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Paper

ABRASIVE KINETIC CUTTING POWER:

A FUNCTION OF POWER CONVERSION

Pete Miles, Axel Henning
OMAX Corporation
21409 - 72nd Avenue South
Kent, Washington 98032 USA

ABSTRACT

The overall cutting performance of any abrasive waterjet comes down to maximizing the abrasive kinetic power of the cutting jet. In its simplest form, the abrasive kinetic power is a function of the abrasive mass flow rate and the velocity of the abrasive particles. The parameters that are typically adjusted in most a cutting processes are the abrasive mass flow rates, orifice size, and operating pressures, because they affect the mass flow rate and velocities of the abrasive particles. Though when individually increasing the orifice diameter or operating pressure has been shown to result in increased cutting speeds, what is often neglected is the fact that these changes result in an increase in the hydraulic power in the system. This paper will show that cutting speeds directly related to the overall power consumption of the pump and not a sole function of individual process parameters. This paper will also show how increasing the efficiency of the pump increases the available hydraulic power to the cutting nozzle. Thus, maximizing the abrasive kinetic cutting power is achieved by maximizing the overall hydraulic power being supplied to the cutting head.

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1 INTRODUCTION

The cutting of virtually any known material with abrasive waterjets has led to become a widely accepted manufacturing technology since its introduction the 1980s. Today, applications of abrasive waterjet cutting can be found in many different industries and range from producing very small high precision parts to making rough separation cuts of 6+" steel plates, from singulating tiny electronic components to medical surgery research. Advancements in understanding the physics of the abrasive waterjet cutting process continues to further advance the state of the art in predictive modeling and motion control software of the abrasive waterjet cutting process [1, 2, 3].

Currently, the most common parameter that is used to evaluate abrasive waterjet cutting performance is the operating pressure of the pump because it is the easiest parameter to adjust by simply varying either the pump's RPM or adjusting pressure regulators. But in reality the jet pressure is an indirect measure of the overall hydraulic power being delivered to the workpiece for removing material. Hydraulic power is the product of pressure and flow rate. For a constant power rating, any increase in pressure requires a proportional decrease in flow rates. Higher pressures are desirable because it drives the velocity of the abrasive particles higher which increases the kinetic energy of each particle. Higher flow rates are desirable since it can carry and accelerate more abrasive particles which increases the abrasive kinetic power.

Single parameter comparisons can be misleading when it doesn't hold the energy conversion constant. For example, in a pressure effects study the orifice diameter is often held constant, and the jet pressure is increased to study its effects. But this also results in an increase in flow rates, and in order to maintain the flow rate at the desired pressure, the pump is required consume more power. Hence two parameters are actually being increased and when one parameter isn't being observed, the results are often attributed to the parameter that was observed.

The purpose of this paper is to study the cutting performance by evaluating the abrasive kinetic power of the cutting jet while maintaining a constant power consumption from a standard 37kW (50 HP) pump. Because the cutting results have non-linear relationships to each when varying the process parameters, and the choice of pumping hardware have their own impact on final cutting results, the overall power input consumption of the pump was held constant for these tests so that comparisons can be made when converting electrical input energy to abrasive kinetic power and its ultimate impact on cutting performance.

2 PUMPING TECHNOLOGIES

In all manufacturing processes, the volumetric removal rates are a direct function of how much energy is delivered to the workpiece to remove material. The greater the energy input, the greater the volumetric material removal rates. Abrasive waterjets are no different, the more power that can be put into the cutting beam, the greater the cutting speed. The heart of the cutting process comes from the pumps.

Currently there are three main pumping technologies available to the waterjetting industry. Hydraulic intensifiers and direct drive crank shaft style pumps have been the main workhorses for the ultra-high pressure waterjet cutting and cleaning industries since the 1970s. Direct drive crank shaft style pumps generating pressures upwards to 420 MPa (60 kpsi), and hydraulic intensifiers upwards to 620 MPa (90 kpsi). Since 2008 electric servo pumps entered the market that are capable of generating pressures upwards to 450 MPa (66 kpsi). Though they are all capable of generating high pressures at a wide range of flow rates, they are all not the same in delivering required power to the cutting nozzle.

The overall pump power ratings are driven by international electrical codes (CE) that are based on the pump's maximum electrical power draw from the electrical grid supply, and all pump manufacturers comply to these international codes. Industrial electric motors are designed to be at their peak efficiency near their peak output power rating. Modern AC electric motors are achieving electrical efficiencies greater than 97%, whereas high powered DC motors have efficiencies upwards around 90%.

Table 1. Pump technology efficiency

Pumping Technology	Efficiency
Direct Drive [5]	80-92%
Electric Servo [8]	71-77%
Hydraulic Intensifier [10]	60-70%

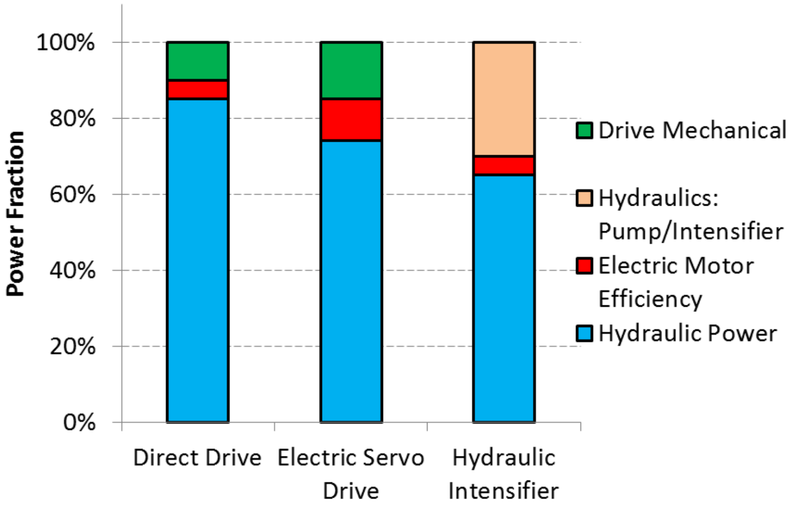

Figure 1. Pump sub-system power fractions within a pump

Table 1 shows various ranges of overall efficiencies of different pumping technologies. Mechanical efficiencies for crank shaft pumps are in the 87 to 93%. Mechanically electric servo pumps are also very efficient since they are using precision ball screws, linear anti-rotation bearings, and roller/thrust bearings with individual efficiencies in the 95 to 98% efficiency for overall mechanical efficiencies around 85%. Hydraulic intensifiers have 2 sources of efficiency losses, hydraulic pump and the double acting intensifier. Herbig [8] showed that theoretically axial hydraulic pumps combined with double acting intensifiers can have efficiencies up to 70%. But because the hydraulic pump is constantly dumping excess flow of oil to the reservoir, the overall efficiency can range from 60 to 70% for operating in the 350 MPa to 400 MPa range. But that is not practical. Peak efficiency occurs at maximum flow and maximum pressure for hydraulic systems. Figure 1 graphically shows power fractions of the various major components within a pump. The remaining hydraulic power is the power being delivered to the nozzle.

