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PERFORMANCES OF ABRASIVE WATER JET CUTTING WITH HYPER PRESSURE OF 900 MPA

Miroslav Radovanović*

University of Niš, Faculty of Mechanical Engineering, Niš, Serbia

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ABSTRACT

Abrasive water jet cutting machines operating at hyper pressure were introduced based on the notion that increased pressure means faster cutting. Applying hyper pressure results to faster cutting, lower abrasive consumption, higher productivity and smaller operating cost. Ultra-high pressure of 350 to 400 MPa is currently standard. However, a clear increase in performances and productivity and decrease in cost of abrasive water jet cutting can be achieved with hyper pressure. Performances of abrasive water jet cutting when applying hyper pressures of 900 MPa is analyzed in this paper.

INTRODUCTION

Abrasive water jet cutting is a very profitable machining process developed in the early 1980s. The process is based on the erosion of material by abrasive particles accelerated by high speed water jet. Since the beginning of the abrasive water jet cutting, water pressure has increased. Abrasive water jet machines operating at hyper pressure were introduced based on the notion that increased pressure means faster cutting. The reason is simple, higher pressure results to faster speed, better quality, lower abrasive consumption, higher productivity and lower cost. Development of abrasive water jet cutting is a result of development of high pressure pumps. KMT invents the first high pressure intensifier pump with 250 MPa (36000 psi) in 1951. Ingersoll Rand invents the first 380 MPa (55000 psi) ultra-high pressure pump in 1971. The first commercial abrasive water jet cutting system was available in 1983. In this system hard abrasive particles are added to the water jet, which makes it possible to cutting practically any material. Pressure has increased every decade since that time, moving to 380 MPa (55000 psi) by the end of the 1980s and reaching the current standard of 413.7 MPa (60000 psi) in the mid 1990s. Flow develops the first 600 MPa (87000 psi) intensifier pumps for laboratory applications in 1992. Flow introduces 413.7 MPa (60000 psi) intensifier pumps to the water jet cutting systems in 1998. First hyper pressure intensifier pump of 600 MPa (87000 psi) as two-stage system was introduced in 2001. and as one stage system in 2004. KMT was developed hyper pressure pump of 620 MPa (90000 psi) in 2004. Flow introduces the first hyper pressure pump of 600 MPa (87000 psi) for water jet cutting in 2006. UHDE was developed hyper pressure pump of 700 MPa (100000 psi) for the treatment of food and hyper pressure pump up to 1400 MPa (200000 psi) for testing and autofrettage. It can expect that trend to continue, with a likely 25 percent to 30 percent increase in pump pressures in the next five to ten years.

There are some studies on abrasive water jet cutting with hyper pressure above 600 MPa. Trieb and Zamazal in [1] have studied the aluminum and stainless steel abrasive water jet cutting with a pressure of 800 MPa. They investigated the effect of pressure and traverse speed on the cut depth. Koerner et al. in [2] have presented the results of abrasive water jet cutting with a pressure of 400 and 700 MPa. Hashish et al. in [3,4] have studied the performances of aluminum abrasive water jet cutting with a pressure of 690 MPa. Susuzlu et al. in [5] have presented the results of the abrasive water jet cutting with a pressure of 700 MPa. Susuzlu et al. in [6] have studied the performances of aluminum abrasive water jet cutting with a pressure of 800 MPa. Mohamed in [7] has studied the performances of abrasive water jet cutting with a pressure of 900 MPa. Perec in [8] has studied the possibilities of abrasive water jet cutting with a pressure of 1000 MPa.

