STONE CUTTING WITH DIAJET

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ABSTRACT: The technical and economic feasibility of using the DIAJet 700 for contour cutting of stone slabs has been studied. Tests on different rocks with various abrasives show that cutting rate is strongly influenced by the type of abrasive employed and, for a given abrasive, by the feed rate. However, as traverse velocity increases, cut quality deteriorates progressively. The paper discusses the results obtained and points out the typical aspects of the technology.

1. THE DIAJET SYSTEM

DIAJet (Direct Injection Abrasive Jetting) basically differs from the entrainment techniques (grouped under the achronym AWJ, Abrasive Water Jetting) in the sense that an abrasive is incorporated into the water inside a pressurized vessel from which the abrasive slurry stream is delivered to the nozzle through a flexible hose (Bloomfield, 1991).

At the present state of commercially available technology, DIAJet and similar systems are operated at relatively low pressures (up to 70 MPa) compared to the entrained abrasive counterpart (up to 400 MPa), although efforts are being made to increase the pressure for better cutting accuracy with lower abrasive consumption (Hashish, 1990; Hashish, 1991).

As a matter of fact, with low pressure systems much larger water flowrates and abrasive dosages must be used to achieve comparable performance, calling for larger nozzle diameters. The consequence is a wider cut and a certain lack of accuracy for a given cutting rate.

The velocity of the jet can reach 450 m/s and the kinetic energy transferred to the abrasive particles carried in the water stream is utilised to remove target material. Therefore a coherent high velocity slurry jet is produced, which is is tolerant to variations in stand-off distance between nozzle and workpiece.

Power is limited only by the choice of nozzle size and working pressure and can be generated by a one-stage plunger pump, which is much less expensive than the intensifier pump used for the AWJ high-pressure systems. Maintenance costs are also lower (Summers, 1989).

A considerable advantage is the possibility of recycling back to the system a large proportion of the used abrasive suspension (Guo, 1992).

The directly pressurized nozzle of the DIAJet is capable of passing coarser abrasive particles than entrainment jets with minor attrition and collision of the particles between themselves, ensuring enhanced effect at the workpiece since larger grains are known to produce a better erosion than fine particles (Summers, 1992). - -

The two-phase jet has no entrained air and it is therefore less noisy with maximum cooling capacity. Reaction force is higher than that with the entrainment systems and this may pose some problems for contour cutting.

A further drawback is represented by a certain unsteadiness in the abrasive flowrate, especially at the moment of shifting from one to the other of the twin pulp-delivery tanks.The abrasive slurry output can be adjusted between 0 and 14 kg/min. The normal abrasive concentration in the slurry is around 12 % by weight.

2. LABORATORY SET-UP

2.1 Pump

The high-pressure generator used for driving the "DIAJet is a Hammelmann triple piston plunger pump capable of delivering a maximum flowrate of 54 1/min. Pressure can be adjusted from 6 up to 240 MPa by acting on the fuel throttle of the Diesel engine and discharging the excess water through a by-pass valve.

This pump is suitable for operating the DIAjet at 70 MPa with a nozzle diameter of up to 1.8 mm.

2.2 Slurry delivery unit

The unit installed at the DIGITA-UNICA laboratories is the Model DIAJet 700, built in UK by FDL, a Subsidiary of BHRGroup.

This is the newest development of a series of equipment widely used for cutting metals and a variety of other materials in the field.

The application to contour cutting of rocks is'not yet commercial due to the greater popularity of AWJ systems.

2.3 Lance driving system

The lance manipulation system allows X-displacement of the nozzle at variable velocity using a frequency generator feeding a 3-phase electric motor provided with an adjustable speed reduction device.

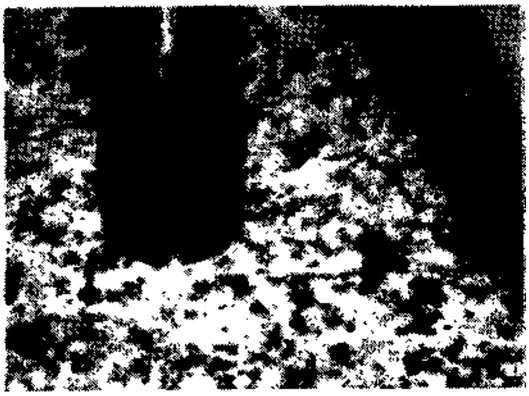

Figure 1. X-Y lance driving device and slurry collection system.

