Industrial Digital Manufacturing; Myth, Hype or Reality?

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Abstract

Implementing digital manufacturing technology into an industrial process has the potential to achieve better performance products at lower cost. Manufacturers are increasingly taking advantage of the benefits that this new technology brings and leaving traditional methods behind. This paper analyses how digital printing penetrated the ceramic tile market, how it is penetrating the textile one and how it will penetrate other markets such as décor, glass and electronics. Those markets are taken as examples and for each, the importance of application and process understanding is discussed, as well as the contribution of printhead technology, software and fluid chemistry in making the implementation successful.

Introduction

In 2008, inkjet accounted for less than 5% of industrial print, in 2012, it was over 19% and in 2018, inkjet is forecasted to account for 30% of this market, with a value of $32 billion.[1]

Analogue printing is still dominating with gravure and flexo used in web applications and screen, pad printing and techniques such as foil stamping widely used to print individual objects.

Inkjet is growing strongly. As a non-impact process, it can be relatively easily integrated. Inkjet fits particularly well when printing is required onto fragile or 3D surfaces, as a deposition technique that is carried out only where needed. Inkjet is advantageous as the deposition pattern can be altered at will and is equally suited to short or long runs. Inkjet can use a variety of functional materials, from organic to inorganic either in solution, colloids or emulsions.[2]

Although the digital graphics market is now mature, the adoption of inkjet in other markets has not been as fast as often predicted. As Moore explains,[3] there is often a 'chasm' to cross between the early adopters of the product, i.e. the technology enthusiasts and visionaries and the early majority, i.e. the pragmatists.

There are four key factors that are believed to be overcome to 'cross the chasm' and adopt digital printing. First, there is a need for a clear market pull from compelling benefits of digital technology. Secondly, communication is of utmost importance so that the market understands these benefits. Thirdly, there are economics; the cost of implementing digital printing must be lower than the cost of current manufacturing methods and/or should be balanced out by the benefits brought by inkjet. In addition, availability of capital for investment is a key factor. And finally, the technology must fulfill the market requirement.

This paper will focus on this final aspect – the technology required for adoption. In this aspect, the key to unleash the benefits of inkjet and realize its potential is highly application-specific. Understanding the end-user product, its technical performance, its production environment and cost and the reasons why the market requires it is essential for successful adoption of inkjet. Printhead technology plays a primordial role in this adoption and recent market launches prove it. However, this needs to be supplemented by two further essential elements, namely fluid chemistry and software.

Several markets will be taken as examples of different stages of inkjet technology adoption lifecycle and the reasons for adoption will be explained. The ceramic tile market is, naturally, the first described; it is the largest, so far, industrial digital market and is fast becoming mainstream. The textiles market will be the second example which, depending on the application, could be considered as just 'crossing the chasm' with adoption happening rapidly. Two other markets, décor and glass, are just before the chasm. Finally, the digital printed electronics market from which novel printed electronics applications will be discussed which is many areas shows little evidence of significant profitable businesses delivering products to consumers.

The ceramics market: a digital market becoming mainstream

Digital printing represented less than 1% of ceramic printing techniques in 2008, 30% in 2013 and is now being predicted to be 55% in 2018.[1]

In the ceramic tile decoration market, there has been extremely rapid growth of inkjet to replace the contact methods of screen and flexo printing previously used. This market was well suited for rapid adoption of inkjet. As a non-impact printing technique, waste was considerably reduced due to the avoidance of tile breakage generating higher production yield. Natural randomisation was a strong benefit of digital printing. Inkjet brought the capability to print onto bevelled edges and textured surfaces enabled shorter product lifecycles and smaller print runs, with reduced inventory cost. It also enabled personalised designs or hybrid technology tiles to be produced.

Three main technological revolutions have made the adoption of inkjet in ceramics able to 'cross the chasm': new printhead and software technologies, as well as novel inkjet ink chemistries. Ceramic tile production is a forgiving application in one sense as designs are usually natural stones and wood effects, printed from generally easier images where noise can be used to mask print defects. In addition, inks are trapped into a thick fired glaze which also helps to masks any imperfections. Therefore the demand on the printhead technology is lower than for a graphics application, however reliability is key especially in the challenging environment of heat and dust of ceramic tile production. The Xaar's recirculating 1001 head has certainly been a technology breakthrough in achieving this goal and systems based on this printhead have been a great contributor of this rapid adoption.

