Diamond wire cutting of cast iron

Tantussi G., Lanzetta M. and Romoli V.
Università degli Studi di Pisa, Dipartimento di Ingegneria Meccanica, Nucleare e della Produzione, Via Bonanno Pisano, 25/B, 56126 Pisa
(tantussi, lanzetta, romoli)@ing.unipi.it

Abstract

Diamond wire has been the standard industrial practice in stone excavation for over three decades now. Today new applications in the construction and controlled demolition industry are emerging, which involve the cutting of metals and sometimes diamond wire seems the only viable solution. Diamond tool life cutting metals is about one order of magnitude lower than stone, so a better knowledge of this process is of direct industrial interest. In this paper we report the main results of experimental tests for a cylindrical and a tapered electroplated diamond bead cutting cast iron UNI G250. Experimental data to estimate the optimal process parameters and predict tool life are reported and an experimental model is presented. In addition a new tool wear criterion and a new standardized testing method for diamond bead cutting of cast iron and to compare the performance of different diamond bead types are described.

Keywords: Diamond bead, metal cutting model, tool wear, tool life, testing machine

1 INTRODUCTION

The diamond wire technology was first developed during the sixties in Italy, where it is mainly based. Diamond wire is the standard industrial practice in stone excavation. After the growing China, Italy is the main exporter of raw stone, with about 10 million tons, for a world estimated production of 80 millions (2003) [Source: Internazionale Marmi e Macchine Carrara S.p.A.].
This activity is addressed to a very active international market, which includes machine and tool manufacturers. The main purpose of this study is to support the local and national leadership in this field for broadening the application of the diamond wire technology in new fields.
Although the potential of diamond wire cutting of stone, particularly marble and granite, is consolidated in industry, few knowledge is available in the literature [5], particularly regarding metal cutting [1] [2] [3].
Among emerging applications is controlled demolition of concrete and reinforced concrete structures [1] [4] in the civil engineering industry.
Current machines in this field are simple-, small-, low power-devices and can be easily moved to drive diamond wires of almost any length and configuration [5]. This makes the technology suitable for a whole new range of applications in manufacturing, de-

manufacturing, maintenance etc. [2], where accessibility is critical and it is necessary to cut large metal objects into smaller parts, like large pipes, tanks, heat exchangers, reactors, in the nuclear [3], off-shore [4], chemical industry etc. and sometimes diamond wire seems the only viable solution.
Large metal structures of industrial machines and plants are often made of cast iron, which has been selected as target material in this first study.

2 EXPERIMENTAL

In a previous paper [5], an overview of diamond wire cutting of stones has been provided. The article also describes a special machine for testing diamond beads, which is used in this study (with minor adaptations).

2.1 Testing methodology

In the actual cutting process, the material removed and the diamond bead wear depend on the following main process parameters: pulling force and wire speed. Both are controllable on our testing machine.

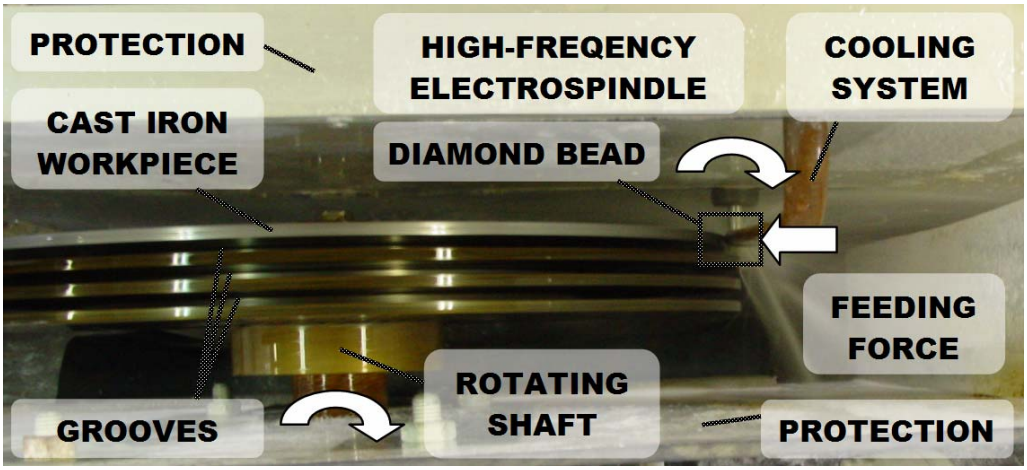

Figure 1. Cinematic configuration of the diamond bead testing machine. Top view.

