NEW GLAZED PORCELAIN TILE MANUFACTURING TECHNOLOGY: PRE-PRESSING DRY DECORATION AND GREEN CUTTING

Bresciani, G.P. Graziani, C. Ricci

SACMI IMOLA - Italy

ABSTRACT

The demand for ceramic tiles characterised by an ever-higher level of quality has determined the success of porcelain tile, first from a purely technical viewpoint, and currently, especially in relation to the possibility of making glazed products rich in natural realism and therefore more appreciated by the market.

However, the decoration technologies used traditionally have demonstrated many limits in increasing the aesthetic characteristics of this product, so that research in this field remains wide open.

The present paper sets out the results of technological research and ceramic engineering, performed with a view to defining a new production system for glazed porcelain tile, focusing on the pressing stage.

In fact, if in-line wet decoration presents obvious inconveniences, the current pressing system, still always associated with new decorating systems, will not allow making particularly valuable products without penalising production in an unacceptable way.

The concept proposed envisages dry decoration, directly before pressing, using an appropriately designed line that only uses powder or semi-processed dry materials.

The specific objectives of this system are above all great flexibility in developing new products, since the use of the various application systems enables making customised products with complex decorations, of high added value but with reduced production costs.

This technique, which envisages partial processing features such as double pressing of the powder and the application of superimposed layers, also has a particular scientific interest, with regard to the study of the forming processes and structural analysis of the resulting composite materials.

After the pressing stage, with the intention of ensuring great flexibility in sizes and valorising the previously conducted decoration process, the possibility has been considered of adopting a system, which is also innovative, of green cutting, which is a particularly effective operation in this process stage.

The cutting parameters have been the subject of extensive experimental study (Design of Experiments) to optimise tool performance and the quality of the profiles that can be made in the ceramic materials.

In conclusion, the processes described previously can be considered to form a new manufacturing technology for glazed porcelain tile without any doubt able to further increase the aesthetic quality, and therefore the spread of this product.

INTRODUCTION

Aesthetics, production flexibility and environmental impact are only a few of the guidelines that inspire innovation in manufacturing technologies for ceramic tiles and in particular for porcelain tile.

To achieve these objectives, it is necessary to develop new production systems that are more focused on the decoration process, both with regard to bodies and surfaces, so that any aesthetic effect can be made and reproduced in the widest range of sizes.

For this reason, growing attention is being focussed on the development of new dry decorating techniques before pressing.

It is not by chance that great interest has always been shown in already making completed products in the pressing stage in the evolution of ceramic tile manufacturing technologies.

The reasons are easy to understanding if we consider: the complexity of the glazing operations (that often need skilled personnel), great size of the lines, reduction of the environmental impact and in short, lower investment and management costs. Historically, in industrial ceramic tile production, chemical stoneware and red stoneware tile can be identified as the materials that laid the groundwork for products "completed in pressing", as precursors of the current unglazed porcelain tile. (Fig. 1).

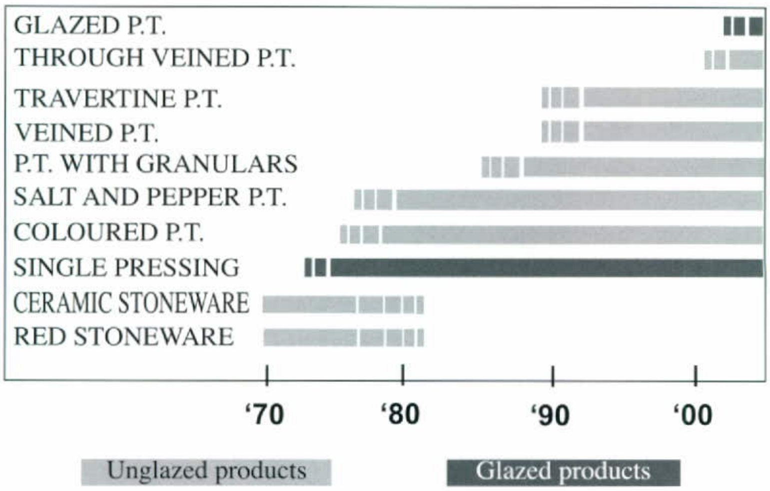


Figure 1 - Products "Finished in pressing".

Interesting and worth mentioning is also the glazed tile pressing technique, i.e. single-pressing or glazing-pressing, introduced in the mid 70s and used even now.

