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# WATERJET CUTTING BEYOND 400 MPA

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## ABSTRACT

Plain waterjet cutting is used to cut only soft materials like rubber, plastic, paper, some soft composite materials and very thin sheet metals in the industry because of its limited power. Cutting of thicker metals and harder composites is possible when the water pressure is increased.

This paper includes a comprehensive discussion of the waterjet cutting of thin sheet metals and laminated metal composites up to 700 MPa. Firstly, the design of a plain waterjet cutting head is discussed. The effects of the upstream tube and the orifice on jet coherency were investigated. The required tightening torque for sealing was calculated. Next, the cutting performance of plain waterjet based on the maximum cutting speed and the maximum depth of cut is defined. It was found that the cutting performance based on the cutting speed improves as the pressure increases. If the cutting performance is defined in terms of the maximum depths of cut, the improvement is much lower.

# 1. INTRODUCTION

In current state-of-the-art waterjet cutting systems, a plain waterjet is used to cut soft materials like paper, food, plastics, cardboard, wood, leather and some soft composite materials while abrasive waterjets are used mainly for harder materials like metals, rocks, marbles, hard composite materials etc [1]. Only very thin sheets of metals can be cut with pure waterjet. It is also not suitable for cutting glass or high strength composites.

In this work, cutting capabilities and the efficiency of plain waterjet are investigated at water pressures higher than 400 MPa, which is the maximum output pressure for most of waterjet cutting systems. Researches in this field is limited since the waterjet pressure units that can supply pressures beyond 400 MPa are rare and most of them are still not commercially available.

The paper consists of two sections. The first section focuses on the design of a cutting head for plain waterjet cutting applications. The main concern in the design is the jet quality and the strength of the structures. In the second part, the cutting results are presented. Maximum cutting speed and maximum depth of cut are determined up to 700 MPa.

# 2. PLAIN WATERJET CUTTING HEAD

## 2.1. Introduction

The plain waterjet cutting head is composed of three basic parts; the upstream tube, orifice and the orifice holder. The upstream tube provides a mean to connect the high pressure tubing to the orifice. Sealing is assured by the proper tightening of the orifice holder. The issues and the parameters related to design of plain waterjet cutting head are listed in the Figure 1. One of the most important issues in plain waterjet cutting head design is the quality of jet. It is desirable for waterjet to maintain its kinetic energy for an appreciable distance. However, somewhere in the downstream, the jet breaks down into droplets and its kinetic energy is divided among small droplets. Although the jet spreading increases the cutting speed, it generates wider cuts with rounded edges and wider damaged zones. It is also not suitable for deep cutting. In case of abrasive waterjet, dispersed jets cause wear at the entry region of the focusing tube. However, they also increase the mixing efficiency of the abrasives, since the abrasive particles can penetrate into the water easily when the jet is not dense.

Another concern is strength of the components working under high pressures. The upstream tube is vulnerable to failure since it is subjected to high, fluctuating stresses. Material and wall thickness should be chosen properly to overcome the stresses. The bore surface of the upstream tube should be defect-free and must have a superior surface quality in order to increase fatigue life of the component. Better surface finish also helps to obtain a better jet quality since the surface imperfections cause disturbances in the flow that makes the jet less stable.

Sealing becomes more difficult with the increase in the water pressures. To assure sealing, high tightening torques should be applied to the orifice holder. This may cause deformations in the mating surfaces of orifice and upstream tube. Another result of high tightening torque is the stress initiated at orifice. If the stress is localized around the jewel of orifice, it may trigger early and sudden breaks of the orifice jewel.

## 2.2. Upstream tube

The design should provide a good quality jet while it is sufficiently strong for very high stresses. The cost of the part should be reasonable.

### 2.2.1. Bore diameter

The pressure system before the orifice generates flows with rotation about the longitudinal axis, with non-uniform velocity distribution across the cross-section and with turbulence that deteriorate the coherency of the jet. Compensation of these effects can be done within the upstream tube. The reduction of the turbulences at the water flow in the upstream tube prior to the orifice increases the jet coherency [2]. The critical diameters which keep the flow in the upstream tube laminar are listed at table 1. Viscosity and density of water is pressure dependent and calculated by using the Bridgman data [3]. The calculations are carried out at 400 MPa, however since the viscosity and water flow rate increase proportionally; the minimum diameter for laminar flow is nearly the same over the entire pressure range.

### 2.2.2. Length of the upstream tube

To isolate the jet from the upstream disturbances, the flow should be fully developed. For a laminar flow, length to diameter ratio (L/d) required for a fully developed flow should be 0.057 times of Reynolds number [4]. Since the maximum Reynolds number for a laminar flow is around 2000, the maximum L/d ratio is approximately 120, which impractically ended with very long tubes.

For most of possible combinations of orifice diameter, pressure, and upstream tube, the flow in upstream tube is turbulent. It is stated that when L/d ratio reaches 15, the wall shear stress and static pressure gradient is fully developed although the velocities, turbulence intensifiers and Reynolds stresses are still continuing to develop until the L/d is 40 [4]. Thomas and Geller [5] developed a cutting head with an L/d ratio of 10, and obtained satisfactory results in terms of the quality of the jet. Hashish also reports that the upstream tube length should be at least 20 times of the tube diameter to produce coherent jets [6].

