Correlation between static indentation and micro cutting marble-based material

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Abstract. *Defining how the chip is formed during micro-cutting can be extremely difficult. The reason is the miniaturization of the process itself in relation to the macro cutting, as well as, the smaller depth of cut in relation to the tool tip radius. Besides, the micro-cutting mechanism is influenced also by the material being machined, as well as the processing conditions. Considering that marble is brittle by its nature, the micro-cutting mechanism does not match that defined for various types of steel, aluminum, etc. Experimental analysis revealed that during the micro-cutting of marble, two different processing modes occur. In the first (ductile mode) micro-cutting is based only on the elastic and plastic deformations. In the second, which corresponds to the brittle fracturing mode, the chip is created by the formation and uncontrolled growth of the cracks within the material. The critical depth of cut that separates the two modes can be determined in many ways, and one of them is the static indentation. In addition, this method can also be used to identify the types of cracks that occur during micro-cutting in a brittle fracturing mode, which is done in this paper.*

Keywords: micro-cutting;brittle; static indentation; ductile mode

Static indentation is one of the methods used to identify possible phenomena resulting from the micro-cutting process. The main advantage of this method is the ability to define the zone to which cracks can occur under the action of an appropriate indentation force. It is well known that cracks are an indispensable phenomenon in the process of chip formation during the machining of brittle materials. The indenters used in this method can be of different shapes. Most commonly found in literature sources are Vickers, Rockwell, Brinell, and Knoop. Not so rarely mentioned are indenters whose geometry is precisely defined by the researcher himself [1, 2], depending on the purpose of the experiment. After the indentation process, a trace remains on the workpiece surface, which, depending on the indentation force, i.e. the depth of penetration of the indenter into the workpiece, can be classified into three groups/phases:

- Phase 1: trace created without the destruction of the material (ductile mode), fig. 1a;
- Phase 2: the formation of a trace which is accompanied by the development of cracks within the material (brittle fracturing mode), fig. 1b;
- Phase 3: the trace that carries with it, not only cracks that extend inside the material but also the separation of small particles of the material (brittle fracturing mode), fig. 1c.

The main disadvantage of this method when describing micro cutting is the presence of only the normal component of the cutting force during the indentation process, while the tangential component is omitted.

The critical and boundary penetration depths separating phases 1 and 2 and phases 2 and 3, respectively, can be determined by microscopic observation of the formed traces. Its value is obtained by determining the depth of indentation at which the initialization of the cracks occurs. The indentation depth value can be determined from the known values of the diagonals d_1 and d_2, whereby the mean value of the diagonals can be written as:

$$d_{\mathrm{sr}} = \frac{d_1 + d_2}{2} \tag{1}$$

Projecting the mean of the diagonal on a line that is collinear with the edge of the trace results in a mean value of the length of the trace edge:

$$l_{\mathrm{eg}} = \frac{\sqrt{2} \cdot \left(d_1 + d_2\right)}{2}, \tag{2}$$

from which with further knowledge of the angle of the tip of the indenter, indentation depth can be derived for the Vickers indenter:

$$a = \frac{\sqrt{2} \cdot \left(d_1 + d_2\right)}{4 \cdot \mathrm{tg}\,\psi}. \tag{3}$$

