"HOW INKJET PRINTING BECAME POSSIBLE - A VIEW OF THE R&D&I CHAIN"

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1. INTRODUCTION

Over the last decade, we have witnessed an ever-growing, massive and spectacular implementation of inkjet technology used for decorating ceramic tiles.

In origin, it is a relatively new technology that dates from the early 1970s with the first dot matrix printer (Centronics Corporation) using ink jets applied to paper printing.

Undoubtedly, that technological innovation can be described as 'disruptive' (Christensen: "The Innovator's Dilemma" published by Granica, 1999) compared to everything that came before because:

- It was the first contact-free means of decorating the work piece.
- For the first time, it touched on many facets of innovation as defined by the Oslo Manual (Oslo Manual, OECD 2007): product, process, service, model marketing and business model.

Thus, it is a clear example of the full meaning of R&D&I:

- **Research**: in piezoelectricity, materials, vehicles.

- **Development**: in printheads (nozzles), machinery, software, compounds, processes and products.

- **Innovation** in the product, service, process, marketing model and business model.

Furthermore, it reproduces the innovation model for the ceramic industry defined in earlier papers: meeting a need that was hitherto unfulfilled but nevertheless demanded, created within the sector's own value chain, provided by direct suppliers from each subsector, successively improved through cross-contributions from players in the sector, its use has become massively widespread and extends through imitation, it systematically generates leaps in improvement, it calls for technical training and professional qualification, etc.

Given that it represents a disruptive innovation of the first order, it is therefore fitting that we reflect on the mechanism that made it possible. This paper examines the phenomenon in the R&D&I chain that made the emergence of this technology a reality and which has been the subject of earlier studies (I. Fernández de Lucio et al., Bol Soc Esp Ceram V 47 (2) 57–80 (2008) and Escardino A., Bol Ceram Soc Esp V. 40 (1) 43–51 (2001)), although over the last 5 years, it seems to be changing.

The quest to make R&D&I come true is constant – to transfer the results of "R" in such a way as to enable "D" and then work successfully down the chain by means of "I". Inkjet ceramic decoration is a clear example of such transfer and of the need for each of the steps.

This concept is also in line with the new trends to be found in the literature on innovation systems and which, among other matters, emphasize the basic idea that, in order for innovation systems to function properly, a number of key, specific activities need to effectively take place (D. Gabaldon and M.P. Hekkert, Journal of the Spanish Ceramics Society, vol 52. 151–158 May–June 2013).

Indeed, it would be impossible to understand this innovation in the absence of basic research about the properties and characteristics of materials such as piezoelectricity, particle size and shape, rheology, etc. or key developments in the interpretation of space and colour coordinates and their transformation into software models, or the practical use of the crystal structure responsible for colour and its correlation with size and performance, or the mechanics, electronics and engineering that correlate and master all these variables within an industrial process, or the properties associated with the nature of materials according to their particle size, structure and energy states.

It was the combination of three basic aspects that brought it to life: Knowledge of materials (materials science), process engineering with the backing of electronics and its associated software, and – this is the radical novelty – the introduction of the "business model" as a variable that to date has remained practically undeveloped in the sector but which is seen as one more form of innovation in the Oslo Manual.

This paper does not intend to review the literature or study the "state of art"; nor is it intended to further the science or knowledge associated with each of the sections it deals with, but merely it strives to analyse the model underlying the onset of inkjet technology applied to the decoration of ceramic tiles and thereby highlight the need for a concerted effort along the entire R&D&I chain. It also proposes a model for generating new innovation based on the concept of "Open Innovation" (Chesbrough: Open innovation).

Furthermore, this paper aims to illustrate the benefits derived from creating the sectorial cluster. According to M. Porter's definition in his "Competitive Advantage of Nations", 1990), a cluster is defined as "geographic concentrations of interconnected companies, specialized suppliers, service providers, firms in adjacent sectors and associated institutions (e.g. universities, government agencies, business associations, etc.) in particular fields that compete but also cooperate with each other".

Last, but not least, it is also pays tribute to the people and companies who have made possible this technological development of the first order, set to revolutionise ceramic tile manufacturing. It is a clear example of what Peter Drucker calls "Innovation and the Entrepreneur" (Ed. Apostrophe 1997) and which could be encompassed within what the author calls Sources of Innovation in categories 5 (the need for progress) and 9 (new knowledge).