The lance-supporting platform can be moved at a velocity variable continuously from 0 to 150 cm/min, with reasonably good steadiness.

The lance manipulator used for linear cutting experiments is shown in Figure 1.

2.4 - Abrasive recovery circuit

The system consists of a receiving vessel designed for absorbing the residual power of the jet by means of a bed of hard steel balls placed in the middle of 1 m water depth.

At the bottom, settling pulp is displaced by means of a centrifugal pump and delivered to a hydrocyclone where a thickened coarser fraction to be re-used after the elimination of the foreign matter is separated from a diluted suspension of slimes.

3. PETROGRAPHIC CHARACTERIZATION OF ROCKS

Rocks used for the cutting experiments were:

- coarse-grained granite commercially known as Silon Red (Sardinia, Italy)
- grey granite, known as Luna Pearl (Sardinia, Italy)
- marble, known as Bianco Carrara (Tuscany, Italy)
- marble, known as Rosa Portugal (Alentejo, Portugal)

From the pétrographie point of view, the two granites are characterized by a holocrystalline, hypidiomorphic structure, slightly porphyritic in the Silon Red.

Marbles have practically a mono-mineral composition since they consist of calcium carbonate with minor proportion of other constituents (Agus, 1994).

Typical features of test rocks are given in Table 1. For the Rosa Portugal information is incomplete but general properties are substantially similar to those of other marbles.

Structural properties are important since ruptures may occur during cutting with the DIAJet, especially at low abrasive feed rate and/or at high traverse speed due to the presence of flaws and discontinuities.

Table 1 Physical and mechanical properties of rock samples

	A	B	C	D
- Volumic mass [kg/m-'l	2,622	2,564	2,720	
- Absorption coeff. [%]	0.33	0.26	9.096	
- Knoop baldness [MPa]	6,442	6,575	1,366	1,273
standard deviation	1,632	1,825	166	217
- Compr. strength [MPa]	165	190	128	
- Flexural strength [MPa]	15.6	14.9	20.2	
- Impact test [cm]	58	51	75	
- Abrasion resist, [mm/km]	2.32	2.65	0.32	
- P-wave velocity [m/s]	4,760	4,510		

A - Luna Pearl C - Bianco Carrara
B - Silon Red D - Rosa Portugal

4 - ABRASIVES USED

The following abrasives, whose main properties are given in Table 2, have been taken into consideration for the cutting experiments:

- garnet (Barton);
- silica sand;
- copper slag (J-Blast Supafine, IMI);

Table 2. Characteristics of the abrasives used for linear
cutting experiments with the DIAJet equipment

CHARACTERISTICS	G	Q	S
- Shape index	6.89	6.84	7.07
standard deviation	0.90	0.97	1.51
- Knoop hardness [MPa]	12,898	8,558	5,050
standard deviation	1,732	421	516
- Volumic mass [g/crn^]	4.08	2.61	3.37
- Young modulus [GPa]	248	96	n.a.
- Size class [micrometres]	-365+150	-800+100	-900+100

G = Garnet; Q = Quartz sand; S = Copper slag;
(*) According to ASBA Image Analysis procedures.

5 - EXPERIMENTAL TECHNIQUE

Rock samples for linear cutting experiments with the DIAJet have been provided in the form of 30 x 30 cm tiles, 20 mm thick.

Tests aimed at finding the maximum cutting rate for each rock and for each abrasive dosage: starting from 4 cm/min, traverse rate was increased until the first drawbacks appeared, such as spalling at the kerf bottom, which was considered as a sign of incipient inefficiency of the jet in cutting through the whole thickness of the sample.

