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Precison Machining Using Abrasive Water Jets

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ABSTRACT

This paper presents the main findings of a BRITE EuRam sponsored research project to investigate the precision machining of materials using abrasive water jets

Experimental procedures for carrying out cutting tests were developed. The information generated by these tests was stored in an interpretive database. This software uses the information to predict cutting parameters to achieve a desired cut quality. To aid in the specification of required cut quality, a draft European standard on abrasive water jet cutting was propsed, similar in nature to existing thermal cutting tool standards.

The test data was also used to build and verify mathematical models of the cutting process. The mechanism in operation were confirmed to be material erosion by solid particle impact. Two different erosion modes were recognised, distinguished by tht relative angle between the impacting particle and the material. Low angles of impact (up to 20 degrees) remove material by a micro-machining process similar to v-point cutting tools, termed cutting wear. Near normal impact angles cause work-hardening of the surface and subsequent fracture and is known as deformation wear.

Materials are classified as either ductile or brittle. Ductile materials are cut by a combination of cutting wear and ductile failure, while brittle materials are cut almost exclusively by brittle fracture. Metals which work-harden easily tend to fail by micro-cutting and brittle fractu

The difference between both types of Abrasive water jetting systems in use has been examined and the increased efficiency of the suspension system (DIAJET) can be explained from consideration ofjet pump efficiency and abrasive degradation within each system.

Guidelines for carrying out trials to test the suitability for Abrasive water jet systems for Aerospace industry use have been developed. However, in order to prove the fatigue requirements for the cutting of advanced Aerospace materials, further work is required.

The project has quantified the impact of the jet, once its exits the material being cut, on the surrounding environment. Subsequently, it has been possible to select material resistant to the impact of the jet and construct the architecture of jet catchers designed to collect the jet.

As a result of procedures developed during this project, each partner has improved th operation of their abrasive water jetting business.

INTRODUCTION

The use of abrasive water jets to machine difficult materials is an emerging technology that can reduce the cost of many cutting tasks and make economic the exploitation of advanced technology materials and fabrication methods. Research into this area is limited, with most of the exploitation being carried out in the US.

The main aim of this project was to carry out the research needed to develop a European Community capability to dominate specific markets for abrasive jet machine tools, and thus provide the technology to enable Community manufacturing companies to exploit these tools.

1. The project commenced with establishing methods and procedures to maximise the benefits of the test programme for the project and provide the means for comparing the performance of different cutting systems, materials and operating parameters.

2. The characteristics of abrasive water jets were studied to relate jet parameters to cutting performance.

3. A combination of linear and contouring cuts were carried out on a standardised test shape on a range of brittle and ductile materials for various operating conditions to build up the database of cutting performance.

4. Designs for compact catchers to intercept and destroy the energy of jets leaving the workpiece were developed and tested.

5. Mathematical and data models were developed to predict cutting performance of a wide range of materials and thickness' and allow complex shapes to be accurately machined.

6. Existing cutting systems were modified to incorporate the results of prior activities in order to verify predicted cutting performance.

