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Design of a machine to rectify ceramic tiles for laboratory tests

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Design of a machine to rectify ceramic tiles for laboratory tests

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Abstract: The tile rectification process, also called squaring, consists of machining the edges of the tile to make them straight, parallel two by two and perpendicular to the other two in addition to controlling the size of the tile (calibrating). The current industrial lines are based on multiple heads (abrasive wheels) where the characterization of the process in terms of product quality and power consumption is hard to be conducted. In this work we present a laboratory machine equipped with a single grinding wheel to be used for testing and simulating the working conditions of a conventional rectification tile. The specifications of the machine that are required and the analysis of the different functional systems designed (clamping and motion, cutting, cooling, structure/enclosure, and electrical/control system) is reported. This machine may lead researchers to characterize the rectification process and propose actions for improving the efficiency and the sustainability of the industrial process.

Keywords: Abrasive tile rectification, Abrasive machining, Sustainable manufacturing, Energy efficiency.

1. Introduction

The rectification process in the tile industry consists of removing a small amount of material (mainly a compact, non-porous and vitrified product made of mix of clays, feldspars and silica) from the edges of the tile to obtain very accurate dimensions by machining the edges of the tile to make them straight, parallel two by two and perpendicular to the other two (squaring), in addition to controlling the size of the tile (calibrating). To carry out this process, abrasive machining is applied using diamond or silicon carbide abrasive wheels that remove material from the edge of the tile. This type of grinding process in the tile industry therefore differs from the grinding process commonly applied in other industries such as machinery and component manufacturing industries.

Initially, these processes were applied only in the manufacturing process of compact porcelain tiles since it was a product with high added value. However, nowadays the rectification stage of ceramic tiles is quite widespread, and it can be found in both polished and unpolished ceramic tiles, especially in the case of medium and large formats, which can reach more than 50% of the total production in many industries.

However, machining processes with abrasives are very inefficient manufacturing processes, in which very often, only between 15% and 30% of the electrical energy consumed is used to remove material [1], and present very low material removal rates. Furthermore, besides being costly and inefficient processes, their productivity and energy and tool consumption (abrasive wheels) are very sensitive to working conditions.

Abrasive machining processes have been widely studied as finishing operations for metal machining (mainly alloyed steels), technical ceramics (alumina, zirconium, silicon carbide, etc.) and glass. For all cases, it is well-known that the performance of the operation depends on the main characteristics of the grinding wheels as well as the cutting parameters. One of the most critical parameters in this operation is the maximum chip thickness and its impact on the specific energy consumed, growing exponentially as thickness decreases [2].

In the ceramic tile manufacturing industry, some research works can be found about abrasive machining processes, but most of them are focused on the tile polishing process. For instance, some works studied the relationship between surface roughness, gloss, and the wear of the grinding wheels [3]. Others included the relationship between material removal rates and power consumption [4], or they proposed experimental models to estimate the final gloss as a function of machining time and material removal rate [5]. However, to the best of our knowledge, very few works addressed the rectification process of ceramic tiles. In [6], it is proposed a control system for adjusting the grinding wheel using fuzzy logic and, as a previous work by the authors, we showed in [7] a general study of the rectification process, where it is proposed some potential research lines in the field. One of these lines is related to the characterization of the process, which has been the basis of the present work.

To conduct the characterization of the process, the use of common industrial equipment with multiple heads is not feasible due to the long life of the wheels together with the interrelation among wheels and cutting conditions. In this work, we propose the design of a single-head machine to test and simulate the working conditions of a conventional rectification tile. This laboratory equipment machine will be used to obtain information on the characterization of the rectification process of ceramic tiles in order to apply this knowledge for process improvement.

The paper firstly shows a brief description of the rectification process and the industrial equipment used in the ceramic tile industry and remarks the specifications required for the single-head machine. Later, all the function systems that composed the machine are described, and a global description of the system is given. Finally, some conclusions are reported.