However, the product par excellence, completely made at the press, has surely been porcelain tile, starting from the first traditional typologies (plain colours and "salt and pepper"), via successive evolutions (products with granules and flakes, veining with single charges, travertines with micronizado powder, etc.), to the most recent proposals characterised by fine through veining, which provides the product with greater natural realism.

To develop even more complex effects in the pressing stage, increasing dry decoration operations is very difficult without penalising line productivity by doing so.

In view of the above, experimental research has been carried out with a view to designing an innovative line that would provide the widest range of decorating possibilities while maintaining the same productivity.

DOUBLE PRESSING TECHNOLOGY

The point of departure for a dry decoration line, separate from the pressing cycle, is the application of double pressing technology, a technique that is well-known though used very little in large-scale industrial productions.

Very schematically it involves a first pressing step that forms the semi-compact body, in which layers of powder decoration are applied, followed by the actual pressing. (Fig. 2).

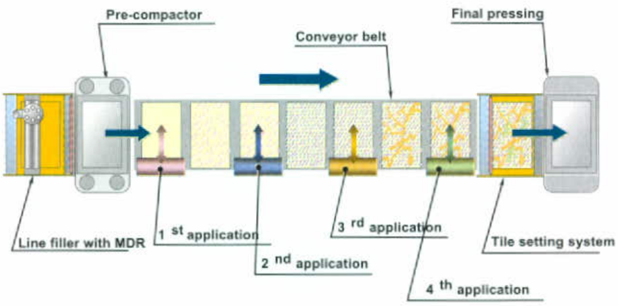


Figure 2 - Scheme of the double pressing line.

The interest in this technique stems from the fact that the pre-compacted body can be ejected by the die and transported toward a convenient line, separating decoration operations fully from pressing operations.

Most of the techniques adopted to achieve aesthetic effects in the press require introducing special systems in the filler and/or die cavity, inevitably reducing production speed. At the same time, the operations carried out near the die, besides being quite complicated, are necessarily limited in attainable effects: partial powder mixes and application of a layer in a double charge.

However, dry decoration on a moving body, along an open and accessible space, allows a variety of charges, over the whole surface of the piece if desired, and especially accurate definition and personalised decorative effects.

PRE-COMPACTION

The pre-compaction step is, in fact, a traditional pressing operation carried out at very low specific pressure values: 30 ÷ 60 bar.

The function of this operation is actually to prepare a usually structured body, with a minimum mechanical strength that enables it to be automatically conveyed, keeping unaltered all the necessary characteristics for re-pressing at normal porcelain tile forming pressures.

It is evident that these conditions will need to be determined experimentally according to the body, since they depend on composition, grain sizes and powder moisture content, i.e., on the body's degree of plasticity.

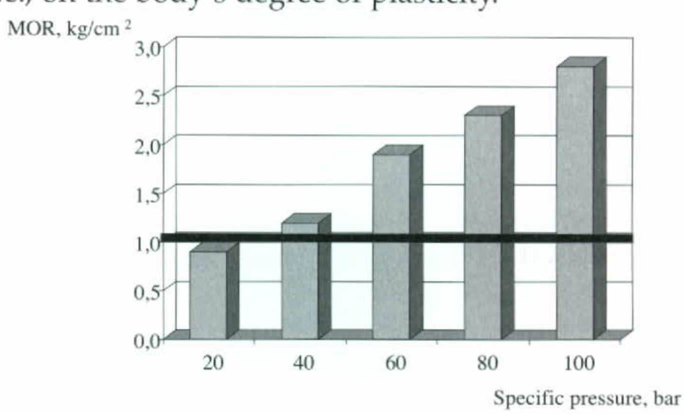


Figure 3 – Pre-compact mechanical strength.

Figure 3 shows an example of the mechanical strength behaviour of a standard porcelain tile body, pressed at low specific pressures (20 ÷ 100 bar).

It can be observed that the strength values are much lower, compared to a typical modulus of rupture of almost 8 kg/cm^2, of a traditionally pressed body at 400 bar, but it is enough to consider that a mechanical strength of 1 kg/cm^2 is already sufficient to extract the piece from the die and convey it along an appropriate line.

For the standard body considered, this bottom limit corresponds to a specific pre-compaction pressure of around 30 bar.

The determination of the top pre-compaction limit requires analysis of density (Fig. 4).

