Surface finishing of marble with abrasive waterjet

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Abstract
Possible safety problems posed by polished stone floors are normally solved by adopting rough finishing methods (sand blasting, bush hammering) that however are often incompatible with the desired aesthetic features. The paper illustrates a new suitable approach based on the use of abrasive water jet, with the aim of reducing the slippery conditions of polished surfaces. In the experimental plan the effect of nozzle geometry, mass flow rate and particle size of the abrasive, traverse velocity and stand-off distance has been studied. Results have been expressed in terms of width and depth of the abraded area as well as of density of impacts determined by image analysis. A statistical model correlating the operational parameters and the results obtained has been defined. The model enables to point out the influence of each variable and to define the optimum conditions for achieving the desired effect.

1 FOREWORD

Surface finishing is the last stage of stone processing. This operation must be carried out with particular care since the aesthetic features, the technical performance and the durability of the work strongly depend on the appropriateness of the technology employed as a function of the characteristics of the material.
A number of technologies are available for the task. They differ essentially for the kind of action applied by the tool to the stone, with the consequence that the resulting quality of the surface treated, which is suggested by end use of the element (for interior or exterior paving, face cladding, artwork, premium types of workmanship), is also somewhat affected.

1.1 Smoothing and polishing

They represent the most common method of surface finishing of stone elements used for interior decoration where the aesthetic quality is of a major concern. Smoothing is the first step of the process for eliminating the imperfections of sawing before the subsequent polishing that gives the final brilliance. At present the operation is carried out with a variety

of bridge or belt machines using tools incorporating the abrasive particles with decreasing size, mounted on a series of rotating mandrels. Modern machines are characterised by high production rates thanks to the degree of automation.
Polishing enables to put into full evidence the chromatic and textural appearance of the material, posing however some safety problems when the stone elements are applied in floors and stairs, due to the onset of slippery conditions.

1.2 Bush hammering

The machines are composed of a metal structural beam carrying a trolley equipped with one or more pneumatic hammers. Roughness patterns can be varied by simply changing the tool. Smaller hand-held machines are used for special works or for a light scarification of floors. Treatment rate in marble can be around 50 m^2 per shift.
However, soft and coarse-grained materials may be broken by the impacts, especially if their texture is unfavourable. This drawback can be overcome only by increasing the thickeness of the slabs and/or by limiting the impact force and reducing the depth of removal. The material can often be damaged or weakened at the smaller scale (less than 1 mm) as the consequence of micro-cracks in addition to the natural porosity, causing a faster deterioration and a deeper development of the weathering process.
Bush hammering gives a very rough finishing resulting in a considerable modification of the natural colours and of the fabric itself. On the other hand the surface provides a marked, slide-preventing grip.
This technique is seldom applied on granite for which flaming is generally preferred. Marble elements treated in this way are therefore suitable chiefly for exterior applications like sculptures, stairways, pavings, curbs and items having a non planar shape.

1.3 Sand blasting

In the factory, sand blasting is performed with machines quite similar to bush-hammers. Abrasive particles (silica sand, carborundum grit or other hard materials like spherular glass shot) are blasted against the surface using compresssed air as the driving fluid. The nozzles are aligned on the beam above the stone slab placed onto a traversing roller-belt. The latest models of machine are equipped with abrasive circulation system for the sake of cost savings. The typical production rate in marble is 150 m^2 per shift.
The surface is faintly rough having a silky appearance without coarse or sharp protrusions, which is highly desiderable in many materials. When the thickness of removed layer is a problem, like in the case of art restoration, the control of the operation becomes critical.
Sand blasting is also used for carving, drawings and writings, especially in funeral art.

1.4 Flaming

The flaming machine has the same frame as the bush-hammering machine but the tool employed now consists of a torch fed by oxygen and propane. If accompanied by water cooling, flaming provokes a thermal shock resulting in a breakage or vitrification of the component minerals, revealing the appearance of their crystal structure. Quartz is particularly sensitive to thermal treatments owing to the allotropic transformations of its crystal lattice as temperature increases, whereas feldspar tends to melt while micas behave as refractory.
Flamed granite slabs are used primarily for flooring and external facing as an alternative to bush-hammering. It has been found that in some cases flaming improves the durability of the stone, especially the resistance to chemical agents. The aspect of the surface is rather soft with attenuated chromatic contrast. In some cases the flaws of the material, clearly evident in polished surfaces, can be somewhat masked by flaming, resulting in a considerable economic benefit.

