Diamond wire cutting of marble: state of the art, modeling and experiments with a new testing machine

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Abstract

The use of diamond wire has been the standard industrial practice in excavation for over three decades, however only few researchers have devoted a systematic approach to understand, model and optimize this peculiar cutting process, and only in the case of granite. In addition to slabbing of stones, this technology is of interest for the construction and demolition industry. The typical configuration of diamond wire cutting in a quarry, with a cinematic scheme and the typical parameters are included in the paper. Experimental and theoretical models are examined and some initial results are also provided. Tests have been carried out on a special laboratory machine, developed within a national project, whose architecture is described.

Keywords: Diamond beads, marble sawing, stone processing

1 INTRODUCTION

The use of diamond wire has been the standard industrial practice in excavation for about three decades, affecting considerably the production rate and efficiency. Despite the widespread use of quarry and stationary diamond wire saws only few literature [1] [2] [3] is available. The process parameters depend on the tool type and are material specific: in [4], statistical models for the diamond bead wear prediction for different stone types based on field and laboratory data are proposed in the case of horizontal and vertical cutting separately. In addition to excavation and slabbing of stones (marble, granite, sandstone, etc.), diamond wire is used to cut hard materials such as steel pipes in the offshore industry [5], concrete and reinforced concrete in the construction industry [6] and in controlled demolition [7].
The University of Pisa has been cooperating with the marble district of Carrara [8] [9] [10] and is currently carrying out a national project [11] [12] [13] on cutting by diamond tools.

1.1 Diamond wire cutting

While in some developing countries, manual tools on a large scale and explosives are still current, diamond wire for stone cutting is a non-destructive technology, with high geometrical accuracy and surface finish, and with minimum material waste. The principle behind diamond wire cutting [14] [15] involves pulling a continuous loop of

wire mounted with diamond bonded steel beads (Figure 1). The combination of pulling by a constant force and spinning (the wire is torsionally pre-charged during setup) a path is cut through the stone.
In stone quarrying (Figure 1), the initial step for making a *primary* vertical, and less often a horizontal cut, is to drill two perpendicular intersecting holes, by a pneumatic drilling machine with a down-the-hole hammer. The diamond wire, usually between 50 and 100 m in length, is then threaded through these holes, mounted around the drive