The compressibility of the water is often not considered when calculating theoretical waterjet velocities, but as the pressure of the water increases the density of the water also increases which then reduces the theoretical velocity of the waterjet, see Figure 1, Eqns. (1, 2), Figure 1. One of the factors that help keep the efficiencies of the direct drive and electric servo pumps at a higher efficiency levels is the ability to recover much of the energy required to compress the water in the high pressure cylinders. At 620 MPa (90 kpsi), the water is almost 18% compressible. Since Direct drive and servo drive pumps are closed systems, the energy from the decompressing of the water is recovered by helping to maintain the angular momentum of the crank shaft by pushing on the plunger at the beginning of the return trip. Whereas in a hydraulic system, the stored energy in the compressed fluid is sent to the hydraulic drain of the pump, and is lost. Equation (1) shows how the density of the of the water increases as the fluid pressure increases. The compressibility coefficients are B=365 MPa and K=2215 MPa.

$$\rho_w = \rho_o\left(1+\frac{p}{B}\right)^{\frac{B}{K}} \tag{1}$$

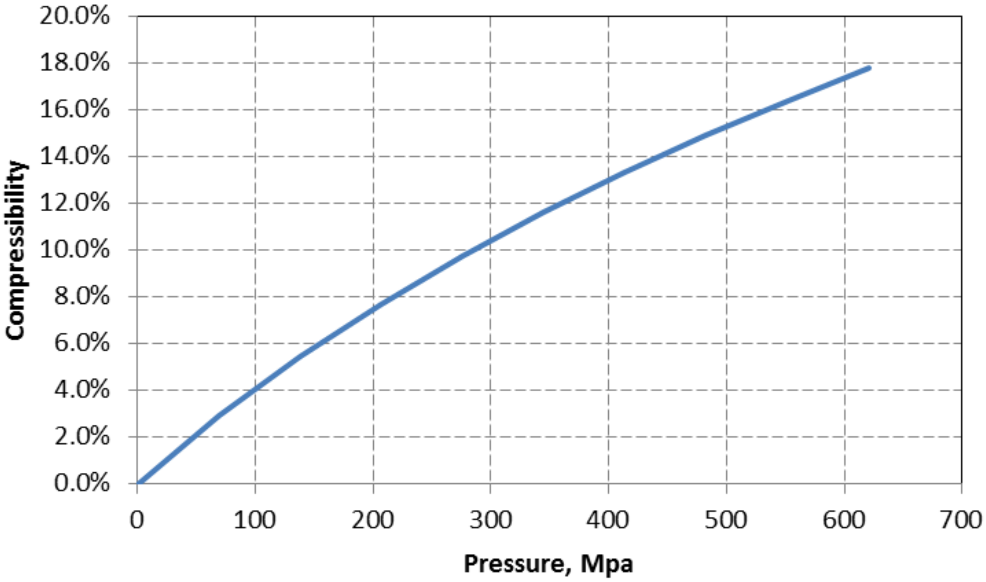

Figure 2. Fluid Compressibility

3 CONVERTING INPUT POWER TO ABRASIVE KINETIC POWER

Ultimately the kinetic power of the abrasive jet exiting the abrasive waterjet nozzle that does all the work in removing material from a workpiece. When looking at the equation for the abrasive kinetic power, it would naturally appear that increasing the abrasive mass flow rate, ma, and/or the abrasive velocity, v_a, will result faster cutting speeds. But in actual practice, increasing either of these properties alone doesn't lead to expected improvements in cutting speeds. One of the main reasons for this is due to the difficulty of efficiently converting the input hydraulic power into high velocity abrasive particles. Bernoulli's equation is used to determine the conservation of nozzle's input pressure into a jet velocity.

$$v_w = \sqrt{\frac{2p}{\rho_w}} \tag{2}$$

$$\dot{m}_w = \frac{\pi}{4} d_o^2 \rho_w C_D v_w \tag{3}$$

Here it can be seen that the velocity of the waterjet is a function of the nozzle's input pressure, and that the mass flow rate of the water is a function of the jet's velocity, and thus it is also a function of the nozzle's input pressure. But the water's mass flow rate is also a function of the nozzle's orifice diameter. The maximum orifice diameter in a waterjet system is pump limited.

$$d_{o,\ Max} = \sqrt{\frac{2^{1.5}\sqrt{\rho_w}}{\pi C_D} \frac{\eta_{pump} P_{pump}}{p^{1.5}}} \tag{4}$$

$$d_{o,\ Max} \propto \frac{\sqrt{\eta_{pump} P_{pump}}}{p^{0.75}} \tag{5}$$

$$v_w = \left(\frac{2^{1.5}\eta_{pump} P_{pump}}{\pi d_0^2 \rho_w C_D}\right)^{\frac{1}{3}} \tag{6}$$

The orifice is the most critical component in the waterjet nozzle for converting the pump's electrical power into kinetic power of the waterjet, and yet it is often over looked. It is the one component that controls both the pressure and flow rate through the nozzle. The orifice is what limits the flow rate so that pressure can be developed in the system. It is the orifice that controls the flow rate at any desired operating pressure. Because the orifice is the central component in the energy conversion, the waterjet velocity can be represented as a function of the pump's electrical power, efficiency, and orifice diameter.

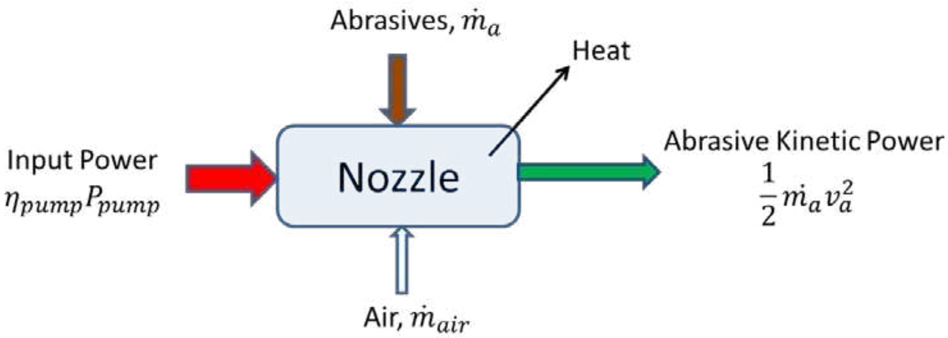

Figure 3. Power conversion within an abrasive waterjet nozzle

The standard operating practice for most waterjet job shops is to choose an office size that will allow the pump to operate near its maximum capacity. Though pressure is the one operating parameter that is the easiest to adjust, ultimately, the only thing that the operator is actually adjusting is the amount of power the pump is drawing.

