New line of diamond tools raise productivity in polishing stone

The future of polishing tools is rapidly changing through the use of composite materials made out of metallic or, more recently, polymeric binders and diamond particles that act as the abrasive (cutting) agents. This has led to the development of highly abrasive tools. Besides the more direct advantages of using these tools, such as higher lifetime and higher productivity, they are also more environmental friendly. Moreover, it is easy to demonstrate that compared to the conventional abrasives, metallic and resin bonded diamond tools for polishing are far more economical, even if their production cost is significantly higher. Nowadays, after an optimisation of the process, it is possible to perform the complete polishing almost exclusively with diamond tools, as shown in this work. This report by P. M. Amaral[1], L. Guerra Rosa[1], Sérgio Pinto[2] and David Pozo[3].

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[4] In this text, 'cutting' is defined as any action that implies a removal of material. Thus slabbing, grinding and even polishing are all cutting processes as they involve material removal although the amount of removal may differ among the three. For example, grinding involves a substantial removal of material but in polishing the amount of material removal is very small.

Stone polishing practices have not evolved over time as rapidly as other processing activities. In order to enhance the stone polishing processes it is imperative to improve tools, machines and methods [1, 2].

Recent developments of resin bonded diamond tools have shown that it is possible to reduce the number of polishing heads in a machine and to save an enormous amount of time in tool replacement [3]. Tests performed in a prototype polishing machine show that it is also possible to increase the productivity by maintaining the number of polishing heads. Likewise, the use of these new diamond tools can reduce the number of polishing stages significantly while maintaining the in-feed rate similar to what is commonly used with conventional abrasives.

The experimental work described hereafter shows that, after executing process optimisation, new polishing diamond tools may gradually replace the conventional abrasives used in standard polishing activities. The work was supported by the Spanish company POMDI that produces diamond tools for mechanics, optics, glass and stone for more than 25 years. Only recently this company has invested in the production of resin bonded diamond tools for ornamental stone slab polishing. Although diamond tools are more expensive, the present work demonstrates that, not only the overall costs using these new products are lower, but also, for certain stones, they allow to obtain a better polishing quality when compared with conventional abrasives.

Characterisation of stone polishing

In the processes of turning out an ornamental stone into a finished product, polishing operations are the final stages and can be divided into: 'rough polishing' and 'fine polishing'. In fact, polishing is a continuous process that uses tools of decreasing grit sizes, but in rough polishing there is still some considerable amount of material to be removed, whereas in fine polishing the removal of material by cutting[4] is very low and only the asperities on the surface of the stone are getting finer after each polishing step.

Most of the industrial machines used for polishing are equipped with a conveyor belt and some have a transverse movement (bridge polishers). The machines are equipped with polishing heads, which have a rotational movement and apply the required pressure on the stone slab. Depending on the type of machine, different types of heads and different tools may be used. However for attaining the best results in a particular variety of stone, the machine's operational parameters have to be optimised, namely, for bridge polishers:

In-feed rate – This parameter i.e. the conveyor belt speed, V_{conv}, must be 'adjusted' with respect to the other processing parameters in order to obtain a good stone polish; and there are two very important aspects to consider:

- First, both the transverse speed, V_t, and the conveyor belt speed must work together so that there will not be any unpolished parts of the slab. During stable processing conditions (i.e. assuming constant non-zero in-feed and transverse speeds), the following relationship is applicable:

$$\frac{V_{conv}}{V_t} = \frac{\ell}{2w} \quad (1)$$

where, ℓ is the distance covered by the conveyor during the period of time that the polishing head needs to complete a 2-way travel across the slab (transverse movement), and w is the width of the slab.

If the movement of the slab, while the rotational head travels across the slab, is more than the diameter of the polishing area, d (the distance between the sides of two opposite tools in the polishing head), then some parts of the slab will be not polished. Therefore, the transverse speed and the conveyor belt speed should be defined so that:

$$\ell = 2w\frac{V_{conv}}{V_t} \geq d \qquad (2)$$

The in-feed rate is closely related to productivity. The higher the conveyor belt speed, the larger will be the quantity of polished slabs. Therefore, a high in-feed rate means high productivity, if no additional polishing heads are added to the process.