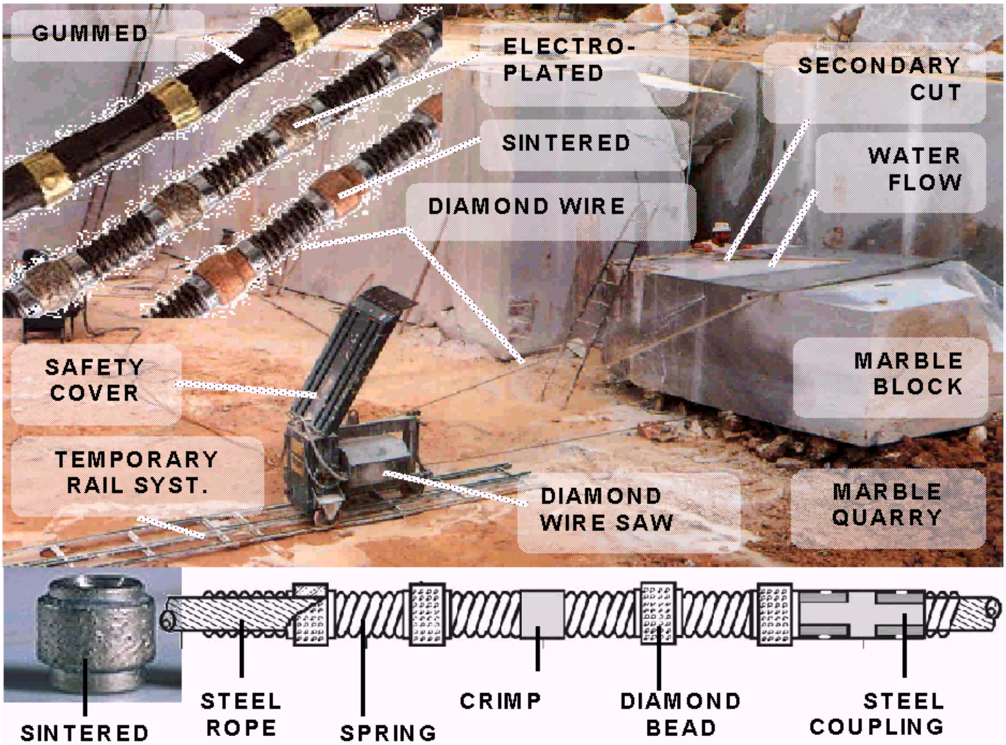

Figure 1. Diamond wire cutting of marble in a quarry. Examples of the two diamond bead types (sintered and electroplated) and of the traditional and *gummed* diamond wire (top left). Detail of the main components

wheel of a diamond wire saw (40 - 60 kW with electric motor and up to 90 with diesel engine), and the two ends are clamped to form a continuous loop (Figure 1 bottom right). On most machines, the drive wheel can be set at any angle, from vertical to horizontal. Additional pulleys may be present for more complex cutting path geometry (Figure 2). After the startup phase, the cutting geometry can be approximated to a circle of gradually decreasing radius.

As the cut progresses, the machine moves backward along a temporary rail system to keep the wire tension constant [16]. This is usually achieved with a control on the absorbed current. On higher cost machines, the flywheel-motor group is driven by an inverter to have an adjustable cutting speed. The Italian laws impose a limit at 40 m/s for safety reasons (even mortal accidents occurred, due to wire breaks). The typical wire speed range for marble is 30 - 40 m/s and 15 - 30 m/s for granite. As the rail end is reached, the machine is returned to its starting point and the wire length is reduced accordingly. Water flowing in the wire direction is used as a coolant and to remove the cut stone powder. Diamond wire saws with lower power (20 - 40 kW) also operate in quarries for *secondary* cuts on blocks and are used in the construction industry, with shorter wires (15 - 20 m). Stationary diamond wire saws for block squaring and

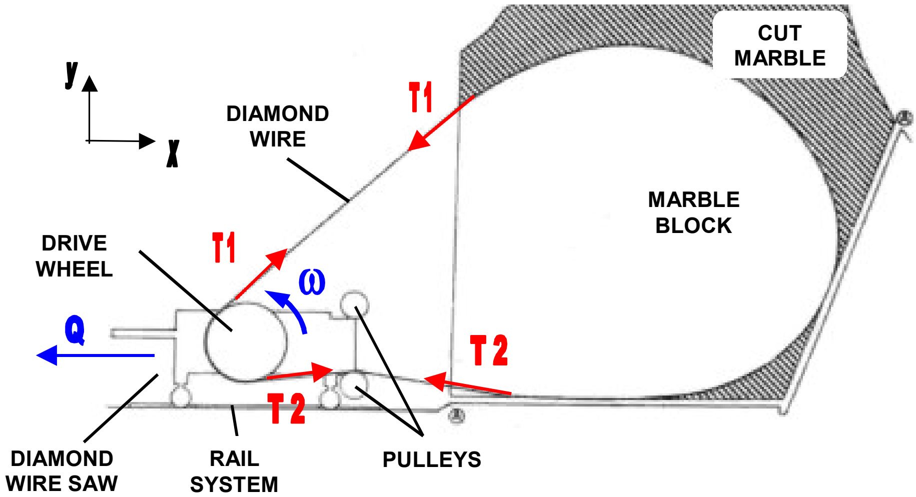

Figure 2. Scheme of diamond wire cutting, process parameters and forces decomposition

slabbing, profiling, etc. operate on the same principle but with different machine configurations.

The diamond wire (Figure 1) is a steel cable with equally spaced steel beads bonded with diamond abrasive. Two diamond wire types exist:

- the traditional wire for marble cutting. Bead diameter ranges between 8 and 12 mm respectively for profiling and extraction/squaring. They are assembled over a stainless steel rope. Preloaded steel springs keep spacing at about 25 mm between beads;
- the so called *gummed wire* has been designed for granites cutting, having in mind efficiency and safety, because the plastic coating protects the wire from the hard granite cut powder. Diamond beads are assembled over the cable in a plastic matrix injected at high pressure.

