

ABRASIVE WATERJET CUTTING

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Abstract: Cutting plate is a difficult and time consuming task, especially when the job calls for a tight tolerance or an unusual shape. In those cases, can choose abrasive waterjet cutting. Abrasive waterjet cutting is an attractive process with many advantages. For efficient application abrasive waterjet cutting it is necessarily to define cutting data, especially cutting speed. High levels of contour precision at precisely defined cutting speed have an important effect on the quality of the cut. This paper gives results of the research referring to the determination of principal parameters by abrasive waterjet cutting. Cutting with waterjet costs less than traditional machining or other cutting methods. Waterjet is now the most cost effective method to cut steels. The cost ranges provide a basis for an cost estimation prior to plan of buying order of waterjet machine. The cost analysis of abrasive waterjet cutting is also presented in this paper.

Keywords: machining, advance machining, abrasive waterjet, cutting data, cost

1. INTRODUCTION

Abrasive waterjet cutting has become a highly developed industry technology. Its development has been favored by the fact that abrasive waterjet cutting can be used in practically all areas in which solids are processed – stone, glass, plastics, composite materials and metals. Abrasive waterjet technology was first introduced in 1984. The technique uses a mix of water and a fine abrasive for cutting hard materials. Mix abrasives with high pressure water give an effective tool to cut metals and nonmetals materials. Abrasive waterjet cutting is the most suitable process for very thick, highly reflective or highly thermal-conductive materials, laminates and composite materials, as well as hard syntetics. The abrasive stream produces a kerf width that is ideal for cutting titanium, armor plate, steel, granite, composites, glass and many other materials. The list includes metals such as aluminum, carbon steel, stainless steel and high nickel alloys, or brittle materials such as marble, reinforced composites, and sandwiched materials. Abrasive waterjet can cut a wide range of thickness. Typical thickness are 100 mm for stainless steel, 120 mm for aluminum, 140 mm for stone, 100 mm for glass, but not limited. Abrasive waterjet cutting is of great interest for various reasons. Almost any material can be cut. The abrasive waterjet makes it possible to cut random contours, very fine tabs and filigree structures. Abrasive waterjet cutting is a very precise technique. Tolerances of ± 0.1 mm can be realized in metal cutting. The workpiece is not heat-stressed. Materials cut by abrasive waterjet have a smooth, satin-like finish, similar to a fine sandblasted finish. Abrasive waterjet cut material at room temperatures. As a result, there are no heat-affected areas or structural changes in materials. Abrasive waterjet can cut hardened metals and materials with low melting points. No heavy burrs are produced by the abrasive waterjet. Parts can often be used directly without deburring. Those parts which do require further processing are easier to machine and finish. Abrasive waterjet cutting is used in many industries, including the automobile, aerospace, and glass industries, to create precision parts from hard-to-cut materials. The characteristics of abrasive waterjet cutting enable to be the main method for contour cutting.

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2. ABRASIVE WATERJET CUTTING

Abrasive waterjet stream is the cutting tool. The cutting process is like grinding, except that abrasives are moved through the material by water rather than by a solid wheel. Most abrasive waterjet cutting theories explain abrasive waterjet cutting as a form of micro erosion. By abrasive waterjet cutting the high pressure pump produces the required pressure up to 400 MPa. A high pressure supply line direct the pressurized water from the pump to the cutting head. The high pressure supply line is terminated by a water orifice at which the pressure is relieved. Water orifice has a diameter of approx. 0.08 to 0.50 mm.

The water pressure is relieved in the orifice and a waterjet is created. The water is pressed out of the orifice at a speed of approx. 900 m/s – nearly three times the speed of sound. The result is a very thin, extremely high velocity waterjet. Solid abrasive particles are added and mixed with the waterjet and subsequently focused by an abrasive nozzle. Abrasive nozzle is with diameter from 0.8 to 1.2 mm and length from 50 to 100 mm. The high speed of the waterjet creates a partial vacuum in the mixing chamber so that abrasive material and air are sucked in and flushed away by the waterjet.

This is known as the injector principle. The abrasive nozzle has two functions: it accelerates the abrasive particles and it focuses the jet. The cutting head makes a circular or pendular motion over the piercing point. The abrasive waterjet penetrates the material and progressively cuts the material guided by the cutting head along programmed contour. In figure 1 is shown abrasive waterjet cutting.