2. METHODOLOGY USED

In order to study the evolution and assembly of knowledge leading up to the application of inkjet in ceramics, the following methodology was employed:

- First the technology was defined as "decisive".
- Then the items (components) that come into play in it were analysed.
- How each of the components has evolved "front to back" was assessed to see the individual origin of each one in order to provide an overview for subsequent assemblies. In this section, the period of time when it was already available is identified.
- The "open innovation" mechanism implemented was identified.
- New (innovative) items not present in previous innovations were incorporated.
- And finally, the frontiers open for future assemblies of knowledge and extensions of innovation. By Frontiers of Knowledge, we refer to research work capable of extending the scope of our knowledge, of pushing the frontiers of our knowledge forwards, with regard to different disciplines coming together and overlapping.
- All of the above would seem to reveal a new model of innovation within the ceramics cluster.

3. RESULTS AND DISCUSSION

3.1. PRIOR DEFINITION OF THE TECHNOLOGY AS "DECISIVE"

Earlier studies ("The Innovation Process in the Ceramic Tiles Sector" Francisco Corma Canós, September 2006, ATC; "Models of Innovation present in the Castellon Ceramics Sector" P. Corma, Qualicer 2018) already analysed post-1980 innovations in the ceramic industry deemed to be decisive. The final table, based on the criteria established in those papers, was as follows:

YEAR	PRODUCT/PROCESS	INNOVATIONS
1980	Stoneware tile	· Transformations in the press dies
1981		
1983	Earthenware tile	· Continuous listels · Monoporosa (Porous single-fired tile)
1984	Earthenware tile	
1985		· Grits · Start-up of tile sales & marketing through manufacturer's own network
1986		
1987		· Design incorporated into glaze sales · New way of marketing glazes · Pellets · New fritting furnaces
1988		· Line-guided vehicles
1989	Porcelain tiles	· CHP co-generation
1990		· Picking
1992		· Continuous clay milling
1996		· Decorating roller
2000	Glazed porcelain	· Quality control based on artificial vision · **Inkjet decoration**

As can be seen, inkjet decoration was already included on the above table in the year 2000 but it was between 2005 and 2007 that its real onset took place.