Once the waterjet is created, it will then accelerate the air and abrasive particles to create the abrasive waterjet for cutting applications. The abrasive kinetic power is a function of the abrasive mass flow rate and the velocity of the abrasive particles.

$$P_{abrasive} = \frac{1}{2}\dot{m}_a v_a^2 \tag{7}$$

The biggest unknown in the abrasive waterjet cutting process is determining the exact velocity of the abrasive particles leaving the mixing tube because it takes a certain amount of time to accelerate the abrasive particles through the mixing tube. One method that has been successfully used to measure average abrasive particle velocities is the use of the Dual Disk Anemometer (DDA) [4, 9]. The DDA measures the abrasive particles by measuring the time of flight between two high speed spinning disks. By knowing the speed of the disks and the spacing between the disks, the particle velocities can be measured.

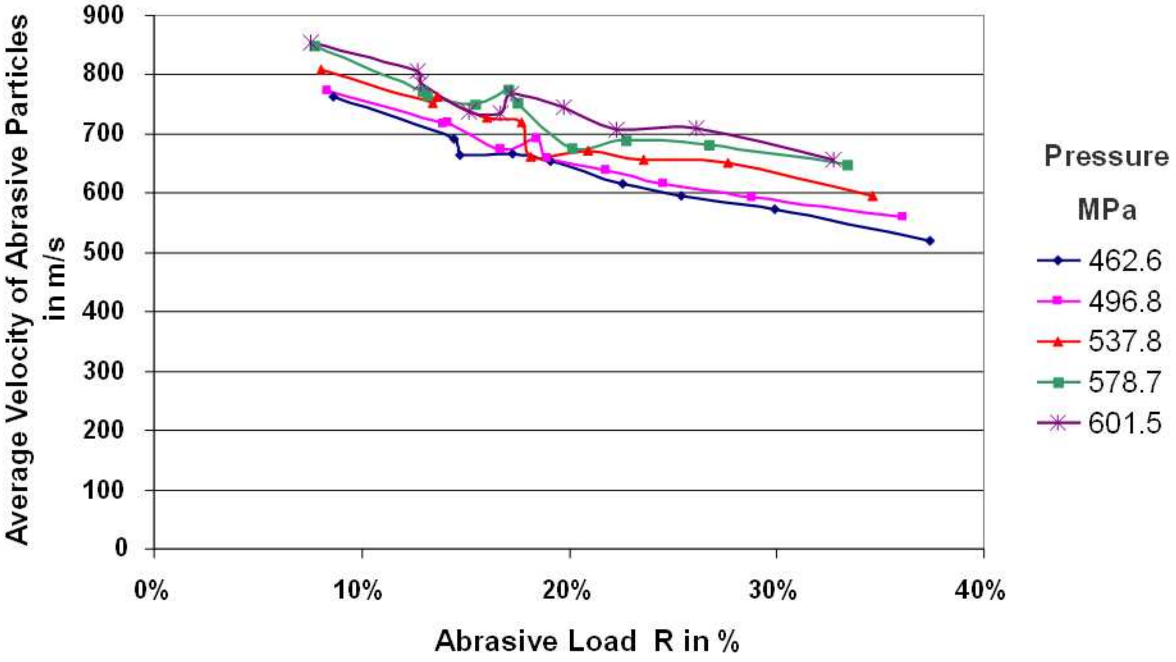

Figure 4. Abrasive particle velocities at various pressures and abrasive mass loadings, R. (d_o = 250µm, d_m = 764µm, and l_m = 100 mm)

Figure 4 shows measured average particle velocities using the DDA for various operating pressures and abrasive mass loadings. The abrasive mass loading, R, is defines as the ratio of the abrasive mass flow rate and the waterjet mass flow rate, $R = \dot{m}_a/\dot{m}_w$. It can be seen that the abrasive particle velocities appear to increase proportionally with jet pressure and it can also be seen that as the abrasive mass loading increases, the abrasive particle velocities appear to be inversely proportional to the abrasive mass loading. Because the waterjet velocity is proportional to the jet pressure, the abrasive particle velocity can be estimated as a function of the waterjet velocity and abrasive mass loading.

$$v_a = \Psi_a v_W \tag{8}$$

$$\Psi_a = \frac{a}{R+b} = \frac{v_a}{v_w} \tag{9}$$

The abrasive speed ratio, Ψ_a, can be thought of as the momentum transfer efficiency. The b term cannot be zero since if only one abrasive particle is being accelerated through the nozzle it will never approach the speed of the initial waterjet. And b will always be greater than a because the abrasive particle velocities can never be greater than the waterjet velocity.