There are about 28 - 34 and 34 - 40 diamond beads per meter respectively for marble and granite cutting. Crimps are also present every 3 - 5 beads to prevent unthreading in case of wire breaks and are not necessary for gummed wires, which are also considered safer. The traditional wire allows a better flowing of the coolant water, a lower cost, and easier assembly (directly in the quarry). The productivity ranges between 6 and 15 m^2/h (1 to 5 for granite), and the wire duration is about 20 - 50 m^2/m (2.5 to 8 for granite), both depending on the stone.
Diamond tools are necessary because stones are very hard (up to 7,000 MPa micro-hardness Knoop for Labrador granite) and can operate at higher cutting speeds, thus increasing productivity.
Diamond beads provide the actual cutting action. Their shape is like a bushing (the support) with a mix of diamond grains and a metal binder brazed along the lateral surface (for *sintered* diamond beads). Binders include cobalt and copper, bronze, nickel, silver, and chrome. An alternative diamond bead type is *electroplated*. In this case, only one layer of diamond grains is present, so they cannot be renewed when they become blunt. They are distributed as the cathode in a galvanic process, where the metal binder is the anode. The layer thickness is in the order of the diamond grit, with protrusions over the binder surface of about 30 - 50% of the maximum grain dimension.
The metal binder has several functions: controlled release of worn grains, heat dissipation and shock absorbing.
Synthetic diamond grains have preferred features with respect to the natural ones: lower cost, higher availability and polycrystalline structure, which allows the generation of always new cutting profiles after breakage. The mesh size ranges between 20 and 50. Of course, the higher the size, the higher the protrusion, and consequently the removal rate, but also the cost is higher.

2 THE TESTING MACHINE

The selected approach is to simulate diamond wire cutting in controlled conditions. Considering the difficulty of collecting data with the actual industrial machines and using the wire in a quarry (§ 1.1), we have focused our attention on a single diamond bead. The idea of building a test machine for diamond beads is not new and different configurations have been tested [1] [2]. A new improved (five-axis) machine (Figure 3) has been developed in this project [11] to determine the impact of the main process parameters and tool features on productivity and costs. Our attention will be focused particularly on the theoretical interpretation of the wear phenomena of multiple cutters tools, such as diamond beads.
An amount of experiments will now be possible with such automated and fully sensorized machine. Experimental and theoretical models are being proposed (§ 3) and some initial results will also be provided in (§ 4).
The machine working principle is described in Figure 4. The workpiece is a disk made of stone with diameter up to 300 mm and width up to 50 mm, with adjustable rotation

speed. Grooves are then created on the disk to make disks of smaller width. These latter are cut individually to allow a correct interaction between the workpiece and the lateral surface of the diamond bead and to prevent rubbing at the diamond bead ends. For this reason, the disk width is slightly smaller than the diamond bead width.
The bead wear depends on the following main process parameters: pulling force (Q in Figure 2) and wire speed. Both are controllable on our testing machine (Figure 4). The relative normal force between diamond bead and workpiece surface is directly controllable on our testing machine and it also acts as feeding force. The relationship