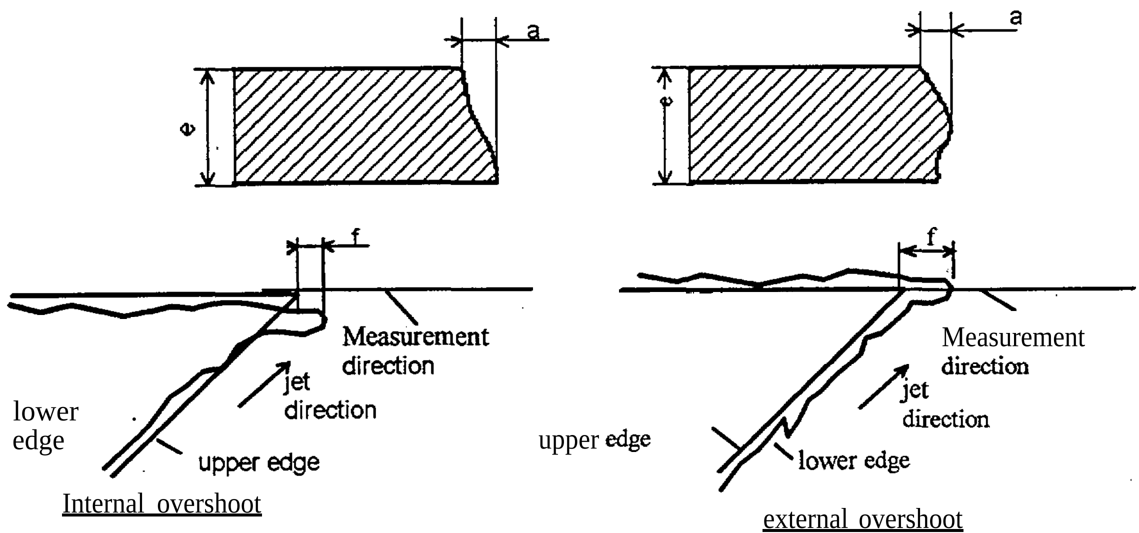
7. An assessment of the cutting trials was carried out during the life of the project to relate actual operating experience to predicted performance using data models and simulations.

8. Recommendations were made for the design of abrasive jet cutting tools and the use of the research results in exploiting abrasive water jets.

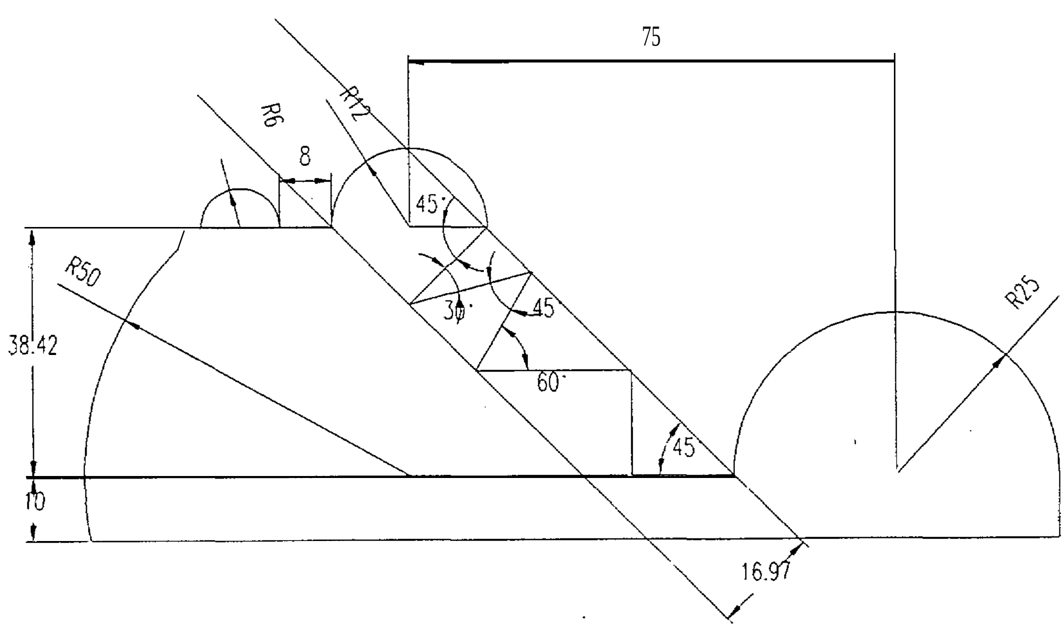
TECHNICAL DESCRIPTION

From partners previous experience, a set of test procedures were drawn up to allow comparison of different abrasive water jet cutting systems. A series of controlled experiments were carried out in order to build a database of cutting results. This database provides a means of quickly accessing data concerning Abrasive Water Jet cutting, allowing an estimation of the operating parameters for a specific application.