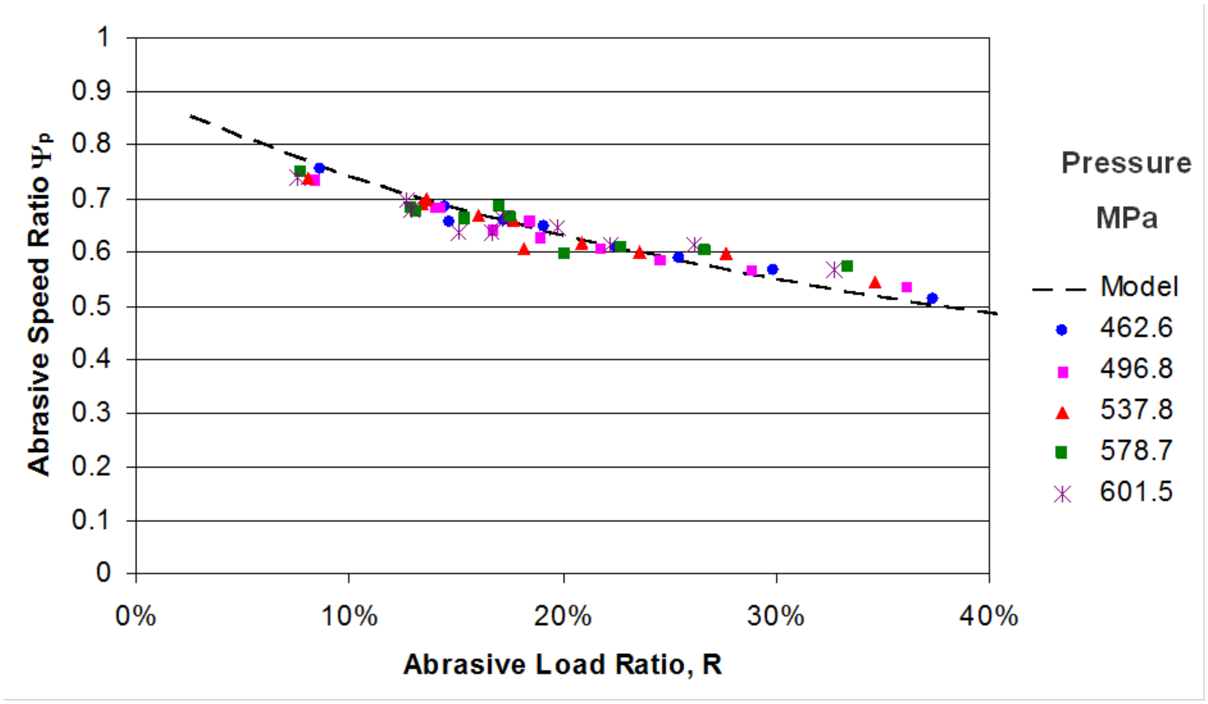

Figure 5. Abrasive speed ratio for various operating pressures and abrasive mass loading, R.

Using a regression analysis the coefficients *a*=0.423 and *b*=0.470 was found to be a good measure of the abrasive particle velocities. Figure 5 shows the abrasive speed ratio for the data shows in Figure 4. The dashed line shows the model fit of abrasive speed ratio function. In traditional waterjet cutting applications the abrasive mass loading, R, is around 12.5%. This equates to an abrasive speed ratio of 71% or an abrasive accelerating efficiency of 71%.

The abrasive kinetic power can now be written as a function of the abrasive speed ratio, abrasive mass loading, and the initial waterjet velocity

$$P_{abrasive} = \frac{1}{2}\dot{m}_a \Psi_a^2 v_w^2 \tag{10}$$

The hydraulic power of the waterjet is defined as

$$P_{hydraulic} = \eta_{pump} P_{pump=} \frac{1}{2} \dot{m}_w v_w^2 \tag{11}$$

Rearranging

$$P_{abrasive} = R \Psi_a^2 \eta_{pump} P_{pump} \tag{12}$$

The kinetic efficiency is the ratio of the abrasive kinetic output power to the overall electrical power consumption (input power) of the pump.

$$\eta_K = R \Psi_a^2 \eta_{pump} = \frac{a^2 R}{(R+b)^2} \eta_{pump} \tag{13}$$

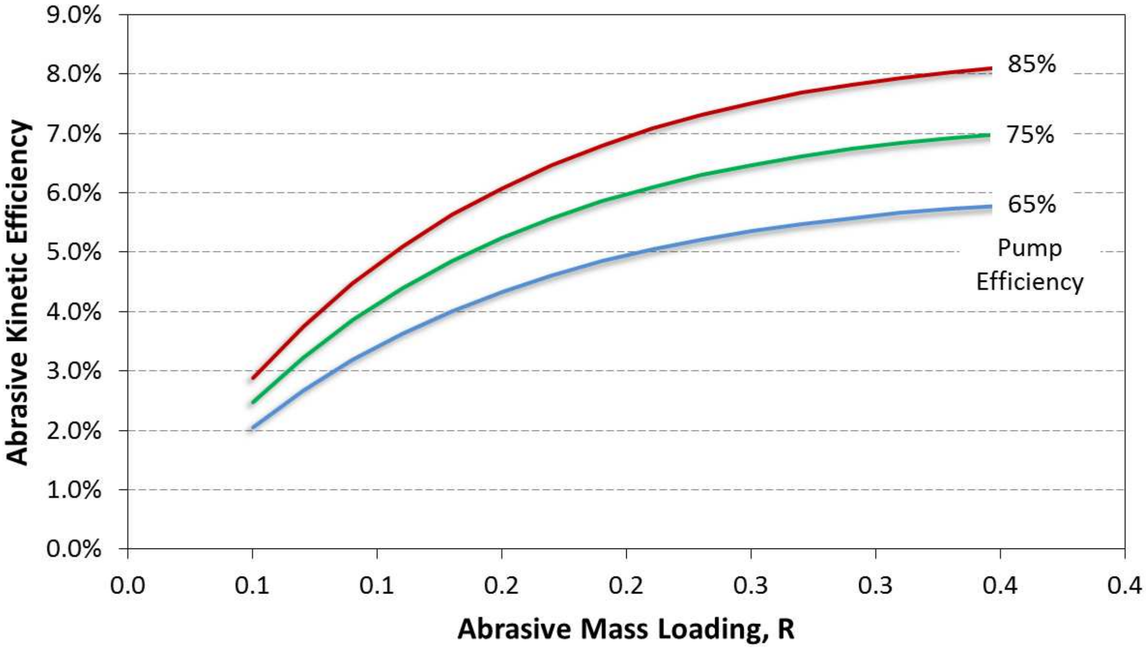

Figure 6. Abrasive kinetic efficiency for various abrasive mass loading ratios, R, and pump efficiencies.

It can be seen that the abrasive kinetic power exiting the nozzle is essentially a function of the abrasive mass loading, and efficiency and overall power consumption of the waterjet pump. Figure 6 shows the abrasive kinetic efficiency for different abrasive mass loadings and different pumping efficiencies. It can be seen in Figure 6 that there is a maximum kinetic efficiency to an abrasive waterjet. By taking the first derivative of Equation 13, the maximum efficiency occurs when the abrasive mass loading, R, is equal to the coefficient, b, or in this case when R=0.47.

Intuitively thinking, higher abrasive particle velocities that results from higher operating pressures should yield greater cutting power because the kinetic power is proportional to the particle velocity squared. But the increase in particle velocities are proportionally offset by a reduction in the mass flow rates of water and abrasives when maintaining constant power and abrasive mass loading. From equation 13 the overall kinetic efficiency is driven by the abrasive mass loading, and the overall efficiency of the pump.

4 EXPERIMENTAL CUTTING RESULTS

To illustrate how kinetic power dictates the overall cutting performance, a series of separation speed tests were conducted with a fixed electrical pump power rating. To keep the hydraulic power of the jet constant, different orifice sizes, and therefor water flow rates were used and the jet pressure was adjusted to keep the power constant. The orifice diameter for each data point is included in these plots so that the hydraulic power and jet pressure relate to each other for a given orifice diameter.

To compare how pump efficiency impacts the cutting performance, a standard 37kW (50 hp) pump rating was used in these experiments. Direct drive pumps that are typically 85% efficient will have 31 kW hydraulic power available at the nozzle, and a 65% efficient hydraulic intensifier pump will have 24 kW of hydraulic power available to their cutting nozzle. The cutting test results presented here compare these two types of pumps.

