ACTUAL RESOLUTION IN INK-JET PRINTING OF CERAMIC TILES: PRELIMINARY ASSESSMENT OF IMPRINT SIZE UNDER DIFFERENT OPERATING CONDITIONS

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1. ABSTRACT

The behaviour of ceramic inks during jetting by drop-on-demand piezoelectric devices is well-known, being investigated in detail by dropwatch observation in the setup of every ink-jet printer. In contrast, the behaviour after the ink drop has touched the substrate is to a large extent unknown. In particular, no data are available about the effect on the printing resolution of drop impact, spreading and penetration into the porous substrates. Such phenomena are affected not only by the ink density, viscosity and surface tension and by the settings of the print heads, but also by the speed of the tiles on the conveyor belt and by wettability, roughness, porosity, and permeability of the substrates. In order to fill this gap, this work will examine the post-jetting behaviour of ceramic inks through observation of drop imprints on the raw surfaces after impact, spreading and penetration, as well as after drying and firing on the finished products. The ink-jet printing was carried out with an industrial printer (equipped with a 400 dpi print head working in grayscale mode) under different conditions: drop volume (30, 50 or 80 pL) and theoretical surface coverage (5% or 10%). Two sets of industrial ceramic inks were used (oil-based and water-based) as well as two different industrial substrates (raw glaze and unglazed

tiles). Imprints were characterized by estimating size and shape by image analysis of micrographs taken under an optical microscope. From these data it was possible to calculate the spreading index (the imprint area to drop equatorial cross section ratio) after both ink application and heat treatment in an industrial drier and kiln. The results show that the imprint of ceramic inks is far from the ideal circular shape, having an irregular outline and suffering from a remarkable shrinkage during firing. Moreover, the spreading index varies significantly from oil-based to water-based inks and from glazed to unglazed tiles, both before and after firing.

2. INTRODUCTION

In the last decade, ink-jet printing (IJP) spread all over the world to become the leading technology to decorate ceramic tiles [1-4]. Nowadays, the conversion from conventional to digital decoration lines ranges from 20% up to over 90%, depending on the country.

The rapid diffusion of IJP has been possible thanks to a double effort: firstly, to identify a range of technological solutions to overcome the many specific problems occurring in ceramic production; this task was mainly performed by printer manufacturers and tile-making factories [3,4]. Secondly, to develop inks, concurrently meeting the technological requirements of IJP devices and end-user demands in terms of ceramic behaviour, stability over time, safety and cost; this task was mostly performed by ink-makers and additive suppliers [4-7].

Among the reasons for the success of IJP, there is the improved printing quality, which is ensured by print heads having a high native resolution, usually 360 or 400 dpi (so-called "transversal resolution"). Nevertheless, the actual resolution on the ceramic tile depends, along with the fire frequency, on the speed of the decoration line: the faster the tiles run under the printer, the lower the number of points printed per inch in the longitudinal direction (so-called "longitudinal resolution"). A printer equipped with 360 dpi print heads has a pixel (i.e., the target surface where to jet the ink drops) of about 70 μm in the transversal direction. Such a pixel is squared (70 μm x 70 μm), with a fire frequency of 6 kHz, when the decoration line runs at 25 m/min, but it turns increasingly rectangular at a faster velocity (e.g., 70 μm x 140 μm at 50 m/min).

The printing quality depends on the actual capacity of the printer to accurately deposit on the same pixel the drops of different colour inks, e.g. four in the case of quadrichromy [5-8]. In principle, to cover a 70 μm x 70 μm pixel by four drops, circular ink imprints of diameter 35 μm are needed to fulfil a full addressability. Any wider imprint will spread over the adjacent pixels, thus lowering the image quality. This constraint is somehow valid for a rectangular pixel too, since the 70 μm width is the native resolution of print heads.

Although there is a strict control on many variables of the IJP process (e.g., drop size and shape, jetting trajectory, print heads alignment, physical properties of inks) little is known about the actual printing quality in digital decoration of ceramic tiles. This is because the result of IJP depends in a complex way on the substrate features. In particular, the way an ink drop spreads over a ceramic surface is affected by several factors: energy at impact (drop mass and velocity), substrate wettability (contact angle), microstructure (roughness, porosity), penetration (ink viscosity and substrate permeability) among others [9-12].