The criteria used to evaluate a cut are:
- The weight loss due to cutting
- The kerf width
- The cutting time
- The edge taper (a) on linear cut and on various circle
- The over-shoot (f)



A standardised test shape was devised to include all the features to be measured, shown below:



The information was also used to aid in understanding the mechanisms involved in abrasive water jet machining. Mathematical models of the machining process have been developed. The models provide a good estimation of the variables involved in the cutting process. The abrasive water jet cutting of materials has been shown to be dependant on the yield and ultimate strength of the material, and Young's modulus.

Both entrainment and suspension jet systems were used to understand the performacne differences between the systems. The inherent inefficiency of the jet-pump nature of the entrainment system cannot fully explain the reduced cutting performance compared to suspension jet systems. To clarify this difference, the abrasive particle size at system exit was measured showing a greater amount of abrasive degradation for the entrainment system. Erosion trials have shown that erosive wear is dependant on particle size. Particles sizes an order of magnitude less than the focussing nozzle size have been shown to produce a double-concave indent in the material. This is caused by the abrasives' path being dictated by the water. The reason for this is attributed to the boundary layer effects, hindering particles for impacting the material surface.

The abrasive concentration was measured using a propotype meter designed for non-intrusivve measuring of instantaneous abrasive concentration. The levels of vibration generated by standard profiling tables was also measured. These measurements did not correlate with cut surface finish, suggesting that the striations observed on the cut surface is an inherent material property and not so dependant on system parameters.

The jet/material interaction was examined whilst discharging into both air and water to determine the jets impact on the surrounding environment. This information was used to suggest improvements in jet catcher design and energy dissipation.

RESULTS

A Database Of Cutting Performance

The test programme (culminating in the database of results) provides the most comprehensive body of work produced in the field of Abrasive water jet cutting to date. The framework for the test programme will provide a basis for future testing and the exchange of meaningful results.

The database could be developed into a stand-alone marketable product. The information contained within it will reduce the set-up time necessary to achieve a required quality. In addition, the trends shown for the materials included in the database will aid in the selection of cutting parameters for other materials. The database is fully open to be upgraded, with the test procedure being repeated to store information on a new material.

This information would also be extremely useful if tied directly into the CAM software of each cutting table. Considerable investment would be required, however, in order to allow the software to interface with any CAM system.

