SYNTHESIS REPORT

FOR PUBLICATION

CONTRACT No: 13RE-CT93-0611

PROJECT No: BE-8032-93

TITLE: Concerted Action

"Quality Improvement of Water Jet Cutting"

PROJECT COORDINATOR: Institut für Werkstoffkunde
Universität Hannover
Germany

PARTNERS:

Biquimar Indústria de Mármores, Lola.; Portugal
I.S.Q. Instituto de soldadura e qualidade; Portugal
Lasindústria technologia laser S.A.; Portugal
Oficinas Gerais de Material Aeronáutico; Portugal
Action Technologique Sézanne; France
A.M.I.F.O.P.; France
Axiome; France
Ecole des Mines Centre Armines de Douai; France
Hydrobar; France
Procer-MVT; France
Mecanic; Belgium
Politecnico di Milano-Dipartimento di Meccanica; Italy
PTC; Italy
Saphintec; CH
TU Wien; Austria
Tecnocut s.n.c.; Italy
Universitá degli Studi di Cagliari, Italy
BHR Group Ltd.; Great Britain
Royal Military College of Science; Great Britain
Stanny F. Kilde A/S; Denmark
RF-Rogaland Research, Norway
Luleå University of Technology, Sweden
Technical Research Centre of Finland (VT'T), Finland
MasiJet Ltd.; Finland
Böhler Hochdrucktechnik GmbH; Austria
Foracon Maschinen- und Anlagenbau GmbH; Germany
Fraunhofer-Institut (IPT Aachen);Germany
WST Winkel GmbH; Germany
Fraunhofer-Institut (IPA, Stuttgart); Germany
Consiglio Nazionale Delle Ricerche (CNR); Italy

REFERENCE PERIOD FROM 01.01 .94to 31.12.96

REPORT No: CA96-6

STARTING DATE: 01.01.94

DURATION: 36 MONTHS

PROJECT FUNDED BY THE EUROPEAN COMMUNITY UNDER THE BRITE/EURAM PROGRAMME

DATE: 25.03.97

Quality Improvement of Water Jet Cutting -

Results of a Concerted Action

Louis, H. and J. Ohlsen

(IW - University of Hannover, Germany)

Co-authors:

Aldridge, T.	(BHR Group, United Kingdom)
Houssaye, G.	(Ecole des Mines Centre Armines de Douai, France)
Meier, G.	(Spitzmüller & Partner, Germany)
Miranda, R.	(Instituto de soldadura e qualidade, Portugal)
Monno, M.	(Dipartimento di Meccanica Politecnico di Milano, Italy)

Abstract

This paper is based on a Concerted Action (CA), which was carried out by a consortium of 31 partners in the frame of the European research programme BRITE EURAM. Aim of the support of the EU was to support the co-ordination of research activities, which were carried out by the partners. Research was not paid, but the co-ordination. The project started in January '1994 and was finished in December 1996.

The paper will give an overview of the structure of the project, the work programme as well as selected results.

The central aim of this Concerted Action was to improve the quality that can be achieved by abrasive water jets to provide a tool for final contour cutting especially for difficult-to-machine materials/parts.

The quality of the cutting result is a topic of common interest for all users, manufacturers and researchers. Many of them had investigated aspects, which influence the quality of cut. The exchange of these experience as well as the co-ordination of research activities multiplied the effort of each partner and supported water jet technology in general.

In the beginning of the project quality criteria were discussed to describe the quality of cut. Experience concerning quality criteria as well as parameters which influence the quality of cut were exchanged and discussed. Quality criteria and standard parameter were chosen to characterise the quality of the cutting result. Working groups (WGs) were found to run parallel R&D activities in relation to the main parameters that influence the quality of the cutting result. The specific results of the WGS were combined, so that every WG could benefit from the results of other WGS.

The CA was always open for new partners who were interested to participate. National co-ordinators disseminated non-confidential activities and results of the CA and recruited new partners.

Introduction

As mentioned above exchange of experience and co-ordinated research activities in parallel WGS were major means to achieve the objectives of the project. The following tasks were defined in the workprogramme:

- **selection of quality criteria to characterise the quality of the cutting result**
- **partners give access and exchange so far obtained results and experience**
- **foundation of working groups (WGS) which run parallel R&D activities in relation to the main parameters that influence the quality of the cutting result**
- **exchange of specific results of the WGS, to show the significance of parameters that influence the quality**

The structure of parallel working groups and the exchange of their results multiplied the know-how of each working group. Figure 1 shows the project flow diagram.

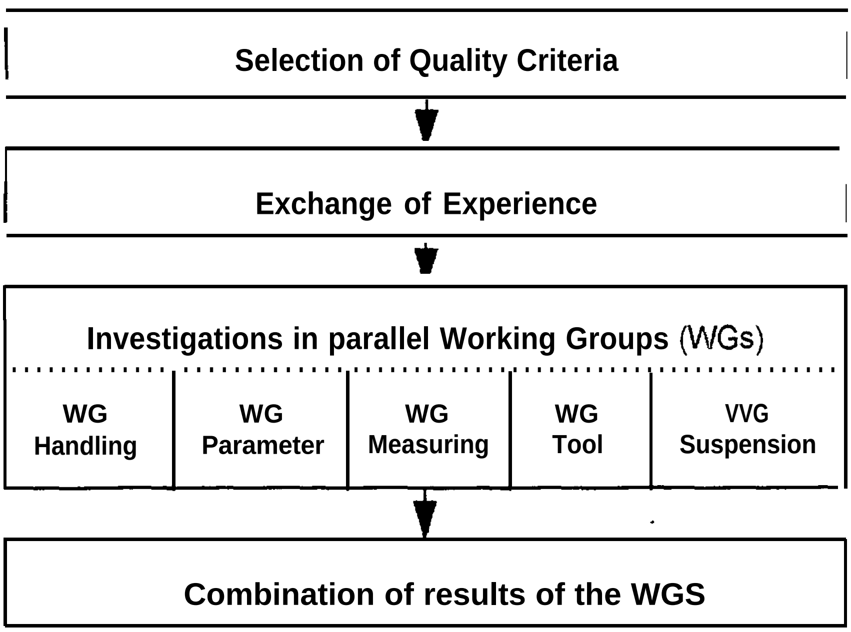

Figure 1: Project flow diagram

The structure of partners was very heterogeneous. The consortium of 31 partners consisted of 18 partners from industry (SMEs: users, system producers) and 13 partners from research institutes. Due to this ratio of companies to research institutes, an intensive and dynamic exchange of practical and theoretical experience was realised.

