DIAMOND WIRE – STONE INTERACTION DURING THE CUTTING PROCESS: MECHANICAL, PHYSICAL AND CHEMICAL INVESTIGATIONS

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ABSTRACT

Stone cutting with diamond wires results in the progressive and concurrent wear of the natural stone and the cutting tool (diamond wires - diamond beads). This phenomenon has been investigated since the beginning of stone machining, but there are still several open questions concerning the parameters controlling it. The aim of this study is to establish correlations between the natural stone mineralogical composition and the diamond wires cut performance in terms of efficiency, productivity and diamond beads consumption. This investigation requires a multidisciplinary approach. Microscopic analysis have been done in order to investigate the wear processes of the diamond beads in terms of super-abrasive grains (diamond grits) damage and pull out. Petrographic analysis and mineralogical investigation have been considered in order to correlate the removal rate during the cutting action with the characteristics of the stones. Muds derived from cutting have been characterized for the complete comprehension of the cutting process. The erosion analysis concerned both stone debris and diamond beads, characterizing both the metal powder and super-abrasive grains (diamond) in the cut waste (mud). Moreover, the metal matrix is the core of the diamond wire technology and it drives cutting performance and efficiency.

KEYWORDS

stone workability, diamond wires, corrosion, diamond beads characterization, diamond wires-stone interaction, granite, sienite, diorite.

INTRODUCTION

Diamond wires are cutting tools for stones (marble, granite, etc.) and concrete. They are composed of a stainless steel cable on which diamond sintered beads, containing diamond grains, are assembled with a regular space between them. A sintered bead is a composite material containing super-abrasive grains (diamond) hold in a metallic matrix, usually cobalt. The main functions of the metal matrix consist in holding the diamond grains (the diamond crystal has to protrude from the matrix during the whole cutting action) and in preventing premature detachment of the diamonds from the matrix (the mechanical and chemical bonding between the diamond crystal and metal matrix must guarantee a stable bond, until the worn diamonds come off, in order to re-establish the best cutting condition). The steel cable is protected from erosion and corrosion by a polymeric coating of polyurethane (TPU), through a plasticization process. The selection of the diamond wire depends on two parameters: (1) the smallest possible diameter, for minimal scrap generation during the cut; (2) the correct diameter because the tool will be shock-proof. [1-2-3] The aim of this study is to establish interactions between the natural stone mineralogical composition and the cut performance of diamond wires, in term of efficiency, productivity and diamond beads consumption.

MATERIALS AND METHODS

A multidisciplinary approach has been adopted during this study in order to combine several investigations and tests for a global correlation of cutting parameters: stone, cutting tool, cutting machine. [4-5]

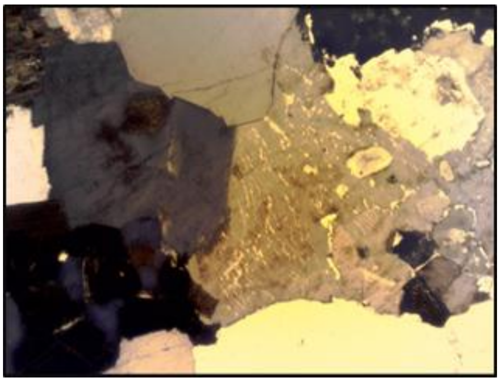
Sintered and plasticized diamond wires, diameter 7 mm, have been assumed as reference standards for the stone slabbing (granite stone, multiwires machine). Moreover, the metal matrix is the core of the diamond wire technology and it drives cutting performance and efficiency.

Microscopic analysis has been done in order to investigate the wear processes of the diamond beads in terms of super-abrasive grains (diamond) pull out and damage. Worn diamond beads coming from diamond wires used in cutting of Fe containing stones were observed by means of a Scanning Electron Microscope (SEM, SEM-FEI, Quanta Inspect 200, FEI), equipped with the back scattering mode (BS-SEM) and with an EDS that was used to verify the elemental composition of the specimens in different areas.

