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Paper

PUMPING EFFICIENCY'S EFFECT ON CUTTING PERFORMANCE

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ABSTRACT

Since the introduction of the abrasive waterjet cutting technology as a manufacturing process in the 1970s, there has been considerable research into predictive modeling of the cutting performance as a function of the various process parameters. The results of these research efforts have greatly expanded their capabilities and the ease of use in almost every sector of manufacturing. With the manufacturing industry's continual strive for improving the overall operational efficiency of manufacturing technologies, improving the output performance versus the input operational costs is one of the primary goals. The purpose of this paper is to present a new way to evaluate potential cutting performance based on actual high pressure pumping hardware, as opposed to a parameter by parameter academic comparison. This analysis will help manufacturing organizations better assess the various available technology options in choosing the best solution for their needs.

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1 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 for most kinds of materials. Due to its small thermal and mechanical forces on the material, which avoids stress and alteration of the material properties, abrasive waterjets have also become well suited for high precision and miniature cutting of delicate parts [1]. With such a variety of possible applications using the same flexible tool, the user still has to choose the right combination of parameters and hardware that optimally suits his application and to provide the best possible and most profitable outcome [2, 3, 7]. The main thrust of this paper is to evaluate one of the main cutting parameters and its dependence on the pumping hardware and its effect on the overall cutting process, so that the machine tool operator/owner can effectively choose the appropriate parameters for their applications.

2 ABRASIVE WATERJET PRINCIPLES

The basic physics of the abrasive waterjet process utilizes ultra-high pressure to accelerate water through an orifice, to form a high-velocity water jet stream at speeds greater than twice the speed of sound. By passing this high velocity waterjet through a mixing chamber and a larger diameter nozzle (mixing tube) a jet pump is created that will draw air into the nozzle assembly. This air flow will carry metered abrasive particles from an abrasive hopper to be entrained into the high velocity waterjet where it is accelerated to form the high velocity abrasive waterjet.

From Bernoulli's equation, the velocity of the waterjet, v_W, is a function of the water pressure, p, upstream of the nozzle's orifice, and the density of the water, ρ_W.

$$v_W = \sqrt{\frac{2p}{\rho_W}} \tag{1}$$

The flow rate of the water, Q_W, that is going through the nozzle is a function of the diameter of the nozzle's orifice, d_o, and the nozzle's overall coefficient of discharge, C_d. The coefficient of discharge includes the effects of water compressibility and the venna contracta of the water stream going through the orifice. Due to the compressibility of the water, it is function of both pressure and the geometry of the orifice. In general, its value ranges between 0.62 to 0.70.

$$Q_W = \frac{\pi}{4} d_o^2 \, C_d \, v_W \tag{2}$$

The hydraulic power of the waterjet exiting the orifice, P_{hyd}, is a function of the waterjet's flow rate and pressure, and the overall power consumption, P_{pump}, of the high pressure pump is a function of the pump's efficiency, η_p.

$$P_{hyd} = p \, Q_W \tag{3}$$

$$P_{pump} = \eta_p \, p \, Q_W \tag{4}$$

3 ABRASIVE CUTTING JET

In the abrasive waterjet cutting process, the mechanism of material removed from the workpiece is due to an erosion process from the collision of the abrasive particles and the surface of the workpiece. Thus, the abrasive particles are doing the actual cutting work. The amount of material a single abrasive particle removes is a function of the particle's mass, m_a, and velocity, v_a, also known as the particle's kinetic energy, $E_{P,kin}$

$$E_{P,kin} = \frac{1}{2} m_a \, v_a^2 \tag{5}$$

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

$$P_{P,kin} = \frac{1}{2} \, \dot{m}_a \, v_a^2 \tag{6}$$

To maximize the abrasive kinetic power of the cutting jet is either: increase the velocity of the abrasive particles, and/or increase the abrasive mass flow rates [6].