- The other important aspect is the relation between the rotational speed of the polishing head and the in-feed rate. If one is high, the other one must also be high. This is due to the fact that there is the need to carry out a certain number of passes of each tool (polishing element in the head) over the slab. This can easily be represented by the following equation:

$$N_{rot} = \frac{V_{rot}L}{V_{conv}} n_{tools} \qquad (3)$$

where, N_{rot} is the sum total of full rotations performed by each tool (in the polishing head) over the slab, L is the length of the slab, V_{rot} is the rotational speed of the polishing head, and n_{tools} is the number of tools in the polishing head.

Water flow – Water has three major functions: cleaning, cooling and lubricating. The polishing process using diamond tools produces much less amount of loose particles (most of the waste comes directly from the stone and not from the tool), which means that the water flow could be lower. On the other hand, the rotational speed of the polishing head is often higher than that with conventional abrasives, therefore the system needs higher water flow to decrease the higher resultant temperatures in the tools. Considering both these two factors, the best action to take is to maintain the water flow more or less the same as when using conventional abrasives (normally, not exceeding 30 l/min).

Pressure – It is important to define the meaning of pressure. In modern polishing heads, the effective pressure is the difference between the positive pressure (giving a downward force) and the counter-pressure (causing an upward force). Not all the machines apply counter-pressure, so in such cases the effective pressure is equal to the positive pressure. The counter-pressure is very important because it helps to maintain the polishing head more stable. In addition, the higher the values of positive and counter pressures, the more stable will be the polishing head and, in general, the polishing process. Some resin bonded tools work more efficiently at higher pressures, while others are more efficient at lower pressures (the lifetime of the tool depends on the pressure applied, and the latter should be kept low in order to preserve the tool life). However, in most cases using diamond tools, the effective pressure should be higher compared to conventional abrasives.

Description of the new resin bonded diamond tools

Although the production of resin bonded diamond tools for ornamental stone polishing is not complicated, the correct selection of materials and process parameters ought to be thoroughly studied before manufacturing these tools. The production process involves the retention of the diamond particles by the polymeric resin. The polymer, normally in the form of pellets, is introduced in a mould along with the diamond particles (with the required grain size and distributed in a controlled manner). The mixture is then pressed and heated up to a certain temperature during a certain period of time, and usually, different thermal cycles have to be defined according to the type of polymer. This is enough to polymerise the thermosetting resin and make it hard. Sometimes (with some polymers), it is necessary to finish the process with a curing cycle. As with the metal bonded diamond tools, a surface layer is left without diamond to attach it to the support of the tool. In a prototype production, the steps involved in the manufacture of diamond tools are those presented in Fig 1.

In this R&D work, Fickert tools, mostly applied in granite, were used to polish two types of materials: Porriño granite and a siliceous artificial stone. The use of Fickert tools allows that the contact between the tool and the slab is approximated to a 'line contact', thus raising the local contact pressure. Since both materials are hard and abrasive, the new diamond tools are tested in severe conditions in order to obtain good quality in the finished surfaces of the stone slabs.