Figure 1 shows the experimental setup.
The relative normal force between diamond bead and workpiece surface also acts as feeding force. The cutting speed depends on the relative angular speed between the

rotating workpiece (8 rpm) and the counter rotating diamond bead mounted on a high-frequency electrospindle (36600 to 49200 rpm).

2.2 Cinematic definitions

We define

R_t : diamond bead (*t*ool) radius [mm]
R_w : metal disk (*w*orkpiece) radius [mm]
V : material (*w*orkpiece) *v*olume removed [mm^3]
d_w : metal *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]
$\overline{R}_t$ and $\overline{R}_w$ are the average tool and workpiece radius in a given test.

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

Table 1. Experimental conditions tested.

Cutting speed, S [m/s]	Feeding force, F [N]	Specific pressure [N/mm^2]
19	9	4,8 to 8,9
26	18	5,45 to 11,9

be considered constant for a single 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.

2.3 Cutting conditions

Cutting tests have been carried out for the conditions reported in Table 1. The upper specific pressure is limited by current testing machine.
Outside the experimental conditions tested it has been observed that:

- at lower cutting speed and cutting force, the removal rate was excessively low;

- higher cutting speed produced sparks, so excessive wear was expected due to thermal effects. In particular, over 500° C graphitization occurs [2];
- the specific pressure achieved seems already higher than that found in the literature [1] [2], although an upper threshold still needs to be detected.

Figure 2 shows the arc of contact between tool and workpiece, whose estimation

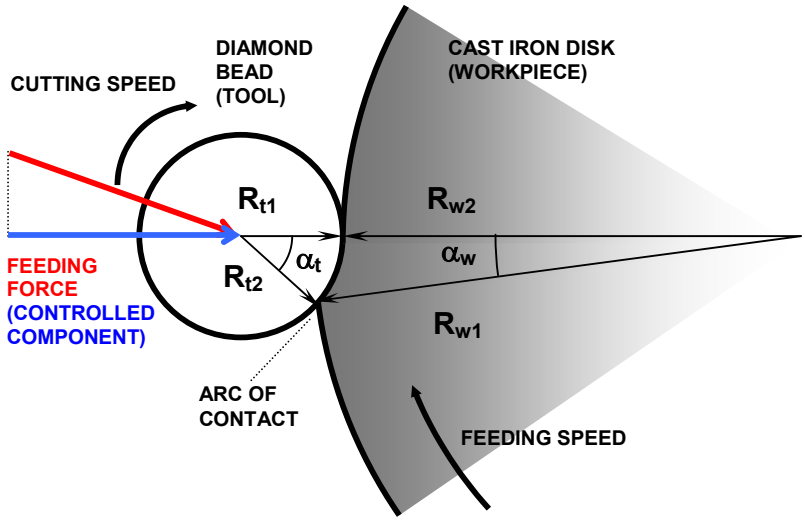

Figure 2. Detail of the interaction between diamond bead and cast iron disk. Section on a plane perpendicular to the tool and workpiece axes. Angles α_t and α_w are exaggerated.

allows to determine the specific pressure from the feeding force, which is provided by the testing machine.

The average duration of tests is more than one hour.

We assume the following hypotheses:

- The pressure is considered to be uniformly distributed across a small surface of contact (Figure 2), which is approximated to a plane in calculations reported in in Table 1.
- The normal force (Figure 2, horizontal component, blue) is kept constant and measured by the testing machine.
- The tangential force (not displayed) is not measured and considered in our model.

The workpiece radius R_w is sampled on the machine at a minimum frequency of 10 Hz. It is indirectly monitored by the tool axis displacement.

