INFLUENCE OF SCRATSCHING ANGLE ON BRITTLE MACHINING OF PORCELAIN STONEWARE TILES

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Abstract*. This work uses tribological and kinematical approaches to identify more efficient conditions on brittle machining of porcelain stoneware tiles. For the tests a scratch test machine developed at TU-Kaiserslautern was employed, equipped with a Vickers indenter as abrasive tool. The behavior and influence of different scratches crossing angles were investigated with 14 N dead weight load and a constant scratch speed of 5000 mm/min. Characterizations of scratches were made with optical microscopy, micro-optical 3D perfilometry measuring. Normal and tangential forces were measured with three axial force platform. The analysis showed for the scratch a average width of 170.00 µm and depth of 32.19 µm. The resultant force was 14.72 N, with friction coefficient of 0.30. The material removal was higher at 112.5° and decreasing for adjacent angles.*

Keywords*: ceramic, porcelain stoneware tile, polishing, tribology, scratching.*

1. INTRODUCTION

The porcelain stoneware for wall and floor tiles is the large-scale production ceramic product with the highest added value and technological development available today. Polished porcelain tile has great acceptance in the world market nowadays due to high mechanical strength, high wear resistance and especially because its high-gloss in polished state, a characteristic that causes great aesthetic appeal. It could be considered a material in which the combined effect between the technology of production and the physical-mechanical properties is optimized when compared to traditional ceramic tiles, such as density, flexural strength, hardness and wear resistance (Wiggers *et al*., 2007). So the polished porcelain absorb the market niche that was previously dominated by natural polished stones, like marble or granite, even if the polishing process increases by about 30 to 40 % the final product price (Hutchings *et al.,* 2005a), (Hutchings *et al*., 2005b).

The general polishing process for ceramics can be divided in two major steps: flat surface grinding and flat surface honing, employing diamond and Silicon Carbide (SiC) as abrasive material respectively. During process the abrasive grain size decreases in order to obtain an even smoother surface after each step. Grinding is responsible to ensure the essential flat surface for the honing process, which these last one provides the desired high glossiness on the worked surface. According to Orts *et al.* (2001), during the polishing process there are three main transformations in the work piece: the weight loss, roughness reduction and brightness increase. An important factor in the honing step is that two thirds of the process is only to remove the defects introduced by grinding. This predisposition originates in the extremely brittle behavior of ceramics, along of the predominant wear mechanism in the stage of grinding is micro-chipping.

Most of these defects occur because the polishing process of ceramic tile is based on empirical knowledge, or on direct extrapolations of the processing parameters from natural stones or metals (Cantavella *et al.* 2004), (Sánchez *et al.*, 2002). Commonly process parameters used in the polishing process of porcelain are obtained by "*cut and try*" and adjustments directly on the industrial line, depending heavily on the "*know-how*" and the operator sensitivity to adjust the machinery. Therefore the process parameters are usually over dimensioned in order to obtain the required minimum quality across the entire surface, injuring the final gloss quality (Sousa, *et al*., 2008). As a direct negative effect, there is an excessive tool wear, increased water consumption for tools cooling, large volume of solid residue, higher energy consumption by machinery, low process productivity, production time lost by stopping the machine for testing, so that at the end increases the overall production costs (Hutching *et al.*, 2005a; Malkin *et al.*, 1996; Dondi *et al.*, 2005; Esposito *et al.*, 2004).

2. EXPERIMENTAL METHOD

2.1. Tribometer

A tribometer was specially developed at the University of Kaiserslautern for the analysis of kinematics and machinability into polished ceramic tiles. This equipment has a CNC control of position and movement in the X and Y axis, control of rotation speed and spinning of tool holder. The forces involved during the test are measured by a platform with three axial sensor (brand ME-Systeme, K3D120). The load is applied through the tool with dead weight attached to the carriage. Figure 1a shows an overview of the tribometer with attached tool, as Fig. 1b shows detail of the three axial sensor platform for force measurement, and the sample holder.