ABRASIVE WATER JET MACHINE

In industrial application currently are in use water jet cutting machines with high and ultra-high pressure pumps of 150 to 400 MPa and hyper pressure pumps of 600 to 650 MPa. Ultra-high pressure pumps of 350 to 400 MPa are currently standard. However, their operation is essentially the same: water flows from an ultra-high or hyper pressure pump, through tubing, out of a cutting head as pure water jet or abrasive water jet and cut material. Basic components of typical abrasive water jet cutting machine are: water pump, tubing system, cutting head, abrasive hopper with abrasive metering, X-Y motion table and controller. Each of these components is vital for the water jet cutting machine to function properly. Water pump is a first vital

* Corresponding author. E-mail: mirado@masfak.ni.ac.rs

component of water jet cutting machine. Water pump is responsible for creating the pressure and flow of water and delivering it continuously. Water jet cutting machine is only as good as its pressure pump. Pumps applied in abrasive water jet machine are classified as shown in Table 1.

Table 1. Pumps in abrasive water jet machine

Pumps	Pressure
Low pressure pumps	p< 69 MPa (p<10000 psi)
Medium pressure pumps	69 MPa <p<103 MPa (10000 psi<p<15000 psi)
High pressure pumps	103 MPa <p<276 MPa (15000 psi<p<40000 psi)
Ultra-high pressure pumps	276 MPa <p<517 MPa (40000 psi<p<75000 psi)
Hyper pressure pumps	p>517 MPa (p>75000 psi)

There are two basic types of pumps in water jet cutting: direct drive and intensifier. Direct drive pumps use a crankshaft to move the plungers that pressurize the water. They are found in industrial applications with pressure to 380 MPa. Intensifier pumps use the concept of pressure intensification to generate the desired water pressure. These pumps use hydraulic to apply a certain amount of oil pressure on one side of a piston of a certain diameter. On the water side of the pump, the diameter of the piston is much smaller. The difference in the surface area between the hydraulic side and the water side gives a multiplication factor, or intensification ratio. Most intensifier pumps have an intensification ratio of 20 times. With intensifier pump can be achieved hyper pressure of 517 MPa and more. In the 600 MPa water jet cutting technique, the use of direct drive pumps is not possible. Their high number of strokes causes tribological problems and accelerated fatigue of high pressure components of the pump. This is exactly why the majority of industries today utilize intensifier pumps. Intensifier pumps of 600 MPa provide good pressure stability and jet quality. Water pumps are specified in either kilowatts (kW) or horsepower (HP) to indicate the size of the electric motor that creates the force to pressurize the water. Motor power range is from 11 kW (15 HP) to 150 kW (200 HP). From the water pressure and the pump power depend maximal water flow rate and maximal orifice size.

In Fig. 1 is shown hyper pressure intensifier pump with a pressure of 900 MPa (BOHLER).

Fig. 1. Hyper pressure intensifier pump with a pressure of 900 MPa

MODELING OF ABRASIVE WATER JET CUTTING

Process of abrasive water jet cutting is based on material removal from the workpiece by erosion. High velocity water jet accelerates abrasive particles that erode the material.

Cutting action can be divided into three steps:

1. Transformation of the potential energy of high pressure water into kinetic energy of water jet.
2. Transfer kinetic energy of water jet to abrasive particles accelerating abrasive particles using the momentum of the water jet.
3. Using the kinetic energy of the abrasive particles for removing small chips of the work material.

