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INNOVATIVE LASER CUTTING PROCESS FOR CERAMIC SLABS

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ABSTRACT

Ceramic production is nowadays turning to ever larger tiles or big slabs, with the aim to fulfil the increasing demand of new products for building and constructions.
As a matter of fact the manufacturing of large-size tiles simplifies the production lines but, at the same time, requires the development of efficient, flexible and cost saving cutting technologies to produce a wide range of smaller formats.
With this respect the methods currently used in the ceramic industry, like diamond wheel cutting, scoring and snapping or waterjet cutting show many drawbacks: poor quality of the edges after cutting, high percentage of rejected products, wastes and sludges generation, low production speed, high needs of man-power and maintenance, ….

To overcome the above mentioned problems, the present study investigates the application of high power CO_2 laser for a non-contact, precise and defect-free cutting onto fired ceramic materials.
In the past years many laser technologies have been tested onto ceramic materials, but no one has been optimized for the industrial cutting of ceramic tiles. The main problem arose respect to the final quality of the cut, generally poor in quality with surface vitrifications and over-burned effects. A further problem was the excessively slow process, as a consequence of concentrating the laser power to rise the temperature up to melt (or even sublimate) the ceramic material.

The present technology is based on a totally different approach; the CO_2 laser source is used as a "heating tool", capable to control the temperature gradients inside the material. The combination of heating and cooling (made by suitable cooling device) induces inside the ceramic material a precise mechanical stress distribution (tension – compression variable across the thickness). This stress distribution generates the fracture of the material, and the process can be perfectly controlled in order to get a straight, defect-free cutting over the entire slab length.

To find the proper working parameters an intense computational analysis was performed. ANSYS FEM simulations were made to study the thermo-structural behaviour of the ceramic material under the effect of heat transfer generated by the laser pulses.
The simulations were validated onto a pilot scale equipment, specifically set up in our laboratories.
Finally, several cutting sessions were performed to split various kinds of ceramic tiles and slabs, mainly made in porcelain stoneware. The control parameters were optimized to increase the cutting speed, while maintaining an acceptable cutting quality.

The preliminary results of our experimentation at pilot scale clearly demonstrates the feasibility of the laser cutting process and this new technique seems actually a real solution for industrial process automation in the manufacturing of ceramic tiles, as it provides a clean, flexible and efficient cutting system.

Key words: Ceramic, tile, cutting, laser.

1. FOREWORD

The cutting of ceramic tiles represents a critical point in the industrial production process. The ceramic material, which is intrinsically fragile, does not easily bear the cutting action, which generally leads to uncontrolled cracks and resulting product reject. Besides, the high hardness of ceramic material (particularly on the surface but even in the mass, in the case of porcelain tiles) involves considerable wear of the cutting tools and, consequently, high costs and low productivity.
During the past decades different technologies of industrial cutting for ceramic tiles have been developed; see below some brief descriptions of such technologies.

Cutting with diamond wheel
This technology, deriving from cutting of stone materials, concerns the use of metal disks having a peripheral section of diamond material (dispersion of diamond granules inside a metal matrix) – see fig. 1a. The cutting is carried out in presence of high refrigeration in order to carry off the generated heat and keep tool efficiency. The cutting machines (fig. 1b) must be very rigid to avoid vibrations (which are harmful for the tools) and to constrain the developing high cutting forces.