2. Description of the rectification process of ceramic tiles

The rectification process in the ceramic tile industry is carried out in lines composed of a succession of pairs of grinding wheels facing each other so that the tile passes successively between each pair of wheels. These grinding wheels attack the two opposite edges frontally, removing each of them a small amount of material until the established dimension is achieved. The line is divided into two sections, and between them a device that rotates the part 90º is placed to machine the other pair of edges. Figure 1(a) and figure 1(b) show a diagram of the arrangement of the line and a partial view of an industrial rectification line. The number of pairs of grinding wheels in each section is usually 6, 8 or 12, depending on the material removal rate goal.

Each grinding wheel is driven by an electric motor, which has a mechanism to individually adjust the distance to the tile (figure 2(a)). The rotational speed of the grinding wheels is usually constant, and it ranges from 1,200 to 1,500 r/min. The power of the motors is usually 5.5 or 7.5 kW, depending on the equipment's material removal rates. The feed movement of the tiles is carried out by two pairs of belts that press and drag the parts along the line (figure 2(b)), and the feed speed is generally from 4 to 15 m/min. Additionally, after the last pair of finishing wheels, another pair of wheels of lower power is placed with an adjustable inclination whose purpose is to perform a chamfer (figure 2(c)).

The abrasive wheels used (figure 3) in the rectification process are made of different materials and granulometries (grain size) depending on their location. The first pair (or the first two on high production lines) is for hard roughing and it is usually made of abrasive diamond; the rest of wheels have a decreasing grain size towards the end of the line and are usually made of silicon carbide or also diamond. The diameter of the grinding wheels is 250 or 300 mm, although the dimensions for the chamfering wheels is 130 or 150 mm.

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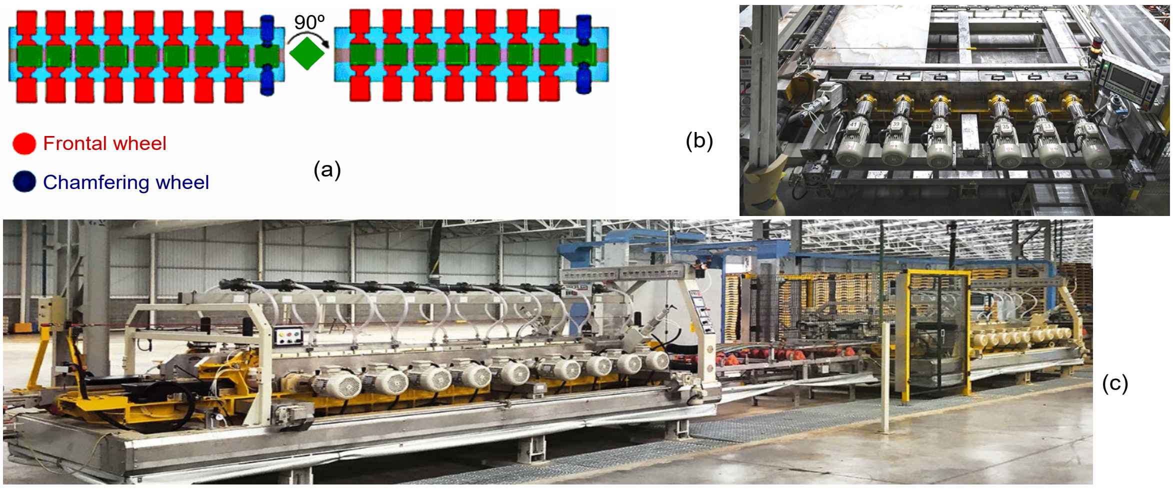

Figure 1. Rectification line: **(a)** Diagram of the process. **(b)** Arrangement of the wheels and tiles [8]. **(c)** Industrial rectification line [8].

