2011 WJTA-IMCA Conference and Expo

September 19-21, 2011 ● Houston, Texas

Paper

Efficient Operation of Abrasive Waterjet Cutting in Industrial Applications

A. Henning, P. Miles, D. Stang

OMAX Corporation

21409 - 72nd Avenue South

Kent, Washington 98032 USA

axel.henning@omax.com

1 Abstract

Abrasive water jets have recently become a popular tool for mechanical machining. It has great advantages of geometric and material flexibility and its ability to cut hard-to-machine material, the technology is quickly spreading throughout many industries. With this process, near net-shape production becomes feasible, while significantly reducing the time necessary for secondary operations like programming, clamping, or tool changing. This allows a significant optimization of the overall manufacturing process chain.

This paper describes how increasing the hydraulic power of the cutting jet is more efficient than increasing jet pressure to improve cutting performance in industrial applications. Experimental analysis of the abrasive particle velocities show that the particle's kinetic power mainly depends on the hydraulic power of the waterjet. Merely increasing the pressure of the jet did not yield any improvement in its acceleration capability. To obtain the most effective cutting performance a higher level of hydraulic power through larger nozzles should therefore be utilized. Additionally, maintenance costs are directly affected as fatigue life of the high pressure components are reduced when operating at higher jet pressures. Efficiencies of three different pump technologies, direct drive, hydraulic intensifier, and servo drive, are compared to evaluate input electrical power and water consumption. By analyzing the combined effects of cutting performance, fatigue life, and pump efficiencies, operating with higher flow rates is economically more beneficial than operating with higher jet pressures.

2 Introduction

Cutting of metals and other hard materials with abrasive waterjets has become a widely used technology to perform separation tasks for a multitude of applications. Its highly focused power allows for efficient cutting of most kinds of materials. Due to its small thermal and mechanical impact on the material, which avoids stress and alteration of the material properties, abrasive waterjets are also well suited for high precision and miniature cutting of delicate parts [18]. With such a variety of possible applications using the same flexible tool, the user still has to choose the right combination of parameters that optimally suits his application and to provide the best possible and most profitable outcome [1, 2, 11].

There are basically two different approaches that can be used to maximize the kinetic power of the cutting jet to achieve maximum cutting performance: increasing the water pressure at the nozzle, or increasing the water flow rates at the nozzle. The main thrust of this paper is to evaluate these approaches and their effects on the overall hydraulic power that is being applied to the cutting process. The goal of this paper is to help guide the operator to optimize his production and to utilize the optimal possible performance of the abrasive waterjet.

3 Waterjet Cutting Power

The process of abrasive waterjet cutting utilizes water and abrasive particles to efficiently cut almost every material even at very high thickness. Some basic physical principals govern the power of the jet and therefore the performance of the cutting operation. High-pressure water passes through an orifice, forming a high-velocity water jet that is used to accelerate entrained abrasive particles. The velocity of the water is solely determined by the pressure of the water upstream of the orifice. The size of the orifice determines the water flow rate, and therefore the number of water droplets that are formed from the water jet breakup. The hydraulic power of this jet, in the form of high-velocity water droplets, is used to accelerate the abrasive particles in the nozzle's mixing tube [10]. The hydraulic power P_{hyd} of the jet can be calculated from the formula

$$P_{hyd} = p \cdot \dot{V}_W = \frac{p \cdot \dot{m}_W}{\rho_W} \tag{1}$$

The kinetic power $P_{P,kin}$ of the abrasive particles is expressed by the formula

$$P_{P,kin} = \tfrac{1}{2} \dot{m}_P \cdot v_P^2 \tag{2}$$

where v_P is the velocity of the particles and $\dot{m}_P$ is the mass flow rate (feed rate) of abrasives particles.

3.1 Abrasive Particle Velocity Measurements

Figure 1 shows measured particle velocity measurements using the Dual Disk Anemometer (DDA) method [5, 15] for different water pressures and abrasive flow rates. As expected, increasing the waterjet pressure resulted in an increase in abrasive particles due to the higher water droplet velocities. The declining trend in the abrasive particle velocities as the abrasive mass flow rates increases shows that the acceleration efficiency decreases as the abrasive mass flow rates increase.

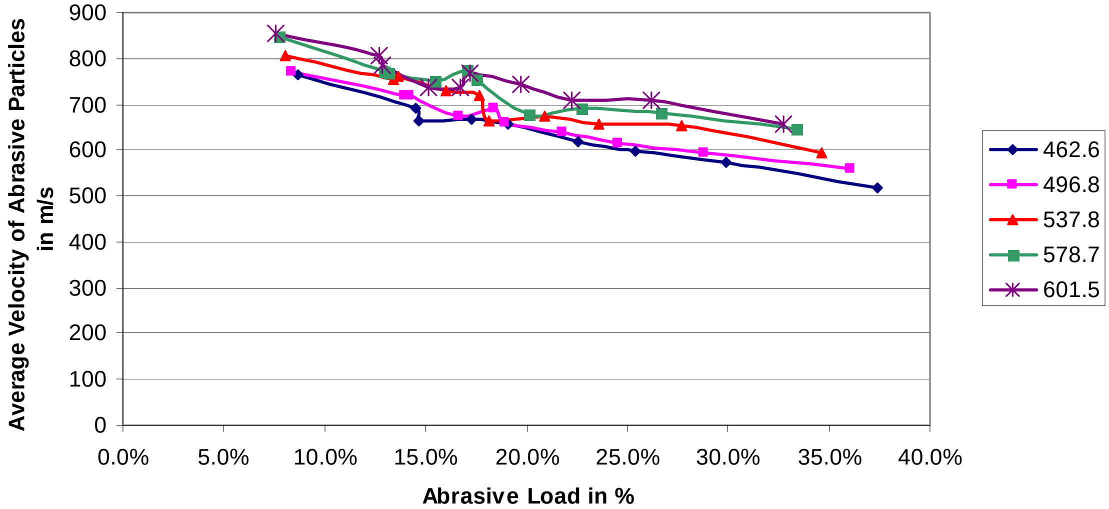


Figure 1. **Particle Velocity at different water pressures over Abrasive Load (d_O=250µm, d_F=760µm)**

