World Academy of Science, Engineering and Technology
International Journal of Industrial and Manufacturing Engineering
Vol:5, No:11, 2011

Experimentation on Piercing with Abrasive Waterjet

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Open Science Index, Industrial and Manufacturing Engineering Vol:5, No:11, 2011 publications.waset.org/3327.pdf

***Abstract*—**Abrasive waterjet cutting (AWJ) is a highly efficient method for cutting almost any type of material. When holes shall be cut the waterjet first needs to pierce the material.This paper presents a vast experimental analysis of piercing parameters effect on piercing time. Results from experimentation on feed rates, work piece thicknesses, abrasive flow rates, standoff distances and water pressure are also presented as well as studies on three methods for dynamic piercing. It is shown that a large amount of time and resources can be saved by choosing the piercing parameters in a correct way. The large number of experiments puts demands on the experimental setup. An automated experimental setup including piercing detection is presented to enable large series of experiments to be carried out efficiently.

***Keywords*—**Waterjet cutting, Piercing, Experimentation

I. INTRODUCTION

WATER jet cutting is a relatively new tool for cutting virtually any type of material.Where abrasive waterjet cutting is the most common for hard to cut materials.To comprehend waterjet cutting and to utilize the full potential a lot of research has been carried out on process modeling and optimisation. Some process models are based on physical relationships and empirical studies [1] and [2] while some are based only on empirical studies [3].

Most of the research has however been focused on contour cutting where maximum depth of cut and maximum feed rate for a certain depth are two objectives. The piercing of the work piece for hole-cutting has not been studied to such extent. The studies that can be found in literature are mainly focused on problem areas such as piercing of very delicate materials [4] which is a challenge in itself. Almost all process models rely, more or less, on empirical data from experiments. It is therefore important to make experimentation on waterjet cutting as efficient as possible.

A great amount of time and resources can be saved if piercing parameters are chosen correctly, since in most cases when a contour shall be cut a starting hole needs to be cut. This implies that the piercing process can be enhanced in terms of efficiency, time and money can be saved for most parts. This paper focuses on mapping the effect of some piercing parameters on piercing time. Studies like this have been done before [5] and [6] but to get a general understanding of the piercing process many more experiments needs to be done. This paper aims to build up on the understanding and give a more complete overview of the effect of the most important piercing parameters.

Measuring the piercing time is a challenge in itself. In the literature methods can be found using high speed cameras to measure the piercing time [6]. This approach puts demands on the waterjet cutting machine that are not very practical for the everyday use. Sensors picking up on vibrations, caused by the waterjet, have been used when studying waterjet cutting [7] In this study similar sensors are used together with some signal processing to measure the piercing time.

Abrasive waterjet cutting is based on the principle of using the energy in high pressure water to accelerate a waterjet which, in turn, accelerates abrasive particles that are used to cut work piece. Once the work piece is cut through the waterjet is caught by some sort of catcher, for instance a tank with typically some decimeters of water. A schematic picture of a waterjet nozzle can be seen in fig 1. Important parts of a waterjet cutting machine are: high pressure pump, piping, orifice, abrasive mixing chamber and a focusing tube. The nozzle is attached to some sort of positing device, e.g. a portal which positions the nozzle to desired positions usually programmed in some numerical controller.

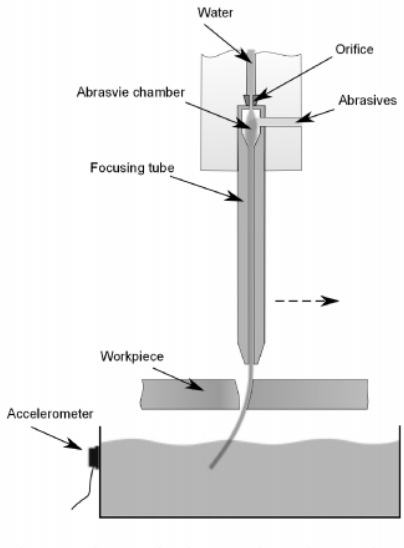

Fig. 1Waterjet nozzle, work piece and catcher tank with sensor

Important parameters in abrasive waterjet cutting include: water pressure, orifice diameter, focusing tube diameter and length, abrasive material, abrasive flow rate, abrasive particle size, traverse speed and angle of cut. The effects of some of these parameters on piercing time are studied in this paper. The main objective is to find parameters giving the lowest possible piercing time.