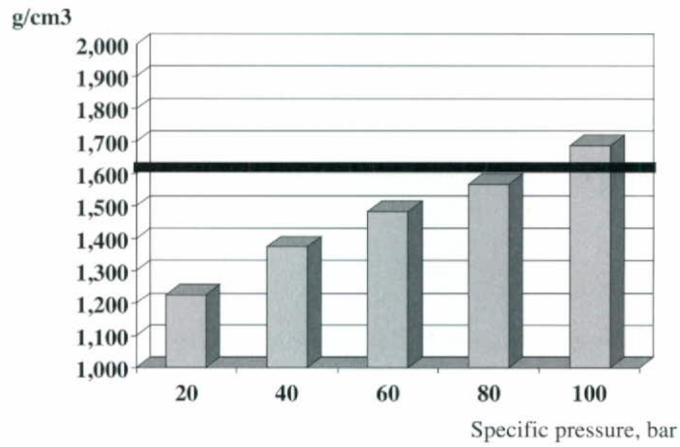


Figure 4 - Pre-compact density.

Bulk density of the spray-dried powder used in pressing is known to lie around 1 g/cm^3, while a tile pressed at 400 bar has almost twice this density.

To allow good "double pressing" of a pre-compacted body, the experience acquired to date allows affirming that density values up to 1.6 g/cm^3 are quite acceptable.

This top limit regarding the standard body considered corresponds to a specific pre-compaction pressure around 90 bar.

Finally, the third fundamental enabling parameter for double pressing technology, is effective de-airing in the pre-compaction step, which can be analysed through the pressing expansion values (Fig. 5).

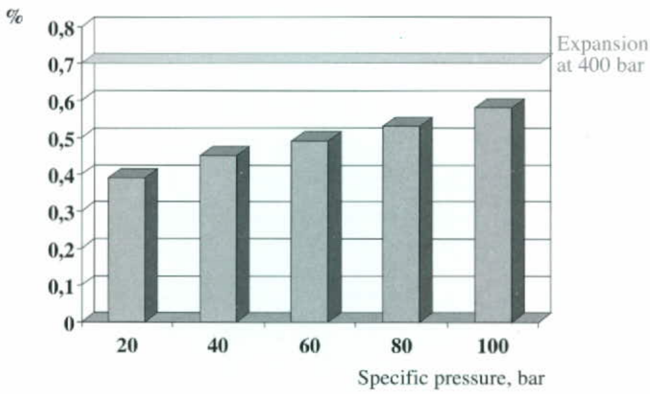


Figure 5 - Pre-compact pressing expansion.

As can be observed, also with very low forming pressures, the pressing expansion values are quite high, 60 ÷ 80% with regard to the definitive value of the product pressed at 400 bar.

This means that, if the first pressing stage has been carried out well, the need to further eliminate air from the pre-compacted part body becomes minimal. Under these conditions the second pressing step has been greatly facilitated and can produce a completed, structurally perfect tile.

DRY DECORATION TECHNIQUES

The objective of dry decoration on the pre-compacted body is to make products with a high aesthetic quality by a variety of suitable techniques for the application of the most varying types of ceramic powder with a wide range of grain sizes (Fig. 6).

	Spray-dried body	Spray-dried glaze	Micronised powder	Granulars	Flakes	Agglomerates
Flat screen						
Cylindrical screen						
Mobile screen						
Low-relief roller						
Rotogravure						
Profiled mask						
Arrayed distributor						
Powder distributor						
Agglomerate distributor						
Granulating machine						

Figure 6 –Dry application systems of powders and semi-processed materials.

The techniques mentioned allow producing "full surfaces" as well as highly defined screen printing decorations, in the first case using proportioning systems in suitable array and, in the second, screens with variable apertures from almost 0.2 mm to a few millimetres.

Also, by means of machines for granular application or vibrating distributors, decorations with grain, flake and agglomerate proportions can generally be integrated.

Consequently, the quantity of powders that can be applied ranges from hardly 100 grams per square meter, a fine veining, to 4 kg/cm^2, i.e. 400 grams on a 30x30 cm item, which when finished weighs 1.8 kg. This means that the applied thickness can account for 20÷25% of the total thickness, for example 2 mm, enabling polishing.

The possibilities afforded by this decorating technique allow producing smooth normal or rustic surfaces of particular naturalness, because the decorations are amalgamated perfectly with the underlying body, maintaining a good definition (in final pressing no surface levelling is performed) or also producing polished glossy products of the highest value.