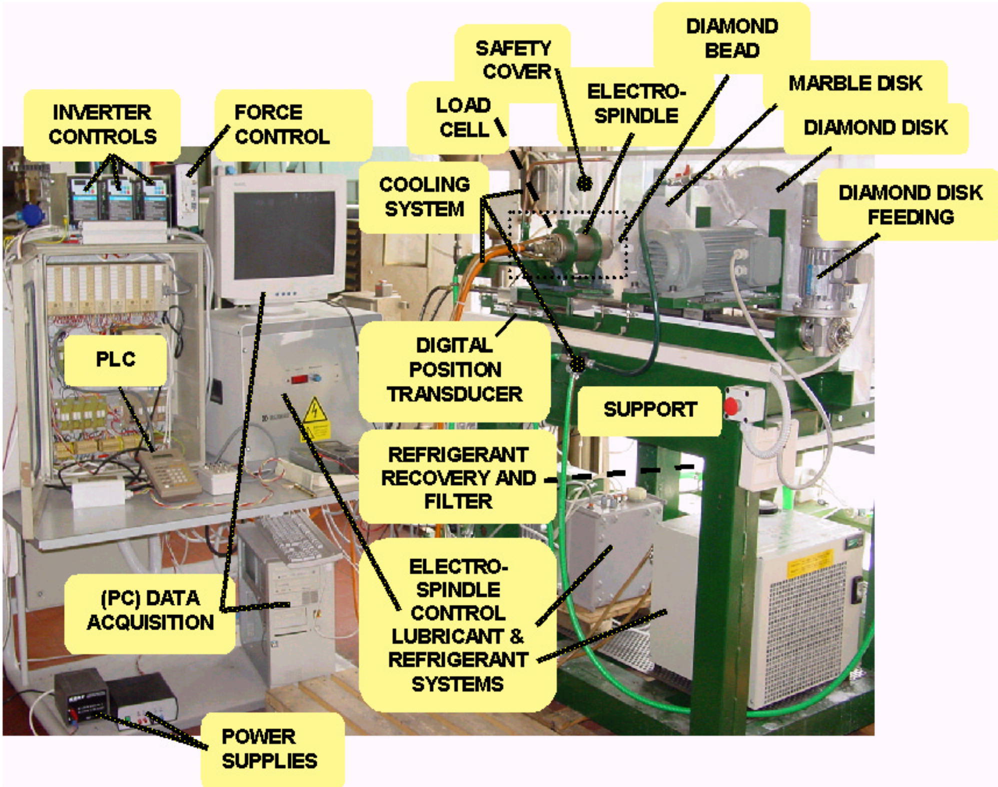

Figure 3. Overview of the developed prototype of diamond bead testing machine

between pulling force and feeding force is shown in Figure 2. The cutting speed depends on the relative angular speed between the rotating workpiece (negligible) and the counter rotating diamond bead mounted on a high-frequency electrospindle (Figure 4).

2.1 The testing conditions

The main benefit of testing a single diamond bead is the greatly reduced amount of work material, as it can be easily estimated from the data in § 1.1. Also the test time is reduced because the diamond bead is always working.
The real displacement direction of a diamond bead in diamond wire cutting is axial. In our machine the diamond bead rotates about its axis, but this should not affect the generalization of results, considering the anisotropy of both the metal binder and the diamond grain distribution.
Cooling water is directed towards the diamond bead, which is completely submerged as in the real conditions.
Diamond beads are uniformly worn out only, if spinning is correctly induced by the

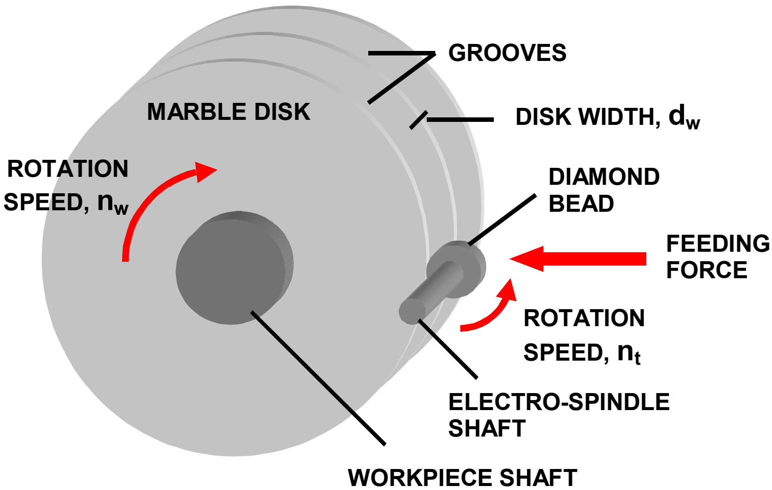

Figure 4. Working principle of the diamond bead testing machine

wire torsional pre-charge. The industrial practice have shown that if diamond beads are worn out on one side because they do not start spinning, afterwards they tend to oppose to spinning more and more because this configuration is stable: slipping on the worn side dissipates the minimum energy. In this sense, the diamond bead life can be overestimated.
The extension of results for a single diamond bead to cutting by diamond wire is not automatic. The following aspects can be included in future versions of our model.