(a) (b)

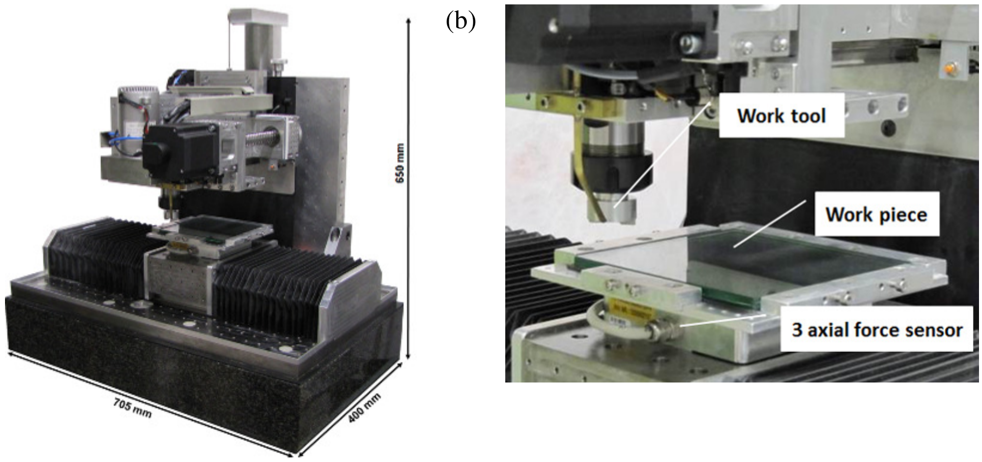


Figure 1. (a) Tribometer overview developed at TU-KL; (b) Work tool, sample holder and 3 axial sensor in detail.

2.2. Material

As working sample a porcelain stoneware tile of commercial brand Spazio d´ItaliaZ, nominal size 597 x 297 mm, tone 2R489, color Ivory, was acquired. These tiles plates were cut into smaller pieces of 150 x 140 mm in order to fit into the sample holder. At the samples surface were delimited test fields with 30 x 30 mm, where the scratching experiments were conducted (Fig. 2).

Figure 2. Tile sample with delimited analysis fields.

2.3. Methodology

To investigate the machinability effect generated by each abrasive grain individually from the grinding wheel, a Vickers indenter was employed as cutting tool. To improve the severity and repeatability of machining, the indenter edge was positioned to be the cutting front in all cases as show in Fig. 3a. The scratches were performed at constant speed of 5000 mm/min and loaded by dead weight of 14 N measured on the force platform. The force measurement worked with rate of 1 kHz during the tests. All tests were performed with 20 mm length scratches, ignoring for analysis the initial and final 5 mm. As a routine to be followed during the tests, the first scratch was initially conducted at 0° in relation to the X axis of the tribometer, the subsequent scratches took always this as reference. As analysis variables, intersection angles were random chosen and with enhance of 22.5°for each step. The studied angles were 22.5°, 45.0°, 67.5°, 90.0°, 112.5°, 135.0° and 157.5°. The scratches were performed following the schematic configuration showed in Fig. 3b.

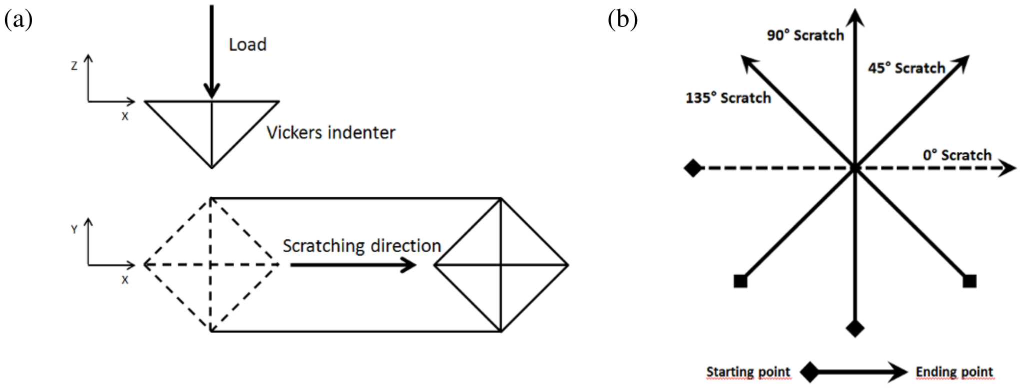


Figure 3. (a) Edge positioning for the scratch test; (b) Schematic configuration showing the scratching sequence;

After the accomplishment of the scratches, the tested fields were clean up with compressed air to remove the generated burr. Digital photographs were taken using an Optical Microscopy (Olympus BX41M) coupled with a CCD camera. The images were analyzed using the software Buehler Ver. 9.0 rev 2b. To determine the cavity contour and depth, an Optical Microscope 3D perfilometer (GFM) was used.