Experiments have shown that the velocity of the abrasive particles is a function of the abrasive and waterjet flow rates, the velocity of the driving waterjet, nozzle geometry, and frictional losses. The following relationship can be used to estimate the abrasive particle velocities:

$$v_P = \frac{c_1}{c_1 + R} v_W \quad (3)$$

Where the abrasive load ratio, $R = \dot{m}_P / \dot{m}_W$ is the ratio of the mass flow rates of the abrasive particles, and v_W represents the exit velocity of the waterjet. Nozzle geometry and acceleration efficiency relationships make up c_1 [15]. As the abrasive load approaches zero the abrasive particle velocity approaches the waterjet velocity. Since it takes time for the abrasive particles to accelerate up to the speed of the waterjet, the term c_1 will always be less than 1. Do to frictional losses within the nozzle, and momentum being transferred to the abrasive particles, the exit velocity can be defined as $v_W = \eta_W \cdot v_{WO}$, where $\eta_w < 1$ and is function of the initial waterjet velocity. Thus the velocity of the abrasive particles can be represented as:

$$v_P = \frac{c_1}{c_1 + R} \eta_W v_{WO} \quad (4)$$

Introducing an abrasive speed ratio, Ψ_P, as the ratio between the mean velocity of the abrasive particles and the initial velocity of the waterjet at the orifice [15], $\psi_P = v_P / v_{WO}$. From equation (4) the abrasive speed ratio becomes a function of the abrasive load ratio, R, waterjet momentum coefficient, η_W, and the geometrical and frictional losses within the nozzle, c_1.

$$\psi_P = \eta_W \cdot \frac{c_1}{R + c_1} \quad (5)$$

Figure 2 shows the results of the DDA experiments for a wide range of jet pressures to estimate the abrasive speed ratio, Ψ_P. All of the measurements followed the same general equation (5) with the same constant c_1=0.47 within a band of +/- 10% which are due to measurement uncertainties. Even though the particles can reach higher velocities at higher operating pressures, the abrasive speed ratio and therefore the efficiency of the process is not affected.

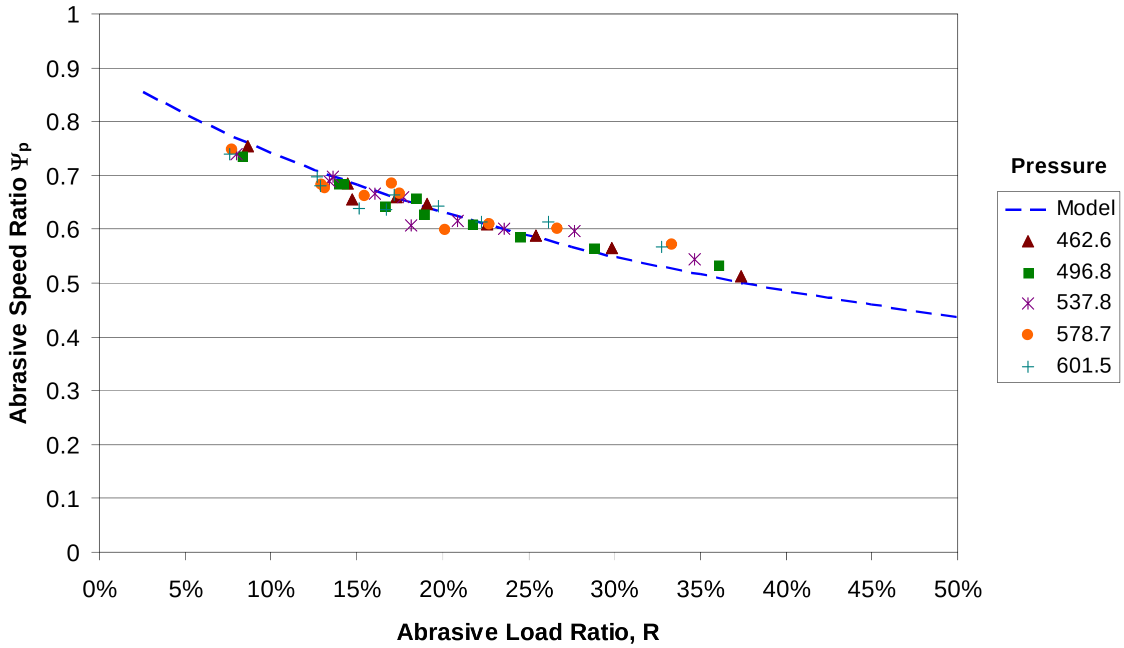


Figure 2. **Experimentally determined Abrasive Speed Ratio at different Pressures (d_O=250µm, d_F=760µm)**

