Evaluation of diamond tool behaviour for cutting stone materials

The cutting behaviour of three different types of diamond grinding wheels is studied using four different ornamental stones: two different marbles, a granite, and a quartzite. The existent equipment allows electric energy consumption measurements to be made exclusively in the tool rotation motor. The behaviour of the tools during the grinding operation is explained by relations between the electric energy consumption needed to perform the grinding work, and the resultant force generated in the tool as shown in this article prepared by **L. Guerra Rosa**[1], **P.M. Amaral**[2], **C.A. Anjinho**[1] and **J. Cruz Fernandes**[1].

Portugal has a wide variety of limestones, granites and marbles that make up the basis of the natural stone industry. Because of that, Portugal is the world's ninth largest producer of ornamental stones, third in Europe after Italy and Spain [1].

Nowadays, diamond tools are used for the extraction of the block from the quarry (drills and diamond wire), sawing the blocks (mono and multiblade gangsaws, diamond wire stationary saws, block cutters), cutting or grinding the slabs (bridge mill machines, multi-disc continuous saws, splitting machines) and polishing the slabs and tiles (polishers). Diamond tools are better when compared to other tools because of their high cutting performance, which is achieved by a combination of extreme hard diamond grits that develop into highly active cutting edges, with the wear properties of the metallic matrix of the tool (binding systems).

Pre-industrial research conducted at IST (Lisbon) led to the development of laboratory equipment for conducting R&D and pre-production trials using new tools and processing conditions [2-8]. Considering that the 'optimum' processing conditions for different stone materials are – in principle – different, the IST group has proposed a novel classification equipment that tries to reproduce the industrial conditions. So far, the experimental procedure has been developed in order to use the classification system in two parallel situations:

- to classify the stone materials based on the measurement of a parameter called 'Relative Abrasiveness' which is simply a 'figure of merit' that quantifies 'the resistance shown by a certain stone material to be processed by a certain tool';
- to study diamond tool cutting behaviour.

In terms of the evaluation of the behaviour of diamond tools (within the scope of this work), the equipment is used, among other examples, to characterise and compare new advanced binder materials with lower content of cobalt (Co) [3,4,7], and to analyse the performance of the recently commercialised pre-alloyed metallic powders.

The present work is concerned with the optimisation of diamond tool processes by studying the cutting behaviour of 3 different types of diamond tools, using 4 different stone materials, and 3 different rotation speeds of the tool, thus trying to describe and demonstrate two major research objectives:

- confirmation of the suitability of the test methodology for characterising diamond tool behaviour, by obtaining consistent measurements of electric energy consumption using the IST classification equipment;
- verification of the relations between electric energy consumption per unit weight of removed stone material and resultant force at different rotation speeds, while carrying out the tests in a similar basis as in previous works.

Fig 1 IST classification equipment

The mechanical properties of the matrices (i.e. binders after sintering) are also measured.

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Description of experiments

The recently improved version of the IST classification equipment was used for the execution of the tests (Fig1). The equipment is fully described in previous works [4,7]. Basically the equipment allows following in real time the cutting process (either sawing or grinding), measuring and controlling the main operating parameters. The correct control of the cutting operation was guaranteed by the use of a new software especially developed for being used with this equipment (Fig 2).

The operating parameters introduced in the controlling software are: the rotation speed of the circular tool; the feed; the initial weight of the stone tile (test piece); the initial weight of the tool; and the coolant flow. The output parameters are: the electric energy consumption (E) measured exclusively in the tool rotation motor and the mean values of the horizontal and vertical components of the generated resultant force (F_r) in the tool. At the end of the procedure, the tool and the stone are weighed again, and then, the values of the electric energy consumption per unit weight of removed stone material (Z) and tool consumption per unit weight of removed stone material (ϕ) are calculated. In this particular work, the parameter ϕ (specific tool consumption) is not considered. All experimental data is stored in a database file managed by the controlling software.

The grinding parameters used in the tests were maintained constant: feed of 10 mm/sec and water flow of 1 litre/min, with the exception of the tool rotation speed in order to establish 3 sets of tests, for each type of tool, at 1000, 1500 and 2000 rpm.