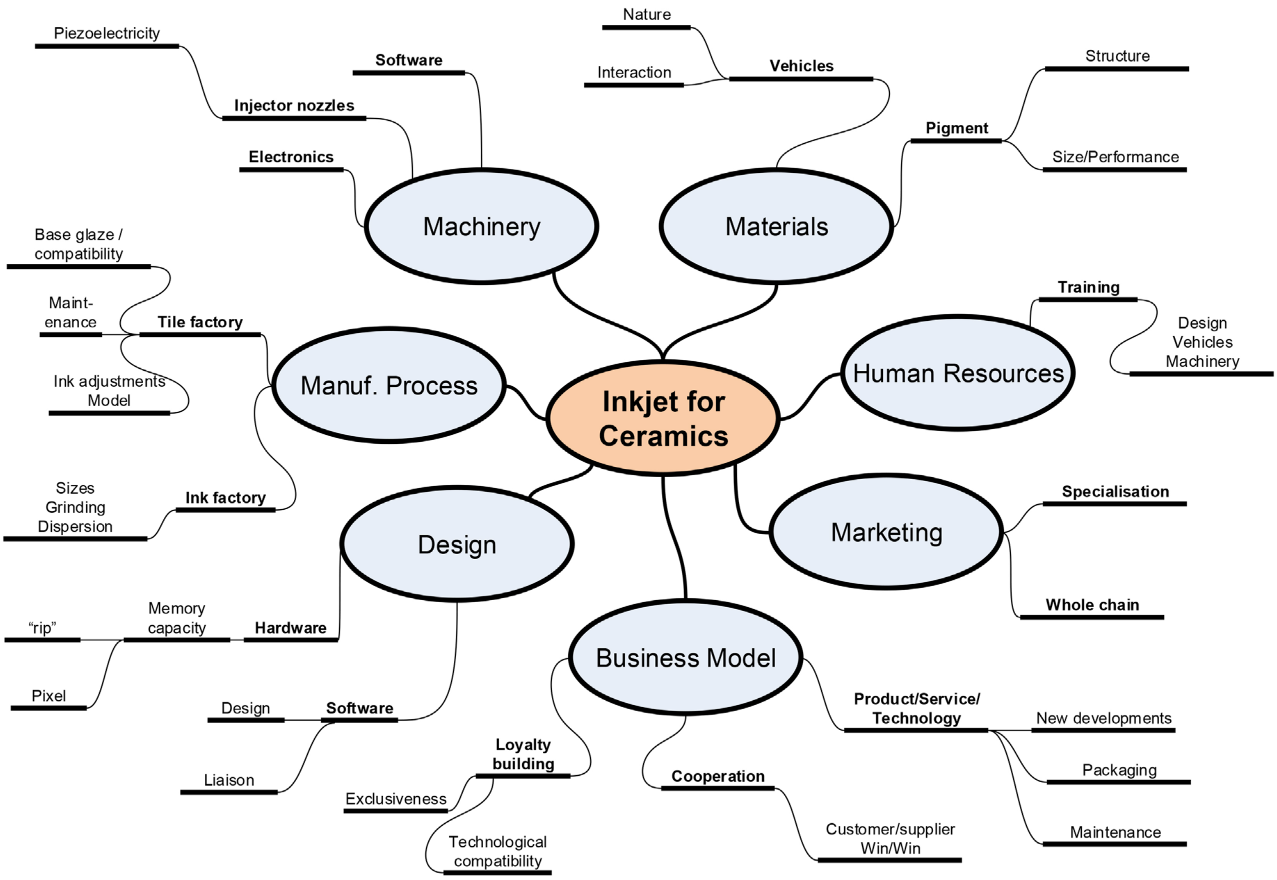
Each of the innovations above encompassed a number of factors in terms of materials, processes or services that made them possible. The afore-mentioned innovations are the result of everything that preceded them and which they have made visible.

3.2. ANALYSIS OF THE ELEMENTS (COMPONENTS) THAT COME INTO PLAY

We built a Mind Map (Tony Buzan: "The Mind Map Book") to locate and organise the elements to be taken into consideration in inkjet technology. To do so, we started with those proposed by the Oslo Manual as vehicles for Innovation.

The Mind Map was deployed on several levels – maximum of 5 and minimum of 3.

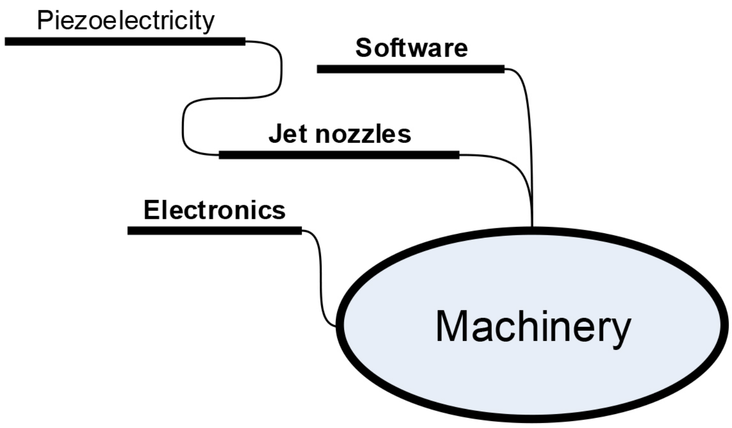
This mapping revealed all the items that play a part in the technology and thus the frontiers of future developments could be defined. It also specifies all the side entrances in the "open innovation" beyond materials and machinery.



3.3. STUDY OF HOW EACH COMPONENT HAS EVOLVED "FRONT TO BACK" TO IDENTIFY ITS INDIVIDUAL SOURCE AND TO PROVIDE A VISION FOR LATER ASSEMBLIES

For this purpose, each branch was taken: an example is given below:

3.3.1.- Machinery - injector nozzles - piezoelectricity



- Objective: To ensure pigment is transferred by means of the "inkjet on demand" method and that the ink drop is only generated when required (fundamental issue in ceramic decoration).

