Effects of particle fragmentation on performance of the abrasive waterjet

A Henning, P Miles, E Schubert
OMAX Corporation, USA

ABSTRACT

Considerable research has been devoted towards studying how the various abrasive waterjet process parameters affect one another and their influence on the final cutting results. From an applicational standpoint the user is most interested in how much area the abrasive waterjet is capable of separating per unit of time. This is typically referred to as cutting performance. While several approaches have evaluated the effect of kinetic energy from the speed of particles, in this paper the focus is laid on the effect of mass of the particle that is interacting with the material. With gaining more insights in the workings of the particle-material interaction it will be possible to gain a thorough understanding of the involved processes which can lead to significant improvements of the cutting process. Optimizing the efficiency of the abrasive waterjet process will further increase the number of viable applications of this innovative process.

NOMENCLATURE

C_D	Discharge coefficient at the orifice
d_p	particle diameter
$E_{P,kin}$	Kinetic energy of particles
$\dot{m}_W$	Water mass flow rate
$\dot{m}_a$	Abrasive feed rate
L_A	Acceleration length of particles
K_A	Acceleration coefficient
p	Water operating pressure
$P_{w,hyd}$	Hydraulic power of jet
$P_{P,kin}$	Kinetic power of particles
R	Abrasive load ratio
v_a	Particle velocity in mixing tube
v_W	Water velocity at orifice, in mixing tube
Ψ_a	Abrasive speed ratio
ρ_p	Particle density
ρ_{MIX}	Density of the three phase mixture (air, water, garnet)

1 INTRODUCTION

Abrasive waterjets have been well established in industrial application since its first introduction in the 1980s. Today, applications of abrasive waterjet cutting can be found in many different industries that range from producing very small high precision parts to making rough separation cuts of 150mm thick steel plates, from singulating tiny electronic components to medical surgery research. Advancements in understanding of 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].

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 speed or adjusting pressure regulators. This is a fallacy, as jet pressure is only a partial and indirect measure of the overall hydraulic power being delivered to the work piece for removing material. Hydraulic power incorporates the product of two variables, not just one: pressure and flow rate. For a constant input power rating, any increase in pressure requires a proportional decrease in flow rates. Higher pressures may be desirable because it drives the velocity of the abrasive particles higher which increases the kinetic energy of each particle. But the resultant decrease in flow rates, at a constant input power, decrease the ability to carry and accelerate more abrasive particles which decreases the abrasive kinetic power [3,4].

In previous experimental studies that examined the speed of the particles we have shown that the overall kinetic power of the abrasive particles is proportional to the applied hydraulic power of the water jet [2].

$$P_{p,kin} = R\Psi_a^2 \, P_{W,hyd} \tag{1}$$

With the abrasive load ratio

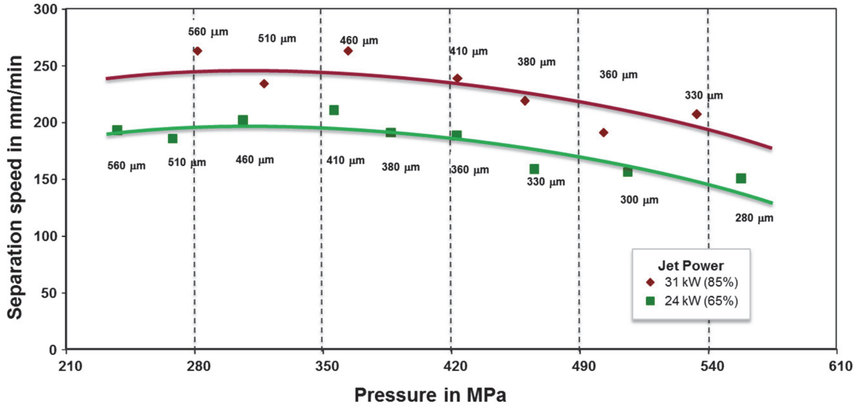
$$R = \frac{\dot{m}_a}{\dot{m}_W} \tag{2}$$

