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CHARACTERISTICS OF WATERJET CUTTING FOR THE OFFSHORE INDUSTRY

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ABSTRACT

Waterjet machining harnesses the kinetic energy of a high velocity waterjet to cut materials. Waterjet cutting for the offshore industry has shown particular interest in recent years. Abrasive Waterjet (AWJ) is seen as an ideal cutting tool for cutting buoys and other structures away from the seabed. The study reported in this paper analyzes certain aspects associated with waterjet cutting in an attempt to improve it as a machining process and to investigate its suitability for offshore use. Specific factors looked at, were the effects of abrasive flow rate on AWJ machining, the performance of waterjet when used underwater, and nozzle design to try and improve the jet focus. From experimentation, cutting while submerged was observed to be possible, although the performance of the jet was slightly stunted due to the interaction of the surrounding fluid. As the nozzle was moved away from the workpiece, thereby increasing the standoff distance, the performance of the jet was found to deteriorate further. An increase in abrasive flow rate was found to aid cutting initially; however at higher flow rates the increase was found to have a detrimental effect on the jets cutting performance. Therefore an optimum abrasive flow rate was found to be between 4.4 g/s & 7.4 g/s. The slope angle of the nozzle axis has no significant effect. The effect of changing nozzle geometry was analysed by computational fluid dynamics. The outcome was that the change in geometry had no effect on the upstream flow.

KEY WORDS

Waterjet cutting, Abrasive waterjet, Offshore industry, Accuracy.

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1. INTRODUCTION

Abrasive waterjet (AWJ) cutting, due to its various distinct advantages over the other cutting technologies such as no thermal distortion [1], high machining versatility, high flexibility and small cutting forces [1, 2& 3], is being increasingly used in various industries. A considerable research has been carried out to study these cutting technologies [4-7]. This includes the topographical analysis of machined surfaces and the associated cutting mechanisms [8, 9, 10], as well as the analysis of kerf geometrical features to optimize the cutting processes [11, 12]. Also, the AWJ cutting of precise 3D contours in pre-formed sheet-metal components can replace laser or plasma cutting, especially where heat affected zones need to be avoided [13, 14, 15]. Waterjet cutting for the offshore industry has shown particular interest in recent years. Although successful on this occasion there are certain problems that become apparent when using AWJ under water. Generally, the abrasive dust is supplied from a hopper on the surface. Echert et al [16] comments on the difficulties associated with pumping the abrasive mixture down to the nozzle head as well as maintaining the high jet velocities required to cut. These problems are said to increase rapidly with depth, thereby limiting surface feed systems to 100 m in depth.

According to many authors such as Hashish [17], solid particle impact accounts for all material removal. Meng & Ludema [18] suggest that there are four mechanisms that account for material removal by impact of solid particles; these are cutting, fatigue, brittle fracture, and melting. Rather than acting separately, material erosion happens due to a combination of these mechanisms. Speed of erosion depends on several factors; impact angle, particle kinetic energy, particle shape, target material properties, and environmental impact conditions. Ramulu [19] suggests that erosion occurs, during the piercing of brittle material by AWJ, due to a combined action of particle impact and a "water wedge". It is said that the impacting particles create micro cracking, with the high-speed waterjet entering the cracks and widening them due to hydrostatic forces. By showing that a pure waterjet can cut through a pre-cracked material, this theory was proven.

2. EXPERIMENTAL WORK AND SET-UP

The experimental tests were carried out on two materials; PVC with pure waterjet and 50D steel with abrasive waterjet. 50D steel, (St 60), is one of the most common steels used in the offshore industry. An especially test set-up was carried out to study the effect of the main cutting parameters, water pressure [P], standoff distance [SOD], nozzle traverse speed [S], nozzle inclination angle [α] and abrasive flow rate, on the cutting performance. The waterjet nozzle diameter is constant and equal to 0.25 mm. The experimental testes was carried out in two cases, first when the cutting in air as well as submerged under water.