3. RESULTS AND DISCUSSION

3.1. Forces

With the force data was possible to analyze the load applied to the samples (Z axis) and tangential forces (X and Y axis) during scratching. Figure 4a shows the forces from the scratch carried out at 0°, i.e. no interaction with any other scratch. In this figure is seen that the force oscillation is very noticeable in the X axis, but it was expected because this axis coincides with the 0° scratch movement. It is believed that the intermittent peaks presented are from the fragile behavior of the sample during machining, where the micro-cracking rules the material removal. The explanation for this behavior is analogous to the stick-slip phenomenon, where the sample was initially compressed by the tool surface until generates localized fracture and abruptly material removal, and immediately after that the tool move unobstructed for a short space until find and hit a new front of material just forward.

Figure 4b shows the force measurement for crossing scratch at 45°, which represents the general behavior of the crossings scratches. From the forces analysis was not possible to identify clearly the intersection point between the scratches. Although all scratching performed were very repetitive, with mean normal load of 14.72 N, resultant tangential force of 4.38 N and apparent friction of 0.30.

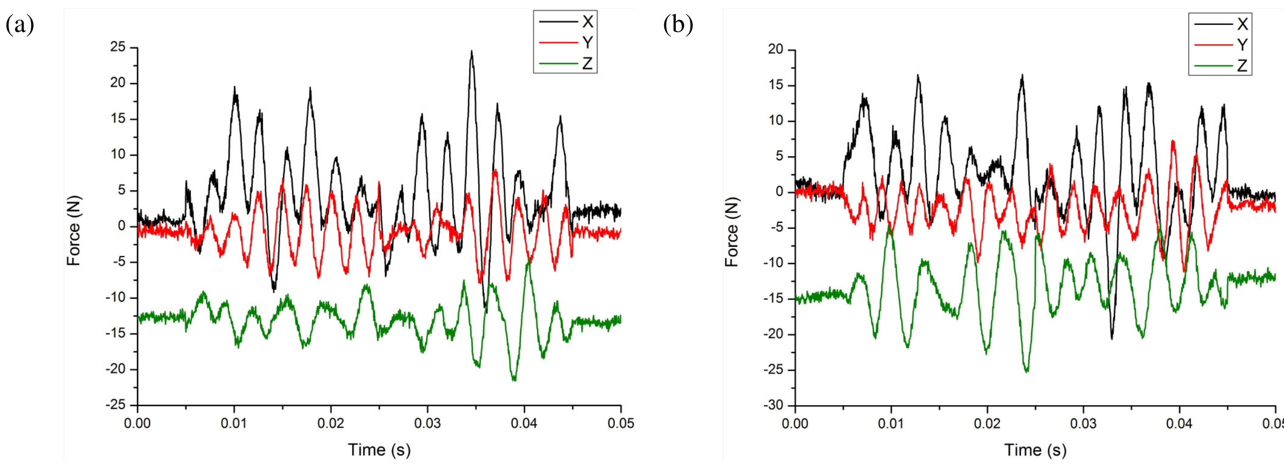


Figure 4. (a) 0° scratch force measurement; (b) 45° scratch force measurement.

3.2. Optical Microscopy – Image Analysis

For direct evaluation between the pictures collected, all measurements were taken with magnifications of 100x, having the horizontal length (L_H) and vertical length (L_V) of 2673.66 µm and 2005.25 µm respectively, with total analysis area (A_T) of 5361011 µm². Employing an image analysis software, it was measured for each sample the not worked area (A_{NW}). The worked area (A_W) was directly calculated by the difference between A_{NW} and A_T. To determine the scratch width (L_S) were used five samples of the 0° scratch as show in Fig. 5a, and the A_{NW} were calculated by the software and marked in green as show in Fig. 5b. With the data of A_{NW} and the L_H, and employing the Eq. 1, was first calculated L_S for each sample, and after by arithmetic mean was calculated the average scratch width as 175.00 µm, with standard deviation of 13.33 µm.

