ROCK DISINTEGRATION USING WATERJET-ASSISTED DIAMOND TOOLS

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ABSTRACT

Mechanical excavation of hard rocks using conventional tools is not yet viable from both the technical and economic point of view due to the poor performance of the equipment in terms of excavation rate and specific energy as well as to the high wear rate of the mechanical instrument if the rock is also abrasive. A new opportunity is opened by the development of tools with special design coated with a layer of polycrystalline diamond. However they are very delicate to handle because of the fragility to impact of the active tip which is also sensitive to the high-temperature heat generated by the contact with the rock. The assistance of a water jet in front of the tool is the only way for efficient cooling as well as for supporting the mechanical action in the initiation and propagation of fractures.

Linear grooving experiments have been carried out at the Waterjet Laboratory of the University of Cagliari in the frame of a bilateral programme involving the National Research Council of Italy and the Academy of Science of Czech Republic. Data of forces and displacement as a function of time have been recorded and processed by means of a computer in order to monitor the tool performance in real time. Tests have been carried out on two rock samples with different toughness by varying the vertical load (pushing force) and the features of the water jet (pressure and flowrate). Performance has been evaluated in terms of specific energy (mechanical and hydraulic) and wear has been assessed with high-resolution optical fibre microscopy.

The paper describes the laboratory set-up used for the tests and illustrates the results obtained outlining the prospects of the technology.

1. INTRODUCTION

In underground mining and civil engineering works, going below surface begins with the process of rock disintegration. Hard rocks present a special problem if mining machines with mechanical tools are to be used (Vašek 1996).
Intensive wear of the edge of wedge-type mechanical tools or their total destruction is the result of the interaction with rocks difficult to disintegrate. Wear process has been intensively studied for decades (Deketh, 1995; Verhoef, 1997) and many findings of interaction process were obtained. Steel wedges were replaced with tungsten carbide bits when harder rocks were to be cut (EU Commission, 1978; Krapivin, Rakov and Sysoev, 1990). Synthetic and polycrystalline diamond seem to be the material for the tool of the future (Field, 1992).
Parallel with the development of materials for tool bits, the possibility of water jet assistance has been studied (Fowell and Tecen, 1983; Barham and Tomlin, 1987; Kovscek and Taylor, 1988; Hood, Nordlund and Thimons, 1990; Vašek, 1992; Vašek and Mazurkiewicz, 1997; Bortolussi, Ciccu, Grosso, Ortu and Vašek, 1997).
A new experimental program on water jet assisted mechanical breakage of rocks and coal within a co-operation agreement involving the CNR Centre at the University of Cagliari in Italy and the Institute of Geonics of the Academy of Sciences of the Czech Republic in Ostrava has recently been undertaken. The first results of this co-operation are the subject of the present paper.

2. EXPERIMENTS

Linear grooving tests have been carried out on two different lithotypes (a granite and a volcanic rock, both from Sardinian quarries) under well defined experimental conditions, aiming at obtaining some preliminary indications, to be confirmed later on with further long-run experiments, concerning the possibility of cutting hard materials with polycrystalline diamond tools availing of the assistance of a water jet.

2.1 Materials

The “Rosa Beta” granite is isotropic in texture and has a holocrystal, hypidiomorphic, uneven grain structure. Its approximate mineral composition is 30.0 % quartz, 35.0 % K-feldspar, 25.9 plagioclase, 9.5 % biotite and accessory minerals. Mean crystal size is about 4 mm for quartz, 4.5 mm for K-feldspar, 2 mm for plagioclase and 0.6 mm for mica and other mafic minerals.
Other properties of interest are:

- Point-load strength: 47.3 MPa
- Porosity: 0.63 %
- Specific surface of pores: 0.04 cm^2/g

The dacitic pyroclastite, locally known as “Serrenti stone”, has a composition characterised by the presence of plagioclase, amphiboles (horneblendite), biotite, quartz and secondary constituents, in order of decreasing importance.
Its fabric is porphyritic with abundant microcrystalline matrix and frequent large phenocrysts (less than 10 % by volume). The rock is rather porous as shown by its relatively low density and by the 30% decrease in compressive strength after freezing cycles.

Some significant characteristics are reported in table 1.

Table 1. Mineral composition, physical and mechanical properties of the rock samples used for the grooving tests.