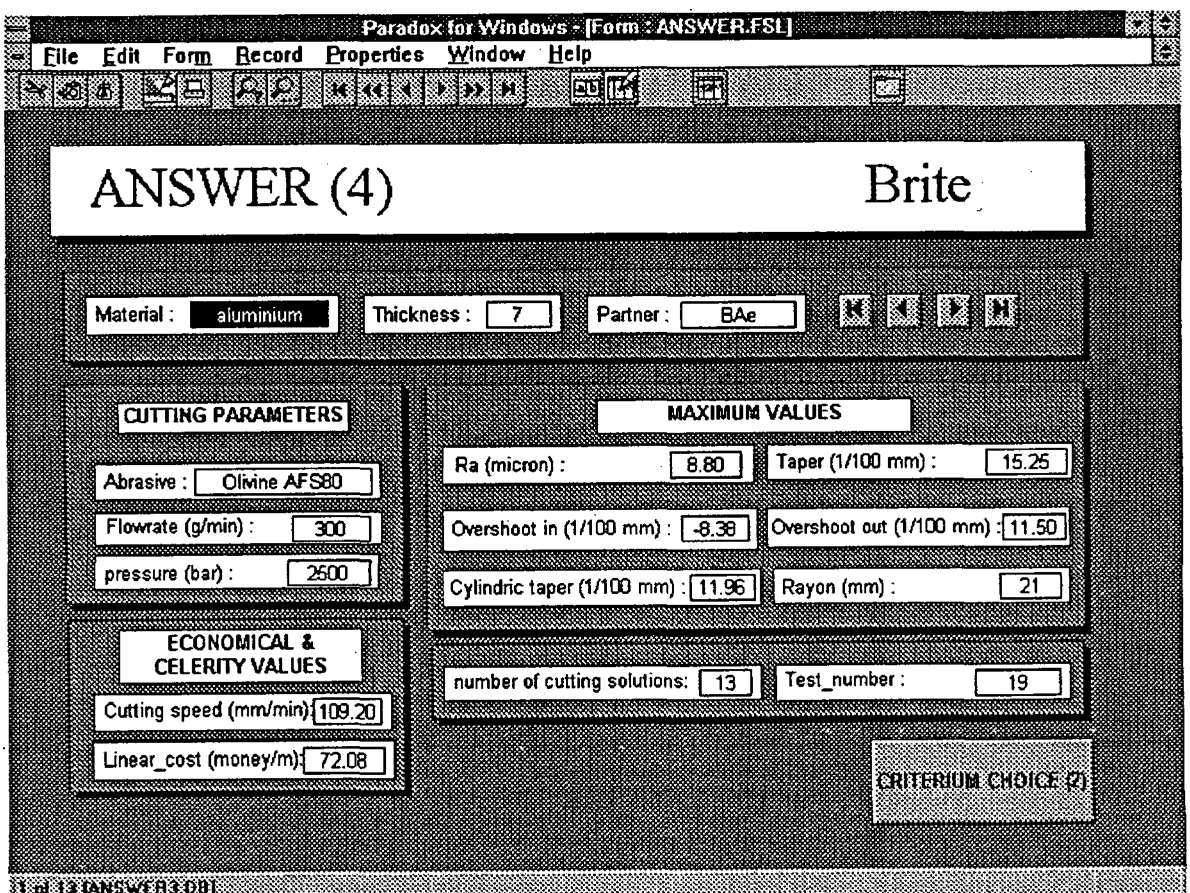
Cutting trials were carried out on a range of materials and thicknesses. The object was to find the maximum parting speed under the specified conditions. A summary of the cutting results are given below.

Thickness mm	304L			Aluminium		
	Aquarese	Mecanic		Mecanic	BAe	BERG
5	160	190		460	230	350
10	75	85		240	110	155
20	42	50		120	45	50
30	25	30		75	16	28
	Titanium			Brass		
	Mecanic	BAe	BHRG	ISQ	ENSAM	BHRG
2	525	230	400			
5	240	120	140	220	220	270
10				120	120	114
20				40	40	42
30				20	20	20
Thickness mm	Glass			Laminated glass		
	Aquarese	Mecanic		Aquarese	Mecanic	
5	1300	1650		1400	1650	
10	500	600		550	600	
20	130	150		150	160	
30	78	80		45	50	
	ISQ	ENSAM	BHRG	ISQ	ENSAM	
10	340	330	360	120	120	
20	150	150	160	40	40	

Cutting parameters for the parting speed trials

Entrainment		
-Sapphire:		Ø 0.35 mm
-Focusing Nozzle:	0 :	1.2 mm
	length:	3,!
DIAJET		
- Focusing Nozzle:	Ø :	0.4 mm
	length:	4mm
-Stand Off :		1 mm
-Abrasive:	Olivine AFS120	
-Abrasive flow rate:	100 g/min	
-Pressure:	2000 bar for British Aerospace	
	2500 bar for other entrainment systems	
	690 bar for BHR Groups DIAJET	

These tests provide a basis for the trials carried out to generate the interpretive database. A sample output is shown below:



European Standard For Abrasive Water Jet Cutting.

As there is a general lack of detailed knowledge on abrasive water jetting internationally, it was suggested that a standard on Abrasive Water Jet Cutting should be considered as part of the contract much the same as those available for electro-discharge machining. These provide guidelines and a classification scheme for surface finish and tolerances. This will improve customers specification of needs and manufacturers statement of process ability, whilst providing operators with a clear set of operating conditions to achieve a given cut. This will be achieved by providing individuals with a common language in which to express their requirements and capabilities.