4.1 Effect of Pressure with constant Abrasive Load Ratio

Equation 13 shows that the abrasive kinetic power is proportional to the pump efficiency when the abrasive load ratio, R, is held constant. To experimentally verify this relationship, a series of cutting tests was conducted with a constant abrasive mass loading of 14% while the jet pressure was varied from 225MPa to 570MPa. Because the waterjet mass flow rate changed with each orifice diameter and jet pressure, the abrasive mass flow rate was adjusting accordingly to maintain a constant abrasive mass loading.

It can be seen in Figure 7 and Figure 8 that the separation speeds are greater when the hydraulic power available to the nozzle is greater. In this case, the higher efficient pump, 31kW at 85%, delivered more hydraulic power to the nozzle than the lower efficient pump, 24kW at 65%. These figures also shows that there appears to be an optimal operating pressure at around 300 MPa where the separation speed is maximized and that separation speed begins to decrease as the operating pressure continued to increase. This optimal cutting pressure appeared at the same pressure for both of the 6061 Aluminum and A36 mild steel tests and with both the 31kW and 24kW tests.

The critical observation to note with these cutting results is that the proportional change in the cutting separation speed test for the 31kW and 24kW follows the proportional changes in the cutting efficiency, which agrees well with the abrasive kinetic power (Equation 13) being a function of the pumping efficiency for fixed abrasive mass loadings.

An explanation for the slightly decreasing cutting performance as the operating pressure continued to increase may be due to a greater amount of particle fragmentation within the mixing tube. The kinetic energy of individual particles decreases with fragmentation, and thus as less energy to remove material when it impacts the workpiece.

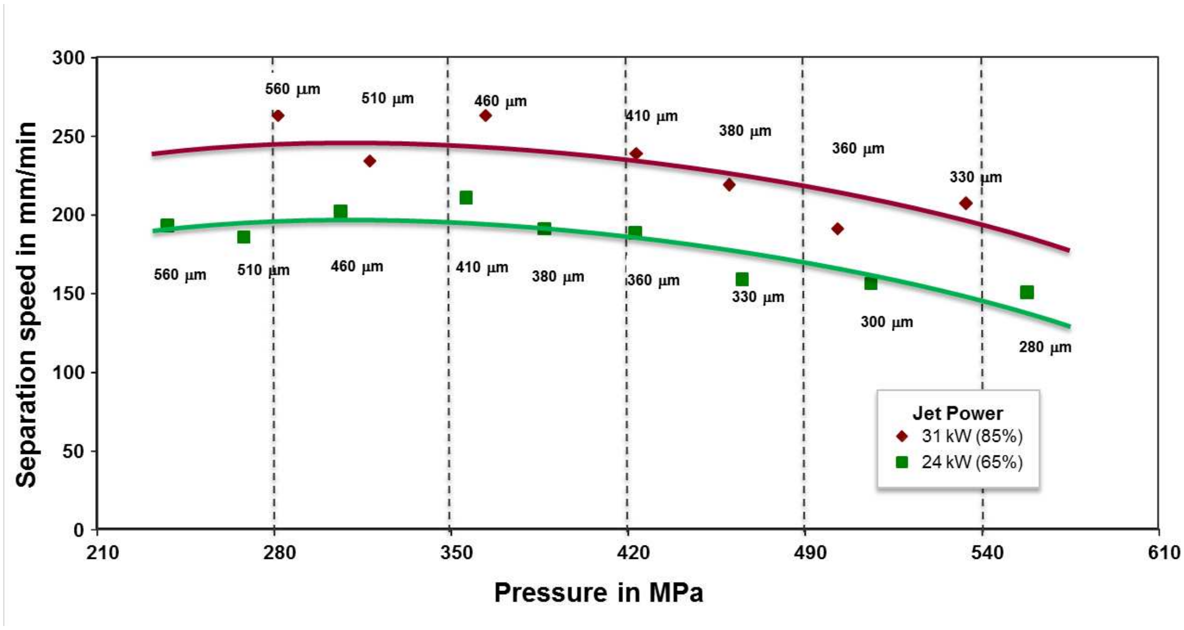

Figure 7: Separation speed for 25.4mm mild steel (A36) with fixed abrasive load (14%) with 37kW pump systems

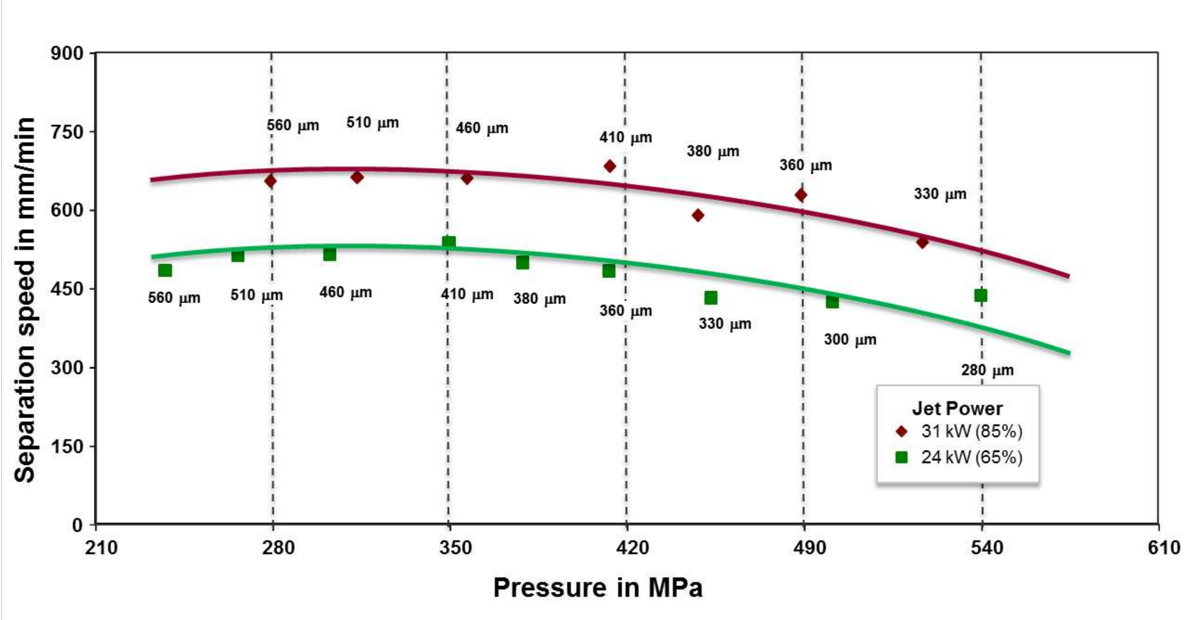

Figure 8: Separation speed for 25.4mm aluminum (6061) with fixed abrasive load (14%) with 37kW pump systems

4.2 Effect of Pressure with constant Abrasive Feed rate

The next series of tests that was conducted held the abrasive flow rate constant at 544 g/min while the jet pressure was varied from 225 MPa to 570 MPa. As the jet pressure as increased, the orifice diameter was reduced to maintain a constant hydraulic power at the nozzle.