3.2 The Effect of Abrasive Flow Rates on the Cutting Power

The experimental findings in the previous sections can be used to analyze their effect on the kinetic power of the jet as described in equation (2). With $v_P = v_{WO} \cdot \psi_P$ and $R = \dot{m}_P / \dot{m}_W$ this leads to

$$P_{P,kin} = 0.5 \cdot v_{WO}^2 \cdot \psi_P^2 \cdot \dot{m}_W \cdot R \qquad (6)$$

The velocity of water, v_{WO}, at the orifice is governed by the pressure p and the density of the water, ρ_W, resulting in $v_{WO}^2 = 2p/\rho_W$. Inserting this in (6) becomes:

$$P_{P,kin} = \frac{p \cdot \dot{m}_W}{\rho_W} \cdot R \cdot \psi_P^2$$
$$P_{P,kin} = P_{hydr} \cdot R \cdot \psi_P^2 \qquad (7)$$

With the experimental findings of the abrasive velocity measurements in equation (5) this leads to

$$P_{P,kin} = \frac{\eta_W^2 \cdot c_1^2 \cdot R}{(c_1 + R)^2} \cdot P_{hyd} \qquad (8)$$

From equation (8) an Abrasive Efficiency Factor Ω_A, that represents the ability of the waterjet to convert hydraulic power into kinetic power of the particles can be derived:

$$\Omega_A = \frac{\eta_W^2 \cdot c_1^2 \cdot R}{(c_1 + R)^2} \qquad (9)$$

For the parametric conditions as described above the abrasive factor can be displayed over the abrasive load ratio R (see Figure 3).

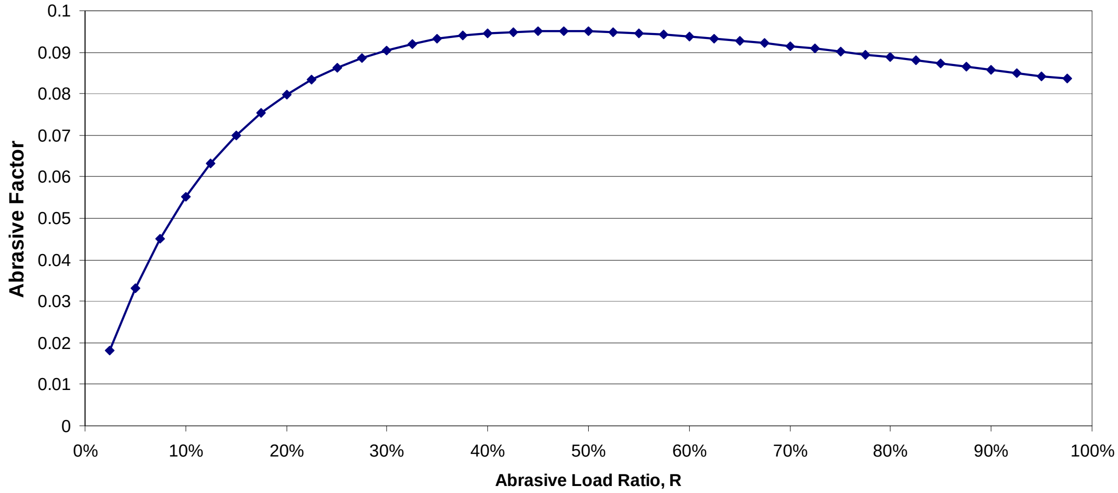


Figure 3. **Abrasive Factor as a function of Abrasive Load Ratio with R_{MAX}=47%**

The Abrasive Efficiency Factor Ω_A has its maximum at $R = c_1$, which leads to introduce c_1 as R_{MAX}, which is the abrasive load at which the best acceleration occurs. Equation (8) can therefore be rewritten as

$$P_{P,kin} = \frac{\eta_W^2 \cdot R_{MAX_1}^2 \cdot R}{(R_{MAX_1} + R)^2} \cdot P_{hyd} \qquad (10)$$

Equation (10) shows the achievable kinetic cutting power of the abrasive particles is mainly determined by the applied hydraulic energy of the jet and the abrasive load. According to these findings the jet velocity and thus the water pressure does not have a significant effect on the efficiency of particle acceleration (compare Figure 2) nor the available kinetic energy of the particles.

In a waterjet milling process, all of the abrasive particles will be striking the surface at the same angle. This causes the volumetric material removal rates to be linear with respect to the traverse rates, and the volumetric material removal rates becomes a function of the abrasive mass flow rates [13]. Laurinat [13] showed how the volumetric material removal rates are affected by increasing the abrasive mass flow rates, Figure 4, which follows the same shape of the abrasive efficiency factor shown in Figure 3. The waterjet mass flow rate in Figure 4 is approximately 28 g/s. The maximum volumetric material removal rate occurs when the abrasive flow rate was approximately 12 g/s for an abrasive loading of approximately 43%. Though the nozzles and machining processes are different, the R_{MAX} from Figure 4 is fairly similar to the R_{MAX} in Figure

3 which shows that the abrasive efficiency factor, Ω_A, is a good relationship for estimating abrasive kinetic power relationships.