- This implies producing drops in a highly controlled manner, of a highly controlled size and with the utmost accuracy in order to achieve precise decorative motifs with a large number of drops per inch (dpi).

- That in turn calls for the presence of a type of permanent "launch-pad" that has to have very high intermittency and be capable of being adjusted to drop size and of being automated. The first dot matrix printers appeared in the 1970s.

- Given the above premises, it was clear that a mechanically actuated nozzle would not provide either the required speed or the necessary precision and degree of automation. A new system was called for and already existed: piezoelectricity.

- The phenomenon of piezoelectricity had been known since the times of Pierre Curie (1881) and his studies on compressing quartz. Piezoelectric materials also exhibit the opposite property, i.e. when an electrical power difference is applied, a current is generated (compression-relaxation). This property, present in crystals and ceramics, was further developed as the so-called PZT (Lead Zirconate Titanate) in the 1960s and 1970s. The first pieces used as means of launching or expelling an intermittent jet of ink appeared and by 1990, work had started on applying the technology to ceramic inks (European Project 'PLZT').

- In order for it to be applied to different fields, first we had to be more knowledgeable about the phenomenon of piezoelectricity, the restrictions imposed by the medium to be transferred (ink), the degree of accuracy and of course the full automation of the process.

- Equipment manufacturers chose different technologies for the specific market segments they were aiming at – the ceramic sector was fairly unattractive at first given its insignificance in terms of quantities used.

- As can be seen in the Mind Map, this branch (machinery–piezoelectricity) is coupled to electronics and software, given they are critical for the whole unit to work properly and to achieve the desired objective. Until all the various branches were assembled, it was not possible to produce the final injector nozzles for inkjet ceramic decoration as we know them today.

- But that was only the Machine. There were still more components to be assembled, now that the road ahead had been cleared.

Identifying the implemented "open innovation" mechanism

In order to do so, the different branches (as discussed in the previous section) were taken into consideration and the "open innovation" items analysed from the viewpoint of developing inkjet ceramic decoration.

Let us consider a concrete case:

Machinery-injectors-piezoelectricity:

- We start from the position outlined in the previous section.

- The injector already existed and could be made available by the manufacturer: Xaar, Spectra and Seiko.

- The Open Innovation concept (Henry Chesbrough, "Open Innovation: The new imperative for creating and leveraging technology", 2003) was launched as a means of combining internal knowledge with external knowledge and to furthering strategy and R&D projects. According to the "Open innovation" model, projects can originate both inside and outside the company, they can be incorporated both at the beginning and in intermediate stages of the innovation process, and they can reach the market through the same company or through other companies (patent licensing, technology transfer, etc.).

- At this point, it is fitting to make specific mention of the manufacturers of the final injection machine who used "collective intelligence" by collaborating with manufacturers of injectors, creators of software, manufacturers of inks and vehicles, etc. In 1998, Kerajet was born for exactly that purpose - see patents and the documentation indicated therein as earlier references (WO2000021760A1/ EP1038689B1/ES2219068T3), and which led to what we now know as the Kerajet machine (see patent application 200930657 and publication number: 2 354 667).

- Simply reading those patents gives a clear idea of the "Open Innovation" process carried out by the manufacturer.

- Simultaneously, participants in the above collective intelligence process also had to implement lateral "Open Innovation" with their suppliers of material treatments, vehicles, which even brought about the definition of new products. See patents GB2268505, GB19910004171 19910227 and US- 5.407.474 dated 1994 and 1995, where inkjet inks for ceramic decoration are mentioned but without resolving certain issues such as the stability of the suspension or abrasion of the nozzle holes.

- One should not overlook the breakthroughs made prior to that time (1992–1993) with pigments based on soluble salts that managed to overcome certain problems but did not solve others (difficulty in obtaining the CMYK colour process, uncontrolled penetration onto the media). See patents US-5.273.575 and EP-0.572.314-A1.

- The above process extended along the entire chain (paradoxically, the least active participant was the end recipient, the tile manufacturer). This issue had been avoided in part because of the inherent nature of the cluster in which the manufacturer is omnipresent:

    - Suffice it to observe the CDTI or IMPIVA projects in the period 2003–2010.