During the kick-off meeting 5 working groups were founded, which ran parallel research activities in relation to the major parameters which influence the quality. Each working group was co-ordinated by a head of the working group. Table 1 shows the WGS and the corresponding number and country of partners. The heads of the WGS were also additional members of the WG - measuring. This WG was founded during the kick-off meeting for the reason that comparability of results can only be guaranteed, when all measurements are carried out by the same laboratory.

After measuring, the results were send to the heads of the WGs, who evaluated and presented them for discussion in their WG.

Partner H = t-lead of a WG x = main activity + = additional WG-member	Working Groups: Handling	Parameter Injection Jets	Suspension Jets	Tool	Measuring	Countries
head number of partners	H 5				+	P DK, P
head number of partners		H 9			+	I A, FIN, G, 1, S
head number of Partners			H 7		+	UK 1, N, UK
head number of partners				H 7	+	F A, F, G
head number of partners			+		H 2	G F

Table 1: Working groups and partners

The exchange of experience and results was realised by periodical six-monthly reports as well as presentations and discussions during meetings. Meetings were always held at different places all over Europe. Besides three plenary meetings several meetings of the working groups, national meetings as well as individual meetings of partners were carried out.

Three plenary meetings were held in accordance to the planned schedule. Aim of the mid-term and the final meeting was the exchange and discussion of results of the WGS. During the mid-term meeting only first results were discussed, but in advance of the final meeting most of the results were available. Due to the fact that discussions are more fruitful, when participants can prepare themselves for discussions on the base of written results, “Proceedings of the Final Meeting” were prepared in advance of the meeting. The Proceedings included all results of the WGS which were obtained so far.

Each WG had to organise 5 meetings. Due to the intensive co-operation of partners and successful discussions, most of the WGS have made more meetings.

Besides the co-operation of partners inside of the CA, intensive information exchange with external companies was periodically organised by so called national co-ordinators. The aim of this exchange was on one hand to gather problems from industries and to find new partners. On the other hand results of the CA were disseminated directly to interested com panics.

The steering committee was formed by the heads of the working groups to provide overall planning and control of the time schedules. The structure of the project is shown in Figure 2.

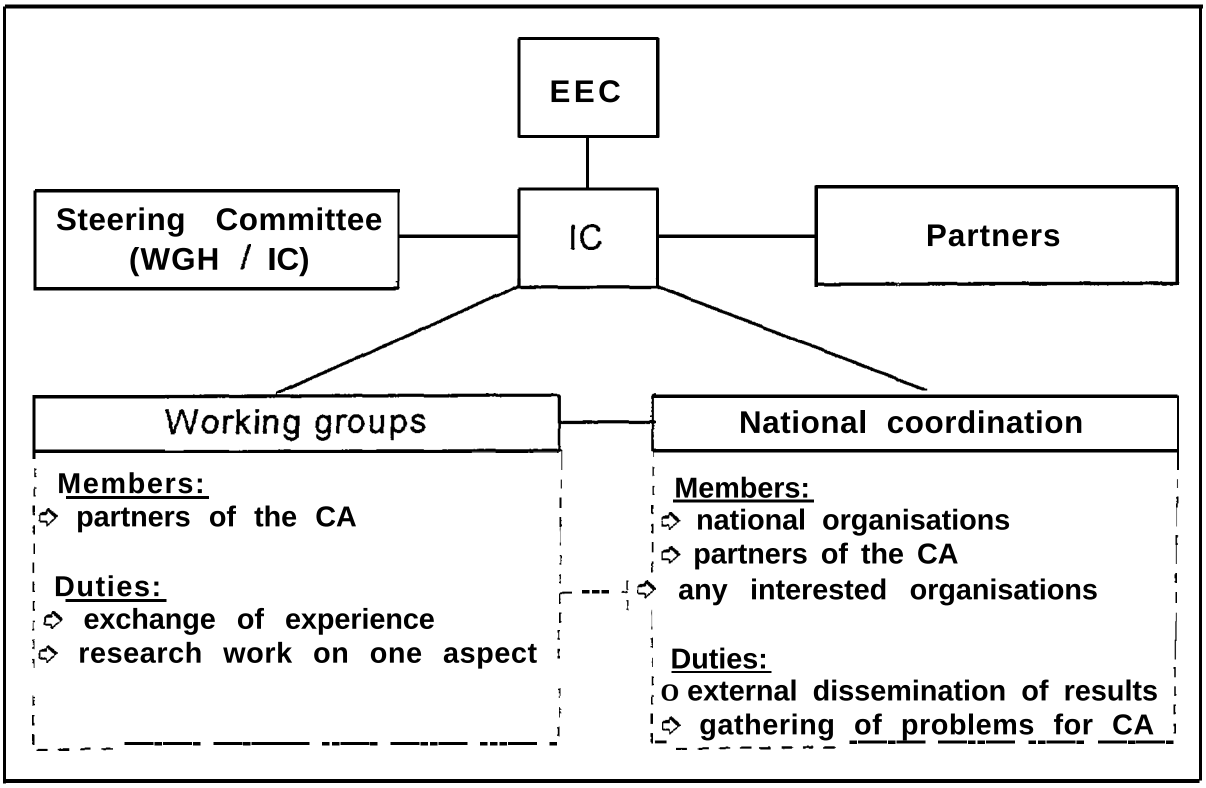

Figure 2: **Structure of the project**

Without the opportunity to exchange equipment, comparison of various industrial used high pressure components would have never been realised, because it would have been to expensive in equipment and manpower. An impressing example for such comparison tests is WG - Tool, who have tested 6 different jet generation tools in their laboratory, using the same handling system. With these results the performance of different jet generation tools is now more transparent.

Technical description

As mentioned above, the parameters that influence the quality of cut can be divided in four major groups. These groups are as follows:

- **WG - Parameter injection jets**
- **WG - Suspension jets**
- **WG - Tool**
- **WG - Handling**

Due to the fact that the influence of parameters is different for injection and suspension jets, two major groups were necessary. The jet generation toot consists in case of suspension jets only of one nozzle. In case of injection jets it consists of the whole mixing head including two nozzles and the geometry of the mixing chamber. For that reason WG - tool investigated only injection jets. The influence of the nozzle size in case of suspension jets was investigated by the WG - suspension jets. The aspect handling is similar for both jets and was investigated using injection jets.

