DECORATING DIFFERENT SURFACES: A CASE STUDY ANALYSIS OF CERAMIC TILES AND GLASS

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1. SUMMARY

In this work, we analyze how to manage defects to improve printing quality when dealing with non-standard tile surfaces in single-pass inkjet printing. In particular, we consider the effect of surface properties of the substrate and its interaction with the jetted ink. Inkjet decoration of raw ceramic tile, which is porous and absorbent, is well known and consolidated. In contrast, non-absorbent glass-like surfaces are a new field of study which requires further investigation. We analyze the effect of the peculiarity of the surface on the printed image and describe strategies to improve printing quality, showing practical applications on industrial machines. From the described case study some general guidelines are drawn, which can be extended to a variety of intermediate situations.

2. INTRODUCTION

The ceramic market is a dynamic and continuously improving field: every year new products are developed, and both a higher quality and an increased level of complexity are required. Existing technologies are constantly improving, and new ones are developed to reach the goal of high performances at a reasonable cost, taking into account the environmental impact. In recent years, the developed devices and achieved knowledge have enabled not only dissemination of ceramic technology all over the world, but also access to new markets, which share with tile manufacturing many aspects and challenges, in terms of both processes and products: third-firing, glass, wood, plastic films and building materials are only some examples [1-3].

A crucial step in terms of quality is decoration. Drop-on demand (DOD) piezoelectric inkjet printing represents nowadays the leading technology due to its high performance and reliability. Piezo-inkjet is used in a wide variety of application fields, thanks to the possibility of jetting various inks and materials with controlled laydown. In particular, single-pass printers represent the best compromise to increase productive rate while keeping a very high quality. Meeting industrial requirements without compromising printing performances and reliability is a tough but fundamental task for print manufacturers, which demands continuous improvement in terms of process control [2, 4].

Digital decoration is now spreading its reach across the whole production line, from glazing through reproduction of graphic designs to the final protective finishing, creating the complex process known as "full digital", where all decoration steps are performed with a digital approach and highly advanced technologies. Full digital application includes the possibility of laying down a high quantity of material, preserving quality and reducing waste and costs. The decoration process is composed of the following steps, each with its own purpose, one collaborating with the others in what we call "cooperative digitalization", where each part plays a precise role and contributes to the final result like the instruments in an Orchestra.

The success of full digital lies in its flexibility, though it requires thorough control of all the phases in the decoration chain. As a direct consequence, digital decoration has to move from a passive condition, where relevant parameters are externally imposed, and thus suffered by the process, to an active situation where the user directly manages all the properties. The control of the parameters moves along two parallel paths: the punctual characterization of the state of the product immediately before undergoing a specific process, and the action to modify this state when and how required. Both analysis and modification technologies have to be developed to achieve the goal of perfect coordination between the parts.

Quality in inkjet printing depends on many factors. First, the combination of printhead, ink and process parameters (i.e. printer settings and working environment) strongly influences drop formation [1-2, 5]. Nonetheless, the interaction between the drop and the surface represents a major point affecting the final printed image: the properties of the printed dot are determined by drop and surface properties, i.e. drop energy, ink surface tension and substrate surface energy, temperature and surface treatment. In this framework, absorption of the liquid from the surface is a relevant and crucial process that needs to be managed.

The expansion of the ceramic market has now led to a wide variety of different products, with peculiar properties, also in terms of the substrate. Suitable examples can be identified in third-firing decoration or considering glaze application on a previously deposited ink layer: in these cases, the deposited drop interacts with a surface that is quite different from an unfired tile.

When laying down a high amount of ink, such as for glaze application, tile surface becomes wet and less permeable. The initial surface state for subsequent ink deposition on the substrate shows different properties, resulting in different effects and possibly in printing defects if the parameters are not properly controlled. A similar situation is represented by third-fire application, where the decorated tile has already been fired and the surface is glass-like and not permeable.

These cases and many more need a new approach to manage printing quality, including the development of both surface analysis and modification, with technologies directly integrated into the production line. Control of jetting is not sufficient to gain a very high quality, but also has to be integrated with surface control.