In ceramic tile decoration, the image quality is usually checked by both qualitative observation (e.g., Altona Test Suite) and quantitative colorimetric measurements (by using test charts). However, these tests are not able to discriminate the effect on the image quality due to drying and firing from that due to phenomena occurring prior the heat treatment. Despite the growing concern on printing quality by the tile-making industry, no figures are available on the effective size of imprints on ink-jet decorated tiles, beyond the preliminary estimates presented by Bourgy et al. [13] and Sanz et al. [14].

In order to fill this gap, this work will examine the post-jetting behaviour of ceramic inks and particularly what happens to ink drops after impact, spreading and penetration (through observation of imprints on the raw glazed and unglazed body surfaces) as well as after drying and firing (through observation of imprints on the finished products).

3. EXPERIMENTAL

Industrially-manufactured porcelain stoneware tiles were ink-jet printed by an industrial printer equipped with a Dimatix StarFire1024 print head (400 dpi of native resolution) under different operating conditions:

- either glazed ("glaze") or unglazed ("body") tile surfaces;
- grayscale with nominal drop volume of 30, 50 or 80 pL;
- printing of oil-based ink (OB, the carrier was a mix of fatty acid esters) or water-based ink (WB, the carrier was a mixture of water and ethylene glycols);
- theoretical ink coverage of the target surface equal to 5% or 10%;

Printed tiles were observed under an optical microscope (Meiji Techno RZ) taking micrographs (Nikon D5200, 75X magnification) that were converted into black & white images (Fig. 1). Image analysis (ImageJ software) was carried out to obtain average area, perimeter and roundness of 10-25 imprints for each sample.

The spreading of ink droplets on the substrate was quantified by a spreading index, S, defined as the ratio between the area of imprint (A_{imp}) and the equatorial cross section of the drop assumed to be spherical (A_{esd}): $S=A_{imp}/A_{esd}$. A value $S = 1$ implies that no spreading occurred; values $S > 1$ indicate the degree of spreading over the glaze or body surfaces.

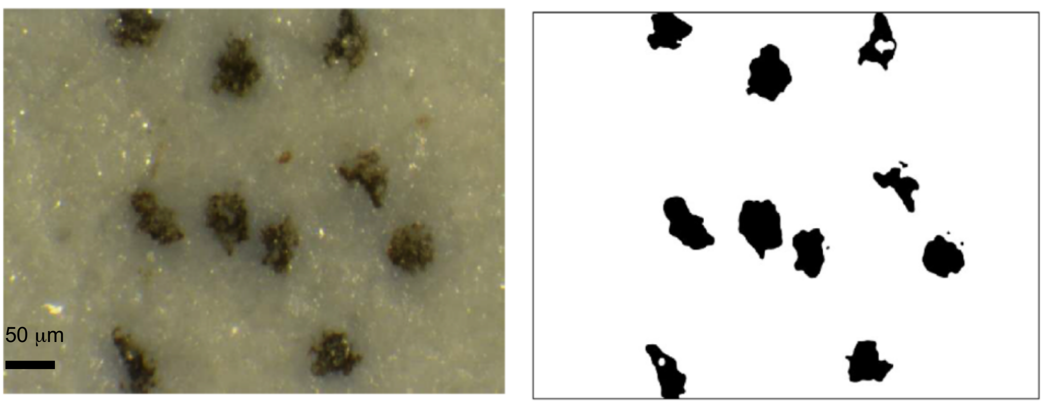

Fig. 1. *Example of conversion from colour micrograph into a black & white image. IJP on fired glaze, 80 pL drop volume, 5% coverage, oil-based ink.*

4. RESULTS AND DISCUSSION

Ink imprints on ceramic substrates have generally an irregular outline, although the spherical shape and trajectory of droplets were accurately checked in operation by dropwatch observations. Most imprints are markedly anisotropic, with a significant deviation from the circular shape (roundness between 0.6 and 0.8). The outline of imprints is frequently jagged (Fig. 2) being severely affected by the physical and microstructural features of the target surface: wettability, roughness, porosity, and permeability [13, 15, 16]. This behaviour is more accentuated in water-based inks, whose imprints appear to be non-uniformly filled (Fig. 3) perhaps as a consequence of a sort of coffee-stain effect [17]. Due to the irregular shape and outline of imprints, the mean values of area, perimeter and roundness are affected by a relative standard deviation as high as 10-15% (unfired tiles) or 15-25% (fired tiles).