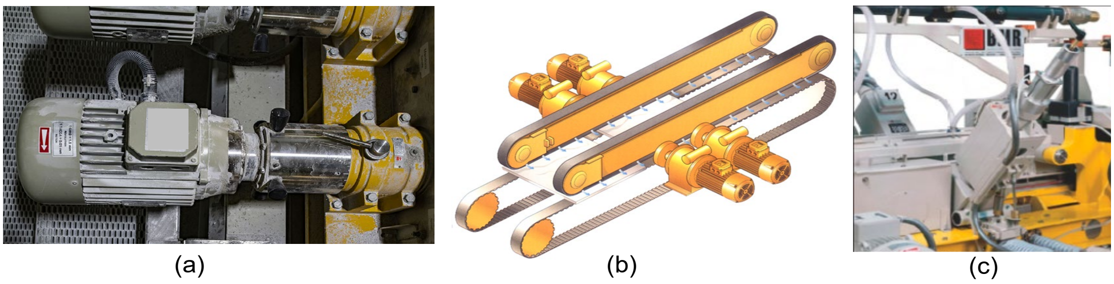

Figure 2. (a) Electric cutting motor and mechanism to regulate the distance [8]. **(b)** Belt system for dragging the tiles. **(c)** Finishing wheels for chamfering.

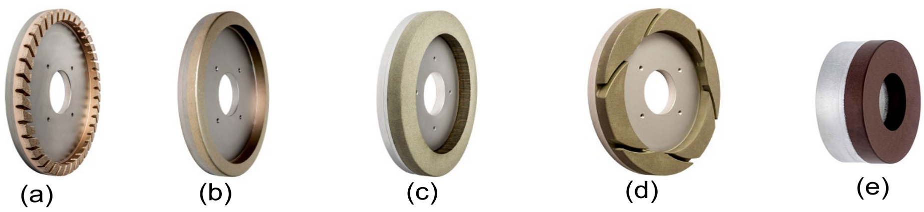

Figure 3. Rectification wheels for: **(a)** Hard roughing. **(b)** Medium roughing. **(c)** Prefinishing. **(d)** Finishing. **(e)** Chamfering. [9]

The rectification process has traditionally been carried out under wet conditions, although dry conditions are gaining popularity, which is less productive but simplifies the process and the required facilities since there is no need of coolants or equipment for wastewater collection and treatment. However, the line requires a specific facility for filtering and dust extraction.

3. Machine design specifications for laboratory tests

Industrial rectification lines are complex, and the operating conditions of each grinding wheel are greatly influenced by the working conditions of the surrounded grinding wheels. Furthermore, life of the grinding wheels is larger than in conventional machining processes, it usually takes several weeks in continuous working conditions to reach a worn condition.

For this reason, the use of an industrial rectification line for studying and testing the operation conditions of the wheels in not feasible, and a single-head equipment that reproduces the process and the working conditions of an industrial line and easily allows the modification of many parameters may be of great interest.

3.1. Functional design requirements
The equipment to be developed must meet the following design specifications:

- Single head equipment.
- Work on a single tile where successive grinding passes can be made intermittently.
- Adaptable to tiles with dimensions up to 600x600 mm and 8 to 16 mm thick.
- Use of grinding wheels, heads and motors from an industrial production line. The diameter of the grinding wheels to be used will be 250 and 300 mm.
- The overhang of the tile between the support and the grinding wheel will be less than 20 mm to avoid vibrations and tile breakage.
- Possibility of working both in wet and dry conditions. Under wet conditions, different cooling systems (jet, air, MQL, etc.) could be used, and flow rates and pressures must be adjustable.
- For wet conditions, it must be able to adapt to different cooling systems (jet, air, MQL, etc.) and different types of fluids, and the flow rates and pressures must be adjustable.
- The inclination of the angle of attack of the grinding head must be adjustable in the range 5º-25º. This is the angle that the axis of rotation of the grinding wheel forms with the direction of the feed movement of the tile.
- The spindle speed of the wheels must be variable between 700 and 2,400 r/min.
- The feed speed of the tile must be variable between 2 and 12 m/min.
- The positioning accuracy that controls the machining allowance to be removed should be accurate to at least ±0.02 mm/100mm.
- The data acquisition system must obtain readings of the instantaneous energy consumption of the cutting and feed motors, and it must be able to incorporate force sensors in future.
- The stiffness of the system must be enough to minimize the impact of the vibrations generated throughout the process.