CHARACTERISTICS	Rosa Beta	Serrenti stone
- Bulk specific gravity [kg/m^3]	2,622	2,277
- Absorption coefficient [%]	0.33	
- Knoop hardness [MPa] (*)	6,442	
- Compressive strength [MPa]	165	78.4
- The same after 20 freezing cycles [MPa]		64.6
- Flexural strength [MPa]	15.6	
- Impact test (minimum fall height) [cm]	58	
- Abrasion resistance [mm/km]	2.32	
- P-wave velocity [m/s]	4,760	

(*) *Weighted average of the hardness of the various components*

2.2 Equipment

The test bench consists of a carrier platform which can be traversed horizontally along a couple of parallel cylindrical bars by means of a hydraulic piston capable of imparting a force of some thousands of N. Friction is kept low with the help of a twin pair of lubricated axial bearings. A rolling ball is placed between the piston head and a vertical plate in the platform in order to allow the vertical displacement of the pick holder which is free to move along two parallel rods, guided by two sets of bearings rigidly applied to the same platform. The pick is forced down against the workpiece under a vertical load which can be varied by applying a known static weight.
The test bench is shown in the photograph of Figure 1.

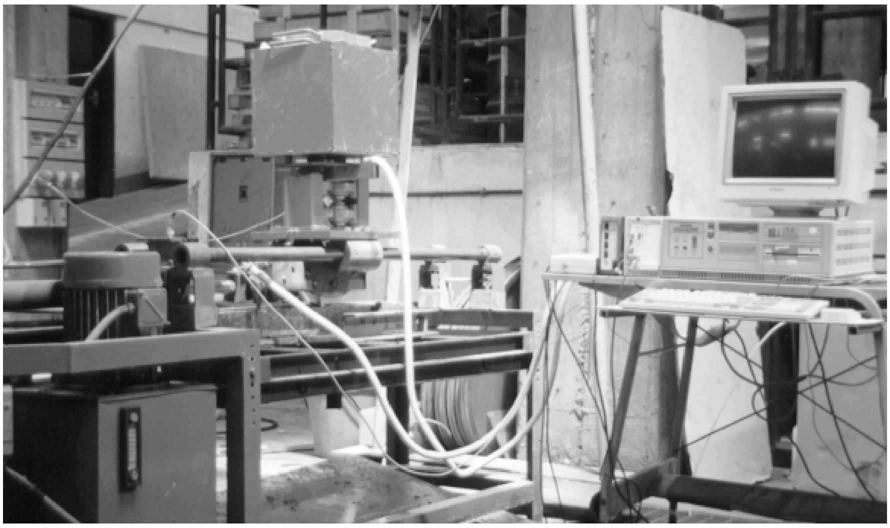


Figure 1. View of the experimental apparatus

Experimental conditions allowed by the test bench are the following:

- Traverse velocity: 0.5 m/s
- Length of the grooves: up to 0.6 m
- Depth of cut: up to 15 mm

- Horizontal force: up to 5,000 N
- Vertical force: up to 3,000 N
- Power of the hydraulic pump: 4.2 kW

The pick is mounted into a cylindrical sleeve inside the holder body. Rotation is hindered by means of a tooth-notch coupling and axial movement is controlled by a multiple-disk spring located at the bottom of the sleeve in order to absorb the dynamic impacts transmitted by the rock.
The position of the pick holder can be adjusted in order to modify the angle of attack.
The pick has the shape of conventional conical tools but the tip is cut flat so that its frontal face is a semicircle with a diameter of 12 mm, entirely covered with a 0.8 mm thick layer of polycrystalline diamond.
Consequently the area of contact with the rock a circular segment delimited by a chord and an arc with a variable length depending on the depth of cut.
A water jet can be applied in front of the pick by means of a nozzle fitted into a nozzle holder, the position of which can be adjusted in order to modify the direction of the jet with respect to the pick as well as the stand-off distance.
Water is supplied via a flexible high-pressure hose connected to a plunger pump capable of delivering a maximum flow rate of 10 l/min under a pressure of 50 MPa.
A detail of the pick assisted by a water jet is shown by the photograph of Figure 2.