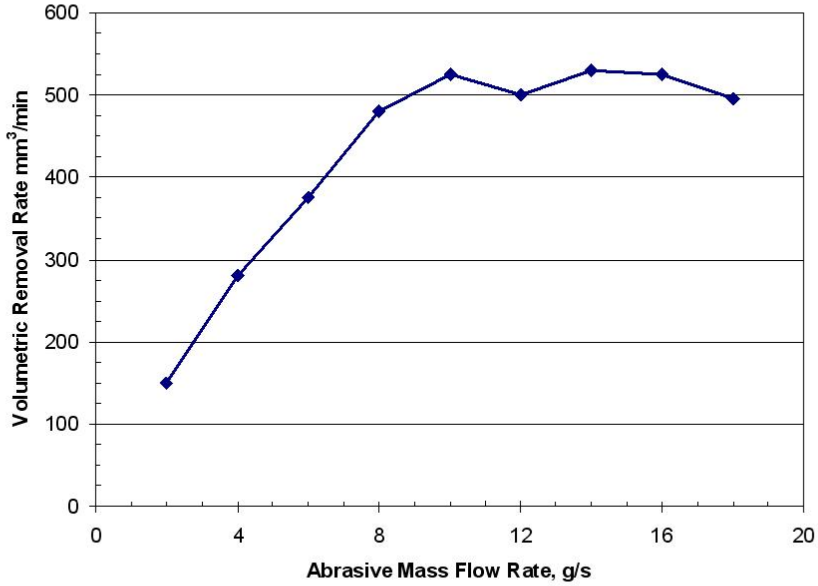
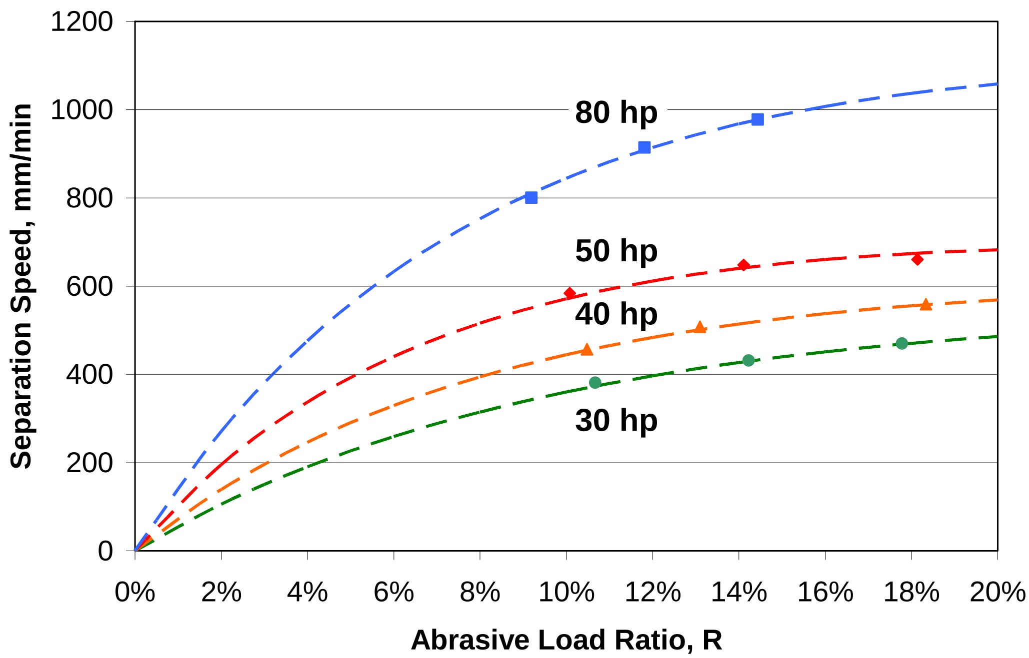


Figure 4: **Volumetric material removal rates as a function of abrasive mass flow rates on steel [13] (d_O=250µm, d_F=900µm, P=300 MPa).**



17.6 kW : d_O = 305 µm, d_F = 760 µm   31.3 kW : d_O = 406 µm, d_F = 760 µm

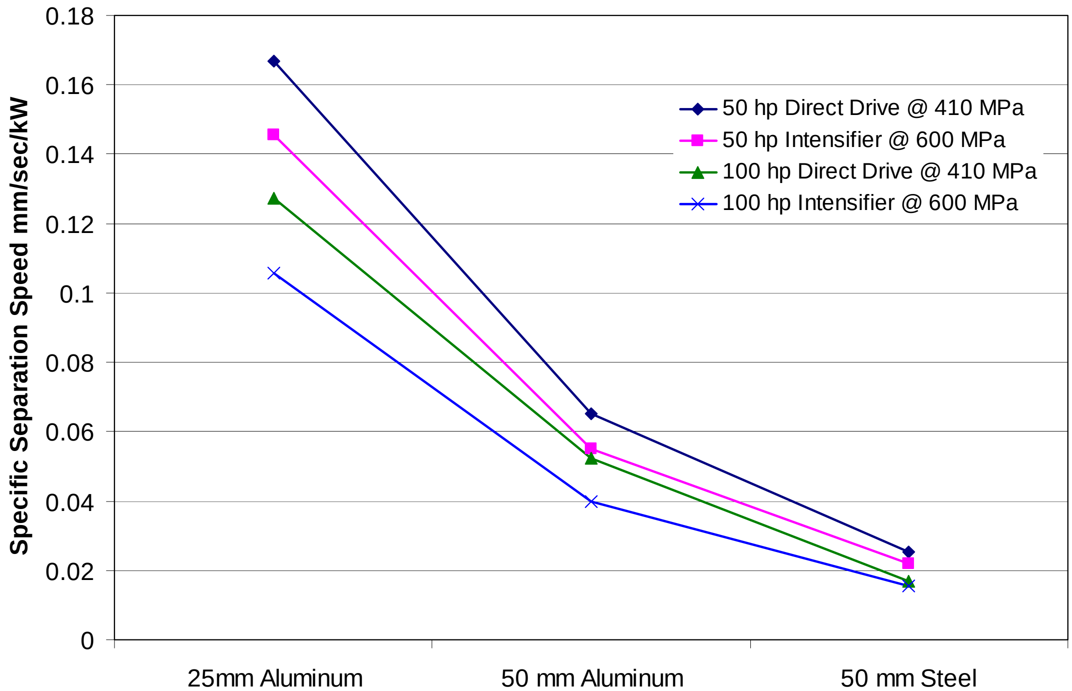
23.96 kW : d_O = 356 µm, d_F = 760 µm   48.9 kW : d_O = 508 µm, d_F = 1066 µm