### 2.2.3. Wall thickness

The upstream tube is a thick-walled cylinder subjected to fluctuating stresses. The wall thickness must be determined according to the desired behaviour of the structure under these loads. The behaviour of structures under variable loading can be classified into five categories (Figure 2). First is the elastic behaviour. If the applied stress is less than yield stress of material, structures behave elastically. Next is the plastic collapse, the least desirable option. If equivalent stress reaches ultimate tensile strength of material, material collapses. If repetitive stress values are somewhere between these two extremes, there are three possibilities. First and the most desirable one is the shakedown condition. Due to the introduction of residual stresses after the first cycle, the structure may behave purely elastic, which means that there will be no plastic deformation in the subsequent cycles. Next is alternating plasticity. If shakedown is not obtained, then in each loading cycle, the component continues to deform plastically. If the strain increments cancel each other at the end of each cycle, it is called alternating plasticity. Finally, if shakedown is not obtained and the strain increments in each load cycle are of the same sign, then the total strain becomes larger in every cycle and the part becomes unserviceable due to the large displacements. This behaviour is called ratcheting or incremental collapse [7, 8].

If the thick-walled cylinder under internal and external pressures behaves elastic, stress distributions throughout the wall can be calculated by the Lame equations. The internal pressure which initiates plastic deformation is not changed significantly with the alterations of different failure criteria (Figure 3a). The required yield strength of the material which avoids initial yielding is depicted at Figure3b for a cylinder loaded by 400 MPa and 800 MPa internal pressures at different material thicknesses. The failure criterion is Von Misses, and the plane strain condition is applied. Materials used in manufacturing of high pressure components have yield strengths less than 1000 MPa. It is clear that it is not enough to ensure elastic behaviour when the part is subjected to internal pressure of 800 MPa. Therefore, initial yielding is unavoidable for a monobloc thick-walled cylinder under these circumstances.

Since the initial yielding is unavoidable, the part should be designed according to shakedown or low cycle fatigue. The analysis to determine the state of the part can be carried out by using finite element method. Commercial FEA software, Ansys 8.1 is used in this study. Two-dimensional model of an open-ended, semi infinite, thick-walled cylinder is developed. The symmetry of the cylinder is taken advantage of and the quarter of the cylinder is modelled. The model is meshed with a linear four-node, quadrilateral element, plane 42. The mesh is denser around the bore where initial and reverse yielding take place. The element is restricted to its plane strain option, i.e. strain in the longitudinal direction is assumed to be zero.

The upstream tube is subjected to water pressure during the cutting operation. The pressure fluctuations are between 1% to 3% of the set pressure value according to the size of the orifice, accumulator and the high pressure cylinder [9]. Therefore, these minor fluctuations are omitted and only main on-off cycles are taken into account. The material is characterized with a bilinear, kinematic strain hardening material model (BKIN), so that Bauschinger effect is included. A martensitic stainless steel, 15-5PH, with a high corrosion resistance, good ductility and high strength, is chosen as the material. Its properties are listed at Table 2.

As an example, an upstream tube with an inner radius of 1.75 mm and an outer radius of 12 mm is analyzed under 800 MPa internal pressure. The results are presented for a node, which is at the bore of the cylinder. The loading is applied and removed in 10 sub steps (increments). Therefore, each loading – unloading cycle takes 20 increments. It can be seen from figure 4 that after the first loading, there will be no additional plastic deformation for both of the cases. The component is in elastic shakedown behaviour at the internal pressure of 800 MPa.

## 2.3. Orifice

The geometry of an orifice and the sealing area around the orifice has a great effect on coherency of the jet. An orifice with sharp edges and streamline designed sealing area which directs the flow into the orifice has the longest coherent length. Several orifices are tested in this study (Figure 5). All of the orifices have cylindrical holes. The orifice 1 and orifice 2 are the plain waterjet orifices, i.e. have sharper edges while orifice 3 has rounded edges and especially designed for abrasive waterjet cutting. The sealing of orifice 1 is conical while the others have flat sealing. Orifice 2 has a raised and isolated cap to avoid the failures of the orifice due to the high stresses introduced during the mounting.

The doubling length is defined as the distance from the orifice exit to the point where the jet diameter is two times of the orifice diameter. It is determined by photographic means (Figure 5) [11]. The results (Figure 6) show that the jet sprayed from the orifice 1 has superior coherency compared to those of the other orifice types with the current upstream tube geometry. Poor performance of orifice 2 as compared to orifice 1 can be explained by its different entry region. The smoother guidance of the flow with tapered surfaces decreases the turbulence before the orifice. Low performance orifice 3 is expected because of its rounded edges. It is clear that the jet coherency is correlated with Reynolds' number of the flow in the upstream tube, which is a function of jet diameter and the water pressure.

## 2.4. Orifice holder

The orifice holder should keep the orifice in place and should ensure the sealing under high pressures. It must be fasten with an adequate torque value which makes the pressure on both side of the orifice at least equal to each other. Lesser tightening torques will lead to leakages.

$$\frac{F}{\pi \cdot D \cdot b} \geq p \quad (1)$$

$$T = K \cdot F \cdot d \quad (2)$$

The minimum tightening torque, T can be extracted from the above equations. F is the force perpendicular to the contact surface, p is the water pressure, D is the contact diameter, b is the contact width and d is the pitch diameter of the thread. K is the torque coefficient which depends on the thread angle, pitch, and friction coefficient [12]. The contact area and the friction coefficient have a great effect on the required torque. Figure 7 shows the results for ¾" threaded orifice holder, when the friction coefficient is 0.15 and the contact diameter is 5.5 mm at several water pressures and contact widths.

## 3. PREVIOUS RESEARCHES BEYOND 400 MPA

The researches about the capabilities of the waterjet cutting with a water pressure more than 400 MPa are limited due to the limited availability of the pressure units. However, there is an increasing interest on the subject recently (Table 3).