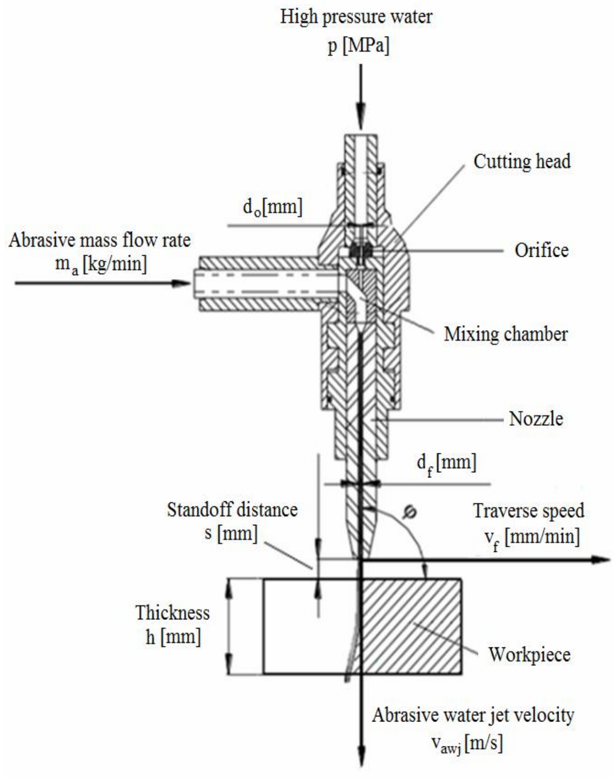

Fig. 2. Scheme of the abrasive water jet cutting

In abrasive water jet cutting water pump via accumulator and tubing directs the pressurized water to the cutting head. Water is pressed out of the orifice in form of jet. Abrasive particles are added in mixing chamber and mixed with the water jet in the nozzle (mixing tube, focusing tube). The high speed of the water jet creates a Venturi effect or vacuum in the mixing chamber, located immediately beneath the orifice, so that abrasive particles are sucked into the water jet. Abrasive particles go on interacting with the water jet and the inner walls of the nozzle, until they are accelerated using the momentum of the water jet. Abrasive particles have mixed with the water jet creating abrasive water jet. Nozzle directs the abrasive water jet to cut the workpiece material. Abrasive water jet cuts workpiece moving cutting head along the programmed contour using computer numerical control motion system of the machine. Scheme of the abrasive water jet cutting is shown in Fig. 2.

For abrasive particles currently uses Barton garnet. Typical sieve analysis for Barton garnet is shown in Table 2.

Table 2. Sieve analysis for Barton garnet

Aperture sizes (mm)	Retained mass (%)			
	Mesh 150	Mesh 120	Mesh 80	Mesh 50
0.053	1			
0.063	4			
0.075	14	6		
0.090	27	7		
0.106	38	16		
0.125	14	28	3	
0.150	1	30	7	
0.180		11	17	
0.212		2	24	2
0.250			31	15
0.300			15	29
0.355			3	37
0.425				16
0.500				1

There is a relation between the mesh of the abrasive and the average abrasive particle diameter.

$$Mesh \approx \frac{17.5}{d_p} \tag{1}$$

Where: d_p(mm)-average abrasive particle diameter.

Average abrasive particle diameter can be approximately determinate as:

$$d_p \approx \frac{d_f - d_o}{2} \tag{2}$$

Where: d_p(mm)-average abrasive particle diameter, d_f(mm)-nozzle diamater, d_o(mm)-orifice diameter.

Abrasive mesh and abrasive flow rate for typical orifice/nozzle combination are shown in Table 3.

Table 3. Abrasive mesh and abrasive flow rate for orifice/nozzle combination

Orifice	Nozzle	Abrasive mesh	Abrasive flow rate
0.178mm (0.007in)	0.508mm (0.020in)	120-220	0.11 kg/min
0.229mm (0.009in)	0.762mm (0.030in)	80-120	0.18-0.27kg/min
0.254mm (0.010in)	0.533mm (0.021in)	150-220	0.14-0.18kg/min
0.254mm (0.010in)	0.762 (0.030in)	80-120	0.23-0.34kg/min
0.330mm (0.013in)	1.016mm (0.040in)	60-80	0.45-0.57kg/min
0.356mm (0.014in)	0.762mm (0.030in)	80-120	0.32-0.41kg/min
0.356mm (0.014in)	1.016mm (0.040in)	60-80	0.50-0.61kg/min
0.356mm (0.014in)	1.067mm (0.042in)	50-80	0.63-0.82kg/min
0.381mm (0.015in)	0.813mm (0.032in)	80-120	0.36-0.45kg/min
0.381mm (0.015in)	1.016mm (0.040in)	60-80	0.57-0.68kg/min
0.381mm (0.015in)	1.219mm (0.048in)	50	0.82-1.09kg/min
0.508mm (0.020in)	1.067mm (0.042in)	50	0.63-1.09kg/min

Traverse speed can be determinate using the specific cutting energy of work material as:

$$v_f = \frac{\xi P_a}{uihd_{awj}} \tag{3}$$

Where: v_f-traverse speed, ξ-cutting energy efficiency coefficient, P_a- abrasive jet power, u-specific cutting energy, i-quality number, h-material thickness, d_{awj}-abrasive water jet diameter.