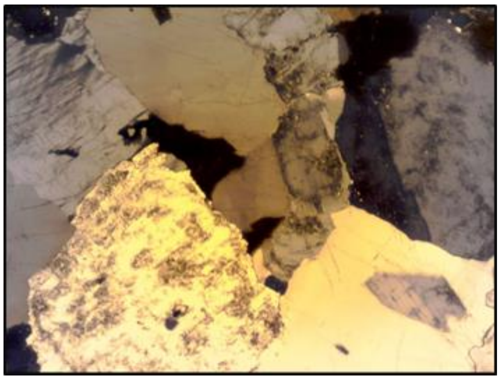
The chemical affinity between iron-based minerals and super-abrasive grains (diamond) gives an answer to early wear of the diamond wire in some case studies.

Petrographic analysis and mineralogical investigation have been performed on the stones and on the muds derived from their cutting. Both have been analyzed by means of the optical microscope Leitz Wetzlar. Image analyzer software IMAGE J (an open source image processing program designed for scientific multidimensional image), in order to define size, dimension and ratio between quartz and feldspar. In

Figure 1 the thin sections of two different kind of Sardinian granite (RG and GP) are reported.



A. RG granite



B. GP granite

Figure 1: Thin sections of RG and GP granite (long side 4.3mm): microscopy crossed nicols, in black the ferrous components (biotite).

The granulometric curve of multiwire muds is shown in Figure 2; it is characterized by an high percentage (40.2%) of particles minor than 0,038mm.