and the abrasive speed ratio

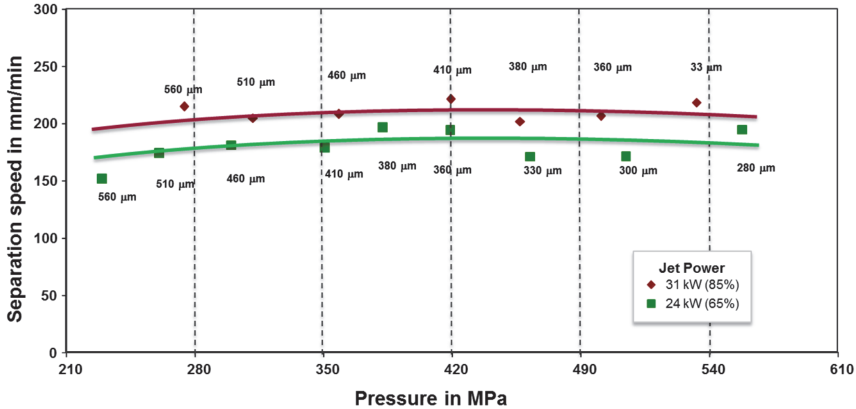
$$\Psi_a = \frac{v_a}{v_W} \tag{3}$$

When evaluating the effect of operating pressure on cutting performance the experimental results show that, even when varying the pressure widely, its effect is negligible or even detrimental (see Figure 1). While keeping the applied hydraulic power the same the cutting performance increased slightly when using the same amount of abrasive feed rate (Figure 1a). It decreased slightly when using the same abrasive load ratio (Figure 1b) [5,6]. The effect of higher hydraulic power through better efficiency largely outshined the effect of pressure.

From equation (1) one would assume that the effect at a constant hydraulic input power would lie in variations of the abrasive speed ratio- meaning how well the jet can accelerate the abrasive particles relative to its own velocity. In the end it is the abrasive particle that performs the erosion process by impacting on the workpiece. In this paper the focus is on how particles can be accelerated and what effect that has on the kinetic power they can obtain.



a) Constant abrasive load ratio



b) Constant abrasive feed rate

Figure 1: Effect of pressure on separation speed for 25.4mm mild steel (A36) with constant hydraulic power [6]

2 PARTICLE SPEED

Determining the actual speed of the abrasive particles separate from the water droplets has been one of the biggest challenges in evaluating abrasive water jets due to their extreme high speeds. In previous studies (e.g. [5]) the Dual Disc Anemometer (DDA) has been very successful in measuring the average speed of particles.

Even though measurements show that the higher pressures result in higher average particle speeds, the net abrasive speed ratio, meaning the ability (efficiency) of the jet to accelerate the particles, decreases with higher pressures (Figure 2).

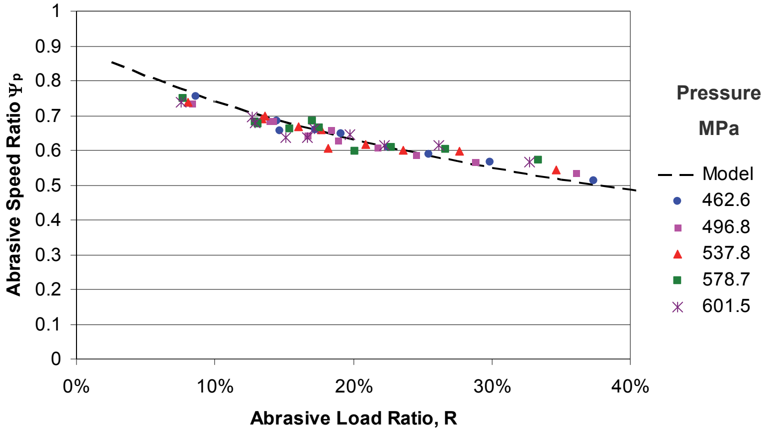


Figure 2: Average Particle Speed from DDA measurements [5]

Blickwedel [7] and others have analyzed the conditions inside the cutting head and specifically inside the mixing tube where the particles are accelerated. It predicts the distance, L_A, required for an abrasive particle to accelerate to a specific abrasive speed ratio Ψ_a, within a mixing tube based on the size of the abrasive particle, d_p, the density of the carrier fluid, ρ_{mix}, and the abrasive mass loading, R. This model is based on classical spherical ball acceleration within a fluid velocity flow field where the accelerating force on the spherical particle is proportional to the square of the particle's velocity, the density of the carrier fluid, and the drag coefficient, C_D, on a sphere. One of the key elements in the utilization of this model is the determination of the density of the carrier fluid. With a fluid density based of the volume fraction of the water going through the mixing tube Blickwedel achieves a good particle exit velocity estimate with respect to actual particle velocity measurements.

$$L_A = \frac{1}{K_A(1+R)^2}\left[\frac{1}{1-\Psi_a(1+R)} - 1 + \ln[1-\Psi_a(1+R)]\right] \tag{4}$$

With

$$K_A = C_D \frac{\rho_{mix}}{\rho_p}\frac{3}{4d_p} \tag{5}$$

Since mixing tubes are fixed in length (typically L_A = 100 mm), the velocity of the particles exiting a mixing tube can be determined by numerical iteration of Blickwedel's model for different particle sizes.