3.2. Functional systems
Based on the above design requirements, the following functional systems have been established for their implementation:

- “Clamping and motion of workpiece” functional system. This system clamps and positions the tile for the rectification process, approaching the tile to the wheel to remove the machining allowance and getting the tile back to the initial position.
- "Cutting" system. It is responsible for carrying out the cutting movement of the grinding wheel and its placement and orientation with respect to the feed movement of the tile.
- "Cooling and lubrication" system.
- "Structure and enclosure" system. It includes the supporting structure and the enclosure of the working area.
- “Electrical system". It supplies the energy to the equipment including control and protection devices.
- "Control" system. It is in charge of setting and controlling the cutting parameters and it also acquires data about energy consumption from all systems (cutting, feed movement, lubrication, etc.).

4. Machine design for laboratory tests
This section summarizes the solutions adopted for each of the functional systems defined above. For each system, the problem to be solved is established and the solution adopted is exposed, justifying the

selection among the possible alternatives when appropriate. Finally, we show the final design of the proposed machine for laboratory tests.

4.1. "Clamping and motion of workpiece" functional system
This system is the one with the highest complexity due to its greater difference from similar industrial equipment. In the rectification line, the tiles move forward linearly passing through successive heads, being held and moved by drive belts (figure 1 and figure 2(b)), that is, the tile does not present a backward movement. However, in the equipment to be designed, the same tile should repeatedly pass over the grinding wheel, reducing its size with each pass progressively. Therefore, two main movements are required (approach movement to the grinding wheel and forward movement for cutting) and two other auxiliary ones (backward movement from the cutting position and a movement to get the tile back to the initial movement), as shown in figure 4.

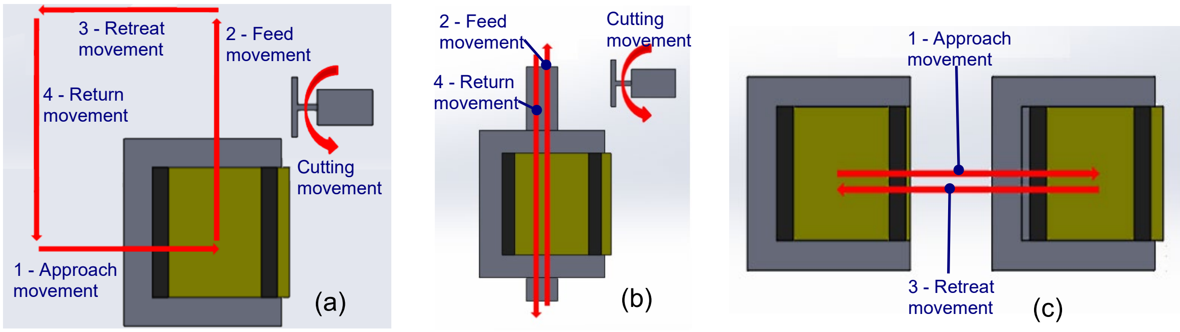

Figure 4. (a) Sequence of movements of the cutting table and the tile. **(b)** Feed movement and return movement to initial position. **(c)** Approach movement and retreat movement.

To clamp the tile, it is necessary to compensate the two main forces during cutting: the feed force and the repulsion force (perpendicular to the feed movement), the last one being about five times greater than the first one. In the industrial process, the repulsion forces are compensated since the wheels are facing one to each other (figure 1(a)), and the feed forces are compensated by the pressure of the rubber belts that hold the tiles and transmit the movement. For this reason and because of the required positioning accuracy, the tile should be clamped on a rigid base with a sound fastening system, and the table with the workpiece has the feed and return movement.

