Abstract
The paper deals with the problem related to abrasive water jet cutting of thick plates made of different materials (marble, granite, aluminium, plexiglass). The solution here proposed is based on the use of high velocity multi-pass cutting strategy, already tested successfully in the case of steel. The influence of the relevant operational parameters, such as traverse velocity (number of passes), mass flow rate and grain size of abrasive has been evaluated and discussed considering the results obtained in terms of specific erosion and quality of cut surfaces. Finally an economic analysis for the cutting process with multiple passes is presented and for each material the optimum cutting conditions are defined in face of cut surface quality requirements.

1 INTRODUCTION
Abrasive water jet technology is nowadays well affirmed in different industrial sectors and its application is worldwide spread. The technology is traditionally adopted for contour cutting of plates of different materials, from softer paper or food to harder metals and ceramics. Normally the cut is obtained by only one pass of the abrasive jet through the slab thickness, the abrasive particles impinging the material in the direction of the jet axis with a low impact angle. In this case the quality of the surface obtained changes with the depth of cut and it is strictly connected to traverse velocity (1, 2).
A new cutting approach has been tested in previous experiments (3) conducted on stainless steel plates. The new solution proposed is based on the multi-pass strategy: the cutting through the plate is obtained by means of successive passes at higher traverse velocity. According to the new solution, the abrasive particles impinge the material with an angle near 90° and the leading edge of excavation direction is not parallel to the jet axis but perpendicular to it, being represented by the bottom of a small kerf deepening after each pass until a cut through is achieved.
Because of the change in impinging direction an important influence is expected to be exerted by the mechanical characteristics of the material. It is well known that cutting mechanism is different in ductile and fragile materials and that the impact angle has different effects according to the cutting mechanism (4, 5). Of course traverse velocity plays a fundamental role, probably even higher than in the case of one pass cutting. In fact the number and frequency of impacts of abrasive particles depend directly on traverse velocity. Other parameters affecting the results in terms of surface quality and cutting rate are the abrasive grain size and abrasive mass flow rate. To clarify and define the influence of material characteristics and setting parameters, a series of tests have been conducted in the Laboratories of the Department of Geoengineering and Environmental Technology -University of Cagliari- and of the Mineral Science Study Centre of CNR.

2 EXPERIMENTAL PLAN

A series of linear cutting tests have been conducted on thick slabs of different materials in order to evaluate the influence of the main parameters affecting the results when cutting according to the multi-pass strategy.

2.1 Materials characterisation
The materials used for the tests are two rocks (granite and marble), a metal (aluminium) and a plastic material (methyl methacrylate commercially known as plexiglass). In Table 1 are reported some of the characteristics of the rocks, in Tables 2 and 3 the characteristics of aluminium and plexiglass, respectively.

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>MATERIALS</th>
<th>Granite</th>
<th>Marble</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compress. strength [MPa]</td>
<td>165</td>
<td>128</td>
<td></td>
</tr>
<tr>
<td>Flexural strength [MPa]</td>
<td>16</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Knoop hardness [MPa]</td>
<td>6128</td>
<td>1366</td>
<td></td>
</tr>
<tr>
<td>Volumic mass [kg/m³]</td>
<td>2600</td>
<td>2720</td>
<td></td>
</tr>
<tr>
<td>Absorption coefficient [%]</td>
<td>0.33</td>
<td>0.096</td>
<td></td>
</tr>
<tr>
<td>Impact test [cm]</td>
<td>58</td>
<td>75</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 - Aluminium characteristics.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength [MPa]</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>Yield point [MPa]</td>
<td>30-40</td>
<td></td>
</tr>
<tr>
<td>Elastic modulus [GPa]</td>
<td>67.5</td>
<td></td>
</tr>
<tr>
<td>Poisson modulus [GPa]</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>Knoop hardness [MPa]</td>
<td>390</td>
<td></td>
</tr>
<tr>
<td>Volumic mass [kg/m³]</td>
<td>2640</td>
<td></td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td>Knoop hardness [MPa]</td>
<td>Volumic mass [kg/m³]</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>76</td>
<td>212</td>
<td>110-1190</td>
</tr>
</tbody>
</table>

General qualitative attributes of tested materials are reported in the following Table 4.