1.5 Shot peening

It consists essentially in a “cold” bombardment of metal surfaces by a stream of solid projectiles of suitable shape, generally roundish, made of pig iron, steel, glass or ceramics, accelerated pneumatically or mechanically, aimed at increasing the hardness and the resistance to fatigue by strengthening the top layer of the material. There are no instances until now regarding shot peening of stone.

1.6 Milling

This technique finds its main field of application for the removal of a thick layer of material, using diamond wheels, for repair purposes of worn floors in order to obtain an even surface free from macroscopic irregularities. The equipment should possess enough power, traction and stability, enabling to maintain a constant removal depth and a good planarity. Generally this operation requires water cooling of the tool.

1.7 Laser beam

Laser technology is sometimes used for printing, drawing and in general for high- accuracy engraving of stone surface. Not all the rocks are amenable to this kind of treatment which is restricted to white carbonate materials.

1.8 Waterjetting

Plain waterjet has been proposed as an alternative to flaming for obtaining a rough finishing of granite slabs. Some commercial machines are offered in the market but the acceptance has not yet been very enthusiantic due to the higher cost of processing. On the other hand the quality of the treated surface is very good owing to the selective action of waterjet that develops along the existing cleavage planes giving the material a natural appearance by preserving the original colours and the textural features of the stone.

In principle, all the above methods are technically viable for surface finishing of dimension stone, taking into account the need to preserve the ornamental potential of the material.
However their practical applicability can be restricted by a number of factors concerning the characteristics of the material and the end use of the stone element in presence of external constraints, with particular reference to climatic conditions.
Problems may arise especially for interior floors where the maintainment of the aesthetic values must be matched to safety. A possible solution can be found in a combination of conventional polishing (for enhancing the textural and chromatic features of the material) with a light erosive action intended to produce a pattern of micro-craters capable of improving the grip without impairing the durability.
To this end a very interesting opportunity is offered by abrasive waterjet which can also be considered for other operations of stone working as a substitute to sand blasting and bush-hammering.

2 EXPERIMENTAL TESTS

The task underlaying the test program was that of studying the effect on the stone surface obtained by changing the various parameters of relevant importance in abrasive waterjet.

2.1 Target material

Results illustrated and discussed in the present paper are related to marble which is the material most frequently used in interior decoration. The ultimate goal of the investigation

was to show that AWJ can replace sand blasting in all the tasks where this latter is presently applied.
Therfore the choice of the target material fell on the customary “Bianco Carrara” marble, well known in the world over centuries, which is a metamorphic carbonate material rather homogeneous, characterised by the typical saccharoid appearance with a relatively coarse crystal size.
It is used in construction engineering for a variety of applications, mostly indoor being it sensitive to deterioration in polluted environment.
The main technical characteristics are reported in table 1.

Table 1. Chief technical characteristics of the “Bianco Carrara” marble.

CHARACTERISTICS		VALUES
Volumic mass	[Kg/m^3]	2720
Compressive strength	[MPa]	128
Flexural strength	[MPa]	20
Knoop hardness	[MPa]	166
Impact resistance	[cm]	75
Absorption coefficient	[%]	0.096

2.2 Equipment used

The equipment used for the tests is the model Waterline 1620 manufactured by Tecnocut s.r.l. The pump is provided with three electronically controlled one-way pressure intensifiers giving the following performance:

- Installed power (three intensifiers) 37.5 kW
- Maximum pressure 390 MPa
- Working pressure 300 - 380 MPa
- Water flow rate 3.2 l/min

The focussing tubes for the experiments have been obtained by cutting the original 75 mm pieces into shorter elements, about 27 mm in length, in order to enhance the radial dispersion of the abrasive.
The abrasive used was Barton Garnet HP50 sieved into two size classes: coarse C (-0.600 +0.355 mm) and fine F (-0.355 +0.212 mm)