The velocity of the abrasive particles exiting the nozzle is a complex function of all the abrasive waterjet process parameters and the geometrical design of the waterjet nozzle. In its simplest terms it can be represented as a function of the momentum transfer efficiency (or abrasive speed ratio), Ψ_a, between the waterjet and the abrasives

$$v_a = \Psi_a v_W \tag{7}$$

The abrasive mass flow rate is an arbitrary input process parameter, but in practice it is generally chosen to be proportional to the waterjet mass flow rates by a proportionality constant, R

$$\dot{m}_a = R\dot{m}_W \tag{8}$$

Hence, the abrasive kinematic power of the cutting jet can now be defined as

$$P_{a,kin} = \frac{1}{2} R \, \dot{m}_W \, \Psi_a^2 \, v_W^2 \tag{9}$$

4 PUMPING TECHNOLOGIES

From a business operations point of view, the goal is to increase production rates while reducing operational costs. With abrasive waterjet cutting, this is done by maximizing the abrasive kinetic power to maximize the cutting speed, while at the same time minimizing the consumable costs such as the abrasive, electrical, and water costs.

Currently there are three main pumping technologies available to the waterjetting industry. Hydraulic Intensifiers and direct drive crank shaft pumps have been the main workhorses for the ultra-high pressure waterjet cutting and cleaning industry since the 1970s. A third alternate pumping technology utilizing electric servo drive pumps entered the ultra-high pressure market around 2008. All three pumping technologies are fully capable of generating waterjet pressures of at least 60,000 psi, and the hydraulic intensifiers are capable of obtaining pressures as high as 94 kpsi.

But all pumping technologies are not the same. Every pump's power rating is based on the pump's electrical input power consumption. The power available at the cutting nozzle is a direct function of the efficiency of the particular pump technology. Hence the maximum obtainable abrasive kinetic power of the cutting jet is also a direct function of the pumping technology's efficiency.

With all pumping technologies, the pump's maximum efficiency occurs when the pump is operating at its peak pressure and flow rate ratings. But due to the mechanical, electrical, and hydraulic constraints of the specific pumping technology also places limits on the range of operating ranges for the end user. For example, reducing the operating pressure at the nozzle, one would increase the jet's flow rate to maintain the same hydraulic output power. But once the output flow rate reaches the maximum flow rate capability of the pump, the output power can no longer be increased. Under these conditions the overall efficiency of the pump decreases since the output power of the pump has been reduced due to the reduction in the operating pressure.

All pump power ratings are based on the electrical consumption of the pump, not the output power of the pump. When operating at peak output power and efficiency, direct drive (crank shaft) pumps have an efficiency of 87% [5], hydraulic intensifier pumps have efficiencies in the 60 to 70% range [10], and electric servo pumps have efficiencies in the 71% to 77% range [8].

Hydraulic intensifier pumps and electric servo drive pumps require active cooling of the hydraulic fluids and the permanent magnet direct current (PMDC) electric motor and ball screw mechanism, 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. For example, a 50 hp hydraulic intensifier pump typically requires a minimum of 1.5 times more cooling water than the waterjet's flow rate, or 5 to 9 liters/min of cooling water. In areas where the cost of water is very high, this can be a significant impact on the water consumption costs or the overall electrical efficiency if a closed loop water cooling system is employed to cool the cooling water. Direct drive pumps utilize an integrated cooling circuit and do not require any external cooling[1].

5 ABRASIVE PARTICLE VELOCITY MEASUREMENTS

Because the volumetric material removal rates are a function of the particle's impact kinetic energy (particle velocity and particle mass) and the number of abrasive particle impacts (mass flow rate) per unit area, cutting performance is controlled by the jet pressure, its flow rate, and the abrasive flow rates. In general, increasing the jet pressure results in increasing the velocity of

[1] 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.

the particles due to the higher waterjet velocity. But due to the nozzle's geometrical design, frictional losses, and abrasive mass loading ratio, the abrasive particle velocity momentum transfer efficiency is unique for each nozzle design and setup. Because of this, determining the actual velocity of the abrasive particles exiting the water jet nozzle is a difficult parameter to obtain.