From the cinematic shown in Figure 2, it can be observed that the tool (diamond bead) and the workpiece (metal 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 2, by simple trigonometric considerations, the dependence of ΔR_w on the cutting geometrical parameters can be expressed as

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

ΔR_t is negligible in first approximation. This is particularly true in the case of electroplated diamond beads, where the abrasive material is distributed on the lateral surface only. According to measurements, ΔR_t is in the order of some hundredths of a millimeter (Figure 8).

Figure 3. A new cast iron disk with three grooves (left) and before preparation (right). The axial hole is for mounting on the testing machine.

Figure 5 and Figure 4 show two examples of cutting data. More than eight tests have been carried out.

2.4 Tool and workpiece characterization

Several diamond bead types are available on the market. Tests have been carried out using two commercial diamond bead types. These tools are indicated by the

manufacturer for cutting reinforced concrete. The tool features (Table 2) are not known or published by manufacturers and have been measured in our laboratory. The shape of diamond grains is polyhedral.
Sintered diamond beads have not been used, because of their low efficiency cutting metal. The grit concentration on the surface of sintered diamond beads is lower because the grit, instead of coating the surface as for the electroplated diamond beads and protecting the binder (about 1,5 mm thick), is dispersed inside it: the cut material (metal) acts on the tool binder (metal) and causes the premature release of still unworn diamond grains [1] [2].

Table 2. Properties of the diamond beads tested.

Diamond bead	Model	Ext. Ø [mm]	d_w [mm]	Grit density per mm^2
CYLIND.BEAD	AZ/35/GCS	10	5	8,36
TAPERED.BEAD	Laser/40/GRC	9,6 to 10	5	8,56

The workpiece (Figure 3) is made of cast iron UNI G250 and has a disk shape Ø 300 mm × 35 mm. Grooves perpendicular to the disk axis are created because diamond beads are only able of cylindrical cutting (Figure 2).

3 MODELING

At the beginning of a new cut, the diamond bead progressively indents the workpiece over a relatively short time: this phase should end before a complete workpiece revolution (usually in less than 10°), for stability reasons. The disk speed is selected accordingly. Indentation progresses until the feeding force (Figure 1), which is controlled in closed loop on our machine, is balanced by the disk reaction. We define the indentation as ΔR_w (Figure 2). After a complete workpiece revolution a new indentation is produced, so the cut progresses at steps of length ΔR_w.
Recalling Figure 4 and Figure 5, given R_w, the volume removal rate and the total volume removed can be numerically derived.

The material removed in one revolution V_{1rev} [mm^3] can be expressed as a function of ΔR_w as

$$V_{1rev} = 2\pi \, \overline{R}_w \cdot \Delta R_w \cdot d_w$$

where upper-lined stands for *average*. 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_{1min} [mm^3/minute] can be directly calculated by measuring the workpiece *b*efore (R_{wb}) and *a*fter (R_{wa}) i disk revolutions from

$$V_{1min} = \pi\left(R_{wb}^2 - R_{wa}^2\right) \cdot d_w \cdot \frac{n_w}{i}$$

Usually $d_w \leq b_w$.

