International Journal of Modeling and Optimization, Vol. 7, No. 5, October 2017

Performances of Abrasive Water Jet Cutting with Hyper Pressure

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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. Performances of abrasive water jet cutting when applying hyper pressures of 600 MPa is presented in this paper.**

***Index Terms*—Abrasive water jet, cutting, hyper pressure.**

I. Introduction

Abrasive water jet cutting is now a widely accepted machining process in industry for contour cutting metals and other materials. The process is based on the erosion of material by abrasive particles accelerated by high pressure water jet. In abrasive water jet cutting water pressure, water flow rate and abrasive mass flow rate are the most important factors that affect to productivity and economy. Since the beginning of abrasive water jet cutting, water pressure has increased. The reason is simple, higher pressure results to faster speed, better quality, lower abrasive consumption, higher productivity and lower cost. KMT invents the first high pressure intensifier pump with 250 MPa (36000 psi) in1951. 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. Flow introduces 413.7 MPa (60000 psi) intensifier pumps to the water jet cutting in 1998. Flow introduces the first hyper pressure pump of 600 MPa (87000 psi) for water jet cutting in 2006. For water jet cutting KMT introduces the hyper pressure pump of 620 MPa (90000 psi) with motor power of 60 HP in 2009. and with motor power of 125 HP in 2010.

There are more studies on abrasive water jet cutting with hyper pressure of 600 MPa. Werth et al. in [1] have presented the results of the comparison of aluminum and stainless steel abrasive water jet cutting with a pressure of 350 and 600 MPa. Hoogstrate *et al*. in [2] have investigated the cut depth and surface roughness when cutting aluminum and stainless steel by abrasive water jet with a pressure of 600 and 650 MPa. Luis *et al*. in [3] have studied the aluminum abrasive water jet cutting with a pressure of 600 MPa. Hashish in [4] has studied the aluminum abrasive water jet cutting with a pressure of 600 MPa. Lefevre *et al.* in [5] have presented the results of abrasive water jet cutting with a pressure of 600 MPa. Susuzlu *et al*. in [6] have studied the performances of aluminum abrasive water jet cutting beyond 400 MPa.

Manuscript received September 28, 2017; revised October 28, 2017.
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II. Water Jet Cutting 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 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. In Fig. 1 is shown water jet cutting machine with pump pressure of 600 MPa (Flow).

Fig. 1. Water jet cutting machine with pump pressure of 600 MPa.

Water pump is a first vital 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 water jet cutting are classified as:

- Low pressure pumps, $p < 69$ MPa ($p < 10000$ psi)
- Medium pressure pumps, $69 \text{ MPa} < p < 103 \text{ MPa}$ ($10000 \text{ psi} < p < 15000 \text{ psi}$)
- High pressure pumps, $103 \text{ MPa} < p < 276 \text{ MPa}$ ($15000 \text{ psi} < p < 40000 \text{ psi}$)
- Ultra-high pressure pumps, $276 \text{ MPa} < p < 517 \text{ MPa}$ ($40000 \text{ psi} < p < 75000 \text{ psi}$)
- Hyper pressure pumps, $517 \text{ MPa} < p$ ($75000 \text{ psi} < p$)

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. In the 600 MPa water jet cutting technique, the use of direct drive pumps is not possible. Intensifier pumps use hydraulic rams. These pumps use hydraulic to apply a certain

DOI: 10.7763/IJMO.2017.V7.597

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, to the pressure from the oil side. With intensifier pump can be achieved hyper pressure. 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. 2 is shown hyper pressure pump Hypertron 6045 (BFT) with a pressure of 600 MPa. In Table I are shown manufacturers of hyper pressure pumps. In Table II are shown performances of industrial applied hyper pressure pumps.

Fig. 2. Hyper pressure pump Hypertron 6045 with a pressure of 600 MPa.