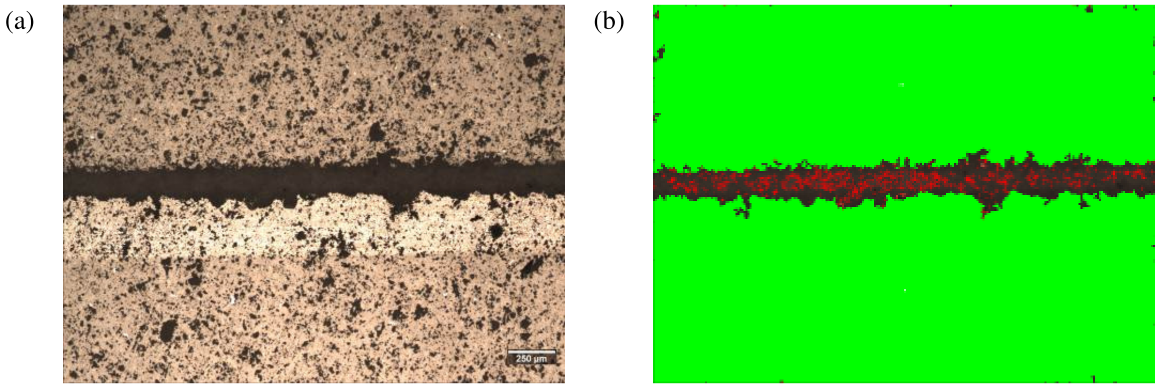
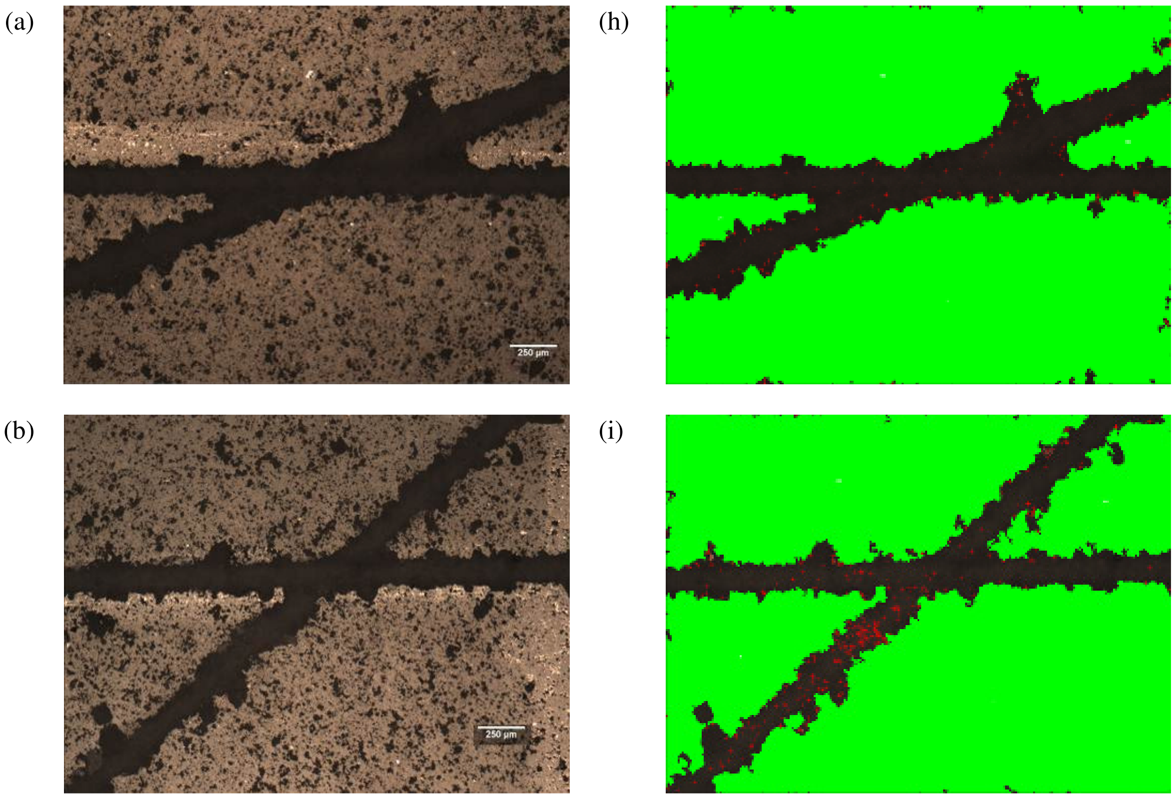