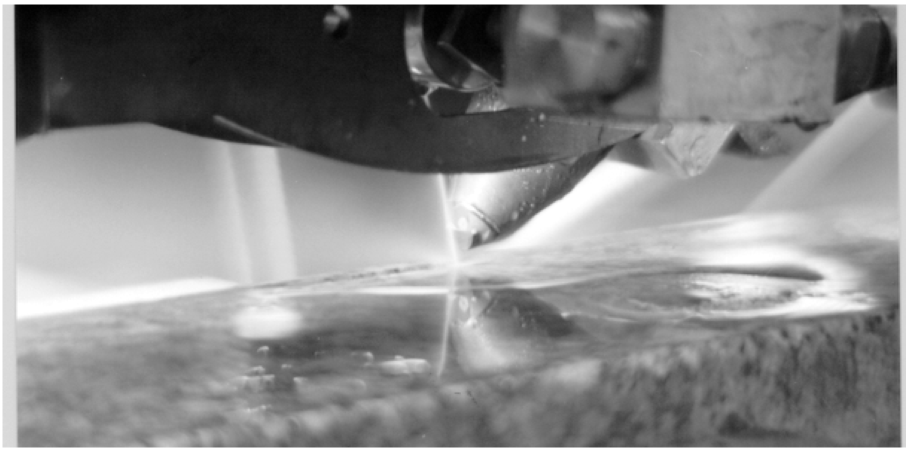


Figure 2. The waterjet-assisted diamond tool used for the experiments

2.3 Tests

Cutting tests have been carried out on each lithotype using two new picks
The vertical loads applied were the following:

- For the dacite: 1.6 kN
- For the granite: 2.0 kN

In the tests with waterjet assistance the working pressure was kept around 30 MPa at the 0.3 mm nozzle, while in the tests without waterjet the tool was cooled by a spray of tap water.
The tests with the first pick enabled to put into light the wear behaviour of the tool without waterjet assistance.
A first series of 32 grooves were made on the dacite stone reaching a total length of about 20 m without observing any major damage except for some occasional chipping near the bottom of the contact arc of the pick.

A second series of 16 grooves with the same pick was made on granite but after 8 tests (corresponding to a total length of less than 5 m) a considerable damage occurred, so that the subsequent 8 grooves were produced with a much lower depth of cut and a considerable loss of efficiency since the pick tended to slide over the rock with reduced penetration.
The tests with the second pick were aimed at putting into evidence the advantage of using a water jet placed in front of the tool.
Four series of grooves have been made as described below:

- First: 31 grooves on dacite with waterjet (total length: 18.6 m)
- Second: 15 grooves on dacite without waterjet (total length: 9.0 m)
- Third: 16 grooves on granite with waterjet (total length: 9.6 m)
- Fourth: 10 grooves on granite without waterjet (total length: 6.0 m)

During the first two series only occasional chipping in the lower tip of the tool was observed but with no loss of efficiency, as witnessed by the constant average value of the depth of cut.
No damage was also observed in the third series in spite of the much higher hardness of the rock whereas during the fourth series a major damage showed up consisting in the detachment of a large scale from the diamond layer after 9 grooves. Therefore the event of rupture and the kind of damage occurred in a very similar way for the two picks.
The features of the test rocks and the grooves obtained are shown in figures 3 and 4.

Figure 3. Typical grooves on dacite with waterjet assistance

In the case of the dacite the grooves were several mm deep and their side contour quite irregular due to the detachment of large scales. In the case of granite the grooves were much smaller and more regular due to the absence of large scales since the cut was essentially the result of a crushing action only.
No difference in the geometric features of the grooves could be observed in both rocks with or without the assistance of a water jet. However after rupture the depth of grooves in granite was reduced almost by half.

