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ECONOMICS OFABRASIVE- WATERJET CUTTING AT 600 MPA PRESSURE

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ABSTRACT

The economics of cutting at 600 MPA using abrasive waterjets is discussed in this paper. The operating cost of the AWJ process consists mainly of the costs of abrasives, nozzle wear, utility, and maintenance of equipment. The cost per unit length of material (specific cost) is determined based on the cutting speed. It was found that increasing the pressure at fixed power or fixed orifice size will increase the cutting speed. In the first case, this increase is due to increased jet power density which is more suitable for thin materials. In the second case, the cutting speed increase is due to increase in the power and the power density, and thus thicket materials can be cut efficiently. The main advantage of increasing pressure in either case is reducing the abrasive consumption per unite time or length of cut. Even if the pump maintenance cost increases by a factor of 2, the cost per unit length will decrease for most common parameters. The reduction in abrasive consumption and the possible increase in maintenance cost were found to be beneficial even if the hourly cost increased

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1. INTRODUCTION

Abrasive Waterjets (AWJ) at 400-MPa pressure have been highly commercialized for cutting a wide range of material such as steel, aluminum, glass, and composites. One of the key strategies to further enhance the performance of abrasive waterjets is by increasing the pressure over 400-MPa. The following are the advantages to be gained when AWJ is operated at higher pressures:

- Increase cutting speeds.
- Increased efficiency as pressure increases.
- Reduced abrasive and water consumption.
- Cutting harder materials such as ceramics.
- Possible reduction in width of cut and kerf taper.

In this paper, we present data on the improvements obtained when using at 600-MPa pressure. First, we present information on 600 MPa equipment followed by general information on AWJ power density and efficiency. This will be followed by discussions on AWJ cutting observations and the potential cost benefits. Conclusions are then presented at the end of the paper.

2. EQUIPMENT

The implementation of 600-MPa cutting jets requires the development of several hardware components. These are:

- 600-MPa pumps
- Tubing and fittings
- On/off valves
- Nozzle systems

Hydraulically-driven intensifier pumps (as opposed to direct drive type pumps) are more suitable at this stage of technology status to use for generating 600-MPa or higher pressures for commercial use. This is because of fatigue and UHP tribology constraints. Also, with intensifiers, the stroke rate is in the order of 20-30 times slower than those used in direct drive pumps, thus elongating the lifetime of pump high pressure cylinders. The relatively high stroke rates of direct drive pumps subject contact components such as seal, bearings, and backup components to severe tribological environment making them difficult to adapt for 600-MPa service.

In our approach, we used a single stage intensifier, as opposed to using cascading intensifiers (1) to minimize the number of components and service time. The output water pressure is determined by the inlet hydraulic oil pressure and the pressure intensification ratio. This ratio can be defined as the area of the oil-side piston divided by the area of the pressurized waterside plunger. Increasing the pressure from 400 to 600-MPa can be achieved by altering the oil pressure or the intensification ratio, or by altering both. Typical 414-MPa high-pressure pumps operate with 21-MPa oil and an intensification ratio of 20. Accordingly, producing 600-MPa would require an oil system operating at 30-MPa. This operating pressure would be at the upper limit for typical commercially available hydraulic pumps and components. For developing a more robust ultra high-pressure (UHP) pump, we used an intensification ratio of 33, which allows pressures up to 690-MPa to be generated using standard 21-MPa hydraulics. Figure 1 shows this intensifier. Observe that tie rods are used to avoid using threaded cylinders. A single intensifier pump with a flow rate of about 0.76 gpm is used for cutting applications while a quad-intensifier pump as shown in Figure 2 is used for providing relatively high flow rates for food vessel pressurization.