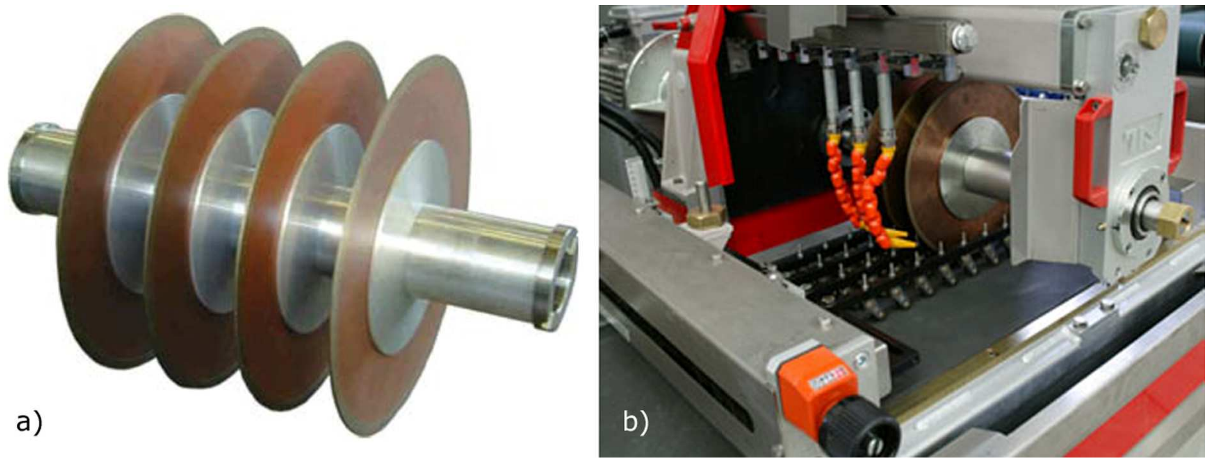

Fig. 1 – *Cutting with diamond wheel: a) series of wheels - b) cutting machine*

The cuttings must necessarily follow a straight line. In order to completely separate the two parts, it's necessary to remove considerable volume of ceramic material, equivalent to the wheel thickness (i.e. a few millimetres).
The quality of cut edges is usually excellent (comparable to grinding), and after cutting only a slight trimming of the upper edge is necessary, performed with diamond tools (chamfering).
The cutting with diamond wheel is surely the most spread system in the ceramic industries, even if it shows some disadvantages:

- low flexibility referred to size changes (as long set-up times are required);
- high costs, related to rather low cutting speeds and large use of diamond tools;
- problems in the disposal of working muds, which must be treated as dangerous wastes since they contain heavy metals.

Waterjet cutting
The waterjet cutting with abrasive material has recently spread in the ceramic field (and similarly in the stone materials) thanks to its great versatility, together with the possibility of not straight cutting (curved, polygonal, open and close lines, etc.). The process consists in forcing a water flow with very high pressure (3000 ÷ 6000 bar) through an orifice of about 0,1 ÷ 0,2 mm diameter up to supersonic speeds (till Mach 3, about 1000 m/s). Just out of the orifice, the jet is mixed with abrasive powder and directed to the material to be cut. High flow energy together with the abrasive particles allows to cut all kinds of materials (as well as metals), with even considerable thickness.

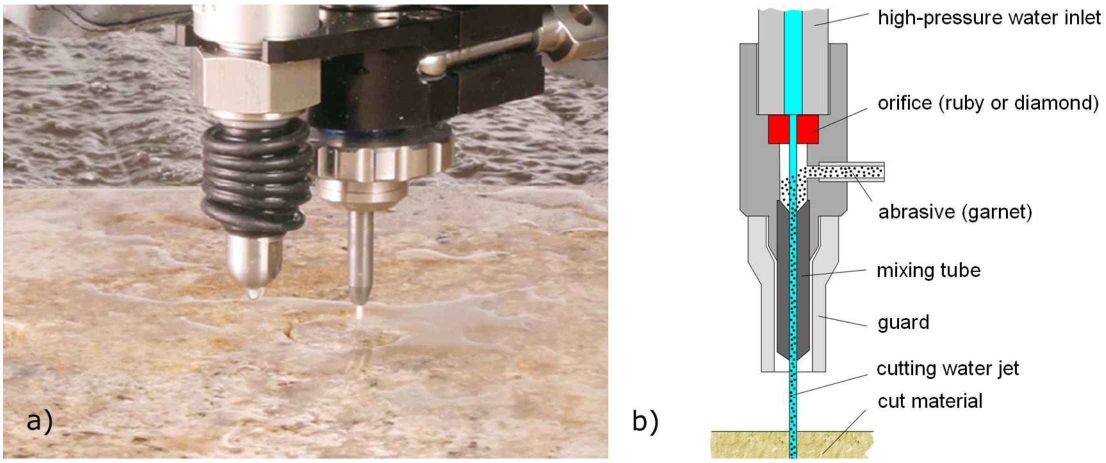

***Fig. 2** – Waterjet cutting: a) cutting of ceramic materials - b) functional draft of waterjet head*

Referring to the ceramic field, waterjet cutting machines are mostly used for carrying out curved cutting and inlays of different materials. The machines are very flexible since they work without any contact. Cutting precision, depending on machine accuracy, can reach the tenth of mm.
Even if it realizes good quality of cut edges, the waterjet cutting shows some drawbacks, which reduce its applicability in the ceramic field:

- low productivity, due to low feed speed (1 ÷ 2 m/min for porcelain tiles);
- high costs, linked to low speed and need of expensive abrasive powders;
- problems in the disposal of working muds, containing waste abrasive materials.