Cutting faster is possible by increasing water pressure, water flow rate and abrasive flow rate.

Cutting energy efficiency coefficient is determined empirically as:

$$\xi = 0.9113 v_f^{0.134} \tag{4}$$

Quality number describes the qualitative level of the surface roughness, the tape angle and the specific cut surface characteristics. Quality number has value from 1 to 10 (1 for rough cut strongly tapered, 5 for smooth cut small tapered, 10 for smooth and square cut).

Specific cutting energy is also determined experimentally. Typical values of specific cutting energy are shown in Table 4.

Relation between the specific cutting energy and machinability number is:

$$u = \frac{6.11 \cdot 10^{11}}{N_m} \tag{5}$$

Operating cost in abrasive water jet cutting can be calculated as:

$$C = \frac{L}{v_f}\left(C_e + C_w + C_a + C_r + C_m\right) \tag{6}$$

Where: C (EUR)-operating cost, L (m)-cut length, v_f (m/h)-traverse speed, $C_e = c_e \cdot P_e$ (EUR/h)-cost of electrical energy, c_e (EUR/kWh)-unit cost of electrical energy, P_e (kW)-electrical power consumption, C_w (EUR/h)-cost of water, $C_a = c_a m_a$ (EUR/h)-cost of abrasive, c_a (EUR/kg)-unit cost of abrasive, m_a (kg/h)-abrasive mass flow rate, C_r (EUR/h)-cost of wearing parts, C_m (EUR/h)-maintenance cost.

Table 4. Specific cutting energy

Material	Specific cutting energy u (MJ/m^3)
Mild steel	6975
Hardened steel	7600
Stainless steel 304	7460
Stainless steel 316	7353
Zink Alloy	4493
Aluminum 6061-T6	2869
Copper	5555
Titanium	5313
Granite	1898
Glass	1025
Plexiglas	885

Cost of water can calculate as:

$$C_w = c_w \cdot m_w = \frac{\pi \psi c_w}{2\sqrt{2\rho_w}} \cdot d_o^2 \sqrt{p} \tag{7}$$

Where: c_w (EUR/m^3)-unit cost of water, m_w (m^3/h)-water consumption, c_v-velocity coefficient of the orifice, ρ_w (kg/m^3)-density of water, d_o (m)-orifice diameter, p (Pa)-water pressure.

Operating cost, according equations from (6) and (7) can be done in form:

$$C = \frac{L}{v_f}\left(c_e P_e + \frac{\pi c_v c_w}{2\sqrt{2\rho_w}} \cdot d_o^2 \sqrt{p} + c_a m_a + C_r + C_m \right) \quad (8)$$

There are three main factors which determine the performances of abrasive water jet cutting process: water pressure, water flow rate and abrasive flow rate.

Characteristics of abrasive water jet cutting process can calculate as follows:

- Hydraulic power

$$P_w = pq \quad (9)$$

- Water jet velocity

$$v_{wj} = c_v \sqrt{\frac{2p}{\rho_w}} \quad (10)$$

- Orifice diameter

$$d_o = \sqrt{\frac{q}{c_d \frac{\pi}{4} \sqrt{\frac{2p}{\rho_w}}}} \quad (11)$$

$$d_o = d_{o\ standard}$$

- Water jet flow rate

$$q_w = c_d \frac{\pi d_o^2}{4} \sqrt{\frac{2p}{\rho_w}} \quad (12)$$

- Water jet mass flow rate

$$\dot{m}_w = \rho_w q_w \quad (13)$$

- Nozzle diameter

$$2.5 d_o \le d_f \le 3 d_o \quad (14)$$

$$d_f = d_{f\ standard}$$

- Abrasive particle diameter

$$d_p \approx \frac{d_f - d_o}{2} \quad (15)$$

- Abrasive mass flow rate

$$\dot{m}_a = R \dot{m}_w \quad (16)$$

- Abrasive water jet velocity

$$v_{awj} = \eta \frac{v_{wj}}{1+R} \quad (17)$$

- Abrasive jet power

$$P_a = \frac{1}{2} \dot{m}_a v_{awj}^2 \quad (18)$$

- Abrasive water jet diameter

$$d_{awj} \approx 1.1 d_f \quad (19)$$

- Power density

$$P_d = \frac{P_a}{\frac{\pi d_{awj}^2}{4}} \quad (20)$$

- Traverse speed

$$v_f = \frac{\xi P_a}{u i h d_{awj}} \quad (21)$$

- Machining time

$$t_m = \frac{L}{v_f} \quad (22)$$

- Abrasive consumption

$$C_a = \dot{m}_a t_m \quad (23)$$

- Operating cost

$$C = \frac{L}{v_f}\left(c_e P_e + \frac{\pi c_v c_w}{2\sqrt{2\rho_w}} \cdot d_o^2 \sqrt{p} + c_a m_a + C_r + C_m \right) \quad (24)$$

Where: P_w-hydraulic power, p-water pressure, q-water flow rate, v_{wj}-water jet velocity, c_v-coefficient of velocity (c_v=0.9-0.98), ρ_w-density of water, d_o-orifice diameter, c_d-coefficient of discharge (c_d=0.6-0.8), q_w-water jet (volume) flow rate, $\dot{m}_w$-water jet mass flow rate, d_f-nozzle diameter, $\dot{m}_a$-abrasive mass flow rate, v_{awj}-abrasive water jet velocity, η-momentum loss factor (η=0.65-0.85), R-abrasive mass loading (R=0.12-0.17), P_a-abrasive jet (kinetic) power, d_{awj}-abrasive water jet diameter, P_d-power density, v_f-traverse speed (cut speed), ξ-cutting energy efficiency coefficient ($\xi = 0.9113 v_f^{0.134}$), u-specific cutting energy, i-quality number, h-material thickness, t_m-machining time, L-cut length, C_a-abrasive consumption, C-operating cost, L-cut length, P_e-electrical power consumption, c_e-unit cost of electrical energy, c_w-unit cost of water, c_a-unit cost of abrasive, C_r-costs of wearing parts per hour, C_m-maintenance costs.

Analysis of the abrasive water cutting performances is given in the case of cutting 25 mm thick aluminum 6061-T6. The example data is: density of water is ρ_w=1000 kg/m^3, coefficient of speed is c_v = 0.98, coefficient of discharge is c_d=0.7, momentum loss factor is η=0.75, abrasive mass loading is R=0.145, abrasive factor is f_a=1 for Garnet, specific cutting energy for 6061-T6 aluminum u=2869 MJ/m^3, quality number is i=1 for rough cut, abrasive is Garnet, cut length is L=1m, unit cost of electrical energy c_e=0.105 EUR/kWh, unit cost of water c_w=0.5 EUR/m^3, unit cost of abrasive c_a=0.7 EUR/kg, costs of wearing parts per hour C_r=0.858 EUR/h, maintenance costs C_m=1.25 EUR/h.