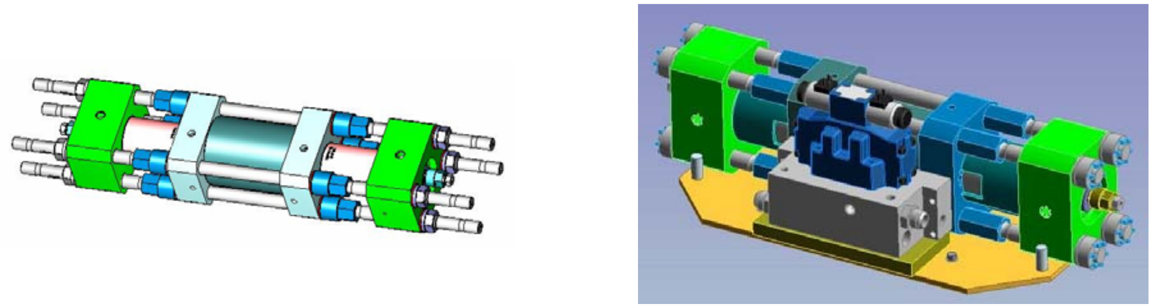

Figure 1. 600-MPa Intensifier

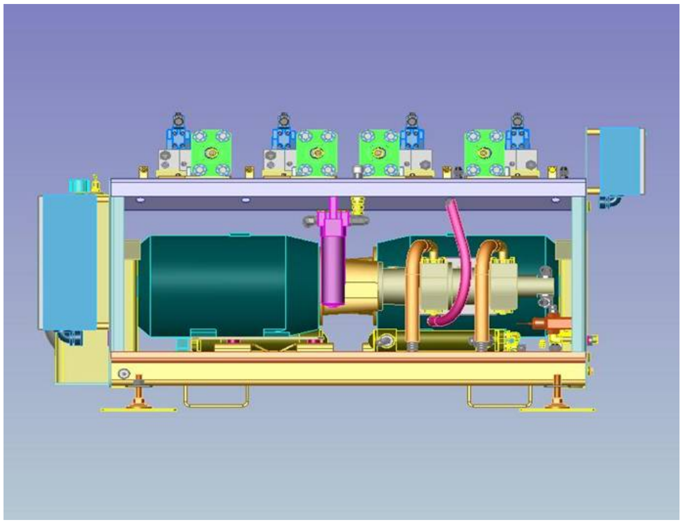

Figure 2. 600-MPa Intensifier Pump

The plumbing of a 600-MPa system for cutting applications include tubing, fittings, and on/off valve. Work has been progressing by tubing suppliers to develop reliable tubing with at least 50,000 cycles lifetime for reliable operation at these pressures. While this goal has been accomplished for 4.7-mm and 3-mm ID tubing, work is still needed for 2-mm ID tubing which is currently at 8000-cycles lifetime. One approach to improve the lifetime of tubing is to improve the bore surface finish. Tests on short length tubing indicate that the lifetime of tubing increase by a factor of 50% when the bore of the tube is machine-finished. Obviously, this approach is not adequate for long tubing and an alternative approach is needed. It must be mentioned here that the tubing used in WJ/AWJ cutting systems are not subjected to fatigue unless the pump is stopped and started, i.e., component upstream of the UHP on/off valve are not subjected to high cycle fatigue. Only downstream components to the on/off valve such as the nozzle body are subjected to higher cycling rates. Nozzle bodies are designed to withstand over 300K cycles. Typical fittings such as crosses, tees, elbows, and unions are also needed in plumbing lines. Recent results indicate that fittings life of over 50,000 cycles can be achieved.

While the use of the 2-mm ID tubing provides flexibility to allow the nozzle manipulation, the use of joint swivels is also of importance to provide additional flexibility and to relieve tubing from excessive bending stresses. 600-MPa swivel joints have been successfully tested for reliable and safe use. To develop a reliable 600-MPa on/off valve, we addressed the 600-MPa fatigue and tribological issues for valve seats, and seals resulting in a MTBF of over 50K cycles. A 600-MPa attenuator has also been developed for use with waterjet cutting systems. This attenuator is a mono-block pressure vessel similar to present 400-MPa design.

3. POWER AND EFFICIENCY

The power (E) of a jet can be expressed as:

$$E = K\ A_n P^{1.5} \tag{1}$$

Where A_n is the orifice cross-sectional area and K is a numerical constant, and P is pressure. From this equation, it can be seen that the power density, defined as the jet hydraulic power per unit area, is only a function of pressure:

$$E / A_n = K\ P^{1.5} \tag{2}$$

For AWJ, the power density can be calculated by dividing the abrasive particle kinetic energy (E_a) by the mixing tube cross sectional area (A_m). E_a can be expressed as:

$$E_a = \frac{1}{2} \dot{m}_a V_a^{\ 2} \tag{3}$$

The following expressions can easily be deduced:

$$E_a / A_m = K_1\ P^{1.5} \tag{4}$$

K_1 in the above equation contains the loading ratio $r = \dot{m}_a / \dot{m}_w$, and the momentum exchange relationship $V_a = \zeta_o V_j / (1 + r)$, and also the area ratio of the orifice to the mixing tube A_n/A_m. If these ratios are kept unchanged, then the AWJ power density will only be a function of pressure. Table 1 shows the jet power density for pressures up to 1000-MPa for a fixed hydraulic power of 25 kW. This table illustrates the power density of typical waterjets and also abrasive waterjets (AWJ). For AWJ, we used d_m/d_n =2.5, r=10%, and ζ_o= 0.9. Observe that increasing the pressure from 400-MPa to 600-MPa results in an increase in power density of 83%, or 1.83 times. This is associated with a decrease in water flow rate, and correspondingly, abrasive flow rate by 33%. The same effect can be achieved by increasing the pressure using a fixed orifice size as shown in Table 2. In this case, the hydraulic power will increase. The same 83% increase in power density (for the same d_m/d_n =2.5, r=10%, and ζ_o= 0.9) will be obtained by increasing the pressure from 400-MPa to 600-MPa (The power will increase from 25 kW to about 46 kW).