This adoption of digital has also required technology breakthrough in software capabilities and a shift in thinking about designs. Companies attempting to reproduce existing designs from analogue printing were missing the opportunity to gain market pull; this is actually a pitfall of many technology adoptions and inkjet isn't an exception; it is part of 'crossing the chasm'. In this transition, software is a key and it is particularly important for ceramic tile production. Industrial ceramic print software has brought the capability of handling very large images and incorporates algorithms to randomly select designs. They also, as faster jetting frequency printheads were developed, enabled high speed data transfer of images to printheads, and technology was incorporated to rip and upload image data on the fly, through job queues, with the capability of adding variable data on each tile. Further addition in those products which recognise the requirements for industrial printing manufacturing is the integration of this software to Enterprise Resource Planning (ERP) systems.

The last enabler of this rapid adoption is the development of appropriate fluid chemistry.[4] Inks for decorating tiles were well known from analogue printing techniques; however they could not be applied to inkjet because of their physical characteristics. Thus, there were two schools of thoughts; those that believed they could start from the analogue inks and adapt them to inkjet inks and those that understood the application and looked for a path that would unify the end-user product requirements and the inkjet technology.

A variety of colours with high tinctorial strength, ink stability and ink reliability were the key technological drivers that the market seeks. Ink reliability was down to the understanding of how the ink interacted with the printhead (e.g. waveforms) but as discussed above the printhead was an important contributor of this. The variety of colours was achieved by combining a range of colours from blue and yellow through to brown, beige and pink. Black was a later addition as the market moved to highly coloured rustic tiles, although it is also possible to achieve black through the combination of blue and brown providing their colour strength is high enough.

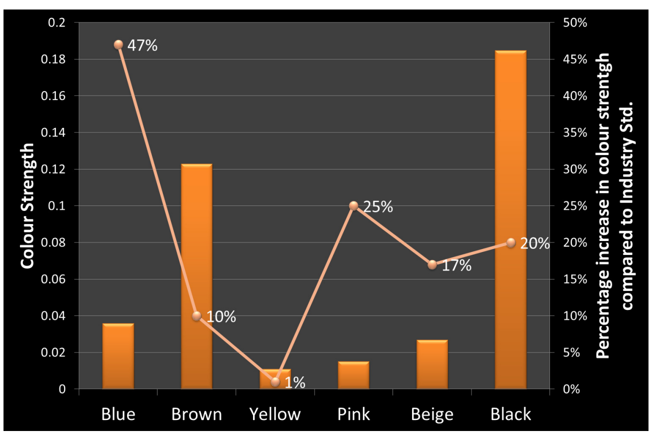

Figure 1*. Colour strength of Zircon inks and the calculated percentage increase to reach the same colour strength using industry standard inks (ink printed at 300x300dpi on single fire glazed tiles)*

The colorants of choice for this application were inorganic pigments that could withstand firing temperatures of 1050ºC to 1300ºC, restricting the choice of chemistry available. From an inkjet point of view, the purity and the physical characteristics of the pigment crystals were also of great importance; namely their structure, size and shape. This is how the best balance of colour strength (Figure 1 illustrates Zircon as an example) and ink storage stability (more than 6 months for Zircon) can be reached. In addition, in order to successfully formulate inks that would fulfil the end-user requirement, the interaction of glaze with each of the coloured inks is then considered. For example, the ceramic blue ink develops its colour by solid-state reaction with the glaze so materials that favour this phenomenon are used. The case of ceramic white ink is similar depending on the chemistry chosen; Zircon white achieves very high opacity (L^*=48.22, +15% of opacity compared to industry standard). A complete understanding of the interaction of the different elements in the glaze with the colours is required. For example, to develop higher chroma browns, lower zinc content in the glaze is required.