In the present scenario, tiles show a wide range of surface properties due to high variety of different applications. Inkjet decoration of unfired ceramic tile, which is porous and absorbent, is well known and consolidated [1-7]. On the other hand, non-absorbent glass-like surfaces are a new field of study which requires further investigation. For a better understanding of non-absorbent surfaces, inkjet printing on glass represents a fruitful case study, due to its completely non-absorbent nature. Study of digital decoration of glass or glass-like surfaces can lead the way for the analysis and management of all partially permeable substrates.

In this work, we approach the introduced topic considering a relevant case study: single-pass inkjet decoration on glass. We describe its peculiarity and stress the specific printing defects, which emerge from a non-absorbent substrate, which shares many peculiarities with non-standard ceramic applications. We present a brief overview describing the main relevant properties for formulating ink for glass-like applications and highlight the differences with respect to ceramic inks. We analyze the interaction between the glass surface and the jetted ink, introducing the concept of contact angle. We describe the most common defects arising from the non–absorbent nature of glass-like surface; we considered methods to reduce the undesired features by acting on substrate properties. We finally propose a general method to evaluate printing quality and to customize process parameters to gain optimal printing quality.

3. INKS FOR NON-ABSORBENT SURFACES

When introducing the topic of digital inkjet for non-absorbent surfaces decoration, a brief overview of ink properties is useful to understand analogies and differences.

Inks for ceramic and for glass-like surfaces show many common characteristics, due to the similar applications. Both are composed of a solid micronized part dispersed in organic solvents using additives. Typically, particle size is below 2 µm and density is lower than 1.6 g/cm3. Both can be formulated with the proper physical parameters to be used in DOD printheads [4, 8-11].

The most relevant difference is the need for rapid evaporation on glass: the solvent in inks for non-absorbent application include molecules with high vapor pressure, resulting in high adhesion of the ink on the surface. A fast-drying application is required in glass technology, as well as in full digital decoration, in the latter case to prevent flotation of one ink on the other and avoid loss of sharpness in the printed image.

Moreover, inks for glass surfaces contain a binder, namely a synthetic resin, not only to maintain the definition of the dot created by the drop landing on the surface, but also to increase the adhesion of the residual solid part of the ink after evaporation of the solvent, before the tempering process. This is useful for storage and transport of glass slabs after printing to the tempering station.

Table 1	Absorbent	Non-Absorbent
Composition	Solid part + organic solvent + additives	
Solid part	Inorganic pigment OR frit	Inorganic pigment AND frit
Particle size	< 2µm	
Density	< 1.6 g/cm^3	
Fast dry	Not required	Required
Binder	Not required	Required

The solid part of glass inks is made up of two components: the inorganic pigment and the glass material, whereas in inks for standard ceramic application there is only one or the other. The presence of the glass part, namely the frit, allows the melting of the ink and the incorporation of the pigment on the glass, resulting in high mechanical and chemical resistance over time. Inks for full digital include not only inorganic pigment, but also frit and raw materials for first and last application (glaze and finishing).

Table 1: *Summary of common and different properties for inks for absorbent and non-absorbent surfaces*

4. ANALYZING SURFACE-INK INTERACTION: CONTACT ANGLE

The control of the printing process starts from the analysis of the properties of the surface: particularly relevant is the interaction between the surface and the jetted ink, which depends on ink and surface properties.

A significant measurable quantity to define ink-surface interaction is the contact angle (CA), describing the wettability and consequently the geometry of the drop landing on the substrate. Wetting of a solid surface has been quantitatively described by Young considering the profile of a liquid droplet, in particular the tangential angle at liquid–solid–air interface.

The static contact angle θ is the result of the mechanical equilibrium among the three surface tensions, liquid surface tension (γ_{LV}), solid surface tension (γ_{SV}), and liquid–solid interfacial tension (γ_{SL}) [12-13] (Fig.1): $\gamma_{SV} = \gamma_{LV}\, cos\theta + \gamma_{SL}$

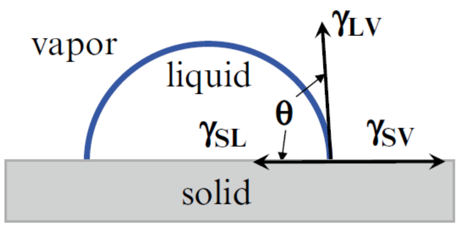

Fig.1: *Schematic representation of a drop on a solid surface, with indication of the solid, liquid and solid-liquid surface tensions and contact angle θ.*

If CA < 90° the behavior is hydrophilic. On the contrary, CA > 90° corresponds to a hydrophobic condition: a higher contact angle is related to lower wettability and vice versa. It is important to notice that the contact angle is not a property of the surface: the contact angle describes instead the interaction between the surface and the liquid. Contact angle is highly influenced by ink surface tension, in addition to surface treatment and temperature.