The Dual Disk Anemometer (DDA) apparatus was used to measure the abrasive particle velocities [4, 9], by measuring the time of flight between two high speed spinning disks. Figure 1 shows the measured mean abrasive velocities for different waterjet pressures and abrasive flow rates using a fixed waterjet nozzle geometry (d_o = 25um, d_m = 764um, and l_m = 100 mm)

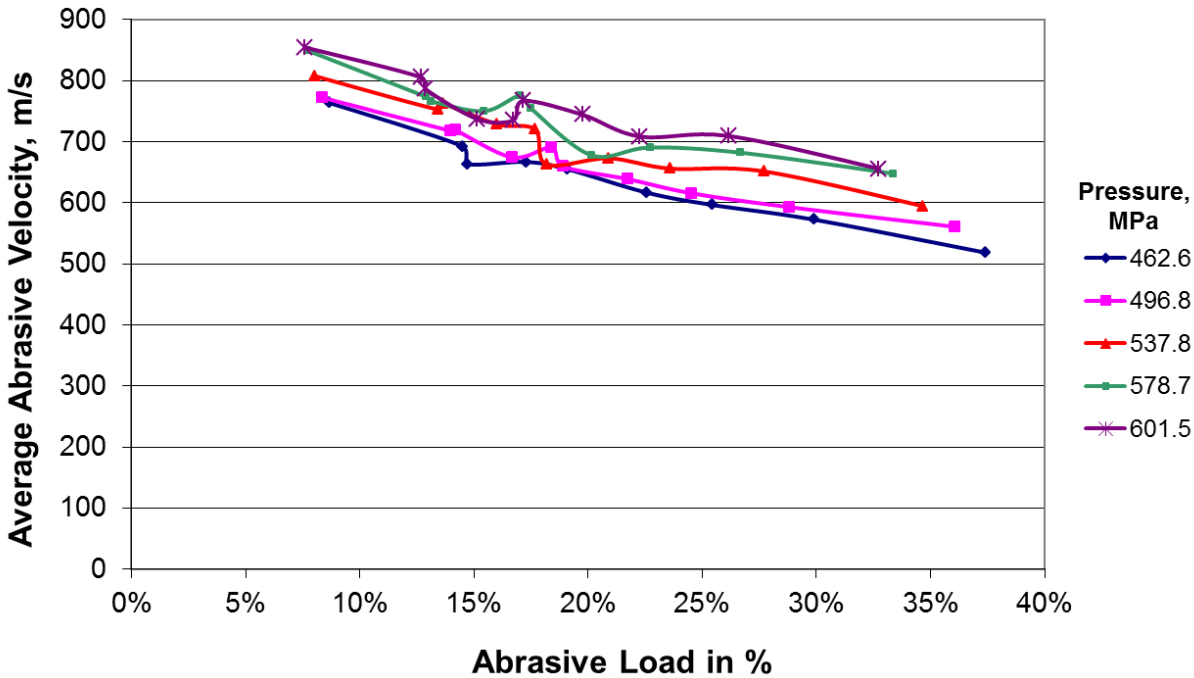

Figure 1. Experimentally determined Abrasive particle velocities at different pressures and abrasive mass loading, R.

It can be seen in Figure 1 that as the jet pressure increases, the average particle velocity increases for a fixed abrasive mass loading ratio. And as the abrasive mass loading ratio increases, the average particle velocity decreases because more of the fixed available energy is used to accelerate the abrasives.