The abrasive waterjet system consists of three main components, the hydraulic intensifier, the cutting nozzle, and the abrasive feed system. This system is illustrated in the schematic diagram as shown in Figure (1).

To allow the nozzle to traverse across the workpiece at a variable standoff distance (SOD), the nozzle is fixed to a mounting, which allows movement along the horizontal and vertical axes, [see Figure (2)], as well as the ability for tilting with respect to the vertical nozzle axis as indicate in the diagrammatic sketch illustrated in Figure (3). The mounting supports are attached to two opposite walls of a collection tank so that the nozzle sits over the tank, allowing the water from the jet to fall into the tank and either drain away or be filtered and recycled. For pure waterjet a simple nozzle is used which is to hold the sapphire orifice nozzle in place.

For abrasive waterjet a more complex nozzle is used. Again it is used to hold the sapphire nozzle in place, however incorporated into the nozzle is after the sapphire is a mixing chamber with an inlet for the abrasive particulate. It is here that the jet accelerates the abrasive particles, giving them the kinetic energy needed to erode the workpiece. After the mixing chamber there is a long focusing tube where the abrasive and water are focused into a coherent jet. The considerations from the previous works [20-25] were taken into account for defined the shape and dimensions of the focusing tube.

3. WATERJET VELOCITY

Water pressure has a major influence on the performance of both the WJ and AWJ. Using classical fluid mechanics, the given model is attempts to predict whether or not material removal will occur, for a set of cutting variables, when cutting underwater and in air.

An ideal fluid is considered to be incompressible and obeys Bernoullis's equation (1):

$$\frac{V_1^2}{2}+\frac{P_1}{\rho_w}+Z_1=\frac{V_2^2}{2}+\frac{P_2}{\rho_w}+Z_2 \qquad \text{..................} (1)$$

By assuming that the initial velocity V_1, initial height Z_1 and final height Z_2 are negligible, also the final pressure P_2 equal to the atmospheric pressure, Bernoullis's equation can be rearranged to give the velocity of the jet on the exit from the orifice, equation (1)

Varying the water pressure has a direct effect on the velocity of the waterjet as illustrated by rearranging Bernoulli's equation:

$$V=\sqrt{\frac{2P}{\rho_w}} \qquad \text{..................} (2)$$

where : V, is the velocity of waterjet
P, is the water pressure
ρ_w , is the density of water

The higher the velocity of the jet the greater the kinetic energy of each particle.

When a fluid flows past a solid boundary, turbulence occurs within a boundary layer. A similar effect is apparent happens when two fluid streams flow past each other whereby turbulent mixing between the two streams occurs so as to equalize their respective velocities. This effect is conceder to know as free turbulence.

3.1 Velocity of a Submerged Waterjet

These effects of free turbulence are observed when a fluid jet encounters a stationary fluid, a similar situation to using a high velocity waterjet underwater. As the jet enters the fluid it sets some of it in motion the adjacent fluid. This effect continues so that more and more surrounding water is accelerated [26]. Figure (4) illustrates this effect by simplifying it to a two dimensional problem. This process is known as entrainment.

As the jet accelerates more fluid, the mass of moving fluid increases. Due to the conservation of momentum, the velocity decreases in axial direction. Since momentum is conserved $V_m^2 R^2$ is constant, where V_m is the maximum velocity of the jet (on the axis) and R is the radius to the edge of the jet, beyond which velocity is zero. By knowing the original jet velocity (V_1) and its radius (R_1), it is possible to work out the jet velocity at any distance from the orifice using the following relationship:

$$V_{m1}^2 R_1^2 = V_{m2}^2 R_2^2 \qquad \text{..................}(3)$$

Where R_2 is the radius of the jet at any axial distance (x) from the orifice, and is giving by:

$$R_2 = \left(x \ \tan\frac{\theta}{2}\right) + R_1 \qquad \text{..................}(4)$$

Where θ, is the angle of divergence and its value is (20°-25°) [21].