An efficient method for measuring the contact angle is the sessile drop technique, where the drop lands on the substrate and the contact angle is measured by optical recognition of the drop profile and base line at the solid-liquid interface from a side view, both fitted with a proper mathematical function (Fig.2).

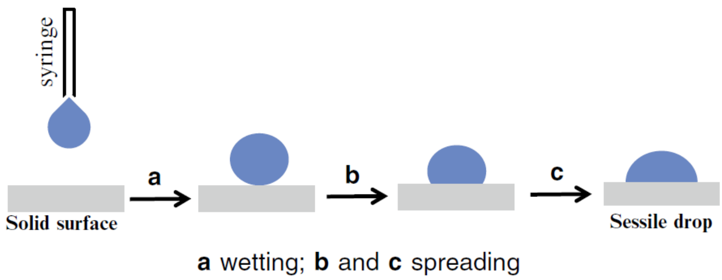

Fig.2: *Schematic showing the main phases of static contact angle measurement with the sessile drop technique: the drop is ejected from a syringe, lands on the surface and spreads.*

In this work we performed contact angle measurements by using the OCA100/100Micro measuring system (Dataphysics, [14]), equipped with an electronic direct dosing systems DDE/x for micrometric drops. A syringe dispenses the ink in a controlled and reproducible way, and the contact angle is measured over time for 30 s after drop landing (Fig.3). Left and right contact angles are both measured, and an average value is calculated.

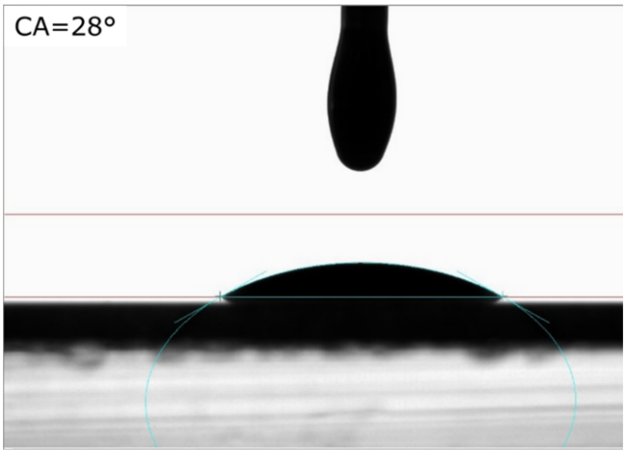

***Fig.3:** Example of contact angle images taken with OCA100 for ink on glass. The operator positions the red as a reference for air and base line. Blue lines indicate the fitting results.*

In this study, we considered three different inks for glass decoration, which we refer to as sample A, B and C and we evaluated the effect of substrate temperature on the contact angle. Glass samples were treated in the exact same condition, by cleaning the surface with a proper cleaning liquid; samples were preheated and measured at various temperature. Ink was ejected from the syringe at the proper working temperature for jetting (35°C).

Results are reported in Fig.4; the error associated with the measurement is about 2°. In each trend two areas can be identified: soon after landing the drop spreads for a certain time, then evaporation begins. The spread phase is characterized by an exponential trend, the evaporation process being described by a straight line. The duration and speed of each phase depends on ink properties and can vary with substrate temperature, for this reason the initial CA value alone is not a significant number for characterizing the samples. CA values and trends are different for each ink, depending on fluid properties and how they affect ink/substrate interaction: there is not a straight and easy interpretation for CA curves, so that complementary techniques and methods are needed to evaluate printing performances.