Figure 5: **Separation Cutting Speed at different Powers at 420MPa (25.4mm Stainless Steel).**

Figure 5 shows that while holding both the jet pressure and abrasive ratio constant, increasing the water flow rates (hydraulic power) increases the cutting speed. For example, with an abrasive load ratio of 14%, the separation cutting speed increased from 430 to 980 mm/min or about 126% when the orifice diameter increased from 305 to 508 μm. Actual cutting data is displayed as data points. The equivalent model from equation (8) is displayed as dashed line.

Figure 6 shows the specific separation speed comparison between 50 and 100 hp rated pumps. The specific separation speed is the separation speed divided by the input power of the pump. When holding input power constant and the abrasive flow rate constant, a comparison between different operating pressures can be made. It can be seen in this plot that the specific separation speed becomes lower as the jet pressure increases. Part of the reduction seen here is due to an efficiency difference between direct drive-crank shaft pumps and hydraulic intensifier pumps. Pump efficiency affects the maximum hydraulic power that is available to the cutting nozzle, and the electrical consumable costs.

When fewer particles are entrained in the jet, acceleration of each particle is better but they do not cut as well because of their smaller numbers. Increasing the abrasive feed rates improves cutting performance until there are too many abrasive particles to be effectively accelerated. At this point cutting performance begins to degrade. But as the hydraulic flow rates are increased, more particles can be accelerated and higher cutting speeds can be achieved. Thus, an optimal abrasive feed rate for maximum cutting performance can be identified.



50 hp Direct Drive: do = 381 μm, $\dot{m}_a$ = 6.1 g/s   100 hp Direct Drive: do = 559 μm, $\dot{m}_a$ = 10.6g/s

50 hp Intensifier: do = 254 μm, $\dot{m}_a$ = 6.1 g/s   100 hp Intensifier: do = 381 μm, $\dot{m}_a$ = 10.6 g/s

Figure 6: Specific separation speed for 410 and 600 MPa cutting pressures.

4 Operating at Higher Pressure's Impact on Fatigue Life

Operating at higher water flow rates using traditional high pressures in the 400 MPa range, standard components such as pumps, swivels, valves, tubing and fittings can be used that have proven characteristics in terms of reliability and expected life. But when increasing the operating pressure to 600 MPa component fatigue lives are significantly reduced. This has the unintended consequence of increasing maintenance costs, more frequent and unexpected down times, and increasing the overall operational costs.

Since the time the 600 MPa systems have been introduced to the waterjet manufacturing industry, the impact of shorter fatigue lives has been underreported, and almost no research has been published on this topic. Because of this, current fatigue life information on actual waterjet components are based more on hearsay and personal anecdotes which are often dismissed due to the lack of hard verifiable experimental data.

Fatigue testing is very statistical in nature, and is difficult to estimate lives in applications outside the original fatigue testing parameters. At these pressures, fatigue lives are very sensitive to the nature of the pressure cycling, material properties, material composition, manufacturing methods, surface finishes, and autofrettage technique, if used, and environment. One factor that is often over looked, but is quite obvious, is that water promotes corrosion of materials [16]. Most basic fatigue testing is done in dry air or a vacuum, but when fatigue cycling under similar stress conditions in water, fatigue lives can be greatly reduced. Depending on the water properties such as pH and chloride content the fatigue curves for materials are greatly impacted. The impact is so significant that a “knee” in the fatigue curve no longer is exists for steels [16]. In addition, it is important to point out that when system pressures are further increased the fatigue of individual components become even more sensitive to the items mentioned above.

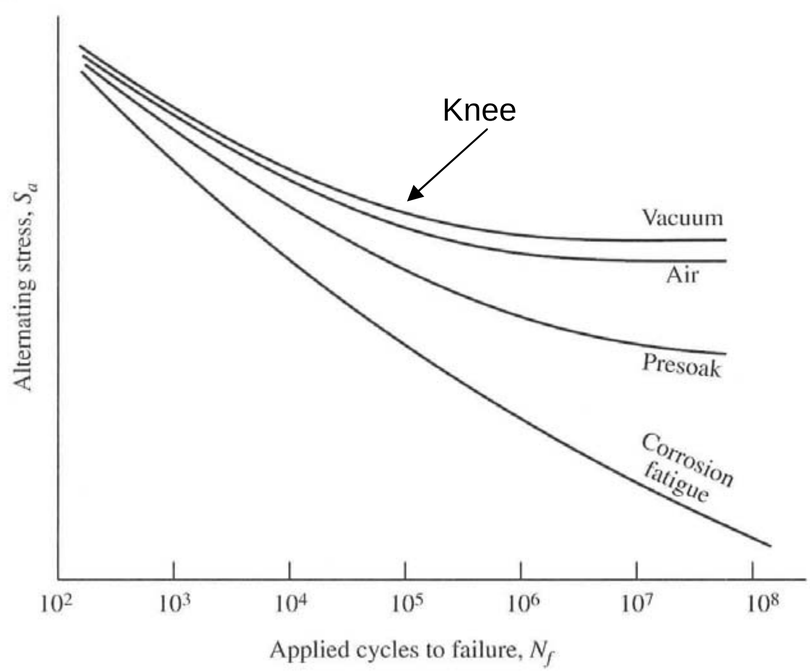


Figure 7: Typical fatigue behavior in different environments [16].