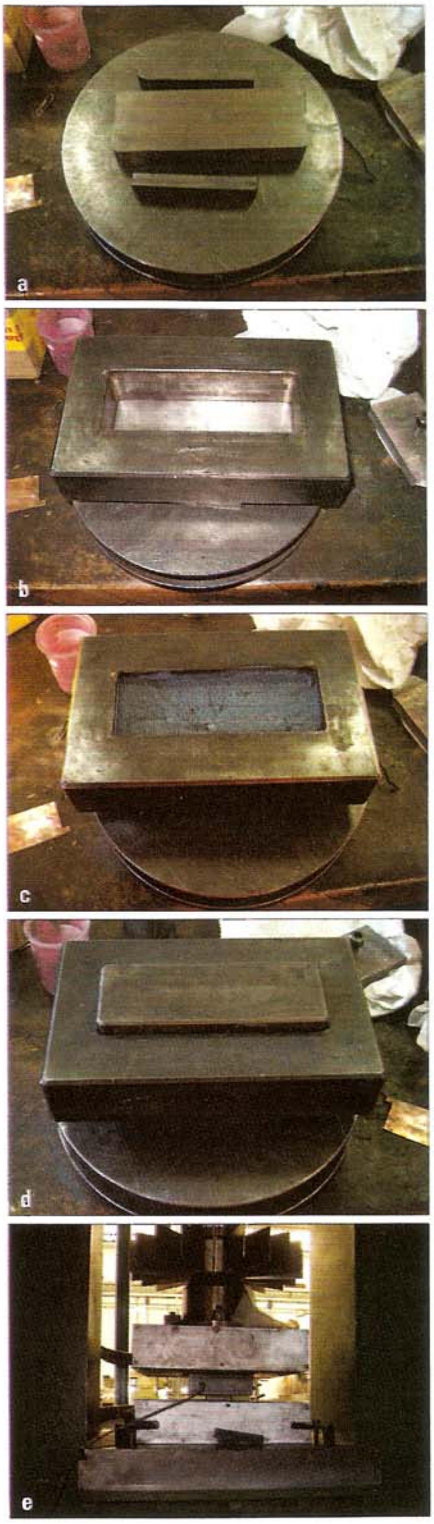

Fig 1 Production stages for manufacturing resin bonded diamond tools:
a) assembling the mould
b) mould ready to be filled
c) mould filled with resin
d) mould closed
e) mould pressed and heated

The quality of the polished surface was assessed by measuring two parameters: gloss and roughness. Using these two parameters it is possible to compare the results of the polishing performed by conventional abrasives with the results of the polishing performed by the new diamond tools. In this work, the gloss[5] was measured – at three different angles, 20°, 60° and 85° – using a 'Sheen Tri-Gloss Master 20-60-85' glossmeter [4]; and the roughness was measured with a 'Surtronic DUO' roughmeter (measuring R_a and R_z [6] [5, 6]). Both measuring instruments are depicted in Fig 2.

The polishing tests involved several types of tools. The details of the tools are listed in Table 1. The first two tools (CALIB and Ab 120) were used uniquely to attain a uniform 'standard' rough surface [7], thus simulating the initial polishing stages and creating standard surface condition for testing the new tools (PD and RD).

Experimental procedure

The polishing tests were carried out with a machine (see Fig 3) equipped with a single polishing head, thus allowing the measurements of gloss and roughness after the use of each type of tool. The machine is instrumented with proper systems that allow to control and monitor all the processing parameters (conveyor belt speed, transverse speed, head rotation speed, pressures, water flow). This polishing machine is over-equipped when compared to the industrial machines but the correct knowledge of all the variables of the process is of crucial importance. Another difference to the industrial machines is the number of tools in the head. Usually a polishing head is equipped with 6 Fickert tools (sometimes 7 or even 8), but the head used in this machine has only 4 Fickert tools. To extrapolate the results obtained with the 4-tool head to a 6- or more tool head we may use the aforementioned equation 3.

For each type of stone, more than 30 polishing tests were performed to establish the proper optimization of the processing parameters and the optimal sequence of tools.

As mentioned, the methodology used for the tests allows to monitor and control the processing parameters used in each polishing stage. Additionally, the methodology enables the comparison of surface quality results (gloss and roughness) between different tests, especially, taking into account the number of stages and/or the in-feed rate. During the work, some trials did not achieve the intended final goal (a good quality polish), but have indicated several relevant aspects about the polishing of these types of stones that were in fact very useful for the optimisation process.