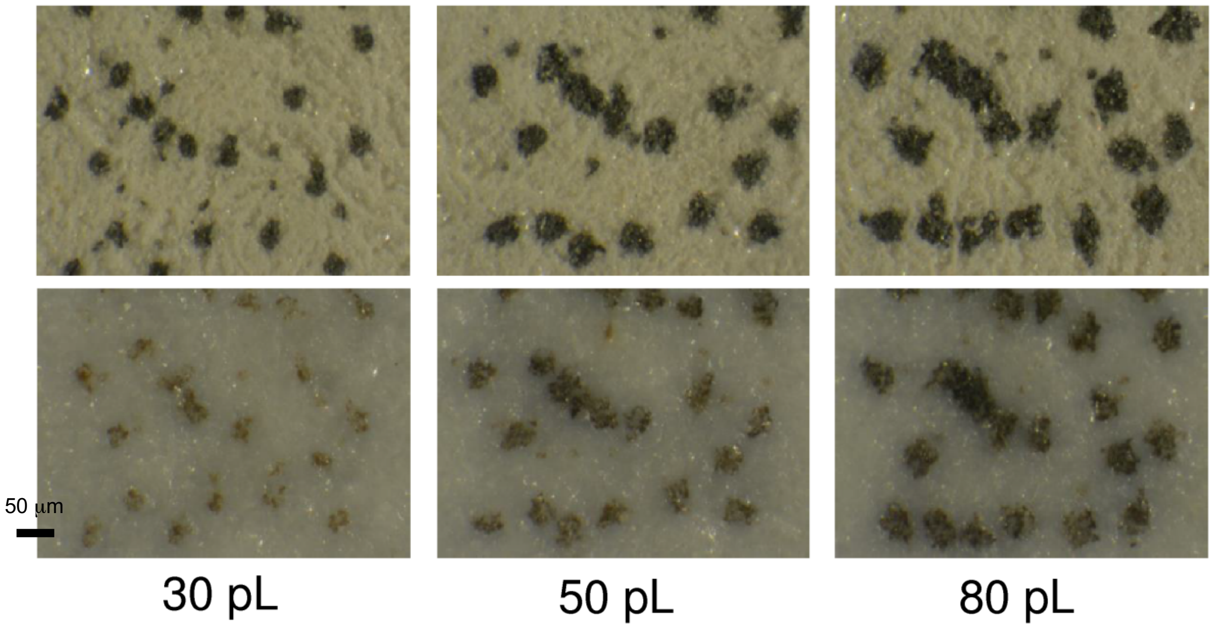

Fig. 2. *Micrographs of porcelain stoneware tiles ink-jet printed with an oil-based ink: different drop volumes on unfired glazed (above) and fired glaze surface (below).*