Indeed, besides the typical classic "travertine" effects of the traditional double charges, using pre-compacted and even very structured bodies, decoration layers can be applied that penetrate and are integrated in the underlying structure. On polishing they yield veined effects with depth, opalescences and transparencies, which are difficult to achieve by processing in pressing or glazing (Fig. 7).

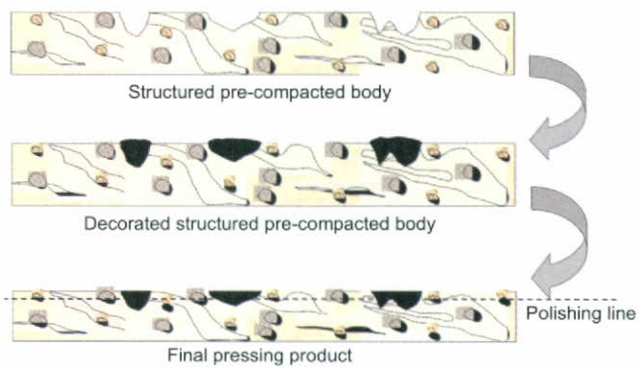


Figure 7 - Development of a structured pre-compacted product.

FINAL PRESSING

After the pre-compacted body has gone through the decoration processes, it has to be set again inside a second die for definitive pressing, at the traditional porcelain tile forming pressures (e.g. 400 bar).

This setting operation is carried out by an appropriate system that centres the tile with regard to the die axis and it places it inside the cavity with the bottom punch flush with the plate (Fig. 8).

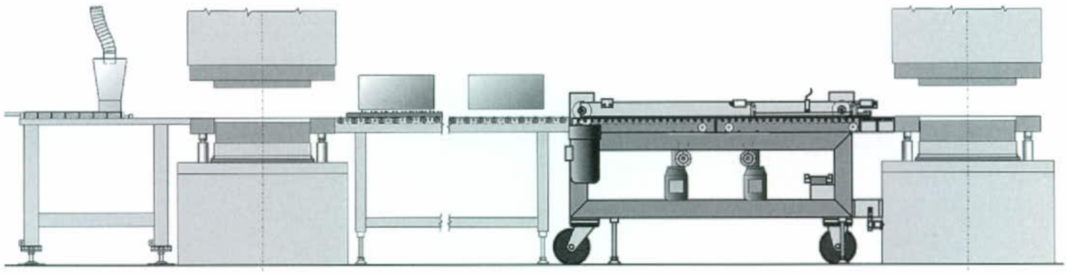


Figure 8 – System for setting the pre-compact in the second die.

Obviously, the dimensions of the second die have to be larger, compared to the pre-compaction die, in order to take into account the expansion the piece has undergone, as well as leaving a certain necessary tolerance for the descent of the piece into the die cavity.

For this, the correlation between the two dies is as follows:

$$D_1 = (D_2 - g) / (1 + e)$$

where:

D_1 = dimension of the 1st pre-compaction die

D_2 = dimension of the 2nd final die that determines the dimension of the completed product

g = tolerance required to assure setting in the 2nd die

e = relative expansion after pre-compaction.

As an example, in the case of a fired 300 x 600 mm size, considering a shrinkage of 7.5%, a relative expansion after pre-compaction of 0.0005 and a tolerance of 1 mm, the dimensions of the two dies would respectively be: 321.7 x 644.4 mm (D_1) and 324.3 x 648.6 (D_2).

The preferable dies are of the mirror type with pushers, or just for final pressing, with top forming.

The top punches, of steel or lined with rubber, can be flat or structured according to the type of product required.

The most common combinations are as follows:

Top Punch 1st Die	Top Punch 2nd Die	Products
SMOOTH or MICRO-STRUCTURED	SMOOTH	- SCREEN PRINT DECORATIONS - "FULL FIELD" GLAZING - TRAVERTINES (incl. polished products)
STRUCTURED	SMOOTH	- DECORATIONS WITH THICKNESS (polished or not)
STRUCTURED	STRUCTURED	- GLAZED RUSTIC

As can be observed, the preference is almost always to provide the pre-compacted body with a more or less pronounced structure, while in final pressing, the selection depends on the surface finish sought in the final product.

PRODUCTION ASPECTS

Double pressing technology with intermediate dry decoration can theoretically be applied to any production situation, independently of product type, size, number of press outputs, etc., etc.

However, current ceramic engineering configurations have been created for sizes that range from 30x30 cm with a 4 to 5 item output, to a single item output of 60x120 cm or 66x132 cm (8 33x33 cm pieces).