Cutting with scoring and snapping
The cutting with scoring and snapping was introduced into the ceramic field by drawing inspiration from the close field of glass machines. The plant is composed of two different working stations. In the first station (fig. 3a), a diamond wheel (or other hard material) is pressed against the ceramic surface, realising an indentation of few hundredth mm depth along the desired separation line. Afterwards (fig. 3b) the scored ceramic slab moves to a second working station, where pressing rollers generate a bending action, causing the breakage due to crack propagation (snapping). The more homogeneous and fragile the material is and the thinner its thickness is, the more efficient the snapping is. With this respect, fully vitrified materials are the most suitable to be cut.

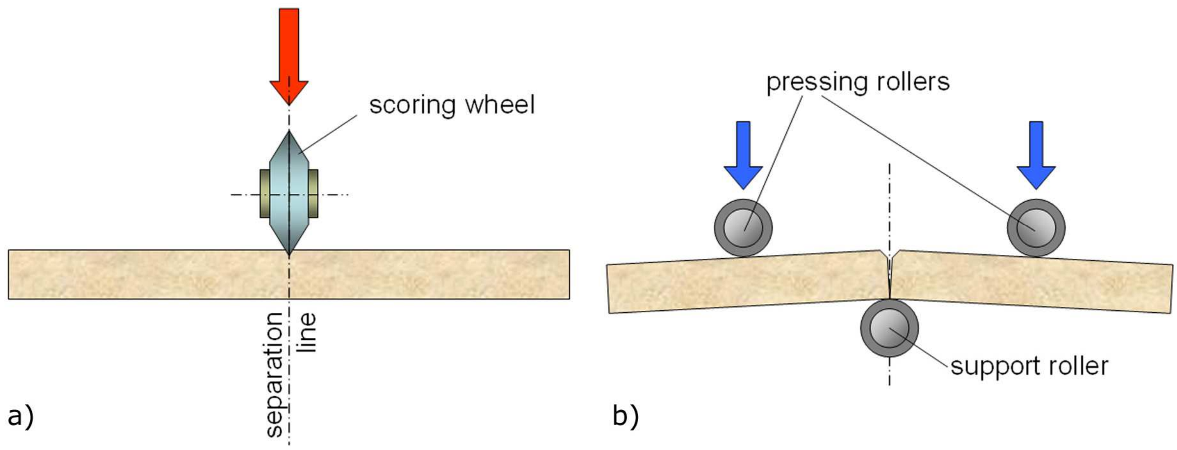

***Fig. 3 –** Cutting with scoring and snapping: a) scoring with diamond wheel - b) snapping*

The productivity of scoring and snapping can be decidedly higher than the previously described technologies; moreover tools cost are negligible.

Anyway, this technology shows some drawbacks:

- material typology can influence cutting process up to make it uncontrollable;
- the scoring operation is particularly difficult on structured (not flat) surfaces;
- it requires further finishing operations on cut surfaces and edges (squaring and chamfering), thus increasing process costs and involving muds disposal.

Green cutting

SACMI introduced the technique of green cutting in 2001 [1], which consists in separating ceramic slabs before firing. The cutting is carried out by means of thin diamond wheels, with high productivity and without using cooling water.

Fig. 4 – *Green cutting machine mod. TPD175*

Pressed green slabs are conveyed into the machine (fig. 4) wherein a series of high speed rotating disks accomplish the cutting. A mobile station first realizes transversal cuts, while a fixed station performs longitudinal cuts. The final sizes can be easily programmed and changed by suitable software interface.

In spite of its high flexibility of use and its low cost, the green cutting performs this operation only on unfired tiles. The following firing phase, according to process variables, could sometimes cause inhomogeneous deformations, which thus require additional finishing operations on the edges (that means an increase in process costs). Even the removal of dust from the working area implies specific suction devices.

From the above survey it is evident that the existing cutting techniques show a series of **limiting aspects**, as follows:

- high costs, due to the wear of cutting tools (diamond disks, abrasive powder, etc.);
- low productivity and/or low flexibility in managing size change;
- problems linked to cutting waste disposal (muds or powders);
- the green cutting represents a solution only for a small range of products.

It is therefore convenient to research a new cutting system for fired tiles, able to overcome the a.m. limiting aspects. To this purpose, the laser cutting can be considered as an interesting opportunity.