Hashish [17] developed a performance parameter based on maximum cutting speed and hydraulic power. Power use efficiency, as it is called, $\eta_v$ is defined as the ratio of maximum cutting speed, $v_{max}$ to the hydraulic power, which equals to flow rate, $q$ times pressure, $p$.

$$\eta_v = \frac{v_{\max}}{q \cdot p} \qquad (3)$$

The argument behind the definition of the efficiency is to see the effect of the pressure increase on the cutting performance in relation with the hydraulic power which is a result of the pressure increase. If they are directly proportional with each other, the benefits of pressure increase are limited since the same amount of hydraulic power increase is possible with other means like using multiple nozzles and / or larger orifices. The results also show that the efficiency increases, i.e. the maximum cutting velocity increases more than the hydraulic power as the pressure increases. He also mentioned that the power efficiency increases while the diameter of the orifice decreases within the range of orifices from 0.076 mm to 0.229 mm.

Cadavid [26] investigated the cutting performance of plain waterjet cutting of aluminium and PVC for a range of orifice sizes from 0.036 mm to 0.3 mm and the water pressure from 200 MPa to 600 MPa at a fixed standoff distance of 12 mm. The definition of cutting efficiency, $\eta_h$ used in this study is based on the relation of maximum depth of cut, $h_{max}$ at a certain cutting speed, $v_c$ with the available hydraulic power.

$$\eta_h = \frac{v_c \cdot h_{\max}}{q \cdot p} \qquad (4)$$

The results show that cutting performance of orifices smaller than 0.2 mm is inversely proportional with the hydraulic power, which is in contradiction with the results of Hashish. It is directly proportional only when the orifice diameter is 0.2 mm and 0.3 mm in these experiments. The changing of the type of relation from directly proportional to indirectly proportional as the nozzle diameter is getting smaller indicates the existence of an orifice size in which the cutting performance is independent of the water pressure, which is 0.17 mm according to the results.

## 4. TEST SET-UP & PROCUDURE

The pressure unit is a two-stage double acting intensifier with a design pressure of 800 MPa developed by Resato Int. The pressure unit is connected to a cutting head by a series of tubing with an internal diameter of 1.6 mm and an external diameter of 9.5 mm. The final section of the tubing is spiral to allow the movements of the cutting head. The cutting head is manipulated by SCARA robot (Figure 8). The catcher tank is lying under the cutting area to absorb the remaining energy. There are two buffer volumes in the system. One is between the two intensifiers and the other is between the cutting head and the final intensifier. They reduce the pressure fluctuation to 1% when 0.1 mm orifice is charge at 700 MPa [9].

Two different types of orifices are connected to the cutting head, orifice 1 and orifice 3; the ones with the best and worst jet qualities. If it is not mentioned, orifice 1 is in charge. Same upstream tube with an internal diameter of 3.5 mm and a length of 212 mm and same orifice holder are used for all of the tests.

Two major concerns are investigated to judge the abilities of the plain waterjet at pressures higher than the industry standard 400 MPa; maximum cutting speed and maximum depth of cut. For determination of maximum cutting speed, the test pieces cut with different cutting speeds. The highest cutting speed that managed to separate the part into two regardless of the quality of the cut surfaces is taken as the maximum cutting speed. The maximum depth of cut is evaluated by using wedge-shaped test samples. With this set-up, the maximum depth of cut can be determined on one single cut for a certain set of parameters by measuring the depth where the continuous cutting operation is ended (Figure 9). 1.5 mm thick 6082 series aluminium is used in maximum cutting speed experiments. Aluminium alloy of series 7000 with yield strength of 130 MPa and a Brinell hardness of 65 is used in the determination of maximum depth of cut. A stand-off distance of 2 mm is used unless it is specified specially.

## 5. RESULTS & DISCUSSION

The maximum cutting speed and the maximum depth of cut are used to measure the performance of the operation. The change of maximum cutting speed with pressure is depicted at Figure 10a for various orifice diameters. The figure clearly shows the significant increase in the cutting speed at higher pressures. Although it is possible to cut faster with larger orifices when the pressure is kept constant due to their higher hydraulic powers, it is interesting to see that the smaller orifices performs better at a fixed power since they need to remove less volume with the same amount of power (Figure 10b). Figure 9b also shows that the cutting capability of jet increases as the standoff distance increases. The increase of cutting speed with increasing standoff distance can be explained by the droplet effects. Not only the core but also the droplets around the core involves into the cutting operation. The lesser increase in the cutting speed for 0.12 mm waterjet orifice is due to the fact that its doubling length (29.5 mm at 600 MPa) is longer than the standoff distance (21 mm), which results in less droplet formation and more compact jet (Figure 6b). However, the 0.175 mm abrasive waterjet orifice starts to disintegrate after only 1.3 mm at 600 MPa.

Unlike the maximum cutting speed, there is a linear relation between the pressure and maximum depth of cut and the results (Fig 11a) show the existence of threshold pressure for aluminium that was also pointed out by the Raghaven [15]. As in the case of maximum cutting speed, the smaller orifices perform better with the same amount of hydraulic power (Figure 11b). However, since the amount of power is limited, its usability is restricted to the thin workpieces. With 0.1 mm orifice, it is possible to cut 3 mm thick aluminium at 710 MPa. Same aluminium can be cut with only 470 MPa with 0.175 mm orifice.