In the following chapter results will be discussed. Due to the variety of tests of the WGS, selected results will represented. Besides quality criteria, which were chosen in the frame of this project, the following chapter will focus on results of WG - parameter injection jets and WG - tool.

The cutting quality of two basically different difficult-to-machine materials was analysed. Alum inium was chosen as ductile material and glass as brittle material. The following results are focused on aluminium.

Results

Quality criteria

In the beginning of the project comparative tests were carried out using different equipment. On the base of these tests quality criteria were discussed and a procedure to measure and describe the quality of cutting was defined. These criteria cover the geometry of the kerf and the roughness of the shoulder of the cut for ductile and brittle material. Following standard parameters (Table 2) and measuring procedure for alum inium are presented.

Criteria for aluminium were fixed during the Kick-off meeting. Measuring procedures were discussed, different results coming from several partners were compared. It was found that even in case of measuring identical values like R_a big differences were obtained when comparing the values of several organisations. With regard to the great importance of comparable measuring results it was decided to carry out all measurements in one WG by the use of a single measuring system.

As one reason for these differences the effect of the sampling length on the roughness values has been discussed. Especially whe ı measuring in the zone of rough cutting the cut-off length has to be long enough to integrate the microroughness as well as the waviness in the measure(value.

	units	standard parameters	WG-Handling	WG-Tool	WG-Parameter Injection Jets
pressure nozzle diameter	MPa mm	300 0,3			200-400 0,2-0,4
focus diameter focus length	mm mm	1,0 75		0,6-1,2 40-100	
kind of abrasive (Barton Garnet) flow rate	 g/min	HP120 250			HP50-HP240 120-600
distance traverse rate (Al; 30mm)	mm mm/min	1-2 50	 10-1000		
cutting direction		straight	square, circle		

Table 2: Standard cutting parameters for aluminium

In order to investigate the influences of the tool design and the parameter it is sufficient to carry out straight cuts. Quality criteria concerning the surface quality are given in Figure 3.

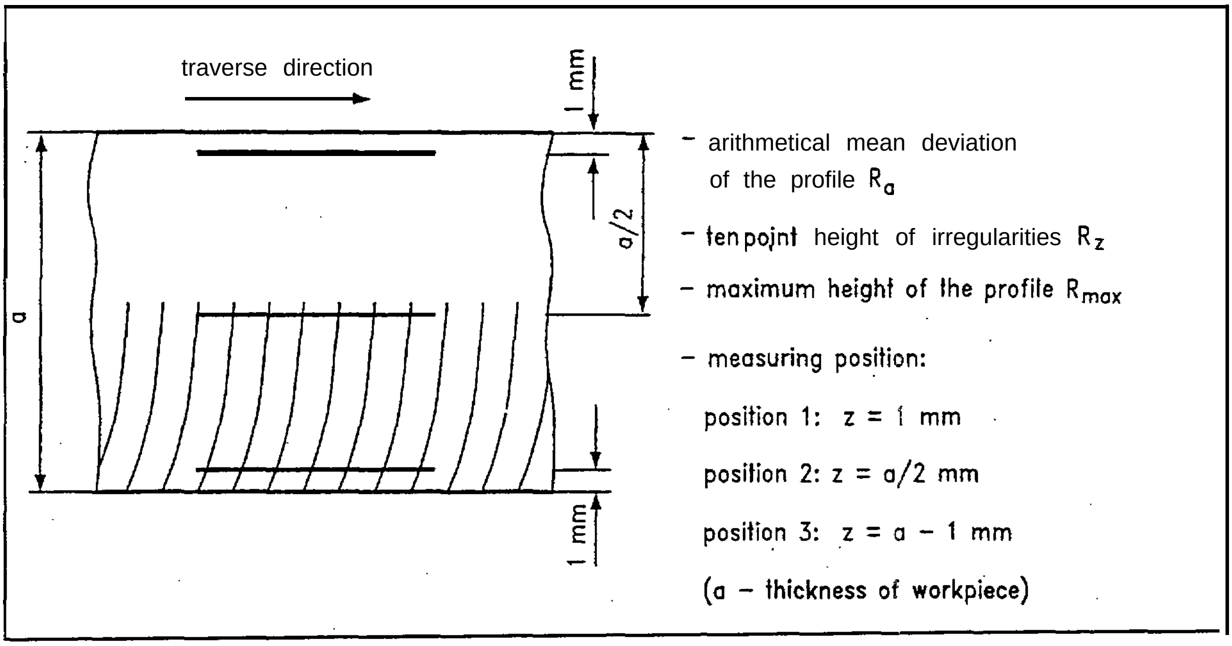

Figure 3: **Quality criteria of the surface quality**

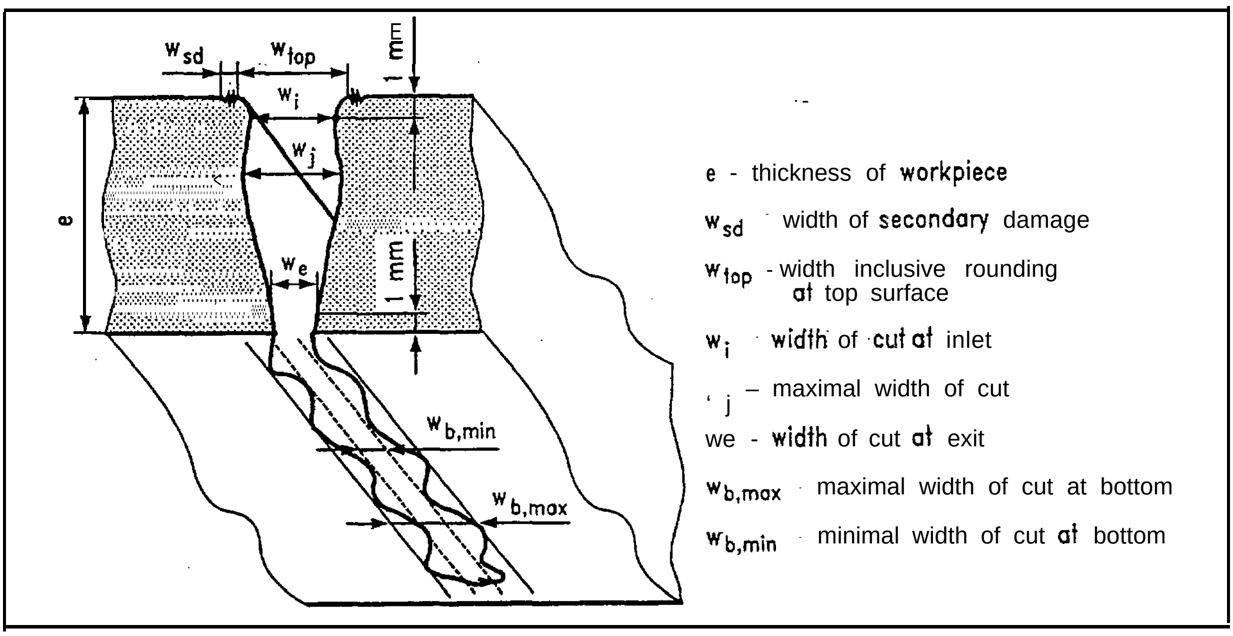

Figure 4: **Quality criteria of the geometry of the cut**

The profile of the surface was described by measuring the arithmetical mean deviation of the profile (R_a) and the ten point height of irregularities (R_z). R_{max} gives the maximum height of the profile in the measuring area. The positions of measuring the profile were:

