Wedge effect influence in water jet cutting of rocks

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Although the excavation mechanism in the application of water jet technology for rock cutting has been object of a number of investigations, it is not yet fully understood. The paper deals with an experimental study aimed at putting into evidence the influence of the “wedge” effect applied by the high pressure water entering the rock fractures. Tests carried out under different operational conditions on rock samples soaked in fluids with different viscosities led to results giving a clear indication of the influence of the wedge effect. On that basis a new hypothesis on excavation mechanism has been elaborated with the help of a simplified numerical simulation.

Keywords: Waterjet, rocks, cutting mechanism

1.0 Introduction

Water jet technology is based on the action of a high velocity jet generated at pressures that can reach hundreds of MPa. The nozzles adopted in the industrial applications of the technology normally do not exceed 1.5 mm in diameter, therefore the corresponding impact areas have a surface of few mm^2. Almost the entire jet energy is transferred to the target material through such an area and the erosion effects strongly depend on the material mechanical characteristics at small scale.

This is in some way the reason of the success of the technology which is commonly adopted in a number of industrial applications, included ornamental stone quarrying and processing [1, 2, 3]. In fact the distinctive aspect of the technology is represented by its flexibility, resulting from the possibility to change the amount of energy carried by the jet (pressure), the impact area (nozzle diameter) and the impact time (jet traverse velocity on the target surface).

Those parameters can be adjusted according to the material characteristics to optimize the working effect required.

In the case of ornamental stone, in particular granite, the setting of the operational parameters is complicated by the heterogeneous structure of the material. In fact the impact area has often a dimension that is lower than the crystal size of the different rock forming minerals. Consequently the jet traversing the rock continuously encounters materials with different mechanical characteristics with the complication of the contacts between mineral crystals which not always are less resistance areas.

In those conditions the developing of an erosion mechanism model is difficult and complicated. As matter of fact even if a number of theories have been elaborated by different research teams along the years not one of them explains satisfactorily the behavior of the rocks when impinged by a water jet.

Some of the proposed theories take into consideration the permeability and porosity of the rocks [4, 5] with no regards for the mineral composition and the crystal size. Further developments of those theories [6] did not improve the quality of the models which have as major weak point the lack of explanation of the existing threshold pressure.

Various theories were focused [7, 8, 9] on the brittle behavior of the material and on the fracture propagation effect, putting into light the influence of crystal size. Other theories [10] put into evidence the different behavior between sedimentary and igneous rocks.

The present experimental work had the purpose to evaluate the cutting performance when the water jet is acting on granite samples saturated with fluids of different viscosity. The analysis of the results can give some interesting indication about the cracks propagation influence on the excavation mechanism.

2.0 Experimental Research

2.1 Materials

Cutting tests have been conducted on a commercial granite extracted in Sardinian known as "Pearl Grey".

The minero-petrographic structure of the granite is holocrystal, hypidiomorphic uneven grain with a isotropic texture. The minero-petrographic characteristics of the granite are reported in table 1.

Table 1 - Minero-petrographic characteristics of the granite "Pearl Grey".

	Quartz	Feldspar	Plagioclase	Mica
Mineral composition [%]	31	38	24.5	6.5
Mean size of mineral grains [mm]	2.9	3.8	1.7	1.4
Standard deviation [%]	51	28	36	34
Granite mean grain size [mm]	2.85			

In table 2 are reported the mechanical characteristics of the "Pearl Grey" granite.

Table 2 - Mechanical characteristics of the "Pearl Grey" granite

Specific mass [Kg/m3]	2,615
Compressive strength [MPa]	189.3
Flexural strength [MPa]	15.10
Knoop microhardness [MPa]	6.367

Considering the purposes of the experimental work, the porosity characteristics of the material are of particular importance. The results of the granite "Pearl Grey" characterization are reported in Table 3.

Table 3 – Porosity characteristics of the “Pearl Grey” granite

Total porosity [%]	0.8			
Porosity [mm^3 Hg/g]	3.1			
Voids dimension [µm]	10 - 1	1 – 0.1	0.1 – 0.001	≤ .001
Void [%]	21.05	44.08	34.87	0
Void specific surface [m^2/g] (assuming a cylindrical shape)	0.05			

2.2 Equipment

The tests have been conducted adopting a Hammelmann pressurizing system capable of delivering 52 l/min of water at a maximum pressure of 250 MPa. The pressurized water reaches through high pressure hoses a cutting head provided of a fix single nozzle.