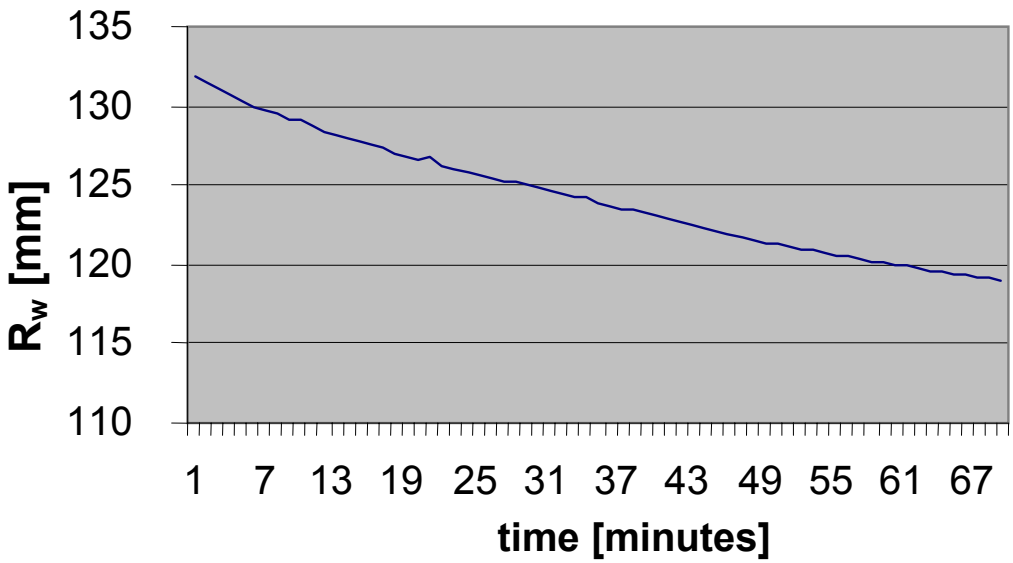

Figure 4. Test 2c (Table 3). Cutting data for a cylindrical electroplated diamond bead. The testing machine output displayed shows the workpiece radius reduction in a 1 hour test at a cutting speed of 19 m/s and with a feeding force of 18 N.

The observation of the volume removed in the graphs of Figure 4 and Figure 5 suggests modeling it according to the following exponential law:

$$V(t) = V_\infty [1 - \exp(-\alpha \cdot t)]$$

where

V_∞ is the maximum theoretical material removed in an infinite time for a given set of testing parameters (cutting speed and feeding force) and
$1/\alpha$ is the time constant, that is the theoretical time for a diamond bead to remove about 63% of the maximum removable material.

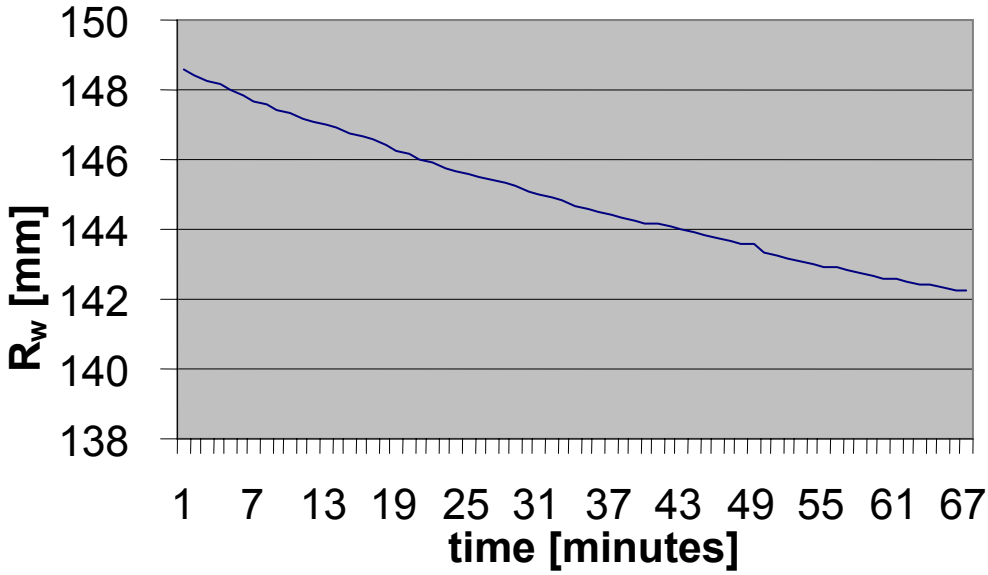

Figure 5. Test 3t (Table 3). Cutting data for a tapered electroplated diamond bead. The testing machine output displayed shows the workpiece radius reduction in a 1 hour test at a cutting speed of 26 m/s and with a feeding force of 9 N.

Table 3. Assessing V_∞ and α by regression for tests for tapered and cylindrical diamond beads at different cutting speed S and feeding force F values.