- The cutting force of a single diamond bead changes smoothly along the arc of contact between wire and stone (Figure 2).
- The contact surface in real cutting is represented by half of a cylinder: the bottom of the groove digged through the stone. Not all the surface is submitted to a

normal force. On our testing machine, the contact surface is theoretically reduced to a limited lateral surface. The load distribution is more uniform, but the active surface is smaller.

- The feeding force produces different specific loads on the diamond bead for disks of different width.
- The feeding force F selectable on our testing machine needs to be correlated with the corresponding force T and finally with the force Q (Figure 2), controllable on the real machines considering the pressure distribution resulting from the above contributions.
- Different direction feeds with respect to the marble disk are possible on the machine: circumferential (as in current experiments) and radial.
- Diamond beads with special shape (e.g. tapered) need adaptations.

3 MODELING

In § 1 it has been shown that only few attempts of modeling diamond wire cutting are available. The wear rate of the diamond bead is a major parameter affecting the operating costs in a marble quarry, so a predictive model would be of great interest. Considering the long setup time of diamond wire, higher tool life is also desirable to reduce machine downtime. Among the main benefits of modeling is optimization of the process parameters for different diamond beads and work material; it can also be thought of developing material specific (*ad hoc*) diamond beads. Optimization implies the maximization of the material removed before reaching a certain tool wear or the cost minimization to remove a given amount of material.

3.1 Cinematic definitions

Given

R_t	:	diamond bead (*t*ool) radius [mm]
R_w	:	stone disk (*w*orkpiece) radius [mm]
V_t	:	*t*ool wear velocity [mm^3/s]
V_w	:	material (*w*orkpiece) *v*olume removal velocity [mm^3/s]

with the working scheme adopted (§ 2), the cutting cinematic can be represented as shown in Figure 5. It can be observed that the tool (diamond bead) and the workpiece (marble disk) radius decrease along the contact area respectively by

$\Delta R_t = R_{t1} - R_{t2}$
$\Delta R_w = R_{w1} - R_{w2}$

From Figure 5, by simple trigonometric considerations, the dependence of ΔR_w on the cutting geometrical parameters can be expressed as

$\Delta R_w = R_{t2}(1 - \cos\alpha_t) + R_{w1}(1 - \cos\alpha_w) + \Delta R_t$

This latter term (ΔR_t) is negligible in first approximation. ΔR_w is directly measured on the machine, as explained later.
The material removal velocity can be expressed as a function of ΔR_w and

d_w	:	marble *d*isk *w*idth [mm]
b_w	:	diamond *b*ead *w*idth [mm]
n_t	:	diamond bead (*t*ool) rotation speed [rpm]
n_w	:	marble disk (*w*orkpiece) rotation speed [rpm]

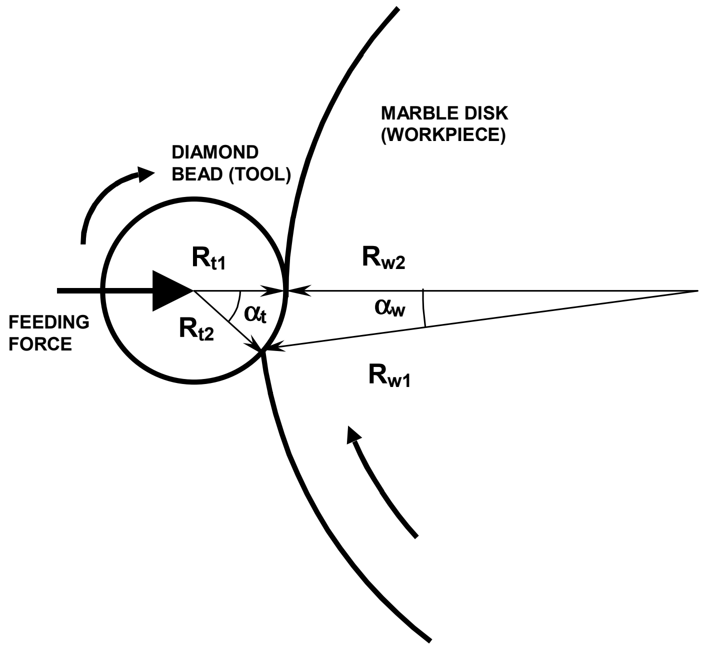

Figure 5. The cutting cinematic with the developed machine

$$V_w = 2\pi \cdot \overline{R}_w \cdot \Delta R_w \cdot d_w \cdot \frac{n_w}{60}$$

