Improvement of abrasive jet efficiency in cutting operations

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1. SYNOPSIS

The paper deals with the results obtained in the frame of a research programme aimed at increasing the cutting performance of plain and abrasive waterjet through the improvement of the jet structure and of the process of energy transfer. The features of plain jets have been investigated at variable experimental conditions (nozzle diameter, stand-off distance and pressure) using different techniques. Concerning abrasive jets, the structure of which is destroyed by the presence of solid particles and of entrained air (in the case of AWJ experiments), the improvement achieved has been directly evaluated on the basis of cutting results.
The advantage of polymers addition due to their stabilising effect on the turbulence produced by the high velocity flow of the water along the pipe and the nozzle is put into evidence.

2. FOREWORD

The paper summarises the results of a research programme carried out at the Department of Geoengineering and Environmental Technologies (DIGITA) of the University of Cagliari and at the Institute of Environmental Geology and Geoengineering (IGAG) of the national Research Council in the frame of the European Project: Improvement of Efficiency, Availability and Quality of Abrasive Water Suspension Jets, involving also the Institut für Werkstoffkunde of the University of Hannover as the main RTD performer and a number of SMEs (1).
The general approach to the problem, the identification of the technologies employed and the results obtained have been jointly discussed by the three Research Performers and the conclusions shared by all partners.
The concept of efficiency entails not only an increase in cutting rate (higher power available at the nozzle for a given power at the prime motor) but also a better accuracy in the cut quality (more jet coherence, even distribution of the abrasive in the jet core).
The technical and economic performance of an abrasive jet can be expressed in terms of specific erosion which represents the cut surface generated by the unit mass of abrasive. The other conditions being the same, this parameter is chiefly influenced by the kinetic energy carried by the abrasive particles incorporated in the jet at the moment of their impact on the target material.
This implies that:

- friction losses along the hose and the nozzle are reduced, thus maximising the velocity of the carrier fluid;
- favourable conditions are created for the transportation of suspended solids;
- particle acceleration in the nozzle is as high as possible, thus maximising the transfer of energy to the solid particles;
- the jet maintains its coherence over longer distances from the nozzle.

3. AVAILABLE WATER-SOLUBLE POLYMERS

A number of water-soluble polymers, having a non polar, cationic or anionic behaviour, are commercially available for a variety of applications based on the modification of the physical properties of aqueous systems. These products can be synthetic, semisynthetic or natural.
Natural polymers can be used as such or after a suitable modification. Semisynthetic polymers are derived either by chemical modification of natural polymers or by microbial actions.
Common uses of polymers are as superabsorbents, detergents, dispersants, additives of hydraulic fluids, adhesives, emulsifiers; for many applications like surface coating, enhanced oil recovery, water treatment, thickening of suspensions; in many branches of industry such as pulp and paper, mineral processing, production of foodstuff, pharmaceuticals and cosmetics.
The idea of using polymers as stabilisers of fluid streams has already been commercially applied for increasing the coherence of plain waterjet and it has been proposed for improving the performance of abrasive waterjet (2, 3, 4, 5).
For this purpose, the most promising are the synthetic polymers starting from aliphatic monomers, mostly characterised by long linear chains with a well defined presence of polar groups.
They are generally produced in large quantities for mass consuming uses and therefore most of them are relatively cheap. Foaming features in the receiving tank can be controlled by the addition of salts or froth-depressing chemicals.
Semisynthetic polymers based on cellulose have often a ramified structure in their macromolecules.
Natural polymers can be interesting, although their properties may vary according to kind and source. The polysaccharides family into which many of them can be classified is generally characterised by the presence of ramifications.
Accordingly, before proceeding to the choice of the polymers to be used for the systematic cutting tests in the frame of the present research, a series of laboratory measurements have been carried out aimed at disclosing the effect of the various candidate polymers on:

- viscosity (directly)
- surface tension (directly)
- stabilising effect on a solids suspension (through free settling experiments)
- frothing potential (after agitation in a mechanically stirred cell)

Solubility in water as a function of temperature was also assessed.
The following goals were identified in order to define the requirements of additives and to make the proper selection on the basis of a comprehensive ranking factor:

- improvement of jet cutting efficiency;
- favourable supply, handling and storage conditions;
- easy use and disposal (safety, health and environment);
- economic advantage.

They were to be pursued altogether since a fail in the achievement of one of them could invalidate the other advantages. About 20 different polymers have been investigated although only two of them (Superwater and Natrosol MR) are considered in the present paper.

4. STUDY OF THE JET STRUCTURE

4.1 Experimental conditions

The influence of selected additives on jet structure has been preliminarily studied by means of experimental tests aimed at investigating the modification in the jet structure as well as at determining the effect on a target surface.
Pictures of the jet have been taken with a digital camera in order to compare the coherence features through a visual inspection.