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II. EXPERIMENTAL SETUP

A. *Measuring piercing times*

An accelerometer mounted on the outside of the catcher tank picking up on vibrations from the tank. When the work piece has been pierced and the waterjet is entering the water in the catcher tank, there is a big change in the signal amplitude. The signal is normalized against its maximum value, and the piercing time is found by detecting a rising edge with a threshold of 0.05. An example of a studied signal and a signal showing the water valve status can be seen in fig. 2 with a piercing time of approximately 13 seconds.

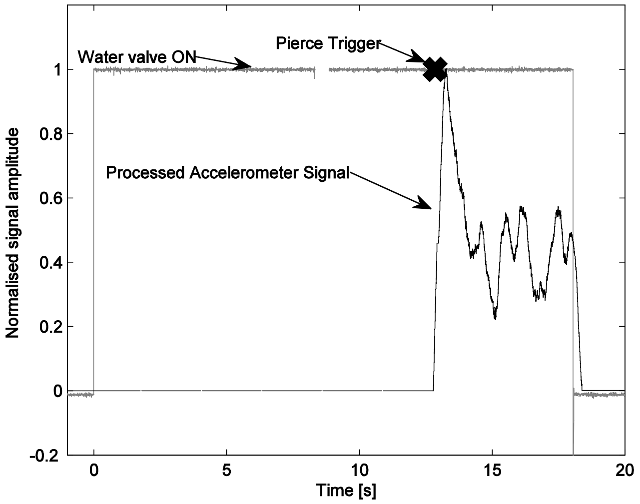

Fig. 2 Example of processed signals

Several factors give uncertainties in the measured values. The waterjet cutting process is not entirely deterministic due to inherent instabilities in the process; the water pressure is varying due to the nature of the intensifier pump as explained in [8], the abrasive feed is normally fluctuating and can also vary over time dependent on moisture in the air, pneumatic pressure in the sand feeder can also vary giving different amount of abrasives. Variations can also be due to the stochastic behavior in the interaction between work piece and jet where erosive material removal is taking place. These variations are extremely hard to foresee and account for when doing experimentation on waterjet cutting, therefore several repetitions of each measurement have to be carried out and used for averaging.

B. *Automated measurements*

Efficient experimentation is a key factor when performing experiments where each measurement is time consuming and many averages needs to be done due to non-deterministic behaviors

A parameterized algorithm for automatic NC-code generation was written in MATLAB. The algorithm produces the NC-code bases on input on variables seen in Table I. All values are saved in a structure with a unique indexing number for easy tracking of the results. The variables for several tests can be saved at once and executed automatically one after the other without human interference enabling an efficient testing procedure.

TABLE I
VARIABLES FOR EXPERIMENT ON LINEAR PIERCING

Variable	Values
Piercing method	[Stationary, Linear, Repeated Linear, Circular]
Feed rate	[0-10000] mm/min, used for dynamic piercing.
Path Length	[0-3500] mm, (used for linear and repeated linear piercing)
Start position	X and Y values for starting position
Dwell time	Pause between Water ON and Water OFF, used for stationary piercing.
Abrasive flow rate	[200-600] g/min
Water pressure	[200-420] MPa
Repetitions	Used for repeated linear piercing and circular piercing
Standoff distance	[0-100] mm

The produced NC-code is executed automatically when the code has been created. At the same time the sampling of accelerometer and water-on signal from the machine begins. When a given number of samples have been collected the signal processing is started and a piercing time is calculated. The calculated time and the saved signals are saved in the same structure as the variables. When the data have been saved the next test in line is executed following the same procedure. When all tests have been carried out the data can be extracted for creation of figures and tables for presentation of results.

C. *Process parameters*

Process parameters used in the experiments are shown in Table II.

TABLE II
PROCESS PARAMETERS

Process parameter	Setting
Pump pressure	400 MPa, except for specific pressure experiment where pressure is a variable
Abrasive flow rate:	350 g/min, except for specific abrasive experiment where flow rate is a variable
Abrasive type:	Garnet, mesh 80
Standoff distance	3 mm, except for specific standoff distance experiment where standoff distance is a variable
Focusing tube	0.76 mm diameter
Orifice	0.25 mm diameter
Material	Stainless steel, 10-70 mm thick.

