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Diamond Tools for Machining of Granite and Their Wear

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The increasing demands of the industry and cultural sculpturing for complex shaped products in natural stone makes the use of flexible and completely automatic machines such as CNC machining centers necessary. These machines mainly use diamond tools such as synthesized diamond mills, circular blades, polishing tools, etc. For the machining of stone, diamond tools are becoming increasingly important and suitable, especially for the machining of granite and other hard stones.

The aim of this paper is to present and describe the structure of diamond tools, to present diamond tools for different CNC machining technologies and to characterize the principles of diamond tools wear and forces which are active during the basic type of machining.

Keywords: diamond tools, CNC machining, wear, force, diamond

0 INTRODUCTION

Diamond tools are key elements in the machining of natural stone, especially hard stones such as granite. Diamond tools are mostly used in CNC machines. They are used in different machining technologies like cutting, abrasive milling, abrasive drilling, grinding and polishing. All diamond tools have the same machining principle (Fig. 1) and that is grinding. In this case, the tool with many cutting edges and coincidental geometry grinds the surface of the stone. Typical diamond tools are wires, circular blades, mills, tools for grinding and polishing. They are composed of support and abrasive segments, which are composed of diamond grains and a matrix. The support is the part of the tool, to which the abrasive segments are fixed. The support gives the right shape to the tool, transmits the kinetic energy from the machine axes to the diamond grains and absorbs the stresses generated during machining. Diamond grains constitute the cutting edges. They are characterized with grain size, shape and concentration. The matrix is a metallic alloy fixing the abrasive grains on the tool support in order to make machining possible. It assures both, the cutting ability and long tool life [1]. For effective and quality machining with diamond tools it is necessary to get the right combination of matrix and diamond grains. Hard stones like the granite have to be machined with tools that have a harder matrix and suitable diamond grains.

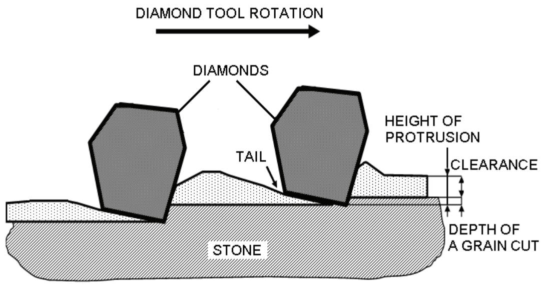

Fig. 1. *Machining principle for diamond tools [2]*

1 IMPORTANT TOOL DATA

Diamond tools have different data, which characterize them, like granulation number, matrix structure, grain concentration, grain type, etc.

1.1 Granulation

Granulation expresses the tool grain size. A large number of granulation designates a small grain size, and inversely. Granulation ranges mostly used in diamond tools are between 16 and 3000. Basic granulation numbers are 16, 25, 50, 100, 150, 200, 300, 400, 500, 600, 800, 1000, 1500, 2000 and 3000. Granulation number defines how many grains there are in a one inch long row. In Fig. 2 a schematic representation of granulation is shown.

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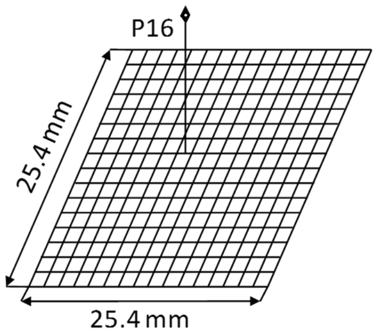

Fig. 2. *Schematic representation of granulation*

Table 1. The *size of diamond grains for different granulations* [3]

Granulation	#150	#500	#1000	#3000
Average grain size (μm)	90 - 106	28 - 34	10 - 16	3.5 - 5

- **Roughness of the machined granite surface**

Roughness for each machining process, from sawing, grinding to polishing, is shown in Figs. 3, 4 and 5. There were grooves visible on the machined surface after sawing. It can be seen, that the depth of the maximum peak-to-valley of the profile within the sampling length was about 18 μm (Fig. 3). To obtain a smoother surface all that material has to be removed. Fig. 4 shows the surface ground with a diamond tool with a granulation of #150. In this case, the groves were 6 μm deep. In the final machining a diamond tool with granulation #3000 was used. After the last machining (polishing), the depth of the grooves was less than 0,8 μm (Fig. 5). The polished surface of granite was highly smooth [3].