The jet coherence has also been indirectly measured through the electric resistance of the water stream between the nozzle and a copper target surface, taking into account that the natural conductivity of water is modified by the additive.

The experiments have been carried out at the following constant conditions:

- Nozzle diameter: 0.3 mm
- Pressure at the nozzle: 20 MPa
- Flow rate: 0.6 l/min
- Kind of nozzle used: type 280 Procer Nozzlemeyer
- Concentration of additives: variable until achieving a kinematic viscosity of 10 mm^2/s.
- Water quality: deionised with regenerated cation-exchange resins.

Pure Water Super Water Natrosol MR

Figure 1. Features of water jets with or without polymer addition

The effect on a target has been assessed in two ways:

- by determining the damage produced on a suitable test material;
- by measuring the load transmitted by the jet on a force transducer.

4.2 Visual features of the jet

Pictures of the jets against a black non-reflecting screen have been taken with a Canon power shot A5 camera using a high-speed flash from a distance of 2 m.

They are shown in figure 1.

From the visual confrontation of the pictures the following aspects are worth underlining:

- The length of the core of the jet before a complete break into a mist of minute droplets varies for the different additives with respect of pure water;
- Some of the additives (Superwater and Natrosol for instance) seem to produce a longer core than that with pure water;
- the loss of coherence with the distance from the nozzle appears with different aspects: in the case of pure water the jet is progressively fragmented into a homogeneous mist of small droplets while in the cases of polymer addition small secondary streams detach from the main jet which assumes the shape of a feather;
- the coherence features are likely to improve using larger nozzles.

4.3. Damage on wax target

Jet damage tests after an impingement time of 10 s, controlled by means of a shutter, have been carried out on a layer of wax (molten and slowly solidified at low temperature for better homogeneity of the material). The stand-off distance was set at 200 mm.

The craters produced were measured in terms of depth of penetration, diameter at surface and volume. Penetration gives an idea on the residual power carried by the jet (flow rate in the core region and stream velocity) while the diameter and volume provide an indication of the radial spreading of the jet (loss of coherence).

Table 1 - Cratering tests on wax

Additive	**Crater geometry**		
	Depth [mm]	**Diameter [mm]**	**Volume [mm^3]**
Natrosol MR	10.0	6.3	60
Super Water	10.8	4.8	45
Pure Water	6.4	4.0	28

Results are summarised in the table 1.

With respect to pure water both additives produce an increased depth accompanied by a larger diameter of the crater. The larger diameter means that the secondary streams hit the target still carrying a significant power, contrary to the droplets of pure water, the velocity of which is rapidly slowed down by the friction of the air in the strongly turbulent environment around the jet.

4.4 Electric resistance tests

The coherence of the jet can also be indirectly measured by the electric resistance between the nozzle and a metal target. The more the jet is coherent the lower the resistance should be, since isolated droplets do not give any contribution to the electric conductance.

It was reasonable to assume that the electric resistance increases with the stand-off distance and the gradient of the curves is a measure of the rate by which the coherence is lost.

Unfortunately the quantity of additives available was not enough for making the tests at variable stand-off distance which was maintained constant at 460 mm.

Of course the additives produce a certain modification in the electric conductivity of water due to their molecular activity against the ions in solution. Therefore the electric resistance was measured also in still water for obtaining a reference value using a cell with two parallel cylindrical electrodes, 2 mm in diameter, 20 mm long and 70 mm apart.

Resistance was measured with a METEX M-3860D multimeter.

Table 2 - Electric resistance measurements

Additive	Electric Resistance [MΩ]		
	Jet	**Still solution**	**Ratio**
Natrosol MR	13.0	2.3	5.6
Super Water	9.9	0.8	12.3
Pure Water	9.2	1.1	8.36

Results are shown in the table 2.
It was found that the resistance of still solution increases with the presence of most additives implying that part of residual ions are captured by the polar groups of the polymers.
The influence of the additives on the electric resistance seems controversial with no clear indication. Maybe a better significance could have been achieved by working at variable stand-off distance.

4.5. Target loading tests
In order to measure the force transmitted by the jet upon impacting on a target, at variable pressure and nozzle diameter, the jet has been directed to impinge at the centre of the circular area, 2 mm in diameter, of a small cylindrical shaft sliding vertically without friction along a sleeve. The shaft stands onto a force transducer connected to a high frequency data acquisition system capable of detecting the static load and the fluctuations at less that 1 ms intervals.
The device can also be moved sideways across a diameter of the jet in order to explore the decrease of impact pressure from the centre to the periphery.
The force sensor employed is the Type ICB Model 200B01 of PCB Piezotronics, capable of measuring a maximum load of 45 N with high sensitivity. The Strawberry Tree data acquisition system includes a DATA shuttle parallel port device connected to a PC capable of handling up to 11 signals at a time. The computer program enables to make mathematical and statistical processing of recorded data. Impingement tests were made at a stand-off distance of 400 mm.
A picture and a sketch of the device are shown in Figure 2.