3.2 Velocity of a Jet in Air

For a jet in air the assumption is made that no significant mass is entrained into the jet, is made. This is because the density of air, in this case the surrounding fluid, is negligible compared to the density of water. Therefore the velocity of the jet remains constant along its length, ie

$$V_{m1} = V_{m2} = V. \qquad \text{............}(5)$$

Hence the velocity of the jet at the workpiece can be calculated using equation (2).

4. RESULTS AND DISCUSSION

4.1 Cutting of PVC with Pure Waterjet

The output of a waterjet cutting operation can influence by a large number of factors. Parameters that were considered most relevant for experimental design are mentioned below. The number of initial experiments during which feasible parameter ranges were identified.

For this test the pure waterjet nozzle was used. The testes was carried out at different pressure [P] ranging from 200 to 500 MPa and standoff distance [SOD] starting from 5 mm up to 60 mm. The nozzle traverse speed [S] varying from 100 to 500 mm/min. The nozzle inclination angles [α] are –30, -60, 30 and 60 degree (referred to vertical nozzle axis). All the testes were carried out in air and underwater.

4.1.1 Effect of water pressure

The water pressure has a great influence on the depth of cut. Figure (5) shows that the depth of cut increases by increasing the water pressure at the same standoff distance and traverse speed. In general, the depth of cut increases with water pressure, as more energy will be able to remove more material. This is due to the fact that higher water pressure tends to open a wider kerf and higher amount of depth of cut. It was observed to be possible to cut with pure waterjet while submerged under water producing a small amount of depth of cut compared with cutting in air, at the same cutting conditions.

4.1.2 Effect of nozzle traverse speed

The cutting performance represented by the depth of cut is strongly influenced by the nozzle traverse speed setting; higher traverse speeds result in lower depth of cut in case of cutting in air and submerged under water. This is attributed to a number of factors. Firstly, the piercing duration time was used as the main criterion for evaluating the piercing ability of the waterjet process under various conditions. Thus, an increase in jet traverse speed (or the jet exposure time decreases) will reduce the depth of cut. Secondly, as the traverse speed increases, the number of particles impinging on a given exposed target area decreases, which in turn reduces the material removal rate. Figure (6) shows the relationship between the traverse speed and depth of cut.

4.1.3 Effect of nozzle inclination angle

The nozzle inclination angle is directly related to the equivalent cutting depth of cut. However, for inclination angles up to 60° (in both nozzle axis direction) these thickness variation, due to the change in cutting angle, cause only limited effect on the cutting depth of cut. Figure (7) shows the effect of nozzle inclination angle on the amount of depth of cut. It is clearly observed from the experimental results that there is no significant effect for the nozzle inclination angle on the depth of cut in both dry and submerged cutting.

4.1.4 Effect of standoff distance

Figure (8) shows the effect of standoff distance on the cutting characteristics. The experimental data show that the standoff distance has a more significant effect on the cutting characteristics than the traverse speed for the tested ranges. It is clearly observed from the experimental results that by increasing the standoff distance the depth of cut will decreases. The same trained was observed in case of cutting in air or cutting under water.

The graphical results shown in Figure (9) taken from the tests comparing, cutting 6 mm PVC, with a pure waterjet, in air to cutting when the nozzle and workpiece were both submerged in water. It is observed that as the stand-off distance between the end of the nozzle and the surface of the workpiece increases, the cutting performance of the waterjet decays both in air and in water. However the results show that the performance drops off in water is steeper than air. This resulted in a difference in cutting ability, with the submerged jet failing to cut right through the plastic at the intensifiers, maximum water pressure of 446 MPa, when the SOD was at 50 mm. At this SOD in air, the water jet only required a water pressure of 258 MPa, which was well within the intensifier range.