The volume removal rate linearly increases with the hydraulic power when the cutting speed is kept constant (Figure 12a). It contains all the data presented at the figure 11a. Although the depth of cut decreases as the cutting speed increases, the volume removal rate increases up to a certain point, and the trend shows that it will decrease from certain point on.
Cutting efficiency in terms of power use per cutting speed increases as the hydraulic power increases (Figure 13a). The efficiency of smaller orifices is higher than the ones of larger orifices at the same hydraulic power. The results are consisted with the previous researchers [17]. Localization of the same hydraulic power to a smaller spot increases cutting speed, and power

efficiency. However, if the power efficiency is defined in terms of depth of cut, the increase in the cutting efficiency is not that significant as the hydraulic power increases (Fig 13b). After a sudden increase, it is almost constant or slightly increases over the rest of the pressure (power) range for a particular orifice. The difference between the power efficiencies defined in terms of maximum cutting speed and maximum depth of cut can also be deducted from the previous figures which show the behaviour of cutting speed and depth of cut with respect to water pressure (Fig 10 & 11). While the cutting speed increases exponentially, the depth of cut increases linearly with pressure. The threshold pressure phenomena may be the reason of the initial increase of the power efficiency. The smaller sized orifices have again better power use efficiencies.

An empirical equation has been developed to predict the depth of cut. Since it known that the depth of cut is directly proportional with hydraulic power (pressure and the orifice diameter) and inversely proportional with the cutting speed, the empirical equation can be written as

$$h_{\max} = \frac{C \cdot p^{a} \cdot d_{o}^{\,b}}{v_{c}^{\,c}} \qquad (5)$$

$p$, $d_o$, $v_c$ is the water pressure, orifice diameter and cutting speed respectively. C is the coefficient depends on the material properties. a, b, c should be determined from experiments. The stand-off distance is not taken into account since it has minor effects on cutting performance within the coherent region of the jet (Figure 13a). It causes a decrease in depth of cut only after jet starts to disintegrate. The correlation coefficient is 0.985 (Figure 13b) when the equation is written as

$$h_{\max} = \frac{0.0051 \cdot p^{1.84} \cdot d_{o}^{\,1.41}}{v_{c}^{\,0.52}} \qquad (6)$$

In the above equation, pressure is in MPa, diameter of the orifice is in mm and the cutting speed is in mm/min. The equation is only valid for the tested material aluminium. More tests should be done to find the C for other materials. It is interesting to see that the pressure coefficient is 1.84. The power coefficient of pressure in hydraulic power calculation is only 1.5.

## 6. CONCLUSION AND OUTLOOK

Cutting performance of plain waterjet above the industry standard 400 MPa is investigated. To benefit more from the waterjet operation, the jet stream must have a high quality. Therefore cutting head should be design carefully to produce coherent jet stream. The results shows that non-turbulent flow before the orifice promotes better quality jets. To ensure a laminar flow, the upstream tube should be large and long enough. However, it is not possible to keep the flow laminar when the water flow rate is high. It is known that the influence of orifice geometry to the jet quality is high. The sharper edge produces more coherent jets. In this study, it also shown that the geometry of the sealing around the orifice also affects the jet. If the flow is smoothly guided to the hole by means of conical surfaces, the waterjet keeps its integrity for a longer distance.

Since the applied stresses are higher, strength of the parts in the cutting head, especially the upstream tube need special attention. Initial yielding of the structure is unavoidable because of the lack of high strength material suitable for high pressure applications. However, by the help of a proper combination of material and thickness of the part, it is possible to avoid early failures due to low-cycle fatigue or ratcheting.

The cutting results with plain waterjet shows that both maximum cutting speed and maximum depth of cut increases with pressure increase. However, the hydraulic power use efficiency is increased significantly only if it is defined in terms of maximum cutting speed. The smaller orifices have better power efficiencies in both cases. The stand-off distance increases the maximum cutting speed, however its effect on depth of cut is limited and in a negative way, i.e. disintegrated jets cuts faster but not deeper. The empirical equation that depicts the relation of depth of cut with pressure, orifice diameter, and cutting speed is developed with a good agreement with the experiments.

Next step will be the investigations of the cutting quality of plain waterjet, and a strategy to obtain high quality cuts.

## 7. ACKNOWLEDGEMENT

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## 9. TABLES

**Table 1.** Critical tube diameters, Reynolds number is 2000, laminar flow limit

| **Orifice diameter, $d_o$ (mm)** | **Minimum diameter for laminar flow, $d_{lam}$ (mm)** | **$d_{lam}$ / $d_o$** |
|---|---|---|
| 0.1 | 2.9 | 29 |
| 0.15 | 6.4 | 42.7 |
| 0.2 | 11 | 55 |

**Table 2**. Mechanical properties of 15-5PH [10]

| *Material*: *15-5PH H1100* | | | |
|---|---|---|---|
| $\sigma_y$, 0.2 % yield strength | 793 MPa | E, Elastic Modulus | 196.5 GPa |
| $S_u$, Ultimate tensile stress | 965 MPa | $E_t$, Tangent modulus | 32 GPa |
| ν, Poisons' ratio | 0.27 | | |

**Table 3.** WJ and AWJ researches beyond 400 MPa water pressure, $P_{max}$: maximum tested pressure, $d_{max}$: largest orifice diameter used in the tests

| ***Research*** | ***Publishing year(s)*** | ***$P_{max}$ (MPa)*** | ***Intensification ratio*** | ***$d_{max}$ (mm)*** | ***Abrasive*** |
|---|---|---|---|---|---|
| Imanaka [13] | 1972 | 1000 | 87:1 | 0.15 | - |
| Oweinah [14] | 1989 | 900 | 73:1 | 0.25 | - |
| Raghavan [15] | 1991 | 690 | 20:1 | 0.2 | - |
| Hashish [16, 17, 18] | 1996 – 2004 | 690 | 33:1 | 0.23 | yes |
| Xu [19] | 1999 | 520 | 25.4:1 | 0.38 | yes |
| Trieb [20, 21] | 2000-2001 | 1000 | 50:1 | 0.1 | yes |
| Louis [22, 23] | 2003-2004 | 900 | 63:1 | 0.1 | - |
| Mohamed [24] | 2004 | 900 | 63:1 | 0.1 | yes |
| Lefevre [25] | 2004 | 600 | - | 0.25 | yes |
| Cadavid [26] | 2004 | 600 | - | 0.3 | yes |
| Susuzlu [9, 11] | 2004 | 730 | 37:1 | 0.175 | - |