2.3 Experimental plan

Tests have been carried out on polished samples of “Bianco Carrara”, 1000 mm long, 150 mm wide and 30 mm thick. The jet was always directed perpendicular to the target and traversed across the width of the sample. One parameter at a time was changed for each test and the next was made by moving the cutting head sideways at enough distance to avoid interference between the traces.
Being the Carrara marble holocrystalline and homogeneous it is believed that the results are little influenced by the variability of the material.
A total of about 300 tests have been carried out by changing the setting parameters independently according to a factorial plan:

- Pressure P 100 and 330 MPa
- Nozzle diameter Φ_u 0.25 and 0.50 mm
- Focussing tube (diameter Φ_f x length) 3.00 x 27.30 and 1.40 x 27.00 mm

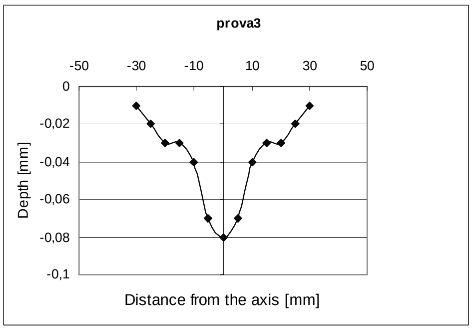
- Abrasive mass flowrate Q* 55.4 (C)–78.5 (F) and 158.7 (C)–183.2 (F) g/min
- Traverse velocity V 1000, 6000 and 10000 mm/min
- Stand-off distance S 50, 100 and 150 mm
- Average particle size of the abrasive G 0.4775 (Coarse C) and 0.2835 (Fine F)

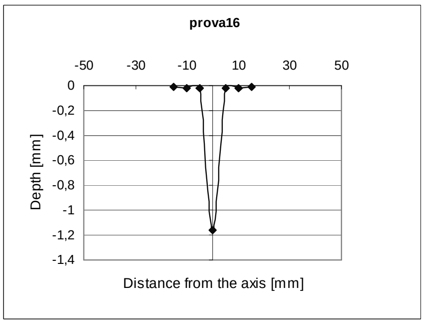
** Lower values for each setting diameter of the dosage hole are for the coarse size class C of the abrasive (F = fine)*

2.4 Results

2.4.1 Roughness profiles

For each test the average cross section perpendicular to the traverse direction of the jet has been obtained through depth measurements at convenient intervals, using a conventional mechanical comparator provided with a needle end with 0.01 mm accuracy. It was not possible to use a more sophisticated method of roughness assessment (1) since in many tests the depth of kerf exceeded the 2 mm limit of the available instrument. The depth was always found to be nearly constant along the kerf.
The knowledge of the profile shape is important for carving and drawing purposes.
Some representative profiles are given in figure1.





	TESTS	
Var.	3	16
P	100	330
Φ_u	0.25	0.25
Φ_f	3.0	3.0
G	C	C
Q	158.7	158.7
V	1000	6000
S	150	100

Figure 1. Cross sections of the kerf for two experimental conditions (tests 3 and 16)

2.4.2 Extent of bands

Generally the damage produced by the abrasive can be divided into three distinct zones parallel to the traverse direction of the jet as shown in figure 2:

- The kerf itself
- A inner band with equal extent at both sides of the kerf, characterised by an apparently even distribution of impacts and having a variable total width as a function of experimental conditions;
- A outer band beyond the limits of the inner band, characterised by a gradual decrease down to zero in the intensity of impacts.

It has been found that the ratio between the widths of outer and inner bands is around 1.5, although it tends to increase with traverse velocity from about 1.3 at 1000 mm/min up to 1.6 at 10,000 mm/min.