4.2 Cutting of 50D Steel with AWJ

The material being cut this time was 50D steel, therefore abrasive waterjet AWJ had to be used, which meant the abrasive nozzle had to be used. This added another cutting variable which was abrasive flow rate. The testes was carried out at different pressure ranging from 200 to 500 MPa as PVC cutting with pure waterjet but standoff distance starting from 1.5 mm up to 50 mm, this because the material being cut was a lot tougher, requiring a smaller standoff distance in general compared to the PVC. The nozzle traverses speed varying from 100 to 500 mm/min. The nozzle inclination angles [α] are -30, -60, 30 and 60 degree. All the testes were carried out in air and underwater.

4.2.1 Effect of abrasive flow rate

During abrasive mixing, the kinetic energy of a high-speed waterjet is partially absorbed in accelerating the abrasive particles. Simple analysis suggests that as the flow rate increases the frequency of particle impact will increase. Given as Figure (10) are the graphed results from the abrasive monitoring test. From the graph it is observed that at low flow rates, depth of cut increases in a linear fashion as the abrasive flow rate is increased. However at higher flow rates the rate of increase begins to diminish until between 4.4 g/s and 7.4 g/s within this range an optimum abrasive flow rate occurs. It was therefore between these two limits at which the abrasive flow rate was set for the underwater testing section of experimentation. After this optimum, the performance of the AWJ begins to decay with the depth of cut getting shallower the flow rate was increased further. The same trend was observed for the dry and submerged cutting

Generally starting off at an abrasive flow rate of zero means that there will be no particle impacts on the workpiece. As the flow rate of abrasive is increased, particle impacts on the workpiece begin. When increased further the particle impact frequency increases, however with a greater mass of abrasive in the flow, the law of conservation of momentum predicts that the velocity of the flow will decrease. Therefore although impact frequency increases each individual particle has less kinetic energy. This drop in kinetic energy happens more rapidly than the increase in frequency of particle impacts, which results in a decreased rate of material removal and therefore a smaller depth of cut. In addition, at higher abrasive flow rates; particle interference occurs which reduces the number of effective impacts.

4.2.2 Effects of water pressure

As mentioned before in case of PVC cutting with pure waterjet, the depth of cut is affected by increasing the water pressure, by means of the higher the water pressure, the larger depth of cut as shown in Figure (11). These experimental results were explained previously in section 4.1.1. It was observed to be possible to cut with abrasive waterjet using optimum abrasive flow rate (6 g/s) while submerged under water producing a small amount of depth of cut compared with cutting in air.

4.2.3 Effect of nozzle traverse speed

Figure (12) shows the effect of nozzle traverse speed on the cutting characteristics. The experimental results show that by increasing the traverse speed the depth of cut will decreases in both cases of cutting, in air and submerged under water. These experimental results were explained previously in section 4.1.2.

4.2.4 Effect of nozzle inclination angle

It could be concluded from the conducted experiments that inclination angles have no significant effect on the depth of cut under all test conditions. Figure (13) shows the relationship between the inclination angle and its corresponding depth of cut. The results are plotted in case of dry and submerged cutting.

4.2.5 Effect of standoff distance

The standoff distance has a great influenced on the depth of cut as shown in Figure (14). Based on the experimental results, it was found that by increasing the amount of standoff distance the cutting depth decreases. This can be attributed to reduce cutting ability (judged by the depth of cut) of the jet at greater standoff distance.

The tests comparing the performance of cutting 50D steel sheet of 10 mm thickness with AWJ are presented in Figure (15), when the nozzle and workpiece are submerged, as opposed to when cutting is done in air. These results portray a similar trend to the results shown on submerged PVC cutting tests whereby there is a greater drop off in performance as the stand-off distance increases. However the difference between cutting while submerged and cutting in air is not as pronounced when compared to the PVC test. This is born out by the fact that under water the AWJ failed, at maximum water pressure, to cut right through the workpiece at SOD of 30mm whereas whilst cutting in air the AWJ failed, at maximum pressure, to cut through at SOD of 50mm. This is a far smaller difference than that during the PVC cutting, whereby the jet could still cut easily through the plastic in air until well after 100mm with it failing under water at 50mm.