Table 1. AWJ Power Density at 25 kW Hydraulic Power

Power kW	*p* MPa	*q* *l/min*	d_n *mm*	AWJ *kW/mm²*
25	100	17.83	1.01	0.34
25	200	8.91	0.60	0.97
25	300	5.94	0.44	1.77
25	400	4.46	0.36	2.73
25	500	3.57	0.30	3.82
25	600	2.97	0.26	5.02
25	700	2.55	0.23	6.33
25	800	2.23	0.21	7.73
25	900	1.98	0.19	9.22
25	1000	1.8	0.18	10.80

Table 2. WJ and AWJ Power Density using a 0.26mm WJ Orifice

Power kW	*p* MPa	*q* *l/min*	d_n *mm*	AWJ *Kw/mm²*
3.1	100	2.23	0.26	0.34
8.8	200	3.15	0.26	0.97
16.2	300	3.86	0.26	1.77
25.0	400	4.46	0.26	2.73
34.9	500	4.98	0.26	3.82
45.9	600	5.46	0.26	5.02
57.9	700	5.90	0.26	6.33
70.7	800	6.30	0.26	7.73
84.4	900	6.69	0.26	9.22
98.8	1000	7.05	0.26	10.80

It is of interest to note that the power efficiency η of an AWJ is independent of pressure as expressed by Hashish (2):

$$\eta = r\zeta_o^2 / (1+r)^2 \tag{5}$$

The power density on the other hand, is a strong function of pressure as equation 4 shows and tables 1 and 2 above illustrate. Whether the power of the jet or the orifice size are kept unchanged while the pressure is increased, the end result is the same as far as power efficiency and power density change provided that the abrasive loading ratio is kept constant.

4. CUTTING OBSERVATIONS

In this section we describe the effect of pressure on cutting speed and kerf width with focus on abrasive flow rate and its consumption per unit length of cut. Prior work (3-5) did not address the effect of abrasives on cutting speed. In addition, the effects on kerf taper have not been addressed before.

4.1 Cutting Speed

Figure 3 shows cutting results for aluminum and steel at pressures up to 572 MPa. A fixed orifice size of 0.23 mm was used in these tests. Accordingly, as pressure increases, jet power increases. A linear trend is observed for the effect of pressure on cutting speed at these conditions. This trend is confirmed by additional test data as shown in Figure 4. In this figure, different orifice sizes, mixing tube diameters, and abrasive flow rates were used for cutting 12.5-mm thick steel. The power of the jet and the water flow rate in these tests also increased as can be depicted from table 2.

A general description of this trend can simply be expressed as:

$$u = K_2 (P - P_c) \tag{6}$$

Where P_c is a threshold cutting pressure and K_3 is a constant based mainly on the target and abrasive materials and to a lesser degree on other parameters. If P_c is ignored, then the cutting speed is directly proportional to pressure. The abrasive consumption per unit length of cut will then be inversely proportional to pressure. For example, if the pressure is increased from 400 MPa to 600 MPa, then the abrasive consumption per unit length will drop by 33.3%. This has a significant effect on the AWJ cost of operation as will be discussed later.

Because the same abrasive flow rate was used, the higher pressure jet was operated at a lower loading ratio (r) and consequently lower power efficiency as explained above. If the abrasive flow rate $\dot{m}_a$ was increased in proportion to the increase in water flow rate, then $\dot{m}_a$ can be expressed as follows:

$$\dot{m}_a = K_3 \ P^{0.5} \tag{7}$$

K_3 is a constant which is dependent on the waterjet orifice size and loading ratio. In this case, a faster cutting speed than the above linear trend would be expected. For simplicity, we can assume that the cutting speed versus pressure trend will still be linear. Similar to the above assumptions, the abrasive consumption per unit length in this case can be expressed as:

$$M_a = \dot{m}_a / u \tag{8}$$

i.e.

$$M_a \alpha \ P^{-0.5} \tag{9}$$

This equation shows that increasing the pressure will result in reducing the abrasive consumption per unit length of cut even with the conservative linearity assumption used. For example, increasing the pressure from 400 MPa to 600 MPa will result is an increase in the water flow rate and abrasive flow rate by 22.4%). However, the abrasive consumption per unit length will drop by 18.3% based on the above simplified equations.