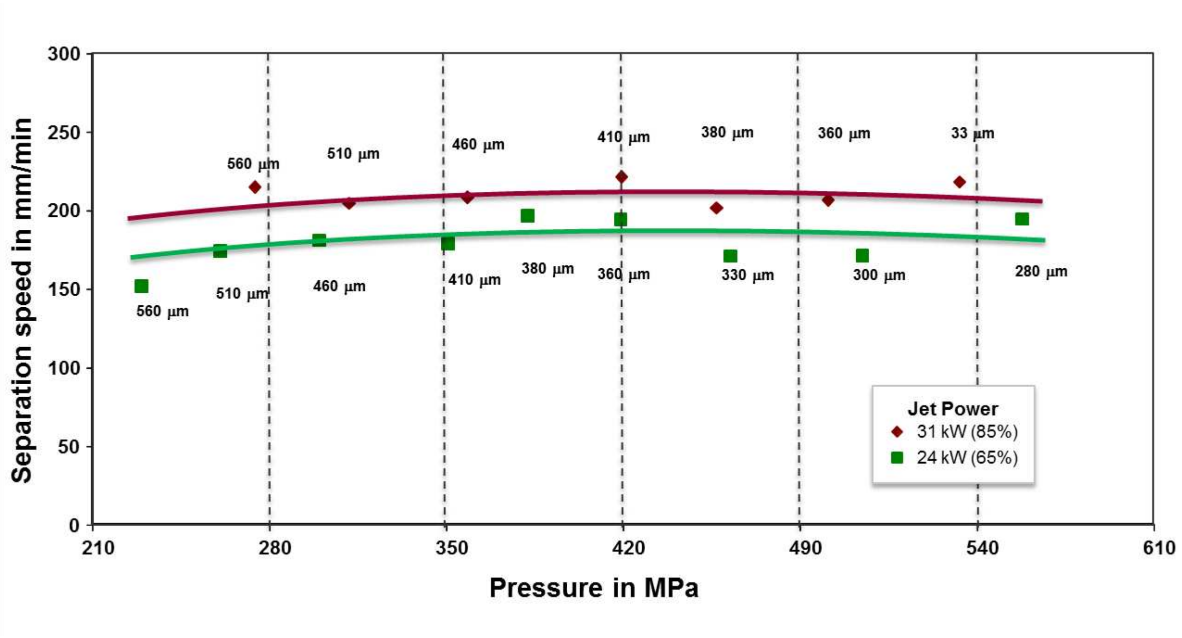

Figure 9: Separation speed for 25.4mm mild steel (A36) with fixed abrasive flow rate (544g/min) with 37kW pump systems

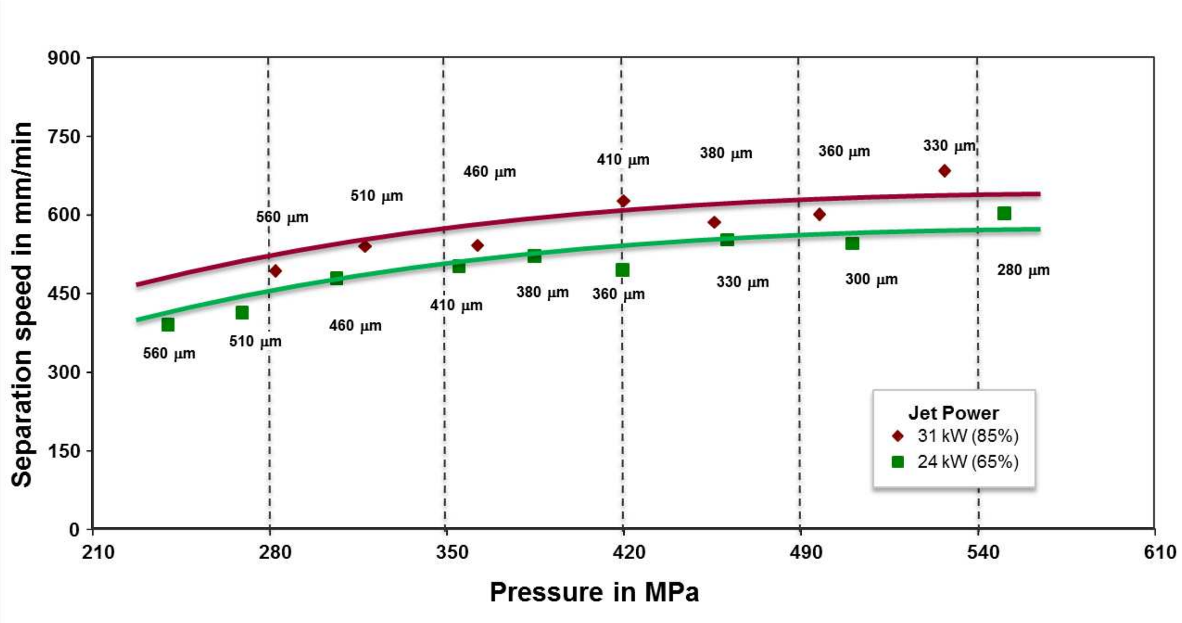

Figure 10: Separation speed for 25.4mm aluminum (6061) with fixed abrasive flow rate (544g/min) with 37kW pump systems

Figure 11 shows the data that was presented in Figure 10 as a function of the abrasive mass ratio, R. It can be seen that the separation speed as a function of the abrasive mass ratio follows the same trend as shown in Figure 6 and the abrasive kinetic efficiency Equation 13. Because the separation speed is following the same general trend, separation speeds could be modeled using the same type of relationship, where the *a* and *b* terms would be material dependent constants.