5. ORIFICE DESIGN

One of the most important components in the waterjet system is the sapphire orifice situated within the waterjet nozzle. It is the high-pressure water being forced through the small diameter orifice that is responsible for the high velocities that are required in waterjet cutting. In an attempt to improve cutting performance in both air and while submerged, Computational Fluid dynamics CFD software package was used to analyse the effect of changing the geometry of the sapphire orifice, on the velocity profile of the jet. The flow through two different orifice geometry's was modeled so that a comparison could be carried out to determine whether or not the flow would be improved by redesigning the orifice so that it converges rather than diverging. For both geometry's the inlet boundary layer was set at 400 MPa and the outlet at 150 MPa to simulate the waterjet nozzle being 150 mm deep in water. Figure (16) provides a comparison of the velocity profiles obtained for the converging & diverging nozzles respectively.

From the two contours as shown in Figure (16) the converging nozzle is shown to be no better in terms of velocity profile. If any geometry offers a better velocity profile it seems to be the existing diverging nozzle geometry. Hence form the output results it seems that changed in orifices geometry have no significant effect on the upstream flow.

CONCLUSIONS

From the analytical study and experimental work, the AWJ process can easily cut 50D steel, which is one of the most common structural steels used in the offshore industry.

The relationship between abrasive mass flow rate and depth of cut was initially linear, however a higher abrasive flow rates an optimum flow rate was reached. This was between 4.4 g/s & 7.4 g/s. By increasing the flow rate further a decrease in depth of cut was observed.

Increasing waterjet pressure increase performance of cutting, while increasing the nozzle traverse speed decreases the jet cutting.

Any position of the nozzle direction, from the slope angle – 60^{o} to + 60^{o}, can be used as a cutting location. However, it is preferred to select a location with a surface normal vector.

It was observed to be possible to cut using both WJ & AWJ while submerged, however decay in performance was evident as standoff distance was increased.

Computational fluid dynamics CFD analysis suggests that a change in geometry of the orifice would have no significant effect on the velocity profile of the jet or on jet divergence.

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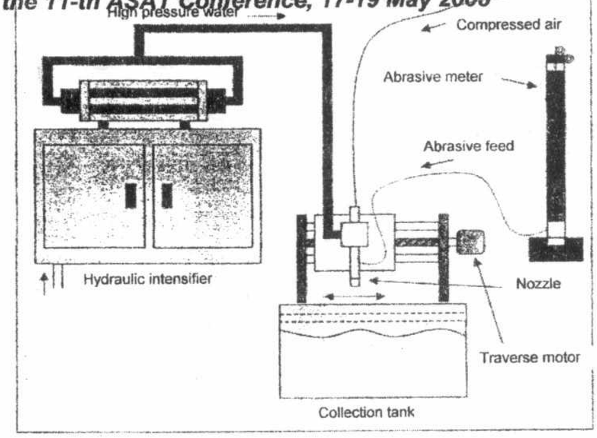