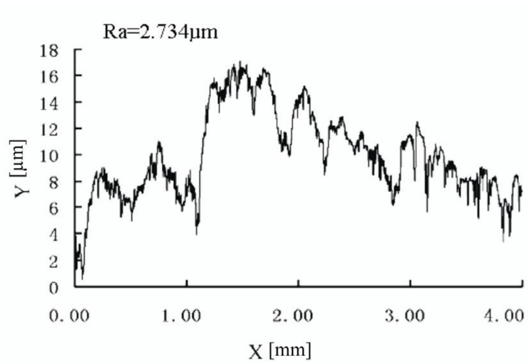

Fig. 3. *Roughness after sawing [3]*

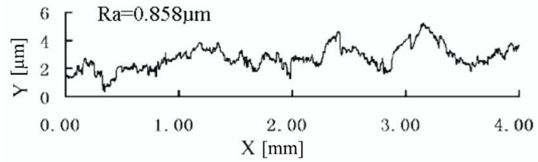

Fig. 4. *Roughness after rough grinding [3]*

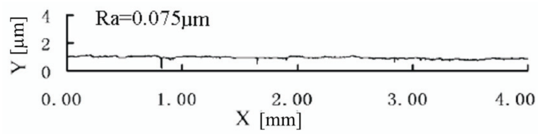

Fig. 5. *Roughness after final polishing [3]*

1.2 Matrix

The matrix is a metallic alloy fixing the abrasive grains on the tool support in order to make the machining possible. It assures both, the cutting ability and long tool life [1]. For an effective and high quality machining with diamond tools it is necessary to get the right hardness of the matrix. Hard stones like the granite have to be machined with tools that have a harder matrix.

Table 2. *Samples of different matrix composition for diamond tools [4]*

Matrix composition (%)
Ni 59; Cu 35; Fe 6
Ni 55; Cu 33; Sn 6.5; Fe 5.5
Cu 61; Co 20; Fe 19
Cu 55; Co 18; Fe 17, Sn 10
Co 89; Sn 11
Fe 77; FeCr 23
Fe 68; FeCr 20; Sn 12

1.3 Diamond Grains

In mineralogy, a diamond is an allotrope of carbon, where carbon atoms are arranged in a variation of the face-centered cubic crystal structure called a diamond lattice. Diamonds are the second most stable form of carbon, after graphite. However, the conversion rate from diamond to graphite is negligible at ambient conditions. Diamonds are specifically renowned as a material with superlative physical qualities, most of which originate from the strong covalent bonding between its atoms. Diamonds also have remarkable optical characteristics. Because of their extremely rigid lattice, they can be contaminated by very few types of impurities (Fig. 6).

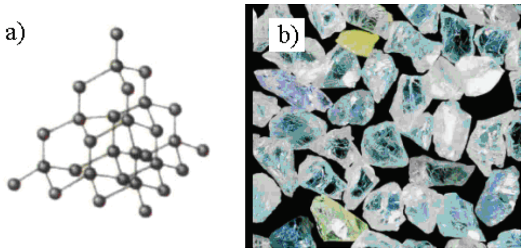

Fig. 6. *a) Diamond lattice, b) Sample of the natural diamond*

In particular, a diamond has the highest hardness and thermal conductivity of any bulk material synthesized so far. Those properties determine the major industrial application of diamonds in cutting, grinding and polishing tools. Diamond tools are mostly used for stone machining. Diamond grains can be arranged in different groups:

- natural and artificial diamonds (Fig. 7),
- diamonds for different materials machining,
- for machining of soft or hard stone,
- for professional or commercial tools.