2. THE LASER CUTTING

Laser cutting of materials is the most common and wide-spread application of power lasers, which is able to melt and even evaporate almost all the materials. During the cutting process, the energy absorbed by the material in the focused area is converted into heat, which locally cause a sudden temperature increase in the piece.

The most common kinds of laser, used for industrial cutting of different material, are:

- CO_2 laser (where the active medium is a gas – carbon dioxide)
- Nd:YAG laser (where the active medium is a solid – yttrium aluminium garnet doped with neodymium)

They differ in the type of source and in the wave lengths of the emitted monochromatic light (10,6 μm for CO_2 and 1,06 μm for Nd:YAG) which are not in the visible spectrum. Both kinds of laser carry out the cutting through a beam focused by means of lenses and mirrors on a little area (even less than 0.5 mm diameter), achieving about 10^5 W/mm^2 surface power. The difference between wave lengths of the two laser types is very important because, in the case of Nd:YAG laser the light can be transmitted through optical fibres while CO_2 laser light is transmitted to the piece through mirrors and optical lenses, and is consequently more suitable for flat surfaces and scoring. The laser Nd:YAG usually operates with pulsating light, while CO_2 laser works with continuous light.

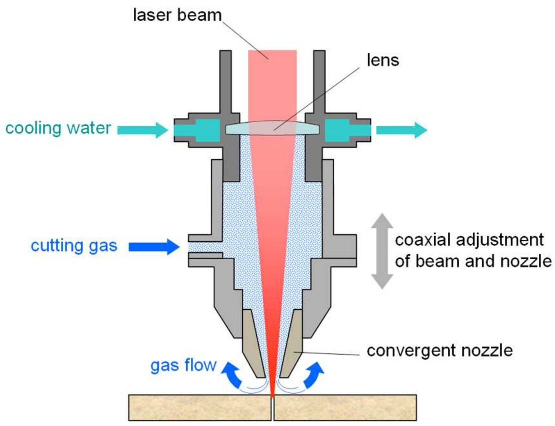

Fig. 5 *– Diagram of Laser Beam Cutting head*

Fig. 5 represents a laser cutting head, generally used for working metals and other similar materials. The laser beam is concentrated for reaching material melting in very short time, without contact and energy transport.

Recently, some attempts to cut directly ceramic tiles with CO_2 lasers were made.
An estimation of the laser cutting efficiency was proposed by Black in 1998 [2]. It allows to determine the best cutting speed V_{opt}, by means of thermodynamic and heat transfer considerations.
The best speed V_{opt} has been found as:

$$V_{opt} = \left(\frac{2}{\pi e}\right)\frac{P}{\rho C R^2 (T_p - T_0)} \quad (1)$$

where P is laser power, C thermal capacity of the material, T_p peak temperature (necessary for complete melting/evaporation), T_0 room temperature, ρ density of the material. The parameter R is defined as:

$$R = \sqrt{r^2 + s^2} \quad (2)$$

where r is the laser spot radius and s is the tile thickness.

The diagram reported in fig. 6a shows the values V_{opt} in function of the thickness of the slab to cut, calculated according to (1), considering 1500 W laser power. Concerning to standard tile thickness values (8 ÷ 10 mm), cutting speed is only about 100 ÷ 200 mm/min. With very thin thickness (< 2 mm) the process is more efficient but useless for traditional ceramic production.