Figure (1) Schematic diagram for the waterjet system

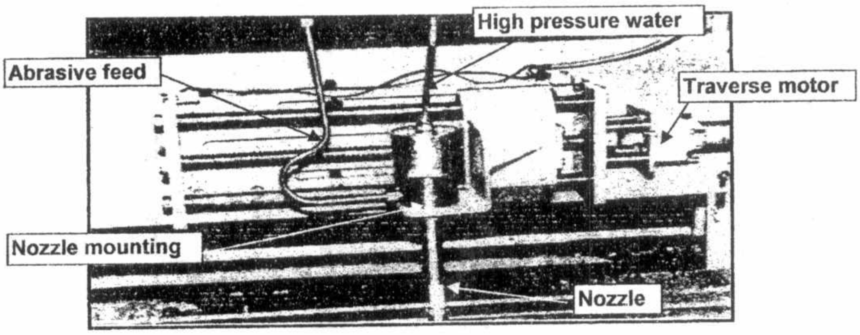


Figure (2) Waterjet nozzle and its mounting

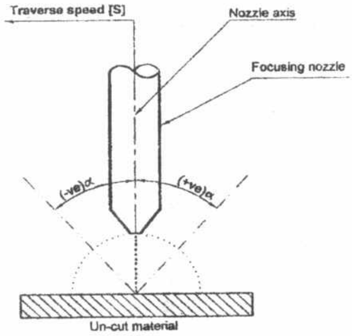


Figure (3): Waterjet nozzle inclination angle [α]

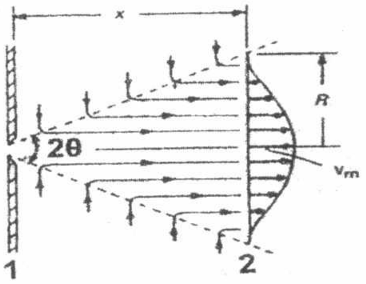


Figure (4): Representive diagram for the velocity of a submerged waterjet

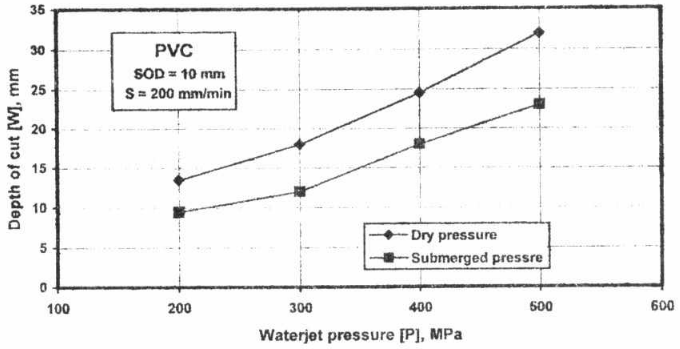


Figure (5): Effect of water pressure on depth of cut, (PVC)

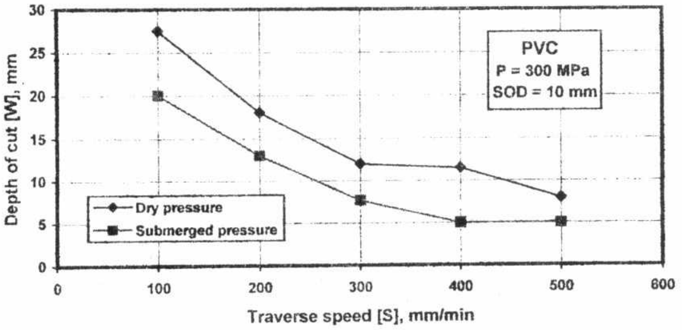


Figure (6): Effect of nozzle traverse on depth of cut, (PVC)

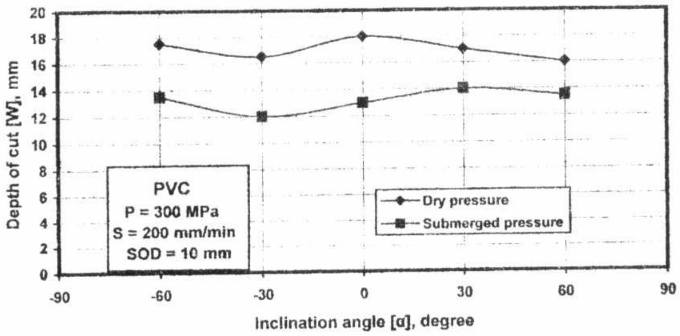


Figure (7): Effect of inclination angle [α] on depth of cut, (PVC)