Table 5. Comparison of abrasive water jet cutting performances

Pump	HP75S (WARDJet)	HyperJet S (Flow)	CP 1000-0,5 (BOHLER)
Motor power	56 kW (75 HP)	37 kW (50 HP)	22 kW (HP)
Operating pressure	413.7 MPa (60000 psi)	600 MPa (87000 psi)	900 MPa (130000 psi)
Water flow rate	5.68 L/min	2.44 L/min	0.50 L/min
Hydraulic power	39.16 kW	24.40 kW	7.5 kW
Water jet velocity	891 m/s	1073 m/s	1315 m/s
Orifice diameter	0.432 mm (0.017 in)	0.254 mm (0.010 in)	0.106 mm (0.004 in)
Water jet flow rate	5.60 L/min	2.28 L/min	0.497 L/min
Water jet mass flow rate	5.60 kg/min	2.28 kg/min	0.497 kg/min
Nozzle diameter	1.295 mm (0.051 in)	0.762 mm (0.030 in)	0.305 mm (0.012 in)
Orifice/nozzle size	17/51	10/30	4/12
Abrasive particle size	~0.431 mm	~0.254 mm	~0.100 mm
Abrasive size	Mesh 50	Mesh 80	Mesh 150
Abrasive mass flow rate	0.810 kg/min	0.330 kg/min	0.072 kg/min
Abrasive water jet velocity	584 m/s	703 m/s	861 m/s
Abrasive jet power	2.30 kW	1.36 kW	0.44 kW
Abrasive water jet diameter	1.424 mm	0.838 mm	0.335 mm
Power density	1.44 kW/mm^2	2.50 kW/mm^2	4.99 kW/mm^2
Traverse speed	674 mm/min	678 mm/min	531 mm/min
Machining time	1.48 min	1.47 min	1.88 min
Abrasive consumption	1.20 kg	0.48 kg	0.13 kg
Operating cost	1.04 EUR	0.49 EUR	0.23 EUR

Comparison of abrasive water jet cutting for various water pressure is shown in Table 5. With decrease the motor power, as operating pressure goes up, water flow rate goes down, water jet velocity goes up, orifice diameter and nozzle diameter goes down, abrasive mass flow rate goes down, abrasive water jet velocity goes up, and power density goes up. Traverse speed is little lesser, but abrasive consumption rapidly goes down and operating cost per meter of cut rapidly goes down. Abrasive mesh size goes up and quality of the cut is better.

CONCLUSION

Abrasive water jet cutting machines operating with hyper pressure of 900 MPa have better economical performances versus abrasive water jet cutting machines operating with ultra-high pressure of 400 MPa and hyper pressure of 600 MPa.

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REFERENCES

[1] F. Trieb, K. Zamazal, 800 MPa pure waterjet and abrasive waterjet cutting. What´s next, 2001 WJTA American Waterjet Conference, Minneapolis, Minnesota, Paper 61, August 18-21, 2001

[2] P. Koerner, W. Hiller, H. Werth, Design of reliable pressure intensifiers for water-jet cutting at 4 to 7 kbar, 16th International Conference on Water Jetting, Aix en Provence, France, pp. 123-132, October 16-18, 2002

[3] M. Hashish, D. Steele, D. Bothell, Machining with super-pressure (690 MPa) waterjets, International Journal of Machine Tools and Manufacture, Vol. 37, No. 4, pp. 465-479, 1997

[4] M. Hashish, Cutting and drilling at 690 MPa pressure, 10th American Waterjet Conference, Houston, Texas, paper 10, August 14-17, 1999

[5] T. Susuzlu, A. Hoogstrate, B. Karpuschewski, Initial research on the ultra-high pressure waterjet up to 700 MPa, Journal of Material Processing Technology, Vol.149,pp.30-36,2004

[6] T. Susuzlu, A. Hoogstrate, B. Karpuschewski, Waterjet cutting beyond 400 MPa, 2005 WJTA American Waterjet Conference, Texas, Houston, paper 4A-1, August 21-23, 2005

[7] M. Mostafa, Waterjet cutting up to 900 MPa, Dissertation, University of Hanover, 2004

[8] A. Perec, Possibilities of materials machining with an hydroabrasive waterjet under 1000 MPa pressure, 3rd International Conference on Machining and Measurements of Sculptured Surfaces, Krakow, September 24-26, 2003