The granite samples were traversed under the jet by means of a support table moved by an electrical motor with variable rotating velocity. A chain-pulley system connected the motor to the supporting table.

2.3 Test procedure

The samples of granite used for the cutting tests had a parallelepiped shape 5 cm high and 20 cm x 20 cm base. Four granite samples have been prepared for the tests by saturating three of them respectively with tap water, wax and oil, while the fourth sample has been dry. To obtain the saturated and dry samples the granite parallelepipeds have been put into a oven at a temperature of 80°C. As mentioned before three of them have been submerged for a period of 48 hours at that temperature in water, molten wax and oil. The fourth has been dry at the same temperature and for the same period. Then the samples have been kept at least 24 hours at room temperature before running the tests. The dry sample has been put in the oven after each test.

By means of the support table the samples have been translated at a constant velocity of 1.5 m/min under the jet acting perpendicularly on the rock surface. For all the tests a nozzle of 1.25 mm has been adopted. The distance between the nozzle and the rock surface (stand-off distance) has been fixed at 10 mm.

For each sample the pressure has been varied obtaining three cuts corresponding at 80, 160 and 240 MPa. The distance of adjacent cuts and cuts and sample edges has been fixed in 5 cm to avoid possible interferences.

The mean depth of cut obtained in each test has been measured by a depth gauge.

2.4 Results

The results in terms of depth of cut as a function of pressure are reported in Figure 1 for the four experimental conditions (samples saturated with water, wax and oil and dry sample).

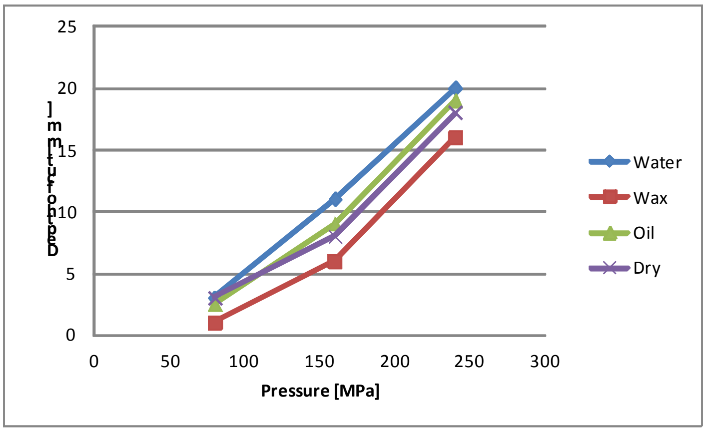

Figure 1- Depth of cut as a function of pressure for the different experimental conditions.

In all cases the depth of cut increases with the pressure, almost linearly for the sample saturated with water. The difference between the depths obtained for the four experimental conditions increases at the intermediate pressure of 160 MPa. The depth of cut obtained for the same pressure in the sample saturated with wax is always the lowest, then the depths obtained increase in order for the dry, the oil saturated and the water saturated samples, except for a value of depth obtained at the pressure of 80 MPa for the dry sample.

In Figure 2 the results are expressed in terms of relative depths having as a reference the depths obtained for the water saturated sample.

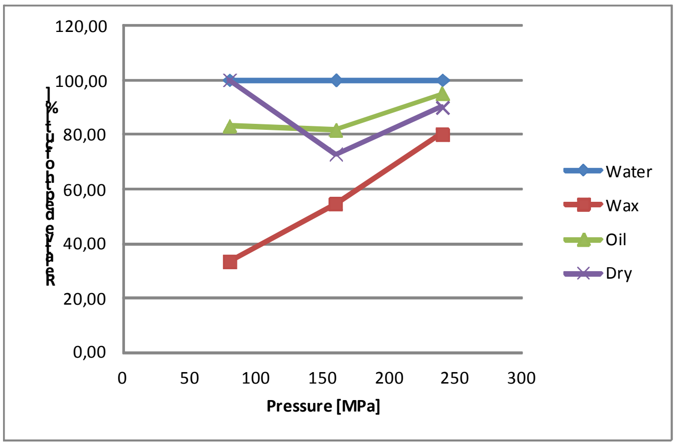

Figure 2 – Relative depth of cut as a function of pressure for the four experimental conditions

Figure 2 shows clearly that the best results in terms of depth of cut are obtained when the rock is saturated with water, while the presence of wax in the granite fractures represents an adverse condition. The dry sample and the oil saturated sample are in a intermediate position, even if the cutting performance seems to be a little lower in the case of the dry sample.