- **1 mm down the upper surface (entrance of the jet)**
- **1 mm up the bottom surface (exit of the jet)**
- **in the middle of the cut surface**

Doing so the mode of cutting (rough cutting or quality (finish) cutting) can be identified by comparing the roughness values measured near the upper and the lower surface: For quality cutting both values are similar, for rough cutting the value near the exit of the jet is much higher than near the entrance. In addition it is necessary to quantify the geometry of the cut as given in Figure 4.

The nomenclature was taken from the B/E-project 4382 as far as possible. Some criteria were added to describe the surface and the geometry of the cut sufficiently for the given aim of the project. In order to get comparable results from the WG - measuring it was necessary to use similar samples. As sample material an aluminium alloy (AlMgSi0.5) was suggested. The thickness was 30 mm.

WG - Parameter injection jets

In this WG nine partners from five countries have investigated the influence of several parameters on the cutting quality. Due to extensive results, a few selected results concerning the surface roughness and the kerf geometry will be presented. Due to very detailed analysis of the surface quality the head of the WG has carried out additional roughness measurements.

The following three figures show the influence of pressure, traverse rate and abrasive mass flow rate on the surface quality (mean arithmetic roughness Ra). The effect of a change in the pressure level (250-350MPa) on surface quality is much more observable with the increasing of cut depth. As pressure increases, there is a systematic improvement in roughness and waviness of cutting surfaces (Figure 5). An increasing in pressure level is generally a way to improve surface quality. On the other side, high pressure level causes a reduction in life of intensifier components.

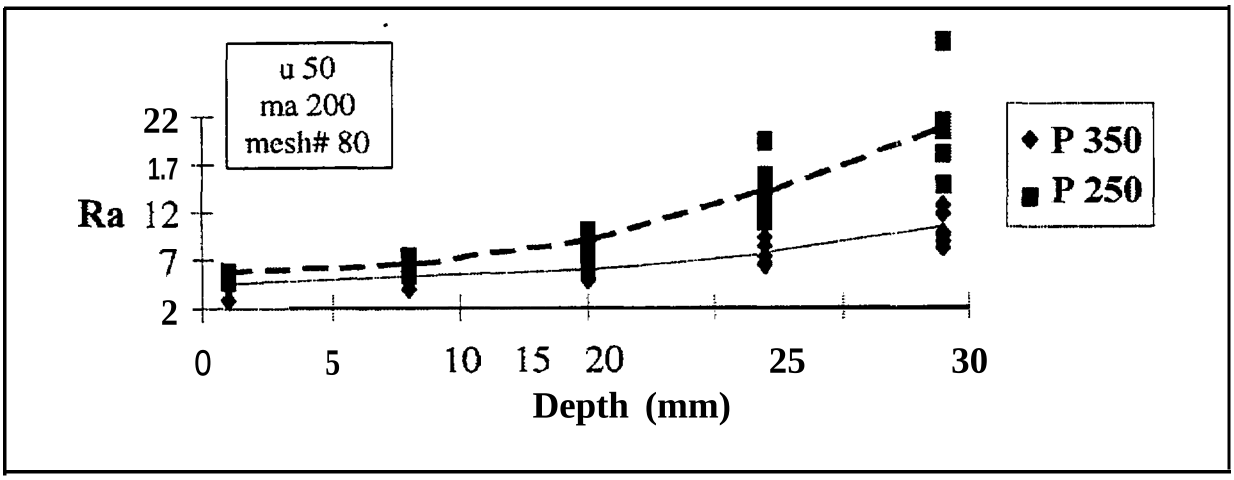

Figure 5: Influence of pressure on surface quality

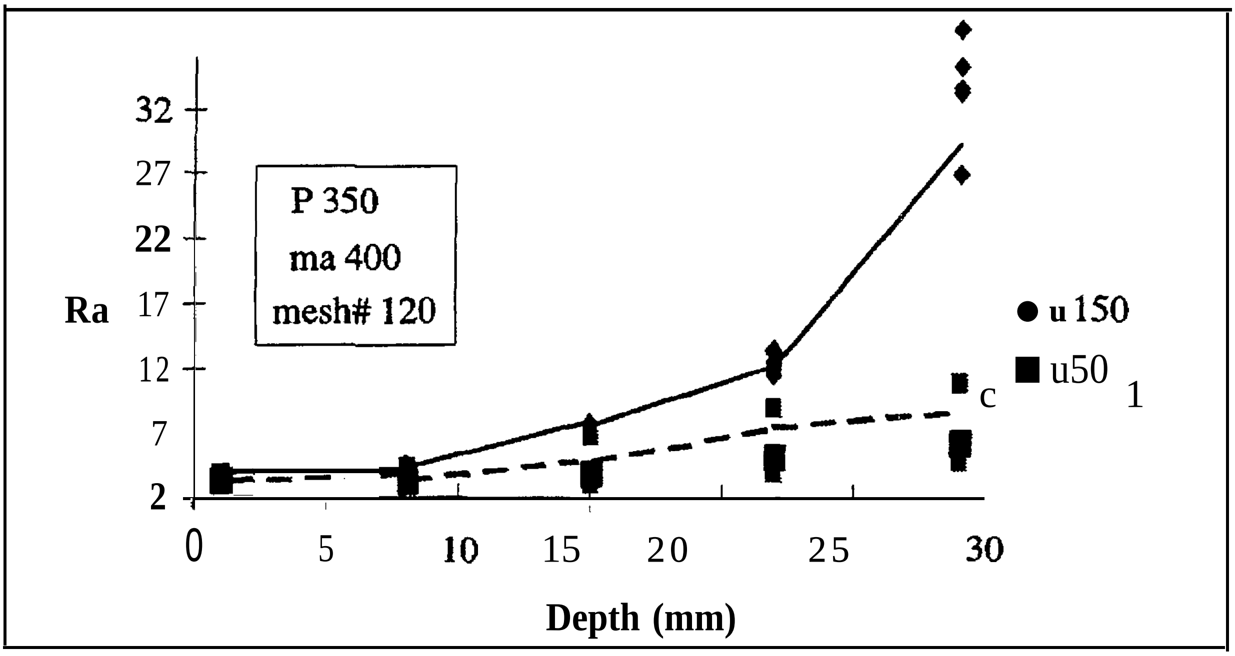

Figure 6: Influence of traverse rate on surface quality

Figure 6 shows that the roughness and waviness of the surface increase as feed rate increases (50-1 50mm/min). The difference was measured by all surface quality parameters and has an significant increase with depth of cut.