Test #	S [m/s]	F [N]	Test Time [min.]	Material removed [mm^3]	V_∞ [mm^3]	Std. error	α [1/min.]	Std. error
1t	19	9	73	9857	14181	293	0,01552	0,00049
2t	19	18	60	35578	53196	765	0,01766	0,00037
3t	26	9	66	25991	44836	520	0,01322	0,00021
4t	26	18	81	61118	73574	594	0,02092	0,00031
1c	19	9	67	18340	29705	337	0,01413	0,00023
2c	19	18	68	45610	63430	1065	0,01854	0,00049
3c	26	9	75	13423	19712	669	0,01463	0,00074
4c	26	18	66	43689	61079	979	0,01878	0,00047

Regression has been carried out using more than 60 material removed data at intervals of one minute (by averaging the R_w values sampled as explained above) for each test and has shown a very good agreement with the hypothesized law, with a correlation coefficient always greater than 0,99. The estimations of V_∞ and α are displayed in Table 3, with the corresponding standard errors.

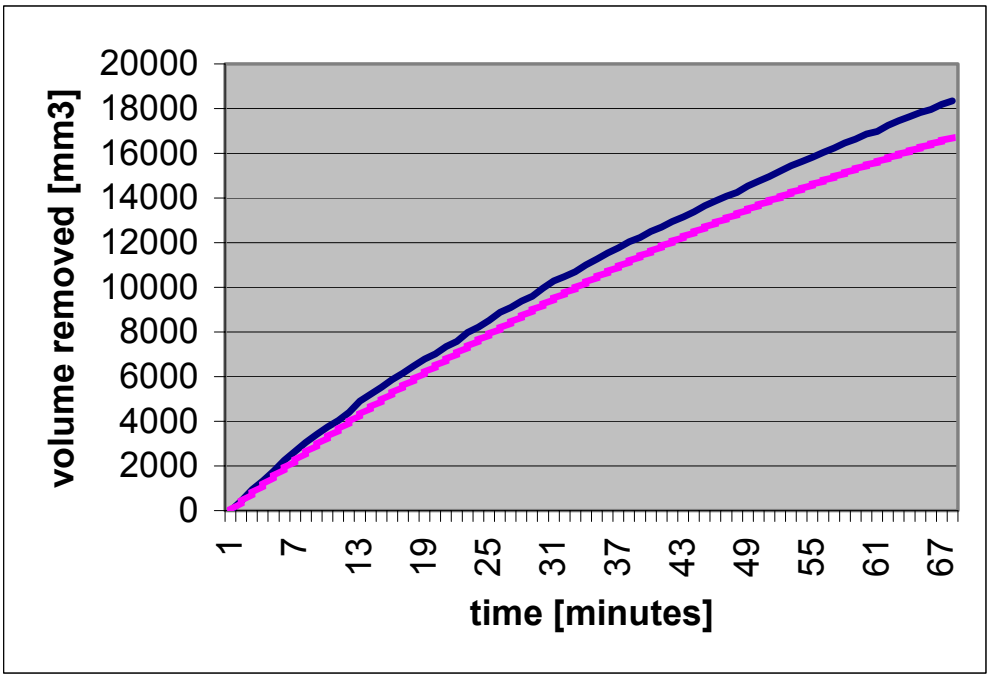

Figure 6. Test 1c (Table 3). The volume of material removed V(t) in a one hour test at a cutting speed of 19 m/s and with a feeding force of 9 N (blue solid line) and after regression (pink dashed line).

Further analysis to determine the influence of independent variables (diamond bead type, cutting speed and feeding force) has shown a non statistically significant influence of the diamond bead type and of the cutting speed.
Assuming a linear dependence of the parameters V_∞ and α on the feeding force F yields the following expressions:

$V_\infty = - 8603 + 3969 \cdot F$
$\alpha = 9775 \cdot 10^{-3} + 0{,}511 \cdot 10^{-3} \cdot F$

(The F-statistic for the two expressions above is respectively 20,283 and 29,839.) Consequently for a feeding force F of 9 N and 18 N respectively

$V_{9N}(t) = 27 \cdot 10^3 [1 - \exp(-0{,}0144 \cdot t)]$
$V_{18N}(t) = 63 \cdot 10^3 [1 - \exp(-0{,}0190 \cdot t)]$

with V expressed in [mm^3] and t in [minutes].