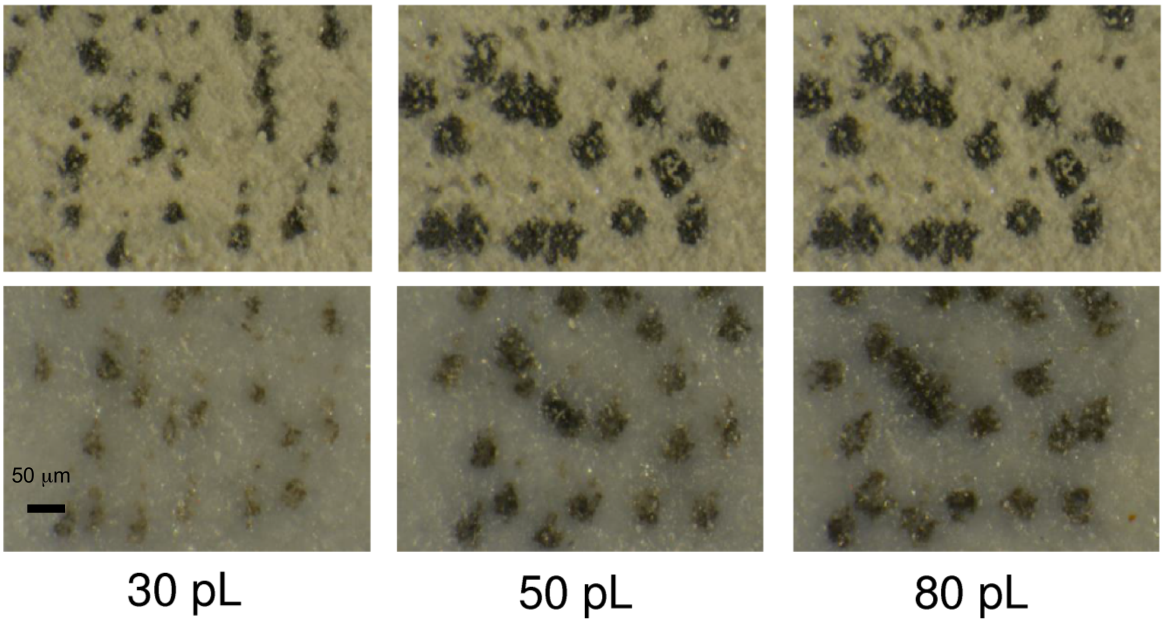

Fig.

Fig 3. *Micrographs of porcelain stoneware tiles ink-jet printed with a water-based ink: different drop volumes on unfired glazed (above) and fired glaze surface (below).*

The ink spreading over the target surface varies according to the ink type (OB or WB), substrate type (glaze or body), and drop volume; on the other hand, the degree of ink coverage (5% or 10%) seems not to substantially affect the spreading index.

The imprint size is proportional to the volume of ink droplets impacting on the ceramic surface, though a clear deviation from the nominal size occurs (Fig. 4). This trend implies that the relationship between ink penetration into the substrate and spreading over the surface is roughly constant for droplet sizes from ~39 μm (30 pL) to ~54 μm (80 pL). What is relevant for ink-jet addressability on ceramic tiles is that the spreading index fluctuates from 2.4 to 4.3 on the raw glaze and from 2.8 to 4.5 on the raw body.

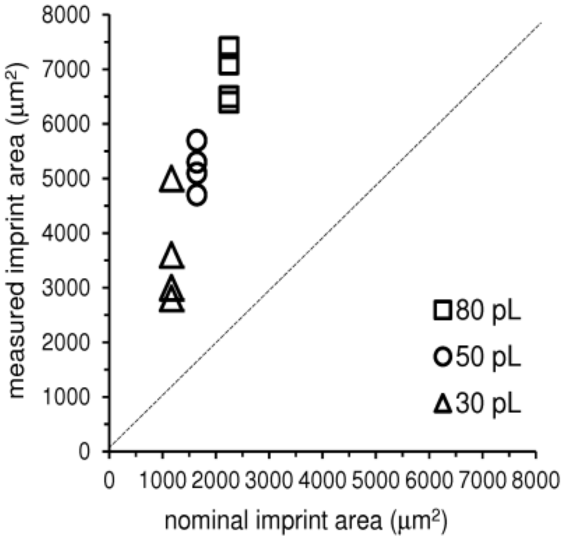

Fig. 4. *Ink imprint areas measured on the unfired tiles at different drop volumes versus the nominal imprint areas of spherical drops.*

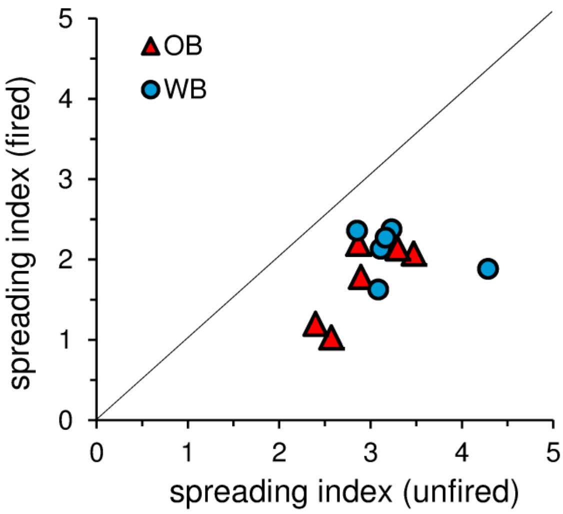

Fig. 5. *Comparison of spreading indexes: unfired versus fired glazed tiles (OB: oil-based inks; WB: water-based inks).*