The production of the initial draft of this document was undertaken by ENSAM, establishing guidelines based on the French standard for thermal cutting (NF A 87-000). This standard can be written in conjunction with the advisory software to further ease the selection of cutting parameters for a required cut.

Production of the standard will also raise the awareness of AWJ cutting within Europe with a corresponding increase in the market.

'Best Practice' Operating Procedures For Cutting Ductile and Brittle Materials

Operating procedures for cutting brittle and ductile materials differ due to the cutting mechanisms involved. A number of *best practice' procedures have been developed during the project.

Examples include :

- clamping arrangements for brittle materials to improve surface finish.
- the use of water rather than spherical balls in jet catchers.
- procedures for piercing brittle and ductile materials.
- the use of lattice supports under materials being cut to reduce splash back imperfections and prolong table/catcher life.
- submerging certain target materials to suppress noise and spray.

Also, guidelines for carrying out trials to test the suitability of Abrasive water jet systems for Aerospace industry use have been developed. The possibility of using abrasive water jet systems for net cutting of Aerospace components could open a new market to these systems. The results of the project suggest that abrasive water jet cut surface are suitable for the Aerospace industry. However, in order to prove the fatigue requirements for the cutting of advanced Aerospace materials, further work is required to establish a suitable surface quality finish of abrasive water jet cut materials.

Jet Catcher Design

Jet catchers have been investigated, and a number of designs proposed. Two types of catcher, flat and cylindrical, have been developed to meet the requirements laid out in this project. Four catchers (1 flat type and 3 cylindrical) have already been sold for aerospace and nuclear applications.

Mathematical Models

Mathematical models were developed for both brittle and ductile materials, and provide a good fit to the experimental data. For the suspension system, these models provide an excellent fit to the experimental data. In addition, they predict the different cutting performance for apparently similar materials. This information has been used to advise on the operating parameters for abrasive suspension systems in new markets.

An improved model of cutting wear depth was developed and verified for the entrainemnt systems. The depth of cut for cutting wear mode is derived from an energy balance, ignoring the hydrodynamic effects of the water. The resulting model yield the depth of cut as:

$$z_c = \frac{1}{k}\left[1-\left(1+\frac{k}{4}c.d_j . A^{\frac{5}{2}}v_0\right)^{-4}\right] \quad (1)$$

$$k = \left(\frac{2\varepsilon d_j u_a}{\dot{m}_a v_0^2}\right), \text{ where } \varepsilon = \frac{\sigma_y + O\text{-}u_e}{2}, \text{ and } A = \frac{56\dot{m}_a}{\pi^2 \rho_p d_j^2 u_a C_k^{2.5}}$$

Nomenclature:

ck	intrinsec velocity defined in improved erosion model
dj	jet diameter
d_p	particle diameter
zc	depth of cut due to cutting wear mode
ma	abrasive particle mass flow rate
m_w	water mass flow rate
ua	cutting speed
v	particle velocity
v0	initial particle velocity
w	width of cut
a	angle of impact
at	angle of impact at top of cutting surface
a1	angle of impact at which erosion peaks
g	is defined in improved erosion model model
Sf	material flow stress
rp	density of particle
σy	yield stress of material
σu	ultimate tensile strength
e	rupture strain

Comparison between experimental and predicted results

To apply equation (1) for determination of theoretical values of cutting wear region depth, the material proprieties, material characteristics and initial particle velocity must be determined. According to Hashish [13], the orifice efficiency cv varies from 0.932 to 0.911, the coefficient of compressibility c_y from ***0.985*** to ***0.974*** and the momentum transfer efficiency h **from** 0.805 to ***0.936.*** The product of these coefficients can be taken equal to 0.80. The material flow stress depend on the Young modulus of material and is equal to E/14 **[15].**