The ceramic tile market is a real success story of the industrial implementation of digital manufacturing. Although the ceramic digital market is still expected to grow, pricing competitiveness is demonstrating a market reaching saturation. Companies are still trying to innovate, in increasing line speed, although somewhat limited by the firing process, or offering solutions for the inkjet deposition of glazes.

The textile market: a digital market which has ‘crossed the chasm’

In 2012, the global market for digitally printed textiles was estimated at $10.3 billion. It is forecasted to more than double by 2017. Traditional textile market is printing 32 billion of m^2 a year and the digital textile market is set to reach 1 billion of m^2 printed in 2017.[5]

The key drivers of the current adoption of inkjet by the textile industry are somewhat different from the ceramic tile industry. As fashion is concerned, the reduced time to introduce new designs is very appealing to the textiles industry. Reduced cost is also desirable, and has inkjet has no requirement for screens this helps to reduce design introduction cost. Digital printing is also bringing the benefit of improved sustainability, which has high profile in the textile industry, through lowering energy, water and material (e.g. dyes) consumption.

The success story is similar as for the ceramic tile industry. Textile printing is also a forgiving application in a different way to ceramic tile decoration. Drops are jetted from high throw distance onto fabrics which can have an open structure and deposited drops usually wick along the fibres. However, in contrast to ceramic tile printing, high resolution printing is required as designs often includes flat tones or patterns with a high degree of detail. It is then no surprise that after the introduction of the Epson printhead DX series in multi-pass printers to serve the Direct To Garment (DTG) market, the Kyocera KJ4B printhead at a native resolution of 600x600dpi was adopted to serve the Roll to Roll (RTR) markets with high speed printing. This latter printhead technology made a great impact on the digital textile printing market, as printers using step-and-scan configuration now reach up to 1,000 m^2/h, or using single pass configuration reaching up to 5,000 m^2/h. This high productivity overcame the last barrier to the adoption of digital printing in the textiles industry.

As for the ceramic tile industry, the development of high speed data transfer hardware and software able to support the high jetting frequencies of up to 40 kHz, as well as software to enable reproduction of particular colours using a 8+ colour set has been a key enabler.

Fluid chemistries have also contributed to this recent rapid adoption. However, formulating inks for textiles present challenges that are very different from ceramic inkjet fluids.

Indeed, the emphasis is on outstanding colour performance with extended colour gamut as well as excellent fastness properties (wash-, rub-, crock-, and light-fastness).

The colour performance of Amethyst, a reactive dye ink, is illustrated in Figure 2, the colour strength is outperforming the industry standard. This enables higher colour performance with lower ink usage, and helps to overcome the colour advantage from analogue inks from their higher colorants and binder content.

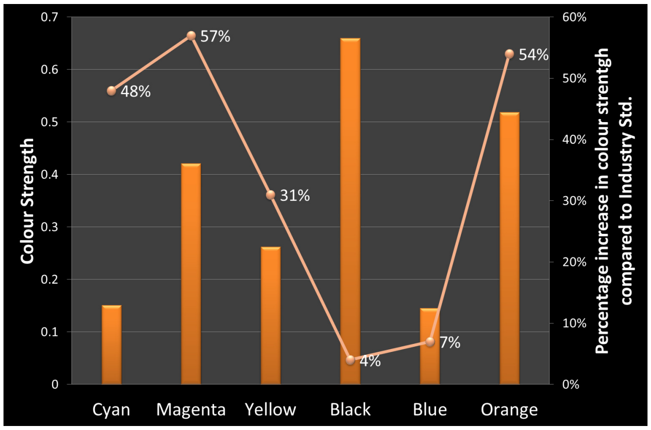

***Figure 2**. Colour strength of Amethyst inks and the calculated percentage increase to reach the same colour strength using industry standard inks (ink printed at 600x600dpi on pre-treated cotton fabric)*