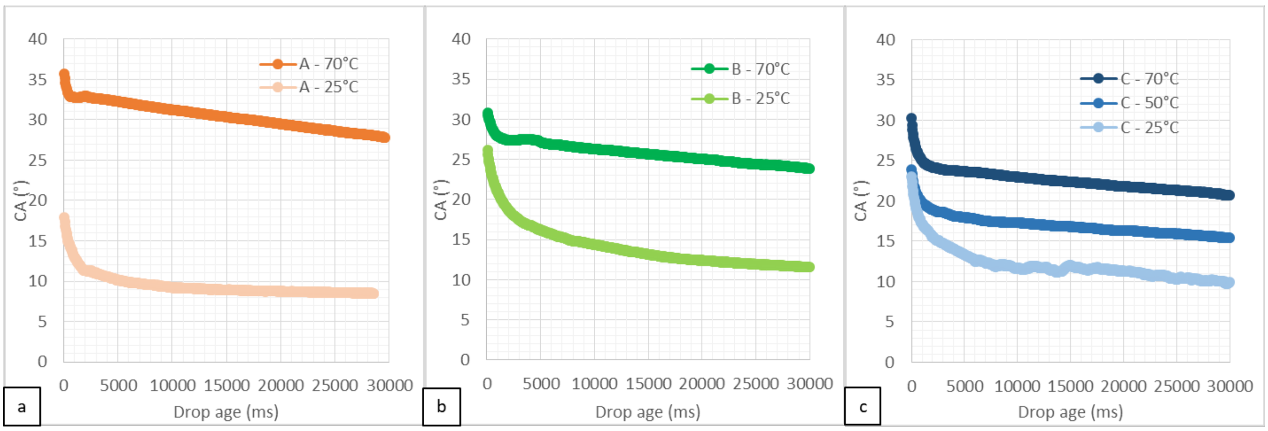

***Fig.4:** Contact angle measurements for three different ink samples at various substrate temperatures as a function of drop age: a) ink A with substrate at 25 and 70°C, b) ink B with substrate at 25 and 70°C, c) ink C with substrate at 25, 50 and 70°C.*

CA is defined as the angle at equilibrium: when a static condition is not reached in the available measurement time, the interpretation of the data is not trivial. Equilibrium is not reached until the evaporation phase ends, which could require a long time, thus in most measurements, a single CA value is not easily identified. In this case, measurements can be analyzed considering a relative approach, by comparing the values corresponding to a specific time. In our case, we chose a condition at which the spread phase is over for all the considered samples and we selected a relevant time in glass decoration process: after printing, the ink undergoes a drying process, so we chose the time needed to reach the drying station (5 s). Table 2 reports the numerical value for CA at initial time (0 s) and after 5 s.

Table 2	CA@0s (°)	CA@5s (°)
A - 25°C	21	10
A - 70°C	37	32
B - 25°C	26	16
B - 70°C	34	27
C - 25°C	25	13
C - 50°C	26	18
C - 70°C	31	24

Table 2: *Contact angle results for ink A, B and C at various substrate temperatures. Values refer to initial time (0 s) and 5 seconds after landing.*

CA increases due to increasing temperature for each tested ink: an immediate result from CA analysis is that a higher temperature corresponds to a lower wetting, resulting in smaller dots and leading to a higher definition. Definition is just one of the key parameters in image quality, whose evaluation requires innovative controlled experimental techniques.

This test represents a useful starting point to characterize ink/surface interaction in a quantitative way and to predict ink behavior after landing. In the next section, we will describe the most common printing defects arising from the interaction between a non-absorbent surface and the ink. Finally, we propose a method to evaluate and improve printing quality.

5. PRINTING ON NON-ABSORBENT SURFACES: THE MOST COMMON DEFECTS

Digital DOD decoration of non-absorbent surfaces shows specific issues, directly related to the interaction between liquid and solid material. Both for glass-like and ceramic printed images, uniformity and definition of edges and details are fundamental. For many glass applications a certain optical density has to be reached, requiring a high laydown; similar requirements apply for the application of effects and finishing on tiles, where a specific laydown corresponds to a resulting optical effect. Moreover, deposition of successive layers of inks one over the other (i.e. finishing over decoration that float over the glaze) show the same behavior as inks over glass.