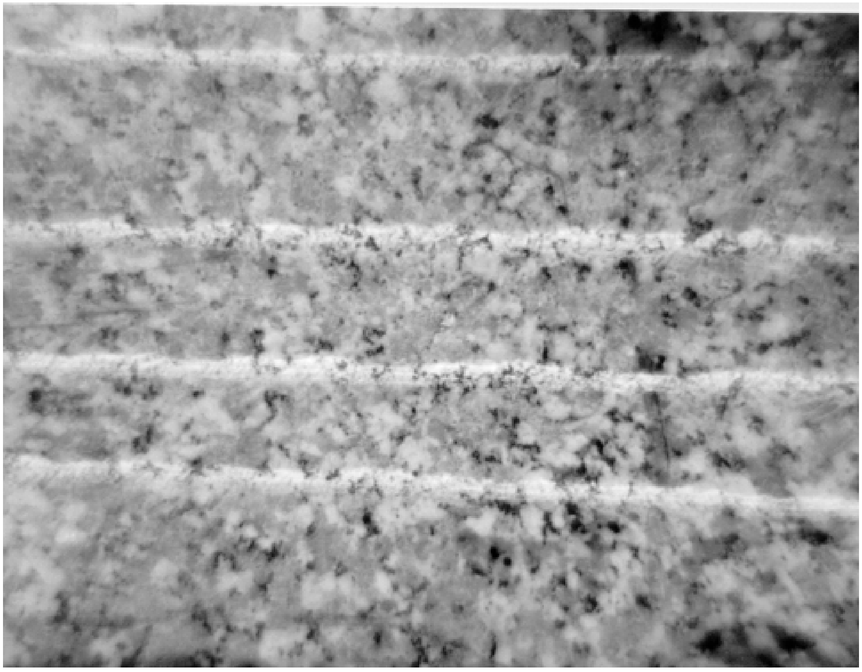


Figure 4. Typical grooves on granite with waterjet assistance

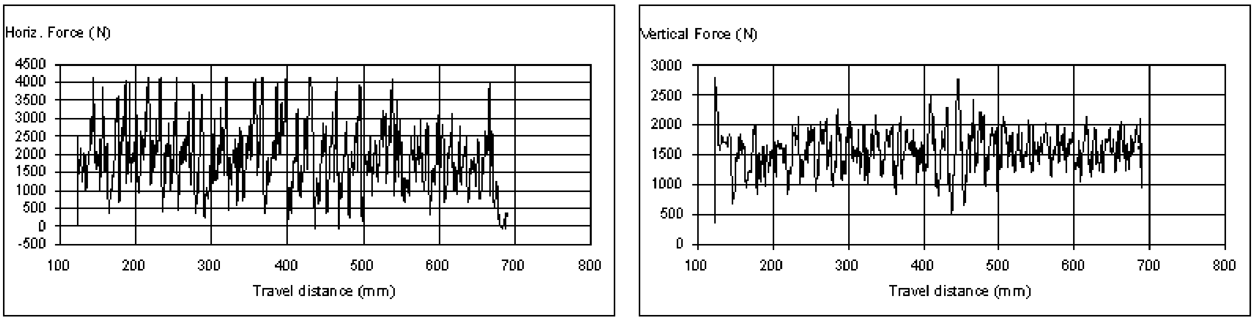
2.4 Mesurements

Both horizontal and vertical forces have been measured in real time by means of piezoelectric probes connected to a high-frequency data acquisition system.
Horizontal displacement has also been measured as a function of time using a wire transducer.
The depth of cut for each test has been determined every 4 cm of groove length using a high accuracy mechanical comparator.
The state of wear of the tool has been observed visually after each test and computer photographs with an optical-fibre microscope have been taken after every group of four tests using a 20 times magnification lens.
The pick was also weighed using a balance with an accuracy of 0.05 g.

3. EXPERIMENTAL OUTCOME

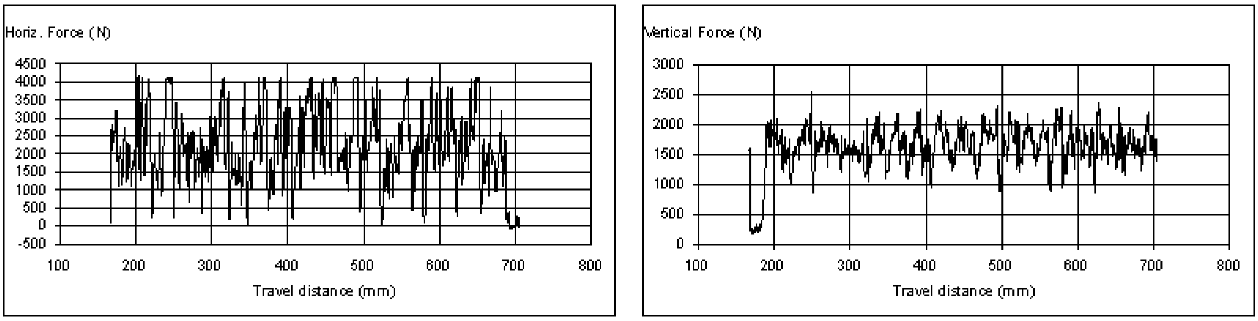
3.1 Cutting results

The diagrams of horizontal and vertical forces for a typical grooving test in the dacite rock is shown in figures 5 and 6, with and without the application of waterjet, respectively. The average value of the depth of cut of the groove is also shown.
Although the difference is not particularly evident it appears that forces with waterjet are slightly lower while oscillation is less frequent and more ample especially for the vertical force.
Similar diagrams are shown in figures 7 and 8 in the case of granite.