By analogy with standard production, the favoured choice is to work with typical floor tile sizes (30÷33 cm or 40÷45 cm) with multiple outputs, solutions that can be carried out absolutely with regard to the pressing steps (pre-compaction, re-setting the pieces and final pressing), but this is relatively complex as regards the number of necessary decorating machines.

Of course, working with a single large size output item simplifies current decoration operations over a front of 120 cm and more.

To facilitate this solution, a green cutting technology has been developed of the pressed pieces, independently of double pressing.

The advantages of cutting a newly pressed tile are evident: on the one hand the decoration process carried out before the press is considerably simplified, and time and money are saved using a single die. On the other hand, complete flexibility is achieved in sizes, thanks to the possibility of freely programming the cutting modules.

On the other hand, the cutting process is already used in a widespread way in a vast range of fired products, and the same process performed on newly pressed tiles is much less expensive: lower energy consumption, less tool wear, lower water consumption, absence of sludges, etc.

However, from a technical viewpoint green tile cutting, to produce a profile as perfect as that of a die, is without a doubt an innovative technology, and as such has been the subject of rigorous experimental study.

GREEN TILE CUTTING TECHNOLOGY

Designing a green cutting system has required a series of technical evaluations, validated with experimental tests, to enable making correct decisions whether of a mechanical or ceramic engineering type.

A first assessment has been the decision to apply the green cutting process, immediately after pressing, to work on pieces in a plastic state (non-dried) and avoid the phenomena of edge cracks.

In fact, it has been verified experimentally that after optimising the installation (machine and tools), even with already dried pieces, in most cases tiles can be cut with an absolutely perfect profile.

Schematically, the green cutting procedure has been developed as follows (Fig. 9):

1. The tile coming from pressing, with the fair face up, is accurately centred and then conveyed to a roller bench, appropriately designed to increase the hold on the pieces and avoid even the smallest vibration; this assures that even very thin, lighter items will not alter their position during the cutting operation.

2. The whole piece first encounters a fixed group of cutting tools that make the multiple lengthways cut with the moving piece.

3. The piece cut lengthways, without being divided up, reaches a mobile group of cutting tools where it stops. These perform the multiple transverse cut.

The material cutting operation takes place by means of circular disks rotating at high speed, made with hard, abrasion resistant materials (diamond, silicon carbide, alumina, etc.).

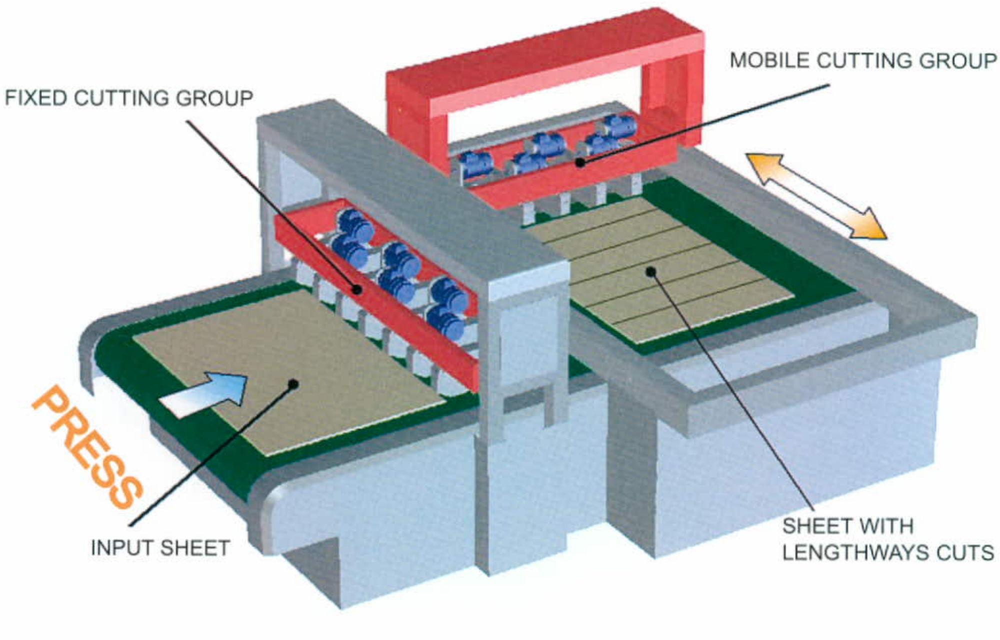


Figure 9 – Schematic illustration of the green cutting machine .