The images shown in this section have been printed with a single-pass industrial printer, equipped with Fujifilm-Dimatix SG777/MC printheads currently running in a glass-printing factory. Tests were performed with two different inks for glass, here referred to as sample A and B as in the previous section. Defects in non-absorbent surface printing are mainly related to the non-uniformity of the printed image: ink can contract and leave lighter frames surrounding a darker area, or, on the hand, it can spread more than desired, worsening the definition of small details. Other defects, such as banding or satellites, show the same properties as in absorbent surface decoration, so they will not be discussed here.

Image quality is strongly compromised by the spreading out of the ink: i.e. it can close the space inside letters, create irregular edges or merge features that should remain distinct. Fig.5 shows examples of a car glass decorated with letters, full shade, and a fade out dot area: the defect of ink spread is quite evident.

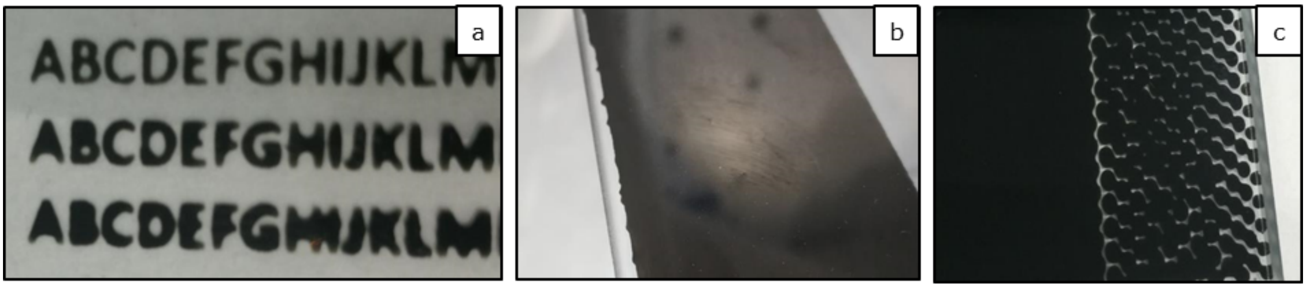

Fig.5: *Spread defect for images printed on glass. a) Letters, b) full shade, c) fade out dot area.*

A very well-known printing defect, in glass as in ceramic tile decoration, is the missing or deviated jet, also known as the "missing nozzle". When, for various reason, a nozzle is not firing properly, or even not firing at all, a lighter line appears in the printed image. Depending on drop size and printhead resolution, the light area can be slightly or strongly visible; the defect is particularly relevant when printing a full shade, but it is visible in most images (Fig.6 a). In some cases, the only solution to solve this issue is to replace the printhead with a new one. In contrast, when dealing with very high ink laydowns, the amount of material can hide the defect, particularly at a very high resolution like 777 dpi. When dealing with missing nozzles, ink spread can help to hide the undesired white line, so in this case the user can decide to lower surface temperature to increase spread and obtain a higher uniformity, if fine details are not the main purpose.

In glass decoration the presence of "holes" in the printed image can be observed, usually occurring when dust particles or dirt are deposited on the glass before printing (Fig.6 b). In glass decoration, dust needs to be avoided and specific tools are installed on the production line to preserve the cleanliness of the surface. A similar situation can be identified in third-firing decoration, where the surface needs to be cleaned before printing. Wettability strongly depends on the surface state, including the presence of dust, so when printing on a non-absorbent surface, the surface condition has to be monitored and controlled.

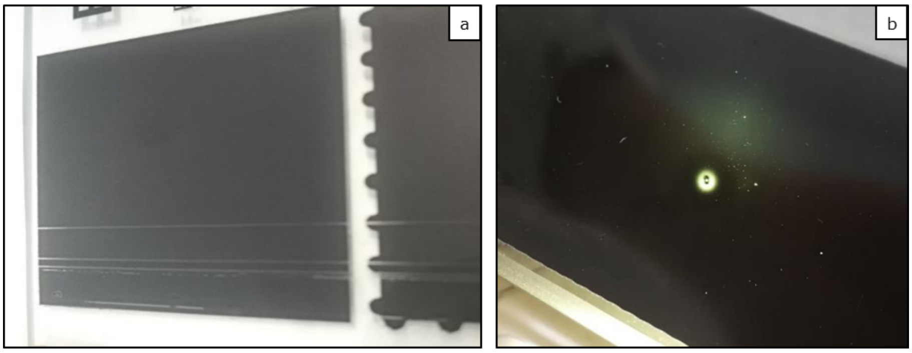

Fig.6: *a) Missing nozzle defect and b) a "hole" defect in a full shade printed on glass.*

The previous description shows that the choice of the right parameter is often a tradeoff between different effects, and the final decision depends on the desired result. If sharpness in details is the main purpose, spread should be kept very low, on the contrary to achieve a high-quality full shade and avoid missing nozzles, spread is a desirable effect.