3 Cutting model

The different behavior of the samples can be explained by taking into consideration a cutting model which is based on the model proposed by Erdman–Jesnitzer et al. [7, 8]. They set up an experimental plan in which a stationary water jet impacted a fixed point of the specimen surface. They measured the time behavior of the jet penetration velocity and proposed the following conceptual model of the water jet excavation mechanism:

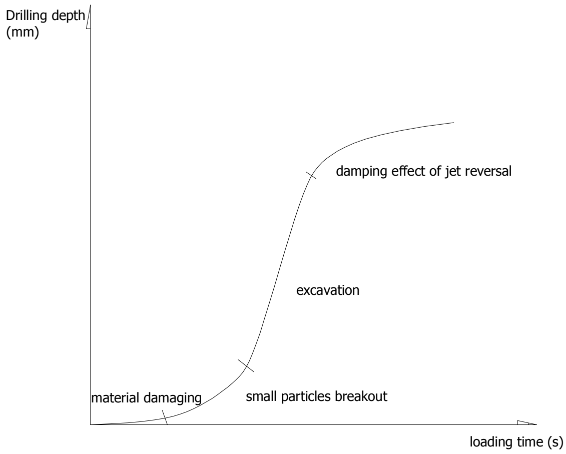

Figure 3 – Excavation model proposed by Erdman – Jesnitzer et al.

- In a first stage of the excavation process, the impacting water jet causes the development of the material defects (microcracks – cleavage planes, crystal boundaries, pores) in a small volume around the impact point (water jet influence volume) and the expulsion of very small rock pieces.
- The second stage is characterized by the intersection of the micro cracks inside the volume of influence that is, consequently, expulsed. As a result an appreciable value of the penetration velocity is observed.
- In the third stage the water jet acts on the concave surface previously created with an amplified impact pressure. In this phase major cracks develop and relatively big rock fragments are removed resulting in a significant increasing of the penetration velocity.
- In the fourth stage the deepening of the groove causes an increasing of the wasted energy and a reduction of the impact pressure that finally results in a progressive decrease of the excavation velocity.

In the delineated conceptual model the defects that typically characterize the crystalline rock structure play a key role; at their boundary, in fact, the stress induced by the impacting water jet is amplified causing the development of the same defects till a cracks net is created and the material is fragmented and expelled. Considering the rock as a system, its load is represented by the stress induced by the water jet at the cracks boundary while its capacity is represented by the cracks propagation strength expressed through the fracture toughness K_{Ic} [MPa x $m^{1/2}$].

The good correlation between the threshold pressure and the fracture toughness found out by the authors, demonstrates the correctness of the model. On the other side it can be argued that the proposed model do not account for the effect of the hydraulic pressure induced by the jet inside the cracks. Actually this inner pressure causes a tensile stress at the cracks boundary that substantially contributes at the crack growth (wedge effect).

Figure 4 synthetizes a development of the Erdman-Jesnitzer model in which the load of the system is represented by the inner cracks pressure induced by the water jet while its capacity is the fracture toughness.

The pressure induced within a crack hydraulically connected with the water jet impacting on the material surface, depends on the jet velocity and on the crack geometry. The velocity v [m/s] and the flow rate q [m^3/s] of a water jet can be calculated, respectively, as

$$v=(2gP/\rho)^{1/2}$$

$$q= v\, Ar$$

where p [Pa] is the generating pressure, ρ [kg/m^3]is the specific weight and Ar [m^2] is the area of the “vena contracta”.

For water jets generated by standard geometry nozzles at stand-off distance smaller than 50 d (d=nozzle diameter), the impact area is nearly equivalent at the area of the vena contracta.

The pressure over the impact area in not uniform: it has a bell shaped distribution characterized by the value of the generation pressure at the center of the impact area and null value at its perimeter. The average value of the pressure over the impact area is roughly half the generation pressure.

The main difference between the two models is represented by the role assigned to the cracks: in the original model they are considered only as stress concentration elements; in the proposed model cracks are seen as elements of hydraulic pressure transmission. This new concept allows to explain the observed influence of the material saturation degree and of the type of the crack filling material on the water jet excavation velocity.

