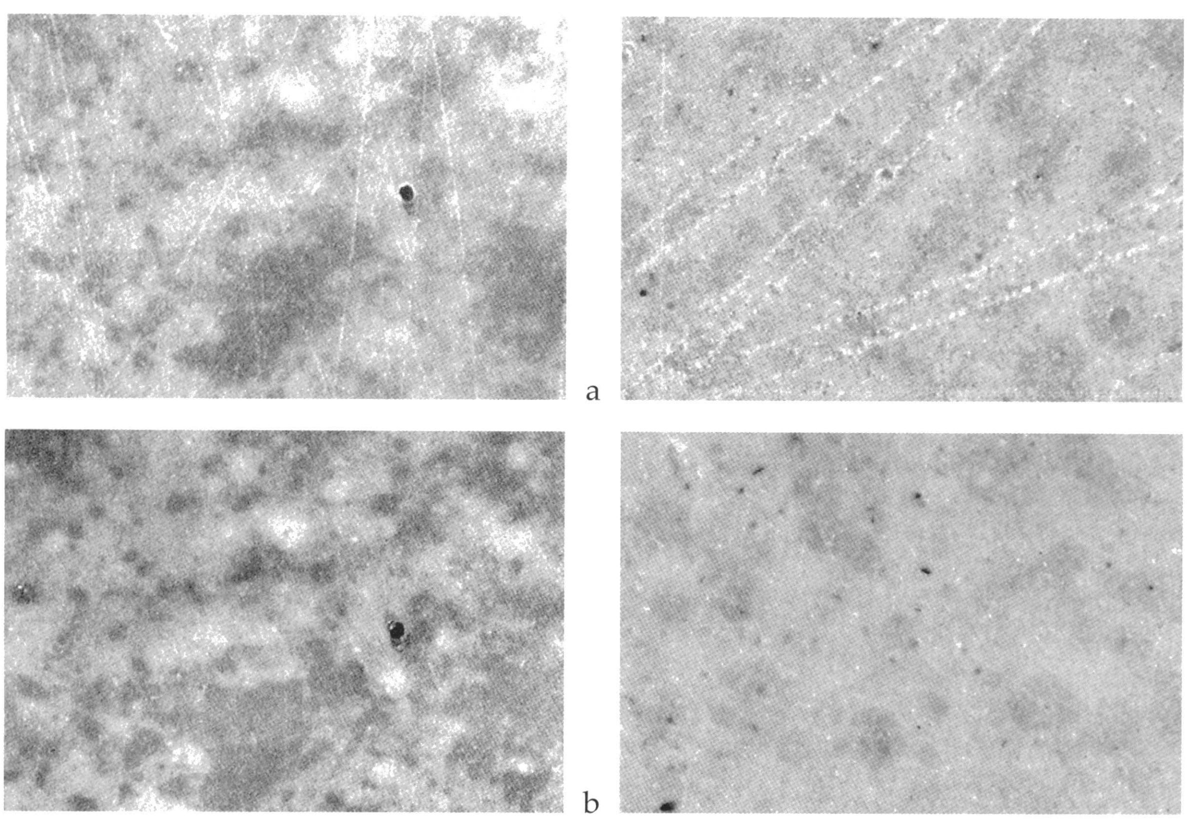
a) b)

Figure 3. SEM micrographs of the surface of product 1, a) as fired, b) after industrial polishing.