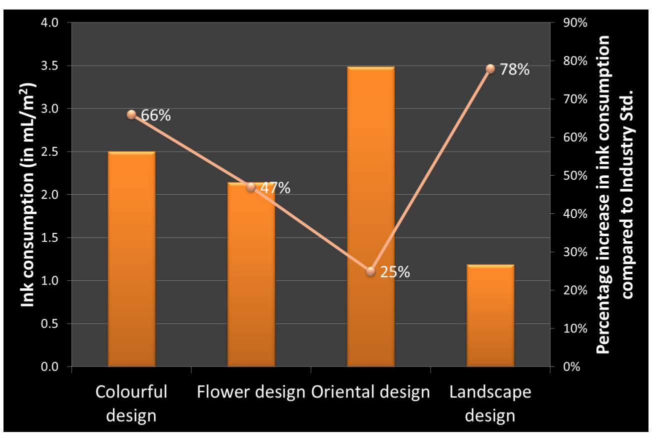

***Figure 3**. Ink consumption of Corundum inks to print 4 different designs and the percentage ink consumption increase to reach the same colour strength using industry standard inks (ink printed by a MUTOH RJ-900 at 720x720dpi on polyester after sublimation transfer)*

Achieving higher colour strength can be seen as a dual advantage for the textile manufacturer: the cost per m^2 is either lower than his competition, i.e. it requires less ink to achieve a particular colour or colours never seen before can now be achieved which opens up a vast horizon for new designs. Figure 3 illustrates the potential cost reduction in the case of Corundum sublimation disperse inks suitable for polyester printing. Four different designs have been printed with Corundum inks and an industry standard ink. In order to match the colour, 25% to 78% more ink was necessary in the case of the industry standard ink.

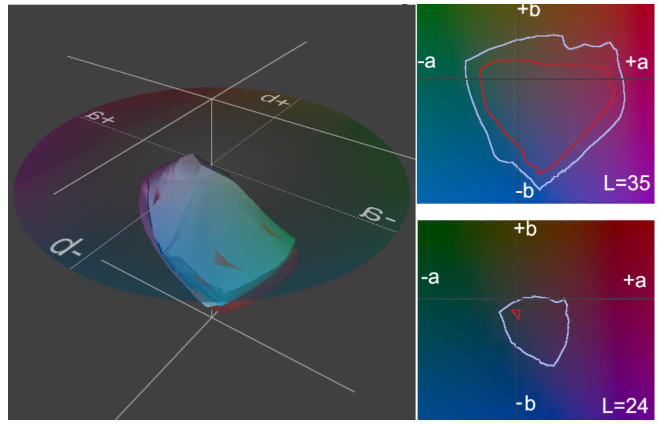

***Figure 4**. Gamut comparison of the Amethyst ink (lighter colour line) set to an industry standard ink set at two different L values (L=24 and L=35)*

Gamut comparison of the Amethyst ink set compared to industry standard revealed that at high L^* values, i.e. superior to 35, the Amethyst inks can generate 33% more colours than an industry standard ink as illustrated in Figure 4.

As discussed above, one of the key requirements for textile printing is excellent fastness properties of the printed fabric. In the case of the Amethyst ink set, a high degree of lightfastness properties of the printed fabric has been reached (Table 1).

***Table 1**. Lightfastness data (ISO 105-B02:1999) after 98 hours from Viscose fabric printed at 600x600dpi*

Amethyst	Lightfastness
Cyan	6
Magenta	5
Yellow	6
Black	6
Red	5
Blue	6
Orange	5/6

In contrast to the ceramic industry, where production line speeds rarely go over 50 m/min, the textile industry is used to double that speed. This presents a challenge to printhead technology, although printhead at frequencies up to 80 kHz are being developed, but also to inks as performing at this speed requires an optimised rheology and surface tension to guarantee the stability of drop formation while minimising satellite formation and misting.

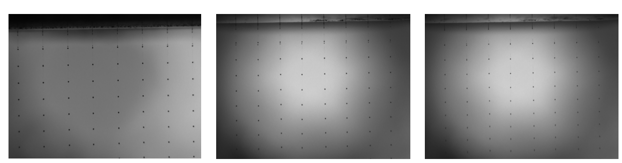

***Figure 5**. Drop formation of 4dpd, 3dpd and 2dpd (respectively from left to right) of Amethyst Magenta at 20kHz*

Figure 5 illustrates the jetting stability of the different grey levels of Amethyst magenta when jetted through a Kyocera KJ4B, at 20 kHz. Satellite formation is minimised and when present merges with the main drop to avoid artefacts on the printed fabric.