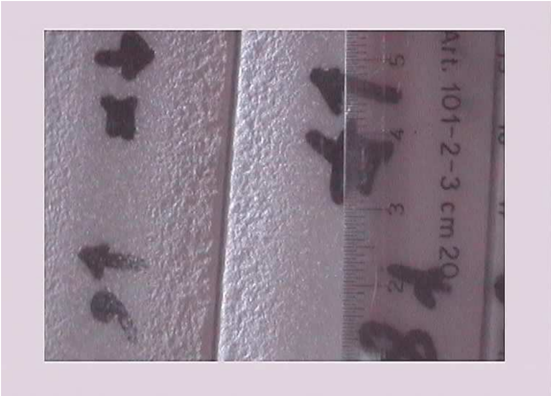


Figure 2. Typical zones of influence of the jet damage onto the stone surface

However the three zones are not always clearly evident: In some instances the kerf is absent whereas at the other extreme it is the only effect of the jet with no bands around it, depending on the setting of the operational variables.
A suitable classification of experimental data enabled to establish some trends that were confirmed later by the statistical analysis.
In particular, the width of the inner band has been divided into three classes:

- A: larger than 40 mm (4.04 % of the tests)
- B: between 20 and 40 mm (43.10 % of the tests)
- C: less than 20 mm (52.86 % of the tests)

As shown in table 2, the results falling in class A were prevailingly obtained with tests carried out at higher pressure (66.7 %) with smaller nozzle (75.0 %) and larger focussing tube (58.3 %), using finer particle size (66.7 %) with higher mass flowrate (83.3 %) at faster traverse velocity (100 %) from longer stand-off distance (100%).

Table 2. Width of the inner band. Effect of each operating variable on the experimental results (% proportion of tests at a given setting value).

Band width	P [MPa]		Φ_u [mm]		Φ_f [mm]		Pt. size G		Q_{av} [g/min]		V [m/min]			S [mm]		
	100	330	0.25	0.5	1.4	3.0	C	F	67	171	1.0	6.0	10.0	50	100	150
A	33.3	66.7	75.0	25.0	41.7	58.3	33.3	66.7	16.7	83.3	100	0	0	0	0	100
B	46.9	53.1	62.5	37.5	42.1	57.8	45.3	54.7	40.6	59.4	44.5	28.9	26.6	4.7	36.7	58.6
C	56.1	43.9	40.8	59.2	54.1	45.9	52.2	47.8	59.9	40.1	18.4	39.5	42.1	57.3	32.5	10.2

A similar analysis has also been made concerning the depth of kerf that has been divided into three classes:

- D: deeper than 1.0 mm (26.60 % of the tests)
- E: between 1.0 and 0.1 mm (39.73 % of the tests)
- F: less than 0.1 mm (33.67 % of the tests)

Results are reported in table 3.

Table 3. Depth of the kerf. Effect of each operating variable on the experimental results (% proportion of tests at a given setting value).

Band width	P [MPa]		Φ_u [mm]		Φ_f [mm]		Pt. size G		Q_{av} [g/min]		V [m/min]			S [mm]		
	100	330	0.25	0.5	1.4	3.0	C	F	67	171	1.0	6.0	10.0	50	100	150
D	5.1	94.9	67.1	32.9	54.4	32.9	45.6	54.4	44.3	55.7	63.3	22.8	13.9	48.1	32.9	19.0
E	50.0	50.0	42.4	57.6	53.4	46.6	48.3	51.7	45.8	54.2	33.9	35.6	30.5	35.6	29.7	34.7
F	89.0	11.0	50.0	50.0	40.0	60.0	49.0	1.0	58.0	42.0	8.0	38.0	54.0	18.0	35.0	47.0

Quite remarkable is the effect of pressure on the depth of kerf which is less affected by nozzle geometry. Stand-off distance and especially traverse velocity also play a major role while particle size and abrasive mass flowrate have a certain influence although not very important.

2.5 Image analysis

An image analysis has been made for each test starting from digital color photographies of the stone surface, using the "Image Pro" software of Media Cybernetics. A preliminary elaboration of the original pictures by means of electronic filters was necessary in order to sharpen the contrast and improve the reliability of counting procedures, as shown in figure 3.