The ornamental stones used in the tests are: two marbles – Rosa El-Rei (also known as Rosa Portogallo) and Creme Veios Castanhos; one granite – Pedras Salgadas; and one quartzite. The dimensions of the stone tiles are 300x300x20 mm. The values of the volume density obtained in these ornamental stones are in the range of 2.7 g/cm^3. The stone's mechanical characteristics (hardness, strength, toughness, etc) vary significantly from one type of stone to the other. The stones also differ in degree of anisotropy as they represent two diverse classes of rocks: the igneous stones (granite) and the metamorphic stones (marble and quartzite).

Fig 2 View of the IST cutting controlling software window

	M1 Co-Cu-Sn*	M2 Co-Cu*	M3 Co-Cu-Fe*
Vickers Hardness HV5	178.2	182.8	228.0
Yield Strength [MPa]	403.0	407.0	454.0
Density [g/cm^3]	8.74	8.72	8.56

* Starting powder binders

Table 1
Properties of the matrices

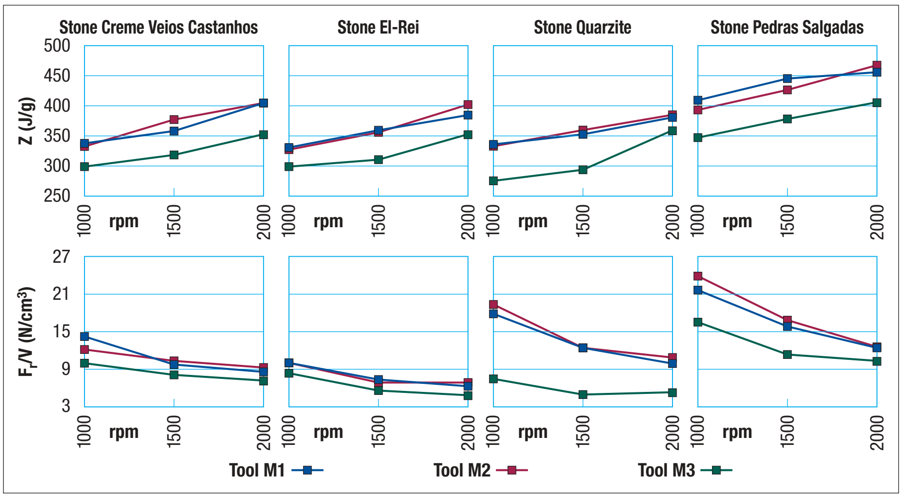

Fig 3 Variation of the electric energy consumption per unit weight of removed stone material (Z) and the resultant force per unit volume of removed stone material versus rotation speed, for the three diamond tools

The diamond tools consist of grinding wheels of 178 mm diameter containing 12 diamond segments of 14 mm thickness [3]. The segments were modified in their matrix to provide three different types of tools, always maintaining the same category (medium toughness index) and content of diamond grit (lower than 5% in weight). The diamond materials have all been supplied by Element Six.

Experimental results

Table 1 shows the values of Vickers hardness, yield strength and density for the three different matrices studied in the present work [3].

The results of the grinding tests are summarised in Fig 3. The ratio Fr/V (resultant force divided by the volume of stone removed V) is used to allow a better interpretation of results, taking into account that the volume of stone removed in each grinding operation can be slightly different for each set of tests. Considering the specific condition in which the test is made, the ratio F_r/V has been used instead of the resultant force divided by the area affected in the grinding operation. In our opinion it is more representative to use a real output parameter such as the volume (by means of dividing the weight of removed stone material by its density) instead of using an estimated value of the area where the force is distributed. Moreover, this works aims to focus on the relation of simple output parameters that can be easily assessed by industrialists.

Discussion and conclusions

Taking into account that the results shown so far are part of a more complex and detailed experimental work, the following discussion will be divided in several items, which will try to embrace the majority of the experiments made by the research group in this field.

In order to validate the test methodology presented in this work, the output parameters (energy consumption and resultant force) have been tested against each other, allowing verifying the correlation. The relationship between the energy consumption (E) and the resultant force (F_r) using constant grinding parameters

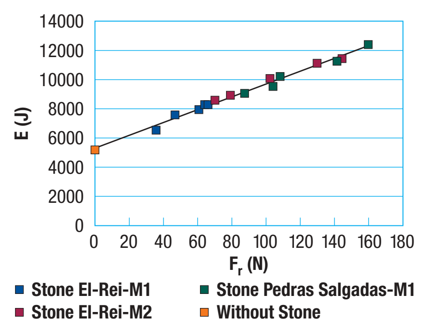

Fig 4 Relationship between the energy consumption and the resultant force in two types of stones and two types of tools (M1 and M2). Grinding parameters: 1500 rpm (rotation speed); 10 mm/sec (feeding speed); 1 litre/min (water flow). Data correlation coefficient R = 99%.