The potential for digital manufacturing in textiles is still huge, and the key is innovation. The market has the potential to grow bigger than the ceramic tile market.

The décor and glass markets: two digital markets just before the 'chasm'

The décor market

Digital printing represented less than 1% of décor and laminates printing techniques in 2008, only 4% in 2013 and is now being predicted to be 10% in 2018 reaching a market value of $1.7 billion.[1]

The décor market which encompasses the wallpaper market and the laminates market are still dominated by gravure and flexo printing, some with embossing to impart texture. Those markets are interested in digital printing, as they would have the capability of moving beyond commodity designs, being able to run experimental fashions and offer shorter lifetime products. Digital printing has already penetrated those markets in a small way to produce short runs and one-off designs, using flatbed wide-format inkjet, either through UV or solvent inks (for direct to board printing) or latex inks (for wall coverings), however the throughput remains generally very low and costs very high.

Both markets present their own set of requirements and challenges for successful adoption of inkjet, however some requirements are common to both. As both industries are used to fast analogue printing techniques, high throughput printing is of utmost importance as well as a low cost per m^2. In terms of end-user product properties, high colour vibrancy and lightfast inks exhibiting very low metamerism are a key enabler. The wallpaper market will require a degree of scrub resistance as well as fire retardancy, low formaldehyde release and limited presence of heavy metals. The laminates market is somewhat different from the wallpaper market as the printed product takes the form of a white or tinted printed paper which is then laminated onto chipboard or medium-density fibreboard (MDF) for use in flooring and furniture. The printed paper needs to be fully compatible with the resin so that no alterations are made to the lamination process. Laminated products also require properties such as abrasion resistance and heat stability.

Advances in digital printing technology are the frontier of décor printing. A key technological challenge lies in the quality that needs to be delivered to the décor market. Indeed, the application is much less forgiving than in the ceramic tile and textiles markets, partly due to the substrate but also due to the requirement for high quality and high consistency of regular patterns, for example a wood grain effect across large areas (width of printed media being up to 2.1m). This places a challenge on the printhead/ink interaction, and resolving this will greatly help the décor market to 'cross the chasm', although other technology requirements need to be met as well. As in the case of textiles, analogue inks used for décor printing are higher in viscosity and generally use higher solid content of colorants. In addition the deposition per m^2 is greater than by inkjet which combined with the high viscosity enables high intensity colours to be achieved.

In order to meet this challenge, new water-based pigment inks are being developed especially for laminates applications. In addition to being compatible with the lamination process (resin impregnation, high pressure and heat stability), the inks demonstrate high colour saturation as illustrated in Figure 4. In this example, the ink set includes a red to help achieve warm brown tones necessary in wood grain printing. Lightfastness properties are not affected by the lamination process and are currently reaching a value greater than 6.

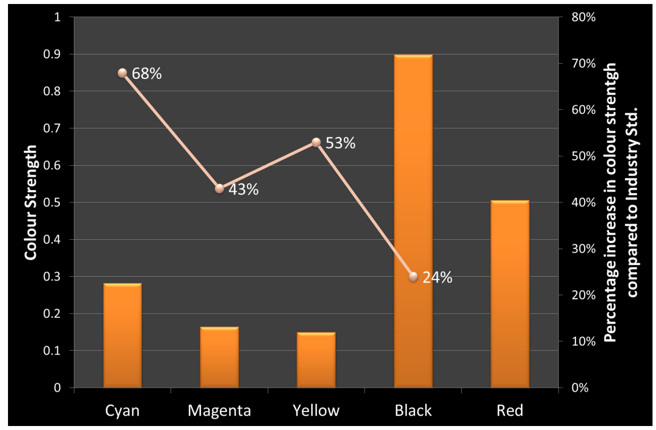

***Figure 6**. Colour strength of Opal inks and the calculated percentage increase to reach the same colour strength using industry std. inks (ink printed at 600x1200dpi on 100g/m^2 digital décor paper)*

Digital printing is growing fast in this industry but one cannot underestimate the size of the 'chasm' to cross, from a technical point of view (the high throughput requirement either achieved as a single pass or step-and-scan) and from a commercial point of view, as the current supply chain may require major transformation.