## 10. FIGURES

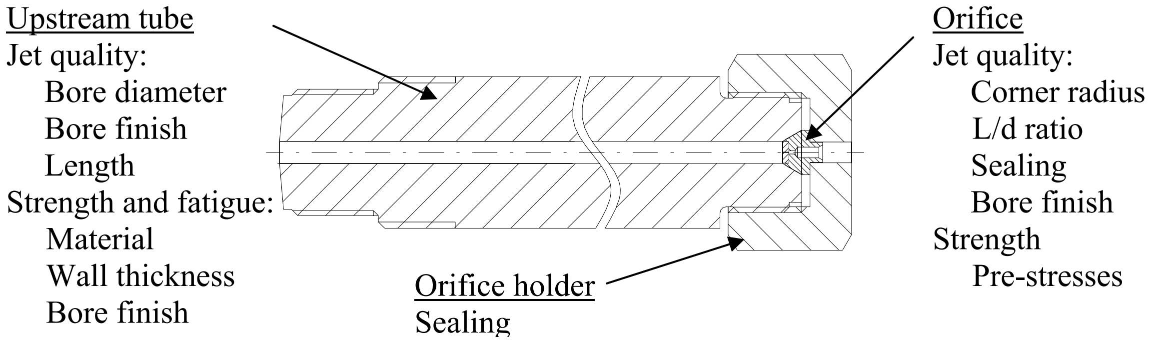
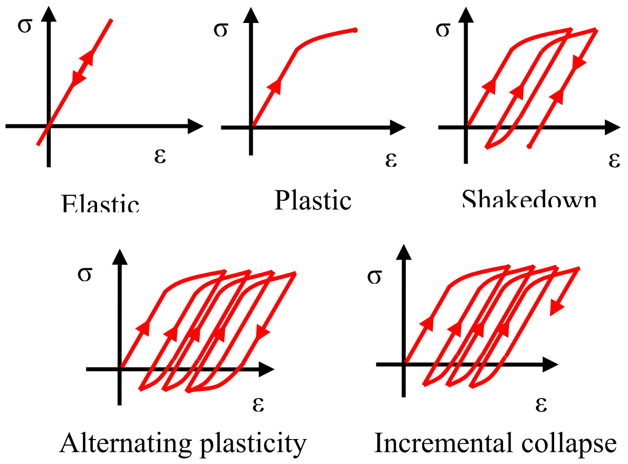


**Figure 1.** Plain waterjet cutting heads and the design issues



Elastic Plastic Shakedown

Alternating plasticity Incremental collapse

**Figure 2.** Behavior of the structures under alternating stresses

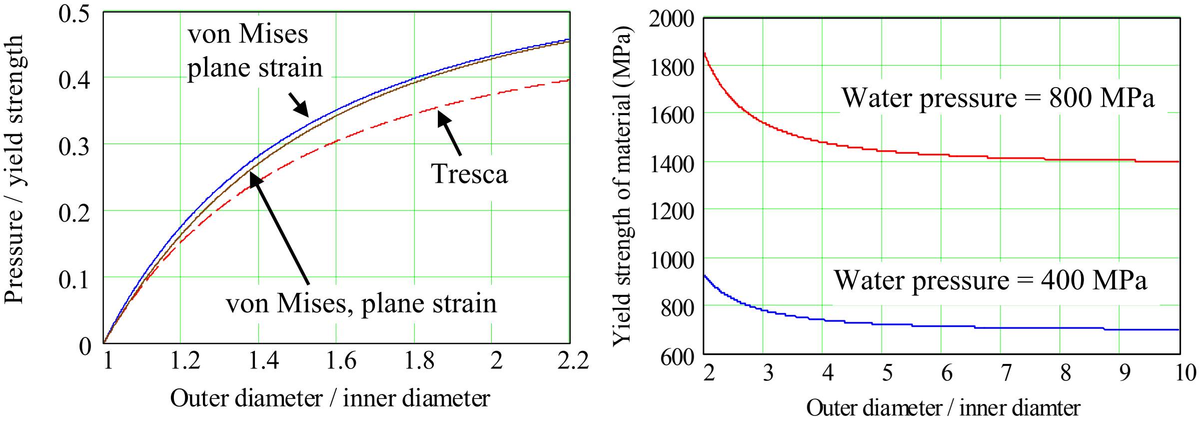


**Figure 3.** (a) Initial yielding pressure according to different failure criteria, (b) required yield strength of the material to avoid initial yielding.