Figure 7 shows the influence of abrasive mass flow rate on the surface quality. There is an improvement in all roughness and waviness parameters as abrasive mass flow rate increases. The effect is much more evident with the increasing of the depth of cut.

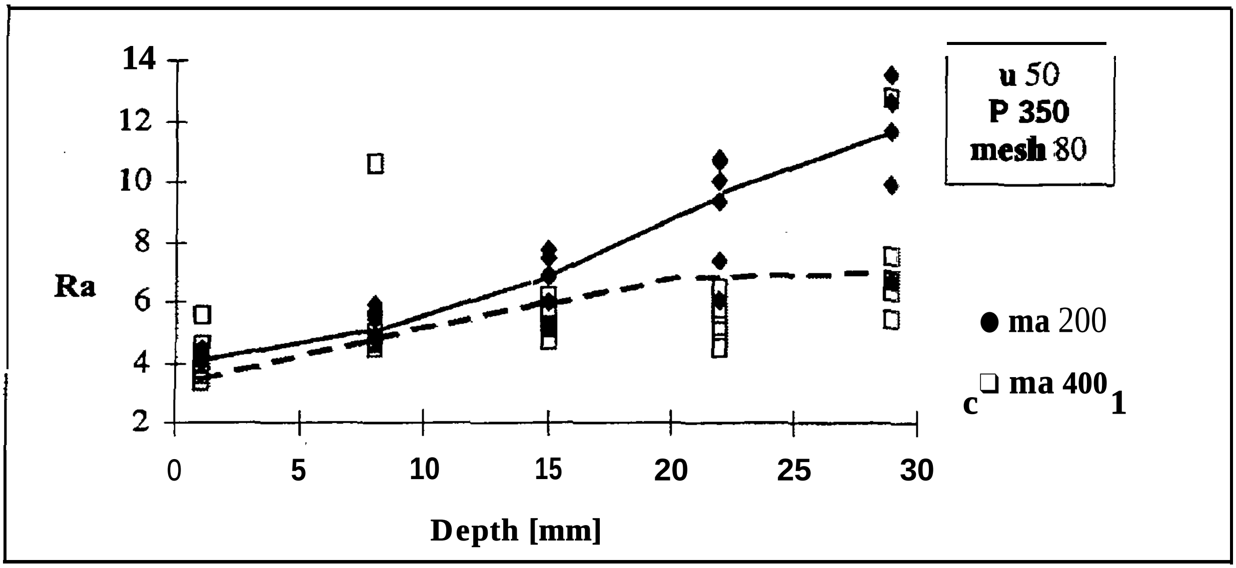

Figure 7: Influence of abrasive mass flow rate on surface quality

A comparison between the roughness of the two surfaces obtained by each cut was made. As expected the data analysis does not highlight a significantive difference in left-right side roughness. Only one group of data point out a left-right difference increasing with depth (Figure 8).

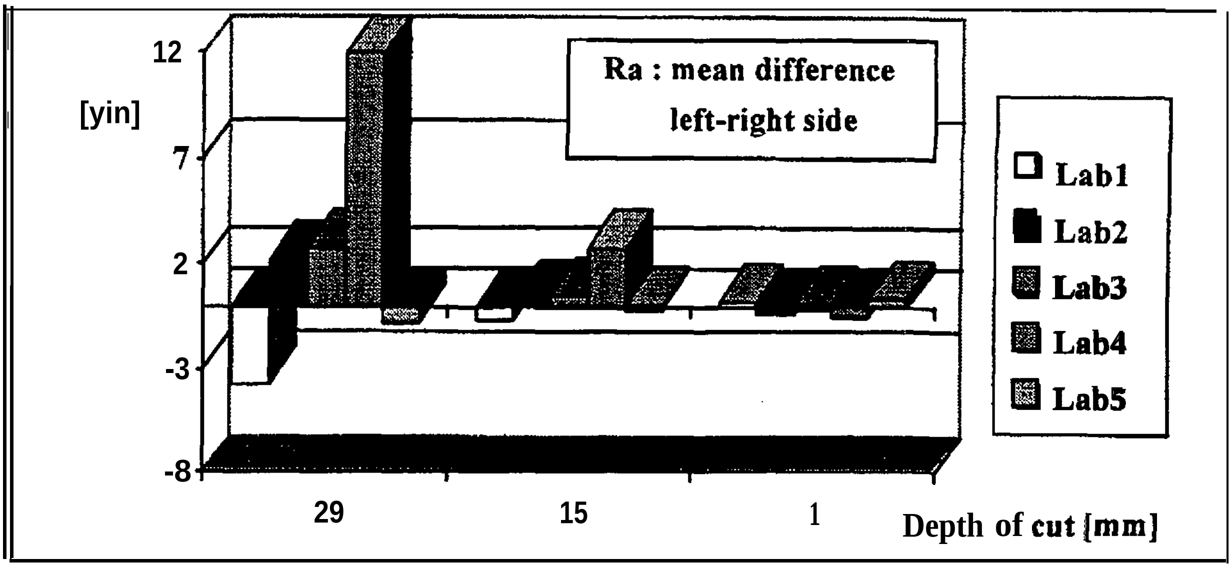

Figure 8: Left-right difference

From the conclusions regarding the influence of abrasive mass flow rate and feed rate on roughness (Ra) a technological model was developed to predict the roughness of the shoulder of the cut in relation to the above mentioned parameters. The model showed good agreement with experimental data.

The following figures are related to the influence of parameters on the geometry of the kerf. Wi is the width of the cut at the inlet of the kerf. All parameters shown in Figure 9 show an significant effect on Wi. With increasing abrasive mass flow rate the width at the top of the kerf increases. As feed rate and mesh# increase the width of kerf decreases.