The glass market

Digital printing represented less than 5% of glass printing techniques in 2008, only 11% in 2013 and is now being predicted to be 27% in 2018 reaching a market value of $300 million.[1]

Currently, glass is printed by pad or screen printing. Printing onto glass is used in several applications: architectural, automotive, display, drinking glasses and bottles and container glassware. Additionally display screens are increasingly made from glass, as are some photovoltaic or solar energy modules. There are also glass ceramic cooktops, optical glass and mirrors.

Performance of the inks onto glass is essential in this application. Both organic and inorganic inks are in use either for non-durable applications or exterior and dishwasher safe use respectively. Inkjet can already be used to print onto small runs of glassware and bottles, while flatbed equipment can be used for mirrors and small batches of architectural glass. The application is even less forgiving than the décor market, as glass is a non-porous substrate with a tendency to be easily contaminated by grease which radically alters the even spread of dots and creates artefacts. The requirements detailed for the décor market are also valid for glass but at a higher level of quality. In addition, high deposition of inks onto glass is usually required as full opacity is a key onto this transparent substrate (using a white ink to complement the set of CMYK inks), and this latter requirement may be what is hindering the glass market to cross the 'chasm'.

A great variety of inkjet inks are already available, although one single solution doesn't exist. As glass is present in different applications, the inks are specific to the application. UV inks offer very vibrant colours and demonstrates reasonable adhesion (when glass is pre-treated with a primer) and scratch resistance. They are usually used to print on the backside of glass. For stricter scratch resistance products, heat tempered UV inks with sol-gel chemistry is used. However, for durable outdoor use, inorganic inks are used, although they are opaque and are less vibrant than UV inks. Those inks contain glass frit particles that are fused into the glass during the tempering process.

High throughput with high quality and consistency are certainly the barriers to the wide adoption of inkjet in the glass market. A number of applications of glass digital printing are still not satisfied, as the ink chemistry is not currently capable of delivering against requirements, for example in high durability automotive printing and decorative glass in high humidity environments.

The printed electronics market: waiting for the ‘chasm’?

Digital printing represented less than 2% of printed electronics market in 2008, only 3% in 2013 and is now being predicted to be 12% in 2018, reaching a market value of $5.5 billion. [1] However, much of the activity in inkjet printed electronics seems to be technology looking for a market, rather than end-user demands.

The interest in the inkjet printed electronics market is its added capability compared to traditional deposition methods. Inkjet is non-impact and so is perfectly suitable to print fragile substrates which cannot run through standard deposition processes. Inkjet can vary patterns and this is particularly attractive in new product designs where multiple types of jobs can be tested without having to replace screens. It has therefore a direct impact on time to market and also a direct impact on development costs. In addition, using an additive inkjet process rather than a subtractive screen printing technique leads to considerable cost savings as generally the materials used in this market are very expensive. Inkjet printing is also far more easily scalable to larger areas than conventional manufacturing methods, and allows printing of circuits onto flexible substrates.

Identifying the right application is key to successfully ‘cross the chasm’; applications that have a requirement to be processed digitally, where the image changes every time, and require non-impact process would be perfectly suited to inkjet.

However, the limitation is in the feature size. Today, inkjet can deliver a 100 µm wide line at slightly better throughput than screen printing, and can probably go down to 50 microns by surface functionalization. As a comparison, gravure and offset are able to print less than 50 µm lines. However, the industry is looking for 10 µm feature size or lower. For this reason, printhead manufacturers are working on smaller drop size printheads which can print down to 1 pl and allow smaller features to be reproduced.

Conclusion

‘Crossing the chasm’ in industry and successfully implementing digital printing as a means of manufacturing requires a convergence of technologies which are unique to each application, although printhead, software and fluid chemistry are the three key technologies that will greatly help the adoption.

While the digital tile ceramics market is now maturing and the textile market booming, other markets are ready for the adoption of digital printing. Printed electronics remains the most challenging where benefits of inkjet have yet to be proven in most applications.

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