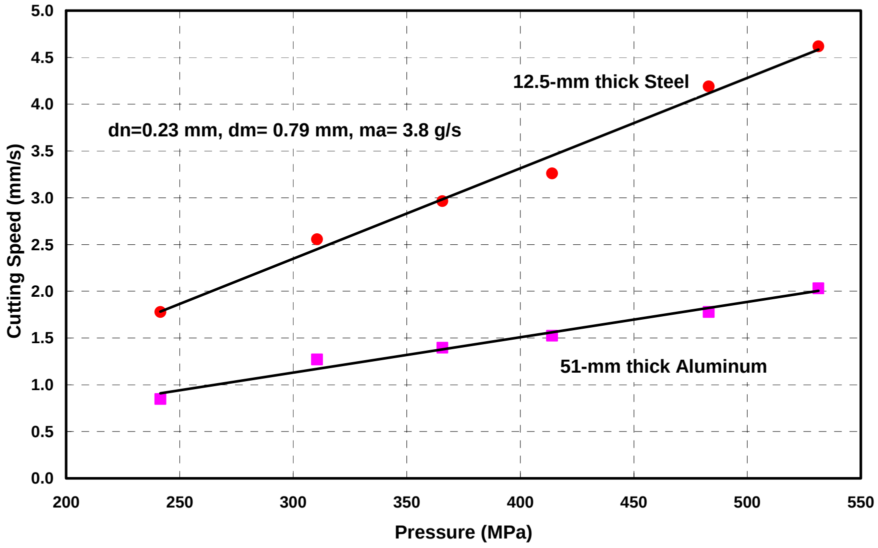

Figure 3. Effect of Pressure on AWJ Cutting of Aluminum and Steel

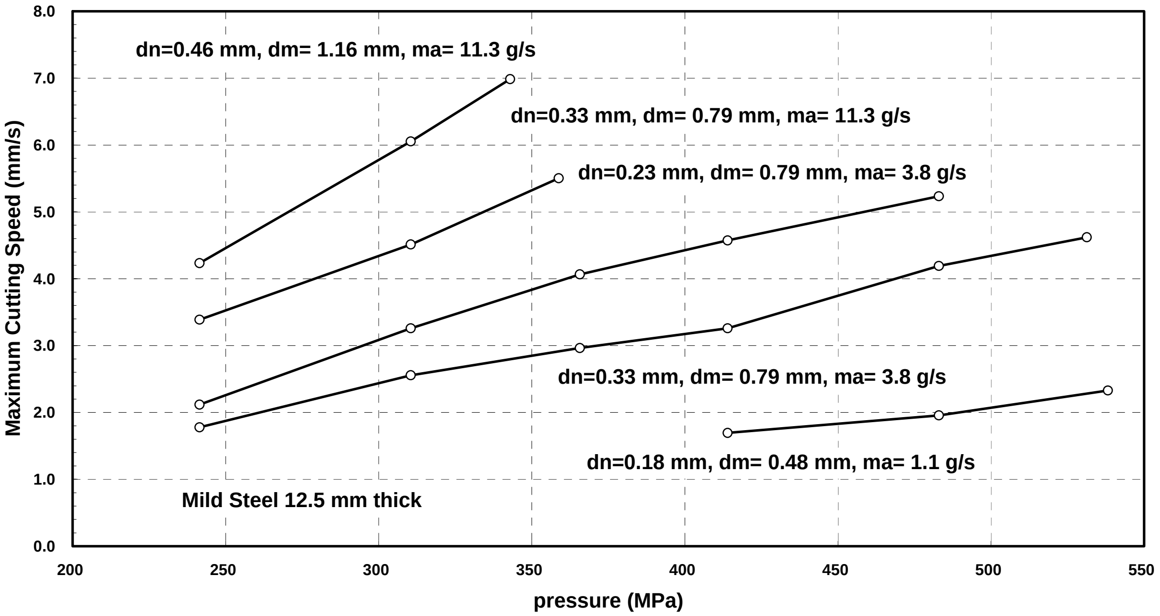

Figure 4. Effect of Pressure and Other Parameters on AWJ Cutting of Steel

An alternative strategy is to maintain the power (not the orifice diameter) fixed while increasing the pressure. This will result in a reduction in water flow rate and corresponding reduction in abrasive flow rate. If the cutting speed remains unchanged, as depicted form Figure 5, then the abrasive consumption per unit length will drop. In this case, the following relationship expresses the abrasive consumption per unit length as a function of pressure:

$$M_a \alpha \ P^{-1} \tag{10}$$

Increasing the pressure from 400 MPa to 600 MPa will be associated with a 33.3% reduction in abrasive flow rate and a 33.3% reduction in abrasive consumption per unit length if the cutting speed remained unchanged. Figure 5 shows data for aluminum cutting at 400 MPa and 600 MPa while keeping the power and abrasive loading ratio fixed. It expectedly shows that the maximum cutting speed did not change by changing the pressure while keeping the power fixed.