where upper-lined stands for *average*. n_t and n_w are constant for each experiment. In addition, the average material removed per unit of time can be experimentally evaluated on the machine with periodical measures of R_w. In practice, V_w can be directly calculated by measuring the workpiece *b*efore (R_{wb}) and *a*fter (R_{wa}) i disk revolutions from

$$V_w = \pi\left(R_{wb}^2 - R_{wa}^2\right)\cdot d_w \cdot \frac{n_w}{60\cdot i}$$

The actual (relative) cutting speed S [mm/s] is given by

$$S = 2\pi\left(\overline{R}_t \cdot \frac{n_t}{60} - \overline{R}_w \cdot \frac{n_w}{60}\right)$$

As the cut progresses, the relative cutting speed changes for the tool and workpiece radius decrease, depending on the relative sense of rotation. The minus sign comes from the case of counter rotation (as in our experiments). In first approximation S can be considered constant for the whole experiment, because the second term is negligible: with the parameters used, in the worst case, the ratio between the first and the second term is greater than 200.
The diamond bead wear per unit of time can also be experimentally evaluated on the machine with periodical measures of period Δt of R_t

$$V_t = 2\pi\cdot\overline{R}_t \frac{\Delta R_t}{\Delta t}\cdot d_w$$

d_w has been used considering that in experiments marble disks (Figure 4) with the following width are used

$d_w \leq b_w$

3.2 Wear parameters

Diamond beads have a similar behavior as other diamond tools, so the same parameters can be used to assess their performance in terms of wear and removal rate.

W_r	:	Wear rate [µm/min]
G	:	Grinding ratio
W_p	:	Wear performance [m^2/µm]

From the above

$$W_r = \frac{\Delta R_t}{\Delta t}\cdot 10^3$$

$$G = \frac{removed\_material\_Vol.}{wear\_Volume} = \frac{V_w}{V_t}$$

$$W_p = \frac{\overline{V}_w}{W_r \cdot d_w} \cdot 10^{-6}$$

where $\overline{V}_w$ is the average of the removal velocities during the time interval Δt.

3.3 Experimental model

A wear criterion can be considering a diamond bead as worn out when it removal ability is reduce to 1/n of the maximum, where n should be fixed depending on the industrial practice. Consequently the total duration T and the removed material Q for a diamond bead can be expressed as a function of the main process parameters V_{rel} and F

$T = f(F,V_{rel})$
$Q = f(F,V_{rel})$

From the decrease of the diamond bead radius and the removed material volume, the parameters W_r, G and W_p above can be measured and expressed as a function of time. For sintered diamond beads, a long constant interval is expected for the function

$G = f(t)$

3.4 Analytical model

A similar model proposed in the project [11] by another working unit for diamond tools can be applied to sintered diamond beads and is described here.
From the diamond granulometry, expressed as US mesh, the average grain diameter ADPD can be obtained, as indicated in [17].
The maximum ideal grain protrusion P_{max}, which represents the maximum theoretical height of a new grain from the matrix before its ejection, e.g. 1/2 APDP, and P(0), the grain protrusion at the beginning of its action, e.g. 1/4 ADPD should be fixed.
An abrasive grain starting its action at the time t_0 with protrusion P(0), will reach his maximum theoretical protrusion and will be ejected at time t_0+t*. So the value of t*, is the active time for a single grain. During this time, the diamond bead radius diminution is P_{max} - P(0), so

$$t^* = \frac{\left[P_{max} - P(0)\right]}{W_r}$$

Considering that for diamond beads with the same matrix, granulometry and abrasive type, higher diamond concentration produces higher t*, testing diamond beads with

different diamond concentration C allows estimating the ratio $\frac{\Delta t^*}{\Delta C}$ and consequently predicting t* for diamond beads with different concentrations, thus optimizing the overall cost.
It can be demonstrated that

$$G = K\,t^*$$

Constant K can be experimentally estimated and used to predict the performance of diamond bead with different grain concentrations. The parameter G can also be used for the cost optimization.