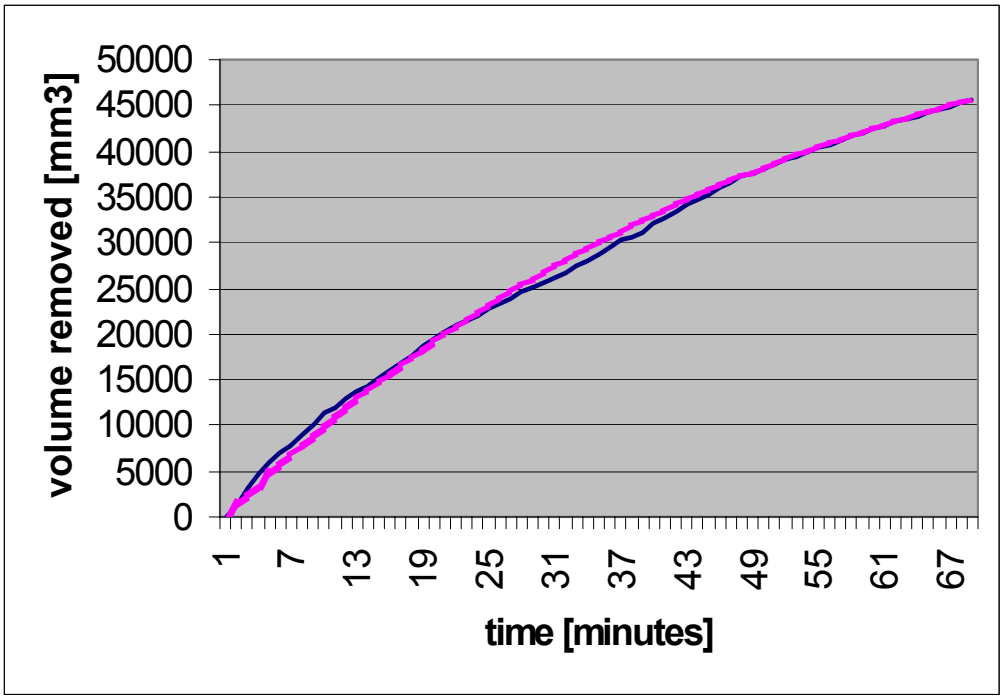

Figure 7. Test 2c (Table 3). The volume of material removed V(t) in a one hour test at a cutting speed of 19 m/s and with a feeding force of 18 N (blue solid line) and after regression (pink dashed line).

The error of this model with respect to the experimental data is less than 25% in 75% of the examined cases. This agreement is quite good considering the simple law used and that several parameters, such as diamond bead type and cutting speed, have not been included because non statistically significant.

4 TOOL WEAR AND WEAR CRITERION

The diamond bead wear rate is a major aspect affecting the operating costs, so a predictive model is of great interest. Considering the long setup time of diamond wire, higher tool life is also desirable to reduce machine downtime. 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.

When observing a new diamond bead at the optical microscope and after cutting the protrusion of small diamonds is reduced and they appear blunt (Figure 8).

In our model the tool wear is indirectly assessed based on the material removal ability. We propose a wear criterion based on the time required to achieve a given ratio: material removed versus theoretical removable material (V_∞). This ratio represents the exploitation of a new tool. Considering a ratio of 75%, the tool duration for a feeding force of 18 N turns out to be only slightly lower than for 9 N (72 minutes versus 96 minutes). On the opposite, the material removed is almost the double (47000 mm^3 versus 20200 mm^3). This also suggests a rule of thumb of 1 hour tool life.

A numerical expression or a graph like those in Figure 6 and Figure 7 allow determining the tool change cost and its optimization, for a given set of cutting parameters.

5 DISCUSSION

From the analysis of Figure 6 and Figure 7 it can be observed that:

- the maximum theoretical removable volume for a feeding force of 18 N is about the double of that for 9 N;
- the time constant $1/\alpha$, for F = 18 N is about 51 minutes versus about 69 minutes for F = 9 N.

From the above it can be concluded that a higher feeding force is desirable in order to achieve a faster material removal and a better tool exploitation. In other words we can say that a lower feeding force produces a lower removal rate but a comparable tool wear. In the examined range of parameters, the cutting speed, which is in the order of that currently used on the market, has no significant effect on the tool performance.

One of the benefits of our testing machine is that the diamond bead is always in touch with the workpiece, so the testing time is reduced as opposed to actual diamond wire cutting, where the contact is intermittent.