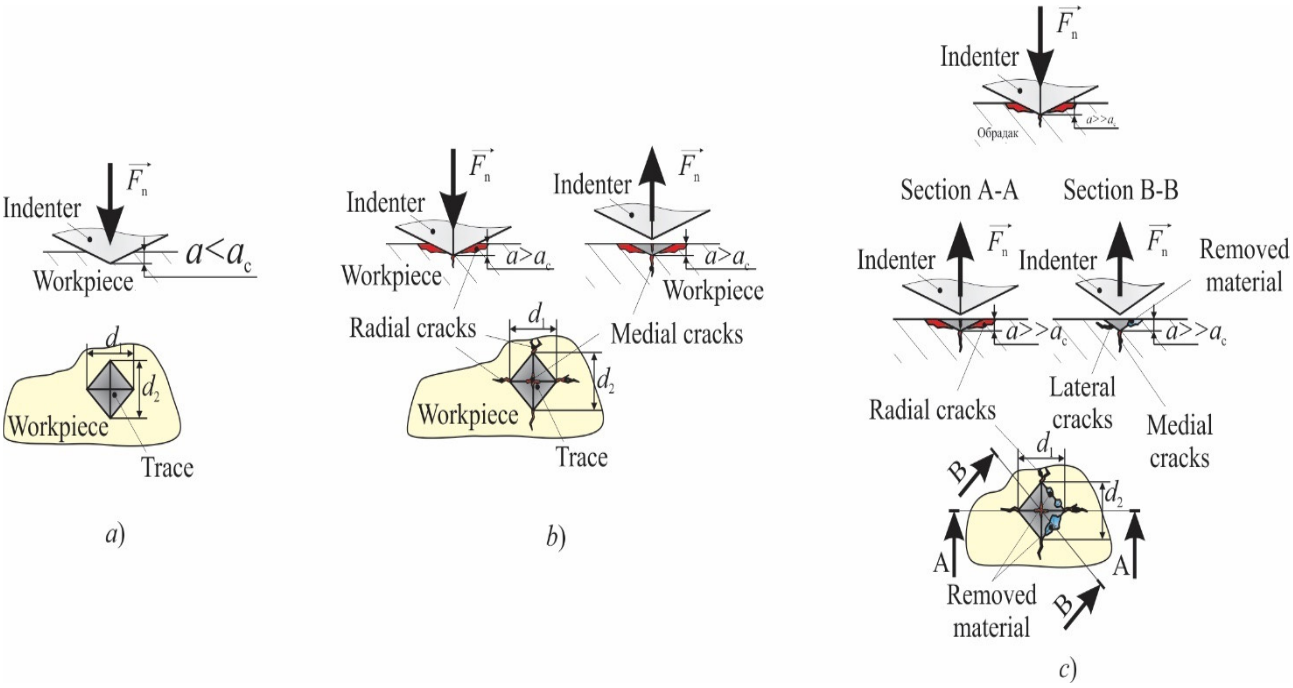

Fig. 1. Static indentation process [3]

Static indentation experiments were conducted on a TIME-TH710 hardness measuring device. The device consists of a diamond tip (Vickers indenter), which performs the indentation process, as well as set of microscopic lenses that provide magnifications of 40x and 400x, and serve to observe the formed trace. Determination of the values of the diagonal of the traces (d_1 and d_2) is made using the focal lines presented in fig. 2. The experimental plan was formed on the basis of a change in the value of the indentation force (F_n) from 0.098 to 9.807 N and the value of the idle time of the indenter in the material T from 0 to 15 sec. The specified range of values of the intensity of the indentation force (F_n) is defined based on the expected values of the critical penetration depth of the tested material. Different values of the intensity of the indentation force (F_n) are necessary to effect changes in the depth of penetration of the indenter (a) into the test material. On the other hand, the reason for changing the value of the idle time of the indenter (T) at the moment of achieving the desired indentation force is the unknown time necessary to stop the uncontrolled crack growth within the material. In other words, this makes it possible to complete the process of uncontrolled crack growth within the test material after the indentation process.

The experiment is based on the fact that for one value of the indentation force (F_n) and idle time (T), several measurements were performed. In this way, a validity of results was carried out. How the properties of each mineral are different and can vary greatly, measurements have been made on several different grains of minerals, of which the material is composed. This achieves a more accurate picture of possible/emerging phenomena within the material. Macroscopic observation of the examined surface reveals that the dimensions of the mineral grains are far larger than the dimensions of the traces formed. Therefore, there was no problem in selecting the indentation site, thus avoiding the possible simultaneous indentation on the two minerals.