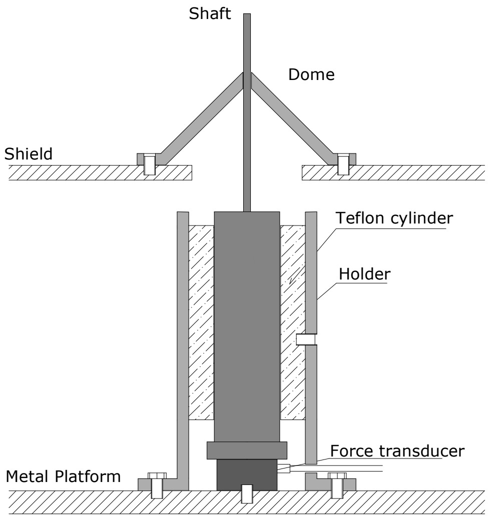
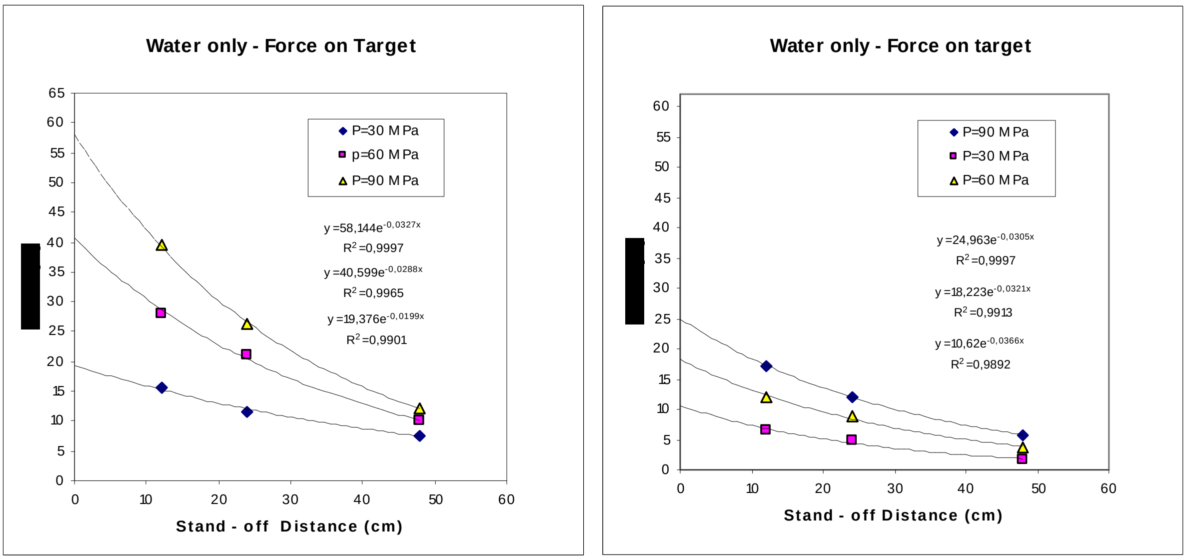


Figure 2. Experimental device for for the measurement of jet impact force jet

The technique has been refined with systematic tests on pure water (figure 3).
Typical records of the force with the data acquisition system are shown in figure 4. The impact force is the average value of 300 data points at a speed of 1,600 points per second, corresponding to about 200 ms, in order to eliminate the instrument noise and the oscillations of the load.

Data are well in agreement with predictions based on viscosity and drag reduction data and are consistent with damage test results on a wax target.
The best additives appeared to be Superwater, Natrosol MR, CMHPG 104 N and Walocel CRT 10000 G in the order, which give rise to an increase in the load by about 1.5 times with respect to pure water.



Nozzle diameter: 0.8 mm *Nozzle diameter: 0.8 mm*

Figure 3. Force on target at variable stand-off distance with plain water jet

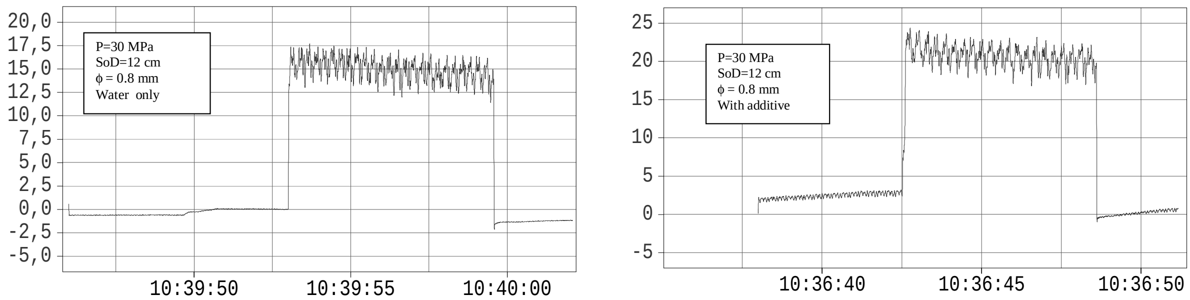


Figure 4. Typical records of the force with the data acquisition system

Comparative results are summarised in table 3.