Figure 3 shows the velocity of the abrasive particles over a wide range of particle sizes for three different abrasive load ratios. It is apparent that as the particle sizes increase, their resultant velocities decrease as they exit of the mixing tube when compared to the smaller particles. Also as the overall abrasive loading increased, the resultant abrasive particle velocities decreased irrespective of size.

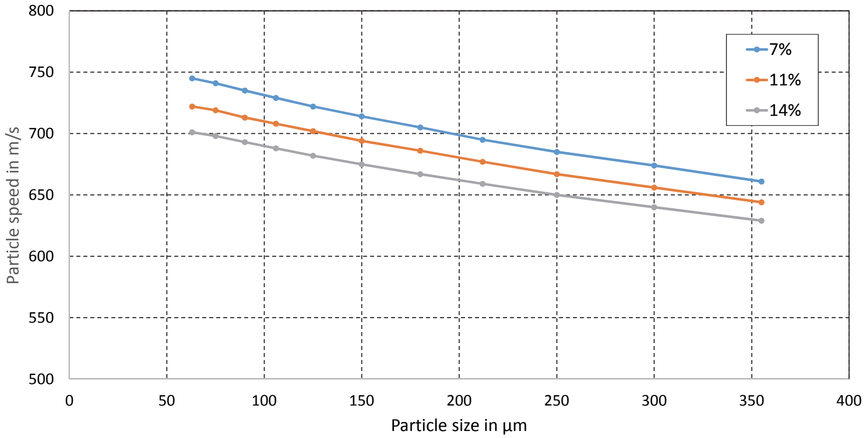


Figure 3: Simulated particle speed for different particle sizes at different abrasive load ratios (orifice 375µm, mixing tube diameter 760µm, mixing tube length 100mm, pressure 345MPa)

In Figure 4 and Figure 5 a set of simulations were carried out where the pressure was varied from 186MPa to 552MPa. The size of the orifice was varied to keep the hydraulic power constant at 18kW. Also the abrasive feed rate was kept constant at 340g/min. In Figure 4 the effect of particle size and pressure on the abrasive speed ratio is shown. This is a measure how effectively the particles can be accelerated. Both variables, higher pressures and larger particle size, show a negative effect on the jet's capability to accelerate the particle. The reduction in efficiency of about 15% when tripling the pressure does not fully explain the effect of reduction in cutting performance that we have seen in previous studies, though [6].

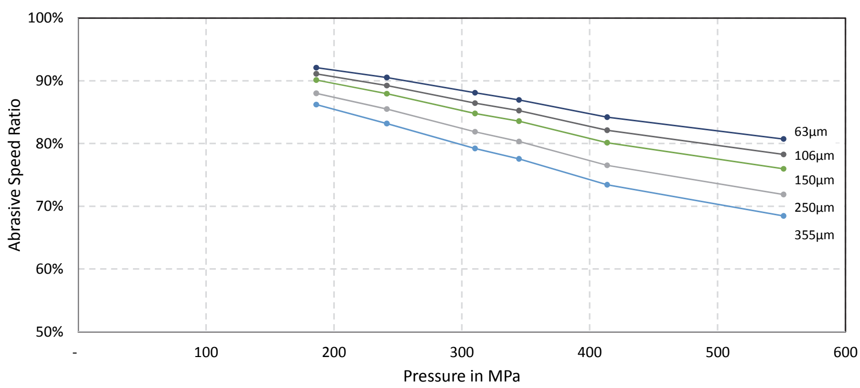


Figure 4: Simulated particle speed for different particle sizes at different pressures with the same abrasive feed rate (orifice 375µm, mixing tube diameter 760µm, mixing tube length 100mm, abrasive feed rate 354g/min)

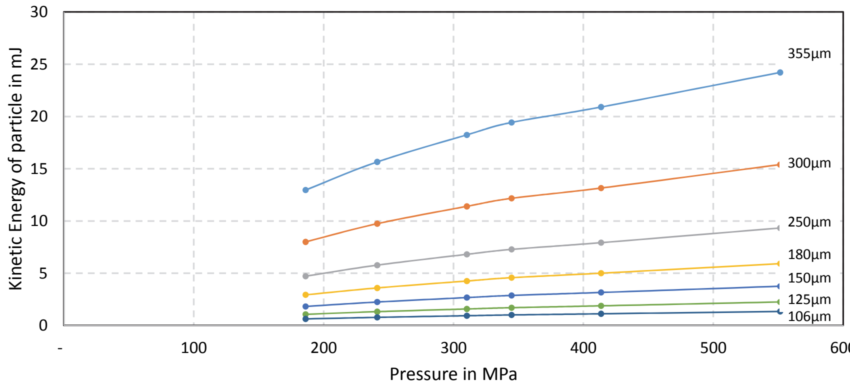


Figure 5: Particle energy over particle diameter at different jet pressures

Also, Figure 5 shows that even though larger particles are not accelerated as efficiently as smaller particles, they still have a much higher kinetic energy due to their far greater mass. Higher pressures of the waterjet do result in higher speed of the water droplets. Increasing the pressure by threefold one would expect the same increase in kinetic energy of the particles. The simulation shows that the kinetic energy only doubles when tripling the pressure. This has definite implications on the performance of the abrasive water jet.