<table>
<thead>
<tr>
<th>MATERIALS</th>
<th>Granite</th>
<th>Marble</th>
<th>Aluminium</th>
<th>Plexiglass</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATTRIBUTES</td>
<td>Porous</td>
<td>Porous</td>
<td>Compact</td>
<td>Compact</td>
</tr>
<tr>
<td></td>
<td>Fragile</td>
<td>Fragile</td>
<td>Ductile</td>
<td>Fragile</td>
</tr>
<tr>
<td></td>
<td>Hard</td>
<td>Mean</td>
<td>Soft</td>
<td>Soft</td>
</tr>
</tbody>
</table>

The abrasive used was garnet having two different grain size distributions (HP 50 and HP 120). Some of the characteristics of the abrasive are reported in Table 5.

<table>
<thead>
<tr>
<th>Knoop hardness [MPa]</th>
<th>Volumic mass [kg/m³]</th>
<th>Shape factor (*)</th>
<th>Mean particle size D_{50} [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12653</td>
<td>4080</td>
<td>1.8</td>
<td>HP 50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HP 120</td>
</tr>
</tbody>
</table>

(*) According to ASBA Image Analysis Procedures.

2.2 Testing procedure
Experimental conditions taken into consideration in the experimental plan:

- Material: 4 (granite, marble, plexiglass, aluminium)
- Abrasive grain size: 2 (garnet HP50 and HP120)
- Abrasive flow rate: 2 (about 300 and 700 g/min for HP50, 200 and 450 g/min for HP120)
- Traverse velocity: 5 (10, 100, 1000, 5000, 10000 mm/min)

The system parameters kept constant were:

- Pressure: 330 MPa
- Nozzle diameter: 0.30 mm
- Focussing tube diameter: 1.0 mm
- Focussing tube length: 75 mm
- Stand-off distance: 2 mm
For all the materials tested the slabs thickness was 70 mm, with a linear cutting length of 200 mm. The distance between one cut and the next one was 15 mm. Preliminary tests aimed at checking the mass flow rate for different settings of the dosing system and for each abrasive grain size have been conducted. Once the experimental parameters were fixed, the test procedure consisted in linear cutting of the material with one or more passes, as a function of traverse velocity. When the cutting through required more than one pass, the lance was moved alternate in opposite direction without stopping the test.

3 RESULTS

Results have been expressed in terms of: number of passes needed to cut through the sample, cutting rate \([\text{cm}^2/\text{min}]\), specific erosion \([\text{cm}^2/\text{g}]\), surface quality (maximum waviness [mm]). For the same material (at equal sample thickness) all the mentioned parameters are a function of traverse velocity, abrasive grain size and abrasive mass flow rate.

3.1 Number of passes
The number of passes needed to cut through the sample thickness has been measured during each test. Figure 1 shows for the different materials the correlation between the number of passes and traverse velocity for the two abrasive flow rate and for each abrasive grain size.

3.2 Cutting rate
Cutting rate has been calculated considering the traverse velocity, the corresponding number of passes needed and the thickness of the sample. In Figure 2 cutting rate is reported as a function of traverse velocity.

3.3 Specific erosion
Specific erosion has been obtained as the ratio between cutting rate \([\text{cm}^2/\text{min}]\) and abrasive mass flow rate \([\text{g}/\text{min}]\) and it represents the average area produced by each gram of abrasive. In Figure 3 specific erosion is shown for the different materials as a function of traverse velocity (parameters abrasive mass flow rate and grain size).