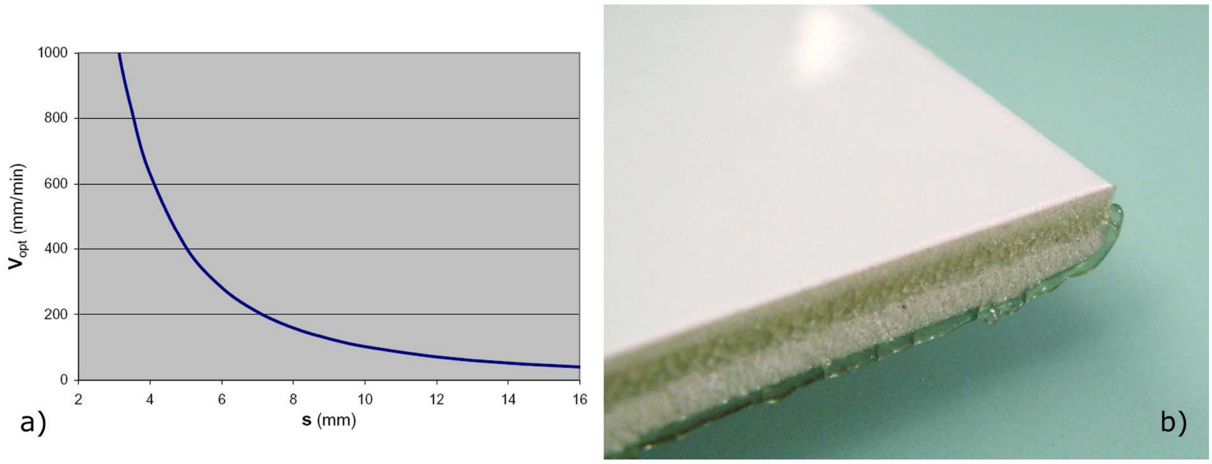

Fig. 6 *– Laser cutting: a) speed vs. thickness relation - b) edge appearance after cutting*

As a consequence this system is not suitable for ceramic industry, due to low cutting speed in function of required energy. Besides, due to the generation of high energy density, the edges are badly altered, with melted and thermally damaged areas (fig. 6b), which would require intensive subsequent finishing operations.

In order to take advantage from the laser cutting benefits, like the lack of contact between tools and ceramic slab, a different solution must be investigated.

3. LASER INDUCED SCORING BY TENSION

The present solution is based on the technique known as Laser induced Scoring by Tension (LiST). This technique makes use of CO_2 laser source for inducing tensional stresses in the material in order to cause a crack and let it propagate along the desired separation line, without melting the ceramic material (as in the case of Laser Beam Cutting).
Such patented technique [3] was originally developed for cutting flat glass slabs; hereunder a version opportunely adapted to the ceramic field is explained.

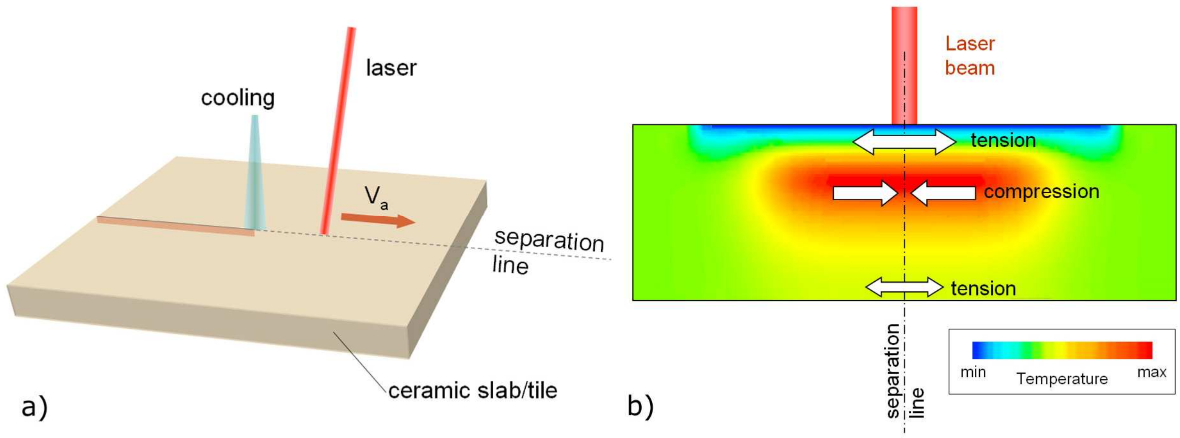

Fig. 7 *– LiST method: a) working principle - b) distribution of tensions inside the material after cooling*

Fig. 7a shows the working principle: the laser beam heats up the surface along the requested separation line, followed by a suitable cooling device. Such sequence of thermal gradients generates compression stress status inside the material while the surface is under tension stress. Fig. 7b represents the temperature distribution in a cross section of the material. Due to alternate thermal gradients, the upper surface is in tension and, overcoming a critical value (K_{Ic}), the crack starts and propagates under control along a straight line (following the mode I "opening" fracture mechanism).

Fig. 8 shows in detail the necessary equipments. Automatic control systems have not been included in such representation.