Table 3 - Impact force and pressure on the 2 mm diameter circular target at 30 MPa, stand-off distance 12 cm and nozzle diameter 0.8 mm.

Additive	Force [N]	Pressure [MPa]
Natrosol MR	19	6.0
Super Water	21	6.7
Pure Water	13	4.1

4.6 Influence on pipe friction
The effect of the additives on pipe friction was assessed by measuring the pressure with two pressure gauges, one placed at the outlet of the pump and the second before the nozzle.

The inner diameter of the pipe was 5 mm and the length 20 m.
For achieving a Reynold's number of the same order as that of the commercial system (DIAJet) during the cutting operations, the nozzle head was removed for increasing the velocity of the fluid along the pipe up to 13.5 m/s. Correspondingly flow rate was 16 l/min.
Results are shown in table 4. Since the tests were made at variable concentration of additives giving the same kinematic viscosity and neglecting the insignificant modification in density, Reynold's numbers were the following:
- Pure water: 70,000
- Additives 7,000

In the pipe of the DIAJet system used for cutting tests (inner diameter: 15 mm, flow velocity: 5.6 m/s, flow rate: 60 l/min at 70 MPa) Reynold's numbers resulted to be approximately:
- Pure water: 84,000
- Additives 8,400

Friction loss with additives was found to be always less than that with pure water (table 4), especially with Superwater (-72%).

Table 4 - Friction loss and drag reduction for the various additives

Additive	**Friction loss [bar]**	**Drag reduction [%]**
Natrosol MR	10.7	14
Super Water	7.2	42
Pure Water	12.5	0

4.7 Influence on the particle acceleration and sedimentation

The influence of the additives on particle acceleration and sedimentation can be evaluated from the results obtained from settling velocity test. In table 5 the values of that parameter expressed as the ratio between the sedimentation time in the polymer solutions and the sedimentation time in water are reported (sedimentation time for water: about 10 s).
The results obtained in the tests give only a rough indication about the influence of the different additives on the particle acceleration, since flow conditions (velocity, turbulence, particles crowding) are different from those encountered in the pipe and along the nozzle.
The effect of additives on viscosity is shown in table 6.

Table 5 - Settling ratio obtained in the various additives solutions.

Additive	**Settling ratio**
Natrosol MR	26
Super Water	31
Pure Water	1

Table 6 – Maximum, medium and minimum flow rates and corresponding viscosity values.

Additive	**Dosage [%]**	**Viscosity [mm^2/s]**
SuperWater® Concentration 1%	0.046	1.7
	0.093	2.5
	0.140	4.1
Natrosol MR Concentration 1.25 %	0.060	1.7
	0.160	4.7
	0.290	11.4

Figure 5. The DIAJet slurry delivery unit

5. CUTTING RESULTS

5.1 Experimental apparatus

5.1.1 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 pressurised vessel from which the abrasive slurry stream is delivered to the nozzle through a flexible hose.

At the present state of commercially available technology, DIAJet and similar systems are operated with a nozzle diameter up to 1.8 mm at relatively low pressures (lower than 70 MPa) compared to the entrained abrasive counterpart (up to 400 MPa), although efforts are successfully being made to increase the pressure for better cutting accuracy with lower abrasive consumption.

5.1.2 Pump

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

This pump is suitable for operating the DIAjet at 70 MPa up to a nozzle diameter of 1.8 mm, by-passing the excess water.

5.1.3 Slurry delivery unit

The unit installed at the DIGITA laboratories shown in Figure 5 is the Model DIAJet 700, built in UK by FDL, a Subsidiary of BHRGroup.

At the time of installation (1994) this was the newest development of a series of equipment widely used for cutting metals and a variety of other materials in the field.

The machine has been designed for a continuous operation using two phase-shifted high pressure bottles, one delivering the slurry while the other being refilled. However for a better control of the operation, the tests envisaged in the CRAFT workplan have been made using only one bottle.

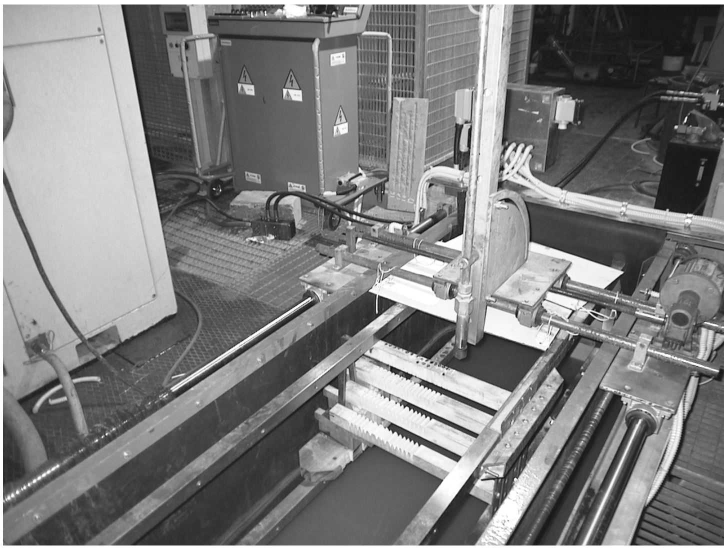


Figure 6. X-Y lance driving device and slurry collection system.