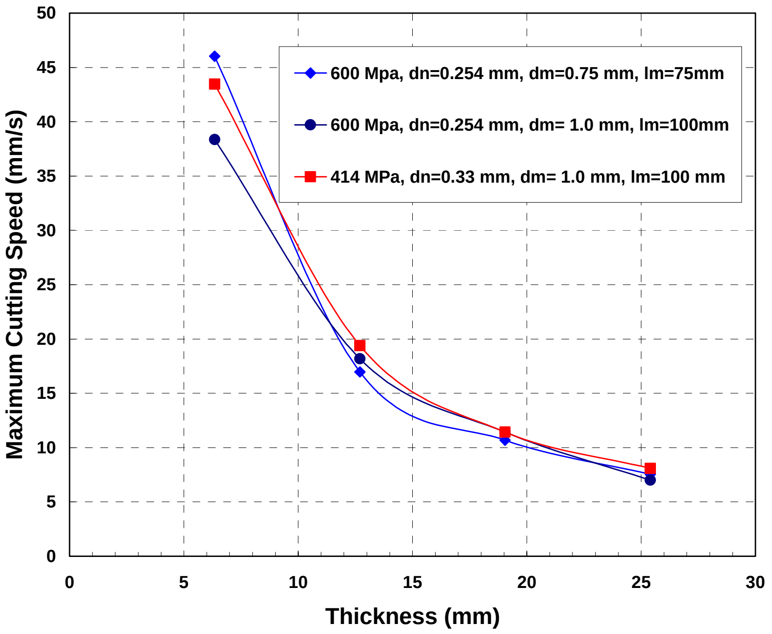

Figure 5: Maximum Cutting Speeds at Fixed Jet Power

The maximum cutting speed, however, may not be the correct criteria for selecting pressure when accurate cutting in needed. In this case, surface quality and geometry, especially kerf taper, will be more important criteria. This is discussed next.

4.2 Kerf Taper

Figure 6 shows an example of AWJ kerf width profile for 102-mm thick Aluminum cut at 572-MPa. The inner lines represent the maximum cutting speed at which complete separation occurs. This speed is about 1.35 mm/sec. A cutting speed of only about 30% of the maximum cutting speed will be needed to have minimal taper.

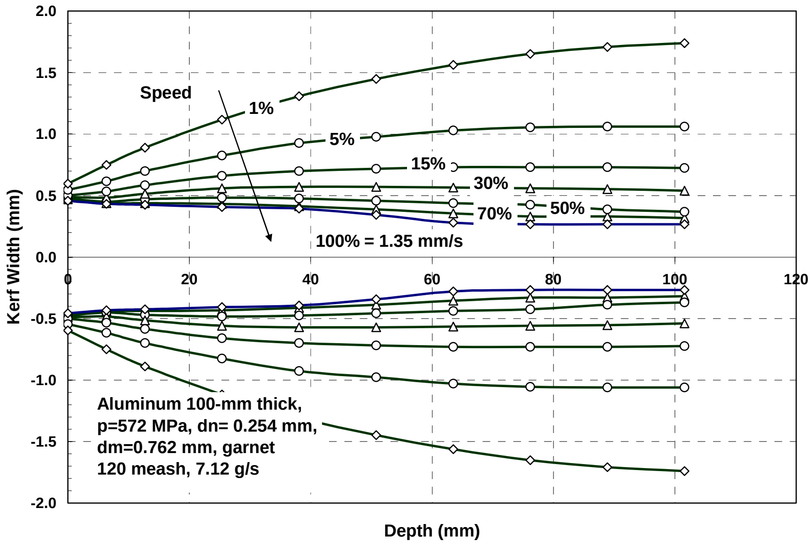

Figure 6. Kerf Profiles in 102-mm thick Aluminum

Figure 7 shows the effect of pressure on taper expressed as one half the difference between the upper and lower kerf widths of a cut. Observe that for the same taper results, the cutting speed for 600 MPa case is higher than the cutting speed for the 414 MPa case, both at the same power and abrasive loading ration. For example, an allowable taper of 0.1 mm can be obtained at about 4 mm/s at 400 MPa or at about 7 mm/s at 600 MPa. This increase in speed (by 75%) is also associated with a 33.3% reduction in abrasive flow rate. The effect on the abrasive consumption per unit length is about 62%. This will have a substantial impact on cost of cutting as will be addressed next.