Abrasive waterjet cutting machines have dozens of parts that convey the high pressure water from the pump to the cutting head. It is the nature of the machining process that various pressure fluctuations take place. There are typically at least three fluctuations of significance. They are: 1) Full cycle pressure from atmospheric pressure to operating pressure, 2) Pressure ripple or dip during pump operation, and 3) Pressure spikes when turning on the jet. When analyzing the fatigue life of components the engineer must take into account the damage cumulated from the above pressure fluctuations [16]. When performing these estimates the components can be split into two groups. There are those that fail by Low Cycle Fatigue (LCF) and those that will fail by High Cycle Fatigue (HCF). The break point between the two groups is normally set at 100,000 cycles. When considering the reliability of an entire system, from a fatigue point of view, the system will stay in service until the weakest link fails. The problematic components in the systems are typically those that fail from LCF. These components are normally tubing, fittings and other components that may have inherent high stress concentrations due to there geometry such as cross drilled holes.

Without question any component exposed to cyclic high pressure water fluctuations will fail at some point whether the system is run at 400 MPa or 600 MPa. A major difference between the two is the stresses that the components are exposed too. It is left to the reader to determine that there is a diminishing return regarding the wall thickness of the vessel versus the stress state at the I.D. of said vessel. As an example, the stresses of two open end simple monobloc vessels with wall ratios of three and five operating at 400 MPa and 600MPa respectively can be compared[1]. For the 400 MPa vessel with a wall ratio of three the von Mises stress is approximately 800 MPa. Similarly the 600 MPa vessel with a wall ratio of five has a von Mises stress of 1120 MPa. This results in a stress intensity ratio increase of 38% for the 600 MPa vessel. Fittings such as elbows, tees and crosses would suffer much larger stress intensity increases to the inherent stress concentrations within the fittings. When operating in the LCF portion of the fatigue curve stress intensity increases such as this can dramatically reduce the life of a component, which already fails in a relatively short period of time.

To reiterate, from the operations point of view of a system, the machine is only as reliable as the weakest link. If we follow the scenario of replacing components as they fail, the machine will suffer frequent downtime due to components failing. An alternative approach which is sometimes used, is replacing all LCF components at once when one of them fails. In either case, it is apparent that operating at 600 MPa would result in higher maintenance cost and more downtime.

Operating at higher pressures reduces the fatigue life of components, which results in increasing the overall maintenance costs, more unexpected down times on the machine, and significantly reduced availability of the overall system due to more frequent and unexpected component failures. Depending on the material being cut and delivery schedules, the more economical operation of the overall system may be to operate at high hydraulic power but at pressure levels that are proven to operate reliably.

---

[1] It should be noted that the analysis was done for a hollow cylinder.

5 Pump Technology Efficiencies

From an economic point of view, the goal is to increase production rates while reducing consumable costs. Increasing hydraulic power at the nozzle results in higher production rates, but it also results in an increase in the electrical and water consumption rates. Electrical and water consumption costs are the 2nd and 3rd highest consumable cost elements and are often hidden in the overall facility's monthly utility costs.

Electrical consumption is the 2nd highest consumable cost element in operating a waterjet system and can be greatly affected by the efficiency of pump and the specific pump technology being used, and the electrical cost rates. Pump efficiency is being defined as the electrical power being consumed by the pump divided by the hydraulic output power being delivered to the nozzle. When operating at peak output power, direct drive (crank shaft) pumps have an efficiency of 86% [9] and hydraulic intensifier pumps have efficiencies in the 60 to 70% range [17]. Efficiency Numbers for electric servo drive pumps can only be sparsely found in literature.

Analyzing the major components of servo drive pumps, an efficiency range can be estimated, though. These pumps are driven by a high powered permanent magnet direct current (PMDC) torque motor that rotates a ball screw nut around a ball screw. PMDC motors have electrical efficiencies, η_{Motor}, up to 89%. Ball screw efficiencies, η_{Ball_Screw}, are typically in the 90-95% range, and the efficiencies of the bearings, $\eta_{Bearings}$, on both sides of the motor are in the 98 to 99% range. An anti-rotation bearing is used to prevent the ball screw from rotating so that it can oscillate back and forth to drive the high pressure plunger can be estimated to have an efficiency, ηanti-rotation, of around 98%. All of the seals in the system have an efficiency, η_{Seals}, that is approximately 95%. This leads to η_{Servo_Pump} being:

$$\eta_{Servo\_Pump} = \eta_{Motor} \cdot \eta_{Ball\_Screw} \cdot \eta_{Bearings} \cdot \eta_{Anti-Rotation} \cdot \eta_{Seals} \qquad (11)$$

This estimation corresponds with the efficiencies published by M. Goletti, et al. [14], who reported an overall pump efficiency between 71% to 77%. Mandatory cooling of the drive would require additional power or cooling water consumption and further reduce the overall efficiency of operating the pump.