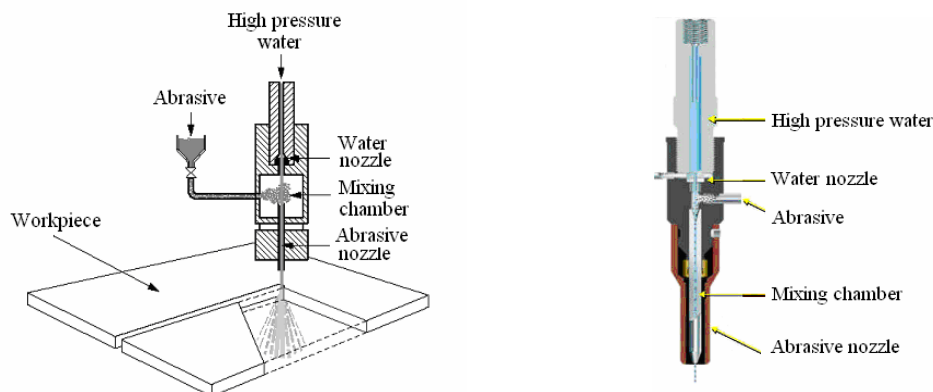


Fig. 1. Abrasive waterjet cutting

Abrasive waterjet's effect upon a workpiece material can be divided into several characteristic phases:

- The abrasive waterjet works itself slowly into material. In the process of cutting, the abrasive waterjet moves along the workpiece at a constant feed rate. The angle between the undisturbed abrasive waterjet and the front edge constantly increases. As a result is also deflected away from the cutting direction due to their inertia, the solid particles can no longer follow the carrier jet. This causes a separation of the jet components which localizes the abrasion process. Material is removed at only a small section of the cutting flank.
- During the cutting process a step is created. The angle of deflection on the step increases constantly. There is increasingly less abrasion below the step. Less and less material is removed beneath the step.
- The step is ground out of the workpiece relatively quickly, until the colliding particles are no longer able to abrade the material. As the step moves downwards, a smooth front edge is created.
- The starting condition has been reached again.

Characteristics of abrasive waterjet cutting. Table 1.

Energy medium	Water
Energy source	High-pressure pump
Energy transmission	Rigid high-pressure hoses
Material expulsion	High-pressure water jet
Typical beam output at workpiece	4 kW-17 kW (400 MPa)
General applications	Cutting, ablation, structuring
3D cutting	Possible; problem of destruction behind the workpiece
Materials that can be cut	All materials
Material combinations	Possible but danger of delamination
Material properties which influence processing	Material hardness
Material thickness at which processing is economical	10-50 mm, depending on material
Most frequent applications	Cutting of ceramics, stone and metals
Minimum cutting slit	0.5 mm
Appearance of cut surfaces	Like sand-blasted, depending on cutting speed
Parallelism of cut edges	Good; "tailed" effect in curves in thicker materials
Processing accuracy	Approximately 0.2 mm
Thermal stress of material	None
Forces acting on material in direction of jet	High; thin parts can thus only be processed to limited degree
Burring	No burring
Personal safety	Protective glasses, ear protection,
Smoke and dust generation	Not applicable
Noise pollution	High
Cutting waste	Large quantities occur on account of mixing with abrasives
Wearing parts	Water and abrasive nozzle, high-pressure components
Consumption of complete system, 20 kW pump	El. power: 22-35 kW; Water: 150 l/h; Abrasive: 36 kg/h;

During the cutting process, the abrasive waterjet emerges from the bottom side of the workpiece with high remaining energy. This energy must be absorbed after cutting. The easiest way to do this is with a water basin. The residual waterjet energy is absorbed by a catcher travelling synchronous to the bridge. Abrasive waterjet cutting is capable of producing high precision parts that usually requiring no further processing. Those parts which do require further processing are easier to machine and finish because the low operating temperature of the process does not produce the hardened edges or create structural changes in the workpiece. Almost any material can be cut. This even applies to very thick materials. As far as sheet metal processing is concerned, this greatly increases the range of thickness that can be processed. Abrasive waterjet is cold slitting process. There is no thermal influence on the workpiece. This is particularly important when processing composite and coated materials. Abrasive waterjet cutting produces very little lateral force, reducing or eliminating the need for fixturing to hold the workpiece. Toxic fumes, recast layers, slag and thermal stress are totally eliminated. Noise and flying dirt can be minimized by underwater cutting. Advantages of abrasive waterjet cutting are: no thermal stress, no hardening, no workpiece tension, no dust or smoke build-up, no toxic fumes, smaller kerf width, very clean cut edges, high cutting speeds and accuracy, burr-free cuts, no post-machining, ideal for any cutting task. Disadvantages are: some materials can not be cut economically, and thick parts can not be cut with dimensional accuracy. Characteristics of abrasive waterjet cutting are shown in table 1.