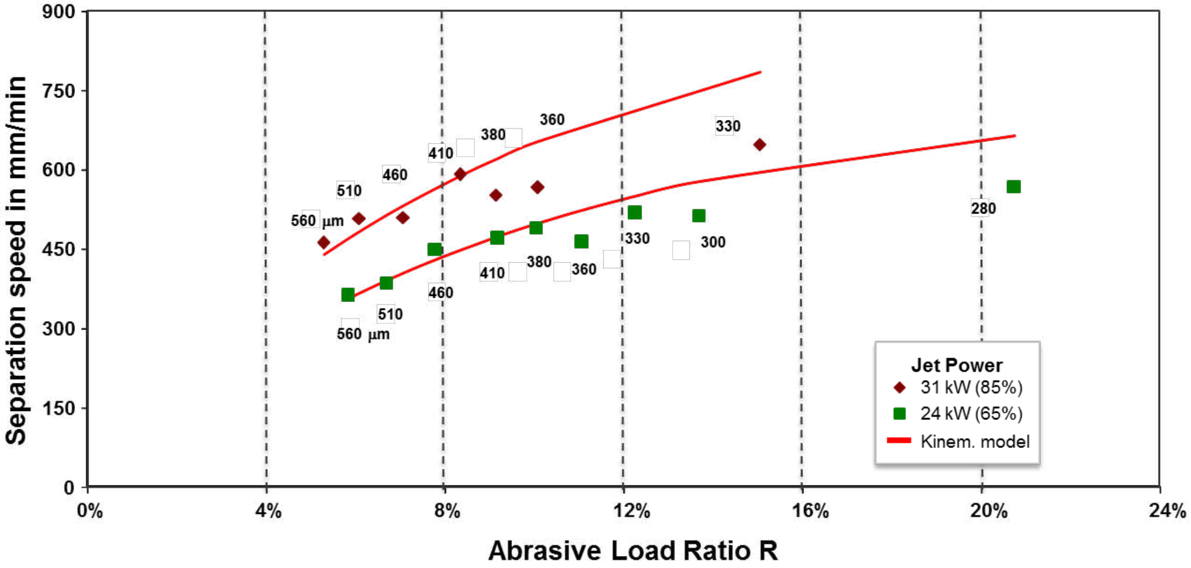

Figure 11: Separation speed for 25.4mm aluminum (6061) with fixed abrasive flow rate (544g/min) displayed over Abrasive Load Ratio, R.

4.3 Specific Cutting Efficiency Index

Some interesting results were observed when dividing the actual separation cutting speeds, v_S, by the abrasive kinetic power efficiency, η_K, to create the specific cutting efficiency index, η_C

$$\eta_C = \frac{v_S}{\eta_K} \tag{14}$$

Figure 12 and Figure 13 it can clearly be seen that the specific cutting efficiency index (SCEI) are identical for both the 31kW and 24kW tests for the various operating pressures. Because both plots lay on top of one another, this behavior appears to be independent of the hydraulic power at the nozzle (pump efficiency) but more on the overall electrical power draw of the pumps. The other interesting observation that as the jet pressure increased, the SCEI continually decreased for both the aluminum and the steel and that the steel decreased at a greater rate than the aluminum.

The exact reason for the reduction of the SCEI as a function of pressure is most likely due to the increased fragmentation of the abrasive particles within the mixing tube as the jet pressure increases, as discussed earlier. For both the aluminum and steel cutting tests the fragmentation ratios would be the same. Since steel requires more energy to remove material, than aluminum, it would be less sensitive to impacts from smaller particle impacts (lower particle kinetic energy). Further research area is needed to be able to model this behavior.

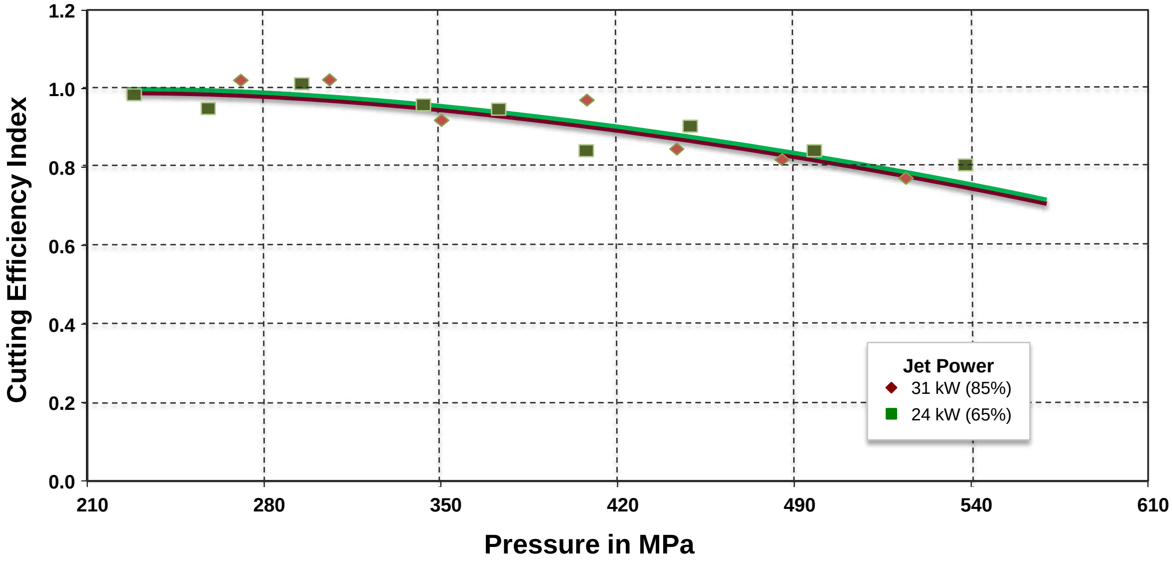

Figure 12: Cutting Efficiency Index for 25.4mm aluminum (6061) with fixed abrasive flow rate (544g/min) displayed over Pressure

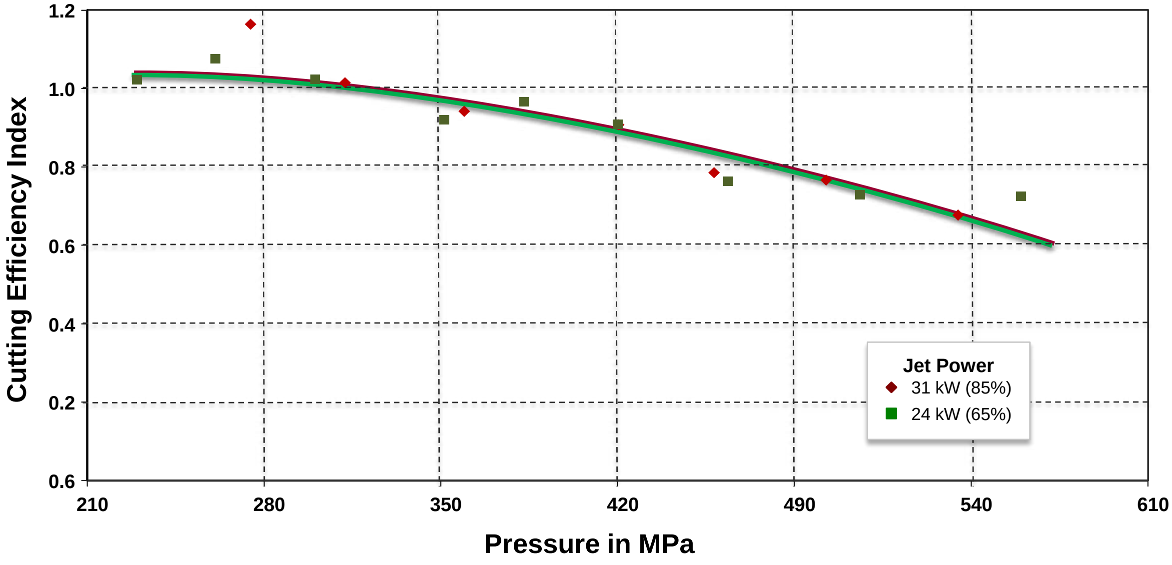

Figure 13: Cutting Efficiency Index for 25.4mm mild steel (A36) with fixed abrasive flow rate (544g/min) displayed over Pressure