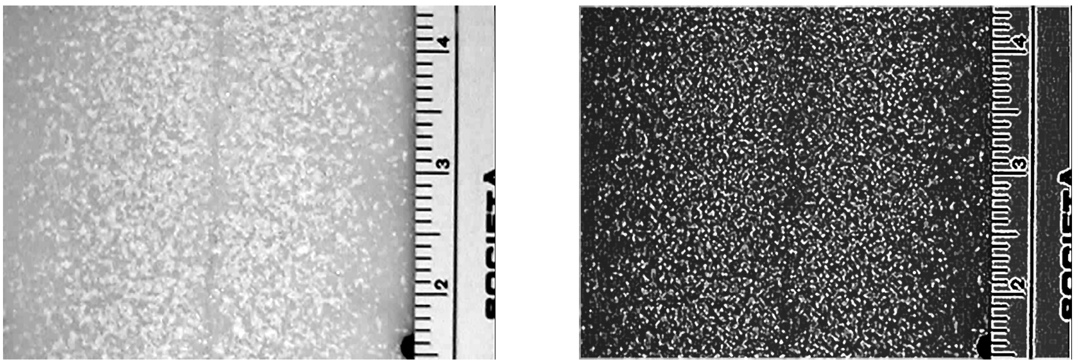
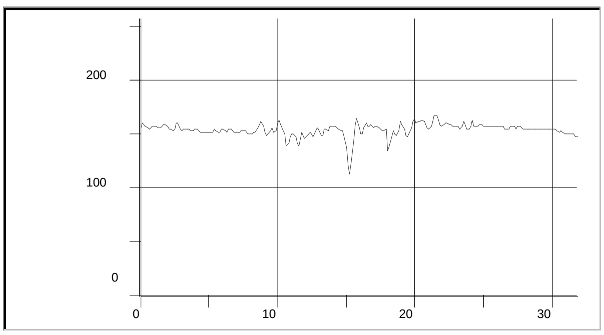


Figure 3. Original picture (left) and processed image (right) of a test

Then the processed image was studied by measuring the "Grey" tonality according to a built-in scale along parallel lines crossing the waterjet trace, thus obtaining a check of the inner and outer band width previously measured according to a visual evaluation. A typical profile is shown in figure 4. The action of the jet is put into evidence by the peaks in the Y scale .



Distance [mm]

Figure 4. Scale of grey as a function of distance across the kerf (in the middle)

This preliminary phase of the investigation has been done with a fully automatic procedure in order to reduce the total time needed for the 297 images and to assure a reliable counting under the same conditions.
The intensity of impacts has been calculated with reference to a 5 mm square named AOI (Area Of Influence), movable across the entire area in the X and Y directions, inside which the impacts have been automatically counted, storing the data in Excel files for further data processing.
For a better response of the method, the AOI has been moved parallel to the kerf taking the average number of impacts per unit area.

3 DISCUSSION

3.1 Statistical correlation

A regression model has been applied to the whole set of the test data, aiming at putting into evidence the influence of each variable on the experimental outcome (2, 3, 4).
The concept followed consists in finding a suitable function of all the relevant variables (setting parameters) to which each effect of waterjet action (such as width of inner and outer bands, depth of the kerf, specific frequency of impacts) can be linked by a simple mathematical relationship F.
The procedure adopted was based on a trial-and-error iterative approach, assuming a given general expression for the function required and searching the numerical values and the mathematical relationship (either linear, exponential, polynomial or fractional power) upon "best fitting" conditions (i.e. maximum value of the Regression Coefficient R^2) .
The resulting equation has only a pretension of "trend disclosure" with no claim to elucidate the complex physical phenomena involved. The general form is:

$$Z = F(X) = F(P^a \cdot \Phi_u{}^b \cdot \Phi_f{}^c \cdot G^d \cdot Q^e \cdot V^f \cdot S^g)$$

where:

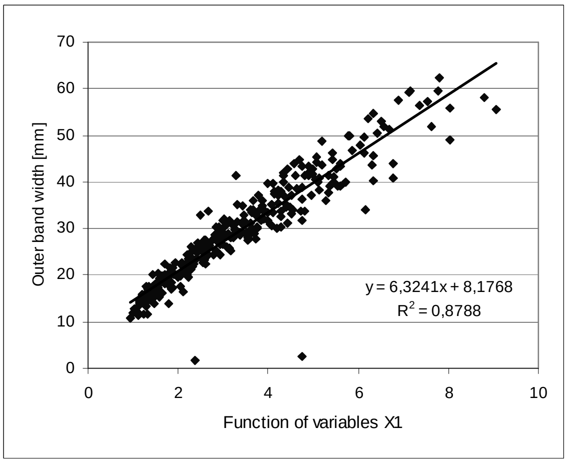
- Z Quantity representing the effect under investigation
- X Function of operating variables each appearing as a factor to a numerical exponent
- P Pressure [MPa]
- Φ_u Nozzle diameter [mm]
- Φ_f Focussing tube diameter [mm]
- G Average size of abrasive particles [μm]
- Q Mass flowrate of the abrasive [g/min]
- V Traverse velocity of the cutting head [mm/min]
- S Stand-off distance [mm]

Exponents a, b, c, d, e, f, and g , either positive or negative according to the favourable or unfavourable influence of the corresponding variable, represent the effect of each variable on the results of waterjet treatment of the stone surface. A small exponent tending to zero witnesses a negligible effect.

3.2 Influence of the variables

3.2.1 Outer band width

In this case the function associated to the variables has been found to be:



$$X_1 = P^{0.1} \cdot \Phi_u^{-0.3} \cdot \Phi_f^{0.2} \cdot G^0 \cdot Q^{0.2} \cdot V^{-0.2} \cdot S^1$$

$$Z_1 = k_1 X_1$$

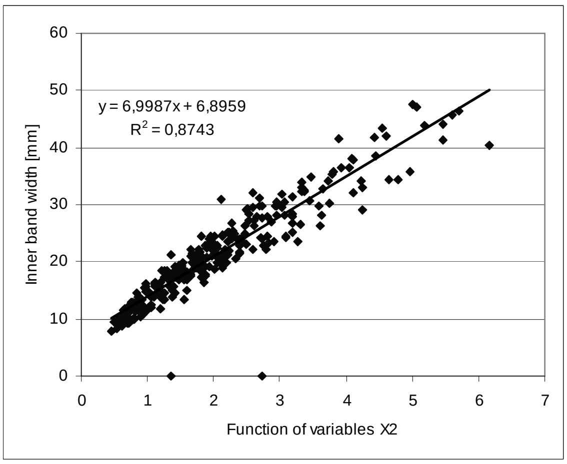
Figure 5. Influence of variables on the width of damaged zone (outer band)

This suggest that:

- The width of the outer band is proportional to the 0.1 power of pressure meaning that the influence of this variable is not very important;
- More evident is the effect determined by nozzle geometry and in particular by the ratio between the diameters of the focussing tube and the primary jewel;
- The particle size of the abrasive has no effect at all;
- An increase in the mass flowrate is beneficial to the extent of the band;
- The contrary happens for traverse velocity;
- The most important influence is that of stand-off distance: the width of the outer band increases proportionally with it, as it could be predicted by trivial geometric considerations.

3.2.2 Inner band width

Very similar considerations hold for the width of the inner band.



$$X_2 = P^{0.1} \cdot \Phi_u^{-0.3} \cdot \Phi_f^{0.1} \cdot G^{-0.1} \cdot Q^{0.3} \cdot V^{-0.3}$$

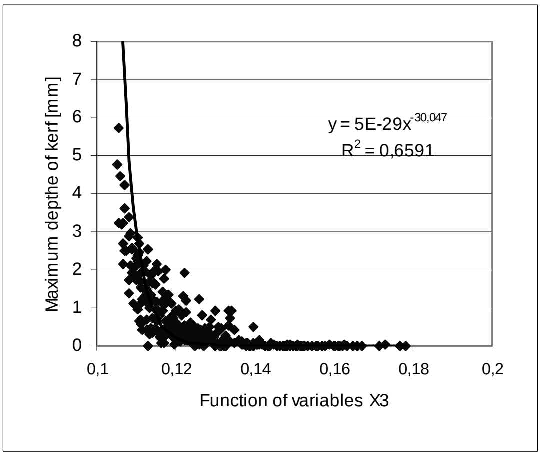
$$Z_2 = k_2 X_2$$

Figure 6. Influence of variables on the width of damaged zone (inner band)

There is only a small change in the exponents but the "style" can be considered practically the same, being it difficult to explain the variations on scientific grounds instead of attributing them to mere experimental fluctuations.