III. STATIONARY PIERCING

There are several methods for piercing. The simplest one is stationary piercing where the nozzle is simply kept stationary during the piercing process. This is the slowest piercing method and its only advantage is that the piercing hole is small. There are two reasons for this piercing method to be slow. These reasons are well described in [5]. The first and most obvious reason is that if the nozzle is stationary the incoming jet is disturbed by the secondary reflected jet, its cutting capability is therefore decreased. If instead the nozzle is moving, the secondary jet is reflected away from the incoming jet. The second reason is that the erosion process is more efficient when the jet is hitting the work piece with an angle instead of perpendicularly as reported in [5]. This much desired angle is created when the nozzle is moving in relation to the work piece and a cutting lag is present. Piercing times of stationary piercing depends strongly on the thickness of the work piece, for very thick work pieces it becomes virtually impossible to pierce with stationary piercing since most of the energy of the incoming jet is lost before any further cutting action can happen.

IV. LINEAR PIERCING

Dynamic piercing is when the nozzle is moving during the piercing process. Dynamic piercing has proven to be much more efficient than stationary piercing due to avoiding the two major reasons why stationary piercing is slow. A drawback with moving the nozzle while piercing is that the jet is not hitting the work piece in one position but in several along a chosen path requiring larger space for the piercing.

One dynamic piercing method is linear piercing (sometimes called direct piercing). It is a piercing method where the nozzle is moved in a straight line along the work piece with a given velocity during the piercing process. Linear piercing is generally faster than stationary piercing.

The objective for the first experiment was to map the effect of feed rates and work piece thicknesses for linear piercing. The experiment covers seven thicknesses and in total 15 feed rates. The variables for the experiments can be seen in Table III. Some of the thicknesses were created by stacking *two* or more sheets on top of each other, this might give a slight deviation compared to using homogeneous work pieces but is believed to have less effect then other uncertainties in the study.

TABLE III
VARIABLES FOR EXPERIMENT ON LINEAR PIERCING

Work piece thickness	Feed rates
10 mm	[0 1 2 4 6 10 20 30 40 50 70 100 140 180 200] mm/min
20 mm	[0 1 2 4 6 10 20 30 40 50 70 90 110 130] mm/min
30 mm	[0 1 2 4 6 10 20 30 40 50 70 80] mm/min
40 mm	[0 1 2 4 6 10 20 30 40 50 60] mm/min
50 mm	[1 2 4 6 10 20 30 40] mm/min
60 mm	[1 2 4 6 10 20 30 40] mm/min
70 mm	[1 2 4 6 10 20 25] mm/min

The maximum feed rate for each thickness is chosen based on estimated maximum feed rate, i.e. if the feed rates are exceeding these values the work piece will not be pierced at all. Each experiment was repeated *five* times to get a representative average, which in total gives 375 measurements. The results from the experiments can be seen in fig 3.