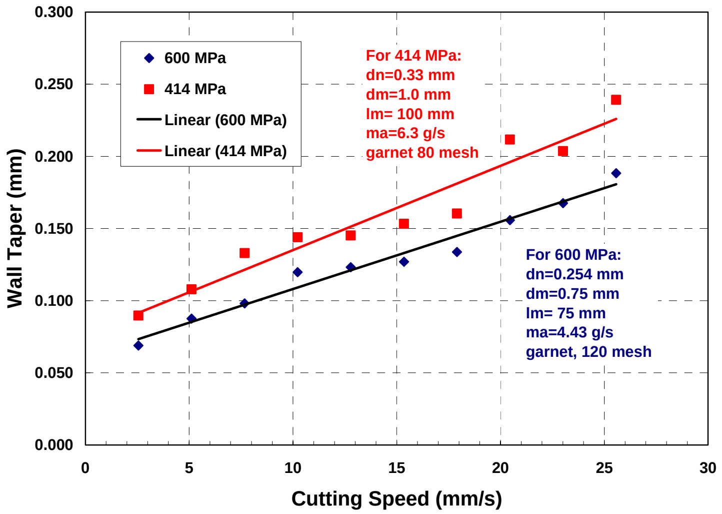

Figure 7. Taper in 6.3 mm thick Aluminum at 400 MPa and 600-MPa

5. COST ANALYSIS

In this analysis, we will keep the hydraulic power fixed and use the pressures of 400-MPa and 600-MPa for comparison.

Figure 8 shows a typical pie chart for the operating cost of an AWJ at 400-MPa. Observe that, excluding labor, the abrasive cost is the highest among all other cost items. The capital cost is next to abrasive cost, but this is highly dependent on the entire system and not just the high pressure system.

The assumptions that were used in calculating the cost are shown in Table 3. Observe that capital cost was conservatively assumed to be 20% higher for the 600 MPa over the 400 MPa cost. Figure 9 shows a cost comparison between using 400-MPa and 600-MPa assuming the maintenance cost at 600-MPa to be conservatively twice that at 400-MPa. With these assumptions, it can be calculated that the hourly cost at 400-MPa is $64.15 versus $63.85 for the 600-MPa condition. In this case, the increase in maintenance cost was offset by the decrease in abrasive cost.

To better evaluate the performance at elevated pressures, the cost per unit length of cut is used. While the hourly operating cost may be about the same for 400-MPa and 600-MPa, the cutting rates at 600-MPa are higher than those at 400-MPa when higher quality cuts are needed as described above. If it is assumed that a speed increase is about 20%, then Figure 10 shows the change in the hourly and cost per unit length of cut for different maintenance cost factors (defined as the multiplier increase in cost of maintenance of high pressure components over the case of 400-MPa).

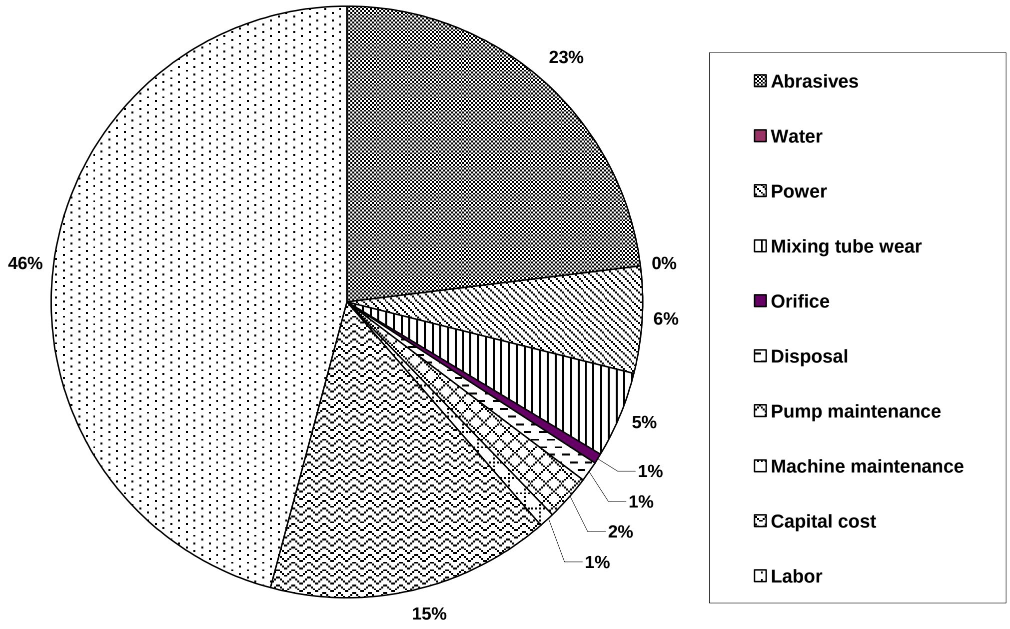

Figure 8. AWJ Cost Breakdown at 400-MPa

Table 3. Cost Assumptions

Cost Assumptions	at 400 MPa	at 600 MPa
Annual Interest Rate	5%	5%
Equipment Cost		20% higher
Payoff Period (years)	5	5
No of Payments	60	60
Power ($/KWH)	$0.10	$0.10
Water ($/m^3)	$0.3618	$0.3618
Garnet ($/kg)	$0.55	$0.55
Mixing tube cost	$250	$250
Mixing Tube Life	80 hr	80 hr
Disposal cost ($/ m3)	$2.70	$2.70
Orifice	$500	$500
Orifice life (hrs)	1000	1000

