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# ANALYSIS OF STONE MICRO-CUTTING MECHANISM USING THE EXAMPLE OF GRANITE AND MARBLE GRINDING

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***Abstract:*** *The paper presents the results of to date investigations in the field of ornamental stone micro-cutting using the examples of granite and marble originating from the stone varieties of Serbian location. The diamond grain - machined stone (the 'Josanica' granite and the 'Plavi tok' marble) interaction was analyzed. The analysis also embraced the changes of the normal cutting force as a function of cutting speed and grain penetration depth in the chosen stone. Based on grain traces (cracks) that occurred on the surface of the machined stone, the critical cutting depths, at which brittle cutting occurs, were established for the mentioned stones. The presented analysis is to be used for the grinding process optimization as a dominant ornamental stone machining technology with the aim of obtaining quality machined surfaces and preserving the stone surface structure and color.*

***Key words****: micro-cutting, grinding, diamond grain, granite, marble*

## 1. INTRODUCTION

Rock materials are widely used in construction industry for lining the aesthetic surfaces. Of all the materials, the most used rocks are granite and marble that high quality surface finish is required from, however, the accuracy of measures and shapes to a lesser degree. Considering the stone surface finish technologies, the most utilized are grinding and polishing technologies that enable preservation of the structure and high gloss surface. The rock structure characteristics depend on the conditions of its formation, and they are defined by textural and structural properties. The structure is determined by the crystallinity degree and grain size, but also by the shape and mutual relations of the breed components. By the grain size, rocks can be distinguished as: coarse-grained, medium-grained and fine-grained. The texture, the totality of attributes, defines the location and distribution of the one rock components relative to another within the space they cover. The specificity of surface finish technology demands a good knowledge of all the rock's characteristics including its structural-textural (continuum, homogeneity and isotropy), physico-mechanical (specific gravity, porosity, moisture, water-permeability, hardness, toughness and abrasiveness) and mineralogical-petrography (grain size, type and content of colored components, etc) properties. It is well-known that tool wear intensity, as the consequence of granite and marble abrasiveness, is related to friction and cutting speed and cutting resistance, respectively.

## 2. OVERVIEW OF CHIP FORMATION MECHANISMS

Machining by grinding occurs as the sum of effects of all abrasive grains, expressed through the development of deformation and fracturing. However, the mechanisms of micro-deformation and micro-fracturing in the grinding zone differ, depending on the grinding parameters and non-homogeneity of the machining material. A large number of researchers dealing with the development of model for deformations and fracturing regarded the cutting action of a diamond grain in the grinding wheel as being identical to the indentation effects caused by a diamond indenter during hardness measurements. Considering the investigations on brittle materials, they go into two directions: by how the force acts during the indentation (dynamic and static) and by the shape of the indenter. Lawn and Wilshaw [1] think that fracture patterns in brittle materials, under blunt indenters of a larger radius, usually occur as a result of cracks' presence immediately outside the contact zone. By increasing the normal load, these surface cracks evolve into the so-called Hertzian cone cracks. Anton and Subhash [2], unlike the traditional static indentation models, which do not capture the strain rate effects, consider that the current dynamic indentation can provide a more realistic picture of the influence of loading rate on the material removal mechanisms during a dynamic process. Conway and Kirchner [3] analyzed the mechanics of crack initiation and propagation beneath a moving of sharp indenter. A fracture mechanics solution for a single embedded penny-shaped crack was used to predict the propagation depth of pre-existing defects. The second group of researchers, though to a lesser extent, performed the cutting process in a variety of brittle materials by a single diamond grain. Mishnaevsky [4] performed the real cutting process in brittle materials and observed different physical mechanisms involved in material destruction (deformation, crushing, cracking and spalling). He considers that neither Hertzian cone cracks nor circumferential cracks are formed. Instead, penny-shaped cracks in the cutting force vector direction are formed. Chiaia [5] provides a system analysis for the current approaches to the issues of micro-cutting processes in brittle and quasi-brittle materials. It was shown that various interaction mechanisms beneath the tools during the penetration process are essentially reduced to plastic deformation and brittle fracturing. The third group of researchers analyzed the crack formation and development in brittle materials. Labuz et al. [6] studied crack propagation in granite and concluded that a large number of micro-cracks occur around the crack tip covering the fracture process zone and together with the fracture free length defines the effective crack length. Germanovitch et al. [7] investigated brittle material fracturing in uniaxial compression which is manifested through spalling or shearing (oblique fracture) as the consequence of a multitude of existing cracks. Abe et al. [8] investigated the formation and proliferation of cracks in the granite and their effects on the fracture process zone. The fourth group of researchers performed the real cutting and grinding processes in brittle materials and analyzed the crack propagation and chip brittle fracturing mechanisms. They measured the cutting forces, and the cutting strength and tool wear in ceramics and granite with the aim to recommend the efficient abrasive machining [9-15].