5.1.4 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. The lance supporting platform can be moved at a velocity variable from 0 to 800 cm/min with good steadiness.

The lance manipulator used for linear cutting experiments is shown in Figure 6.

5.1.5 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.

5.1.6 Additive metering device

Three solutions have been considered, related to different adding points:

a) before the pumping system;
b) in the abrasive storage vessel;
c) directly along the main branch, after the by-pass valve, by means of a dosing pump.

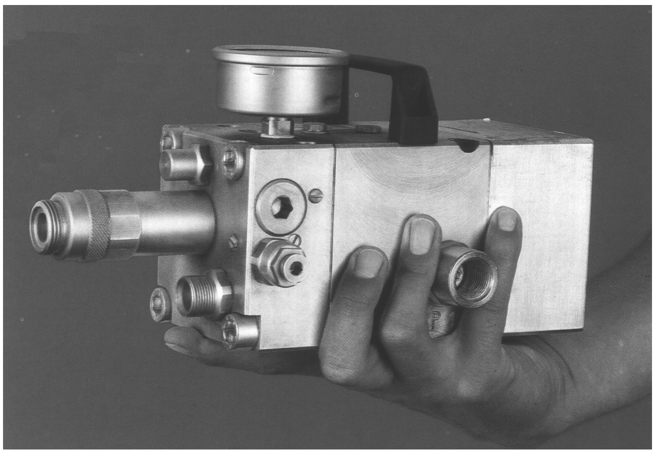


Figure 7. Intensifier pump for additive injection

Adding unit before the pumping system.

A mixing system has been developed. The system consists of a vessel (about 70 l), an agitator, a heater and a thermostat. Water and additive are let in the vessel in the right proportion, at constant temperature, and agitated for the needed time. The resulting solution is fed to the high pressure pumping system.

Adding unit feeding the abrasive storage vessel.

The solution has proved to be not practically acceptable. In fact the additive fed in the abrasive storage vessel in a concentration about ten time higher of the final concentration (in the by-pass branch flow rate is about 10 % of total) causes problems related to the pasting of abrasive particles. Moreover the final concentration of additive would depends on the abrasive feed rate and it is not easily controllable because of the complicated flow distribution inside the storage vessel.

Adding unit directly along the main branch, after the by-pass valve, by means of a dosing pump.

This third solution offers a series of advantages compared to the first two. Injecting the additive along the main branch avoids all the problems related to the presence of additive in the pumping system, i.e. consenting higher concentrations (no viscosity limits), and the quantity of additive introduced can be modulated very finely by a dosing pump. This solution has been adopted for the experiments: the intensifier pump for additive injection is shown in figure 7.

The additive has been injected into the main line of the delivery circuit about 5 m ahead of the nozzle, shortly after the inlet point of the abrasive slurry from the pressurised tank.

5.1.7 Target material

Cutting experiments have been made on hardened aluminium alloy (Duralumin) containing about 4% copper, 0.5% magnesium and 0.5% manganese.

The cross section of the bars was:

- 40 x 40 mm for the assessment of the depth of cut
- 60 x 20 mm for the assessment of cut quality

The workpieces have been clamped into a sample holder and placed at variable depth from the nozzle in order to explore the effect of stand-off distance.

The sample holder can be lowered into the catcher vessel for the tests under submerged conditions.

5.2. Cutting rate

Linear cutting tests have been carried out using the DIAJet Mixing Unit installed at the Waterjet Laboratory on aluminium bars.

Experimental conditions were:

- Operating pressure: 65 MPa
- Nozzle diameter: 1.0 mm
- Abrasive used: GMA garnet (two size classes)
- Additives used: Superwater, and Natrosol (injected in the main line after the abrasive feeding point by means of the intensifier dosing pump described earlier).

The following ranges have been explored for the operational variables:

Stand-off distance: 2, 50, 100 and 150 mm

Traverse velocity 200 and 800 mm/min

Polymer dosage: from 0 (pure water) up to 0.3 %

5.1. Tests on 40 mm aluminium bars

The depth of cut with additives compared with that achieved with pure water is shown in the following tables for garnet HP 50 and garnet HP 80 at the maximum concentration of additives (the one giving the maximum allowable viscosity).

Cut depth was measured with a comparator introducing a thin metal lamina into the kerf.