TABLE I: MANUFACTURERS OF HYPER PRESSURE PUMPS

Manufacturer	Web-site
Flow	http://www.flowcorp.com
UHDE	http://www.uhde-hpt.com
KMT	http://www.kmtwaterjet.com
H2O Jet	http://www.waterjetparts.com
BFT	http://www.bft-pumps.com
Hypiont	http://www.hypiont.com
CMS	http://www.cmsindustries.us

TABLE II: INDUSTRIAL APPLIED HYPER PRESSURE PUMPS FOR WATER JET CUTTING

Pump	Max. operating pressure	Motor power	Max. flow rate	Max. orifice size
HyperJet 50HP (Flow)	600 MPa (87000 psi)	37 kW (50 HP)	2.44 L/min (0.64gpm)	0.254 mm (0.010 in)
HPS 6045 (UHDE)	600 MPa (87000 psi)	45 kW (60 HP)	3.0 L/min (0.79 gpm)	0.279 mm (0.011 in)
Hypertron 6045 (BFT)	600 MPa (87000 psi)	45 kW (60 HP)	2.9 L/min (0.78 gpm)	0.279 mm (0.011 in)
EdgeStream 60 (Hypiont)	600 MPa (87000 psi)	53 kW (70 HP)	3.1 L/min (0.82 gpm)	0.305 mm (0.012 in)
HyperJet 100HP (Flow)	600 MPa (87000 psi)	75 kW (100 HP)	5.2 L/min (1.37gpm)	0.381mm (0.015 in)
HPD 6090 (UHDE)	600 MPa (87000 psi)	90 kW (120 HP)	6.0 L/min (1.58 gpm)	0.381 mm (0.015 in)
Greenjet 6200 (CMS)	620 MPa (90000 psi)	34 kW (45 HP)	2.61 L/min (0.69 gpm)	0.28 mm (0.011 in)
XStream xp 90-50 (CMS)	620 MPa (90000 psi)	37 kW (50 HP)	2.61 L/min (0.69 gpm)	0.279 mm (0.011 in)
Streamline Pro-III 60 HP (KMT)	620 MPa (90000 psi)	45 kW (60 HP)	2.9 L/min (0.78 gpm)	0.279 mm (0.011 in)
XStream xp 90-100 (CMS)	620 MPa (90000 psi)	75 kW (100 HP)	5.5 L/min (1.45gpm)	0.432 mm (0.017 in)
Streamline Pro-III 125 HP (KMT)	620 MPa (90000 psi)	93 kW (125 HP)	6.0 L/min (1.59 gpm)	0.406 mm (0.016 in)
H2O Jet EP94-50S (H2O Jet)	650 MPa (94000 psi)	37 kW (50 HP)	2.38 L/min (0.63 gpm)	0.254 mm (0.010 in)
H2O Jet EP94-100D (H2O Jet)	650 MPa (94000 psi)	75 kW (100 HP)	4.77 L/min (1.26 gpm)	0.381 mm (0.015 in)

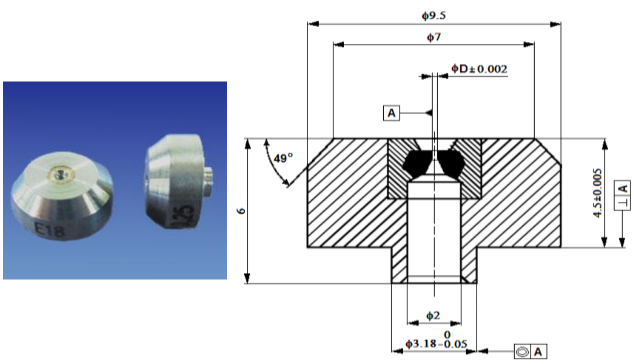

Fig. 3. Diamond orifice for pressure of 600 MPa.

Cutting head is a second vital component of water jet cutting machine. Cutting head consists of orifice, mixing chamber and nozzle. Cutting head is specially designed for water jet cutting with pressure of 600 MPa. Orifice has a very tiny hole in it. The purpose of this hole is to convert the high water pressure created by the pump to high speed water jet. Orifice has an inner diameter of 0.076 mm to 0.508 mm (0.003 in to 0.020 in). Orifice is made of sapphire, ruby or diamond. Sapphire and ruby orifices are cheaper, but prone to wear and crack and due to their life time of approximately 50-100 hours they must be frequently changed. Diamond orifices have good quality, better reliability and life time of approximately 1000 hours. Diamond orifice for pressure of 600 MPa is shown in Fig. 3.