The imprint size is heavily affected by firing in both oil-based and water-based inks (Fig. 5). The imprint shrinks during firing, so that the spreading index on finished tiles is smaller than that on raw surfaces by a factor of 0.6-0.7. For instance, a 50 pL WB drop (diameter ~46 µm) spread on the unfired glaze to ~90 µm (S=3), then shrank on the fired glaze to ~75 µm (S=2.2). It must be noticed that this firing shrinkage, on average 24% for oil-based inks and 19% for water-based ones, is much higher than that of the porcelain stoneware tiles (5% to 9%).

There is no significant distinction in the spreading index of oil-based and water-based inks on raw ceramic surfaces (Fig. 6). This observation confirms data obtained by Sanz and co-workers [14].

In contrast, a systematic difference arose comparing the fired glazed and unglazed tiles: due to their larger firing shrinkage, oil-based ink imprints on finished tiles spread by 1<S<2.2, while water-based inks are characterized by 1.5<S<3.3 (Fig. 7).

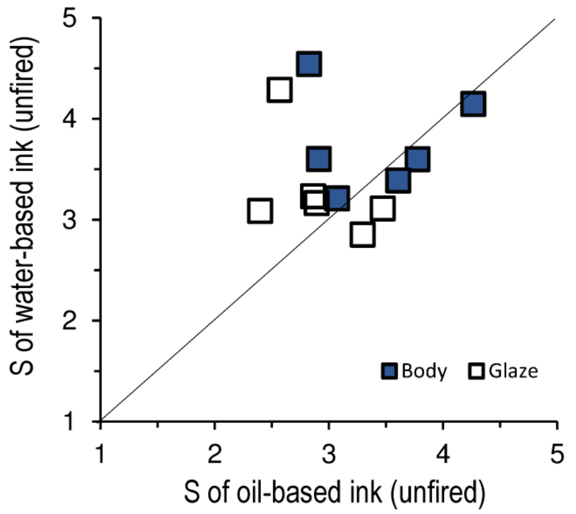

Fig. 6. *Comparison of the spreading index on unfired tiles (glazed and unglazed) for water-based versus oil-based inks.*

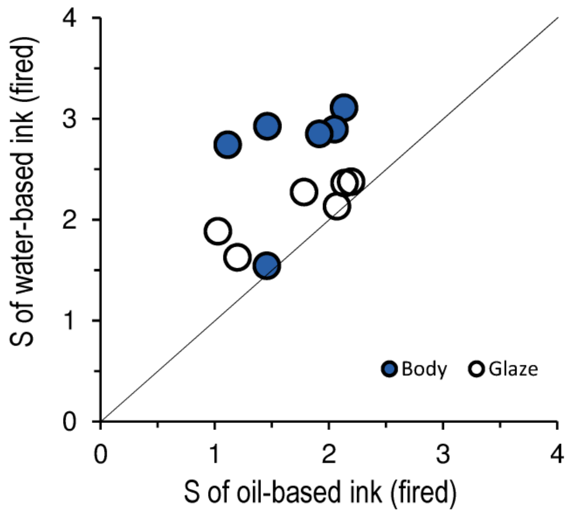

Fig. 7. *Comparison of the spreading index on fired tiles (glazed and unglazed) for water-based versus oil-based inks.*

This distinct behaviour of OB and WB inks has relevant repercussions on ink-jet addressability, as displayed in the reconstruction based on imprint size measured on unfired and fired glaze (Fig. 8). Oil-based inks and particularly water-based ones form much wider imprints than expected (as resulting from the drop volume, assuming spherical drops), which appear extensively superimposed on each other in the same pixel. The higher firing shrinkage of the OB inks makes their imprints to fit the 70 μm x 70 μm pixel contour with no overlapping. The lower contraction of WB inks during firing leaves wider imprints, which fully cover the pixel.