3 FRAGMENTATION OF PARTICLES

As we have seen in the previous chapter the particle size has a large impact on speed and acceleration of the particles and on the available kinetic power to perform the cutting task. Therefore the question at hand was which distribution of particle sizes we should expect to impact on the material. The original abrasive material that is fed into the cutting head already consists of a wide distribution of particle sizes (see [8]) and previous evaluations [9,10] have shown that fragmentation of particles occurs in the cutting head.

3.1 Experimental Setup and Procedure

This project goal was to characterize the amount of fragmentation of the abrasive particles that have passed through an abrasive water jet (AWJ) cutting head. Experimental data was collected to characterize levels of abrasive fragmentation based on perturbations of certain operating conditions. The data was characterized by altering one variable at a time while holding others constant in an effort to correlate direct cause and effect of each parameter.

The experimental setup consisted of a 60 inch tall, 10 inch diameter PVC pipe standing on end. The pipe was fitted with a close fitting cover and a removable plug at the bottom that had an integral drain. AWJ cutting heads were mounted to the top cover by means of an adaptor that ensured the head was aligned to fire axially into the tube. The tube itself was filled with water to decelerate and collect all the fired abrasives while preventing impact with any solid surface (Figure 6).

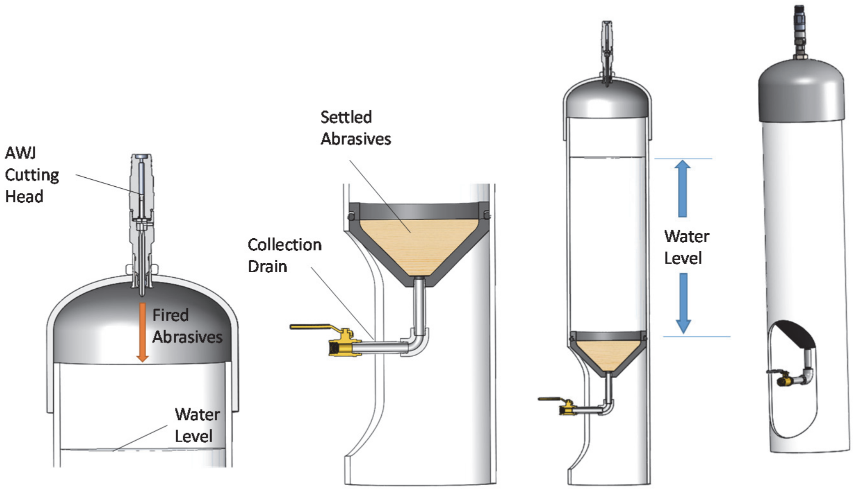


Figure 6: Abrasive Fragmentation Test Apparatus

For each test the nozzle was fired into the catcher at different pressures and abrasive feed rates without hitting a workpiece. After the test the abrasive material was collected by fully draining and flushing the catcher. The liquid and abrasives that were collected were passed through a filter in a dewatering process and then subsequently dried in an electric convection oven. Once dried, the particles were separated from the filter and classified by a vibratory sieve. The individual sieve pans were weighed and the resulting weight and screen size data recorded. The filter was also weighed and the additional weight of the trapped abrasive added to the fines figure. Particles smaller than the finest sieve, 63 µm, were collected and weighted together and considered 'fines' or 'pan'.

3.2 Experiments

In Figure 7 the particle size distribution of original garnet abrasive HPX80 is compared against the particle size distribution at the exit of the mixing tube. While the largest portion (35%) of the original abrasive was classified at 250µm, the accelerated garnet showed a rather flat distribution with a maximum of 18% at 150µm. Notably approximately the same weight portion of fines were discovered. Due to its small size this portion will most likely not result in a significant erosion on the workpiece.