Depth 40 mm means that a separation cut was obtained.

Table 7 – Depth of cut at varying additive dosages..

DEPTH OF CUT Abrasive: HP50

Additive	Traverse velocity: 200 mm/min				Traverse velocity: 800 mm/min			
	Stand-off distance [cm]				Stand-off distance [cm]			
	0	5	10	15	0	5	10	15
Superwater (0,14 %)	40	38	19,27	11,35	20	10	4,2	4,01
Water only	40	37	18	8,19	18	7	1,54	1,89
Increment [%]	0,0	2,7	7,1	38,6	11,1	42,9	172,7	112,2
Natrosol (0,29 %)	40	40	32	18	20	12	3,6	2,6
Water only	40	36	19,1	8,19	18	8	1,54	1,89
Increment [%]	0,0	11,1	67,5	119,8	11,1	50,0	133,8	37,6

DEPTH OF CUT Abrasive: HP80

Additive	Traverse velocity: 200 mm/min				Traverse velocity: 800 mm/min			
	Stand-off distance [cm]				Stand-off distance [cm]			
	0	5	10	15	0	5	10	15
Superwater (0,14 %)	40	40	37	28	18	11	5,8	6
Water only	40	33	26	19,65	16	5,2	2,44	2,31
Increment [%]	0,0	21,2	42,3	42,5	12,5	111,5	137,7	159,7
Natrosol (0,29 %)	40	40	31	18,59	20	12	2,53	1,95
Water only	40	35	25	11,76	17	7	2,05	1,83
Increment [%]	0,0	14,3	24,0	58,1	17,6	71,4	23,4	6,6

Results with the coarser abrasive appear worse that those achieved with the finer abrasive. Depth of cut with Superwater looks better than those with the other additives especially at faster traverse rates and at higher stand-off distances.

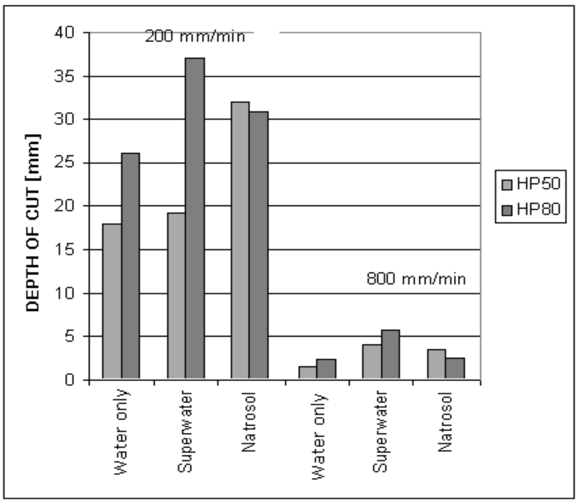


Figure 8. Depth of cut in aluminium with and without additives

The width of cut was found to be narrower when using the additives compared with that achieved with pure water.
The comparison becomes more evident if represented by means of bar diagrams showing the depth of cut (Figure 8) and the incremental depth and width of cut with respect to the tests with pure water (Figure 9). Both diagrams are related to a stand-off distance of 50 mm since at 2 mm the comparisons is misleading due to the necessity of extrapolating the data beyond the thickness of the sample bars.