5 DISCUSSION

The most important parameter in a waterjet cutting system is the hydraulic power that is being delivered to the waterjet nozzle because it is this power that will be converted into the cutting jet's abrasive kinetic power which does all of the actual cutting work. Though studying individual parameters is useful in understanding their relative effects on the cutting performance, but ultimately it is the overall hydraulic power that affects the overall cutting performance, not the individual parameter by itself.

The kinetic power of the abrasive particles was shown to be a simple function of the abrasive mass flow rate, an abrasive speed factor (which is also a function of the abrasive mass loading), the power consumption of the pump, and its efficiency. This relationship was shown to be independent of the operating pressure but more on the actual power consumption the pump. It was also shown that the velocity of the water exiting the nozzle is a function of the orifice diameter and power consumption of the pump. Generally waterjet velocity is shown to be a function of the upstream jet pressure, but in reality it is the orifice diameter that controls the jet velocity. For a fixed pump power rating, the efficiency of the pump has a significant impact on the resulting kinetic power of the abrasives exiting the nozzle since it limits the available hydraulic power being delivered to the nozzle.

A series of cutting tests were conducted by varying the waterjet pressure from 225 MPa to 570 MPa, while maintaining a constant abrasive load ratio of 14%. During these tests the orifice diameters were changed so that the overall power consumption of the pump was constant for all of the tests. The results showed a general trend of the cutting speed decreasing as the cutting pressure increased. The important observation from the cutting results was that the relative cutting speeds, in both the aluminum and steel tests, were proportionally identical to the proportional change in the pumping efficiency.

According to results published from other researchers, it is speculated that one of the reasons for a reduction in cutting speed as the jet pressure increases is due to particle fragmentation within the nozzle. Perec [11] showed that for 80 and 120 mesh garnet being accelerated through a waterjet nozzle operating at 390 MPa, that over 40% of the original garnet exiting the mixing tube has fragmented to less than 80μm when the original garnet had less than 1% by mass that was less than 80μm. The fragmentation rate was shown to be independent of the abrasive mass ratio between 15 and 25%. Ohlsen [12] showed that the average fragmented particle sizes exiting the nozzle decreased almost linearly with increasing operating pressure. Kulekci [13] showed that the cutting penetration depth rapidly drops towards zero as abrasive grains got smaller than 80 um in both aluminum and steel. Kulekeci also showed that for tests using abrasives whose average grain size ranged between 80 and 500 μm, their penetration depths remained within +/- 20% of a nominal penetration depth of 80 mesh garnet (~230μm average particle diameter). When looking at the totality of these researchers, it appears that as the jet pressure increases the particle fragmentation rate increases and this leads to an increase in smaller abrasive particles within the kerf. Since smaller particles are less efficient at removing material, this is resulting in a lower volumetric material removal rate within the kerf. Though the effect of particle fragmentation was not the focus of this paper, it does indicate that future research is needed to fully understand the impact of particle fragmentation on cutting performance to help further improve nozzle designs and abrasive cutting models.

A second series of cutting tests were conducted by holding the abrasive mass flow rate constant at 544 g/min while varying the operating pressure from 225 MPa to 570 MPa and varying the orifice diameters so that the overall power consumption of the pump was constant for all of the tests. Here the general results showed that for aluminum, there was a small increase in the separation speed as the jet pressure increase, but was relatively flat for the steel cutting results. The separation speeds were consistently higher with the higher efficient pumps. When the separation speed was plotted as a function of the abrasive load ratio, it showed that separation speeds followed the same trends as modeled from the abrasive kinetic power equation (a function of pump power, pump efficiency, abrasive mass loading, and abrasive speed factor). Again, the cutting results are driven by the abrasive mass flow rate, power consumption and the efficiency of the pump.

When the separation speed is divided by the efficiency of converting the power consumption to abrasive kinetic power, a specific cutting efficiency index is created. The interesting thing to note is that the curves for both 65% and 85% efficient pumps lay on top of one another, and that the cutting index continually declines as the operating pressure rises.

6 CONCLUSIONS

For any given waterjet cutting technology, the maximum material removal rates occur when the pumps are operating at their maximum output capacity. When the input power consumption is held nearly constant the actual cutting results shows that separation speeds tends to slow down as the operating pressure increases (within the normal operating pressure ranges of cutting systems). When all parameter ratios are held constant, actual cutting separation speeds increase proportionally with pumping efficiency since more hydraulic power is available at the nozzle when the input power consumption is held constant. This clearly shows that pumping efficiency plays a significant role in comparing cutting performance. Even though the average velocity of the abrasive particles decreased (abrasive kinetic energy) as the abrasive mass loading increased its abrasive kinetic power increased with the increase in the abrasive mass flow rate. A greater increase in the abrasive kinetic power resulted in an increase in actual separation cutting speeds.

The general trend in all of these cutting results shows that when the overall power consumption is held constant the available hydraulic power delivered to the waterjet nozzle that is converted into the abrasive kinetic power of the jet determines the actual separation cutting speeds. Greater hydraulic power results in greater cutting speeds. And for constant power consumption higher operating pressures tends to result in lower cutting speeds.

7 ACKNOWLEDGEMENTS

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9 NOMENCLATURE

C_D	Coefficient of Discharge
d_m	Diameter of the mixing tube
d_o	Orifice diameter
l_m	Length of the mixing tube
$\dot{m}_a$	Abrasive mass flow rate
$\dot{m}_{air}$	Air mass flow rate

$\dot{m}_W$	Waterjet mass flow rate
p	Water operating pressure
P_{pump}	Overall pump power consumption
$P_{hydraulic}$	Hydraulic power of the jet
$P_{abrasive}$	Kinetic power of particles
R	Abrasive load (mass) ratio
v_a	Particle velocity in mixing tube
v_W	Water velocity at orifice, in mixing tube
v_S	Cutting separation speed
η_C	Specific cutting efficiency index
η_K	Abrasive kinetic efficiency
η_{pump}	Pump efficiency
ρ_W	Density of water
Ψ_a	Abrasive speed ratio
a, b	Constants for abrasive speed ratio
B, K	Water compressibility coefficients