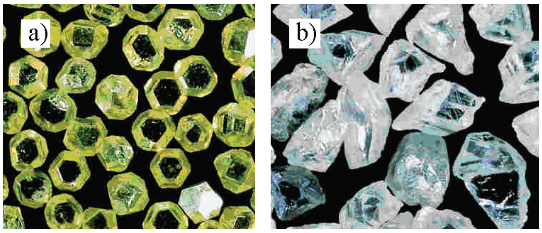

Fig. 7. *a) Artificial diamond, b) Natural diamond, both are designed for stone machining*

2 DIAMOND TOOLS FOR DIFFERENT CNC STONE MACHINING

The importance of the stone CNC machining technologies is increasing. Nowadays, the shapes of stone products are becoming increasingly complex. To machine complex shapes, CNC technologies and different shapes of diamond tools are needed. All diamond tools have the same machining principle - grinding. Tools for CNC machining technologies mainly differ from each other in shape and grain size. Typical CNC machining technologies and basic tools for each technology are:

- **cutting:** for CNC cutting diamond circular blades with the diameter in range from 150 to 450 mm are used,

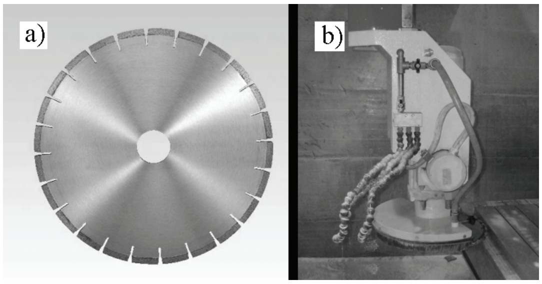

Fig. 8. *a) Sample of diamond circular blade, b) CNC cutting*

- **drilling:** for CNC drilling diamond drill bits and diamond core drills are used; drill bits are used for smaller holes and core drills for bigger,

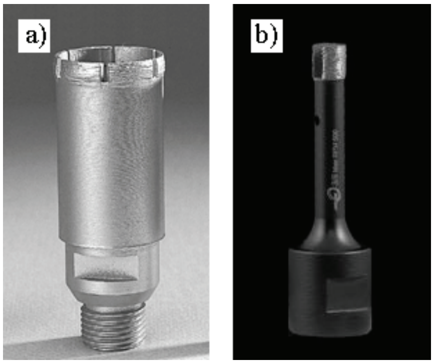

Fig. 9. *a) Sample of diamond core drill, b) Sample of diamond drill bit*

- **milling:** for CNC milling diamond routers with different shapes (profile routers, finger routers, etc.) are used,

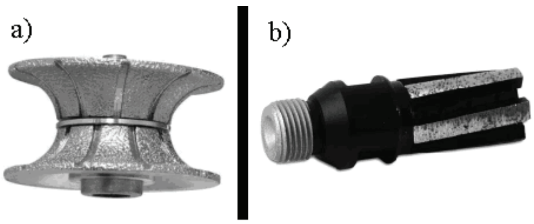

Fig. 10. *a) Sample of diamond profile router, b) Sample of diamond finger router*

- **grinding:** for CNC grinding tools with different shapes like disc, finger, profile and granulation in range from #50 to #400 are used,

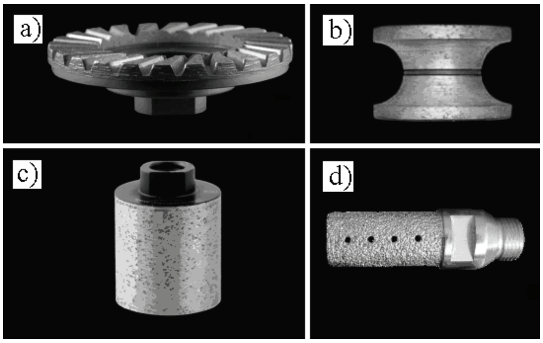

Fig. 11. *a) Sample of diamond disc grinding tool, b) Sample of diamond profile grinding tool, c, d) samples of diamond finger grinding tools*

- **polishing:** Like grinding, we also use different-shaped tools for CNC polishing, however, the granulation for polishing tools is in the range from #400 to #3000.