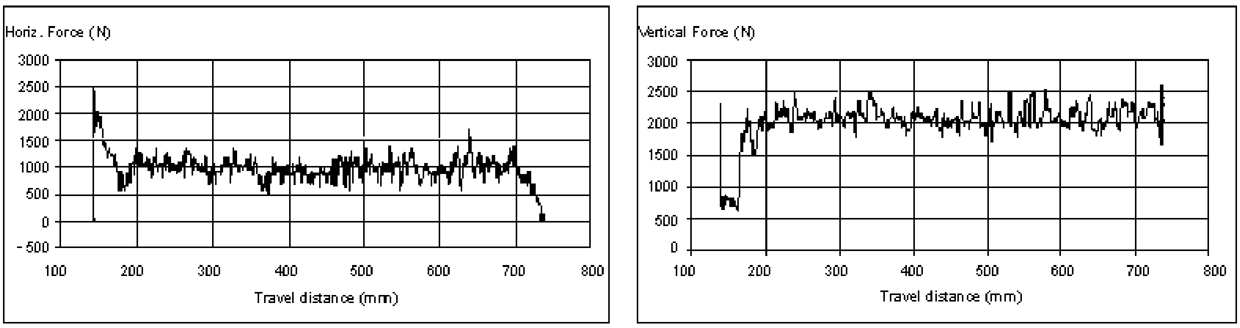
AVERAGE DEPTH OF CUT: 4.55 mm

Figure 5. Horizontal force (left) and vertical force (right) in a grooving test in dacite with the assistance of a water jet in front of the pick.



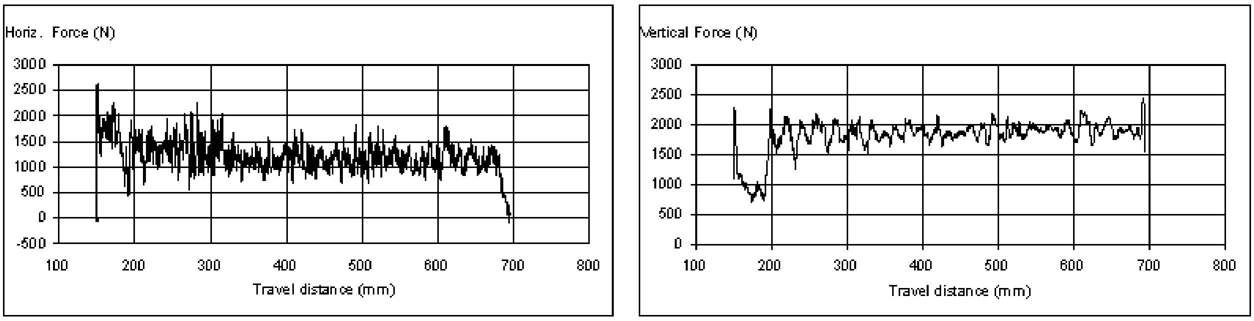
AVERAGE DEPTH OF CUT: 4.71 mm

Figure 6. Horizontal force (left) and vertical force (right) in a grooving test in dacite without waterjet



AVERAGE DEPTH OF CUT: 0.61 mm

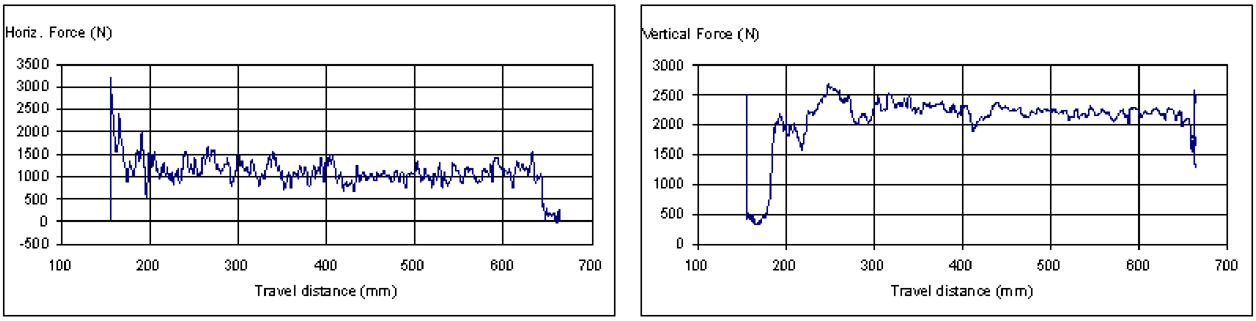
Figure 7. Horizontal force (left) and vertical force (right) for a grooving test in granite without waterjet