6. PRINTING QUALITY MANAGEMENT

In order to manage the hard goal of high printing quality we developed a helpful method, a controlled experimental technique allowing qualitative and quantitative evaluation of different printing defects. The proposed method is based on the analysis of images specifically designed to highlight the defects to be detected.

Fig.7 (a-c) shows the images used for qualitative evaluation of full-shade uniformity, (a) holes and ink contraction, (b) detail definition and sharpness and (c) missing nozzles, respectively. The image is designed to be printed aligning the vertical direction with process direction.

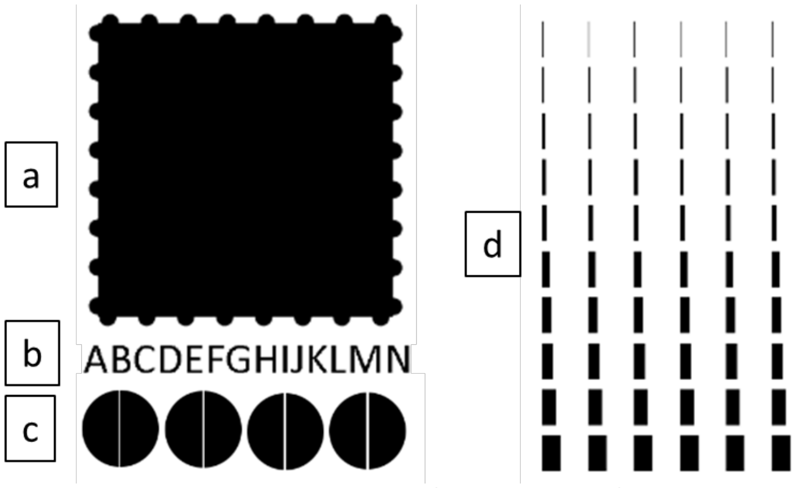

Fig.7: *Images created to qualitatively analyze a) full-shade uniformity and holes, b) definition of details (letters and numbers) and c) missing nozzles; the white lines in the circles correspond to 1, 2, 3 and 4 white adjacent pixels. d) Image for a quantitative analysis of spread.*

A quantitative analysis of spread can be performed considering Fig.7 d): the image includes 6 repetitions of lines printed with an increasing number of pixels, from 1 to 20; repetitions allow performance of a statistical analysis and it is obviously possible to include a higher number of lines. The range from 1 to 20 pixels allows different printing situations to be considered, from the finest detail to a thicker line. In a specific situation, the proper line thickness can be considered, or it is possible to analyze all the data to include a wider range of possibilities. The image can be analyzed manually by using a microscope, or automatically, with a scanning system and a specific software. We measured the width of the lines and obtained spread as the extra-width with respect to pixel expected space:

$$s = w - n \cdot d$$

Where s is spread, w is the measured width, n is pixel number and d is pixel space. Pixel space depends on the selected resolution in the perpendicular direction with respect to process direction: for a 777 dpi printhead this is 32.7 µm.

Images can be printed considering various printing conditions, acting on surface, ink or device settings. As discussed in the previous section, various factors contribute to the final result in printing: this method can be generally applied to investigate the single contribution for each and every parameter. Here we present the analysis performed to optimize one of the most relevant parameters in solid/liquid interaction, namely substrate temperature, as a case study. We analyzed two different inks for glass, sample A and B, varying glass temperature in the specific working range for each ink.