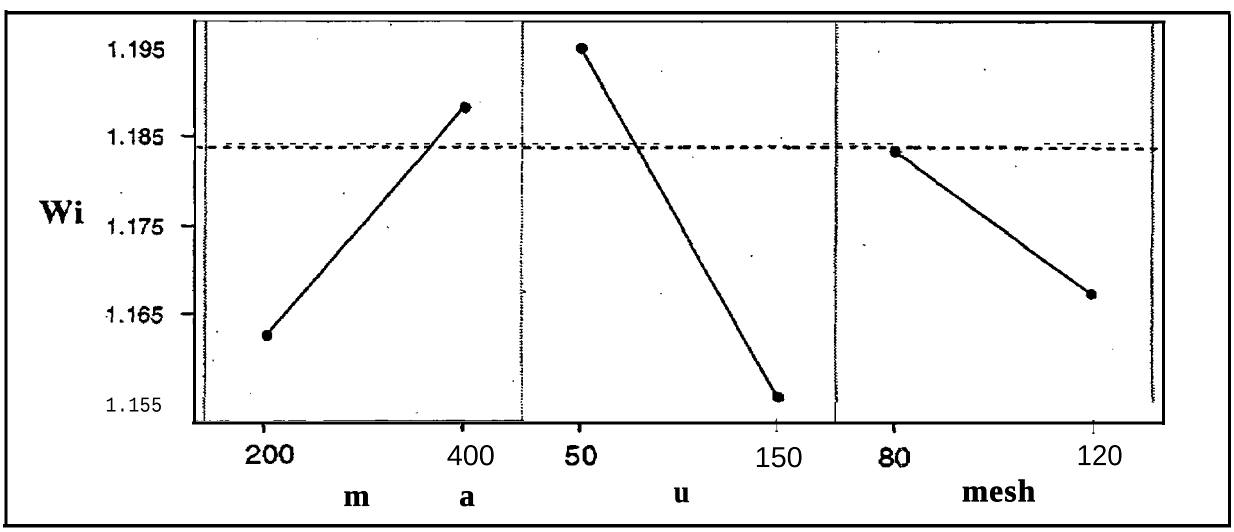

Figure 9: Influence of abrasive mass flow rate, traverse rate and mesh on Wi

The width of kerf at the outlet of the kerf shows also significant effect by parameters shown in Figure 10. The width at the outlet of the kerf increases as water pressure increases. It decreases as feed rate and mesh increase.

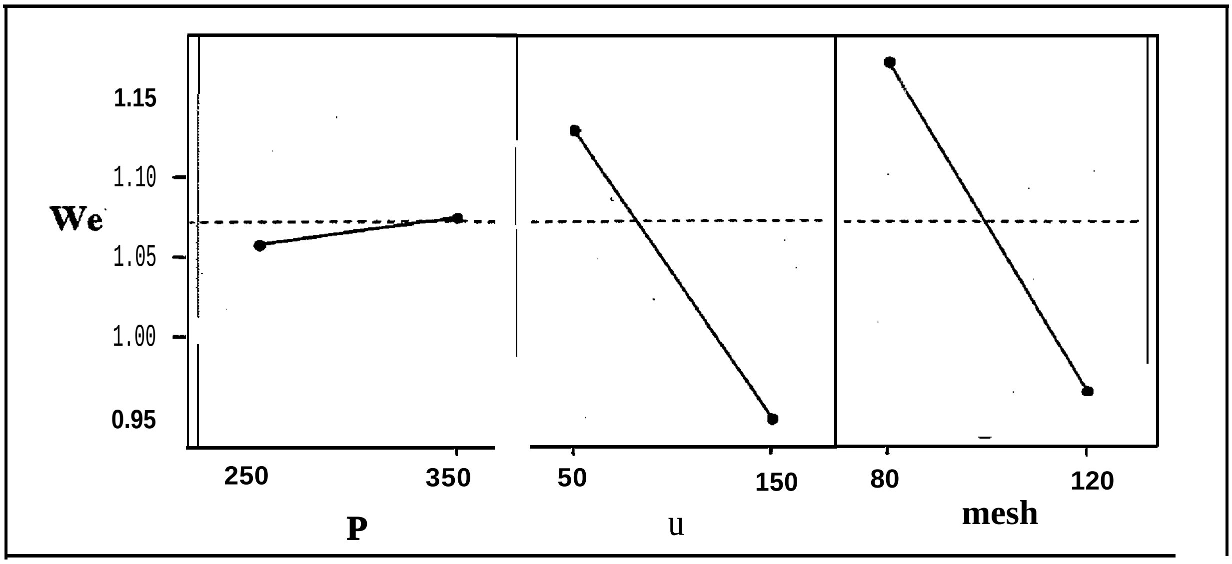

Figure 10: Influence of pressure, feed rate and mesh on Wi

Pressure, feed rate and mesh# have also an effect on kerf tapering (Figure 11). Tapering of kerf decreases as water pressure increases. It increases as feed rate and mesh# increase.