In the application of our model it should be noted that

- only the active cutting time should be considered to estimate the diamond wire change;
- the actual cutting direction is axial, while in our machine it is circumferential, so the actual tool life might be shorter for tool damages due to shocks when the tool enters the groove in the workpiece, although they are absorbed by the soft metal binder;

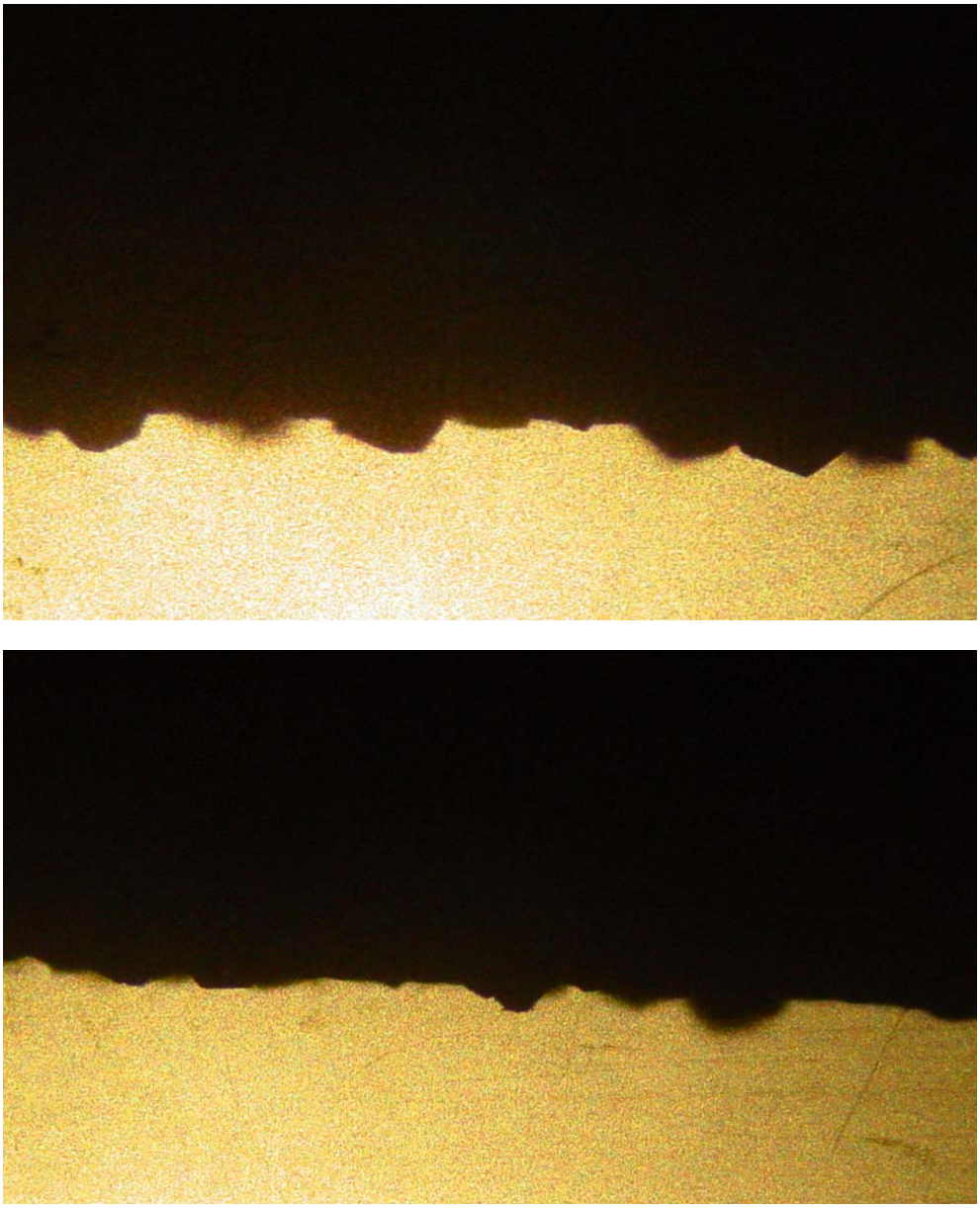

Figure 8. Profile of a new electroplated tapered diamond bead (top). After cutting for 1 hour (bottom), most diamond grains are still in place but they appear blunt (no breakage).