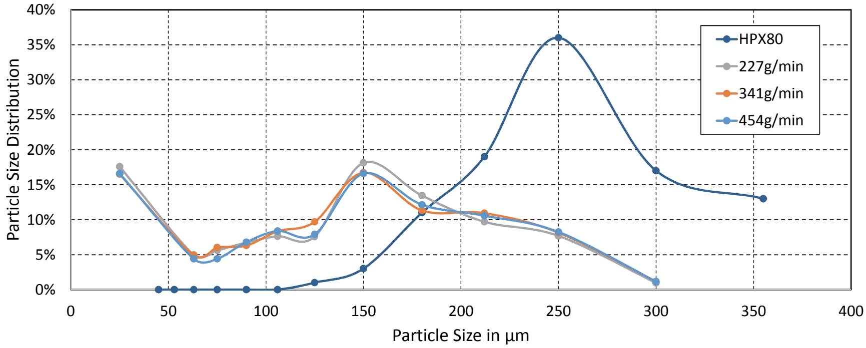


Figure 7: Particle Size Distribution at different abrasive feed rates

Also, it is very notable that changing the abrasive feed rate from 227g/min to 454g/min had no impact on the fragmentation of the particles. Changing the abrasive feed rate would increase the number of particles inside the cutting head at any given time and therefore the likelihood of particle interaction. Since this did not have a significant impact one can conclude that particle to particle interaction is not a significant factor in the fragmentation process.

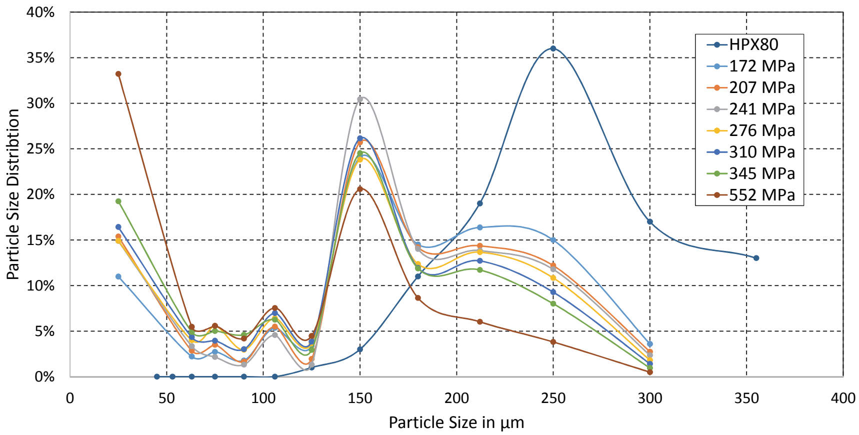


Figure 8: Particle Size Distribution at different pressures with different hydraulic power (orifice 250µmm Mixing Tube 760µm, Abrasive 340 g-min)

With the second set of experiments the size of the orifice and mixing tube were kept constant while changing the operating pressure from 186MPa to 553MPa. This results in a significant increase in hydraulic power with higher pressure. As can be seen in Figure 8 the portion of fines significantly increased with higher pressures while the portion of large particles decreased with pressure.

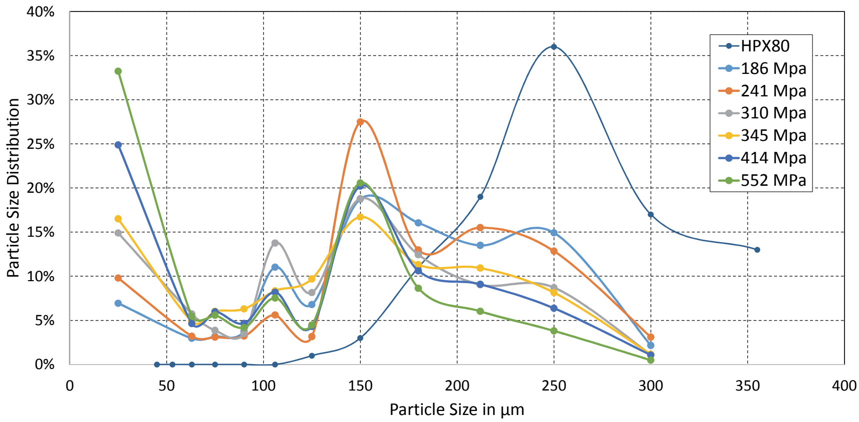


Figure 9: Particle Size Distribution after firing at different pressures with same hydraulic power

In the third set of experiments the pressure was varied from 186MPa to 553MPa. But this time the orifice size was varied to keep the hydraulic power the same. Even though the conditions are very different from the previous set, the result is fairly similar: The portion of fines increases with higher pressures and the portion of large particles decreases with higher pressure (Figure 9).