## 3. MICRO-CUTTING EXPERIMENTAL SCHEMES

The cutting ability of a single diamond grain in the process of its acting upon the machined material (granite and marble) is primarily determined by the physico-mechanical properties and geometrical parameters, conditions and strength of its gracing into the bond and also by the kinematic and thermodynamic conditions of the grain's operation. The grain strength characteristics, as opposed to the action of forces and temperature effects, cause significant differences in tool cutting properties. The diamond grain shape influences the basic parameters of the grinding wheel cutting properties: tool life, productivity, cutting forces, grinding temperature, surface layer state, etc. Unlike the tools with geometrically defined cutters, the geometry and shape of diamond grains is complex and undefined to some extent. The analysis of work of such grains includes experimental determination of the size, shape and geometry with the aim of replacing such non-defined grains, in the final calculations, with the grains of equivalent shape. The micro-cutting process was performed in two modes:

The first model (Fig. 1): cone shaped diamond grain, a $120^0$ tip angle, a 0.1 mm tip radius, was placed and rigidly fastened to an aluminium disc 150 mm in diameter that was statically and dynamically balanced. On a cutting table of a HMC 500 machine, a dynamometer was mounted with a fixture for clamping the stone specimens (granite, marble). The fixture enables the rotation of the stone specimens (granite and marble) under an inclination relative to the axial motion of the cutting grain ($v_w$), thereby achieving varying depth of cut. The 1:200 inclination enables achieving varying grain penetration depth up to 0.28 mm.

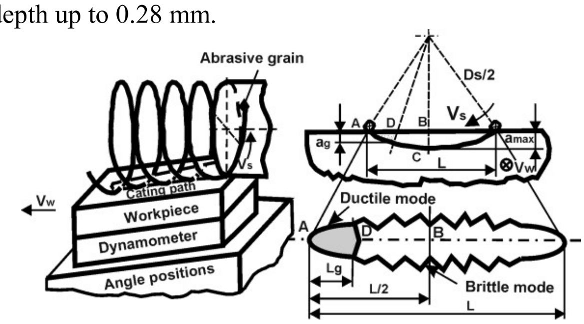


*Fig. 1 Micro-cutting with diamond grain rotary and radial motion – scheme 1*

The second model of the cutting process is reduced to the principle of the peripheral milling with a single grain, with the grain penetration depth adjustment by moving the disc in the $z$-direction (Fig. 2). The chip formed in the process is a space between the two epicycloids.

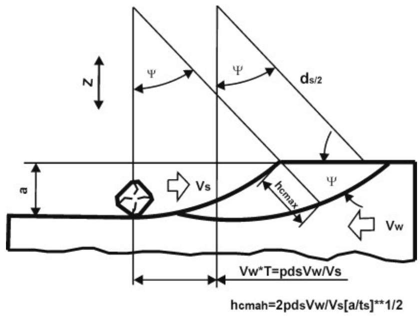


*Fig. 2 Micro-cutting with diamond grain rotary and radial motion – scheme 2*

## 4. EXPERIMENTAL RESULTS

The micro-cutting process was performed on two types of stone: the 'Josanica' granite (GJ) and the 'Plavi tok' marble (PT) whose physico-mechanical properties were examined and presented in Tab. 1. The values of the listed properties were determined as mean values obtained from a larger number of measurements, depending on the petrography nature of the stones (granite and marble). The measurements indicate pronounced differences in physico-mechanical properties of the examined stones (GJ granite and PT marble).