Nozzle (mixing tube, focusing tube) has an inner diameter of 0.381 mm to 1.778 mm (0.015 in to 0.070 in) and is long of 38 mm to 152 mm (1.5 in to 6 in). Nozzle is generally made of tungsten carbide (powder metallurgy product). In Fig. 4 is shown cutting head Autoline Pro (KMT) for pressure of 620 MPa.

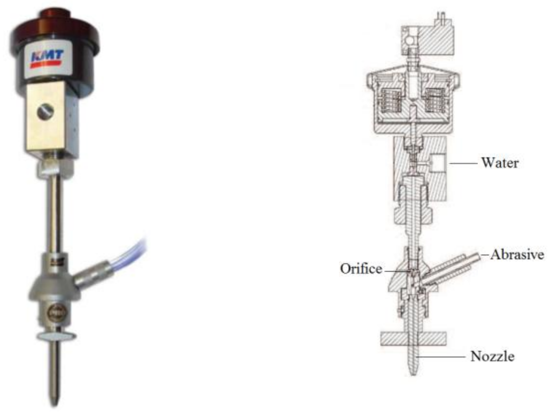

Fig. 4. Cutting head Autoline Pro for pressure of 620 MPa

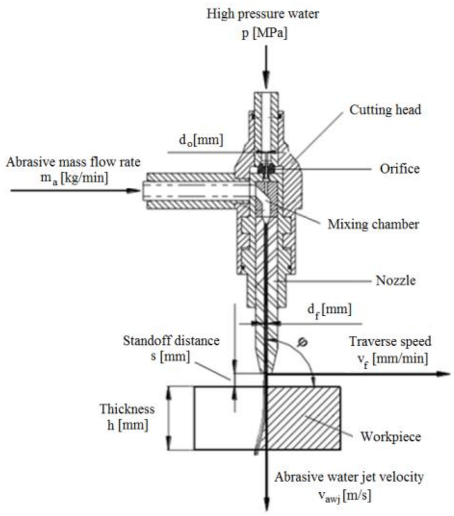

Fig. 5. Scheme of the abrasive water jet cutting.

III. 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. 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. Result is a very thin, extremely high velocity water jet. Abrasive particles are metered from abrasive hopper to the cutting head. 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 in the mixing chamber. 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 mixed with the water jet create 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. 5. [7]

There are three main factors which determine the performances of abrasive water jet cutting process: water pressure, water flow rate and abrasive flow rate. By increasing these factors, cutting can be faster and have cleaner edges. Material type (hardness) and thickness to be cut determine a water flow rate requirement. Thick materials require larger streams of water which have greater velocity and more energy to cut. Traverse speed (cut speed) vary based on the thickness of the material, the operating pressure, water flow rate, the quality and quantity of abrasive, the shape to be cut and type of edge finish desired. Cutting faster is possible by increasing pressure, water flow rate and abrasive mass flow rate.

Characteristics of water pump (motor power, water pressure and water flow rate) are constant for concrete abrasive water jet machine. Characteristics of abrasive water jet cutting process can calculate as follows:

- Hydraulic power

$$P_w = pq \tag{1}$$

- Water jet velocity

$$v_{wj} = c_v \sqrt{\frac{2p}{\rho_w}} \tag{2}$$

- Orifice diameter

$$d_o = \sqrt{\frac{q}{c_d \frac{\pi}{4}\sqrt{\frac{2p}{\rho_w}}}} \tag{3}$$

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

- Water jet flow rate

$$q_w = c_d \frac{\pi d_o^2}{4}\sqrt{\frac{2p}{\rho_w}} \tag{4}$$

- Water jet mass flow rate

$$\dot{m}_w = \rho_w q_w \tag{5}$$

- Nozzle diameter

$$2.5 d_o \le d_f \le 3 d_o \tag{6}$$

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

- Abrasive mass flow rate

$$\dot{m}_a = R\,\dot{m}_w \tag{7}$$

- Abrasive water jet velocity

$$v_{awj} = \eta \frac{v_{wj}}{1+R} \tag{8}$$

- Abrasive jet power

$$P_a = \frac{1}{2}\dot{m}_a v_{awj}^2 \tag{9}$$

- Abrasive water jet diameter

$$d_{awj} \approx 1.1 d_f \tag{10}$$

- Power density

$$P_d = \frac{P_a}{\frac{\pi d_{awj}^2}{4}} \quad (11)$$

- Traverse speed (Zeng & Kim, [8])

$$v_f = \left(\frac{f_a N_m p^{1.594} d_o^{1.374} \dot{m}_a^{0.343}}{788\, i h d_f^{0.618}} \right)^{1.15} \quad (12)$$