The cut, as we can see in Figure 10, can be carried out with one or two disks; in this last case the first one acts as a pre-engraver.

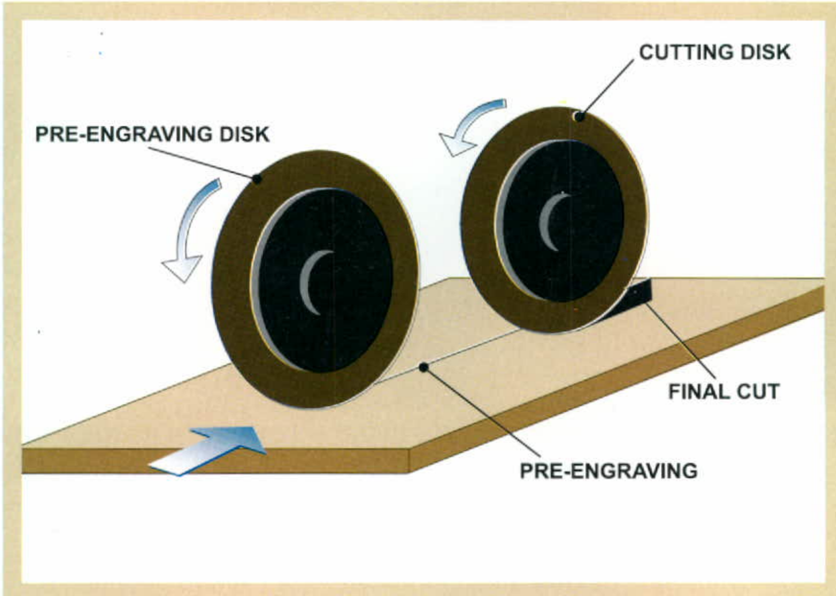


Figure. 10 - Configuration of the green cutting tools.

The double disk arrangement can be advantageous, not just to increase the linear cutting speed but also, especially to produce the desired profile at the edges of the cut pieces.

In fact, simply having different disk thicknesses enables creating the separating foot and, by suitably profiling the pre-engraver disk, 45° or rounded bevelling can be produced (Fig. 11).

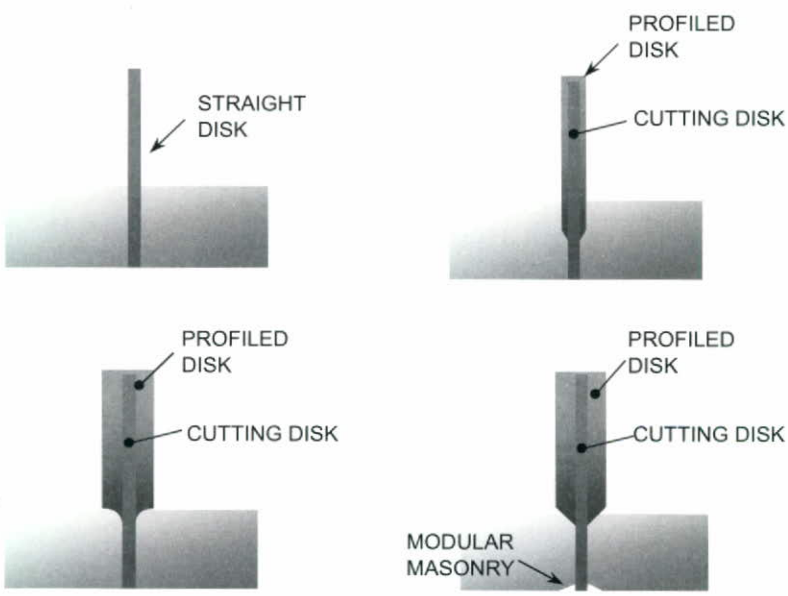


Figure. 11 - Examples of cutting profiles.

Perfecting this technology could allow the exact reproduction of the profile determined by the die used for each type of product.

However, this is not absolutely necessary since it can also be more convenient to machine the edge of the piece laterally, thus obtaining sub-multiples, with completely identical sides, independently of the positions.

The waste coming from this operation, such as the powder produced during cutting, evacuated through an appropriate extraction system, is very limited (~ 1%) and it can be easily recovered and recycled in the body milling process.

In view of the foregoing, green cutting technology was considered to be a process potentially applicable to the production of ceramic tiles and, hence a more detailed study was undertaken of all the variables in the fundamental operation: cutting.