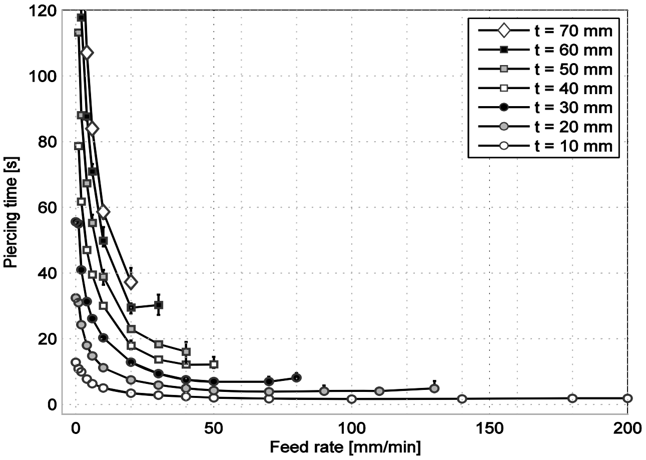

Fig. 3 Linear piercing with different feed rates and thicknesses

The seven work piece thicknesses are each represented by individual lines in fig. 2. The penetration rate is higher for smaller thicknesses. As the depth of penetration increases the jet looses energy and the penetration rate decreases which exponentially increasing piercing times. The error bars represents the largest and the smallest value for each measurement point, this indicates how much the values are spread around the given average.It is shown that higher feed rates are giving higher penetration rates, for thinner materials too high feed rates can give a slight increase in piercing time but this is close to negligible. For the thinner thicknesses up to 40 mm the piercing time levels out at a minimum level at approximately 50 mm/min. For the thicker thicknesses this leveling never occurs until the maximum feed rate is reached, this indicates that it is of even greater importance for thicker materials for a correct choice of feed rate since there is no wide window of feasible feed rates. A higher penetration rate can be seen for higher feed rates, up to a limit where an unnecessary amount of material is being removed or that the maximum feed rate for the present thickness is reached. Very low feed rates gives the same issues as for stationary piercing, namely that the reflected jet is disturbing the incoming jet and the jet is hitting the work piece almost perpendicular which is highly undesirable. For 10-40 mm thick work pieces stationary piercing was done as a comparison, for stationary piercing the piercing times are increasing even more rapidly with an increase in thickness. The following experiments were carried out with a work piece thickness of 30 mm. The feed rate was chosen to 60 mm/min which is considered as close to an optimal value for this thickness. Table IV shows the variables for the following *three* experiments. In total 20 experiments was carried out which in total becomes 100 measurements with 5 repetitions.

TABLE IV
VARIABLES FOR EXPERIMENTS ON LINEAR PIERCING

Variable	Values
Pressure	[250 300 350 380 400 420] MPa
Standoff distance:	[1.5 2 3 4 5 6 7 8 9] mm
Abrasive flow rate	[250 350 450 550 650] g/min

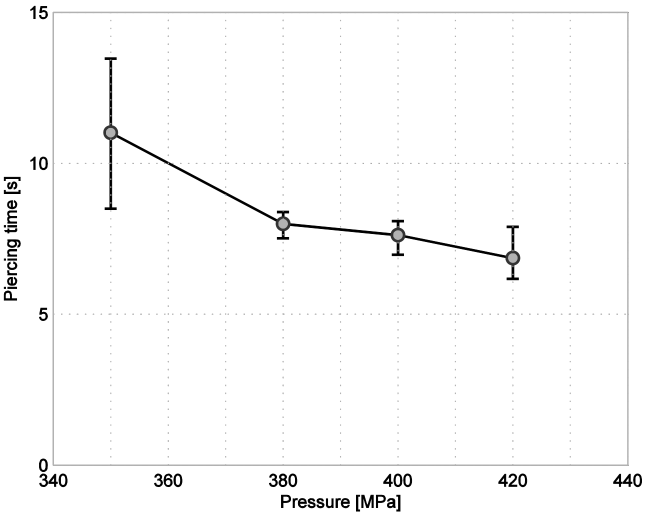

Fig. 4 Effect of water pressure on piercing time

The results from the experiment with varied pressure can be seen in fig. 4. It is evident that increasing the pressure decreases the time it takes to pierce the work piece. Here again the error bars can be seen as an indication of how deterministic the behavior is for certain variables. The variation in piercing time is rather large for low pressures. The reason for this is that 350 MPa is just enough to penetrate the material for the present cutting parameters and a relatively small variation in the process will give large variation in the piercing time. Since pressures of 250 MPa and 300 MPa were not enough to pierce the work piece, these pressures are therefore not presented in the figure. Next the effect of standoff distance on piercing time was studied. Standoff distance is the distance between the focusing tube and the work piece. The results are shown in fig. 5.