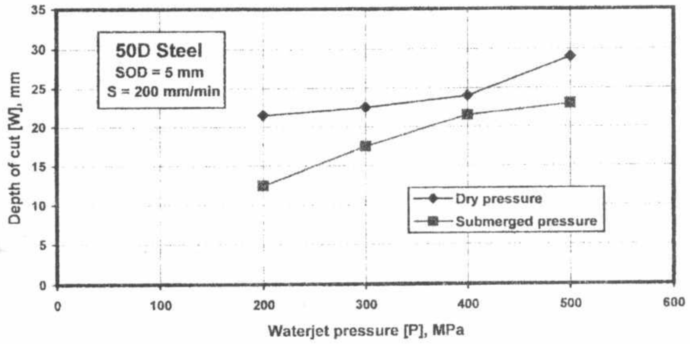


Figure (11): Effect of water pressure on depth of cut, (50D steel)

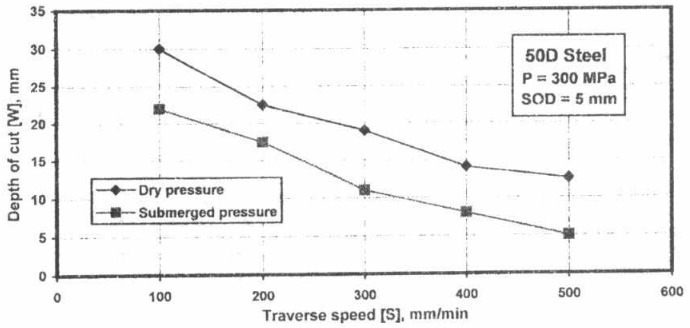


Figure (12): Effect of nozzle traverse speed on depth of cut, (50D steel)

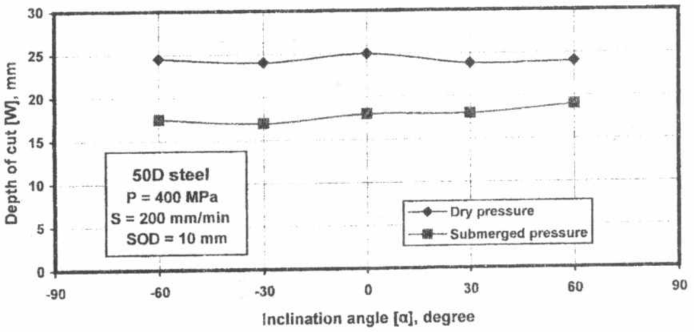


Figure (13): Effect of inclination angle [α] on depth of cut, (50D steel)

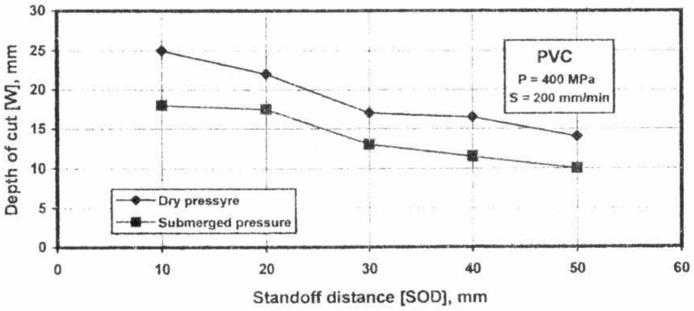


Figure (8): Effect of standoff distance on depth of cut, (PVC)

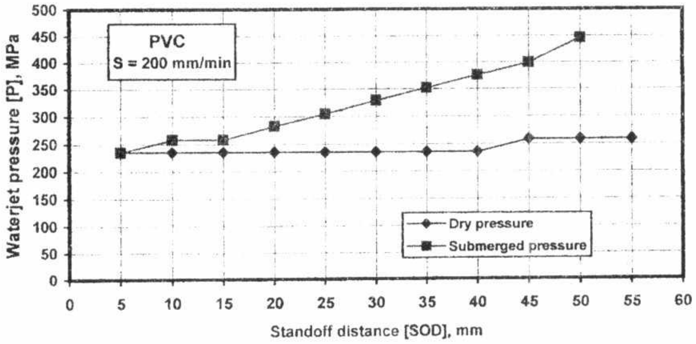


Figure (9): Comparison of WJ cutting performance in air and underwater, (PVC)