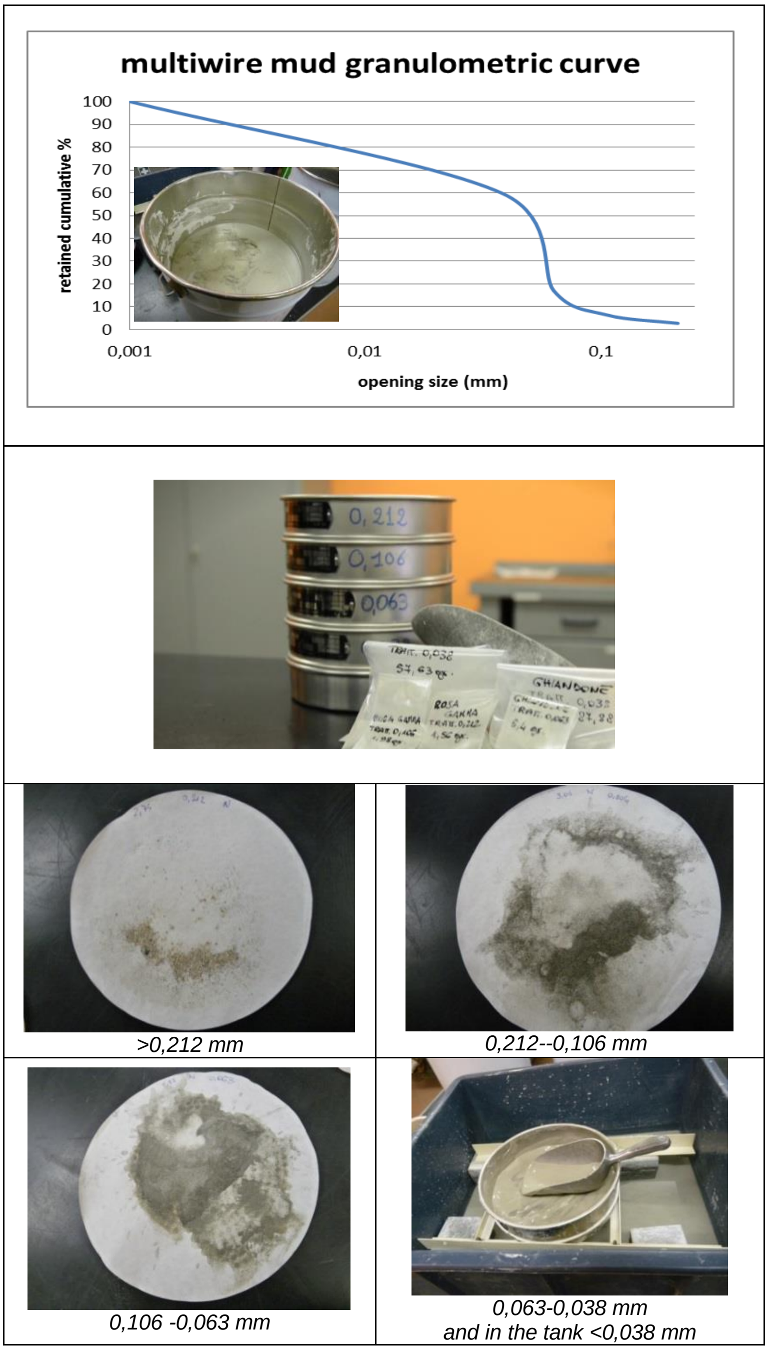


Figure 2: size distribution process and characterization of multiwire muds

Each one of the classes obtained through the granulometric separation has been processed with a wet magnetic separation (Co-Al – Ni magnet). On the size classes minor than 0,063mm a further analysis by means of X – Ray Diffraction (XRD) have been performed.

RESULTS AND DISCUSSION

There are significant differences in the interaction between stone and diamond beads when considering different stones. The major variability consists in the mud particles dimension and in the type of wear and damage of the diamond beads, but also the shape and conformation of the mud particles are important parameters to be considered. A double examination (beads and stones) represents a whole and complete approach to the issue under investigation, characterizing both the metal powder and super-abrasive grains.
In the case of diamond wires used in cutting of Fe containing stones, we observed by SEM that the junction between the diamond beads and the steel cable is good and no wear was observed in this area (Figure 3). The steel cable is well covered by a thin or thick polymeric coating (polyurethane) at the junction between the cable and the diamond bead, without any erosion, detachment or wear of the coating (Figure 4).

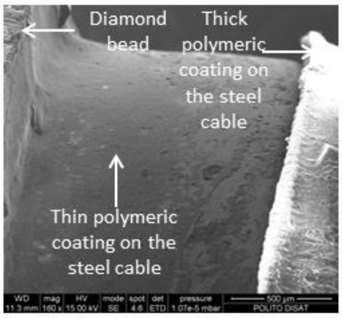


Figure 3: SEM image at low magnification of the junction between the diamond beads and the steel cable

On the other side, erosion of the metal matrix and damage of the diamonds can be clearly observed on the beads after stone cutting: this is the main issue in the wear of diamond wires and it will be one of the main focus of the present work. [6]
As first, we observed at low magnification that the beads almost maintain their shape after stone cutting and they are almost uniformly worn (see Figure 4) on all their length. The direction of cutting and rotation of the diamond wire can be derived by observing the presence of "comet tails" behind the diamond grits and the slight lower diameter of the bead on the left of the image: the first impact of the bead with the stone during cutting was on the left side, in this case.

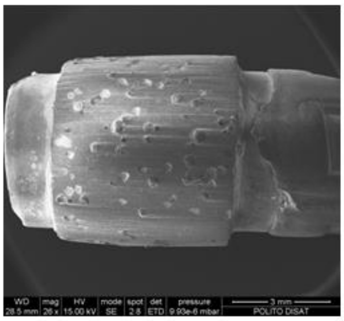


Figure 4: SEM image at low magnification of a worn diamond bead

Diamonds are well dispersed on the surface of the bead without evidence of clusters and polycrystalline agglomerates. The diamond beads wear rate can be classified according to diamond grits pull out, damage or breakage, and to the diamond retention ability of the metal matrix, through a morphological analysis of the beads surface.
The diamond grains observable on the surface of a worn diamond bead used in stone cutting can be classified in the following way: diamonds arising from the surface without any damage, diamonds protrusive from the surface, diamonds polished, micro-fractured, macro-fractured, pulled out and etched. [7]

In this case, we observed diamonds arising from the surface without any damage, macro fractured, pulled out and etched (Figure 5).