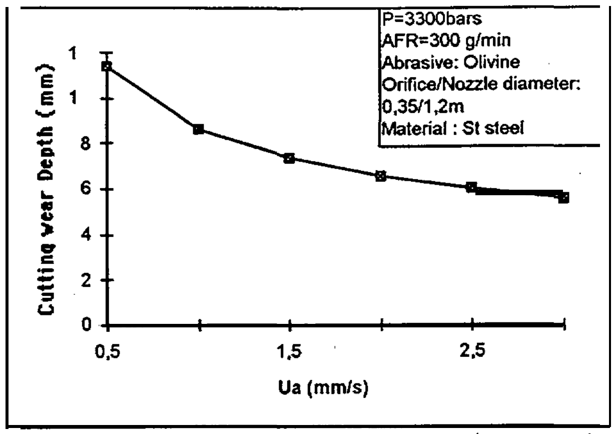


Fig. I Cutting wear depth verse cutting speed

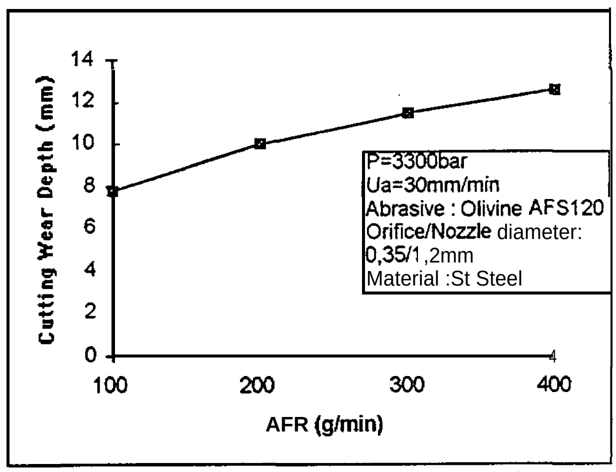


Fig.2 Cutting wear depth verse abrasive flow rate

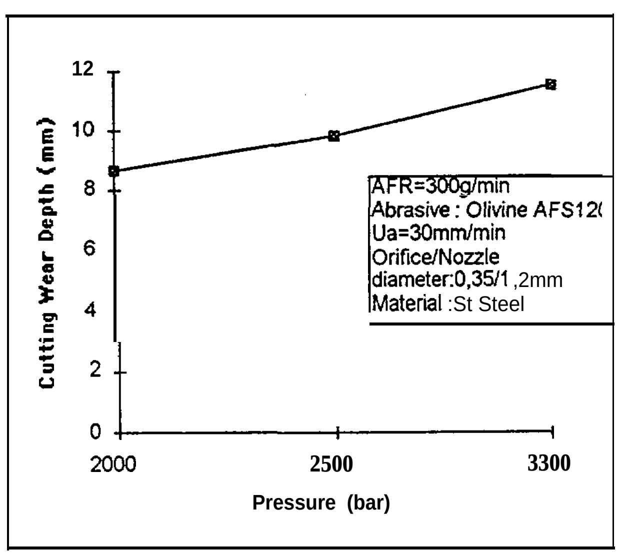


Fig.3 Cutting wear depth verse pressure

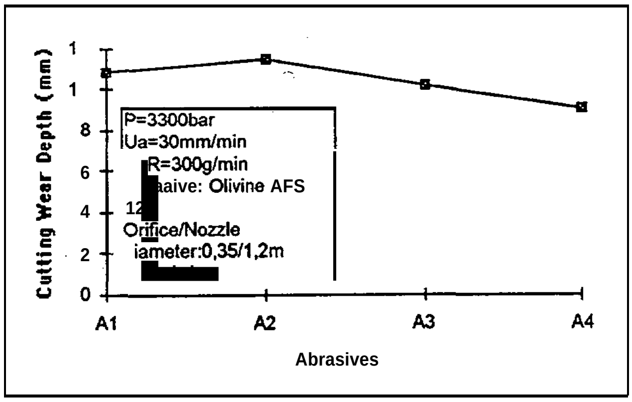


Fig.4 Cutting wear depth for different abrasives

Conclusions

1) The AWJ cutting process in Cutting wear region is associated with impacts of abrasives particles at low incidence angles. The material removal mechanism in this zone is a single microcutting process for ductile materials.