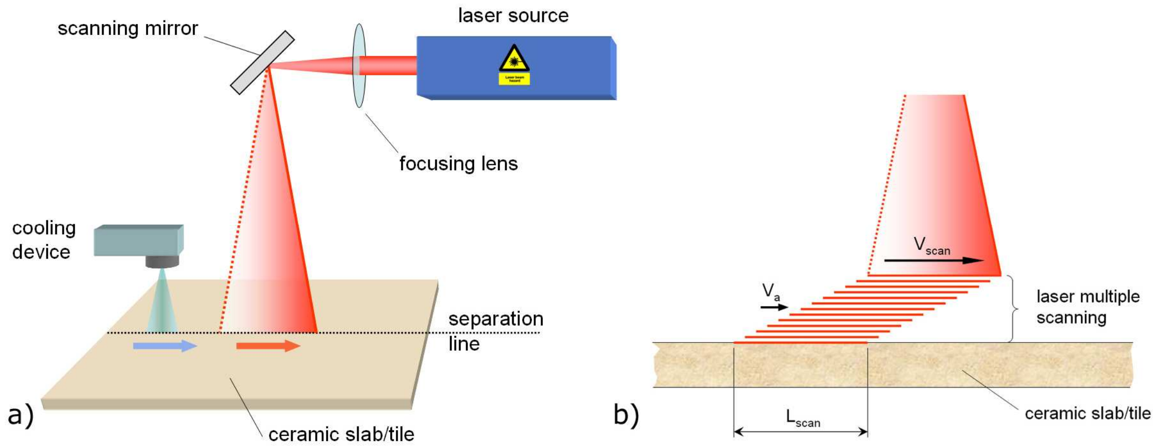

Fig. 8 *– LiST method: a) cutting equipments – b) detail of multiple scanning*

The beam coming out from laser source is focused by an optical group and directed to a scanning mirror. The scanning mirror, properly controlled by software, deflects the beam along the separation line, according to a series of superimposed multiple passages (see fig. 8b). The laser scanning speed V_{scan} is about 10 ÷ 20 m/s and it moves within a certain length L_{scan}. The length L_{scan} advances according to V_a speed, that represents the total cutting speed. In this way it is possible to fully control the temperature distribution inside the ceramic slab. At certain distance from laser beam, the cooling system moves in parallel and jets air and nebulised water onto the slab, making the upper surface cool down quickly.
The energy applied E_{spec} to each surface unit by the laser beam is expressed as follows:

$$E_{spec} = \frac{P}{d\ V_{scan}} \qquad (3)$$

where P is the laser power, d the spot diameter, V_{scan} the beam scanning speed along the separation line.
The value E_{spec} must be kept inside a limited range of values; otherwise, undesired effects could appear, such as transversal cracks and other kinds of breakage. This value is related with both thermodynamic characteristics (thermal conductivity, thermal capacity, emissivity and diffusivity) and mechanical properties (density, bending strength, thermal dilatation, etc.) of the material.
The values used in the test equipment (see §4) for cutting ceramic slabs are as follows:

$P = 800$ W
$d = 4{,}2 \div 11{,}5$ mm
$V_{scan} = 5 \div 25$ m/s

which give:

$E_{spec} = 0{,}003 \div 0{,}038$ J/mm^2

It should be pointed out that LiST technology uses laser energy for heating the cutting zone, without melting the material. As a matter of fact, it is necessary to set opportune temperature distribution in the area near the cut, through an accurate control of multiple laser scans.

4. TEST EQUIPMENT

In order to verify LiST technology possibilities at laboratory scale and evaluate its applicability to the industrial field, a test equipment has been manufactured. The system is provided with a CO_2 laser source capable to work discontinuously onto a single ceramic slab (up to 120 x 120 cm). The CO_2 laser source, with 1000 W nominal power, is placed in the upper side of the equipment to achieve a distance between the scanning mirror and the tile surface of about 2 m.