    - Those were the boom years for research projects on inkjet technology, even though it had still not been commercially deployed.

    - That in itself is a clear example of the "Open Innovation" process in the cluster.

- At this point, mention should be made of the contents of an earlier paper ("The innovation process in the Ceramic Tile sector" by Francisco Corma Canós. September 2006) which defined the sequence in which the knowledge was developed and applied – what we call the 'Switch from Research to Technological Development': Most patents relating to the subject were published between 1998 and 2008, whereas the Technological Development and Innovation projects are dated from 2006 to 2010.

- This same process can be seen in the Materials or Design branches, where in-house knowledge was combined with external knowledge to generate "collective intelligence" through a process of "open innovation".

Incorporating novel (innovative) items not hitherto present in previous innovations

From the point of view of how its mass application evolved over time, inkjet ceramic decoration comes one step behind flexography, or specifically Rotocolor, as a significant milestone in decorating.

Like any other disruptive innovation (Chrystensen C.M.: "The Innovator's Dilemma", Ed. Doubleday (1999)), it takes advantage of what existed beforehand and then positions itself on the frontier of knowledge before eventually leaping forward as a breakthrough. As far as its evolution is concerned, the surface decoration of ceramic tiles can be seen as follows:

- Direct involvement of the human hand using natural oxides. The hand does the drawing.
- Application of natural oxides and ceramic pigments using transfer items (brushes). The hand uses a brush to draw.
- Application by manual transfer using some intermediate item that creates the drawing (stencil). The drawing is pre-defined.
- The same as above but this time using first mechanical transfer and subsequently automated transfer, i.e. from the stencil to the silk screen. Use of structured dot grids or Amplitude Modulation (AM).
- The same as above but now with the capability of altering the drawings. Up to this point, it had only provided 100% repetitions but now slight differentiating changes started to appear. Recent silkscreen technology that lasts over time.
- Following growing demands for improved accuracy and image quality, the 30 dots/cm threshold was reached thanks to more refined inks and the use of Frequency Modulation (FM) grids. FM provides enhanced quality of the illustration while also calling for further technological advances.
- Pad printing and flexography. Transfer is still by contact but becomes less repetitive by spreading further over the drawing.
    - At this point, a simple search of patents registered under the name of Franco Stefani (System) reveals the evolution of technology and the implementation of "Open Innovation" in the case of the Rotocolor.
- From then on, any subsequent step forward was obliged to provide great image quality (FM or stochastic grids) and therefore a smaller (much smaller) particle size and high ink stability to produce small, static dots.
- The next step to be achieved on two fronts was both logical and necessary:
    - Maximum differentiation between work pieces (no repetition)
    - Avoid contact with the workpiece.

- The possibility also arose of transferring technology from inkjet paper printing and digitisation – that is the disruptive breakthrough.

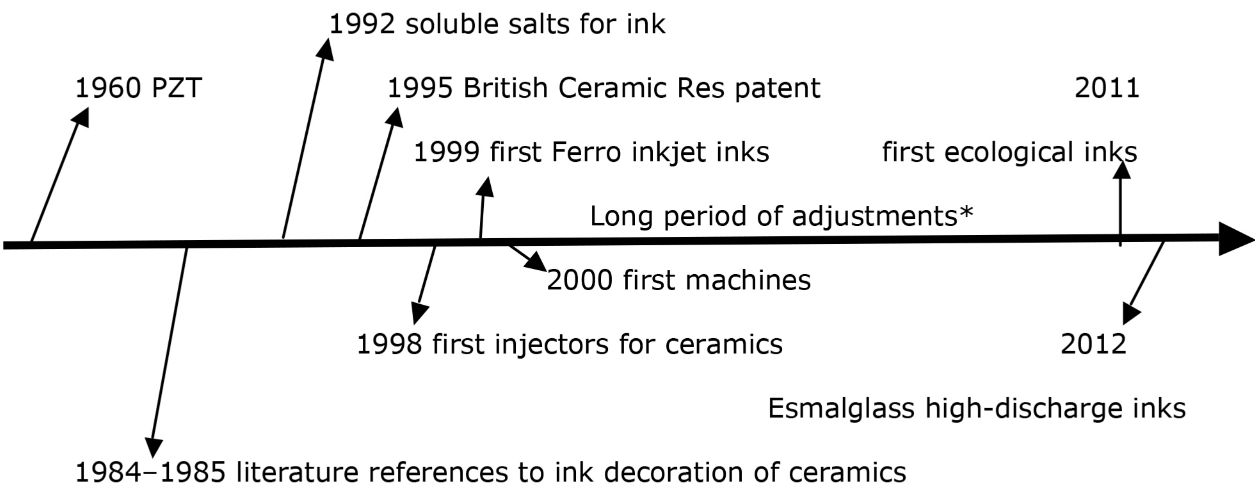
Forthcoming assemblies of knowledge and extensions of innovation