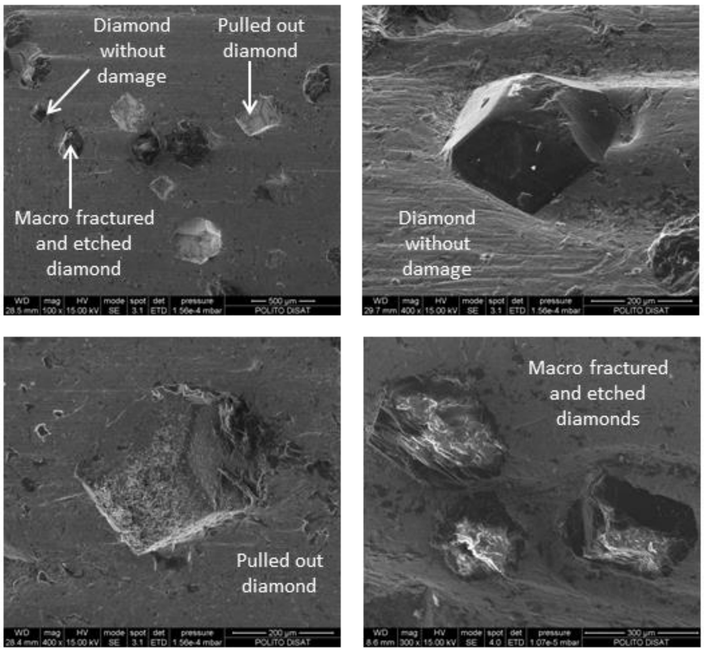


Figure 5: Image of the surface of a worn diamond bead with diamond bits differently damaged

Diamonds without any damage are diamonds still able to cut stones and a “comet tail” is clearly visible behind them, because their presence prevent erosion of the metal matrix behind them by stone debris, during cutting. [8] The interface between the un-damaged diamond bits and the metal matrix is continuous and without any cracks, showing a high retention ability of the metal matrix and good sintering of the beads. [9] EDS analysis performed on the smooth surface of the un-damaged diamonds only shows the presence of carbon.

Some diamonds were pulled out during cutting and some voids are observable on the surface; the voids are often quite deep, showing that in these cases diamonds were pulled out before they were highly worn. The EDS analysis performed inside the voids deriving from pulled out diamonds shows the presence of Co and WC, which are the main components of the matrix. No porosity can be seen inside the voids of the pulled out diamonds, confirming a good sintering of the metal matrix.

The most interesting diamonds grits are the macro fractured and etched ones. These diamonds are no longer able to cut stones and they do not show any “comet tail” behind them. Macro fractured diamonds do not highly protrude from the surface level and they still show a good interface with the metal matrix, showing that in some cases the retention ability of the metal matrix is too high: un-efficient diamonds without cutting ability are still maintained on the surface by the strong interface with the metal matrix. [10] The surface of the macro fractured diamonds shows both some smooth cleavage planes, deriving from a brittle fracture mechanism, and some rough areas probably deriving from etching (Figure 6). On the rough areas of the etched diamonds, EDS analysis shows the presence of an adherent layer of stone containing Fe, Ca Na, K, Mg and Si, suggesting that Fe containing stones are able to react with the diamonds causing a high degree of damage and macro fractures follow this etching.

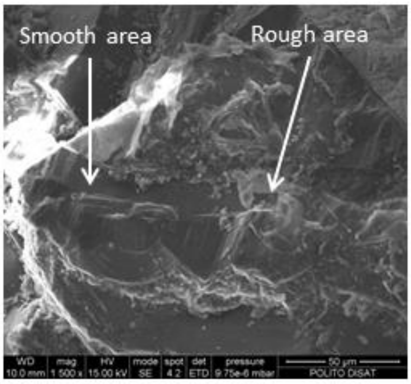


Figure 6: Macro fractured and etched diamond

On one diamond grain, arising from the surface with an almost un-damaged and smooth surface, it was interesting to see the damage, probably due to etching and reaction with iron, in a first stage (Figure 7Figure 7), limited to small areas: in this case macro fractures did not occur because of the limited etching.