The solution adopted is a table where the tile is placed and held over mechanical stops. In a first movement, the approach movement, the table will be positioned at the required distance from the grinding wheel with a high precision. In a second movement, the feed forward movement, the table will move towards the wheel for cutting the tile.

For the approach movement, two alternatives were evaluated: i) a rubber belt or tape sliding on a stainless-steel plate with a rigid stop for positioning the table (figure 5(a)); ii) a table of rollers moved driven by a spindle or by a toothed belt system slides (figure 5(b)). Due to the robustness and the precision of the system, a roller table driven by a ball screw (accuracy grade C5, ±0.040 mm/300 mm) was chosen as the final solution (figure 5(c) and figure 5(d)). Under this solution, the tile is positioned on the table by mechanical stops, and it is clamped by pressing it against the rollers which allows the overhang of the tile at the cutting zone (figure 5(c)). The friction force is enough to hold the part since the cutting forces (feed and repulsion forces) are absorbed by the mechanical stops. Furthermore, the table is made of A-5038 aluminum because of its machinability, resistance to corrosion, and its lightness which minimizes the inertia during the acceleration movements (starts and stops movements).

On the other hand, the feed forward movement of the table is carried out on round chrome-plated steel guides with bronze bearings, and the movement is transmitted by a toothed belt from a motor controlled with a variable frequency drives (figure 8(b)).

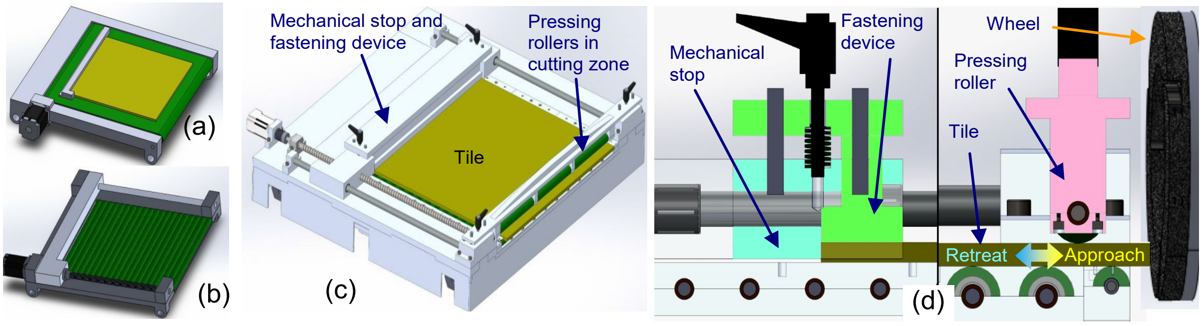

Figure 5. Cutting table: **(a)** First alternative based on a belt. **(b)** Second alternative based on rolls. **(c)** Final solution for the clamping. **(d)** Positioning system and detailed view

4.2. "Cutting" functional system

This system is the one that carries out the material removal. It must have a motor with an appropriate head for mounting the wheel, as well as a device that allows modifying the separation of the head to the table to compensate for the wear of the grinding wheel. Furthermore, it will have a device that allows modifying the angle of inclination of the grinding wheel with respect to the tile.

The proposed solution is the use of a three-phase 5.5 kW industrial motor (3,000 r/min) with its corresponding head, mounted on a small table with movement over lineal guides and with a device to orient the wheel for a specific angle (figure 6). This later device is usually missing in current industrial machines.