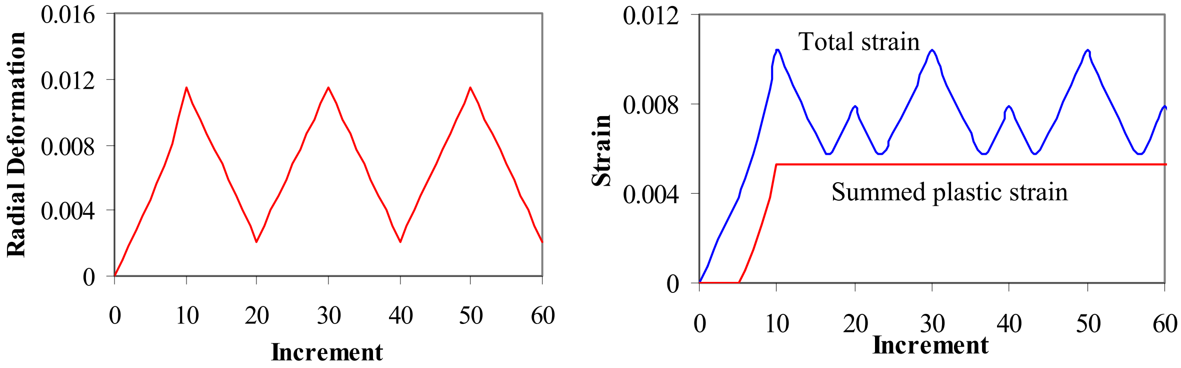


**Figure 4.** (a) Radial deformation and the (b) strain under cyclic loading of thick-walled cylinder with internal diameter of 1.75 mm, and external diameter of 12 mm