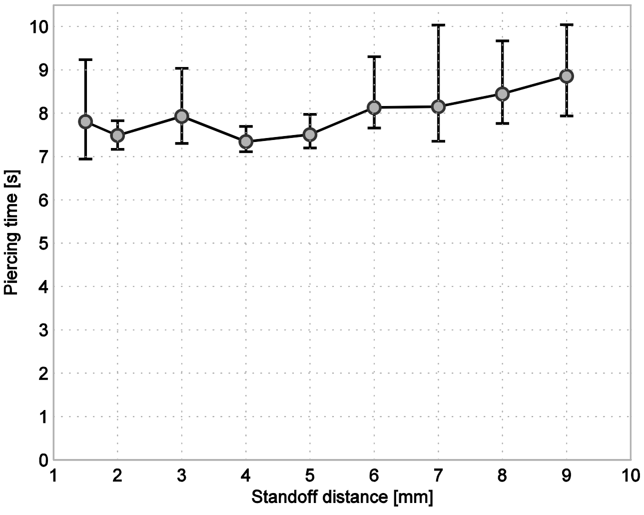

Fig. 5 Piercing time as a function of standoff distance

There is a slight increase in piercing time with increased standoff distance, a minimum value of piercing time can be found at approximately *five* times the nozzle diameter, which is larger than the recommended standoff distance for contour cutting. It is also standoff distances around this value that have the smallest variation among the repeated measurements. It shall however be noted that the deviation from the average values are larger than the variation between different standoff distances, i.e. standoff distance is not a very important variable when it comes finding an optimal piercing time, at least not in comparison with the other studied variables. One advantage of choosing a larger standoff distance is the reduced risk for clogging the nozzle which can cause the jet to stop. It is therefore a better choice to increase the standoff distance to some degree while piercing the work piece and, lower it to optimal settings for cutting the contour.

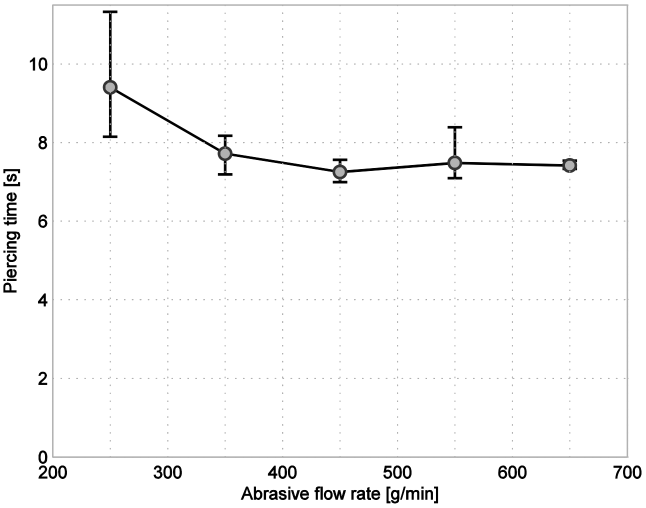

Fig. 6 Piercing time as a function of abrasive flow rate

Fig. 6 shows the effect of abrasive flow rate on piercing time. It is obvious that a too low flow rate will give an increase in piercing time as well as in variation between measurements. For the given conditions 250 g/min is a too low abrasive flow rate and it will barely pierce the material. It can be seen that an optimal flow rate exists at around 450 g/min for the given cutting conditions. An increase of flow rate from this rate gives a slight increase in piercing time, this indicates that there is similar relationship between optimal piercing time and abrasive flow rate as there is between optimal depth of cut and abrasive flow rate reported in [9]. It is likely that this optimum relates to an optimum ratio between abrasive mass rate and the mass rate of water, i.e. if the water pressure or nozzle diameter is increased or decreased the optimal abrasive flow rate will change in a similar fashion.

A. Shape of pierced hole with linear piercing

For piercing with linear piercing the nozzle is moving in the same manner as for contour cutting and therefore a cutting lag is created in the same way as for contour cutting. The piercing hole has the shape shown in fig 7. A slight angle can be seen in the left part of the hole where the piercing process started. When the nozzle is moving along the path the jet lags and penetrates deeper and deeper until it penetrates the material.

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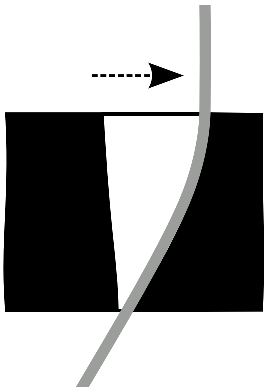

Fig. 7 Shape of pierced hole with linear piercing with waterjet at pierce through

It is important to understand the shape of the piercing hole since contour cutting can only be started where the waterjet has penetrated the work piece, i.e. close to the beginning of the path.

B. Repeated Linear Piercing

There are many cases when linear piercing cannot be used. When small holes shall be cut and slit produced by linear piercing is often too long to fit inside the hole. Therefore a multi pass strategy is used to decrease the size of the piercing hole.

Repeated linear piercing also called wiggle piercing is, when the nozzle is moving in a similar fashion as for linear piercing but instead of only moving in one direction it is repetitively moved back and forth over the same linear path. There are two main variables for repeated linear piercing; length of the path and the feed rate. Multi passing enables the feed rate to be increased in comparison to pure linear piercing. Table V shows the variables used in the experiment, once again with *five* repetitions, given a total of 80 measurements.