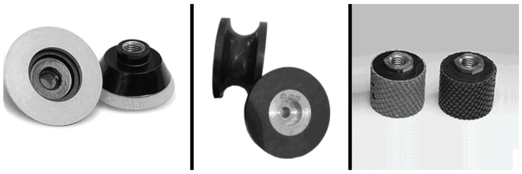

Fig. 12. *Samples of different diamond polishing tools*

3 CHARACTERIZATION OF A DIAMOND TOOLS' WEAR

The diamond tool wear is the result of the wear progression of both, the diamond grit and tool binding. It is characterized by a sequence of steps. Firstly, there is a progressive increase of grit protrusion with respect to binding surface due to binding erosion that allows the grit to come into contact with the work-piece. An emergent crystal appears on the tool surface: its cutting ability is scarce because of its small height of protrusion. A too-hard binding would make the abrasive grit exposition so difficult that the tool sector would be polished before the diamond grits are completely emerged by binding. The progressive erosion of the binding makes the whole crystal appear on the surface of the tool sector. A whole crystal is a diamond grit that has a large height of protrusion and a minimum surface damage. It has the best cutting performances. Once the work-piece is contacted, the grit is rounded off so much that a plateau is generated on the grit top. It generates mechanical friction and thermal effects that polish the diamond grits. A high percentage of polished grits makes the surface of the tool sector so vitreous that it causes a less efficient cutting ability. The intermittent contact with the work-piece caused by the tool rotation, leads to a cyclic load on the diamond grit, which deteriorates the grit ability to contrast the cutting forces and, finally, the grit breakage. This phenomenon is enlarged by the heterogeneous nature of the work-piece and by machining vibrations. Diamond grits are characterized by micro-fractures and micro-cracks that increase the number of cut edges on grit surface, even if they reduce the penetration depth. Wear progression leads to a completely fragmentary particle or to a worn matrix in such a way that the diamond grit is released. The pull-out is the phenomenon due to the release of diamond grit from binding, and consequently to the formation of a cleavage. It may accelerate tool wear when the diamond grit is removed from the metallic binding before its useful life is completed. In this case, the resulting cleavage will be very big and it will involve a considerable binding wear before a new abrasive grit emerges. Conversely, if the grit is removed from the metallic binding after its useful life is reached, the cleavage will be less deep and a smaller volume of binding will be consumed in order to remove a new grit. The pull-out is due to an increase either of the cutting efforts or of the cohesion power to keep the diamonds fixed. New grits will emerge on the tools' cutting surface and the wear cycle will begin again [1].

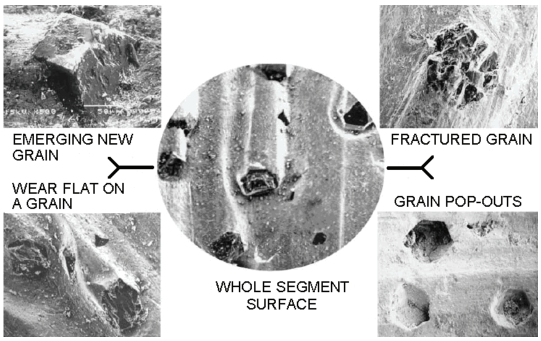

Fig. 13. *Steps of diamond tools wear [5]*

4 ACTIVE FORCES DURING THE BASIC TYPE OF MACHINING

Active forces during the basic type of machining (basic cutting, milling, grinding and polishing) can be determined with measurements of horizontal forces, vertical forces and axial forces. Other needed forces that are necessary for calculations can be determined from the geometry of process.

$$\cos\delta = \frac{F_v}{F_c} \quad (1)$$

$$\sin\delta = \frac{F_h}{F_c} \quad (2)$$

$$F_n = F_c \cdot \cos\left[\left(k\varnothing\right) - \delta\right] \quad (3)$$

$$F_n = F_c \cdot \left(\cos\left(k\varnothing\right) \cdot \frac{F_v}{F_c} + \sin\left(k\varnothing\right) \cdot \frac{F_h}{F_c}\right) \quad (4)$$