- Machining time

$$t_m = \frac{L}{v_f} \quad (13)$$

- Abrasive consumption

$$C_a = \dot{m}_a \, t_m \quad (14)$$

- Machining cost

$$C_m = c_h \cdot t_m \quad (15)$$

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), f_a-abrasive factor, h-material thickness, N_m-machinability number, i-quality level index, t_m-machining time, L-cut length, C_a-abrasive consumption, C_m-machining cost, c_h-machining cost per hour.

Analysis of the performances of the abrasive water cutting is given in the case of cutting 25 mm thick aluminum 6061-T6. The example data is as follows: 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, machinability number is N_m =213 for aluminum 6061-T6, quality level index is i=1 for rough cut, abrasive is Garnet, cut length is L=1m, machining cost per hour is c_h=50 EUR/h.

TABLE III: COMPARISON OF ABRASIVE WATER JET CUTTING WITH MOTOR POWER OF 37KW (50HP)

Pump	SL-V 50 Classic (KMT)	SL-V 50 Plus (KMT)	XP90-50 (Jet Edge)	HyperJet S (Flow)
Motor power	37 kW (50 HP)	37 kW (50 HP)	37 kW (50 HP)	37 kW (50 HP)
Operating pressure	380 MPa (55000 psi)	413.7 MPa (60000 psi)	520 MPa (75000 psi)	600 MPa (87000 psi)
Water flow rate	3.8 L/min (1.00 gpm)	3.5 L/min (0.92 gpm)	2.6 L/min (0.7 gpm)	2.44 L/min (0.64 gpm)
Hydraulic power	24.06 kW	24.13 kW	22.53 kW	24.4 kW
Water jet velocity	854 m/s	891 m/s	999 m/s	1073 m/s
Orifice diameter	0.356 mm (0.014 in)	0.330 mm (0.013 in)	0.279 mm (0.011 in)	0.254 mm (0.010 in)
Water jet flow rate	3.63 L/min	3.27 L/min	2.58 L/min	2.28 L/min
Nozzle diameter	1.067 mm (0.042 in)	0.991 mm (0.039 in)	0.838 mm (0.033 in)	0.762 mm (0.030 in)
Orifice/nozzle size	14/42	13/39	11/33	10/30
Abrasive size	Mesh 60 - 80	Mesh 60 - 80	Mesh 80 - 120	Mesh 80 - 120
Abrasive mass flow rate	0.530 kg/min	0.470 kg/min	0.370 kg/min	0.330 kg/min
Abrasive water jet velocity	522 m/s	544 m/s	610 m/s	656 m/s
Abrasive jet power	1.20 kW	1.16 kW	1.15 kW	1.18 kW
Power density	1.11 kW/mm^2	1.24 kW/mm^2	1.72 kW/mm^2	2.14 kW/mm^2
Traverse speed	650 mm/min	680 mm/min	810 mm/min	930 mm/min
Machining time	1.54 min	1.47 min	1.23 min	1.08 min
Abrasive consumption	0.816 kg	0.691 kg	0.455 kg	0.356 kg
Machining cost	1.28 EUR	1.22 EUR	1.02 EUR	0.90 EUR