(rotation speed, feeding speed and coolant flow) has been achieved by increasing gradually the grinding depth, in two types of stones and two types of tools. The results are depicted in Fig 4 and, as far as it is possible to observe, there is a linear relation between these two parameters, and, as it was expected, the energy consumption increases with the increase of the force. It was also verified that when a test is conducted without a stone test-piece (i.e. $F_r = 0$), the measured energy consumption is 5100 J (also shown in Fig 4). This is explained by the fact that energy consumption measurements are made exclusively in the tool rotation motor, and the simple fact that the tool is rotating during the time needed for a test (about 14 sec) is enough to achieve that value of energy consumption.

Considering the results pointed out in Fig 3, it is possible to confirm that at 1000 rpm the resultant force per unit volume of removed stone material is higher than at the other two rotation speeds. This can be explained by the decrease in the rate of diamond particles that pass through a certain cutting area (surface) using 1000 rpm, for a given feeding speed. Following this idea, it is natural that higher forces will result in higher tool wear rates. This conclusion has been recently demonstrated during field tests, although no suitable relation between tool wear and resultant force is yet available at public domain.

On the other hand, the specific energy consumption is higher at 2000 rpm – since it becomes necessary to provide more energy for performing the grinding work – but the F_r/V ratio does not differ significantly from the value obtained at 1500 rpm. It might be possible to say that at 2000 rpm the system is using more energy than the one exclusively needed to perform the grinding operation. Moreover, at 2000 rpm there is no significant change in the resultant forces compared to 1500 rpm. The analysis of these two parameters (F_r/V and specific energy consumption Z) allows concluding that, using these types of diamond tools and working conditions, the 'optimised' rotation speed will be around 1500 rpm. This conclusion gives an additional advantage for this system because it allows the tool producer to establish optimum processing parameters that suit the stone processor needs.

Comparing the three tools in terms of Z and F_r/V (Fig 3), it could be stated that tool M3 (i.e. using matrix M3) is capable of doing the same grinding work (same volume of stone removed) using less energy, which consequently results in lower forces. In this sense, the main conclusion is that tool M3 will be the best diamond tool for grinding the ornamental stones used in this work, considering the previously mentioned grinding parameters. Moreover, if one considers that resultant forces are directly related with tool wear rate, this conclusion is also supported in terms of tool consumption.

For the four types of stones used in this work, the performance of tools M1 and M2 is very similar (similar results of Z and F_r/V). These tools consume more energy and generate always higher process forces than tool M3. To explain this fact it is better to observe the mechanical properties of the matrices presented in Table 1. The conclusions are obvious: matrix M3 has the highest values of Vickers hardness and yield strength, and the matrices M1 and M2 do not differ significantly in these two important mechanical properties. In tools with the same type and amount of diamond grit, the mechanical properties of the matrices may have a strong influence on the grinding behaviour of the tool. Furthermore, it seems that hardness is the matrix mechanical parameter that has more influence in the grinding behaviour of the tool.

The results at 1500 rpm allow pointing out that, for the tested stones, matrices with analogous hardness values around 180 HV5 (matrices M1 and M2) differ approximately 17% in energy consumption from matrices with hardness values around 230 HV5 (matrix M3). However, this same conclusion is not possible to observe using the F_r/V relations at 1500 rpm. The results clearly show that values of F_r/V change dramatically when the granite stone is processed. In fact, this change of behaviour was also observed for matrices M1 and M2 using quartzite stone, demonstrating that these specific types of matrices are not especially adequate for these types of granite and quartzite stones. Nevertheless, matrix M3 shows a very fair behaviour in grinding the quartzite stone. This can be partially attributed to the nature of the stone (far from being isotropic) and to the nature of the matrix material. Matrix M3 was found to have higher values of impact energy (as reported in [7]). ◆

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