Fig.8 shows two working conditions for sample B, printed at substrate temperatures of 25°C and 40°C, which have been chosen to show the effect of substrate temperature on printing quality. The test image highlights the effect of glass temperature on each feature: at 40°C, definition is higher, as clearly observable in details like letters (b) and in the sharp edge of the frame (a). On the other hand, at a lower temperature, missing nozzles are masked even when there are 3 missing adjacent jets (Fig.8 c), while in the sample at 40°C, the spread can mask only up to 2 adjacent missing jets. A similar behavior has been observed considering sample A at various glass temperatures.

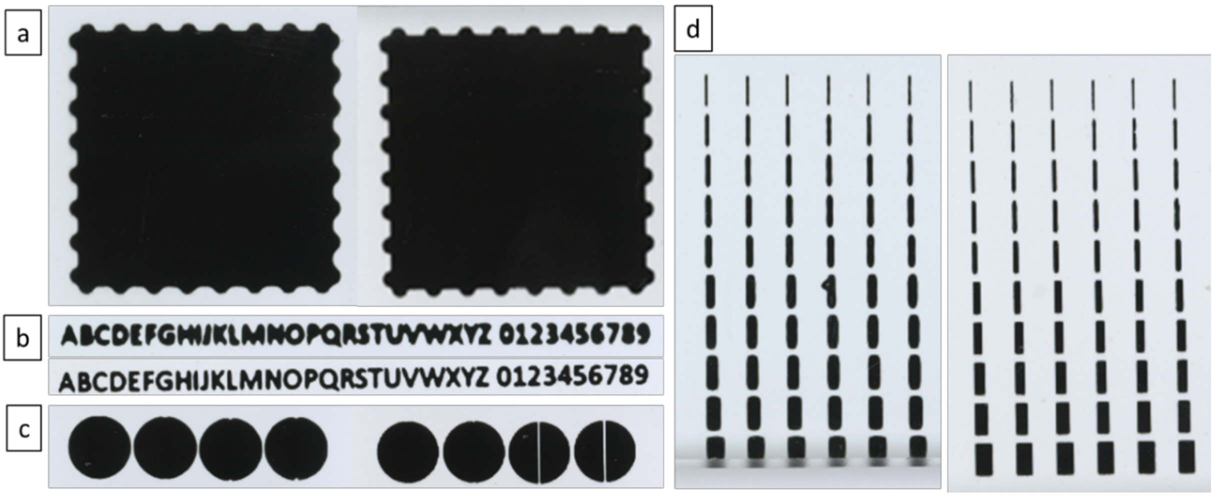

***Fig.8:** Image printed on a glass with ink B, taken with a high-resolution scanner (1200 dpi): on the left 25°C, on the right 40°C glass temperature. Letters printed at 25°C are the upper ones. Description as in Fig.7.*

Table 3 reports a summary of the qualitative evaluation for each sample, which considers full shade, letters, edges and missing nozzles. Full shades, letters and edges are simply marked as "pass" or "fail" to identify acceptable or not-acceptable conditions. In our study full shades are acceptable if the color is uniform, letters if holes are not closed and symbols do not touch each other, edges if corners are sharp and straight line are not bent. For missing nozzles, the number indicates the minimum number of adjacent missing jets not masked by spread: the higher the number, the better the quality; as a reference, it is quite uncommon to see 3 adjacent missing jets. The acceptability and the requirements can be tuned according to customer request.

Ink	Ts (°)	Full shade	letters	edges	Visible missing nozzles	Ink	Ts (°)	Full shade	letters	edges	Visible missing nozzles
A	**60**	Pass	Fail	Fail	3	**B**	**25**	Pass	Fail	Fail	4
A	**65**	Pass	Fail	Fail	3	**B**	**35**	Pass	Fail	Pass	3
A	**70**	Pass	Fail	Fail	3	**B**	**40**	Pass	Pass	Pass	3
A	**75**	Pass	Pass	Pass	3	**B**	**50**	Pass	Pass	Pass	2
A	**80**	Pass	Pass	Pass	2	**B**	**60**	Pass	Pass	Pass	2

***Table 3:** Qualitative evaluation for ink A and B at various substrate temperatures.*

The spread effect can be qualitatively detected in Fig.8 d): rectangles show sharp and straight edges for the sample printed at 40°C. Quantitative numerical results for spread measurement are reported in Fig.9. All tested conditions show a similar trend, with a maximum, for 4-6 pixels for ink A and for 2-4 pixels for sample B images, respectively. This inversion of trends should be considered while designing the graphics to be printed in a real application: i.e. for sample A, a 8 pixel wide line shows much less spread than a 6 pixel wide line, thus the definition is better.