6 - RESULTS OBTAINED

6.1 - Cut geometry

The following values have been measured as representative of cut geometry:

a - width of cut at inlet
b - width of cut at exit
c - minimal amplitude of undulation at bottom
d - maximal amplitude of undulation at bottom

The study of cut features revealed that:

- Parameter a, i.e. cut width at inlet, always decreases with traverse velocity at equal abrasive feed rate;
- the curve representing a-value as a function of traverse velocity shifts upwards with increasing abrasive feed rate;
- parameter b, i.e. cut width at exit, follows the same trend, although with different gradients;
- taper, i.e. the measure of cut narrowing towards bottom, increases considerably with traverse speed, especially at higher abrasive feed rates. However, taper values are smaller for thicker slurries that maintain a better erosive power at depth;
- parameter c, which gives an idea of undulation at cut exit when compared to parameter b, gradually decreases with traverse velocity and increases with abrasive dosage;
- parameter d, whose knowledge completes the description of cut irregularity at the bottom, is sensitive to abrasive dosage only at slow traverse speed. As a function of traverse speed this parameter first slowly decreases then increases due to unsteadiness of the cutting process at the kerf bottom. This evenness-breaking point was therefore considered for determining the maximum cutting rate, together with other elements of evaluation.

- the values of all parameters increase with stand-off distance, i.e. the gap between nozzle and workpiece, due to the radial spreading of the jet, the more as the lance is traversed faster. Taper i.e. (a-b)/2a, which describes the downwards convergence of the cut walls, also follows the same trend.

6.2 - Cutting rate

Maximum cutting rate achievable for the various rocks with the different abrasives is reported in Table 3, column 1, as a function of abrasive feed rate.

Table 3. Maximum cutting rate [cm/min] (column 1) and specific erosion [cm^2/kg] (column 2) as a function of abrasive dosage.
Slab thickeness: 2 cm.

ABR.	kg/min	L		S		C		S	
		1	2	1	2	1	2	1	2
G.	1.0	30	60.0	35	70.0	80	160.0	25	50.0
	2.0	70	70.0	70	70.0	110	110.0	60	60.0
	3.0	110	73.3	90	60.0	150	100.0	140	93.3
G_r	2.0	65	65.0		.	.	.	.	.
Q	1.0		-	-	-	40	80.0	30	60.0
	2.0	40	40.0	-	-	90	90.0	65	65.0
	3.0	85	56.7	-	-	140	93.3	115	76.7
S	2.0	-	-			70	70.0	60	60.0
	3.0	15	10.0	10	6.7	130	86.7	120	80.0
	4.0	17	8.5	13	6.5	150	75.0	150	75.0
	5.0	18	7.2	15	6.0	-			

L - LUNA PEARL granite S - SİLON RED granite
C - BIANCO CARR. marble R - ROSA PORTUGAL marble

G-GARNET G_r - GARNET recirculated
Q- QUARTZ SAND S - COPPER SLAG

The most important facts ensuing from the comparison of the above results, having a condiderable importance to the assessment of industrial viability, are summarized here below:

- For a given abrasive/rock pair, maximum traverse velocity achievable in a through-cutting operation is roughly proportional to abrasive feed rate, although with some discrepancies;
- the gradient of cutting rate as a function of abrasive feed rate varies greatly from rock to rock, depending on the abrasive used;
- garnet performs well with all rocks, with some differences between granite and marble, lesser anyway than it would be expected on the basis of their hardness; performance of quartz sand on granite is almost half that achieved with garnet at equal feed rate, but approaches the same level on marble;
- cutting rate with garnet on Rosa Portugal appears somewhat penalized due to the weakness of this rock which easily undergoes premature spalling at the kerf bottom when working at low abrasive feed rate;
- cutting performance of copper slag is very poor on granite even at high feed rate, not exceeding 20 cm/min; the increase in abrasive dosage does not produce any significant advantage, meaning that its erosion power is definitely inadequate;
- on marble stone, all abrasives approach performance levels that are very close to each other, with only minor differences between them; therefore there would be no advantage in using high-quality expensive abrasives, also because their recovery for recirculation is not satisfactory, as it will be discussed later on.