*Table 1. Physico-mechanical properties of stones*

| Properties | Granite | Marble |
|---|---|---|
| | Jošanica GJ | Plavi tok PT |
| Specific gravity, KN/m$^3$ | 29.70 ± 0,3 | 26.65 ±0,2 |
| Micro-hardness , HK75/HK25 | 3.1 | 1.9 |
| Compressive strength , MPa | 185 ±20 | 75.04± 3.5 |
| Ultimate strength , MPa | 16.6 ± 1 | 8.20 ± 0.3 |
| Cohesion , MPa | 31.8 | 14.10 |
| Abrasion coefficient , % | 21.5-23.0 | 29-30.5 |

Experiments were carried out using the following measuring equipment: a two-component piezo-electric dynamometer (Kistler 9271), a data acquisition card ED2110-AD, a laser microscope (Carl Zeiss – LSM 510) with an Axioscope F32. Figs. 3 and 4 show diagrams of changes in the normal cutting force (resistance) during machining of stones (granite and marble) as a function of grain penetration depth at cutting speeds $v_s$ = 7.85, 11.1, 15.7 and 22 m/s.

The results presented are mean values of 40 measurements, with the standard deviation of ±10% for GJ and ±5% for PT. On the basis of the dependences obtained, it is concluded that as the grain penetration speed increases the cutting resistance increases in both types of stone (granite and marble), being higher in the granite (GJ) machining than in the marble (PT) machining, due to the granite's higher hardness and strength compared to the marble. If analysis is performed of the changes of forces in both schemes of loading, it is observable that both types of stone have approximately identical values for the same grain penetration depth, which confirms the correctness of the measurements concept and the accuracy of the obtained results. The non-linearity in the change of $F_n$ is the consequence of the stones' non-uniformity (granite and marble). Also, as the grain penetration depth increases, the cutting force increases. It can be stated that at places where the force decreases this is the result of a soft phase presence in the stone (granite and marble). The processing of the experimental results makes possible to arrive at a mathematical model of the force for a range of changes in speed ($v_s$) and grain penetration depth ($a$):

$$F_n = 52{,}04 \cdot v_S^{\,0{,}738} \cdot a^{1{,}237} \rightarrow GJ \qquad (1)$$

$$F_n = 15{,}7 \cdot v_S^{\,0{,}68} \cdot a^{0{,}78} \rightarrow PT \qquad (2)$$

The analysis of the traces from the stone micro-cutting (granite – Fig 5 and marble – Fig.6) can provide the description of the chip formation mechanism. When entering into the material, the diamond grain establishes strain and deformations followed by radial and lateral cracks that increase as the cutting depth increases. At a certain cutting depth, the mentioned cracks become interconnected, causing the detachment of the machined material in the form of blocks with non-equal dimensions. On the grain's leaving the contact, median cracks emerge too. At smaller cutting depths, there occurs the diamond grain's trace that causes elastic and afterward plastic deformations followed by lateral, radial and median cracks that are smaller in intensity. At larger cutting depths, the mentioned cracks enlarge and become interconnected, causing the fracturing of blocks of the machined surface. In this zone, fracturing, crushing or detachment of the entire stone grains (granite and marble) is noticeable, which causes the non-uniform fracturing along the channel formed by the diamond grain. Beneath the machined surface there remain the cracks formed not only during the stone formation process (granite and marble) but also during the machining process, so they can essentially influence the work piece hardness. This indicates that cracks formed during the machining process should be of as small dimensions as possible, because the detachment of blocks of the machined material will be smaller in volume and the corresponding characteristics of the machined surface quality (*Ra, Rz, Rmax)* lower, respectively. In stone (granite and marble) micro-cutting two regions are observable, which can be restricted by the grain penetration depth (critical grain penetration depth) that separates the region of plastic deformation followed by crack formation from the region of fracture-induced detachment of the machined material.

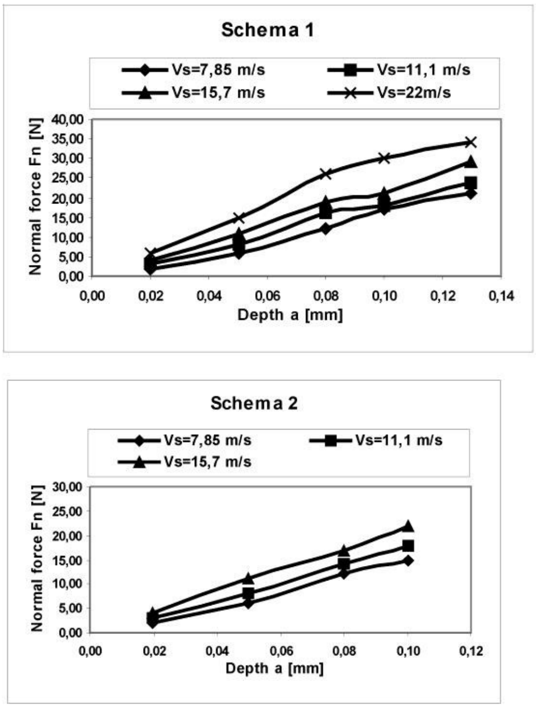


*Fig. 3. Change of the normal force as a function of grain penetration depth in GJ granite micro-cutting: (a) Scheme 1 (b) Scheme 2*