The appearance of any disruptive innovation, especially if it is successful, is always accompanied by an upsurge of other incremental innovations (not necessarily disruptive):

- Self-cleaning printheads or heads that require no cleaning
- Intra-head particle sorting filters
- Application of the entire layer of glaze
- "Off line" operation
- Generation of low particle sizes without grinding
- Creation of the monobloc production line
- Combination of the decorating operation with firing (colour fusion) by coupling different technologies.
    - The above technique was to lead to off-line customisation.
- Automatic correction of colour via in situ automation of mixes.

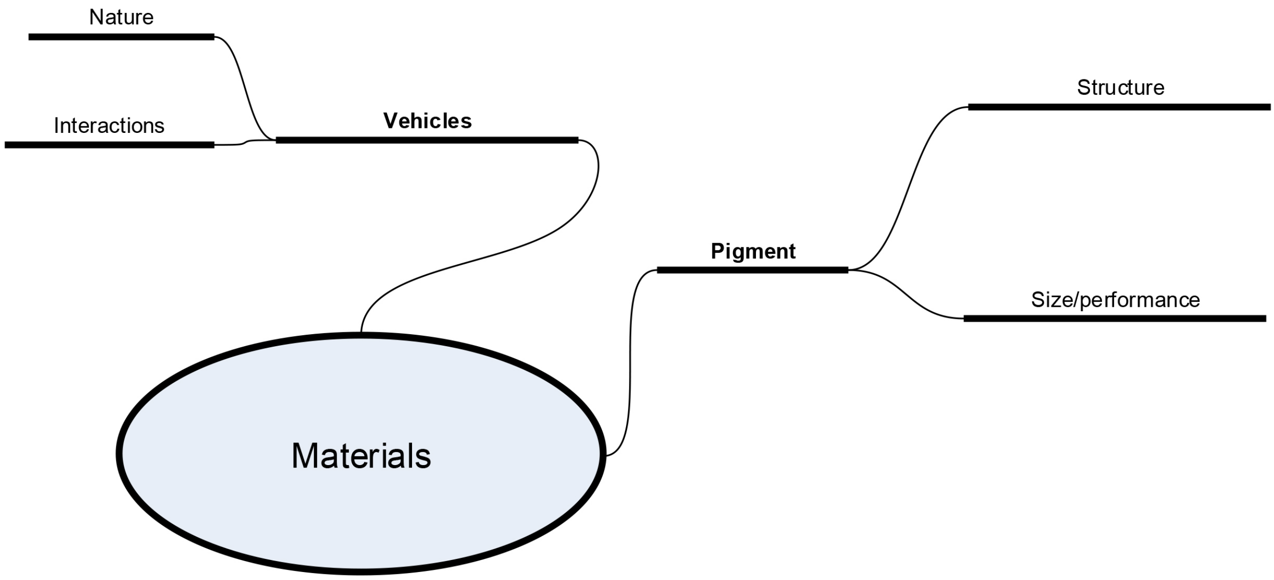
It is important to remember that inkjet decoration as we know it now was a derivation on the border of earlier innovations.