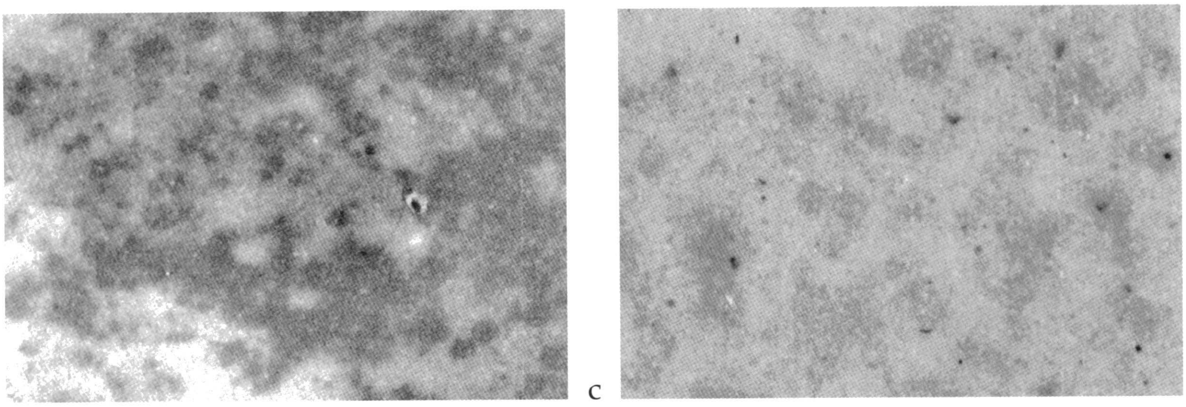


a) b)

Figure 4. SEM micrographs of surface damages caused by the first stages of the laboratory machining procedure, a) product 1, b) product 2.


a

b



c

Figure 5. Same areas of the surface of products 2 and 3 after the laboratory grinding stages with the a) 60 μm, b) 22 μm, and c) 14 μm diamond abrasive discs: product 2, on the left, magnification 8x, and product 3, on the right, magnification 17x.

Indeed, the maximum roughness, measured after polishing, does not depend only on the choice of the machining procedure and parameters

Fast industrial firing cycles lead to a lack of homogeneity in the microstructure along the cross section, characterised by different flaw distributions. The removal by machining of the more dense surface layer induces widespread damage and uncovers the closed or bulk porosity, which generally is higher than that present on the as fired proper surface (Fig. 3 a and b). Obviously, the geometry, morphology, orientation and distribution of these flaws are unknown and it is difficult to predict their influence on the roughness after machining. A machining procedure [5] can be considered to be correct when, after the complete removal of the damage induced by grinding (Fig. 4), the flaws present on the polished surface can be associated with the microstructural porosity.

The evolution of the proper surface during machining can be better understood considering the micrographs of Figure 5. Reported in this figure are the sequences of the same selected area of the proper surface of product 2 (on the left) and product 3 (on the right) after the laboratory grinding stages with the 60, 22 and 14 μm diamond abrasive discs. After stage I, induced damage is clearly visible on the surface of both products (Fig. 5 a). Some pores, uncovered by the removal of the surface layer, are also evident. At this first grinding stage, the following observations would seem to be important: i) grinding induces damages in the form of scratches and cuts, ii) removal of the surface layer uncovers the closed porosity and, iii) the ground surface is characterised by two concurrent flaw populations, one that can be ascribed to grinding and another that can be ascribed to processing. Figures 5 b and c show the positive evolution of the same surfaces constituted by a considerable reduction in the number and size of the scratches. The sequence of the micrographs for product 2 shows the reduction of the size of a closed pore, uncovered during the first grinding stage. The behaviour of the more porous product 3, however is different. Although there is reduction of the induced damages, the

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closed porosity uncovered by grinding stage I does not appear after grinding stage II. Indeed, the uncovered porosity is clearly different, like that after grinding stage III (14 μm). Although the grinding induced damages can be completely removed by a correct machining procedure, the microstructural features of the material represent an intrinsic limitation to the degree of surface improvement that can be reached. In this regard, the behaviour of product 2, more dense than product 3, is less sensitive to the lack of homogeneity between the surface layer and the bulk material, as a consequence of good processing.

On the basis of these results, a simple machining model can be suggested. Starting from the very small flaws present on the as fired proper surface due to the high degree of sintering of this class of tiles (water absorption < 0.1 %), the first grinding stage induces a dramatic worsening of the surface conditions. The subsequent less drastic stages improve the surface by progressively removing the scratches and cuts. Therefore, although the induced damages and more dangerous induced flaws are removed step by step, the uncovered closed porosity prevails and characterises the new machined proper surface.

Although the polishing stages with the 10, 5 and 2 μm diamond abrasive discs may further improve the surface conditions, i.e., by removing the residual stress, they are not able to overcome the microstructural features. Since these characteristics can be directly attributed to the processing, excessive extension of the polishing stage is not justified by the surface improvements that can be achieved.