TABLE V
VARIABLES FOR EXPERIMENTS ON REPEATED LINEAR PIERCING

Variable	Values
Length	[4 6 8 10] mm
Feed rate	[60 120 240 480] mm/min

Fig. 8 shows the effect of the feed rate on piercing time. It is shown that an increase in feed rate generally increases piercing time particularly for shorter path lengths. For most of the tested path lengths it seems like an optimum feed rate is around 120 mm/min, it is however hard to say for sure since there are too large variations between the repeated measurements.

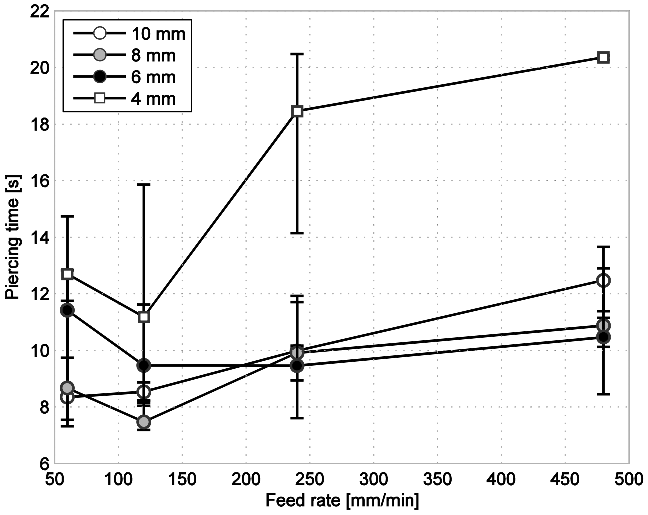

Fig. 8 Piercing time as a function of feed rate for repeated linear piercing

Repeated linear piercing is generally slower than linear piercing because of the continuously changing circumstances for the jet. Every time the jet changes direction it needs to penetrate more material than before the change, due to the look of the pierced hole, see fig. 7.

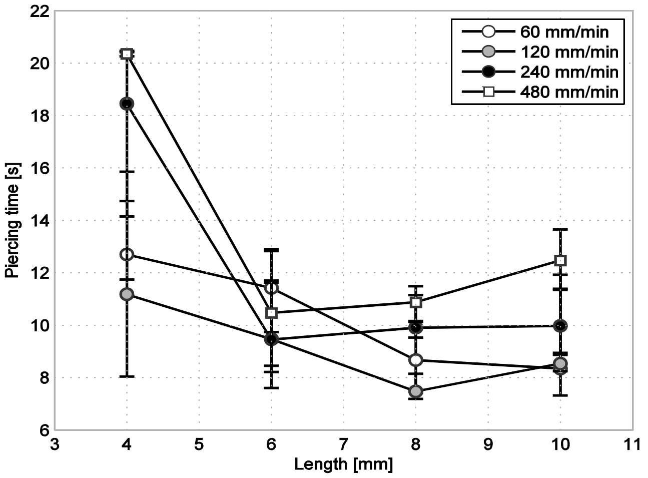

Fig. 9 Piercing time as a function of path length of repeated linear piercing

In Fig. 9 it is shown that a too short path length will give long piercing time, this is for the same reason that stationary piercing is slower than dynamic piercing namely that the incoming jet is disturbed by a secondary reflected jet and the angle between the jet and the work piece is unfavorable. A minimum piercing time can be found at around eight mm. for the present cutting conditions a path longer that this does only increase the amount of material being removed along the path and does not give higher penetration rates.Once again the variation between the repeated values is very noticeable. The large variations are most likely due to multi passing. For every pass a relatively small amount of material is being removed which leads to that small variations in the process gives high relative variations in depth. This can lead to large variations in piercing time. The reason for the variations can be explained by considering two cases. One case where the jet is close to penetration at one pass but really penetrates first at the next pass, at the same position along the path. And one case where the jet is penetrating at the earlier off the two passes. The reason for the first one not to penetrate and the second to penetrate might be due to a very small variation in the process, but it gives a significant difference in measured piercing time.An example of how such a signal is looking can be seen in fig 10 where the jet is first penetrating in one short pulse and then pauses for a while to again penetrate when it passes the same position at the next pass. If the pulse should not be detected the measured piercing time would be almost two seconds longer.