6.3 - Specific erosion

This parameter is essential to the evaluation of cutting cost. It is defined as the rock surface that can be cut by the unit mass of abrasive and is calculated for the maximum cutting rate achieved (Yao, 1991).

Values of maximum specific erosion are reported in Table 3, column 2.

They suggest that:

- Granite is cut with good efficiency by garnet, still acceptable by quartz sand and very poor by copper slag;
- marble is cut with good to excellent efficiency by all abrasives.
- In granite cutting, garnet productivity reaches a top level of about 70 [cm^2/kg]; additional abrasive beyond 3 kg/min, though producing a further increase in cutting velocity, would not be beneficial as far as abrasive consumption is concerned. In other words, any incremental gain in cutting rate is attained with increasingly larger quantities of abrasive, with the additional drawback of cut quality deterioration;
- again in the case of granite, quartz sand allows a

productivity slightly above 55 [cm^/kg] to be reached; however, since specific erosion is still growing at 3 kg/min, it is likely that a level around 60 [cm^/kg] can be achieved working at 4 kg/min feed rate;

- on the same rock, productivity of copper slag appears very poor and decreases with increasing feed rate, meaning that there is no way to improve its performance;
- garnet, quartz sand and copper slag are in the same order of efficiency also in cutting Carrara marble, which can be considered as a rock of medium toughness. However, performance levels are closer to each other than in the case of granite, with a spectacular jump in efficiency of copper slag (about 10 times higher than on granite). Top productivity is reached by garnet at 1 kg/min, at 3 kg/min by the other two;
- similar considerations hold also for the Rosa Portugal but here the differences between the various abrasives are even smaller. Somewhat surprising is the unsatisfactory efficiency of garnet at low feed rates, even worse than that with the other two abrasives.

The above outcome suggests that abrasive properties must be matched to those of the rock for achieving optimum efficiency while improving economic profitability (Vasek, 1993).

In particular: the harder the stone, the harder the abrasive should be, whereas for softer stone most abrasives might be suitable: the choice is dictated by the price-to-performance ratio.

6.5 Recirculation of the abrasives

Compared to the curves for new abrasives, those corresponding to spent abrasives after cutting through the various materials appear reacher in finer fractions at the expense of the intermediate size classes.

- No significant differences in particle shape before and after cutting can be found in the case of garnet, even after having been recirculated twice without any intermediate addition of new feed. Sharp edges still appear at the border, meaning that aggressive power is potentially preserved. This is confirmed by the results of cutting tests with recirculated abrasive, as it will be illustrated later on;
- regarding quartz sand, a certain modification in particle shape looks evident, as the presence of grains having round borders is more frequent in used abrasive. Maybe particles still showing sharp points are those originated from disintegration of coarser grains.

6.6 Abrasive recovery

Abrasive recovery for re-use, i.e. the percent proportion of solids collected at the hydrocyclone underflow, at a separation size of roughly 50 micrometers, was found to be very high (well in excess of 90 %) for garnet on granite, even in the case of tests with recirculated abrasive. It drops sharply down to a level around 60 % when cutting marble, especially in the case of the Rosa Portugal stone.

Recovery with copper slag and with quartz sand is considerably lower for all rocks, markedly for the Portuguese marble.

On the other hand, recirculation of cheap abrasives is not a critical problem from the economic point of view;

It seems that recovery is directly proportional to the hardness of the abrasive and inversely proportional to the hardness of the rock.

A cutting test using recovered garnet, gave a result that was basically similar to those obtained using the original abrasive.

6.7 Correlations

The study of the existing correlation between cutting results and jet parameters and operational variables points out that, for a given total power of abrasive flow, specific erosion, i.e. the area cut per unit mass of abrasive, increases with the Knoop hardness and with the shape factor of abrasive particles.

These results refer to granite but it is believed that they also hold for marble, at least qualitatively.

7. ECONOMIC APPRAISAL

For a predetermined accuracy level depending on the final destination of stone manufacts, the cost of cutting per unit area is of a capital importance for the industrial viability of the technology (Ciccu, 1993).

A provisional analysis is given below on the basis of the results obtained with the DIAJet.