3.4 Surface quality
The quality of the surfaces has been evaluated by considering the distance from top within which waviness did not exceed 1 or 2 mm. These two values are reported in Table 6 for different traverse velocity. The general appearance of the surface after cutting is shown in Figure 4; those surfaces correspond to the conditions of peak cutting rate obtained for each material. The higher irregularity of granite compared to the other materials is clearly apparent.

4 DISCUSSION

4.1 Technical performance
At a traverse velocity of 10 mm/min the cut through has been always obtained with only one pass, increasing the traverse velocity the number of passes needed increases exponentially, with a different trend for each material.
Figure 1 - Number of passes as a function of traverse velocity.
Figure 2 - Cutting rate as a function of traverse velocity.
Figure 3 - Specific erosion as a function of traverse velocity.
Table 6 – Distance from top corresponding to a waviness W below 1 mm and 2 mm

<table>
<thead>
<tr>
<th></th>
<th>Granite</th>
<th>Marble</th>
<th>Plexiglass</th>
<th>Aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HP 50</td>
<td>HP 120</td>
<td>HP 50</td>
<td>HP 120</td>
</tr>
<tr>
<td>Tr. Vel. [mm/min]</td>
<td>W &lt; 1mm</td>
<td>W &lt; 2 mm</td>
<td>W &lt; 1mm</td>
<td>W &lt; 2 mm</td>
</tr>
<tr>
<td>10</td>
<td>70 70 66,5 70</td>
<td>70 70 70 70</td>
<td>70 70 70 70</td>
<td>70 70 70 70</td>
</tr>
<tr>
<td>100</td>
<td>59 70 64 70</td>
<td>70 70 70 70</td>
<td>70 70 70 70</td>
<td>70 70 70 70</td>
</tr>
<tr>
<td>1000</td>
<td>33 70 35,5 70</td>
<td>39 46,5 45 70</td>
<td>39 46,5 45 70</td>
<td>39 46,5 45 70</td>
</tr>
<tr>
<td>5000</td>
<td>24 47 18,5 21,5</td>
<td>56 60 24 31</td>
<td>56 60 24 31</td>
<td>56 60 24 31</td>
</tr>
<tr>
<td>10000</td>
<td>15 35,5 11,5 18</td>
<td>29 58,5 24 36,5</td>
<td>29 58,5 24 36,5</td>
<td>29 58,5 24 36,5</td>
</tr>
</tbody>
</table>

*Table values are in millimeters per minute (mm/min).*
Figure 4 - General appearance of the samples after cutting tests at peak cutting rate conditions (multiple passes).
Except for the case of aluminium, at given traverse velocity the number of passes is lower when using the higher mass flow rate or the coarser abrasive grain size. For such conditions, corresponding cutting rate is higher, confirming (6, 7), within the explored range for the parameters and for the materials tested, that the increase in abrasive mass flow rate and grain size is beneficial.

In the case of aluminium, a ductile material for which the cutting is obtained meanly on the base of a shaving mechanism (8), probably the effect of increasing the flow rate caused an over crowding of particles in the cutting area and, as a consequence, a reduction in cutting efficiency.

Considering the technical results in terms of cutting rate, the multi-pass strategy is always advantageous.

Except for the case of aluminium, the influence of abrasive grain size and abrasive flow rate is higher when the traverse velocity increases. Such behaviour is probably due to the change in the dynamics of the cutting mechanism, since the average distance between single impacts is larger when traverse velocity is higher, giving the particles a higher chance of undisturbed impact on the target surface. This phenomenon seems to be more effective in the case of brittle materials for which the rupture is a result of impact breakage than for ductile materials where the excavation is produced by shaving mechanism, which takes a longer time thus enhancing the chance of more particles to be involved in the interaction with the target.