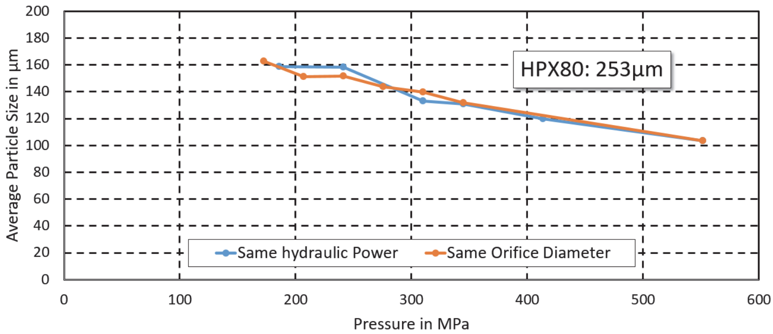


Figure 10: Average particle size after firing at different pressures

One way of comparing different fragmentation results is to calculate a weighted average particle size. The original garnet that was used in this test had an average particle size of 253µm. In Figure 10 the average fragmented particle size is shown for both sets of experiments with very different conditions. One with constant hydraulic power with varying orifice size and one with constant orifice and therefore varying hydraulic power. It is very notable that both experiments resulted in a similar fragmentation behavior for a given pressure. It can therefore be noted that the average particle size and therefore the fragmentation is mainly effected by operating pressure.

4 POWER OF PARTICLES

While it is an important first step to analyze the speed and size of the particles that are hitting the workpiece and eventually perform the cutting operation, the true measure for cutting performance is the kinetic power of the particles. Each particle obtains a certain amount of kinetic energy.

$$E_{P,kin} = \frac{1}{2} m_a \, v_a^2 \tag{6}$$

The overall kinetic power, $P_{P,kin}$, of the cutting jet can be represented as a function of the particle's mass flow rate, $\dot{m}_a$, and its velocity

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

4.1 Varying Hydraulic Power

In Figure 11 the power of each particle size portion is displayed for different conditions. All tests were performed with the same orifice diameter (250µm) and the same abrasive feed rate (340g/min) while the pressure was varied from 186MPa to 553MPa. This means that the available hydraulic power changed from 3kW to 19kW. It is therefore no surprise that the test with the highest hydraulic power also showed the highest kinetic power. All different tests showed a peak kinetic power at the particle size cluster of 150µm. It is very notable, though, that the portion of fines, that do not have a significant impact on erosion increased with pressure and proved to be a major portion of the overall kinetic power especially at higher pressures.

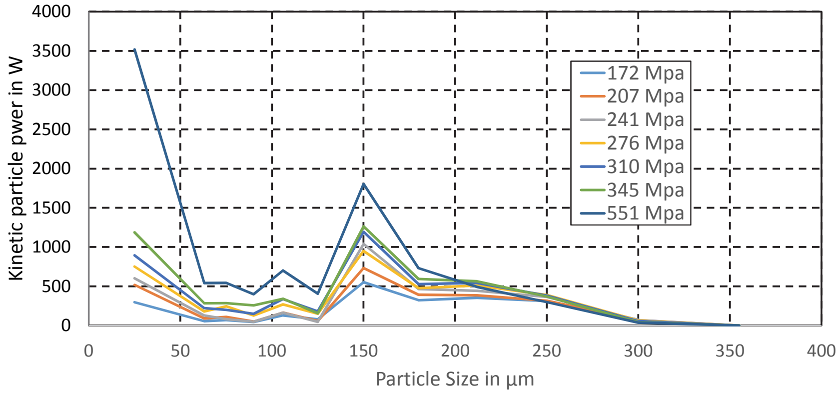


Figure 11: Total kinetic power at different pressures with the same orifice (250µm) and the same abrasive feed rate (340g/min)

By comparing the hydraulic power of the jet with the total kinetic power of effective particles it becomes clear that the kinetic efficiency is linearly decreasing with higher pressures (Figure 12). At 172MPa the kinetic efficiency is about 60% whereas at 553MPa the efficiency has dropped down to 30%. This will have a significant impact on cutting performance of the abrasive waterjet and might explain the behavior that we have experimentally observed in Figure 1where higher pressures actually were seen to have a detrimental effect on cutting performance.