Figure 2 shows the DDA average abrasive particle velocities in terms of the abrasive speed ratio (momentum transfer efficiency), Ψ_a, as a function of the abrasive mass loading, *R*. A simple regression analysis of the simple abrasive speed for the nozzle geometry under test yields empirical constants of a=0.423 and b = 0.47.

$$\Psi_a = \frac{a}{R+b} \tag{10}$$

Since the abrasive speed ratio can be written as an empirical function of the abrasive mass loading, the abrasive kinematic power can be written as a function of the abrasive mass loading, pump efficiency, and pump's energy consumption

$$P_{a,kin} = \frac{a^2\, R}{(R+b)^2}\, \eta_p\, P_{pump} \tag{11}$$

By dividing abrasive kinematic power by the electrical power consumption, an abrasive kinematic power ratio, $\Gamma_{abrasive}$, can be defined for the nozzle. It can be seen in this equation that the abrasive kinematic power ratio is a function of the abrasive mass loading and the efficiency of the high pressure pump, and is independent of the operating pressure which is in agreement with similar trends found with the abrasive waterjet power efficiency models [12].

$$\Gamma_{abrasive} = \frac{P_{a,kin}}{P_{pump}} \tag{12}$$

$$\Gamma_{abrasive} = \frac{a^2\, R}{(R+b)^2}\, \eta_p \tag{13}$$

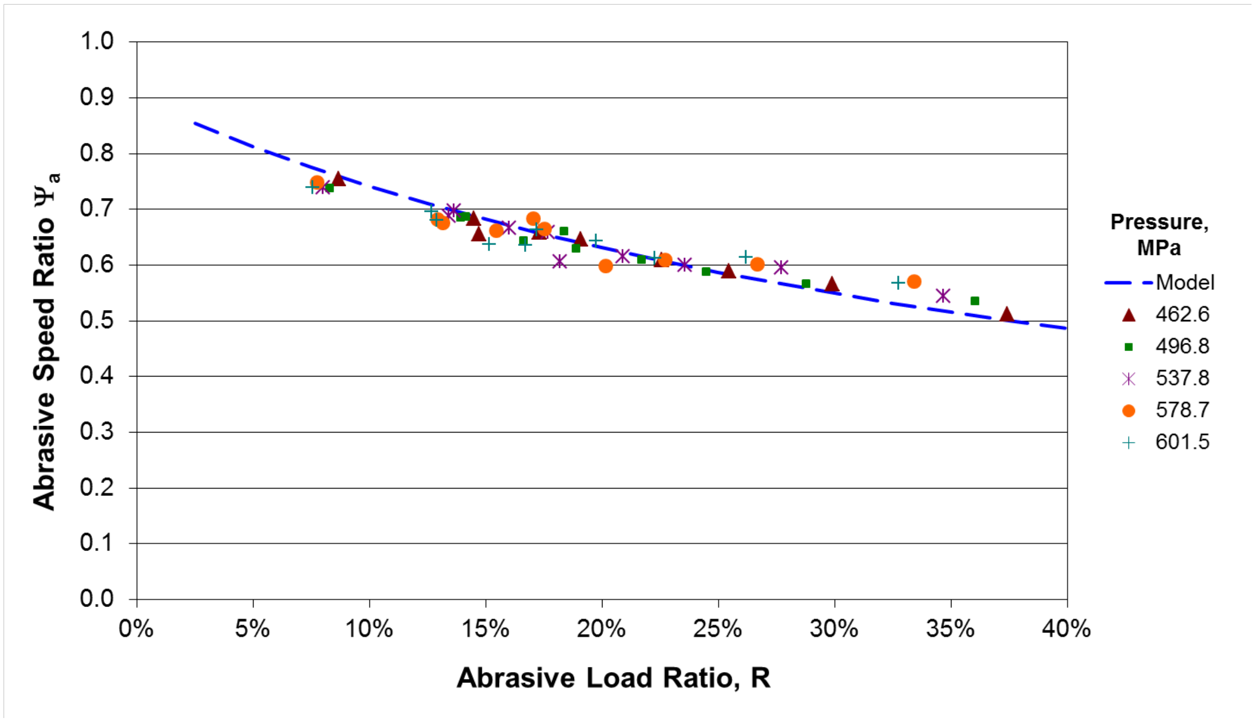

Figure 2. Experimentally determined abrasive speed ratio at different pressures and abrasive mass loading, *R*, with a = 0.423, and b = 0.47.