For the stones used in the work (Porriño granite and a siliceous artificial stone), the following two examples representing the final optimisation process are given:

- As mentioned earlier, the diamond tools allow for a high in-feed rate. One of the final tests made in the granite was carried out with high in-feed rate (1 m/min). In this case, the number of stages for polishing the granite (usually around 18) was decreased to 12 polishing stages (including the preliminary stage using Ab 120). From the results of gloss presented in Fig 4, it can be seen that it is still possible to remove from the process the second stages of RD3 and RD5 without a loss in surface quality (gloss). Therefore, we can decrease the number of stages from 12 to 10.
- The second example concerns some interesting results obtained in the siliceous artificial stone. The final gloss measurement at 60° obtained with the new diamond tools increased from 42 gloss units using conventional abrasives (work performed by the artificial stone supplier) to 54 gloss units. This value is maintained even

Fig 2 Photographs of the glossmeter (left) and the roughmeter (right)

Tool	Bond	Diamond grit size	Diamond concentration
CALIB	Metal	About 500 µm	Low
Ab 120	Conventional abrasive with a 120 grit		
PD1	Prototype Diamond tools[7]		
PD2	Prototype Diamond tools[7]		
RD1	Resin	64 µm	Medium
RD2	Resin	20-30 µm	Medium
RD3	Resin	5-10 µm	Medium
RD4	Resin	5-10 µm	Medium
RD5	Resin	2-4 µm	Medium
1500	Finishing LUX abrasive with 1500 grit		
3000YEL	Yellow finishing LUX abrasive with 3000 grit		
3000GRE	Grey finishing LUX abrasive with 3000 grit		
LD	Finishing LUX diamond tool		

RD stands for Resin Bonded Diamond tool
PD stands for Prototype Diamond tool
LD stands for LUX tool made of Diamond

[7] These diamond tools are prototypes and so their characteristics are not available in the public domain.

Table 1 Different tools used in this work

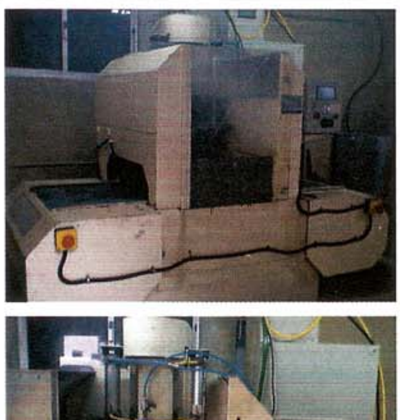

Fig 3 Polishing machine

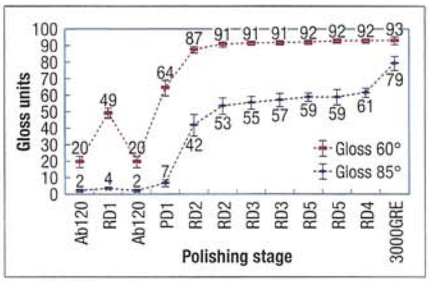

Fig 4 Variation of gloss at 60° and 85° during different polishing stages in Porriño granite (V_{conv} = 1 m/min

[5] Light is emitted into the stone's surface through an angle (20°, 60° or 85°) and there it is reflected into a detector. In very simple terms, the value of the gloss is the percentage of the emitted light that is captured in the detector.

[6] R_a is the medium value of the variations of the peaks to the medium line (for which all the areas above equal all the areas below). For the measurement of R_z, the measured line is divided into 5 parts. In each part the medium of the maximum peaks are calculated, and finally the value of R_z is the medium of these 5 peaks.

when a 3000 grit LUX tool is used for finishing, meaning that this last tool does not add value to this particular polishing process. Moreover, after using the 3000 grit LUX tool, the macro aspect of the surface of the stone (when looked at different angles) slightly changes its tonality compared to the last stage where the diamond tools were employed (RD4). This is explained by the significant decrease in gloss at 85° (from 91.7 to 77.5 gloss units). The in-feed rate of this test was 0.44 m/min using the 4-tool Fickert head (about 0.60 m/min using a 6-tool head).