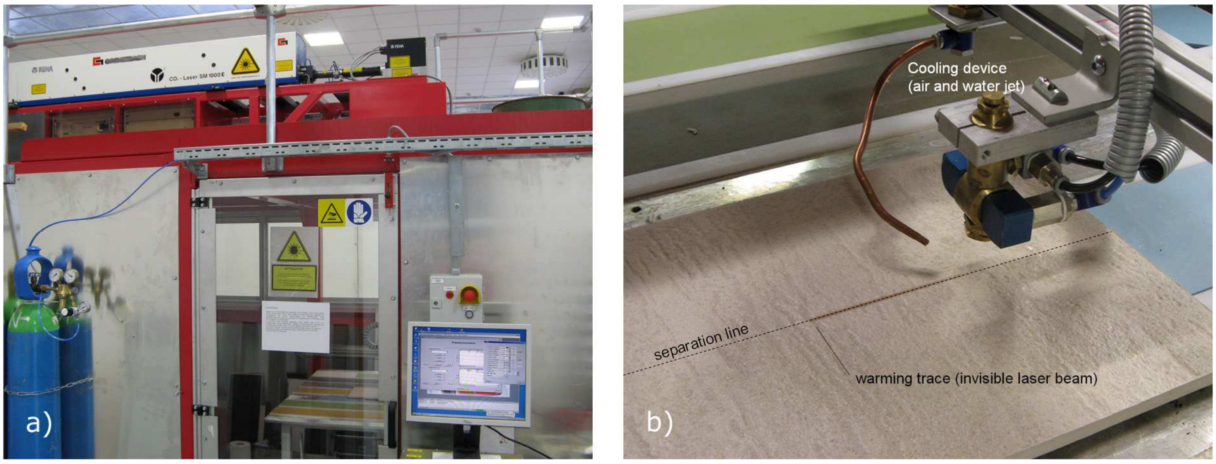

Fig. 9 *– Laser test equipment: a) overall view – b) cutting zone detail*

Fig. 9 shows the laser test equipment operating inside SACMI laboratories. The complete shielding of the machine (fig. 9a) is realized with metal and glass walls, in order to completely block laser radiations for operators' safety. Moreover, additional precautions have been taken to prevent beam reflections outside the working area. Fig. 9b shows the cutting zone during machine operation; the invisible laser beam heats up the separation line some mm before the cooling device. Only a temporary brownish trace reveals the laser action.

The managing software was developed for investigating the main parameters, which could affect the final quality of cutting. In particular:

- Laser beam power P
- Scanning speed V_{scan}
- Cutting speed V_a
- Laser beam diameter d
- Scanning length L_{scan}

In order to simplify the whole study and reduce the number of tests, a parallel thermo-structural finite elements analysis has been carried out, by means of Ansys simulation software.
First two-dimensional models for a preliminary estimation of the influence of different thermo-mechanical parameters were studied; thus, more complex three-dimensional analyses were carried out, which required huge effort even from computational resources point of view.
Fig. 10 shows the result of one of a.m. analyses, carried out for simulating temperature and stress distribution in correspondence of the separation line.

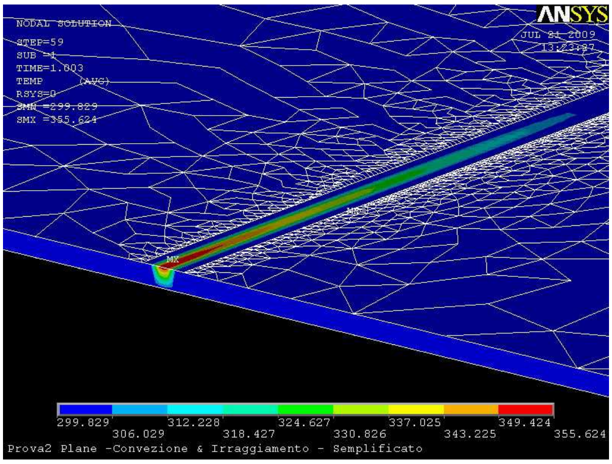

Fig. 10 *– FEM analysis of thermal and stress distribution*

5. EXPERIMENTAL TESTS

After computational optimization, a series of cutting tests of porcelain stoneware slabs have been realized. The tests were performed with the following constant parameters: 800 W laser power, 30x60 cm slab size, cutting along the centre line of the short side (i.e. cutting length: 600 mm).
The results are summarised in the following table:

No. test	**Thickness** [mm]	**d** [mm]	E_{scan} [J/mm^2]	L_{scan} mm	V_{scan} [m/s]	V_a [m/min]	**Cutting quality**	**Remarks**
1	3,4	4,2	0,013	300	15	2,0	Good	
2	3,4	4,2	0,011	400	17	2,0	Good	
3	3,4	4,2	0,013	300	15	3,0	Quite good	
4	3,4	4,2	0,013	300	15	4,0	Low	
5	3,4	4,2	0,008	300	25	2,0	Quite good	
6	3,4	4,2	0,038	300	5	2,0	Low	Surface burnings
7	10	11,5	0,005	300	15	0,6	Good	
8	10	9,2	0,006	300	15	0,6	Good	
9	10	11,5	0,005	300	15	1,2	Low	
10	10	11,5	0,005	100	15	0,6	Low	Surface burnings
11	10	11,5	0,005	600	15	0,6	Low	

According to the results reported in the table above, good quality pieces were obtained with cutting speed V_a of 2 m/min or less. If slab thickness increases, the acceptable value of V_a further reduces.
The increase of scanning speed V_{scan} (without proportionally increasing the power P) does not lead to any benefit for the cutting speed V_a (Test #5 vs. Test #1).