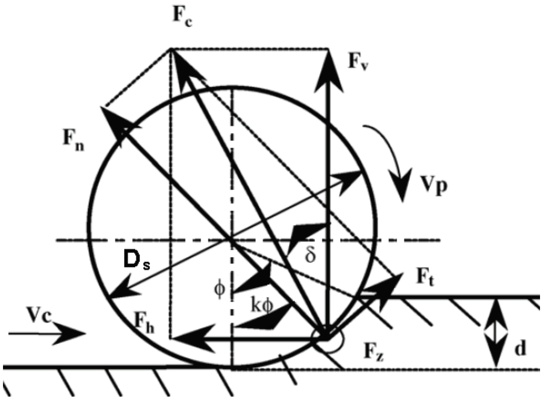

Fig. 14. *The kinematics of basic machining process [6]*

$$F_n = F_v \cdot \cos\left(k\varnothing\right) + F_h \cdot \sin\left(k\varnothing\right) \quad (5)$$

$$F_t = F_c \cdot \sin\left[\left(k\varnothing\right) - \delta\right] \quad (6)$$

$$F_t = F_c \cdot \left(\sin\left(k\varnothing\right) \cdot \frac{F_v}{F_c} - \cos\left(k\varnothing\right) \cdot \frac{F_h}{F_c}\right) \quad (7)$$

$$F_t = F_v \cdot \sin\left(k\varnothing\right) - F_h \cdot \cos\left(k\varnothing\right) \quad (8)$$

$$F_c = \sqrt{\left(F_n^2 + F_t^2\right)} \quad (9)$$

$$\varnothing = \cos^{-1} \cdot \left(1 - \frac{2 \cdot d}{D_s}\right) \quad (10)$$

$$k\varnothing = 0,7 \cdot \varnothing \quad (11)$$

$$SE = \frac{F_t \cdot V_p}{d \cdot W \cdot V_c}, \quad (12)$$

where F_h is the horizontal force (N), F_v the vertical force (N), F_z the axial force (N), F_n the normal force (N), F_t the tangential force (N), F_c the resultant cutting force (N), D_s the tool diameter (mm), d the cutting depth (mm), V_c feed rate (m/s), V_p the cutting speed (m/s), *Ø* the total included angle of the contact zone (degrees), *kØ* is the angle showing the location of the resultant force (degrees), *W* the machining width (mm) and *SE* the specific energy (J/mm^3).

Specific energy decreases if depth, width and work-piece traverse speed increase, and increases with increasing tangential force and cutting speed. A decrease of specific energy is limited with optimal depth of a single diamond grain d_g cut.

Brook has analyzed different cutting parameters. According to Brook [7], each grain on the surface of the segments protrudes p from the surface and indents the stone for a depth d_g. Protrusion p depends on the time t, its minimum value is $p = 0$ and the maximum is $p = p_{max}$ (the crystal pops out or crushes). Brook assesses optimum feed depth is $d_g = 1/6 \cdot ADPD$ and he hypothesizes $p_{max} = 0,5 \cdot ADPD$ [2].

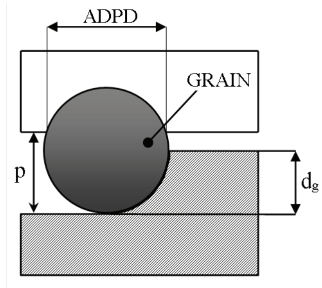

Fig. 15. *Brook model [2]*

5 CONCLUSIONS

To obtain complex shapes of stone products, different diamond tools are needed. To get quality machined products, it is important to understand the machining process and the significance of tool data. It is also necessary to know how the type of diamond grains, hardness of matrix, water cooling and machining process influence the quality and productivity of machining. The right combination of diamond grains type and matrix hardness enables productive, quality machining and long tool life. The structure of diamond tools and the principle of machining, which is the same for all diamond tools from cutting tools to polishing tools, are presented. This is followed by a presentation of basic tools for different machining technologies. The wear of a diamond tool is presented, which is also equal for all types of diamond tools and machining technologies. Different states of wear also have an influence on the tool and the machining process performances.

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