The values of roughness are not presented in these figures but they were of extreme value for optimising the polishing process. The roughness should be as low as possible in order to obtain a good gloss value. If the roughness of the surface is high, then light is dispersed. So, especially in the first polishing stages, the goal is essentially to decrease the size of the asperities, thus decreasing the surface roughness (R_a values decrease from 1.32 μm down to 0.12 μm). After a few stages, the roughness measurements can not be made using traditional measuring instruments (R_a values bellow 0.12 μm). The only way to verify to what extent the roughness decreases along all the polishing stages is through the use of special measuring instruments such as the laser roughness meters. According to the results, tools PD1 and PD2 were crucial for allowing the use of the RD tools. The majority of the resin diamond tools are only possible to be used when applying tools that decrease dramatically the values of roughness.

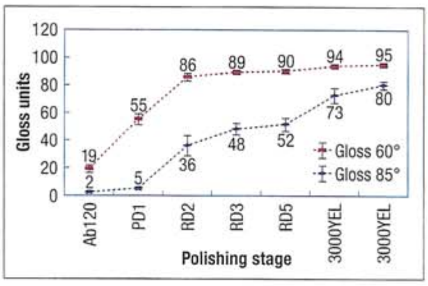

Fig 5 Variation of gloss at 60° and 85° during different polishing stages in the siliceous artificial stone (V_{conv} = 0.44 m/min)

Conclusions

The tests show that POMDI's resin diamond tools perform better than the conventional abrasives. It is possible to have higher in-feed rates with diamond tools. Moreover there is a need for fewer polishing heads. With these tools industries can reduce the costs incurred in the polishing process.

It is to be noted that the polishing line can not consist entirely of resin diamond tools as they cannot remove the high amount of asperities produced in the calibration stage (the stage after the sawing of the blocks). Besides, in many cases there is still the necessity of having an additional tool for the final polishing stages. For example, at 60° angle, the gloss of the granite is about 60% with resin diamond tools and about 80% when a finishing LUX abrasive tool is added. However with the finishing LUX abrasive the gloss value decreases at 85° even though there is an increase at 20°. Consequently it is necessary to optimise the configuration of the tools before using these diamond resin tools with the other types of tools.

As the examples in this article show, there is a need to optimise all the variables of the process before these tools can be put into market. The optimisation of the tool configuration will ensure that the tools will be properly used in the factory, minimising the risk of obtaining less encouraging results which could lead to a negative outlook towards the introduction and popularisation of these diamond tools by the industry.

In what respects the economical advantages of these tools, it is very easy to demonstrate that the diamond tools are cheaper in the longer run as it can be seen from Table 2.

	Conventional Abrasives	Resin diamond tools
Cost per tool	1€	150€
Number of tools in one machine	18 x 6 = 108	10 x 6 = 60
Number of tool replacements per year	3x22x11=726	Aprox. 5
Number of tools bought per year	726 x 108 = 78408	5 x 60 = 300
Annual tool cost	78408 x 1€ = 78408€	300 x 150€ = 45000€
Waste treatment costs	high	very low
Costs for tool replacement (time spent with the line stopped)	7260 min	50 min

Table 2 Comparative costs of conventional and diamond tools

The waste treatment costs presented in Table 2 are the costs associated in handling the wastes coming out from the polishing line (normally, a mixture of water and abrasive residues): high cost means larger amount of wastes that need to be treated (e.g. water recovery, waste disposal). The cost for tool replacement is the cost that is incurred when the production line is stopped for changing the tools. For calculating the tool replacement cost it has been assumed that the time taken to change all the tools is about 10 minutes. With 726 replacements per year, this means 726 x 10 = 7260 minutes lost in tool replacements. Considering that a polishing machine works 11 months per year, 22 days per month, 8 hours per day and 60 minutes per hour, this means that it works out to be 116160 min/year. The 7260 minutes lost in tool replacement is about 6.25% of the total working time of the machine. Using diamond tools, the time spent in tool replacement is just 5x10 = 50 minutes per year, 0.04% of the total working time of the machine.

This figures used above for diamond tools are quite conservative, for instance, the number of replacements is probably less than 5 while using resin diamond tools. The price of the diamond tools has also been assumed to higher than it normally is and the number of tools in a machine using diamond tools does not have to be so large. ◆

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