Hydraulic intensifier pumps and servo drive pumps require active cooling of the hydraulic fluids and the PMDC electric motor, respectively. This is done either by electrical cooling equipment or traditional water heat exchangers. If electrical coolers are used, the overall pumping system's efficiency is further reduced due the addition electrical input required for the same hydraulic output. The second approach is to use a regular water based heat exchanger. Though very effective, it does significantly increase the overall water requirements for the system. A 50 hp hydraulic intensifier pump typically requires 12 to 16 l/min of cooling water which multiplies the overall water consumption costs by a factor of 4 and puts a significant burden on the environment. Direct drive pumps utilize an integrated cooling circuit and do not require any external cooling[2].

---

[2] All three types of pumps require water is at a reasonable temperature level- typically max. 20C. If this cannot be provided additional cooler have to be used.

Drive Technology	Efficiency	External Cooling	Stroke Rate	Attenuator	Noise	Reliability
Direct Drive	80 – 90%	Not needed	High	Not needed	Low	High
Intensifier	60 -70%	Required	Low	Required	High	400MPa: High 600MPa: Low[3]
Servo Drive	70 - 80%	Required	Low	Required	Low	Moderate

6 Summary

In manufacturing environments improving operational efficiency comes down to increasing production output while reducing the overall costs of manufacturing. To increase the production output, there is a heavy focus on increasing the cutting speeds of all of the various manufacturing processes. The most common technique used on the shop floor to increase cutting speeds is to increase the waterjet pressure at the nozzle. Though this technique is very effective, it has led to the misunderstanding that increasing the jet pressure alone is the sole reason for the improvement in cutting speed has developed.

The kinematic power of the abrasive particles striking the workpiece is what determines the material removal rates of a waterjet cutting process. Equation (8) shows that the kinetic power of the abrasive particles is a function of the abrasive mass loading and the input hydraulic power. Increasing the jet pressure will result in increasing the hydraulic power, but increasing the waterjet flow rates will also increase the hydraulic power. When holding the hydraulic power constant, an increase in the jet pressure requires a reduction of the waterjet flow rates. This results in an increase in the abrasive mass loading which results in a reduction in the kinematic power of the waterjet, (compare Figure 6.) While keeping the jet pressure and abrasive flow rates constant, an increase in water flow rates will increase the hydraulic power, but it will also reduce the abrasive mass loading, thus increasing the abrasive particle velocity and kinetic energy (Figure 1.) Abrasive particle efficiency increases because there are more water droplets present to improve the momentum transfer efficiency.

Another factor that affects the overall operational costs of a manufacturing process is the efficiency of the specific pump technology. There are three different types of pumping technologies that are capable on generating the high pressures for effective cutting; direct crank-shaft, hydraulic intensifier, and electric servo drive pumps. When considering the overall efficiency of the waterjet cutting operation and evaluation of the pumping technology needs to be considered. Direct drive-crank shaft pumps are the most efficient of the three at around 86%. The new servo drive pumps come in 2nd with efficiency ratings in the 70-80% range, and the hydraulic intensifiers have the least efficient operation at around 65%. Both the electric servo drive and hydraulic intensifiers require additional cooling requirements to protect the pump from overheating, and the water cooling flow rates can exceed the cutting water flow rates by a factor of 4.

[3] Accelerated wear and fatigue of high pressure components significantly reduces mean time between failure

One of the unintended side effects of running at higher pressures is the reduction in the fatigue lives of all of the high pressure components. Early fatigue failures adds to the overall maintenance costs, more frequent interruptions in the production cycle, greater risk in operator injury, and scrapping high value parts, due to failed components. In addition, increased maintenance costs are further multiplied due to the higher costs of the components. Using 690 MPa rated components, but running at 410 MPa doesn't guarantee that the components will last proportionally longer. In fact, they may have a shorter life because the materials are different between the two pressure ratings.

Pumps are designed to operate at their optimal efficiency at the pump's maximum flow rate and operating pressure rating. When a pump is operating at its peak hydraulic output power, the cutting performance has been maximized from a fluid dynamics point of view. Cutting software, nozzle lead and taper compensation, and optimizing the abrasives can help improve processing times.

The most efficient approach to maximizing cutting performance is to operate the pump at its maximum hydraulic output power, not its maximum pressure rating. Since all pumps have flow rate and pressure constraints, operating at a lower pressure with a larger orifice diameter may yield higher hydraulic power at the nozzle. If addition cutting performance is needed, increasing the available hydraulic power is required. This is best done by adding a 2^{nd} high pressure unit (be it direct drive or intensifier) to run in parallel with the first pump. A second pump has the benefit of adding redundancy in the overall cutting system, so if one pump is down for maintenance, the second pump can still be used to cut parts, and production schedules maintained. When low powered cutting job is being conducted, the second pump can be turned off and the first pump can be operated at a higher efficiency level.

This paper has shown that in order to maximize the cutting efficiency, the overall hydraulic power must be maximized at the nozzle. Increasing jet pressure alone does not increase the cutting performance in fixed hydraulic comparisons. In fact, cutting performance is reduced due to the abrasive loading increasing because the waterjet flow rates decrease. Abrasive mass loading has a significant effect on overall cutting performance because the resulting abrasive kinetic energy is a function of the abrasive loading and the hydraulic power in the system. Maximizing cutting performance is achieved by maximizing or adding additional the hydraulic power to the nozzle. When considering the overall economics of the waterjet cutting process, maintenance costs due to component fatigue needs to be considered, and the electrical and water consumption efficiencies of the actual pumping technology needs to also be considered so that maximum product output rates can be achieved with the minimum input/ongoing operational costs.