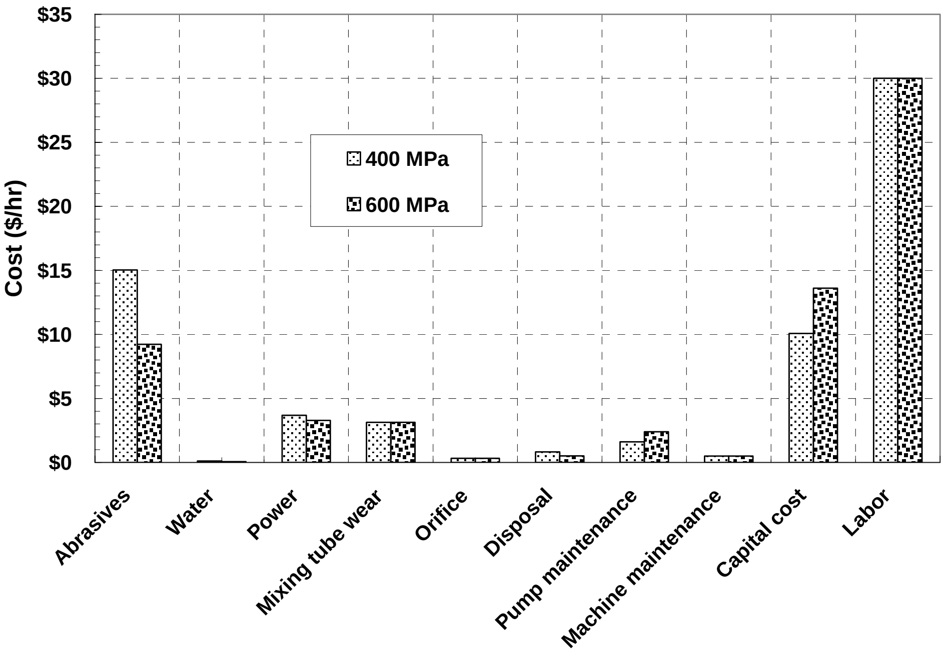

Figure 9. Comparison of Cost Elements at 400-MPa and 600-MPa

It is observed that even if the maintenance cost at 600-MPa is 4 times that at 400-MPa, the cost per unit length is about 13% less. Observe that the hourly operating cost is about the same at maintenance cost factor of about 2.2. Actual data indicated the maintenance cost factor is less than 2. At this level, the cost saving per unit length of cut is about 17%. This data is for a case when the cutting rate is increased by 20%. Figure 11 shows different cases for the % increase in cutting speed at 600-MPa and different maintenance cost factors. At 10 % increase in cutting speed and maintenance cost factor of 4, a 5% saving is realized for the cost per unit length.

Observe in table 3 above that we assumed a 10% reduction in up time for the 600-MPa condition. While this is conservative, it still shows the cost saving benefits at 600-MPa.

It may be argued that if the abrasive cost is low, then the benefit of cutting at elevated pressures is reduced. While this is true, the range of pricing and expected enhancement in performance suggests that increasing pressure will always be beneficial. Figure 12 shows the effect of abrasive cost on the cost per unit length of cut. Observe that at a maintenance cost factor of 2, the saving at 600-MPa using the lowest cost abrasives is slightly over 12%. Lefevre (6) observed similar cost benefits when operating at 600 MPa for cutting titanium and steel in a job shop setting but there was no information on itemized costs.