2) Dissipation of the abrasive particles energy in cutting wear zone is due to plastic deformation of the material removal by impacts of the particles.

3) The dissipated energy is determined and the decrease of the abrasive particle velocity is found to be a function of three material proprieties which are: yield stress, ultimate tensile strength and rupture strain.

4) The model is limited to the cutting wear region; the theoretical depth correlates well with experimental results and data given in literature.

5) The model was developed based on Hashish modeling study and some simplifications are made. Some of them should be reduced for extending our model to second region of the cutting kerf which is characterised by striation marks and large waviness.

Comparative Performance of Suspension & Entrainment Jet Systems

The entrainment system is essentially a jet pump, and has an inherent system efficiency of about 30’% maximum. The suspension jet, on the other hand, could have an efficiency approaching 100%, the only loss being piping losses through the system. One would expect the suspension jet to be approximately three times more efficient than the entrainment system. However, suspension jet systems are actually closer to 4 to 5 times more efficient than entrainment systems. To investigate this effect we have examined both systems in terms of cutting performance as well as their effect on the abrasive being used.

From literature previously presented, and a new series of trials, the extent of particle degradation in entrainment and direct injection systems was measured, both through the system alone and after cutting material. A catcher designed to minimise damage to the abrasive was developed considering the preliminary results of catcher designs.

The results show that entrainment systems can damage up to 80% of the abrasive, with direct injection systems causing negligible damage. This is consistent with the findings of previous reports. The net effect in entrainment system nozzles is a downward shift of the average particle size.

Further effects may be weakening of the grains by induced cracks, leading to particle break-up on impact, and a dulling of the particles cutting edges.

Prototype Abrasive Concentration Meter.

A non-intrusive abrasive concentration meter has been developed to give a real time output of delivered concentration. The device is capable of discerning abrasive particle size and will currently work with DIAJET jetting systems up to an operating pressure of 690 bar. It can measure concentration to within 10°/0 of the actual value. It will operate on a concentration range from O to 20°/0 by volume with a particle density range of 1,000 to 1,400 kg/m^3.

Two transducers are used, both resonant at 1.25 MHz. The emitter transducer is pulsed with three cycles of a 20 V peak to peak sine wave burst. This pulse causes the transducer to resonate and emit a 1.25 MHz ultrasonic wave. This wave propagates through the wall and across the slurry flow to the receiving transducer. This transducer resonates under the influence of the ultrasonic wave and the amplitude of this resonance is examined by a high speed oscilloscope. As the ultrasonic wave passes through the slurry flow its amplitude is reduced by the slurry content, hence the amplitude of the signal exiting the receiving transducer and the amplitude of its associated resonance is a measure of the concentration of abrasive within the flow.

CONCLUSIONS

Critical parameters for Abrasive Water Jet Cutting were identified and characterised during the cutting trials and subsequent measuring activities. The work has yielded a standard methodology to evaluate the performance of water jets for cutting parts in different types of material During the cutting trials, the following defects were detected: overshoot, striation and material removal, These variables have a large influence on the final cut surface quality.

The innovative aspects of this work were to define, quantify and qualify the quality and cost effectiveness of abrasive water jet cutting with respect to :

- Surface roughness
- Cutting/profiling velocity
- Overshoot or Undershoot
- Abrasive and abrasive flow rate
- System pressure
- Edge taper

The project developed a standard test shape and defined an extensive array of test conditions including :

- 4 Abrasive concentrations
- 4 Abrasive materials
- 4 Abrasive flow rates
- 4 Cutting pressures
- 4 Cutting speeds

• 8 Sample materials (ductile and brittle)
. 2 to 4 Sample thickness'

A recommended Abrasive Water Jet quality standard document was proposed within the programme, establishing Sidelines based on the French standard for thermal cutting (N'F A 87-000).