The process over the last few decades can be depicted in the following diagram:



*Period when ROTOCOLOR absolutely dominated the scene

3.3.2. Materials–pigments–structure–particle size–performance



- Ceramic colouring using inorganic pigments is one of humankind's oldest technologies.
- Compositions were based on achieving suitable colour and on the application technology (handcraft).
- The borders, lines and overlaps of the surface to be decorated already called for mixtures beyond the suspension of the pigment in water.
- Industrialisation and mechanisation forced the development of longer-lasting suspensions that nevertheless had to be compatible with the transfer mechanisms. That is when particle size became a factor to be taken into account.
- The speeds at which colour could be transferred and of the subsequent firing were made possible thanks to the use of new structures, compositions and suspensions.
- As efforts were aimed at improving the precision of the decoration, the passage of ink through the transfer mechanism was reduced (i.e. fewer threads on printing screens). Particle size had to be made smaller and viscosity reduced, which was the inherent restriction when the entire process was automated.
- Transfer items relying on physical contact (fabrics) entail certain restrictions for those compositions.
- The appearance of contact-free transfer (see above section on injection) called for very small particle sizes (0.2–0.4 microns) and a solution to the issues of suspension and viscosity. See patent GB-2.274.847 (1993).

- In 1991, application was made for the first patent for these inks (See U.S. Pat. No. 5,407,474).

- Particle sizes were now approaching the size of a unit cell of the pigment. Particle break-up would have a significant effect on colour yield.

- Likewise, it was difficult to find a set of colours that would enable a full colour reproduction process (CMYK - Cyan, Magenta, Yellow and Key Black). See patent WO 00151573 A1.

- Such small particle size and distribution made it necessary to reconsider the suspensions – furthermore, they could not be detrimental for the injectors.

- All of the above led to:

    - A study of crystal structures, the colouring oxides that compose them and their potential interactions in order to obtain colour.

    - A study of crystal structures and their sizes

    - The development of new milling techniques to achieve small particle sizes and narrow distributions within short milling times.

    - Research into new milling devices

    - The development of new additives that enable the production of suspensions and low viscosities while still preserving the machine's mechanical parts.

Identifying the implemented "open innovation" mechanism

- Starting from the position outlined in the previous section.

- The injector was now available from the manufacturer:

    - Steps of 10–100 microns

    - Inorganic suspensions might obstruct the nozzles

    - Suspensions of organic products were therefore used in an organic medium (See GB patent 9104171.5).

- The initial inks were based on soluble salts but with a number of inherent drawbacks.

- They required temperature stability and mastery of colour accuracy (to avoid irregularities as a result of salt penetration).

- The ink produced no chemical attack on the equipment.

- Particle size was defined as the only restriction for injectors and that was directly related to the milling operation.

- The relationship between particle size on one side and opacity and intensity of the pigment on the other was now known (Williams CH, Pigments for printing inks, Inklings, 132 (1985); and Ferguson LD Introduction to printing tech and ink chemistry, 1992).

- What was required was to combine that knowledge in three directions:

    - Particle Size.

    - Achievement of the desired colour (strength and opacity).

    - Ability to keep the resulting high-viscosity suspension stable.

    - Avoidance of damage to injectors.

- All that involved direct collaboration of the manufacturers of the injector (or machine), of the pigment and of the suspension in "Open Innovation", with the additional benefit that it could take place within the same cluster to take advantage of the customer–supplier relationship in future technological developments.

- And thus the cycle was gradually closed based on:

    - Reaping the rewards of existing knowledge (in the specialist literature and patents)

    - Direct customer–supplier partnerships

    - Available connections to external technology (injectors and software)

    - The building of multidisciplinary teams.

Incorporating novel (innovative) items not present in previous innovations

Obtaining suspensions of ceramic pigments for decoration is almost as old as humankind itself.

- The automation of ceramic screen printing was the first hurdle to be overcome in achieving stable suspensions. The subsequent need for smaller particle sizes and higher pigment concentration brought with it the second challenge of maintaining very high viscosity suspensions stable.

- At the same time, reducing particle size to the limits required by the printheads (0.2–0.5 microns) entailed three difficulties to be dealt with:

    - The large amount of energy needed to obtain such particle sizes and the milling material to be used.

    - The effect that it has on actual colour yield considering that those sizes are practically the same as the unit cell itself.

    - The distribution of particle sizes, their restrictions and the method of controlling them in order to avoid build-ups that might affect the injectors.