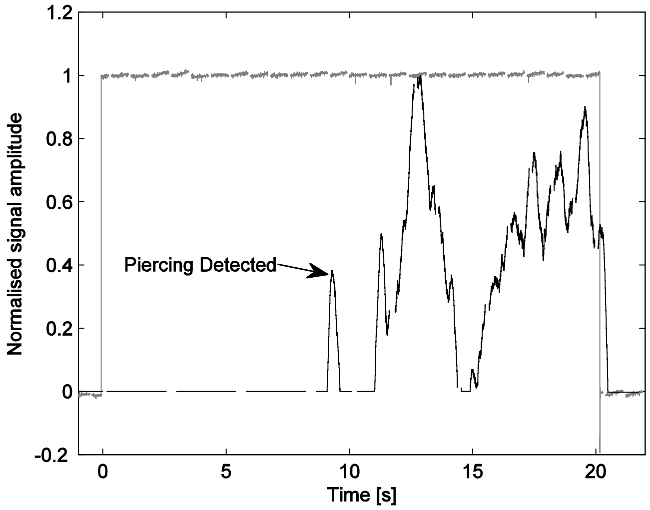

Fig. 10 Example of signal with short pulse of penetration

Due to the large variations described above it is hard to find any optimal settings for this piercing method, since it is impossible to know if the change in piercing time is due to a change in a variable or due to variations in the process.

V.CIRCULAR PIERCING

Circular piercing is another dynamic piercing method that is widely used in industry when relatively small holes need to be cut. Instead of moving the jet in a straight line it is moved in a circular pattern which is becoming multi passing when the circle is completed more than once before the material is pierced. There are two specific main variables effecting the piercing time namely the diameter of the circle and the feed rate. Experiments were carried out aiming at showing the effect of both variables. The values chosen for the variables can be seen in Table VI. The experiment was carried out with five repetitions, giving a total of 160 measurements. In fig. 11 the effect of the diameter can be seen.

TABLE VI
VARIABLES FOR EXPERIMENTS ON REPEATED LINEAR PIERCING

Variable	Values
Diameter	[0.25 0.5 1 1.5 2 2.5 3 3.5] mm
Feed rate	[60 120 240 480] mm/min

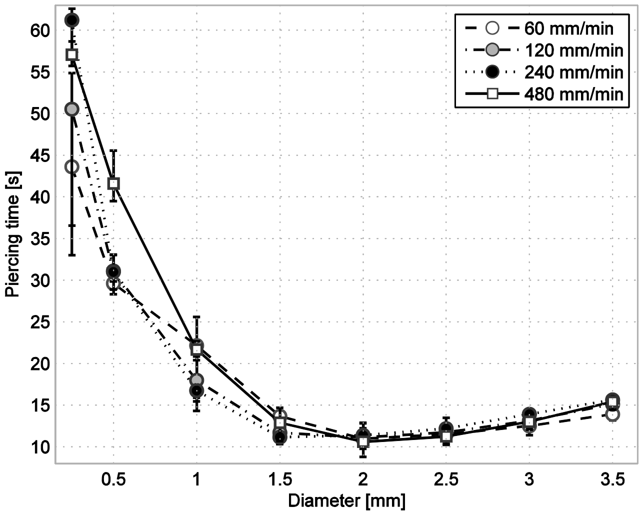

Fig. 11 Piercing times as a function of diameter of circular piercing

Very small diameters shows similar results to very small path lengths for repeated linear piercing and stationary piercing; the secondary jet is not reflected away from the incoming jet and the angle between the jet and the work piece is undesirable. For larger diameters the secondary jet is reflected away from the incoming jet and a more desirable angle is created between the jet and the work piece. For even larger diameters unnecessary material is removed and the piercing time once again increases. For the present cutting parameters an optimal piercing time can be found with a diameter of approximately 2 mm independently of the feed rate used.