The Unit cost of cutting U [US$/m] is given by:

$$U = (C_a*F*60+C_e*Re+C_m+C_r)/(V*A)$$

where:

F Abrasive feed rate [kg/min]
Re Energy consumption [kWh/h]
V Cutting rate [m/h]
A Machine availability [%]
C_a Abrasive price [US$/kg]
C_e Unit cost of energy [US$/kWh]
C_m Cost of manpower [US$/h]
C_r Cost of replaceable« (nozzle) [US$/h]

Calculations according to the above approach taking into account the current prices of the various production factors give the results summarized in Table 3.

Table 3. Cost comparison [US$/m] of the various abrasives for different rocks as function of feed rate. Machine availability: 100 %
First line: Direct cost
Second line: Overall cost (including general expenses)

ROCK	GARNET [kg/min]			GARNET (*) [kg/min]			QUARTZ S. [kg/min]			COPPER SLAG [kg/min]			
	1	2	3	1	2	3	1	2	3	2	3	4	5
L	5.2	3.9	3.6	3.1	2.2	1.9	-	1.8	1.1	-	10.1	11.3	12.9
	11.7	6.7	5.4	9.6	5.0	3.7	-	6.6	3.4	-	23.3	22.7	23.7
S	4.4	3.9	4.4	3.6	2.2	2.4	-	-	-	-	15.6	14.9	15.4
	9.9	6.7	6.6	9.1	5.0	4.6	-	-	-	-	36.4	29.8	28.3
C	1.9	2.5	2.6	1.2	1.4	1.4	1.3	0.8	0.7	1.6	1.2	1.3	-
	4.3	4.3	3.9	3.6	3.2	2.7	6.1	3.0	2.1	4.4	2.7	2.6	-
R	6.2	4.6	2.8	3.8	2.6	1.5	1.7	1.1	0.8	1.9	1.3	1.3	-
	13.9	7.8	4.2	11.5	5.8	2.9	8.2	4.1	2.5	5.1	2.9	2.6	

(*) Under the assumption mat 50% of spent abrasive is recirculated at steady state
L - Luna Pearl granite; S - Silon Red granite; C - Bianco Carrara marble; R - Rosa Portugal marble

It is worth noting that:

- cutting cost per unit length is very sensitive to traverse velocity and less so to the purchase price of the abrasive and to abrasive feed rate;
- in the case of granite, cutting cost with garnet is as cheap as with silica sand: in fact, the higher cost of the abrasive is compensated by a higher cutting rate. Copper slag is unsuitable due to its very low cutting efficiency;
- in the case of marble, all the abrasives appear competitive and cutting cost is very cheap for all of them;
- taking into account also cut accuracy, it seems reasonable to work with a somewhat lower cutting rate than the maximum achieved, according to the roughness specifications required. In agreement with this, cutting cost further increases.

7. CONCLUSIONS

The appropriate choice of the abrasive is the decisive factor for cutting successfully any material and rocks in particular. Traverse velocity is the chief operational variable upon which the unit cost of cutting is strongly dependent.

On the basis of experimental tests on granite it appears that garnet is technically superior over the other abrasives, and its gain in performance is expected to diverge as slab thickness increases. Below 2 mm, silica sand becomes economically competitive due to its low purchase cost.

In the case of marble, the choice between the various abrasives appears indifferent.

The technical performance of silica sand (ground quartz) is surprising: despite the fact that its characteristics of a recognized meaningfulness in abrasive jet cutting (volumic mass, hardness, elasticity features) are not particularly favourable, results achieved are not far from those of garnet.

Regarding the development of commercial equipment for contour cutting, efforts should be directed to design a device for stopping the abrasive flow immediately on automatic control input.

The driving device must be strong enough to withstand the reaction force of the jet, especially at high feed rate.

Compared to the entrained method, recirculation of the abrasive is easier with the DIAjet. In fact, recovered suspension can be fed back directly without the need for intermediate drying, which is an energy consuming step.

Moreover, recovery of spent abrasive is considerably higher, adding economic significance to the operation.

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