As shown in Figure 5 for the coarser abrasive grain size (HP 50), peak cutting rate, obtained by adopting the multi-pass strategy, ranges from about 120 % for granite to 2-3 % for aluminium, being it near 85 % for marble and 75 % for plexiglass, while in the case of finer abrasive grain size (HP 120) the corresponding values are generally lower, 14 % for granite and almost zero for aluminium and plexiglass, whereas for marble it approaches 100 %.

Maximum cutting rate has been obtained for a traverse velocity of 1000 mm/min, except for marble and plexiglass for which the maximum cutting rate has been reached at 5000 and 10000 mm/min respectively, using coarse abrasive grain size and higher abrasive mass flow rate.

![Figure 5 - Increase in cutting rate obtained for the different materials adopting the multi-pass strategy.](image-url)
The conditions of maximum cutting rate obtained for each material normally does not correspond to the conditions of maximum specific erosion (reached in most cases for the higher abrasive mass flow rate) always obtained at the lower abrasive mass flow rate.

In the case of granite, marble and aluminium the specific erosion is higher for coarser abrasive grain size; in case of plexiglass it is higher for the finer abrasive.

It is interesting to point out that for granite, plexiglass and aluminium the peak specific erosion corresponds to a traverse velocity of 100 mm/min, for which the cut through has been obtained in few passes. For the same materials the combination of low traverse velocity and low mass flow rate is a condition in which each gram of abrasive is able to excavate at optimal conditions in terms of productivity. For marble the most favourable conditions correspond to a low abrasive mass flow rate combined with a higher traverse velocity, giving an indication that the characteristics of the material, fragile but not too hard, favours an effective excavation when inter-particle spacing is larger.

Results in terms of cutting rate or specific erosion are significantly important only if the product of cutting operation is subjected to further processing. In particular the requirements concerning the technology are often expressed as quality of the new surfaces obtained. For the purpose of the present work, in compliance with the requirements in the field of stone processing or mechanical manufacturing, the quality of the surface has been defined by tolerable waviness levels, for which two limits have been considered: 1mm and 2mm.

Data of Table 6 show that generally the cut thickness corresponding to a maximum waviness of 1 and 2 mm decreases with increasing the traverse velocity, often independently of cutting rate. This is true for all the materials except for aluminium for which, in the explored range of variation of parameters, there is no significant influence of traverse velocity, probably because of its ductile nature.

While marble, plexiglass and aluminium show a progressive regular increase in waviness with increasing the traverse velocity, the material most worstly affected by traverse velocities is granite, presenting a very irregular surface in the lower part of the sample, with deep lateral cavities, starting from 100 mm/min. A possible explanation is that, contrary to the other tested materials, granite is not homogeneous, being it constituted by minerals having different mechanical characteristics. Consequently the abrasive jet has the tendency, when impacting on hard crystals, to deviate from the linear path towards the adjacent softer crystals. Such behaviour is enhanced when the jet is traversed at high velocity since abrasive particles do not have enough time to erode the harder minerals, starting a mechanism of side excavation.

In any case, taking into account the surface quality, the results have to be reconsidered for evaluating correctly the process effectiveness, as shown in the next cost analysis.

### 4.2 Costs analysis

Linear cutting cost $U$ [€/m] has been calculated according the following formula:

$$U = \left( \frac{C_a + C_d}{F_a 60 + C_e P/R + C_m + C_v + C_s + C_w F_w + D} \right)/(60 \times 10^{-3} \text{ VE/H})$$

in which symbols, corresponding meaning and eventually assumed value are:

- $C_a$ Purchase price of abrasive: 0.2 €/kg
- $C_v$ Cost of nozzle and focus: 2.2 €/h
- $C_s$ Cost of spare parts (electric and mechanical components): 6 €/h
- $C_m$ Cost of manpower: 18 €/h (one worker)
- $C_w$ Cost of water supply: 0.7 €/m³
- $C_d$ Cost of waste disposal: 0.1 €/kg
- $D$ Depreciation: 18 €/h
- \( F_a \) Mass flowrate of abrasive [kg/min]
- \( F_w \) Water consumption [l/h]
- \( P \) Hydraulic power [kW]
- \( R \) Transformation efficiency
- \( E \) Technical efficiency = 0.8
- \( V \) Cutting rate [mm²/min]
- \( H \) Thickness of the workpiece [mm]