3.2.3 Depth of kerf

The function X_3 represented in the diagram is :



$$X_3 = P^{-0.7} \cdot \Phi_u^{-0.1} \cdot \Phi_f^{0.3} \cdot G^{-0.1} \cdot Q^{-0.2} \cdot V^{0.3} \cdot S^{0.6}$$

$$Z_3 = \alpha X_3^{-\beta}$$

Figure 7. Influence of variables on the depth of kerf

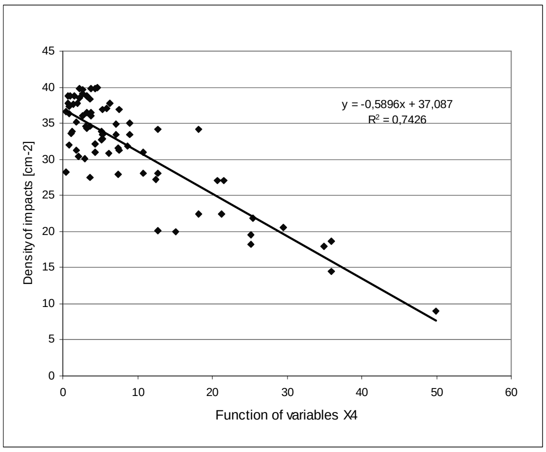
Now the form of the mathematical relationship for Z_3 is a power function of X_3 with a negative exponent. Accordingly, The maximum depth of kerf increases considerably with pressure, less so with nozze diameter and abrasive mass flowrate and decreases with traverse speed and expecially with stand-off distance. However the correlation coefficient is not very high.

In general the findings described in the above are in agreement with the results obtainel elsewhere (5, 6, 7).

3.2.4 Density of impacts

Concerning the density of impacts Z_4 determined by the image analysis, the inverstigation has been restricted to a subset of data including only the tests for which the depth of kerf is shallower than 0.03 mm (reflecting an even distribution of impacts over the explored area).

Following the same iterative procedure as in the above, the best fitting analytical relationship resulted to be the following (figure 8), with a inear regression coefficient R^2 equal to 0.7426:



$$X = P^{-0.6} \cdot \Phi_u^{-2} \cdot \Phi_f^{2.5} \cdot G^{0.1} \cdot Q^{-0.8} \cdot V^{0.7} \cdot S^{1.3}$$

$$Z_4 = k_4 X_4$$

Figure 8. Influence of variables on the intensity of impacts

However this time the linear relationship is characterised by a negative gradient. The following considerations are worth noting:

- All the variables show a certain influence except for particle size;
- The most important contribution seems to be accredited to the diameter of the focussing tube (impact density decreases as Φ_f increases, as expected);
- The opposite is found for the diameter of the primary nozzle. It is the ratio Φ_f / Φ_u that actually counts: as it increases the jet spreads radially very soon;
- Stand-off distance is also quite important: impact density decreases if the nozzle is moved farther away from the target surface;
- Impact density is is also sensitive to the abrasive mass flowrate, although not proportionally since a higher abrasive load induces some disturbances which somewhat contribute to the radial spreading of the particles;
- Finally impact density diminishes at faster traverse velocities.

5 CONCLUSIONS

The database obtained and the model proposed as the result of the experimental plan enable to predict the effect of abrasive waterjet on a given stone surface as a function of setting conditions of the operational parameters (especially pressure, nozzle geometry, abrasive mass flowrate, traverse velocity and stand-off distance).
Therefore it is possible to make the best use of the technology for fulfilling the desired tasks: surface treatment, carving, drawing, as a substitute to sand blasting.
Concerning safety, micro-craters produced as a result of the impact of abrasive particles on the polished surface of stone render the floor and stairs less slippery with minor modification of the visual appearance of the material.

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