Figure 5. (a) 0° scratch optical microscopy; (b) 0° scratch optical microscopy after image analysis.

$$L_S = \frac{A_{NW}}{L_H} \tag{1}$$

Despite the extremely weak behavior in machining of ceramics, the scratch was considered reasonably constant throughout its analyzed field. There were no extreme variations in scratch width or isolated material removal. The photos sequence in Fig. 6a until 6g shows examples of the original photos for the scratching crossing angles of 22.5°, 45.0°, 67.5°, 90.0°, 112.5°, 135.0°, 157.5°, respectively. Figure 6h until 6n shows the A^2_{NW} recognition by image analysis software.



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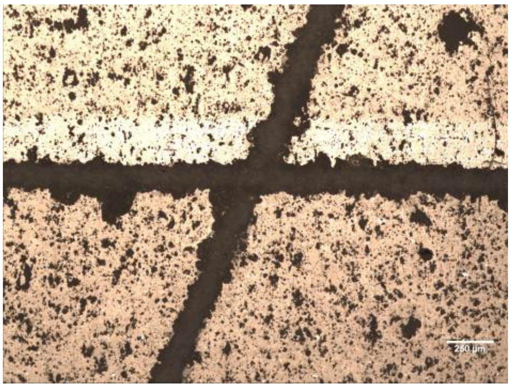

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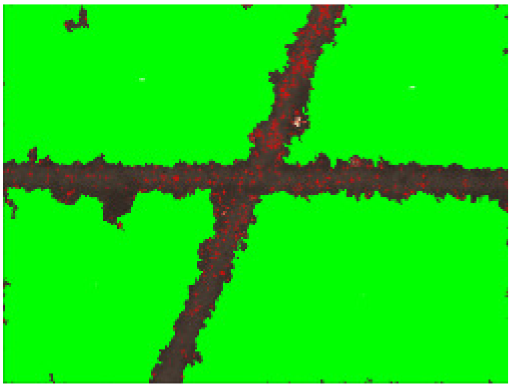

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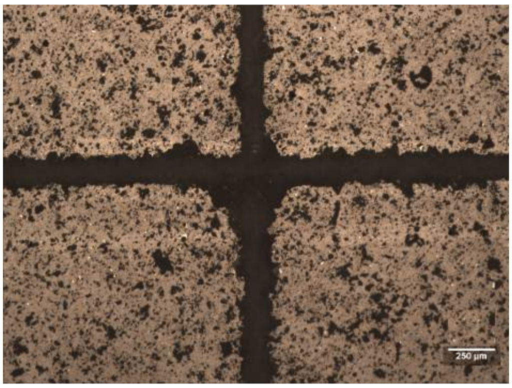

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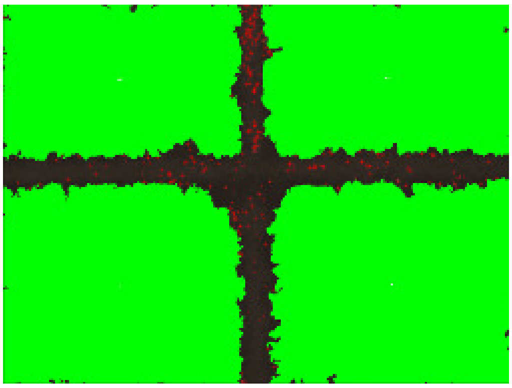

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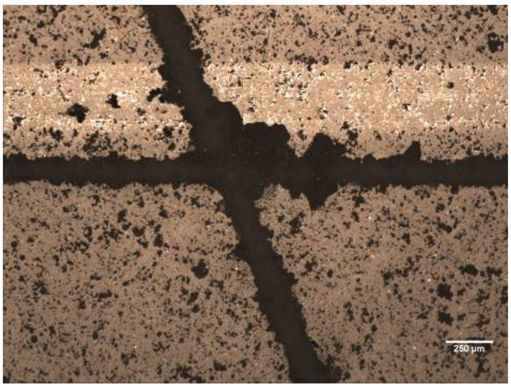