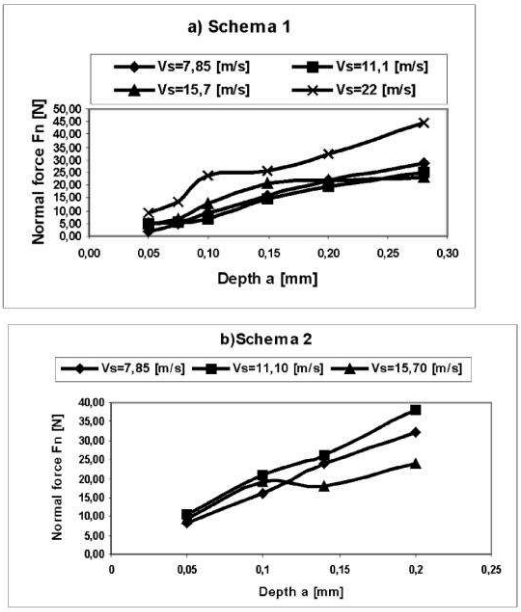


*Fig. 4. Change of the normal force as a function of grain penetration depth in PT marble micro-cutting: (a) Scheme 1 (b) Scheme 2*

The critical penetration depth can be used as one of the criteria for the optimization of the grinding process. The measurements established the critical grain penetration depth in the GJ granite of 0.020 mm ($v_s$ = 7.85 m/s) and that the critical depth declines to 0.015 mm as the speed increases to 15.7 m/s. The lengths of the radial cracks at the critical depth are 0.35 – 0.30 mm for the range of penetration speeds given above. In the PT marble machining as early as at grain penetration depth of 0.02 there occurs fracturing along the grain trace. In both types of stone (granite and marble) the increase of speed leads to the increase of radial cracks and fracturing along the grain trace, resulting in decrease of the critical grain penetration depth.

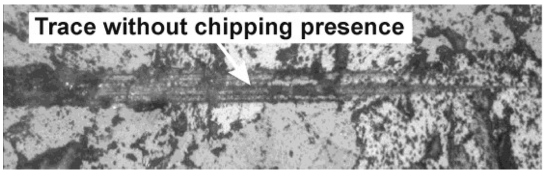


*Figure 5. Micro-cutting trace on GJ granite, scheme 2. ($v_s$=15.7 m/s, a=0.025 mm), x100*

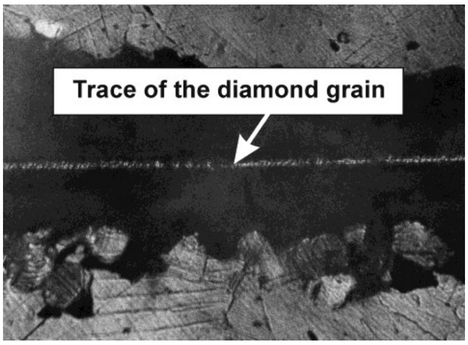


*Figure 6. Micro-cutting trace on PT marble, scheme 2. ($v_s$=7.85 m/s, a=0.1 mm), x125*

## 5. CONCLUSION

The development and application of new diamond tools for ornamental stone (granite and marble) machining implies the knowledge of processes that take place at the point of interaction between the abrasive grain-granite and the abrasive grain-marble, respectively. The choice of the cutting mode and tool characteristics are greatly affected by granite and marble physico-mechanical properties, primarily abrasiveness (wear resistance) that directly influences tool wear. Fine-grained and medium-grained varieties of granite and marble are more suitable for machining, because the fracturing phenomenon is also less pronounced than in coarse-grained structures. Beneath the machined surface there remain cracks formed not only in the granite formation process but also during the machining process, so they can essentially influence the work piece hardness. This indicates that cracks formed during the machining process should be of as small dimensions as possible, because the fracturing of blocks will be smaller in volume and the corresponding characteristics of the machined surface quality lower, respectively. The investigations carried out provided for establishing the critical grain penetration depth, thereby micro-cutting at stone (granite and marble) machining as well as the components of cutting resistance as a function of cutting speed and grain penetration depth.

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