In Figure 6 the cutting cost is reported as a function of traverse velocity at the different particle size and mass flow rate, irrespective of the quality of the surface produced. For all the tested materials the cutting cost decreases as the traverse velocity increases, reaching a minimum value beyond which, in most cases, it starts increasing again. When cutting granite and aluminium, the minimum value is reached for a traverse velocity of 1000 mm/min, using garnet HP 50 at 300 g/min. In the case of marble and plexiglass the minimum of cost corresponds to a traverse velocity of 5000 and 10000 mm/min respectively, using garnet HP 50 at 700 g/min.

The use of coarser abrasive grain size has proved to be the most economic solution, with low mass flow rate combined with intermediate traverse velocity in the cases of granite and aluminium, with a high flow rate combined with high traverse velocity in the cases of marble and plexiglass. This different behaviour can be explained considering that marble and plexiglass are fragile and softer materials, for which the abrasive is able to cut efficiently even at high traverse velocity, using enough abrasive flow rate, while granite and aluminium, respectively fragile/harder and ductile/softer, require a lower traverse velocity for the abrasive to act efficiently and consequently do not need a high abrasive flow rate. Such behaviour can probably be explained for granite by its high hardness and for marble by the shaving mechanism involved.

If surface quality is taken into account, the cost analysis should be revised using the data reported on Table 6. For each cutting condition (material, traverse velocity, abrasive grain size and mass flow rate) and quality level (waviness lower than 1 or 2 mm), the maximum achievable depth of cut, corresponding ideally to the maximum thickness of a slab that can be cut at the given quality, has been identified. Then, the cutting cost has been calculated for different slab thickness (10 to 70 mm, step 10 mm) and for each of the possible combinations of cutting parameters. Finally the minimum cutting cost has been calculated for variable slab thickness.

The curves of Figure 7 represent for each material the correlation between the slab thickness and the minimum cutting cost calculated for different levels of surface quality (no control, max waviness \( W = 1 \) mm, max waviness \( W = 2 \) mm). The curves have been obtained as best fitting of experimental points with a squared correlation coefficient always higher then 0.90. Minimum cutting cost has always been obtained by adopting a multi-pass strategy, except for one case (granite, slabs thickness 70 mm, max waviness \( W < 1 \) mm and \( W < 2 \) mm), where minimum cutting cost has been obtained with the single pass strategy.

For plexiglass and aluminium the curves of Minimum Cost with no quality limit and \( W < 2 \) mm are coincident, showing that in any adopted combination of cutting parameters the maximum waviness measured was always lower than 2 mm.

As expected for all the materials, cutting cost increases by increasing the slabs thickness and lowering quality level.

Cutting cost for granite is considerably higher then those of the other materials, confirming (9) the difficulty encountered by the abrasive jet when cutting this hard and heterogeneous material.
Figure 6 - Cutting costs as a function of traverse velocity.
Figure 7 - Minimum cutting costs as a function of slabs thickness for different surface quality.
5 CONCLUSIONS

Multi-pass strategy has proved to be an efficient solution from both the technical and economical point of view.
The optimal set of operational parameters depends on the characteristics of the material being cut. In particular for brittle/harder materials or for ductile/softer materials a combination of relatively lower traverse velocity and abrasive mass flow rate appears to be more effective, while in the case of brittle/softer materials better results have been obtained with a combination of higher traverse velocity and abrasive mass flow rate.
In any case the use of a coarser abrasive grain size has been the most convenient solution.
The research work will be developed in the future by exploring the application of multi-pass strategy for more complex cutting contours, where other cutting quality parameters, like for instance the trail back, are also important.

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REFERENCES