Figure 3 shows the abrasive kinematic power ratio as a function of the abrasive loading for three different pump technologies efficiencies. Increasing the abrasive mass loading ratio increases the abrasive kinematic power ratios due to the abrasive mass flow rate increasing. While maintaining the ratios constant, increasing the pump efficiency increases the abrasive kinematic power because more power is available at the nozzle due to higher pump efficiency for a fixed input power consumption.

It is interesting to observe from Figure 3 that for maintaining a fixed abrasive kinematic power ratio (horizontal dashed line A-B example at 4.2%), the abrasive mass loading must increase for lower efficiency pumps. This is because there is a reduction of available hydraulic power at the nozzle. Then for a fixed abrasive mass loading (vertical dashed line B-C example at 15%), higher efficiency pumps yield higher abrasive kinematic power ratios since more hydraulic power is available at the nozzle. Since the abrasive mass flow rate is an external parameter that can be arbitrarily set, increasing this parameter will result in an increase in the abrasive kinetic power regardless of the hydraulic power at the nozzle. Due to the nonlinear nature of the abrasive speed ratio, there is an optimal abrasive flow rate that maximizes abrasive kinematic power. This maximum can be found by finding the roots of the first partial derivative of the abrasive kinematic power ratio function. For this nozzle geometry, $R_{max} = b$.

$$\frac{\partial \Gamma_{abrasive}}{\partial R} = \frac{a^2(b-R)}{(R+b)^3}\eta_p \ = 0 \tag{14}$$