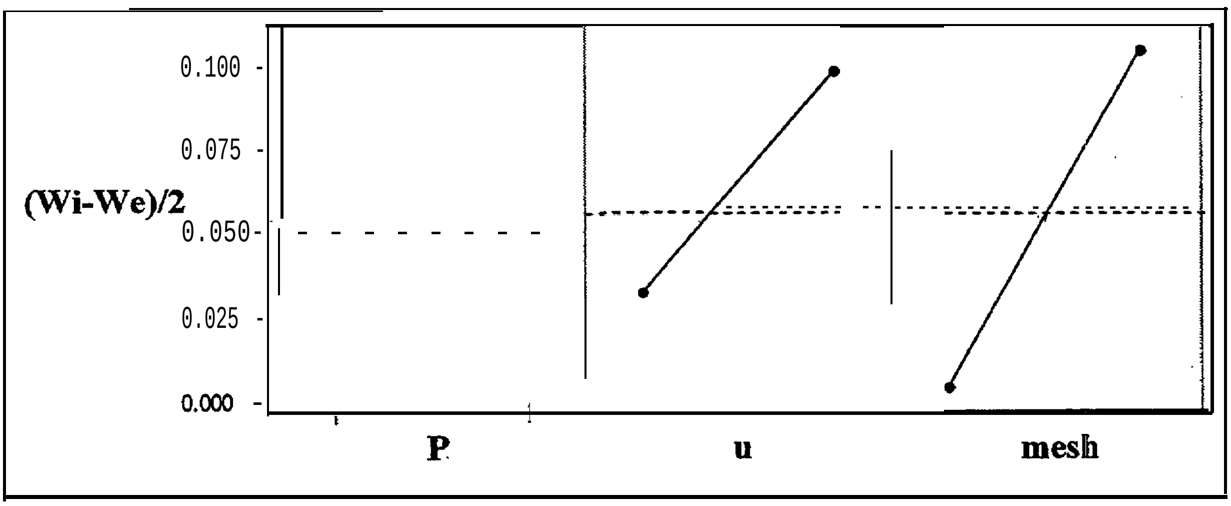

Figure 11: Influence of pressure, feed rate and mesh on tapering of the kerf

The width of kerf varies with cutting parameters, especially with feed rate. Sometimes, in abrasive water jet practices, the relevant quality parameter is not the width of the kerf, but the tapering generated from the decreasing energy of the abrasive water jet. In general, an increase in feed rate has a negative effect on tapering. Water pressure has some influence, but the improvement of surface quality does not seem to be so relevant comparing the consequences of an high pressure level on maintenance costs of abrasive water jet equipment.

WG - **Tool**

Design of abrasive cutting heads leads to more or less powerful and effective jets that cause different qualities. Shape and size of the nozzle as well as the mixing chamber design, influence the jet generation and the quality of the cut.

The WG-tool carried out some tests in order to quantify the influence of the abrasive cutting head designs on the cutting quality. Six different, industrial used cutting heads were tested. The surface quality was evaluated by measuring the surface parameters such as R_a, R_z, R_{max} and the width of kerf.

Small variations of the kerf width were not significant to draw a conclusion concerning the design of the cutting head. Therefore, the working group noticed a great difference of air flow rate at the entrance of the different mixing chambers and studied the influence of the air volume on k_{min} and k_{max} for the 6 heads.

To evaluate the influence of the mixing chamber designs on the quality of cut, alum inium samples were cut by the 6 different abrasive cutting heads. The assessment of surface quality was evaluated by measuring the surface parameters R_a, R_z, R_{max} at different depths of cut. The kerf geometry was evaluated by measuring the width of cut as well as the depth of kerf k_{min} and k_{max} (Figure 12).

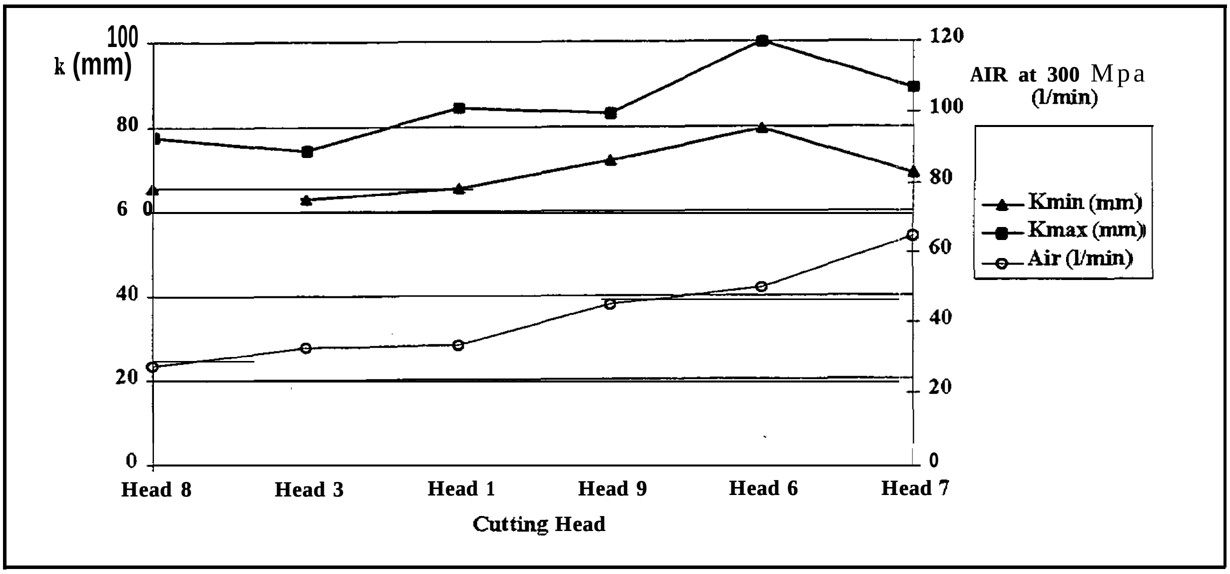

Figure 12: **Influence of cutting head on air flow rate and depth of kerf**

It was expected that an increase in volume of air would spread the jet inside the mixing chamber. Excessive spreading of the water jet would disperse the jet energy and reduce the depth of cut. It was reported [1] that a more coherent jet produces deeper cuts at the same pressure, but the volume removal rates increases with a slightly spread jet. However, Figure 12 shows that the maximum depth of cut does not correspond with the minimum of airflow rate.

Experimental tests were identical for the six cutting heads (pressure, abrasive flow rate, diameter of water nozzle, length of focusing tube) but other parameters must be taken into account:

- **Studies from Hashish [1] presented the effect of the abrasive pipe diameter on the air flow rate. He noticed that increasing the pipe diameter beyond an optimal value will reduce the suction capability. For our tests, the diameter was dependent on the abrasive cutting head design.**
- **A study of Mr Osman [2] reported the influence of tube diameter on the material removal rate. He observed that the mass removal increases as the tube diameter increases, and as the diameter of the tube decreases, the velocity of air and abrasives increase for the same flow rate. The effect of friction in the pipe could influence the particle distribution in the feeding tube which could probably affect the particle distribution near the mixing tube entrance.**
- **Geometries of the mixing chamber employed during the tests were similar (cylinder with entrance of abrasive at 900), except for cutting head n°8 with inclination of the abrasive entrance (600).**
- **The mixing tube entry section design was not similar for all the cutting heads. It is expected that the angle of tube entry affects the abrasive velocity in the focusing tube.**
- **Distance between abrasive entrance and focusing tube has a significant effect on the system performance [3].**

After discussions and considerations of the experimental conditions, it could not concluded that increasing the volume of air increases the depth of cut.

Concerning the quality of cut, it was observed, based on experimental results, that the volume of air has an influence. It can be noted that increasing the volume of air will decrease R_a, R_z and R_{max}.