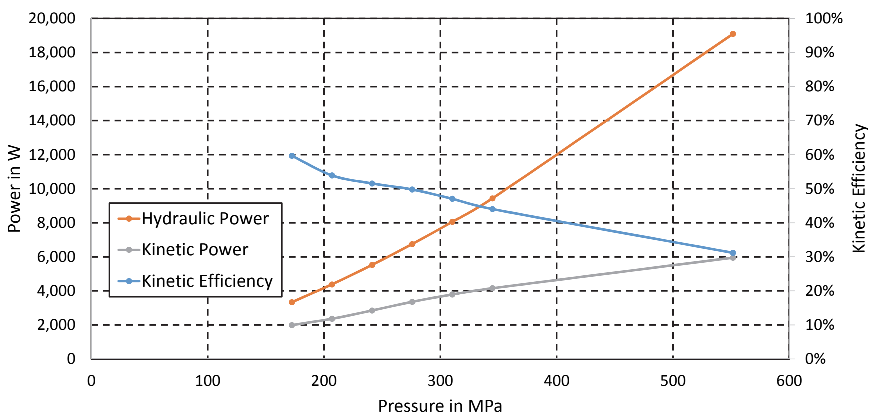


Figure 12: Efficiency of converting hydraulic power into kinetic particle power (same orifice)

4.2 Constant Hydraulic Power

The next set of experiments were performed with the same hydraulic power while changing pressure. This was accomplished by using different orifice sizes to adjust the hydraulic power. In the first batch the same abrasive feed rate (340g/min) was used with all experiments. This means that at higher pressures where a smaller water flowrate is utilized, the abrasive load ratio is higher. In Figure 13 the kinetic power is displayed for each portion of particle sizes.

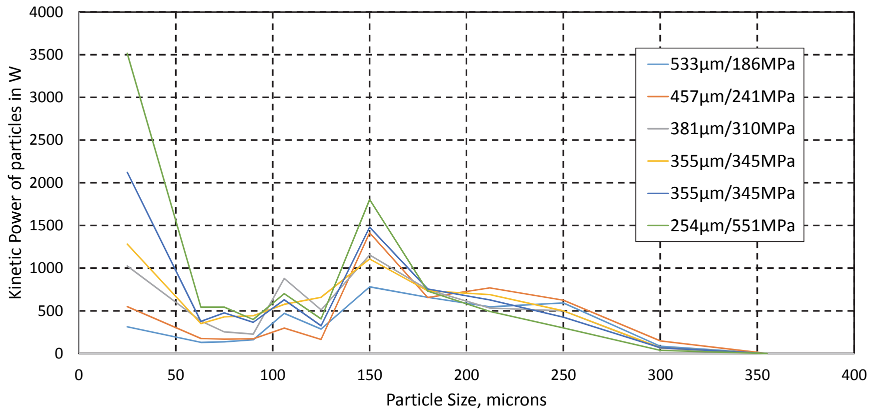


Figure 13: Kinetic Power of particles at different pressures, same hydraulic power (18kW) and same abrasive feed rate (340g/min)

As can be seen in Figure 13 the distribution of kinetic power is fairly similar with a slight edge toward the experiment with the highest abrasive load ratio. But also here as in the previous test the amount of kinetic power within the fines is significantly increasing with higher pressures.

In the typical application of abrasive waterjets a nozzle configuration with a low water flow rate typically has a smaller abrasive feed rate. There are many practical reasons for this setting with the most important being that the capability of reliably delivering particles into the cutting head depends on the amount of air delivered through the venturi process for that orifice. In Figure 14 the experiment was carried out with an abrasive load ratio of 11%. This means that the abrasive feed rate is larger at lower pressures due to the larger water flowrate at the same pressure. With those conditions it becomes clear that the experiment with the higher pressures show lower kinetic power of different portions of particle sizes. Also, as we have seen before, the amount of power that goes into fines, which are not effective in the cutting process, is the largest at higher pressures.

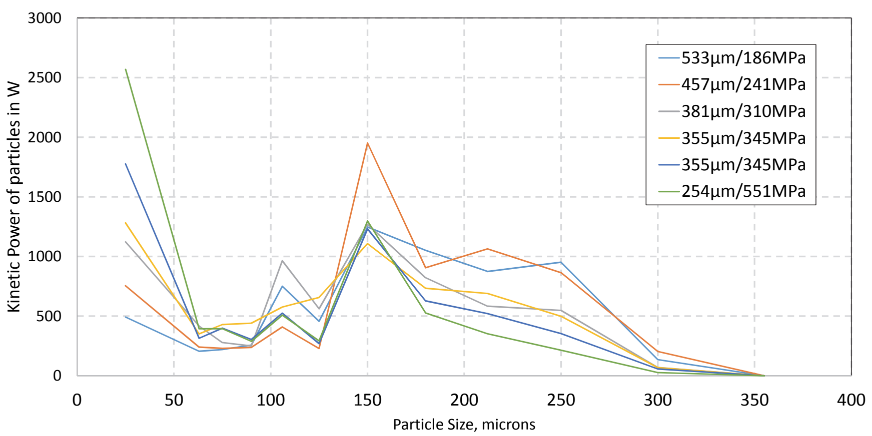


Figure 14: Kinetic Power of particles at different pressures, same hydraulic power (18kW) and same abrasive load ratio (11%)

Figure 15 shows the total abrasive kinetic power for the tests that were carried out using the same hydraulic power, where in one case the abrasive flow rate was held constant (344 g/min), and the other case the abrasive loading was held constant (11%). We can make out two distinct trends. Using the same abrasive feed rate the total kinetic power increases at the lower pressures but then appears to find a maximum level after around 400MPa where there is no significant change at higher pressures.