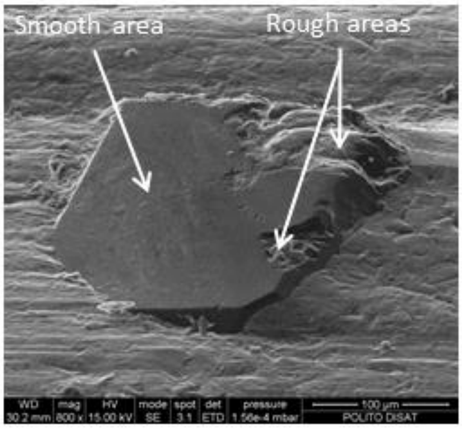


Figure 7: An almost un-damaged diamond bit showing etching in a first stage

Muds generated by stone cutting are mainly composed by stones debris and fraction of heavy metals (e.g. Co, Ni, Cu, Zn, Cr, W and their alloys) deriving from metal matrix. In particular, the magnetic separation shows, in the 0,038mm-0,063mm class, a higher amount of ferromagnetic particles coming from the metal matrix erosion, while, in the fine class (<0,038mm) the rock minerals (quartz in particular) are predominant: this is confirmed from the diffractometric analysis too (Figure 8). The sawmill mud contains heavy metals coming from the sawing tools: an example of 4 different muds sample (M1-M2-M3-M4) is in
Table 1 and

Table 2.

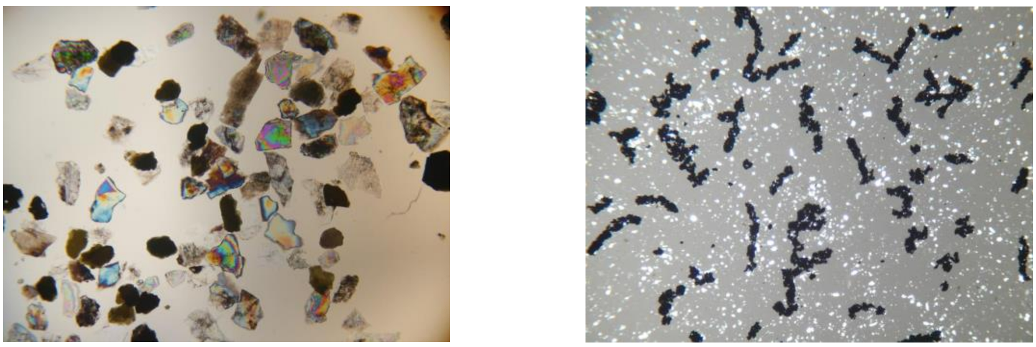


Figure 8: On the left micro-photo (6.9x5,19mm) with crossed nicols of mud particles >0.212mm and on the right micro photo (10.6 x 8mm)with parallel nicols of mud particles between 0.038-0.063mm.