After the experimental study of Mr Osman (PhD student at the Ecole des Mines de Douai) about the optimisation of mixing chamber and comparison of cutting head geometry of different WG partners, the group decided to conceive a new abrasive cutting head.

Measurement of the pure water jet velocity, without the mixing chamber, according to the distance from the exit of water orifice was carried out by Mr Osman [5]. Data show that the maximum velocity of the water jet is reached at a distance of 10-12 mm (Figure 13). So, a shortest chamber length is more desirable because it limits abrasive mixing to the coherent part of the jet.

At present, ENSAM Water Jet Laboratory (Paris) studies the influence of the "entry cone" and the length of the focusing tube on the abrasive water jet. For the computing simulation, they use a two phase flow program called "Melodif". Experiments were conducted with 2 angles (40° and 600). They noticed that reducing the tube angle increases the cutting performance.

After analysis of the results and comparison of the six different mixing chamber designs, the WG developed a new concept of an abrasive cutting head and noticed an increasing of the efficiency of the new "Euro cutting head".

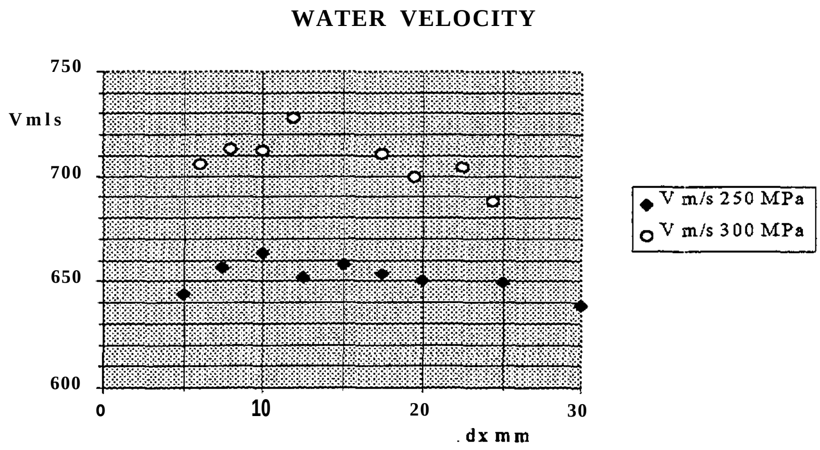

Figure 13: Water velocity as function of distance from the water orifice exit in air [5]

The main purpose of thework presented bytheworking group inthispaper was to illustrate the influence of the mixing chamber designs on the quality of cut. For some conditions of jet formation, experimental investigation have shown that 95% of jet volume flow rate are held by air [6]. This study quantifies the volume of air for different abrasive cutting heads and considers the effect of air flow rate on the surface of cut quality.

A new generation of abrasive cutting head has been developed with improvement of cutting efficiency. The originality was to conceive and machine in a single piece the mixing chamber and the focusing tube. Based on the results, further works could be done in the field of reducing the manufacturing cost for this head.

Conclusions

In the frame of this project a consortium of 31 partners from research and industry has investigated major groups of parameters which influence the quality of the cutting result. With results of this Concerted Action the know-how concerning the use of abrasive water jets for final contour cutting of difficult-to-machine materials was significantly improved. H has to be summarised, that the general structure of the project, existing of:

- intensive information exchange in the beginning
- parallel research activities in WGS
- combination of results in the end

was very successful. The final evaluation of the CA lead to the following statements:

- The aim of the CA, to improve the cutting quality by better knowledge about the main parameters that influence the quality was successfully reached.
- It was pointed out that such comprehensive and concrete research programme and exchange of information was necessary and successful. The size of the consortium of 31 partners underlines the meaning of the project.

- The opportunity to use equipment of other partners offered opportunities for tests, which would have been impossible without this consortium, because they would **have been too expensive** in equipment and manpower.
- All kind of meetings (plenary, WGS, national co-ordinated, individual) were necessary and beneficial for the co-ordination and exchange of research activities.
- Personal contacts were extremely important for the success of the project due to the fact that discussions about failures and unpublished experience only occur in a confident and personal atmosphere.
- Work of the national co-ordinators was appreciated. They recruited nine associated partners. This success was also caused by the close collaboration with national societies.

Besides these statements, the final discussion lead to topics, on which further R&D activities should be concentrated to advance abrasive water jets for further industrial applications.

Finally it has to be emphasised that co-operation and co-ordination of research activities as well as intensive exchange of experience has multiplied know-how of all participating partners.

Acknowledgement

At first we like to acknowledge support of the European Community, who made this project possible. Besides the financial support the quick and uncomplicated help in concern to all administrative questions has to be positively recommended.

Special acknowledgements belong to the heads of the Working Groups, who have always done an excellent job in co-ordinating the research activities in their WG and in supporting the International Co-ordinator. National co-ordinators are acknowledged for contacts to interested companies and the dissemination of results. We also thank national societies in the field of water jet technology in Europe for their kind support.

We also like to acknowledge the active co-operation of all partners, who joined the meetings without getting financial support, especially the partners from former EFTA countries.

References

[1] Hashish M.:
"Pressure Effects **in** Abrasive Water Jet Machining" Journal of Engineering Materials and Technology, July 1989, Vol. 111, pp. 221-228.

[2] Osman, A. H. and D. Buisine:
"Measure of airflow rate according to the mixing chamber design". 13th Conf. on Water Jet Technology - Applications and Opportunities. London, UK MEP Limited, 1996, S.223 -236.

[3] Mazurkiewicz, M. and L. Finucan:
"Investigation of Abrasive Cutting Head Internal Parameters", Proceedings of 9th International Symposium on jet cutting technology, 1988, Sendai, Japan.

[4] Cornier, A.; Kremer, D.; Raissi, K. and O. Simonin:
"Mixing tube geometry influence on abrasive water jet flow" l 3th Conf. on Water Jet Technology - Applications and Opportunities. London, UK: MEP Limited, 1996, S.223 -236.

[5] "Application de la Vélocimétrie Doppler par Interférométrie de Fabry-Perot a la mesure des vitesses clans un jet d'eau supersonique" Internal Report, LDMP University de Line 1- ONERA IMFL de Line - Ecole des Mines de Douai, le 09 Sept 1995.

[6] Abriak, M.; Parsy, F.; Schmitt, A.; Tazibt, A. and B. Thery:
"Effect of air on acceleration process in AWJ entrainment system". 12th Conf. on Water Jet Technology - Applications and Opportunities. London, UK: MEP Limited, 1994, S. 47-58.