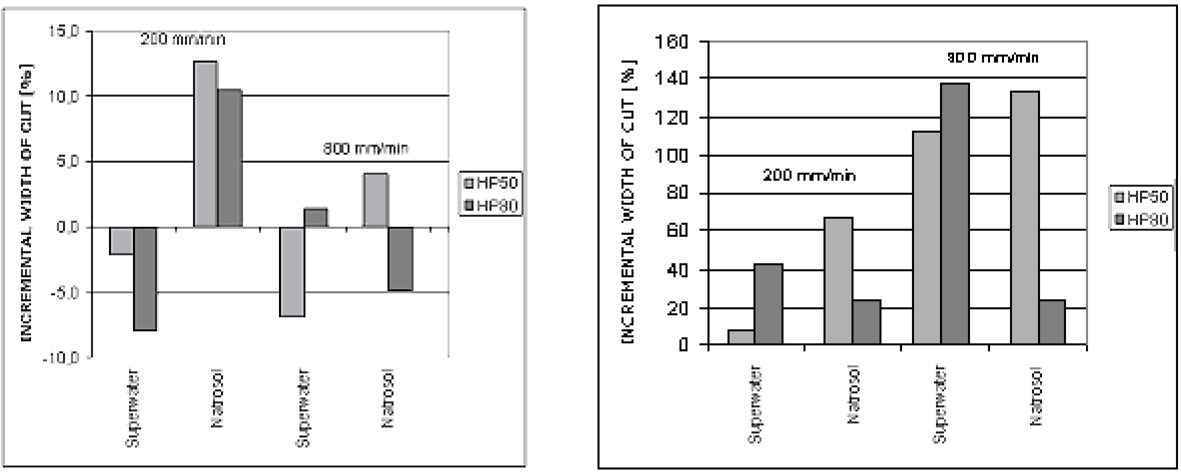


Figure 9. Incremental depth of cut in aluminium with and without additives

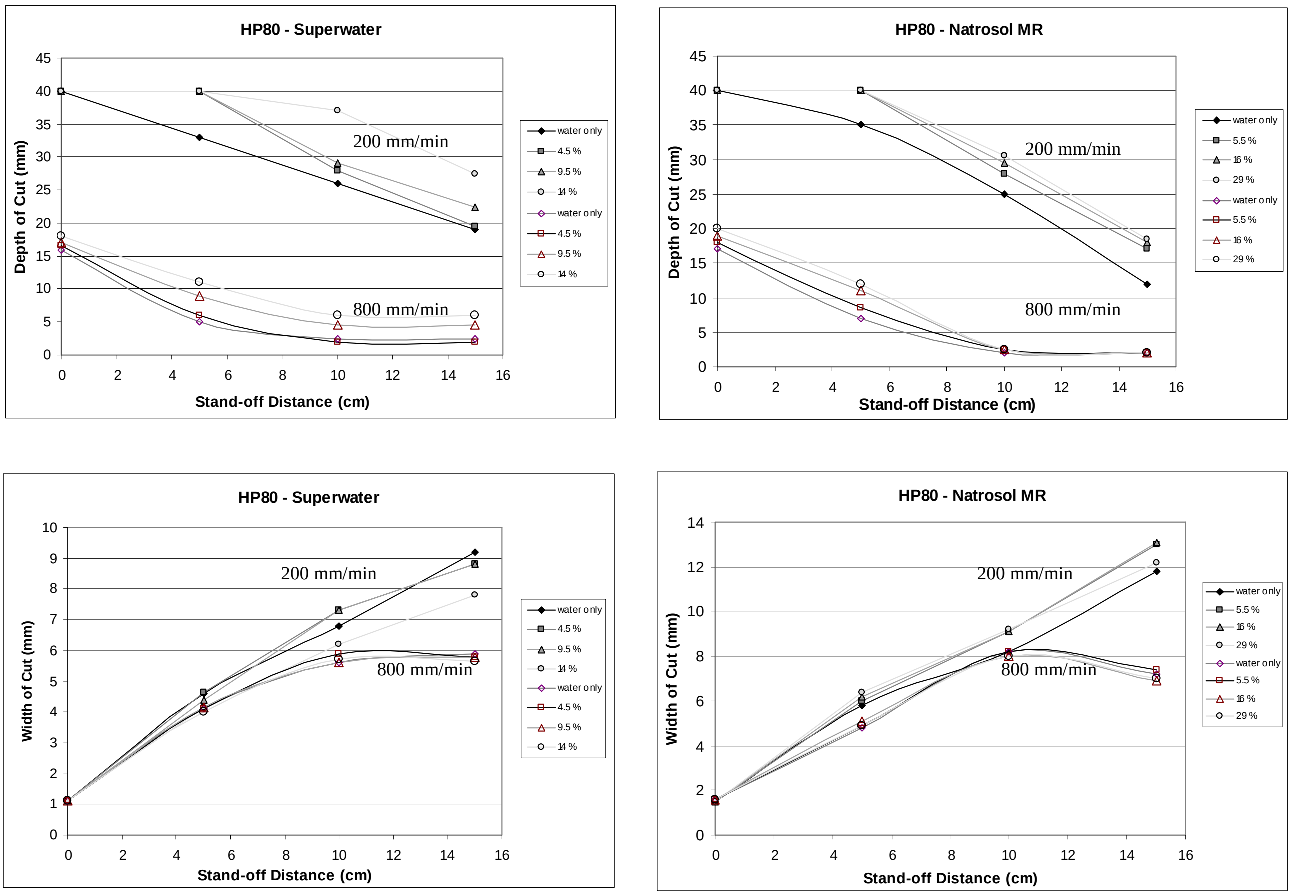


Figure 10. Depth of cut ad variable stand-off distances with different additive dosages

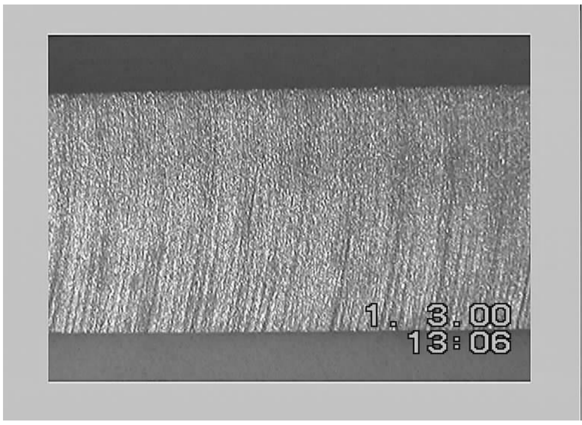
The advantages of using additives become more evident when working at high traverse rates and at higher stand-off distances.