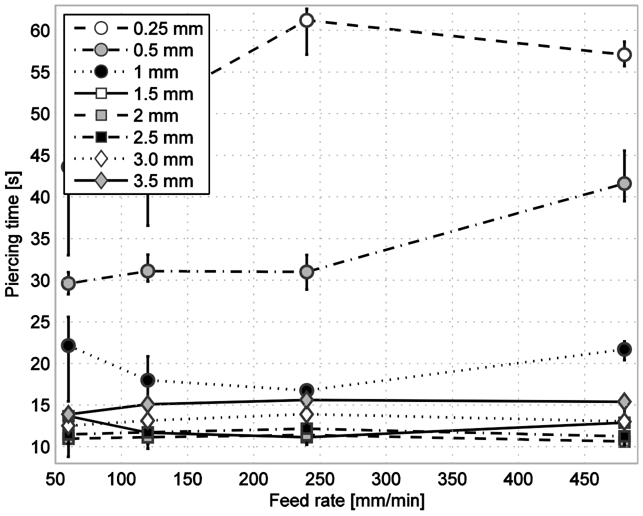

Fig. 12 Piercing time as a function of feed rate of circular piercing

In fig. 12 it can be seen that the feed rate does not affect the piercing time to any large extent, with two small exceptions: for very small diameters where low feed rates decreases the piercing and for high feed rates which generally increases piercing time to a small extent.

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VI. CONCLUSION

Over 700 holes were pierced during the experiments giving a lot of information on the effect of piercing parameters on piercing time. It can be concluded that it is of great importance how piercing variables are chosen if a short piercing time is to be achieved. Dynamic piercing is generally faster than stationary piercing. Stationary piercing is only useful when cutting really small holes.

Linear piercing is the most efficient piercing method of the ones investigated. For linear piercing as high feed rates as possible, for the given work piece thickness shall, be chosen. For thicker work pieces this is a challenge since a too high feed rate will not pierce the material at all but a too low feed rate will increase the piercing times exponentially.

Repeated linear piercing and circular piercing is not as sensitive against changes in piercing parameters but they are however generally slower. They have the advantage of being useful when smaller holes shall be cut.

Experiments on standoff distances show that a slightly larger standoff distance can preferably be chosen for piercing in comparison with cutting, with no risk of increasing the piercing time but with less risk of clogging the nozzle.

This study shows examples where the benefits of using an automated measurement setup are clearly seen due to the big amount of tests done. A lot of time was saved during the experimentation due to the efficiency of the automated experimental setup. Large series of experiments could be run without human interference. A similar measurement set-up can be used for normal cutting and can therefore be used to improve productivity in waterjet cutting in general and not only for piercing.

Future studies should be made focusing on spedific important parameter ranges and also including the effects of economic aspects for different piercing approaches.

ACKNOWLEDGMENT

Financial support from Blekinge research foundation as well as from the Faculty Board of Blekinge Institute of Technology is gratefully acknowledged. We are also indebted to Water Jet Sweden AB, Ronneby, Sweden, KMT Robotic Solutions AB, Ronneby, Sweden as well as Kockums AB, Karlskrona, Sweden for invaluable support.

REFERENCES

[1] M. Hashish, “A model for abrasive-waterjet (AWJ) machining,” *Journal of Engineering Materials and Technology*, No.11, 1989.

[2] S. Paul, A. M. Hoogstrate C. A. van Lutterwelt and H. J. J. Kals, “Analytical and experimental modelling of the abrasive water jet cutting of ductile materials,” *Journal of Material Processing Technology 73*, 1998, pp. 189-199.

[3] J. Zeng and T. J. Kim, “Parameter prediction and cost analysis in abrasive waterjet cutting operations,” in *Proc. 7th American Water jet Conference,* Seattle, 1993, pp. 175-189.

[4] H.-T. Liu and E. Schubert, “Piercing in delicate materials with abrasive-waterjets,” *Int J Adv Manuf Technol*, 2009, 42:263-279.

[5] L. Ohlsson, J. Powell, A. Ivarson and C. Magnusson, Optimisatoin of the piercing or drilling mechanism of abrasive water jets, in *Proc 11th International Conference on Jet Cutting Technology*, St Andrews, 1992, pp. 359-370.

[6] A. Akkurt, “The effect of material type and plate thickness on drilling time of abrasive water jet drilling process,” Materials and Design 30, 2009, pp. 810-815.

[7] H. Louis, D. Peter, C. Scheer and U. Suedmersen, “Controlling the cutting process of abrasive waterjets for remote controlled systems,) in *Proc. 17th International Conference on Water Jetting*, Mainz, 2004, pp. 361-373.

[8] E. J. Chalmers, “Pressure fluctuation and operation efficiency of intensifier pumps,” in Proc. 7th *American Water jet Conference*, Seattle, 1993, pp. 327-336.

[9] G. Holmqvist and U. Honsberg, “CUT – Competitive use of waterjet technology,” Research report, Nordic Innovation Centre (NICe) poject number: 03031, Oslo, 2007.