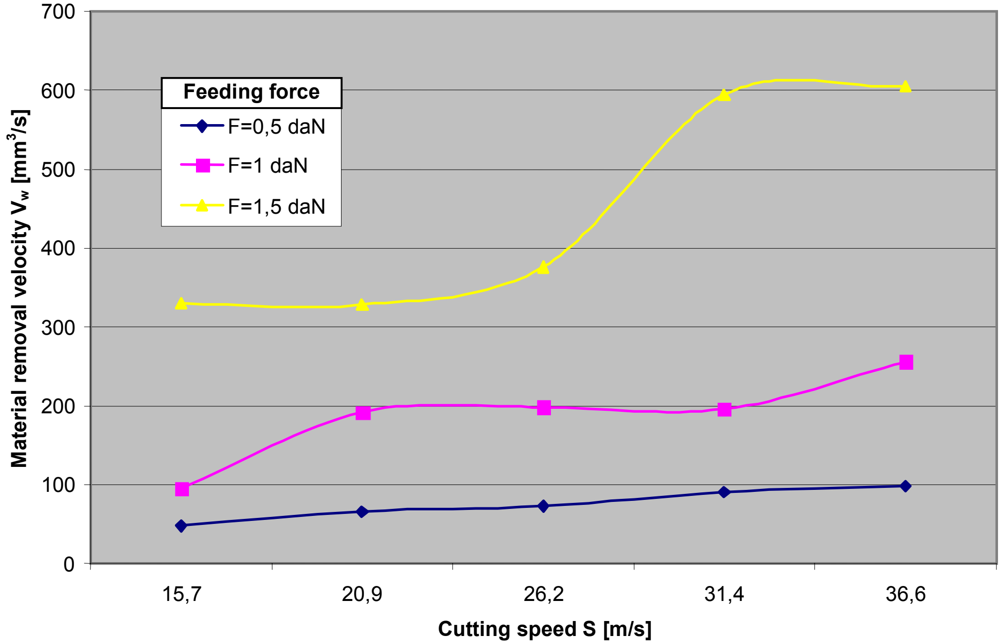

Figure 6. Cutting data for electroplated diamond bead on the testing machine

4 RESULTS

In this paragraph we will discuss the preliminary results obtained with the developed testing machine. In this first set of experiments we evaluate the initial efficiency of new diamond beads as a function of the main process parameters: cutting speed and feeding force.

Electroplated diamond beads (model T.3540, ∅ 10 mm) have been used because their wear is associated to a very small radius reduction.
Considering their high rotation speed (between 30 and 70 thousand rpm by increments of 10 thousand), also the disk rotation speed can be neglected, and consequently the (relative) cutting speed mainly depends on the diamond bead rotation speed.
Six marble disks (d_w = 4.5 mm) have been cut. The cutting time ranges between 5 and 20 min. The period of acquisition of R_w is 80 s. n_w = 8 rpm.
In Figure 6 the material removal velocity V_w is expressed as a function (increasing, as expected) of the cutting speed S for different values of the feeding force F.
The estimation of W_r, G and W_p will be included in next papers, related to tool life on different diamond bead and work material types.

5 CONCLUSIONS

A theoretical and an experimental model of diamond wire cutting have been presented.
Preliminary tests have shown the good performance of the new developed machine for bead testing. Its intended use is twofold: process modeling and optimization, as it is being done in this project [11], and commercial exploitation. The stone community does not yet share common practices, standard methods or equipment to assess the performance of beads made of different materials and in different working conditions. So, in this regard, a direct interest from machine manufacturers (as producers) and tool manufacturers and certified laboratories (as final users) is expected.
Further activity includes testing different models and types (sintered) of beads and other stone types (Coreno marble and granites).

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