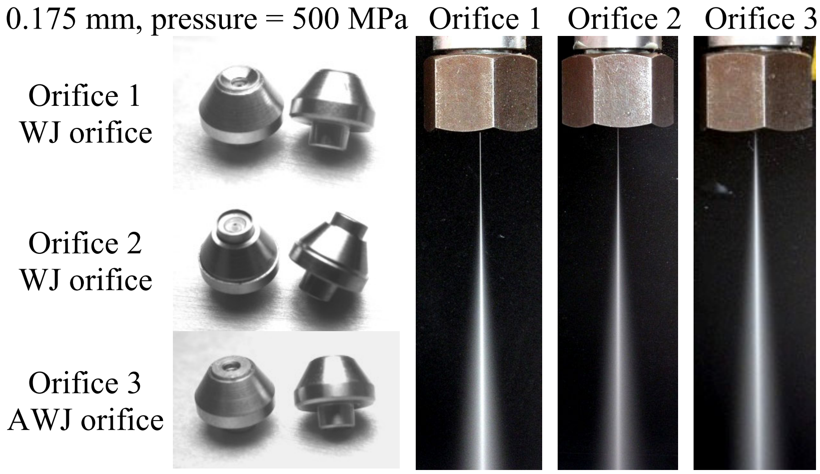


**Figure. 5.** Types of orifices used in the experiments

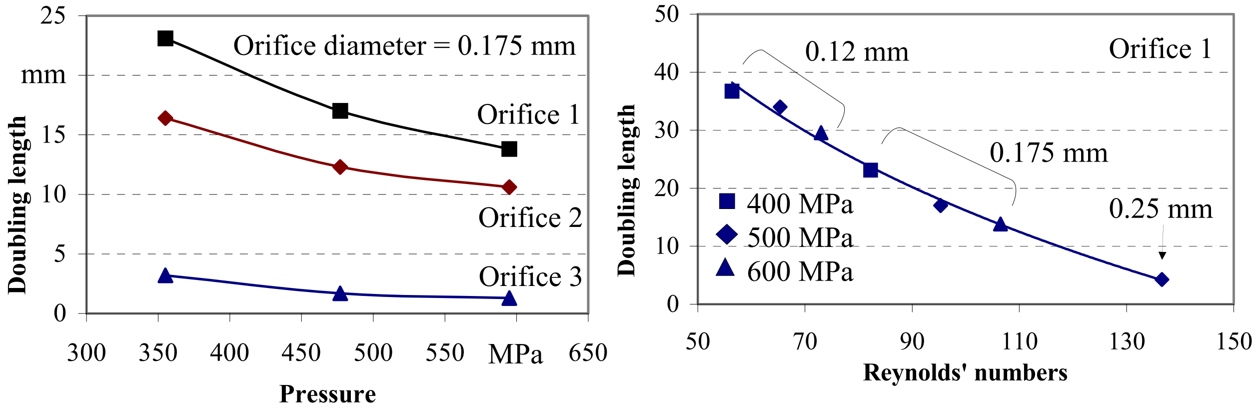


**Figure 6.** Doubling length with respect to (a) water pressure and Reynolds number

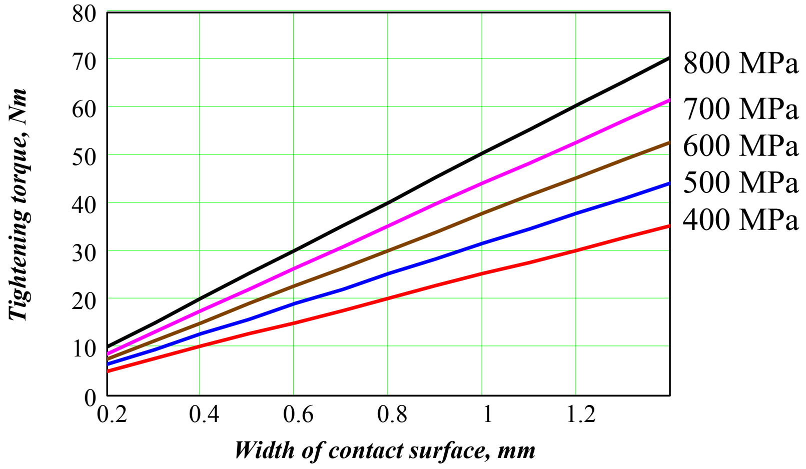


**Figure 7.** Required tightening torque to prevent leakage

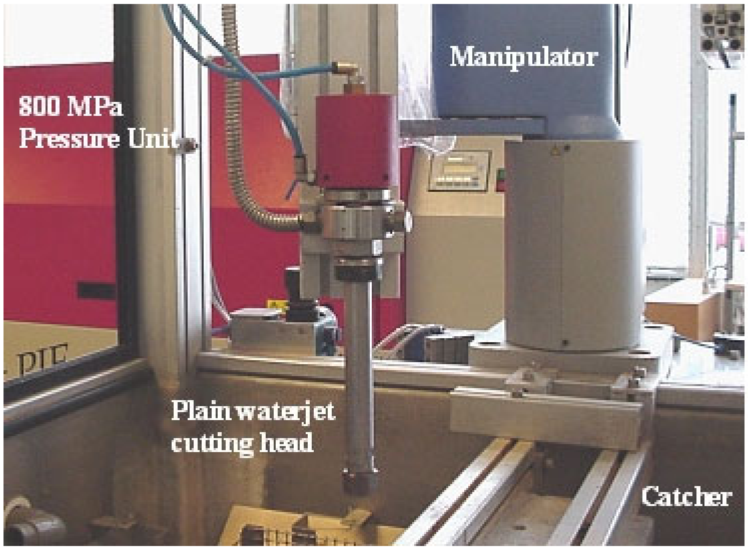
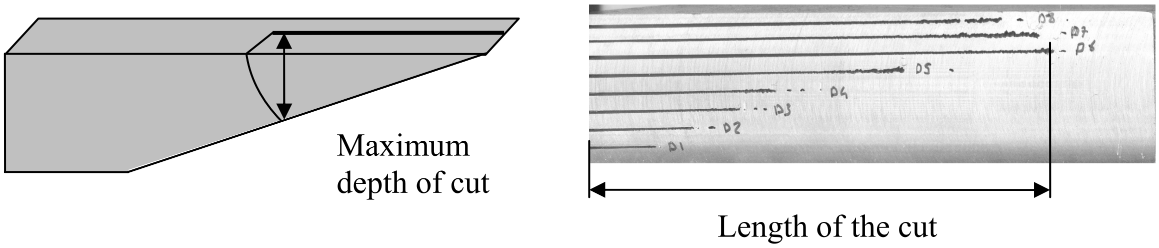


**Figure 8.** Waterjet cutting system



(a) Wedge like test-piece (b) Bottom view of the cuts

**Figure 9.** Maximum depth of cut determination

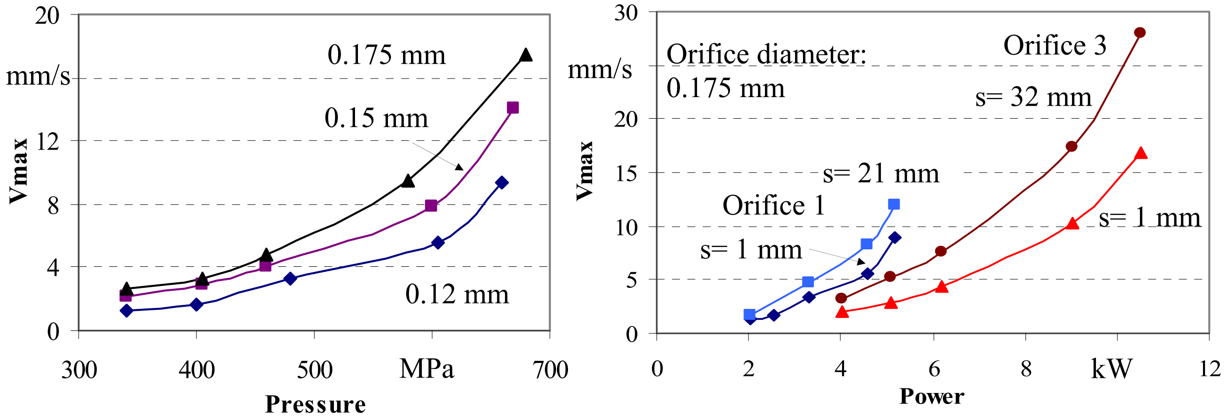


**Figure 10.** Maximum cutting speed with respect to (a) water pressure, (b) hydraulic power at different stand-off distances, s