Generally speaking, for the best quality in fine details, spread should be kept to a minimum, corresponding to a higher temperature, whereas to reduce ink contraction and the effect of missing nozzle, a lower temperature is preferable. In all the considered cases, the spread value is much higher than pixel space for 777 dpi, so the minimum spread can be the right choice. However, the maximum considered temperatures are quite close to the maximum working temperature for the ink and prolonged use can damage the fluid and/or the printhead: for this reason, a slightly lower temperature can be preferred.

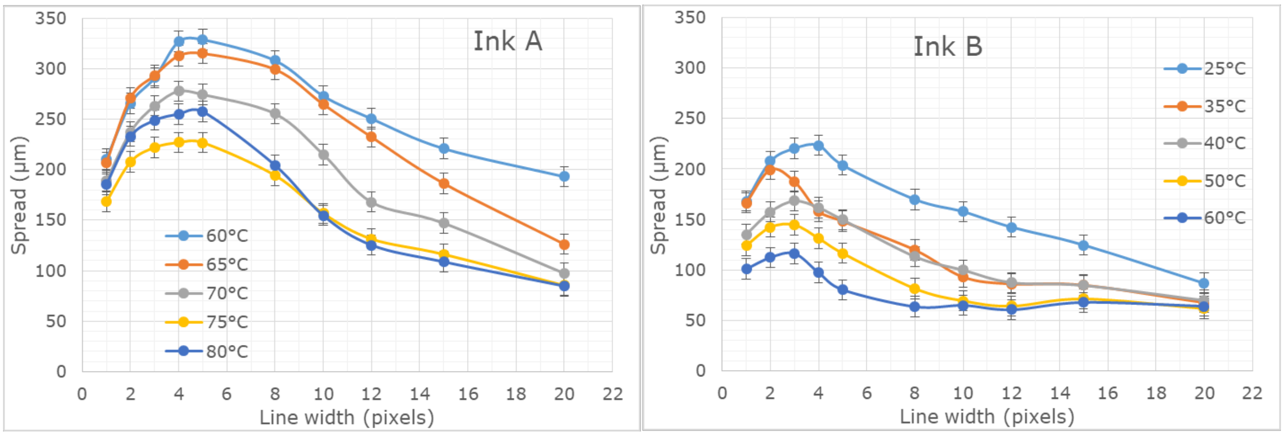

Fig.9: *Measure of spread for ink A and B at various glass temperatures and increasing line width.*

In ceramic tile decoration, as for glass, many parameters play a significant role affecting printing quality. The test described in this section can be easily applied to non-permeable substrates, determining the best working condition considering the application. Substrate temperature is only one of the main parameters strongly influencing dot geometry in non-absorbent substrates, such as in third-fire decoration: analysis methods and correcting procedures have to be implemented to achieve the best performance.

7. CONCLUSIONS

In our study we analyzed how to manage printing quality on a non-absorbent substrate, which shares several common properties with third-fire decoration and full digital applications. We introduced the contact angle measurement, which can be used to predict ink behavior on a substrate. We described the most relevant printing defects, which arise from the non-permeability of the surface and propose alternative solutions to mitigate these. Finally, we developed a general and practical method to evaluate printing quality both qualitatively and quantitatively, considering the different features to be printed, namely details, full shades and edges. The method can be easily applied to tune all the relevant parameters in terms of process and product, such as substrate temperature, to find the optimal combination for the best performance.

We considered glass application as a case study for non-permeable substrate. However, the method is very general and can be applied to a variety of systems, including third-fire application and full digital. All the described concepts can be transferred to ceramic manufacturing, with the proper adjustments.

The wide range of different products and processes now included in ceramic manufacturing has introduced the need for specific tools to analyze and manage the production line. It is now up to manufacturers to develop both the proper advanced technologies and methods, which take into account the peculiarity of each process and products. We have thus developed our study, which will be pursued in depth in the near future to include different new substrates and properties.

8. ACKNOWLEDGEMENTS

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