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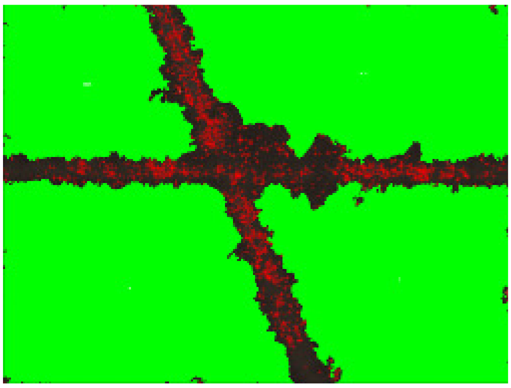

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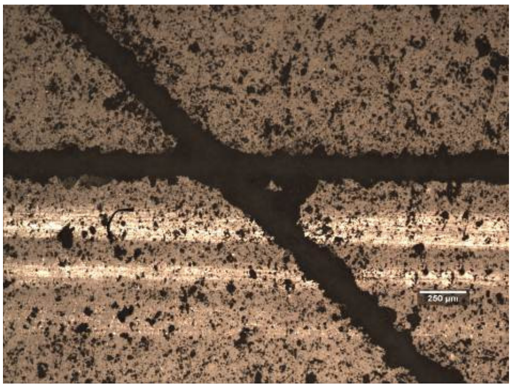

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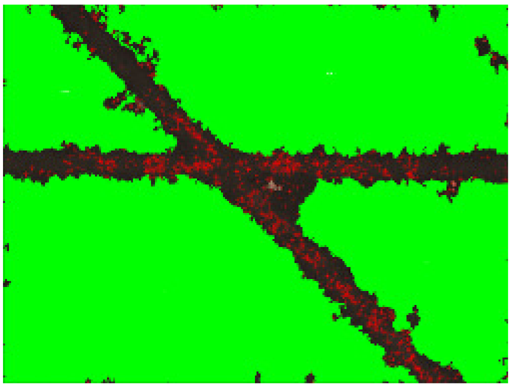

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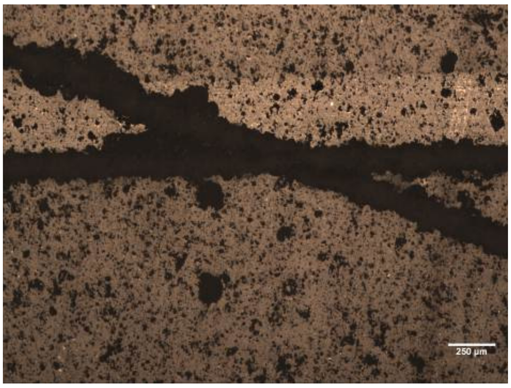

(n)

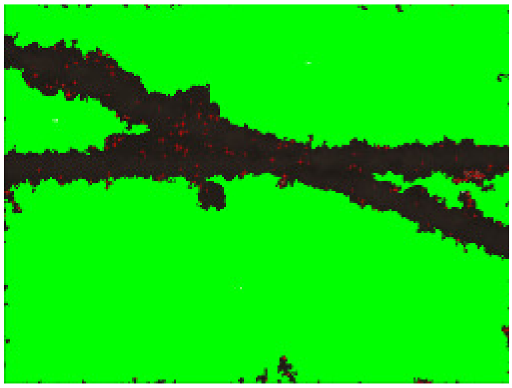

Figure 6: Optical microscopy for crossing angle (a) 22.5°; (b) 45.0°; (c) 67.5°; (d) 90.0°, (e) 112.5°; (f) 135.0°; (g) 157.5°. Image analysis recognition from (h) until (n).

In order to quantify the additional material removed by the interaction of crossing scratches, was calculated the relation between the μm^2_W and the supposed area for a scratch with 175 µm width (μm^2_S). Results of percentage additional material removal are showed in Fig. 7.