The impossibility of restoring the original condition of the as fired unpolished proper surface can be explained in light of i) differences between the surface and bulk microstructure and, ii) intrinsic limitations of the machining procedure.

The behaviour of the Vickers hardness as a function of the indentation load (Fig. 1) is in agreement with the above considerations. The decrease in hardness due to the industrial machining can be attributed to i) differences in microstructure between the surface layer and the bulk material, ii) a widespread system of subsurface microdamage induced by grinding, still present after polishing, and iii) incorrect machining procedure and parameters. The industrial machining procedure not only induces scratches, cuts and detachment of material, but in removing the surface layer also uncovers the closed porosity. Therefore, in comparison with the as fired surface, the proper surface of the machined material is characterisd by different and more dangerous flaw distributions with a resulting negative effect on the properties of the material. The more careful laboratory polishing procedure is able to decrease step by step the damages induced by the grinding stages and always allows recovery of the surface hardness. Although the presence of closed porosity at the surface as a result of removal of the original surface layer makes it impossible to reach the same values of Vickers hardness found for the as fired unpolished samples, the increase in bulk density may reduce the differences. In this regard, the behaviour of product 1 is of particular interest: complete recovery of the original characteristics was possible with the laboratory polishing procedure.

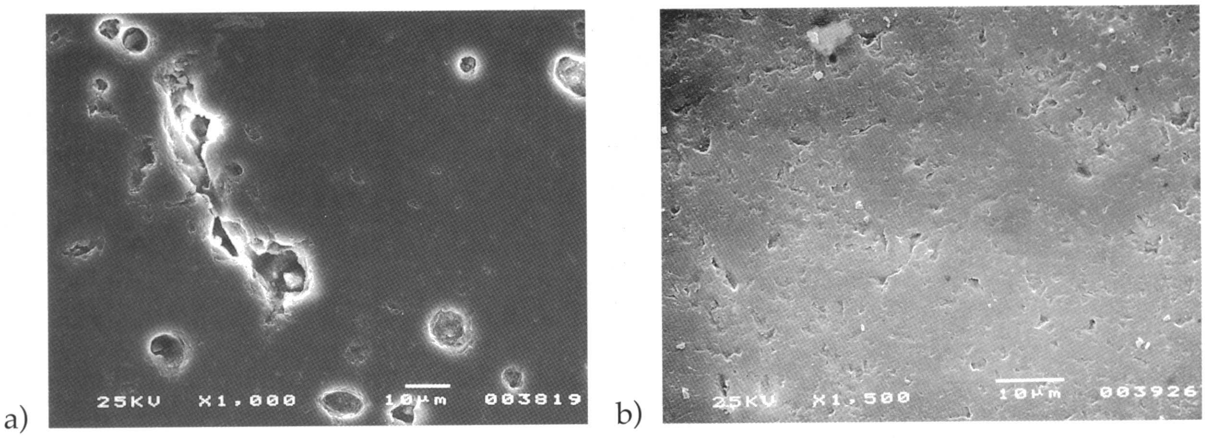

Figure 6. *SEM micrographs of the surface a) of product 1 after the laboratory polishing stage with the 10µm diamond abrasive disc, b) of product 3 after the laboratory polishing stage with the 2 µm diamond abrasive disc.*