5.2 Influence of additive concentration on depth of cut

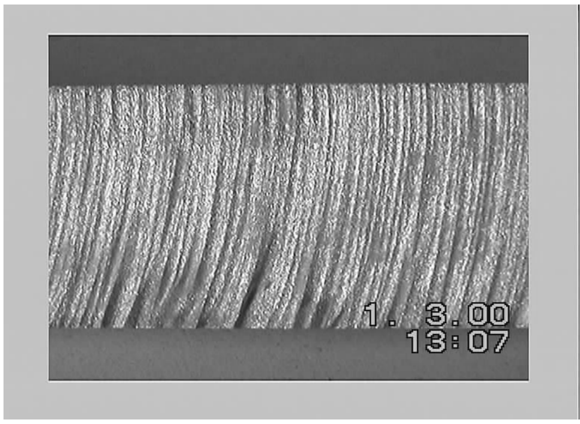
Increasing the additive concentration produces an increase in the depth of cut and a decrease in the width of cut, although with different gradients according to the additive used, as shown in the graphs of Figure 10 for Superwater and Natrosol at various stand-off distances and for the two traverse velocities explored.
Curves of depth of cut are always growing, suggesting that results can be increasingly better beyond the maximum concentrations explored.
On the other hand cut width decreases gradually with additive concentration and the effect is more marked at high stand-off distances.
Similar curves have been obtained with the other additives.

5.3 Influence of additive concentration on cut quality

The use of additives affects in some way also the quality of the cut that has been assessed by roughness measurement with Perthometer.
The appearance of the surface has also been examined visually through digital camera pictures (Figure 11).

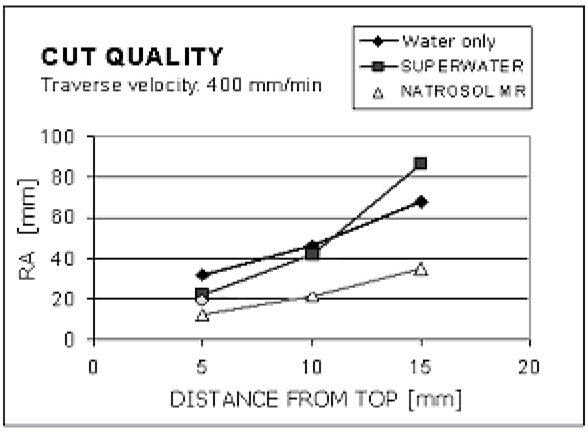


A smooth cut



A rough cut

Figure 11. Cut quality at different experimental conditions



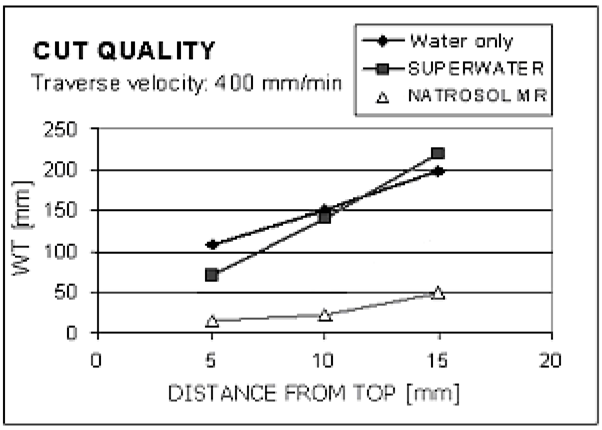


Figure 12. Cut quality with and without polymer addition

Figure 12 shows parameters RA (roughness) and WT (waviness) across the sample thickness as a function of the distance from top of the sample for each additive at maximum concentration.
Near the bottom of the cut (15 mm from top) cut quality improves when using additives although with some discrepancies due to possible experimental instability especially regarding the steadiness in abrasive dosage.

6. CONCLUSIONS

Experimental evidence shows that he use of additives can improve significantly the efficiency and the cut quality of ASJ.
In fact:

- the depth of cut increases with the concentration of additive in water especially at higher traverse velocities;
- the width of cut decreases owing to a better coherence of the jet;
- roughness parameters are generally improved;
- the use of additives can be economically advantageous since the additional cost is outbalanced by a higher performance;
- conditions at the working site (noise) are slightly better;
- side effects (foam generation) may be important but can be controlled with suitable measures (addition of salts in the vessel, working under a shallow liquid seal);
- the use of additives is beneficial also in submerged conditions especially at slow traverse velocity and at short stand-off distance;
- according to the results of preliminary field tests, the additives proved to be beneficial also in the case of plain waterjet for cutting soft materials (thick polystyrol plates, plywood) as well as for cutting hard materials (glass, stainless steel) using the abrasive injection jet.

ACKNOWLEDGEMENTS

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