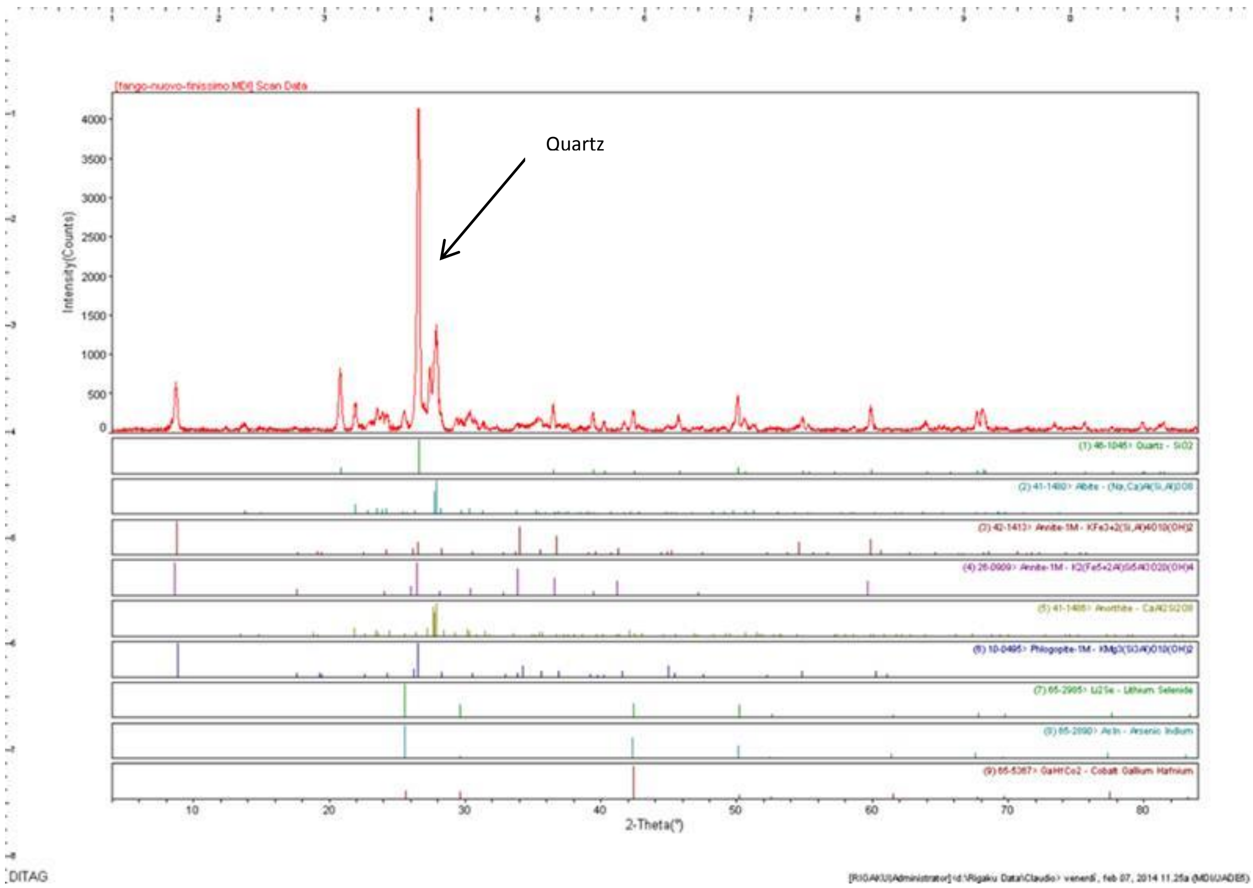


Figure 9: X- Ray Diffration of muds <0,038 mm

Content in weight (%)	M 1	M 2	M 3	M 4
SiO2	77.1			
TiO2	0.1			
Al2O3	12.0			
Fe2O3	1.2	1.1	1.4	1.1
MgO	0.8	0.6	0.4	0.4
CaO	0.7	0.8	0.6	0.6
Na2O	5.7	5.5	5.9	4.2
K2O	5.1	5.0	5.3	5.2

Table 1: Oxydes in % in muds coming from gneiss and granites cutting

Content in ppm	M1	M2	M3	M4
Cd	<1.0	1.0	<1.0	<1.0
Co	140.0	76.0	78.0	180.0
Cr	5.0	36.0	20.0	26.0
Cu	162.0	230.0	162.0	110.0
Mn	114.0	100.0	82.0	90.0
Ni	2.0	3.0	3.4	3.0
Pb	82.0	78.0	72.0	72.0
Zn	100.0	98.0	92.0	106.0

Table 2: Metals in ppm in multiwire diamond machine muds

CONCLUSIONS

The obtained results confirm that deep knowledge of interaction between the diamond beads and stones turns into a whole comprehension of the cutting process. This will allow to optimize cutting action: a double examination (stones and beads) represents a whole and complete approach to the comprehension of the wear processes during stone cutting.
Petrographic analysis and mineralogical investigation gave us the opportunity to understand the interactions between stone and diamond beads. The major variability consists in the muds particles dimension, but also the shape and conformation of stone debris are important parameters to be considered.
Erosion analysis concerned both the stone debris and diamond beads, characterizing both the metal powder and super-abrasive grains (diamond beads) in the cut waste.
Chemical composition of the metal matrix of the diamond beads directly impact on the efficiency of the diamond wire cutting action, because of the great influence in the diamond grains retention. Diamonds must be firmly retained till they show cutting ability, but the must be pulled out when they have no cutting efficiency. In the considered case study, this equilibrium was obtained, even if some highly damaged diamonds are still present on the worn surface of diamond beads.
Chemical interaction between the diamonds and Fe-based stones would accelerate the wear processes through etching phenomena, drastically reducing the long-life of the diamond wire.

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