AVERAGE DEPTH OF CUT: 0.66 mm

Figure 8. Horizontal force (left) and vertical force (right) for a grooving test in granite with the assistance of a water jet in front of the pick.

Again the vertical force is a bit lower when using a water jet but in this case the frequency of oscillation appears somewhat higher.
The diagram of horizontal and vertical forces for a grooving test in granite without waterjet immediately after the rupture of the pick is shown in figure 9.



AVERAGE DEPTH OF CUT: 0.45 mm

Figure 9. Horizontal force (left) and vertical force (right) for a grooving test in granite without waterjet immediately after the rupture of the pick.

The vertical force resulted to be even higher than that before rupture while the depth of cut is much lower. At the same time the horizontal force appears steadier showing that the pick tended to slide on the rock

3.2 Wear process

Wear undergone by the picks during the grooving tests is documented by the photographs of figures 10 and 11, a and b.
The results of the parallel series of tests with the two rocks enable to draw the following conclusions regarding the wear of the picks, although further investigation with new picks is needed in order to establish their full technical life in different rocks with or without waterjet assistance:

- In medium-tough materials like a dacite diamond-hardened tools show good strength properties and their duration can be expected to be long enough for a industrial application even without the assistance of a water jet, although no figures of duration can be provided being the research still at its early stage.

a) *b)*

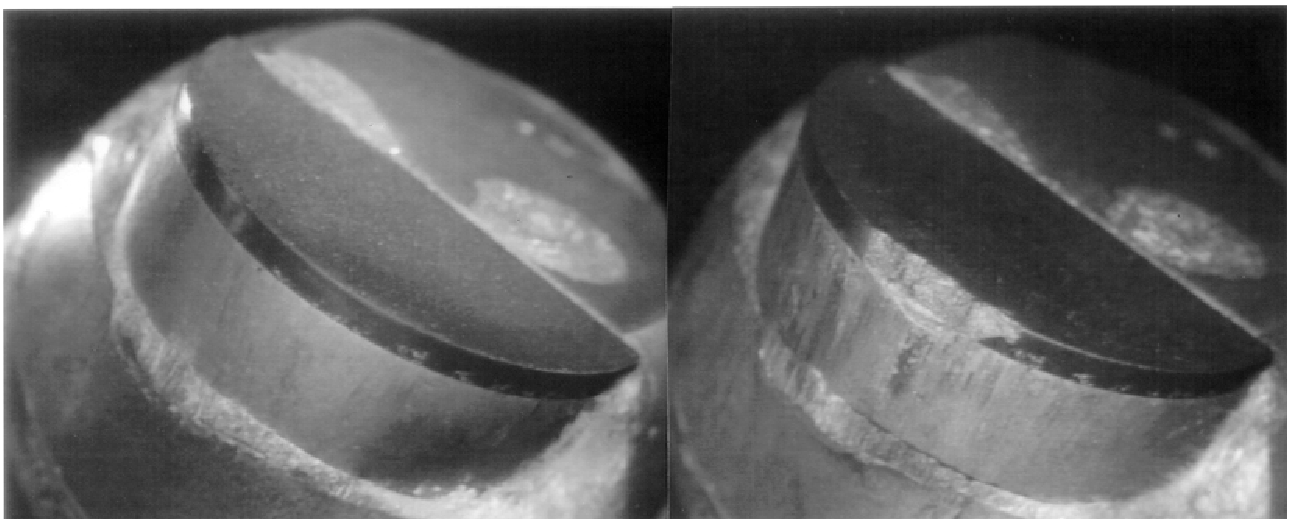


Figure 10. Aspect of the tool tip at 20X magnification in cutting experiments without waterjet assistance