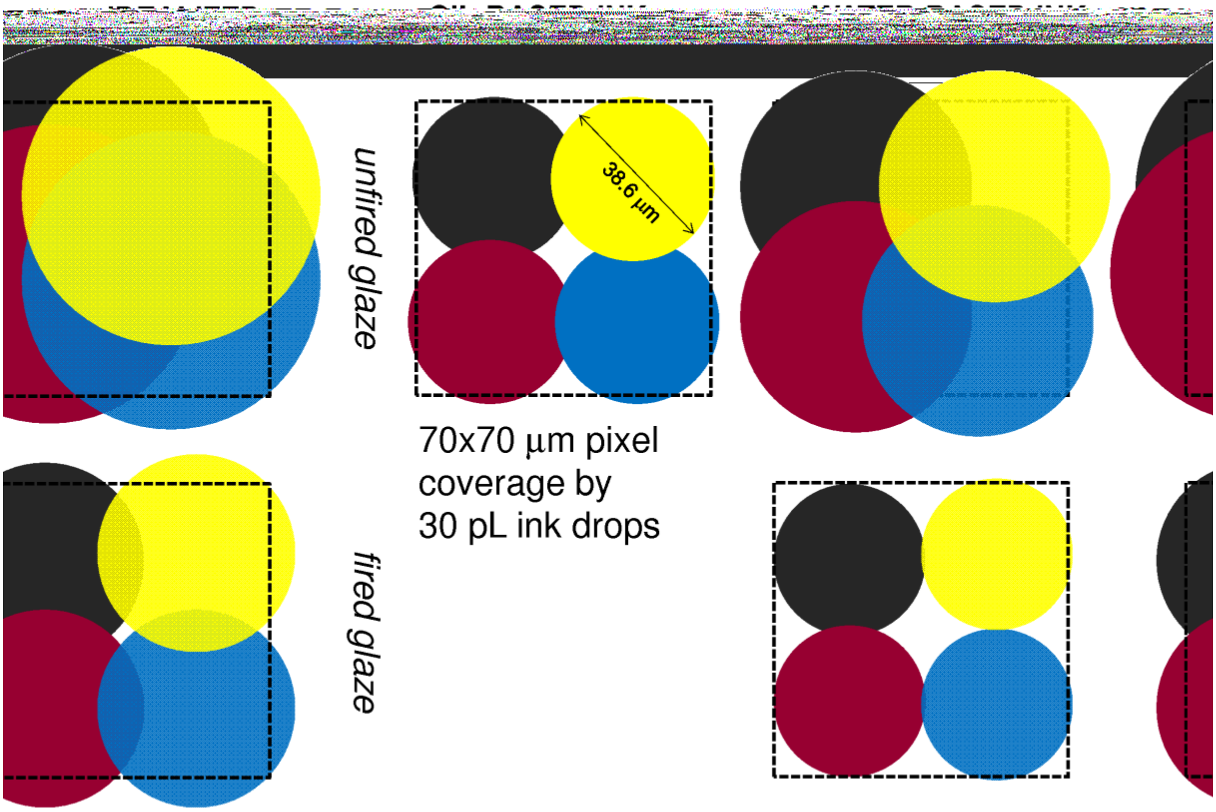

Fig. 8. *Addressability of oil-based and water-based inks on unfired and fired glaze substrates in comparison with an idealized pixel for 30 pL drop volume.*

5. CONCLUSIONS

Preliminary data on the imprint size and shape of real ceramic inks represent a first attempt to define the actual resolution of ink-jet printing on ceramic tiles. The quantitative approach followed to determine a spreading index demonstrated the basic influence of:

- jetting conditions (drop volume);
- ink properties (oil-based versus water-based ink);
- target surface (glaze or body);
- firing stage.

Nevertheless, more data are needed (different inks on different targets) to confirm the observed behaviours.

In order to comprehend the ink behaviour over ceramic tiles, it is necessary to shed light on the relationship between spreading over and penetration into the porous unfired substrate. Experimental simulations of ink spreading and penetration on real ceramic surfaces are in progress to look for the proper predictive model.

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