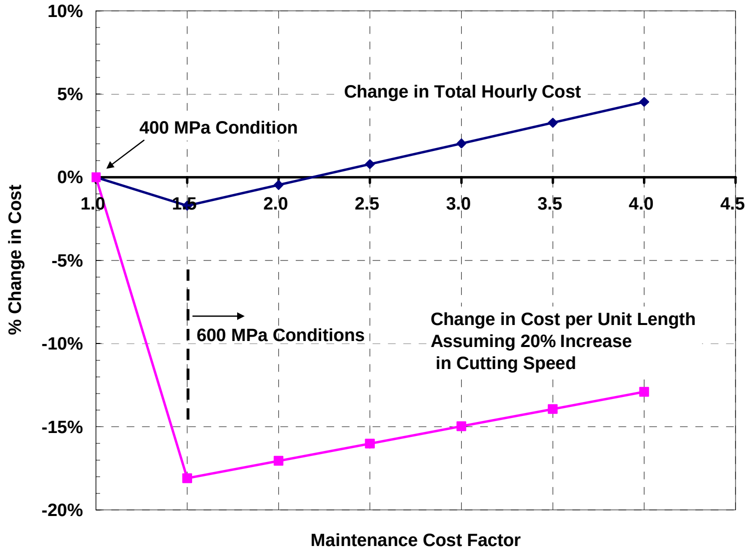

Figure 10. Effect of Cost Maintenance Factor of % Cost Change at 600-MPa

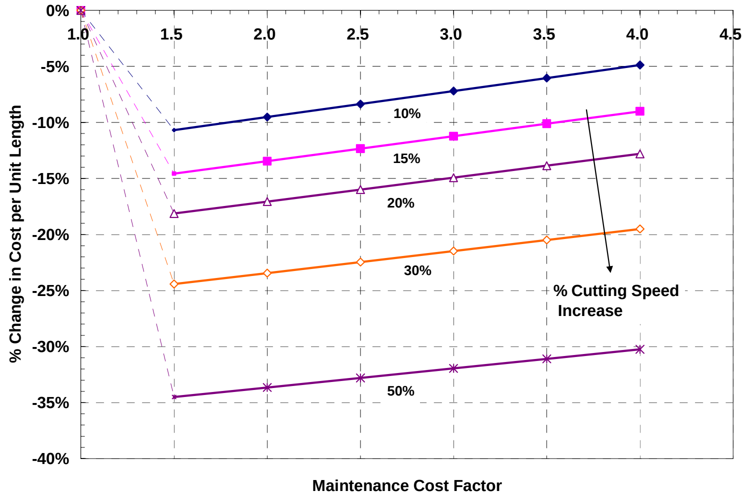

Figure 11. Percent Change in Cost at Different % Increase in Cutting Speed and Maintenance Cost Factors at 600-MPa

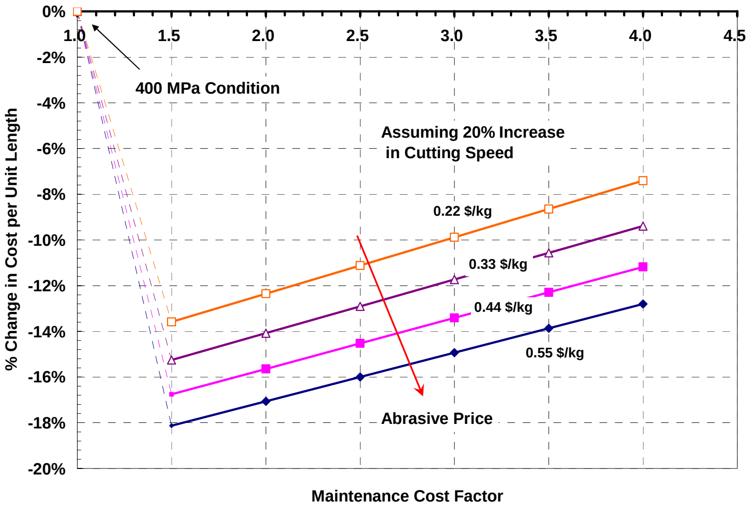

Figure 12. Effect Abrasive Cost on % Change in Cost per Unit Length at 600-MPa

The effect of pressure on the cost of the different items can be summarized in Table 4 as follows:

Table 4: Effect f Pressure on Cost factors

Cost Element	Effect of Pressure
Abrasives	decreased
Water	decreased
Power	unchanged
Mixing tube wear	unchanged
Orifice wear	increased
Disposal	decreased
Pump maintenance	increased
Machine maintenance	unchanged
Capital cost	increased
Labor	unchanged

6. CONCLUSIONS

1. Increasing the pressure is associated with increase in power density whether this is done at fixed power or fixed orifice size.
2. Increasing the pressure results in reducing the abrasive consumption per unit length of cut whether the power or the orifice size are kept constant.
3. The maximum cutting rates of 600-MPa AWJs is approximately equal to those at 400 MPa when the same power is used, but using 33% less water and abrasives.
4. For reduced-taper cutting, 600 MPa AWJs will result in significant increase in cutting speed compared to the case of 400 MPa AWJ using the same power.
5. The use of 600-MPa AWJ offer cost saving per unit length of cut in comparison to using 400-MPa AWJ at the same power level or the same orifice especially when reduced taper cuts are needed.

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8. NOMENCLATURE

A_n	Orifice cross-sectional area
A_m	Mixing tube cross-sectional area
d_m	Mixing tube diameter
d_n	Waterjet diameter
E	Power (Hydraulic)
E_a	Power (Abrasives)
K, K_1, K_2, K_3	Numerical constants
m_a	Abrasive flow rate
m_w	Water flow rate
P	Pressure
P_c	Critical pressure
q	Flow rate
r	Ratio of abrasive to water flow rates
V_j	Waterjet velocity
V_a	Abrasive velocity
ζ	Momentum transfer efficiency
η	Power efficiency
u	Cutting speed