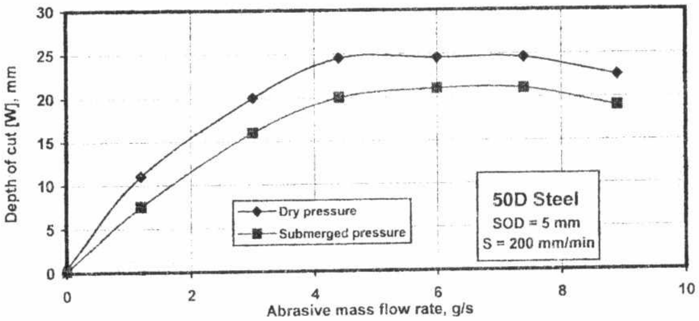


Figure (10): Effect of abrasive flow rate on depth of cut, (50D steel)

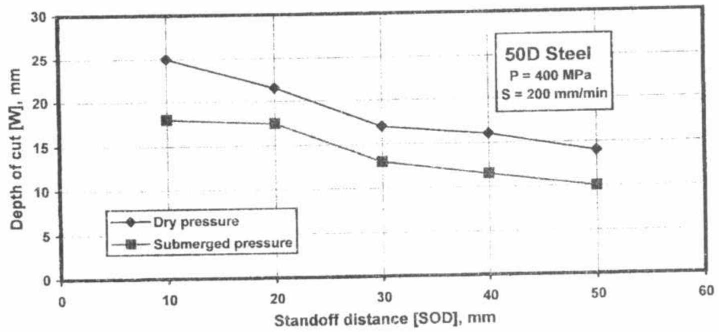


Figure (14): Effect of standoff distance on depth of cut, (50D steel)

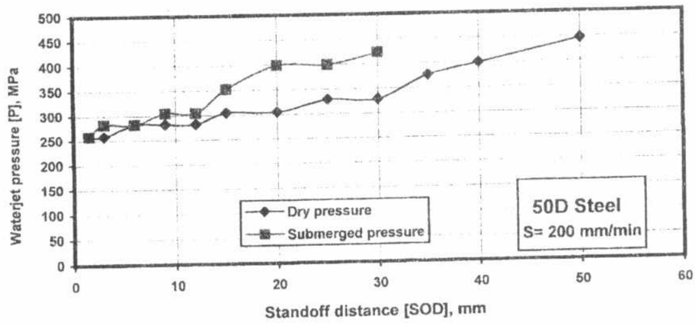
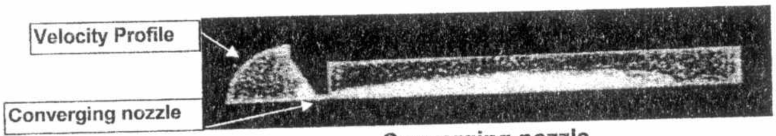
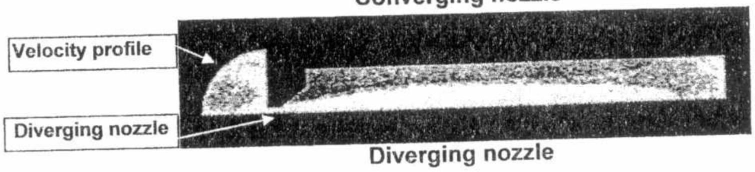


Figure (15): Comparison of AWJ cutting performance in air and under water, (50D steel)



Converging nozzle



Diverging nozzle

Figure (16) Velocity profiles for converging and diverging nozzles using the CFD