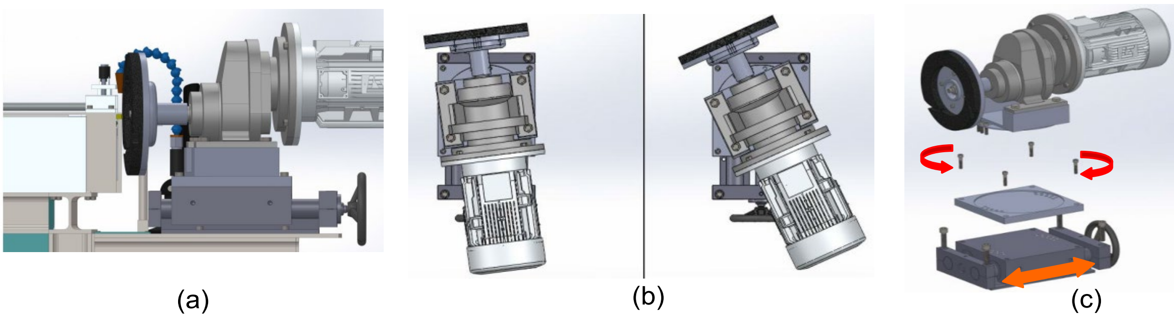

Figure 6. Cutting functional system: **(a)** Position of the system during cutting. **(b)** Wheel orientation and limiting angles. **(c)** System components and orientation and positioning movements.

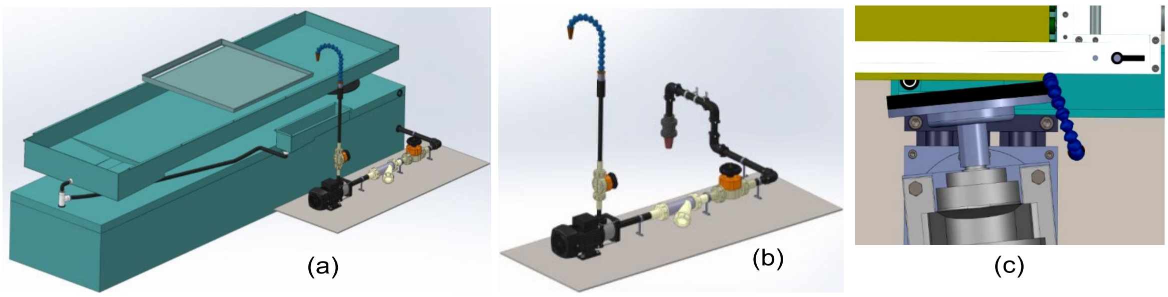

Figure 7. Cooling system for wet rectification: **(a)** General overview with the collection tray and the treatment tank. **(b)** Components of the pumping system. **(c)** Coolant delivery point in the cutting zone.

4.3. "Cooling" functional system

This system is in charge of cooling the cutting area and removing the resulting debris. It should be designed to make possible the incorporation of different cooling systems (liquid jet, air, MQL, etc.).

In the case of a liquid jet (wet rectification), the elements for pumping the correct flow must be available at the corresponding pressure together with additional items for collecting and treating the used fluid. In the case of dry rectification, the cutting area must be closed, and it should be available a device for supplying air under pressure and another one for filtering the air.

The most complex system is the wet rectification unit, which is why the equipment has been designed with this cooling alternative, in addition to providing it with a semi-tight enclosure that allows it to incorporate the rest of the cooling alternative in the future. Figure 7 shows the designed system and its components.

4.4. "Structural and enclosure" functional system

This system constitutes the frame of the equipment that supports the remaining functional systems. It must offer sufficient rigidity and partial resistance to corrosion due to cutting fluids, and it should provide a semi-watertight and partially soundproof enclosure of the cutting area.

For the structure, HEB100 profiles made of S 275 JR steel joined by welding operations have been chosen. For the flat supports, tanks, etc., the S 235 sheet steel has been used, and the same steel but with an internal polyurethane foam to increase soundproofing was used for the enclosure. All elements are protected with an epoxy paint primer, given the good resistance to corrosion that it offers. Figure 8 shows the main structure and the assembly of the "clamping and positioning" system on it.