- considering that tapered diamond beads enter the workpiece groove more smoothly, our results are more conservative for those, with respect to the traditional cylindrical diamond beads.

The values predicted by our model assume a uniform wear of the tool surface, which might not occur in the real conditions if it does not spin as desired. This irreversible effect is however well known to operators and can be easily detected in process.
Considering the anisotropy of both the metal binder and the diamond grain distribution results seem valid, has experimented in the case of marble disks [5].
An abundant cooling water flow is directed towards the diamond bead (Figure 1) as in the actual conditions. Thermal effects are not considered in our model for the high efficiency of the cooling system. Of course the machine is not able to simulate the case of aquaplaning (no cutting).
The controllable parameters in industrial machines (diamond wire pull force and speed) can be determined with the simplified model in [5] from the cutting speed and pressure on a single diamond bead. It should be noted however that, while speed is constant, the pressure on single diamond bead changes across the arc of contact between diamond wire and workpiece.
The real volume removal rate is also determined by: wire length, number of diamond beads per meter and number of currently active diamond beads.
The correspondence between the pressure distribution on a small area during our tests and that on the larger contact surface (half of the axial surface) in real cutting is under study.

6 CONCLUSIONS

An experimental model of cast iron cutting by a diamond bead has been presented.
The experimental data obtained in this study are ready for use to estimate the optimal process parameters and tool life and have a direct industrial interest.
In addition a new tool wear criterion and a new standardized testing method have been proposed to compare the performance of different diamond beads for cutting cast iron.
Further activity aims to extending the range of cutting parameters and testing more diamond bead types (in particular the effect of grit size and density) and metal materials to validate the generalization of the proposed model.
Open problems include: understanding and estimating the interaction between diamond bead and metal workpiece, and finding a simpler correlation between test parameters and real process parameters.
This study also demonstrates the potential of the diamond bead testing machine developed at the University of Pisa [5].

ACKNOWLEDGEMENTS

We would like to thank Mr. Simone Carelli involved in this study for his undergraduate final MEng project. Technical support from Mr. Michele Giuri is acknowledged. Support from Lochtmans S.r.l. Avenza - Carrara (MS) Italy is appreciated. Financial support from the Italian MIUR [6] is acknowledged.

REFERENCES

[1] Tönshoff H. K., Hillmann-Apmann H., Asche J., Diamond tools in stone and civil engineering industry: cutting principles, wear and applications, Diamond and Related Materials, Vol. 11, N. 3-6, March-June 2002, pp. 736-741.

[2] Tonshoff H.K., Friemuth T., Hillmann-Apmann H., Diamond tools for wire sawing metal components, Abrasives, August/September, 2001, pp. 31-37.

[3] Rule K., Perry E., Larson S., Viola M., Madaris S., Rose R., Jenkins N., Demonstrating diamond wire cutting of the TFTR, WM00 Conference, Feb. 27 – Mar. 2, 2000.

[4] Beckman T.R., Hulick R.M., Diamond wire sawing speeds dam project, Industrial Diamond Review, Vol. 51, n. 547, Jun., 1991, pp. 272-274.

[5] Tantussi G., Lanzetta M., Romoli V., Diamond Wire Cutting of Marble: State of the Art, Modeling and Experiments with a New Testing Machine, A.I.Te.M VI, Proceedings of the 6th International Conference of the Italian Association of Mechanical Technology, Enhancing the Science of Manufacturing, Ed. L. Carrino, Pub. D'Arco Edizioni, Gaeta (LT), Italy, September 8th-10th, 2003, ISBN: 88890210121, pp. 113-126.

[6] Ministry of Instruction, University and Research, DM 23/01/2001 ref. 10/2001. Program: Co-financing research programs of national interest (2001). Project: Stone processing technologies. Subtask: Design and development of a testing apparatus for the optimization of cutting of natural stones with diamond beads. http://cofin.cineca.it.