EXPERIMENTAL OPTIMISATION OF THE CUTTING PARAMETERS

To optimise the fundamental aspects of the cutting process, an experimental study has been carried out using the statistical methodology involving Design of Experiments (DOE)[1].

This statistical technique allows identifying the factors that most influence the desired result and quantify their contribution.

In the specific case examined, the following fundamental characteristics have been selected for optimisation: the quality of the cut, absorbed power, type of abrasive tools and tool wear.

The study of the first two points has been completed: quality of the cut and absorbed power, which have been defined and measured as set out below:

Quality of the cut

To express numerically the concept of cut quality, the following aspects have been taken into consideration:

1. Number of defects (edge chips) present in a certain part of the cut surface.

2. Defect size.

3. The greatest weight is attributed to a large size defect compared to a smaller one (a single large size defect affects tile quality as much as a continuous series of small flaws).

After experimentally verifying that the most common shape of a green cutting defect is of the type shown in Figure 12, the characteristic size of this defect has been considered the one marked with the letter **d**.

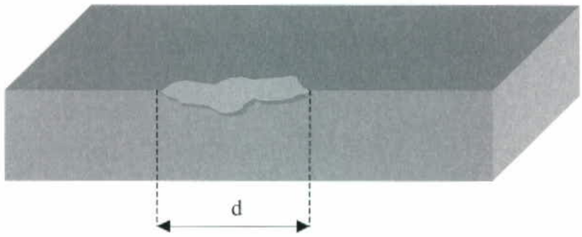


Figure 12 - Schematic illustration of a cutting defect.

The quantitative calculation of the defects was carried out over the length of a 50 mm sample, taken at a distance of 100 mm from the surface, to avoid possible interferences not due to the cut but to pressing defects.

In accordance with these considerations, it was decided to create a suitable parameter **Q**, which we will call the cut quality index, defined by the expression:

$$Q = \sqrt{\sum_i (di)^2}$$

Thus, parameter **Q** takes into account the number of defects present in the part of the edge examined, since it is made up of their sum and as established, attributes greater weight to the larger defects, since the value **d** is present to the power of two.

To make the defect measurement and calculation operation easier and faster, a "discrete" scale set out in the following table has been used:

Defect dimension **i** , mm	0÷0.5	0.5÷1	1÷2	2÷3	3÷4	>4
Value of $\mathbf{d_i}$, mm	0.5	1	2	3	4	5

For defects with **d** >4, the real value of **d** has been divided by 4 and the whole part of the number found has been taken as the number of defects >4 equivalent to the initial defect.

Therefore, in the best hypothesis **Q** = 0 will be found, i.e. absence of defects; in the worst, for example a faulty edge along the whole sample, where **d** = 50, i.e. 50/4 = 12.5 = 12 defects sized larger than 4 mm, this will give **Q** =17.32.

<u>Absorbed power</u>

Cutting power has been measured through a special instrument, at the terminals of one of the tree-phase asynchronous motors that drive the movement of a cutting group; therefore the values used in the study are those actually measured expressed in kW.

After setting the objectives, cut quality and absorbed power, the process variables considered most significant were selected (Figure 13).

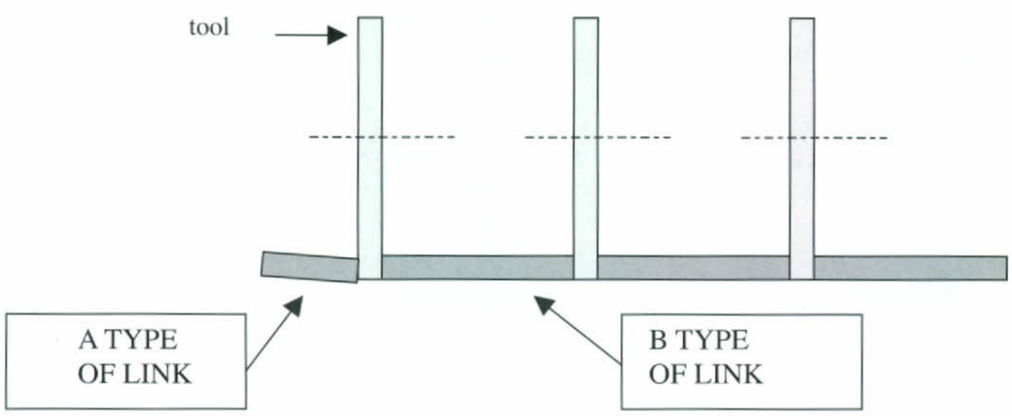
PROCESS VARIABLE	SYMBOL	UNIT	LEVEL 0	LEVEL 1
Ceramic (tile) sheet advance rate	V_a	[m/min]	15	25
Tool (disk) rotating speed	V	[rpm]	4500	7000
Sheet thickness	H	[mm]	7.5	10.8
Tool thickness	h	[mm]	0.7	1.2
Tool rotating direction	*rot*		Concord	Opposition
Sheet bending load	R_f	[N/mm^2]	0.6	0.9
Type of link	T		A	B