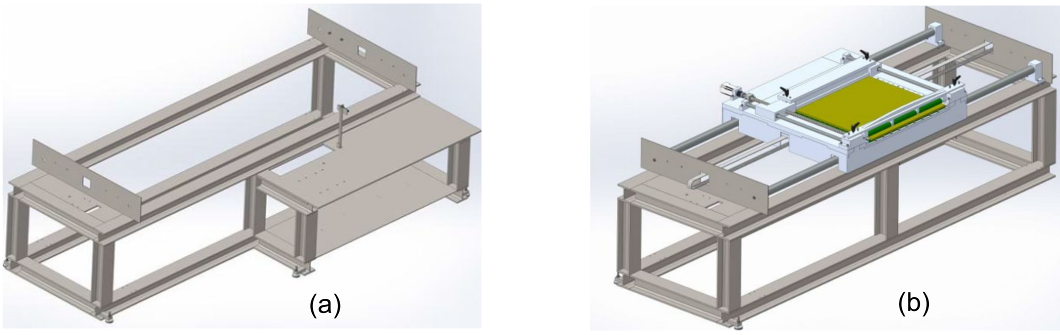

Figure 8. (a) Chassis of the designed machine. **(b)** "Clamping and motion of workpiece" system on the chassis.

4.5. "Electrical" and "control" functional systems

This section briefly describes the main components of the electrical and control systems.

The electrical system is made up of the electrical power supply unit, the cabinet with control and protection devices, the wiring of all the components, and the drive motors. The motors used for the cutting system, the feed movement of the cutting table and the cooling pump are three-phase motors with 5.5 kW, 750 W and 500 W, respectively, and all of them are driven by variable frequency drives to allow the speed control. The motor for positioning the tile is a stepper with its corresponding control driver. The control system is made up of an Arduino ATMega to control the movements of the cutting table, and another Arduino is placed to capture electrical consumption data and to control the variable frequency drives. Both Arduino microcontroller boards are communicated via USB to a PC where a LabView program is executed to control and monitor the machine operation.

4.6. Developed machine

Figure 9 shows a general view of the developed machine, with and without a protection cover, as well as a screenshot of the machine's monitoring and control program.

5. Conclusions

In this work we have presented the result of the development of a machine to carry out tests for the rectification process of ceramic tiles at the laboratory level, exposing the solutions adopted for each functional system. The importance of the equipment developed is justified by the difficulty of studying the process in an industrial facility, whereas the proposed machine can reproduce the working conditions of an industrial line at the laboratory level.

The equipment developed will let researchers to carry out tests about the rectification process at laboratory level and learn more about the process, which is nowadays a field where few studies may be found. Furthermore, this equipment can also be used to carry out tests with wheels offered by different manufacturers to characterize their performance, being a useful equipment for both abrasive wheel manufacturers and tile industries.

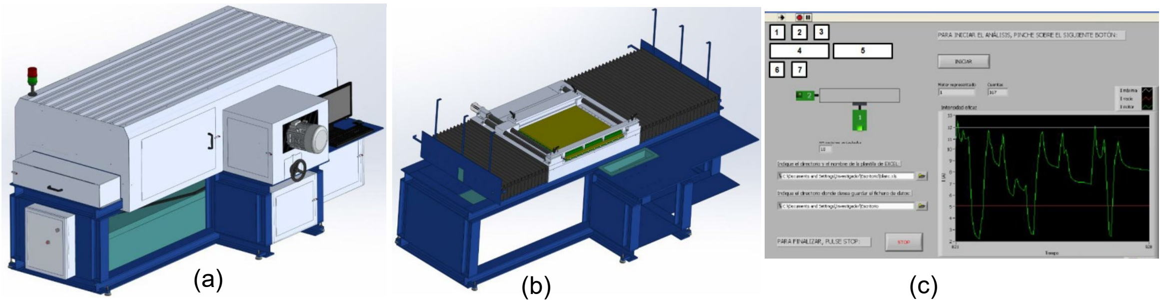

Figure 9. Designed machine: **(a)** General view. **(b)** Without protection cover (the cutting table and flexible accordion bellows to protect the guides are shown). **(c)** Screenshot of the control software.

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