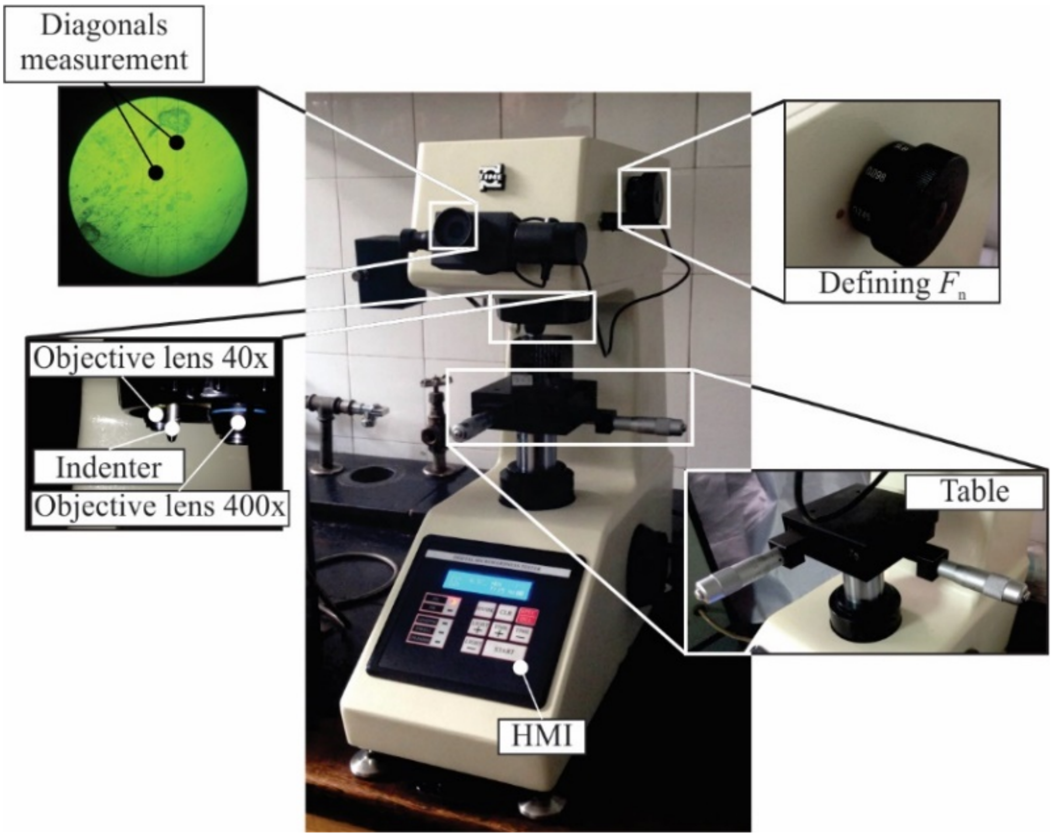

Fig. 2. Experimental setup

Using microscopic observation on the mentioned device, it was possible to determine the values of the diagonal of the traces (d_1 and d_2). Thanks to the known geometry of the indenter, where the angle between the opposite edges, in this case, was $2\psi = 136^{\circ}$, and the measured values of the trace diagonals (d_1 and d_2), the values of the penetration depths of the indenter were obtained using the expression represented by equation (3). Based on the data collected, such as penetration depth values and information on the presence and development of cracks within the materials obtained by microscopic observation, a boundary was defined between the ductile and brittle fracturing mode.

Figures 3a and 3b, as graphs, show the values of the hardness of the Plavi tok material as a function of the penetration depth of the indenter for the idle times $T = 0$ and $T = 15$ sec. In the mentioned graphs, it can be observed that for both T values, the hardness values decrease equally with the penetration depth of the indenter. The decrease in the hardness of this marble is due to the uncontrolled growth of cracks within it from the moment when the penetration depth exceeds the critical value. The micro-cracks formed around the indentation site increase the penetration depth of the indenter. Similar phenomena occur with other materials, brittle in nature, such as various types of ceramics [4–6] and glass [7].

Due to the roughly balanced value of the hardness of the minerals in the Plavi tok marble, it is expected that by indentation at a static force, each grain will have a similar response. In other words, the crack propagation through the grain as well as the penetration depth will be similar between the grains. Figure 4 show some of the traces obtained by the method of the static indentation with the Vickers indenter on the various grains of a previously prepared material surface. Different values of the force of indentation, led to the formation of the traces in the tested marble according to the model presented through the three stages.

Figures 4a-d clearly show the formed traces during phase 1, which did not cause cracks inside the material. At this stage, the material is purely plastically deformed. The penetration depth did not exceed its critical value which separate the ductile from the brittle fracturing mode. The value of maximum penetration depth achieved at this stage, without cracking, is a = 5.73 μm.

However, in the case where the value of the intensity of the indentation force is Fn = 0.245 N, while the value of the penetration depth of the indenter exceeds a = 5.74 μm, phase 2 begins. During this phase, as noted above, the formation of trace is followed by the formation of cracks (medial and radial) in the indentation zone. The range of traces depths in the test material, which are formed in phase 2, ranges up to a = 11.33 μm. Some of the traces formed in phase 2 are shown in Figures 4e-h.