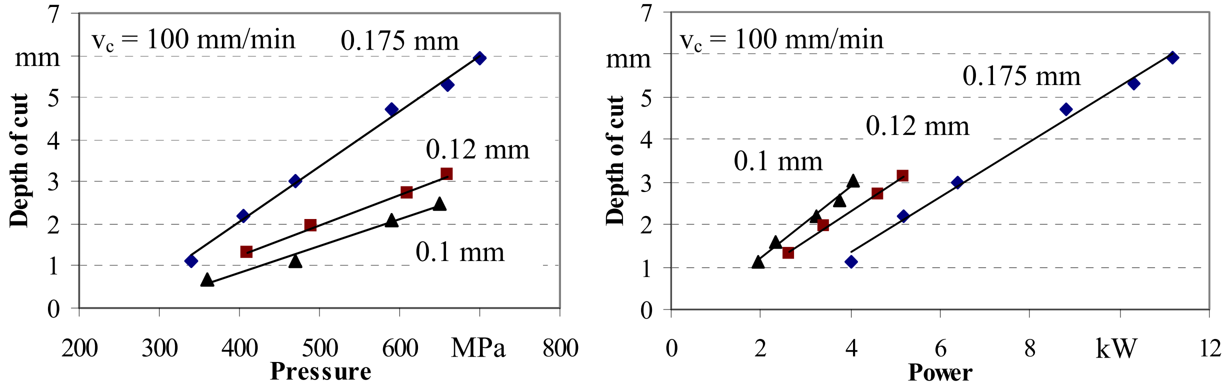


**Figure 11.** Maximum depth of cut with respect to (a) water pressure, (b) hydraulic power

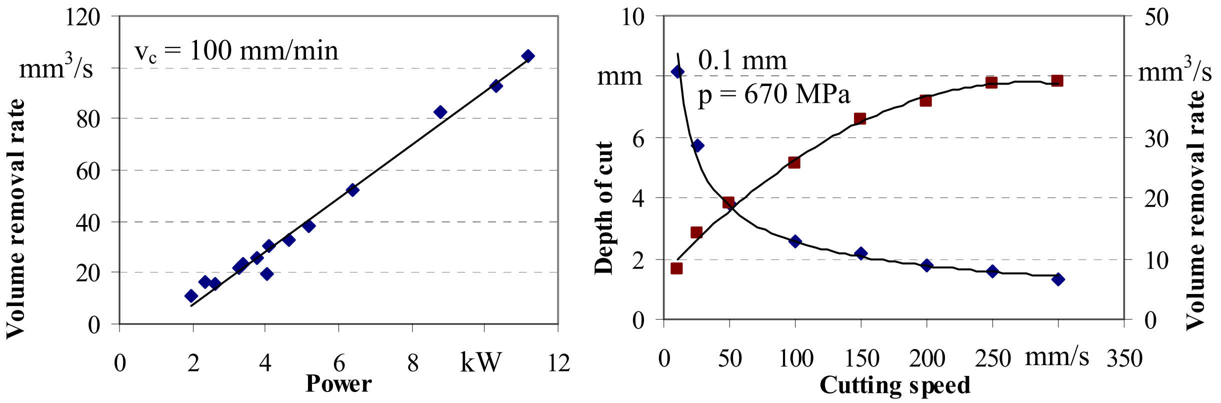


**Figure 12.** (a) Volume removal rate with respect to hydraulic power, (b) volume removal rate and depth of cut versus cutting speed

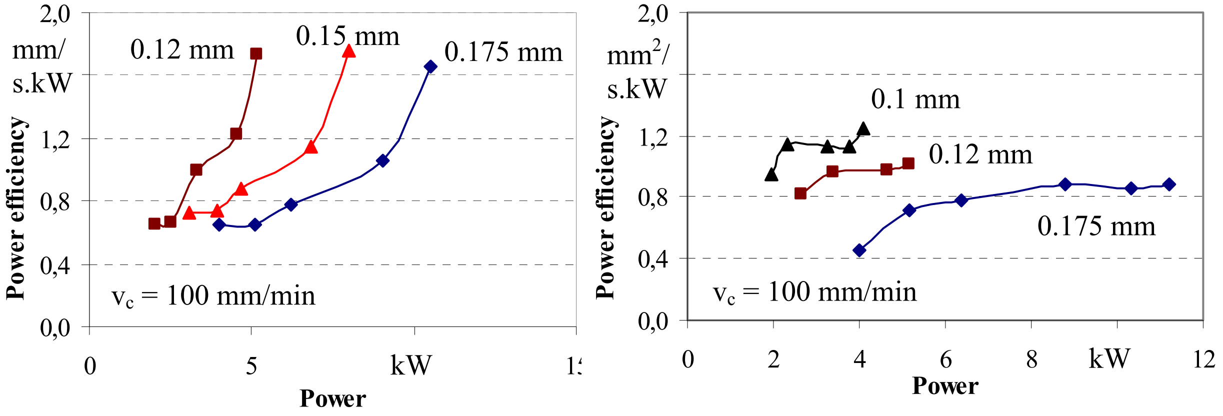


**Figure 13.** Power efficiency with respect to hydraulic power in terms of (a) maximum cutting speed, (b) maximum depth of cut

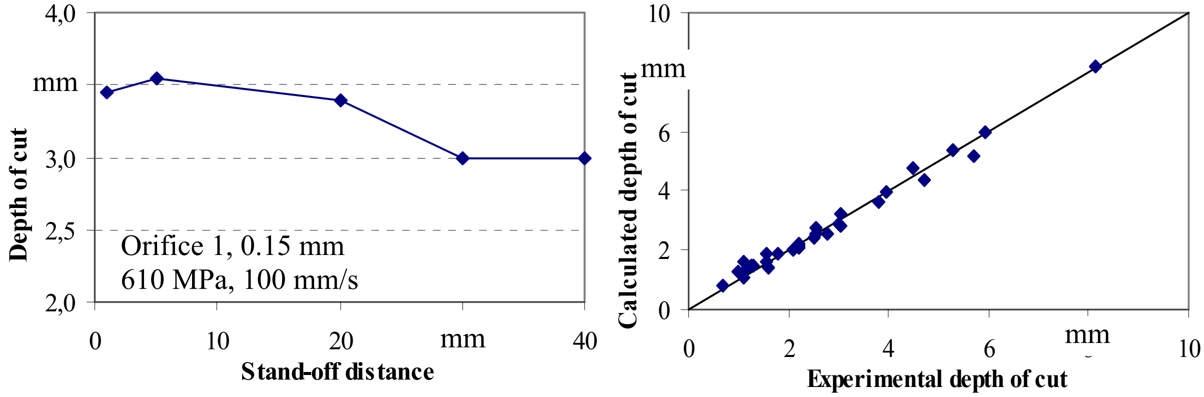


**Figure 14.** (a) Maximum cutting speed with respect to stand-off distance, (b) Verification of the empirical cutting model