The difference between both types of Abrasive water jetting systems in use has been examined and the increased efficiency of the suspension system (DIAJET) can be explained from consideration of jet pump efficiency and abrasive degradation within each system.

The cutting tests on brittle and ductile materials, have allowed us to establish a vast database giving the cutting results (edge quality and accuracy) versus the cutting parameters (pressure, abrasive, cutting speed, flow etc.. .).

Mathematical models were developed for both brittle and ductile materials, and provide a good fit to the experimental data.

Guidelines for carrying out trials to test the suitability for Abrasive water jet systems for Aerospace industry use have been developed. However, in order to prove the fatigue requirements for the cutting of advanced Aerospace materials, further work is required.

The project has quantified the impact of the jet, once its exits the material being cut, on the surrounding environment. Subsequently, it has been possible to select material resistant to the impact of the jet and construct the architecture of jet catchers designed to collect the jet.

Two types of catcher, flat and cylindrical, have been designed the efficiency of such catchers has reached now a high degree of perfection, Four catchers (1 flat type and 3 cylindrical) have already been sold for aerospace and nuclear applications.

BIBLIOGRAPHY

1. Bitter, J. **G. A.,** "A Study of Erosion Phenomena-Part I," Wear, Vol. 6, 1963, pp169-190.
2. Bitter, J. G. **A.,** "A Study of Erosion Phenomena-Part II," Wear, Vol. 6, 1963, pp 169-190.
3. Finnie, **I.,** " The Mechanism of Erosion of Ductile Metals," Proc of 3rd US Nat. Cong. of Appl Mech., ASME, New York, 1958, pp 527-532.
4. Finnie, I., Wear, Vol. 3, 1960, pp. 87-103.
5. **Finnie,** I., "Erosion by Solid Particles in a Fluid Stream," Erosion and Cavitation,, ASTM STP 307, 1962, pp. 70-82.
6. Finnie, I., Wear, Vol .19, (1972), pp. 81-90.
7. Finnie, I., et **al.** Erosion : Prevention and Useful Applications, (1977) ASTM STP 664.
8. Finnie, I., **and** Mc **Fadden, D. H. M.,** "On the Velocity Dependence of the Erosion of Ductile Metals by Solid Particles at Low Angles of Incidence, " Wear, Vol. 48, 1978, pp 181-190.
9. Finnie, L, et al., Erosion: Prevention and useful Applications, ASTM STP 664, 1979, pp36-58.
10. Hashish, M., "On the Modeling of Abrasive Waterjet Cutting,'' 7th Int Symp on Jet Cutting Tech , (paper E1), June 26-281984.

11 .**Hashish, M.,**"An improved Model of Erosion by Solid Particle Impact, " Proceedings of the 7th internatinal Conference on Erosion by Liquid and Solid Impact. (paper 66), Cambridge, UK, September 7-101987.

12. **Hashish,** M.,''Visualisation of the Abrasive Waterjet cutting Process," Experimental Mechanics, June 26-281984, pp 159-169.

13. **Hashish, M.,** "Advances in Abrasive Waterjet Machining," Proceedings of the 1st Asian Conference on Recent Advances in Jetting Technology, Singapore, May 7-81991, pp 43-60.

14. **Hashish, M.,** "Pressures Effects in Abrasive Waterjet Machining,"J. of Eng. Mat.and Tech.. Vol. 111, JULY 1989, pp 221-228.

15.**Hashish, M.,** "A Model for Abrasive Waterjet (AWJ) Machining,''Journal of Engineering Materials and Technology., Vol. 111, April 1989, pp 154-162.

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