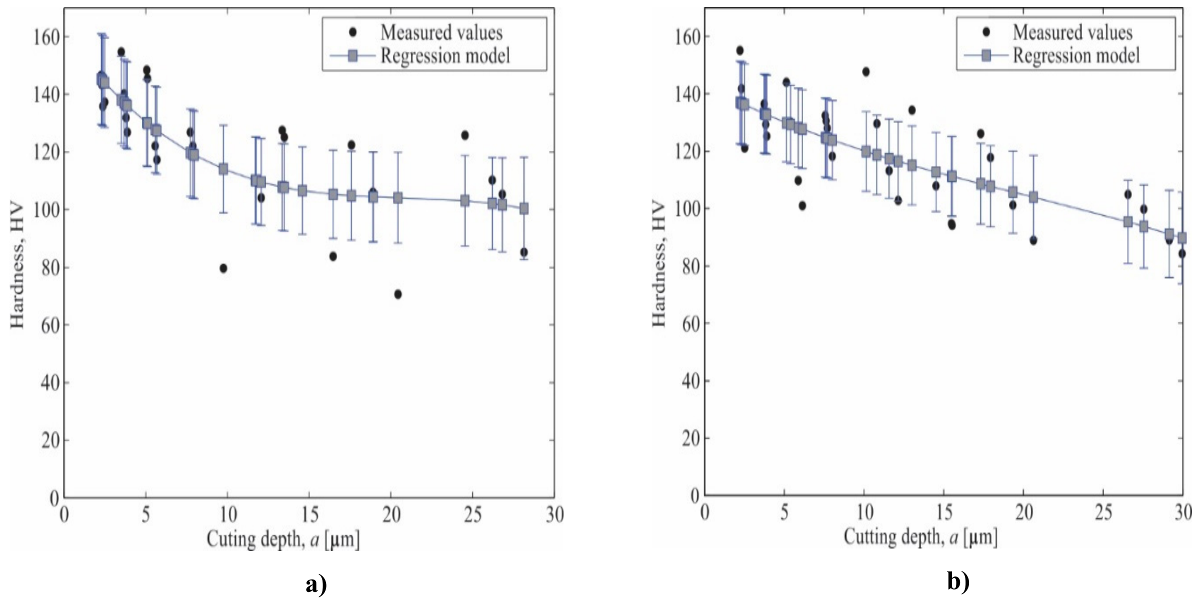

Fig. 3. Values of the hardness for a) *T*=0 and b) *T*=15 sec

Exceeding this range, phase 3 occurs, in which lateral cracks begin to appear in addition to the medial and radial. During the static indentation, the presence of lateral cracks leads, on the one hand, to the removal of small parts of the material and, on the other, to the partial separation (lifting) of one part of the material, as shown in Figures 4i-p.

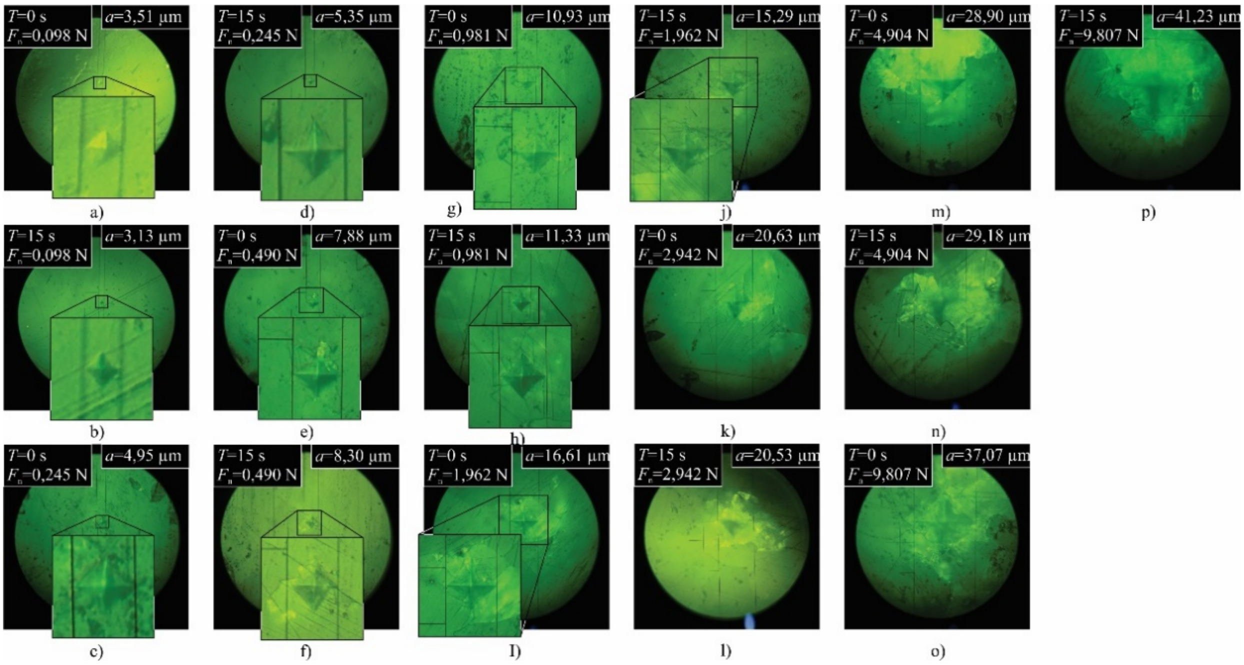

Fig. 4. Formed traces

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