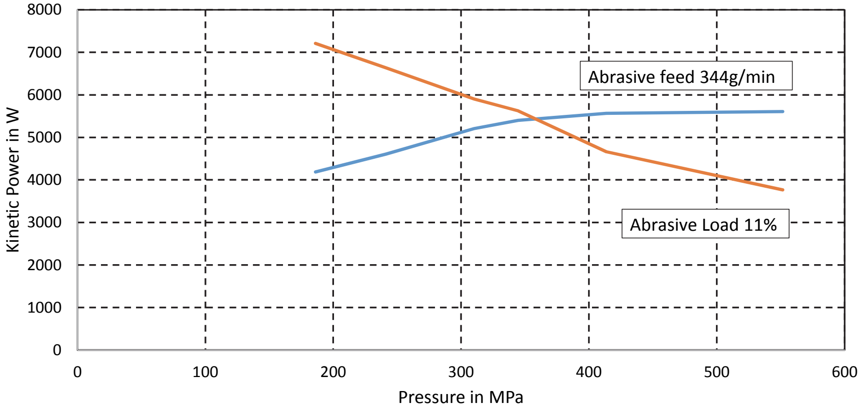


Figure 15: Total Kinetic power of particles over pressure at different abrasive feed rates

The other case where the abrasive load ratio was kept constant clearly shows a decrease in total abrasive kinetic power. The main reasons here are probably an insufficient supply of particles that could be accelerated and the large portion of fines that do not have a significant impact in the erosion process.

5 CONCLUSIONS

Abrasive waterjet cutting has found large application in different industrial applications. As its usage widens the abrasive waterjet can be applied in areas that traditionally have been occupied by competing cutting methods. It is therefore of essential importance to understand its potential and opportunities for optimizing the cutting process. Over the years since its inception in the 1970s innovations in pumping technology have not only increased reliability but also hydraulic power and pressure. In pure waterjets higher pressures have shown some benefits that users have not been able to match in cutting with abrasive waterjets. Experimental data actually showed minimal effect and even detrimental effects of higher pressures. By focusing on the actual particle this paper tries to analyze the reason why nominally faster water jets do not translate in higher abrasive cutting performance.

In this paper we have been analyzing the behavior of abrasive particles during the acceleration process in the cutting head. For this we have looked at different conditions where either the hydraulic power of the process was kept constant or the orifice size was kept constant, which results in changing hydraulic power. Also the effect of different abrasive feed rate conditions were taken into account.

In the first section we analyzed the expected speed of particles under different conditions. It was shown that even though higher pressures typically resulted in higher speed particles the effectiveness of acceleration dropped significantly with higher pressures, higher abrasive load and larger particles.

In the second section the size distribution of particles exiting the mixing tube was analyzed. These are the particles that impact on the workpiece to perform the cutting operation. It was shown that pressure has the most significant effect on the particle distribution. The portion of larger particles decreases significantly with higher pressures and the amount of fines that have no significant impact in the cutting process increases substantially. Even though we were applying very different conditions the average particle size showed the same behavior of linearly decreasing with increasing pressure. Massive fragmentation of particles into small ineffective fines would be a first indication why the abrasive waterjet is not as effective at higher pressures.

The third section then focused on the kinetic power of the abrasive water jet. Again it showed that the higher rate of fragmentation at higher pressures limited the capability of the abrasive jet to perform the cutting process. Only increasing the abrasive load at higher pressures helped to overcome the losses caused by massive fragmentation to maintain and eventually increase the total kinetic power. This is limited by the ability to feed the abrasives into the cutting head, though. With the same abrasive load, the kinetic power was significantly reduced at higher pressures.

In this paper the kinetic behavior and fragmentation of particles has been analyzed in a wide range of different conditions. With new insights into fragmentation of the particles especially at higher pressures we were able to explain the behavior of experimental cutting studies where higher pressures did not provide a significant improvement and in many case a decrease of cutting performance. Studies like this will not only help us understand the very processes that are involved in the cutting operation but also help us to optimize the overall process to increase performance and reliability and also be competitive against other cutting methods while providing ample new applications in the future.

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