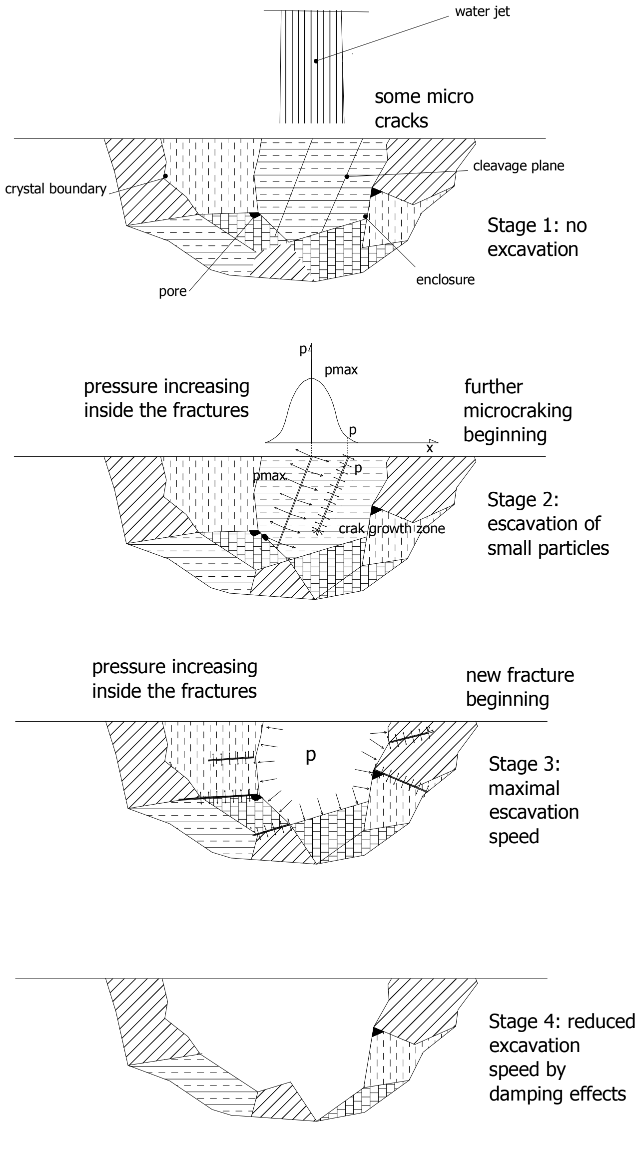

Figure 4 – Schematic representation of the new cutting model

4.0 Discussion

When a water jet impacts the surface of a saturated rock, according to the proposed model, the impact pressure is transferred, ideally without flow, to the fluid inside the rock cracks, generating a tensile stress at their boundaries. If the fracture toughness is exceeded, cracks develop inside the influence volume, finally producing the material excavation.

If the water jet impacts on a dry rock surface, part of its kinetic energy is used for the penetration of the water in the material porosity: the pressure within the cracks will result smaller than that obtained in case of saturated rock. Furthermore the time spent for the water to penetrate the rock cracks is lost for the excavation process and results in a reduction of the excavation rate. In a cutting process, where the impact point moves over the rock surface, the time spent for the saturation of the material causes the decrease of the cutting rate and a corresponding increment of the excavation specific energy.

In the case of the sample saturated with oil the jet pressure is transmitted to the pore faces through a fluid characterized by a viscosity which is hundreds of time higher than that of water and which does not transmit the tension as efficiently as water. At the same time in the case of sample saturated with oil the disadvantages encountered in the dry pore condition, as explained before, are not present.

When the pore are, at least partially, saturated with wax the pore are practically closed by a solid material and the effects of the jet are reduced to the stress transmitted through the rock structure, with practically no wedge effect.

The fact that at higher pressure the results obtained under the different condition are closer indicates that when the stress state increases (higher pressure) an excavation process developing according the original Erdman-Jesnitzer model is predominant and the wedge effect is less important.

5.0 Conclusions

The water jet excavation mechanism in case of rock cutting is not yet completely clarified, even if different theories have been proposed.

The experimental work carried out on granite samples characterized by pores filled with different fluids allows to draw the following conclusion:

- when the rock is saturated with water the cutting rate is higher, while when the wax is filling the pores the performance decreases; intermediate results are obtained when the samples are dry or filled with oil;
- the cutting performance is less affected by the pore conditions (dry or saturated with different materials) when the pressure is higher;
- the experimental results can been explained by a cutting model which takes into consideration the wedge effect of the pressure applied to the fracture faces by the jet action.

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