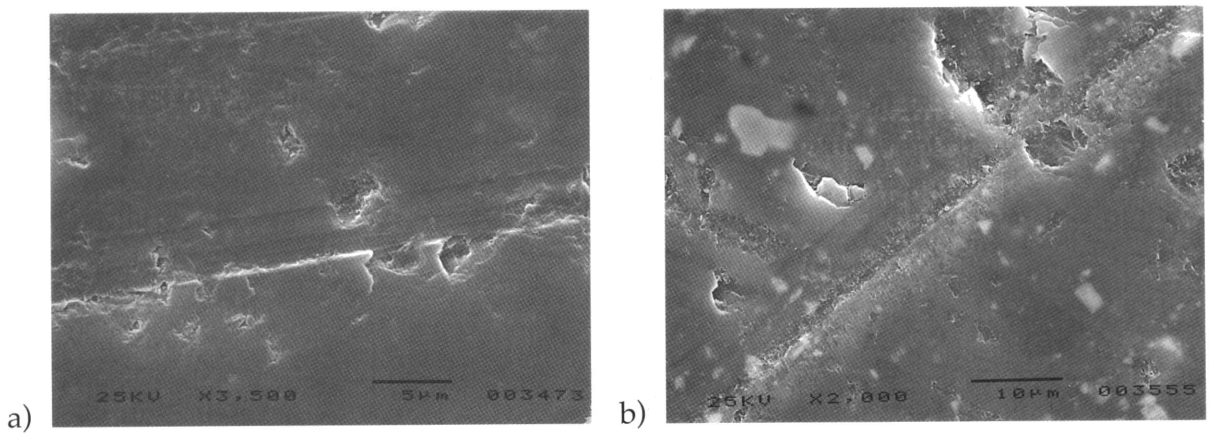

Figure 7. *SEM micrographs of the surface a) of product 2, b) of product 3 after the industrially polishing.*

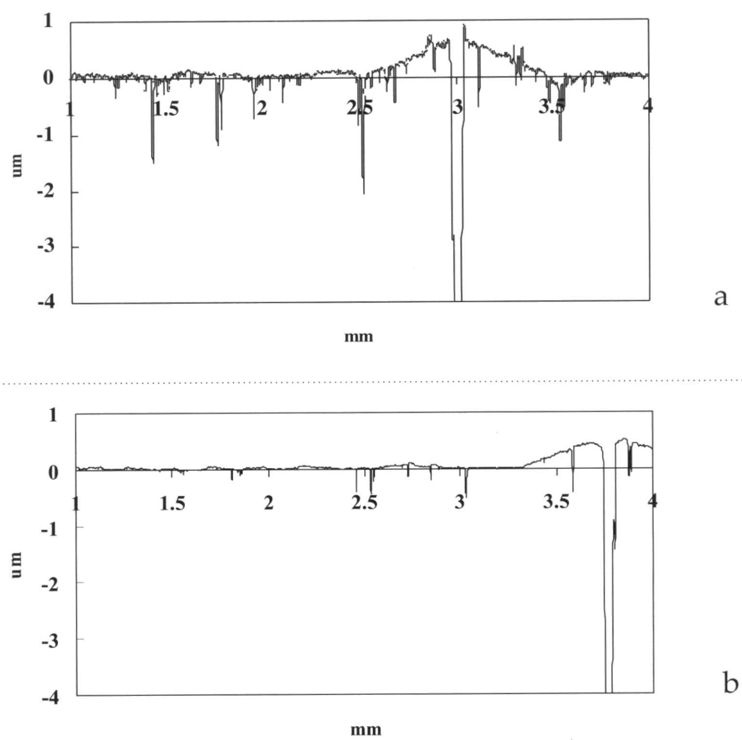

Figure 8. *Roughness profiles for the product 3, a) industrially polished, b) laboratory polished.*

5. CONCLUSIONS

The characteristics of the proper surface of some commercial porcelain stoneware tiles were studied. Microstructural observations, roughness measurements and Vickers hardness tests were carried out on the as fired unpolished surfaces and the polished proper surfaces produced with the current industrial machining procedure. In addition an interrupted laboratory machining procedure was used to follow the evolution of the surface morphology.

The results obtained can be summarised as follows:

- Removal of surface unevenness and asperities usually leads to a decrease in the average roughness, R_a. In contrast, the maximum roughness R_M is affected by the bulk porosity.

- After machining, the Vickers hardness of the surface is usually considerably less than that of the original surface. Scratches, cuts, and interaction and coalescence of cracks, if not reduced and/or completely removed contribute to mechanical degradation of the proper surface.

- Recovery of the characteristics and performance of the proper surface of porcelain stoneware tiles depends on the i) machining procedure and parameters, and ii) microstructure of the material. In this regard, dense homogeneous materials have the best performance.

- Microstructural features represent the intrinsic limitation to the improvements that can be obtained by polishing.

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