- Such on-the-frontier innovation called for new components and even for milling methods that just ten years earlier had been non-existent. The same is true for the size control systems used in industrial laboratories.

- Stability in these inks made from inorganic ceramic pigments of very high viscosity due to the particle size had not been possible just a few years earlier with the vehicles used.

- These are all additional innovative features demanded by this technology.

Forthcoming assemblies of knowledge and extensions of innovation

Once again it is worth underlining the fact that any disruptive innovation, especially if successful, will also bring about an upsurge of other (not necessarily disruptive) incremental innovations:

- New methods of obtaining smaller particle sizes. At this point, we should mention the so-called sol-gel process as one of the most anxiously awaited (Zhou Zhen-Jun et al., Trans Nonferrous Met. Soc. China 18(2008) 150-154).

- Development of new pigments that do not require special vehicles to remain in suspension. Prasad P.S.R. et al., Journal of Materials Processing Technology, 2006, 176(1/3) 222-229.

- Methods of on-line monitoring to determine stability and particle size.
- New fields where the technology can be applied i.e. exported to other materials.
- Off-line application.

4. CONCLUSIONS

Inkjet decoration of ceramic tiles has been made possible by suitable management along the entire R&D&I chain.

Such management practices did not take place "from the cradle to the grave", given that more than a century has elapsed between one and the other (although the latter is still in the making).

But thanks to the innovative vision of certain individuals and specific companies, knowledge derived from research was tapped to produce technological developments, which, once assembled, led to the innovative inkjet decoration of ceramic tiles.

The process has witnessed the emergence of innovations not included in earlier Technology Developments, namely:

- It clearly entailed **Product Innovation** (machinery, injectors, pigments, vehicles)
- It also entailed **Process Innovation** (assembly of injector software and the decorating process, milling of new pigments, new design process).
- It further involved **Management Innovation** of the actual implementation of the main project, ramifications, technology monitoring, adaptation of the design and adjustment of in-house structures in the companies involved.
- **Marketing Innovation** in that it assembled the design in a non-traditional manner by tightening customer–supplier relationships along the entire supply chain and by providing the decoration with additional benefits (logistics, change management, stocks).
- A highly significant question is that it is destined to be replicated in future innovations, thus **Business Model Innovation**.

Indeed, inkjet decorating has led to the emergence of a new business model in which the former customer–supplier relationship based on technological support and design (between two parties) takes a new stand as a partnership based on the interrelationship of various stakeholders along the chain (tile maker – machine supplier – ink supplier). A new way of establishing such relationships has been generated – technological support, certification of inks, design, and financing – that in itself represents an innovation which opens the way for the future and which will also allow for a greater availability of resources in future projects.

Our review of the R&D&I chain when analysing the case of inkjet development for ceramic tile decorating also reveals other changes taking place in recent years within the cluster's innovation system:

- Companies (especially producers of glazes and machinery) have teams with greater qualifications in R&D&I.

- The generation of knowledge is now focused inside those organizations, which then interact with the outside world, whether with suppliers or other sources of knowledge not necessarily from within the cluster.

- A more open-minded concept of the objectives of innovation has appeared with a shift from the simple product (always necessary but not sufficient) to include the process, marketing, management and thus an adaptation of the business model.

- The significance of having greater availability of financial resources, which is becoming more and more important, positions risk sharing as the underlying basis of customer–supplier relationships. The win–win concept is to become the basis of trade relations and the concentration of suppliers a necessity.

- Subsequently, in order to disseminate that new knowledge through the cluster, deployment training becomes critical so that new actors may play a part in the cluster's innovation system.

- The innovation system is being redefined and each player is required to take their place and in several instances, question their individual role.

In view of the above, one can clearly conclude that the cluster has started down the road of "Open Innovation", in which customer–supplier relations (in different formats) will be key and the players involved will be different, coming from different fields and with a significant amount of technology transferral. That in turn will require companies to have teams of highly skilled R&D&I personnel if they are to take an active part in the innovation chain.

5. ACKNOWLEDGEMENTS

The authors wish to express their gratitude and appreciation to the professionals of the ceramic cluster of Castellón who made the technological breakthrough of inkjet decoration possible and to the enterprises that have consolidated it.