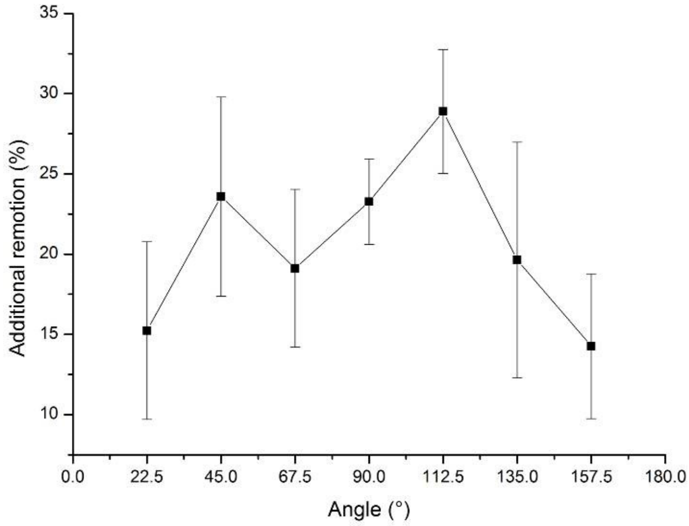

Figure 7: Additional material removal vs. scratching crossing angle.

Although the additional material removal as a function of the scratching crossing angle has not made a regular pattern, it became clear that the crossings angles near the transverse direction generate the greatest influences. What in practice might be related to minor work required in the industrial grinding of ceramics if the adopted kinematics promotes crossing angles nearby 90°.

3.3. Optical Microscopy 3D

Using a sample only with the 0° scratching, 5 optical profilometry transverse to the scratching direction were made on the surface of ceramic. Figure 8 shows the graphic result obtained, in which is clear that the groove depth generated range between 20 µm until 30 µm. From the raw data, by arithmetic mean, was calculated the average cutting depth of 32.19 µm with standard deviation of 8.80 µm.

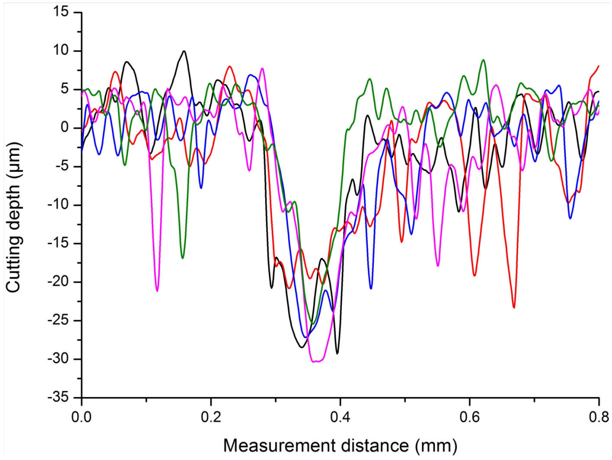

Figure 8: Optical perfilometry for cutting depth.

3.4. Scratch depth and width relationship

Assuming that the groove generated during the scratching of ceramic will have geometry similar to the tool employed, it was assumed that the scratch wall angle will have the same angle of 22° from the Vickers indenter. As a way to check the veracity of this hypothesis, it was calculated the value of scratch depth as a function of measured scratch width, and vice versa, the width as a function of measured depth. Table 1 presents the results obtained and the percentage difference between the measured and calculated values.

Table 1: Scratch width and depth.

	Measured	Calculated	Difference
Scratch width	150.00 µm	159.34 µm	6,23 %
Scratch depth	32.19 µm	30.30 µm	- 5.87 %

Based on the errors found and the precision of the techniques employed, it is possible to say that the hypothesis in which the groove generated is similar to the tool geometry used is valid. The confirmation of this hypothesis will be of great value for preliminary evaluations during new scratching tests, improving the speed of new tests conditions. This result is import because the technique of optical microscopy 3D for groove depth evaluation of scratches requires much more time and skill of the operator when compared to the digital image analysis to evaluate the scratch width.

4. Conclusions

- The tribometer developed at the University of Kaiserslautern was capable of to simulate the brittle machining of ceramics by scratches with a Vickers indenter;
- The force measurements during the performed scratches had a significant oscillation. This comportment is due the extreme fragile behavior of the stoneware tiles during the tests, analogous to the stick-slip phenomenon;
- For the crossing scratches, it was not possible to identify the intersection point in the force measurements;
- The force measurements during the tests were very similar, with a mean normal load of 14.72 N, resultant tangential force of 4.38 N and friction coefficient of 0.30;
- It was observed a influence of the crossing angle at the material removal for brittle scratching of stoneware tiles;
- The crossings angles near the transverse direction ($\alpha = 90°$) generate the greatest influences, improving the material removal to 20 % or higher;
- The hypothesis in which the groove generated is similar to the tool geometry used was found to be valid, and it can be helpful to improve future works;

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