TABLE IV: COMPARISON OF ABRASIVE WATER JET CUTTING WITH HYPER PRESSURE OF 600 MPA

Pump	HyperJet S (Flow)	HPS 6045 (UHDE)	HyperJet D (Flow)	HPD 6090 (UHDE)
Motor power	37 kW (50 HP)	45 kW (60HP)	75 kW (100HP)	90 kW (120HP)
Operating pressure	600 MPa (87000 psi)	600 MPa (87000 psi)	600 MPa (87000 psi)	600 MPa (87000 psi)
Water flow rate	2.44 L/min (0.64 gpm)	3.0 L/min (0.79 gpm)	5.2 L/min (1.37gpm)	6.0 L/min (1.58 gpm)
Hydraulic power	24.4 kW	30 kW	52 kW	60 kW
Water jet velocity	1073 m/s	1073 m/s	1073 m/s	1073 m/s
Orifice diameter	0.254 mm (0.010 in)	0.279 mm (0.011 in)	0.381 mm (0.015 in)	0.406 mm (0.016 in)
Water jet flow rate	2.34 L/min	2.82 L/min	5.20 L/min	5.95 L/min
Nozzle diameter	0.762 mm (0.030 in)	0.838 mm (0.033 in)	1.143 mm (0.045 in)	1.219 mm (0.048 in)
Orifice/nozzle size	10/30	11/33	15/45	16/48
Abrasive size	Mesh 80 - 120	Mesh 80 - 120	Mesh 60 - 80	Mesh 50 - 80
Abrasive mass flow rate	0.340 kg/min	0.408 kg/min	0.757 kg/min	0.861 kg/min
Abrasive water jet velocity	656 m/s	656 m/s	656 m/s	656 m/s
Abrasive jet power	1.22 kW	1.46 kW	2.71 kW	3.01 kW
Power density	2.21 kW/mm^2	2.19 kW/mm^2	2.20 kW/mm^2	2.13 kW/mm^2
Traverse speed	920 mm/min	1068 mm/min	1790 mm/min	1984 mm/min
Machining time	1.087 min	0.936 min	0.559 min	0.504 min
Abrasive consumption	0.370 kg	0.382 kg	0.423 kg	0.434 kg
Machining cost	0.91 EUR	0.78 EUR	0.47 EUR	0.42 EUR

Comparison of abrasive water jet cutting for various water pressure with motor power of 37 kW (50 HP) is shown in Table III. For equal motor power, as operating pressure goes up, water flow rate goes down, hydraulic power is equal, water jet velocity goes up, orifice diameter goes down, nozzle diameter goes down, abrasive mass flow rate goes down, abrasive water jet velocity goes up, abrasive jet power is equal, power density goes up, traverse speed (cut speed) goes up, machining time per meter of cut goes down, abrasive consumption goes down and machining cost per meter of cut goes down.

Comparison of abrasive water jet cutting with hyper pressure of 600 MPa for various motor power is shown in Table IV. For operating pressure of 600 MPa, as motor power goes up, water flow rate goes up, hydraulic power goes up, orifice diameter goes up, nozzle diameter goes up, abrasive jet (kinetic) power goes up, traverse speed (cut speed) goes up, machining time per meter of cut goes down and machining cost per meter of cut goes down. Larger abrasive particle can be used. Larger abrasive particles cause a higher kinetic energy and higher depth of cut. With larger pump can cut thicker material and can cut at higher traverse speed.

Abrasive water jet cutting machine with pump of 600 MPa can operate with two or many cutting heads simultaneously. The users are able to produce twice as many pieces at the same time. Two cutting heads with the smaller nozzle combination produce more parts at a lower cost per part. Abrasive water jet cutting machine with two cutting heads and with a smaller nozzle combination is most cost-effective for application. Alternatively, the abrasive water jet cutting machine can run with a single cutting head to cut extremely thick materials.

IV. Conclusion

Abrasive water jet cutting machines operating with hyper pressure of 600 MPa have better performances versus abrasive water jet cutting machines operating with high and ultra-high pressure. Increasing pressure of 380 MPa to 600 MPa significantly improves water jet cutting productivity and reduces machining cost. For equal motor power, as operating pressure goes up, abrasive water jet velocity goes up, power density goes up and traverse speed go up, while machining time goes down, abrasive consumption goes down and machining cost goes down. For pressure of 600 MPa, as motor power goes up, abrasive jet power goes up and traverse speed goes up, while machining time goes down and machining cost goes down.

Acknowledgment

The paper is a result of the technological project TR35034 which is supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

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