7 References

[1] Westkämper, Engelbert; Gottwald, Bernhard; Henning, Axel: Intelligent means of process control during the high pressure water jet cutting. In: IEEE Industrial Electronics Society u. a: IECON '98 - Vol. 4: Proceedings of the 24th Annual Conference of the IEEE Industrial Electronics Society, August 31 - September 4, 1998. pp. 2361-2365

[2] Henning, Axel: Computer Aided Manufacturing for Three-Dimensional Abrasive Water Jet Machining. In: Hashish, Mohamed (Hrsg.); Water Jet Technology Association: American Waterjet Conference <9, 1997, Dearborn> -1997, pp. 729-742

[3] Neusen, K. F., Gores, T. J., and Labus, T. J., “Measurement of Particle and Drop Velocities in a Mixed Abrasive Water Jet Using a Forward-Scatter LDV System,” *Jet Cutting Technology*, Lichtarowicz, A. (Editor), pp. 63-73, 1992.

[4] Chen, W.-L., and Geskin, E. S., "Measurements of the Velocity of Abrasive Waterjet by the Use of Laser Transit Anemometer," *Proceedings 10th International Symposium on Jet Cutting Technology*, BHRG Fluid Engineering, Amsterdam, Netherlands, October 3-November 2, pp. 23-36, 1990

[5] Liu, H.-T., Miles, P., Hibbard, C. and Cooksey, N. (1999) “Measurements of Water-Droplets and Abrasive Speeds in Waterjets and Abrasive Waterjets,” *Proc. 10th Ame. Waterjet Conference*, Houston, Texas, August 14-17.

[6] Zeng, J., Olsen, J., and Olsen, C., The abrasive waterjet as a precision metal cutting tool, Proceedings of the 10th American Waterjet Conference, Houston, Texas, August 14-17, 1999, Paper 65.

[7] Olsen, J., Zeng, J., Olsen, C. and Guglielmetti, B., Advanced error correction methodology applied to abrasive waterjet cutting, Proceedings of the 2003 American Waterjet Conference, Houston, Texas. August 17-19, 2003, Paper 5-D.

[8] Zeng, J., Olsen, J., Olsen, C. and Guglielmetti, B., Taper-free abrasive waterjet cutting with a tilting head, Proceedings of the 2005 American Waterjet Conference, Houston, Texas. August 21, 2005, Paper 7A-2.

[9] Veenhuizen, Scott, Operating Efficiency of Crankshaft Drive Pumps, Proceedings of the 6th Pacific Rim International Conference on Water Jet Technology, Sydney, Australia, October 9-11, 2000: pp 249-252.

[10] Henning, A. : Modellierung der Schnittgeometrie beim Schneiden mit dem Wasserabrasivstrahl, Dissertation, Universitaet Stuttgart, ISBN 978-3-939890-28-7, Jost Jetter Verlag, Heinsheim

[11] Westkämper, E.; Henning, A.; Radons, G.; Friedrich, R.; Ditzinger, T. (2000): "Cutting Edge Quality through Process Modeling of the Abrasive Waterjet" In: Teti, Roberto (Hrsg.); CIRP; Proceedings of 2nd CIRP International, Seminar, June 21-23, 2000, pp. 179-188

[12] Zeng, J. and Kim, T. (1992). Development of an abrasive waterjet kerf-cutting model for brittle materials, in Proceedings of the 11th International Conference on Jet Cutting Technology

[13] Laurinat, A. (1995): Abtragen mit Wasserabrasivinjektorstrahlen. VDI-Fortschritt-Berichte, Reihe 2, Nr 327.

[14] Goletti, M., Monno M., Dal Lago S., (2010) "Pressure Signal Comparison in WJ/AWJ Intensifiers," *20th International Converence on Water Jetting*, BHR Group, Graz, Austria, 20 - 22 October 20, pp. 233-245.

[15] Henning, A., Liu, H.T., Olsen, C., (2010) "Economic and Technical Efficiency of High Performance Abrasive Waterjet Cutting," *Proceedings of the 18th International Conference on Pressure Vessels*, PVP2010, ASME, 18-22 July, Bellevue, Washington.

[16] Stevens, R.I., Fatemi, A., Stevens, R.R., Fuchs, H., (2001) Metal Fatigue in Engineering, 2nd Ed. Wiley-Interscience, pp. 345-356.

[17] Herbig, S., Trieb, F., (1999) "Calculation of the Efficiency Rate of High Pressure Pumps," *Proc. 10th Ame. Waterjet Conference*, Houston, Texas, August 14-17.
[18] Liu, H.-T., Schubert E., and McNiel, D. (2011) "Micro AWJ technology for meso-micro machining," *Proc. of 2011 WJTA-IMCA Con.*, Houston, September 19-21 (submitted).

8 Nomenclature

$\dot{m}_W, \dot{V}_W$	Water flow rate (mass, volume)
$\dot{m}_P$	Abrasive feed rate
P_{hyd}	Hydraulic power of jet
$P_{P,kin}$	Kinetic power of particles
p	Water operating pressure
R	Abrasive load
ρ_W	Density of water
η_W	Momentum transfer efficiency
v_P	Particle velocity in mixing tube
v_{WO}, v_W	Water velocity at orifice, in mixing tube
Ψ_P, Ψ_W	Abrasive and water speed ratio
c_1	Constant for abrasive speed ratio
Ω_A	Abrasive Efficiency Factor