a) before cutting experiments
b) after 20 m of groove in dacite

c) *d)*

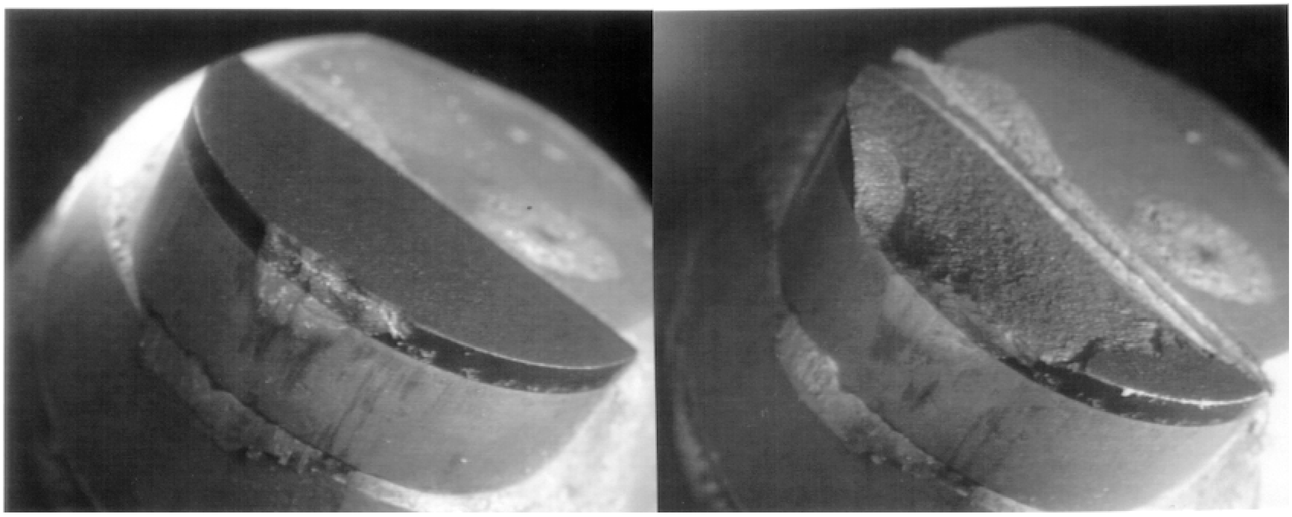


Figure 11. Aspect of the tool tip at 20X magnification in cutting experiments without waterjet assistance in granite

c) before rupture of the tip
d) after rupture of the tip

- In very tough materials like sound, not weathered granite, tool duration is much lower but it can be substantially increased with the assistance of a water jet. In fact the diamond tip broke-off into large scales after less than 5 m of groove with both picks, whereas in the case of waterjet assistance no chipping was observed after an overall travel distance of 10 m.
- It should be very interesting to investigate the behaviour of the tool in granite by applying larger forces in order to increase the depth of cut and thence the excavation rate to a level of industrial significance. Under these conditions wear rate can be higher but maybe not proportional to the applied load since stress will be distributed over a longer contact arc which is a critical factor for picks working with a sharp edge like those used for the experiments.

4. CONCLUSIONS

The first range of cutting tests with polycrystalline diamond tool with and without assistance of water jet at 30 MPa pressure were performed on softer dacite and hard granite (compressive strength: 78,4 MPa for dacite and 165 MPa for granite).
After 31 grooves (with total length of 18.6 m) without assistance of water jet and after the next 15 grooves (with total length of 9.0 m) cut on dacite, only minor wear of cutting wedge was observed. Moreover, no notable influence of assistance of water jet was detected, too.
After the next 16 grooves (with total length of 9.6 m) on granite with assistance of water jet no more wear on cutting blade was observed. On the other side, without water jet assistance, after the next 10 grooves (with the length of 6.0 m) total rupture of polycrystalline diamond layer happened and tests with this pick were finished.
The new range of tests under broader scale of water pressure and of water flow rate is scheduled in order to find out the conditions enabling to prolong the life time of this tools.

ACKNOWLEDGEMENTS

Work carried out in the frame of a joint research program between CNR of Italy and the Academy of Sciences of Czech Republic with the financial support of MURST (Special Projects with 60% contribution) and the support of the project No: A2086801 of the Grant Agency of the Academy of Sciences of the Czech Republic.

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