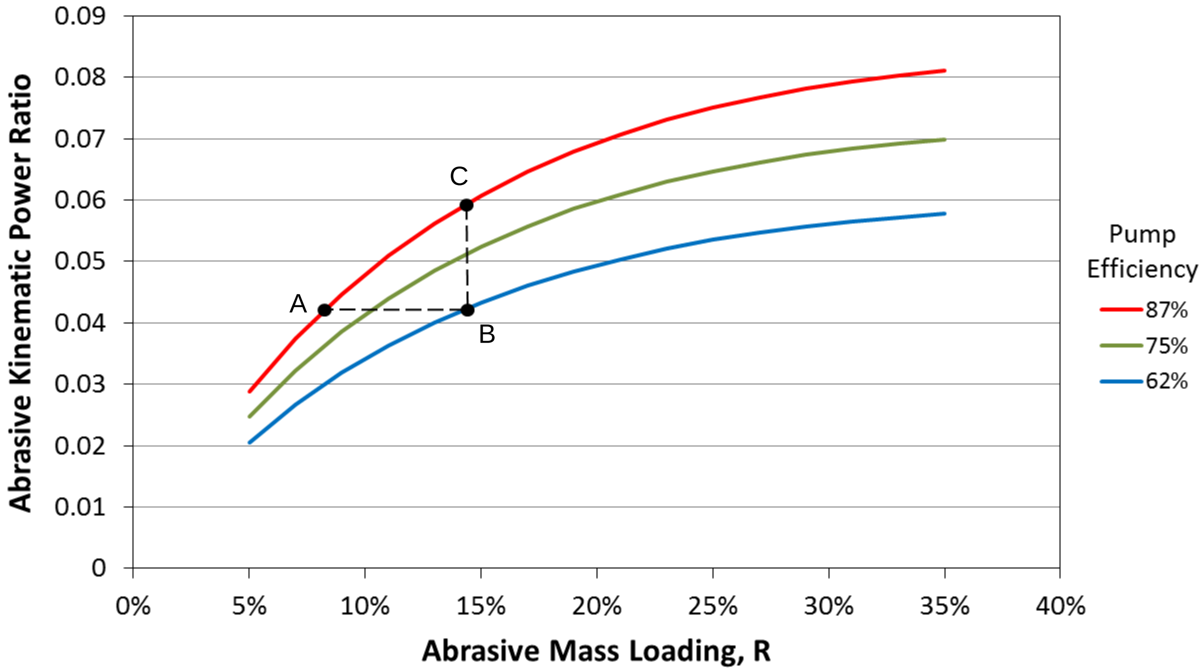

Figure 3. Abrasive kinematic power to electrical power consumption ratios for different abrasive mass loadings and pumping efficiencies, with a = 0.423 and b = 0.47.

When looking at the overall abrasive kinematic power ratios it becomes very obvious that the efficiency of converting the input power to the high pressure pump to the energy in the jet to remove material is less than 10%. This shows that there is a tremendous potential for significantly improvements in the abrasive waterjet cutting performance.

6 NOZZLE GEOMETRY AND THE ABRASIVE SPEED RATIO

The formula for the abrasive speed ratio is unique to the specific nozzle geometry under test. This is due to many factors. For example, the air mass flow rate entering the nozzle decreases the theoretical Bernoulli jet velocity exiting the nozzle when compared to operating the same nozzle in a vacuum [4]. The air mass flow rate entering the nozzle is a directly related to the amount of vacuum generated by the nozzle's jet pump effect, and it is also affected by the abrasive feed line diameter and length, and abrasive flow rates [13]. The momentum transfer between the air, abrasives, and water droplets do not instantly occur, but takes time to accelerate up to the exit velocity. The length and diameter of the mixing tube has an effect on the final exit abrasive particle velocities, along with the size of the abrasive particles [11]. And, acceleration times for larger and denser particles are a function of the velocity of the carrier fluid and the mixing tube geometry. Because of all of these factors, precise comparison of nozzle performance from one manufacturer to another is extremely difficult. This is part of the reason why one manufacturer can advertise that they have a better cutting nozzle over another manufacture under identical process parameter conditions.

7 CONCLUSIONS

When selecting the appropriate abrasive waterjet hardware for a manufacturing process, it is important to understand how the various abrasive process parameters relate to one another and how the overall equipment performs for the needed tasks. Often the driving factor in manufacturing is maximizing production rates while minimizing consumable costs. One of the obvious ways to maximize throughput is to maximize the amount of energy of the cutting jet at the workpiece. In the case of abrasive waterjets, this is maximizing the abrasive kinetic power of the cutting jet itself. It was shown in this paper that the abrasive kinetic power ratio is primarily driven by the abrasive mass loading and the efficiency of the pumping technology, and is independent of the operating pressure, which is counter intuitive to the observed practice of higher pressure means faster cutting. But the entire process needs to be considered when evaluating various pieces of hardware. The input power consumption must be the baseline comparison between different technologies. When technology comparisons are made from a uniform input power basis, it turns out that it is the efficiency of the pumping technology, not the operating pressure that has the greatest impact on cutting performance. Hence, higher efficient pumps result in lower consumption operating costs.

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9 NOMENCLATURE

$\dot{m}_W$, Q_W	Water flow rate (mass, volume)
$\dot{m}_a$	Abrasive feed rate
P_{pump}, P_{hyd}	Pump and Hydraulic power of jet
$P_{P,kin}$	Kinetic power of particles
p	Water operating pressure

R	Abrasive load
ρ_W	Density of water
η_{pump}	Pump efficiency
v_a	Particle velocity in mixing tube
v_W	Water velocity at orifice, in mixing tube
Ψ_a	Abrasive speed ratio
a, b	Constants for abrasive speed ratio
$\Gamma_{abrasive}$	Abrasive kinematic power ratio