Fig. 11 shows an example of good quality cut obtained during the tests. In this case, the cutting profile is quite rectilinear and the two parts completely fit one to the other. The LiST technique acts like a real “zero width” laser cutting technology.

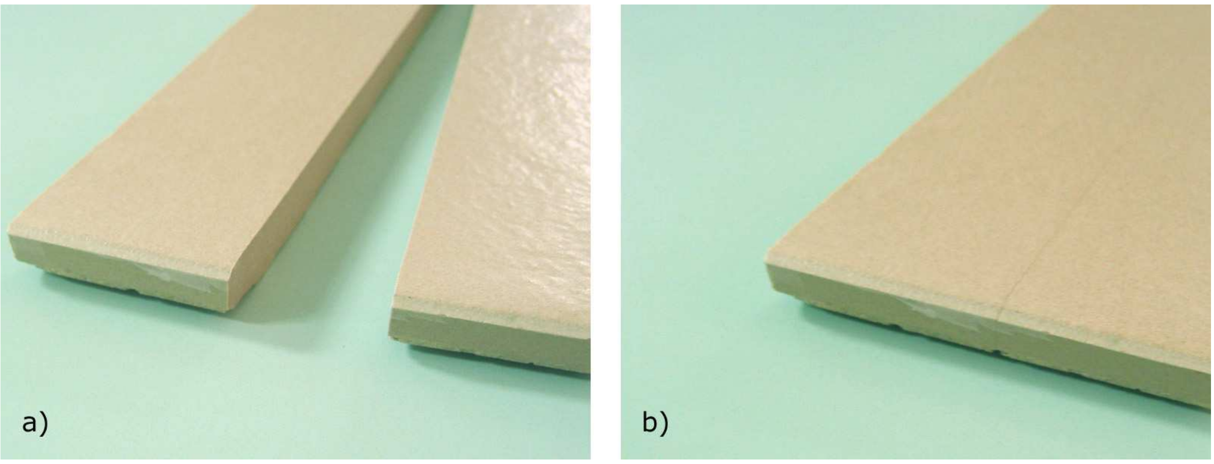

Fig. 11 *– Example of cutting with LiST: a) separated parts – b) re-approached parts after cutting*

The flatness of the separation surface is acceptable and does not require further finishing. If required, only a slight trimming can be carried out on the upper edges (chamfering).

6. CONCLUSIONS

The Laser induced Scoring by Tension (LiST) cutting method represents a potential alternative to present cutting systems for the ceramic field, since it shows the following **advantages**:

- cutting without contact (no wear of tools);
- high production flexibility (by simply modifying the cutting program);
- good quality of the resulting cut surfaces (compared to scoring and snapping);
- no working wastes (muds, powders, …) that means a reduced environmental impact.

On the contrary, LiST system still has some **aspects to be improved**, namely:

- the cut quality varies depending on ceramic body composition;
- the cutting speed V_a is not sufficient (2 m/min instead of a 5 m/min target) and decreases if the tile thickness increases;
- rather high energy consumption, due to low efficiency of current CO_2 laser sources;
- need of adequate protection guards for operators' safety.

LiST technology applied to the ceramic field (even if at laboratory level) shows encouraging results. However, further verifications are necessary to determine its potentialities and costs at industrial level. If the final results, compared with the other technologies, are positive, it would be feasible to introduce in the ceramic process a clean, flexible and efficient solution for automatic cutting of fired tiles.

BIBLIOGRAPHY

[1] A. Bresciani, G.P. Graziani, C. Ricci, "New glazed porcelain tile manufacturing technology: pre-pressing, dry decoration and green cutting", Qualicer 2002, Vol. 2, P. GI, pp. 255-270

[2] I. Black, "Determining cutting speeds for the CO2 laser machining of decorative ceramic tile", The International Journal of Advanced Manufacturing Technology, Springer London 1998, Vol. 14, No. 9, pp. 651-655

[3] Patent US 2007/0151962 A1, "Method for Laser-induced thermal separation of plate glass", publ. 05/07/2007