Figure 13 – Selected process variables.

The only variables that need an explanation are the direction of tool rotation and type of link.

The former accounts for the tool rotating direction with regard to the advancing piece, since in the two possible cases, the fair face will be subject to loading by the entering or exiting tool, with possibly different results in quality:

The type of link, on the other hand, has been introduced in the study to evaluate anomalous behaviour in the side cuts (for example edge sharpening) compared to the central ones:



The experiments were made applying 2-level factorial design, and in particular using the orthogonal Tagouchi matrix of the L_8 type (2^7), which envisages the following array of 8 tests:

Array L_8 (2^7)

Test no.	*PROCESS VARIABLE$_{LEVEL}$*						
P_1	A_0	B_0	C_0	D_0	E_0	F_0	G_0
P_2	A_0	B_0	C_0	D_1	E_1	F_1	G_1
P_3	A_0	B_1	C_1	D_0	E_0	F_1	G_1
P_4	A_0	B_1	C_1	D_1	E_1	F_0	G_0
P_5	A_1	B_0	C_1	D_0	E_1	F_0	G_1
P_6	A_1	B_0	C_1	D_1	E_0	F_1	G_0
P_7	A_1	B_1	C_0	D_0	E_1	F_1	G_0
P_8	A_1	B_1	C_0	D_1	E_0	F_0	G_1

The two values programmed for each variable have already been indicated in Fig. 13.

The series of tests P1÷P8 has given the following values for the quality index and mean power, which have been ordered in the following table, starting from the best result in each case:

Test no.	*Cut quality*
1	1.06
8	1.55
6	2.83
4	2.63
3	4.72
7	5.59
2	5.52
5	7.89

Test no.	*Absorbed power, kW*
1	1.00
2	1.44
8	1.76
6	1.90
7	2.09
3	2.17
4	2.33
5	2.41

The best combination of variables that optimises both the quality of the cut and absorbed power is therefore test P1, with all the variables at level 0.

The statistical methodology used also allows determining, by means of variance and noise analysis (3 repetitions were carried out for each test), which process variables most influence the final result.

Regarding cut quality, the variable that most influences tool entry into the surfaces is without a doubt **rot**, the direction of tool rotation and, in the second place, the advance rate **Va**; **h** is also observed to be important, i.e., the surfaces processed by the thinner tool exhibit a better cut.

With regard to the absorbed power, the most critical variables are, in order of importance, tool thickness, sheet thickness, sheet advance rate and tool rotating speed; the remaining factors have little effect.

In summary, the analysis carried out has allowed setting a rigorous and scientific framework for the green cutting process and has provided technicians with fundamental knowledge to enable designing an industrially valid machine.

CONCLUSIONS

The two innovative technologies described in this paper: dry decoration with double pressing and green cutting, have been subject to extensive experimental study, and have been demonstrated to be particularly suitable for application in porcelain tile manufacture.

Two technologies are involved that could eventually be combined. However, even considered individually, they have great value and good development potential.

The importance of double pressing certainly lies in the limitless possibility of creating new porcelain tile products, whether glazed or not, in the pressing stage and of personalising these with effects that aesthetically give no reason to envy rustic or polished natural stones.

On the other hand, the same concept of marble or natural granite slab suggests that the cutting process could find an appropriate application in the production of "artificial" slabs.

As last analysis, the industrial success of these, as of other technologies, beyond technical and aesthetic product factors, will depend on economic evaluations and on ceramic production engineering, but it cannot be denied that these proposals, fruit of applied research, will stimulate new ideas, which will thus continuously drive the progress of the ceramic tile sector.

REFERENCES

[1] G. E. P. BOX, W. G. HUNTER, J. S. HUNTER, Statistics for experimenters, John Wiley & Sons Inc. (1978).