3. ABRASIVE WATERJET MACHINES

Abrasive water jet machines designed for a specific applications are just as varied as the field of application. Concepts range from systems with fixed cutting head, machines equipped with an XY guided cutting head and robot guided cutting head. Machines designed in the form of a portal are used primarily in sheet metal processing. Abrasive water jet cutting machine with a portal construction combines high positioning precision with a very dynamic freedom of movement. The basic components of abrasive water jet cutting machine are: high pressure pump, high pressure delivery system, cutting head, storing, delivering and metering abrasive material, mechanical machine for movements, workpiece rest, catcher, disposal unit and control unit. In figure 2 is shown abrasive waterjet cutting machine with a portal design. The high pressure pump is the heart of a water jet machine. It creates the required operation pressure and transports the water through the system. The pressure pump for water jet cutting machine is high performance pump. It creates a pressure of up to 400 MPa. The back and forth motion of the pressure intensifier causes pressure fluctuations in the piston's end of a travel. For that reason, pumps for this pressure area are usually equipped with a pulsation damper to smooth out pressure fluctuations. The high pressure delivery system safely conducts the water under pressure from the pump to the cutting head. It consists of thick walled high pressure pipes made of strain hardened austenite steel. The cutting head is the most important component of a water jet cutting machine. It consists from water nozzle, mixing chamber and abrasive nozzle.

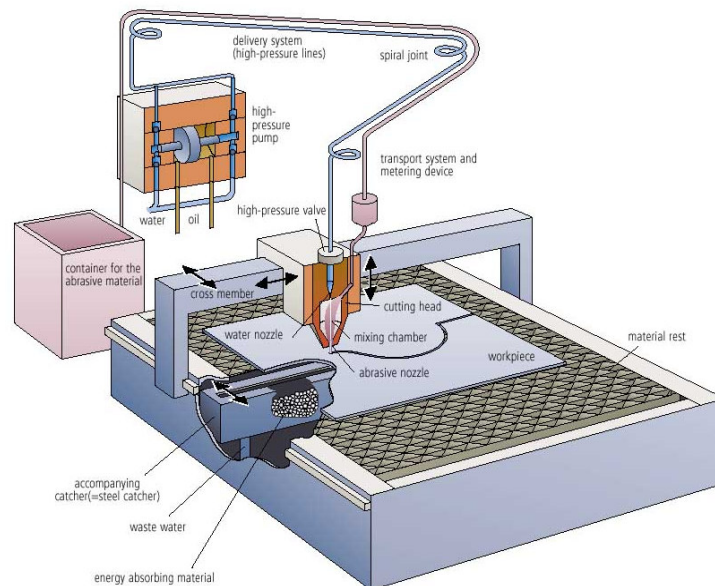


Fig. 2. Abrasive waterjet machine

Water nozzle is made from a sapphire, ruby or diamond. Diameter of water nozzle is from 0.08 to 0.5 mm. Abrasive nozzle is made from hard metal. Abrasive nozzle is with diameter from 0.8 to 1.2 mm and length from 50 to 100 mm. Container for the abrasive material is located next to the machine. The abrasive material is transported from the container by means of a vacuum system to either the cutting head or to a metering device located on the cutting head. During processing, the workpiece lies on a rest. It is normally located directly on the machine frame. Depending on the machine concept, the workpiece is situated either above or below the water surface during processing. The catcher is filled with balls. It moves along with the cutting head and absorbs the remaining energy after the cutting process. Sludge (cutting chips and abrasive material residue) and waste water are separated in the disposal unit. Modern machines can hold tolerances of ± 0.1 mm or better. Automating the process with programmable systems in conjunction with the CNC control provides high flexibility and a wide variety of parts. There are many manufacturers of abrasive waterjet cutting machines. Industry leaders of manufacturers of abrasive waterjet cutting machines are: Bystronic, ESAB, Ingersoll-Rand, OMAX Corp.,

TRUMPF GmbH, and WaterJet Sweden. In table 2 are shown some manufacturers of abrasive waterjet cutting machines.

Manufacturers of waterjet machines. Table 2.

Manufacturers	Web-site
Bystronic	www.bystronic.com
ESAB	www.esab.com
Ingersoll-Rand	www.iraautomation.com/wjs
Jet Edge	www.jetedge.com
OMAX Corp.	www.onax.com
TRUMPF GmbH	www.trumpf.com
WaterJet Sweden	www.waterjets.org
PTV Hostivice	www.ptv.cz
Knuth	www.knuth.de

4. CUTTING DATA

Technological problems related to the application of abrasive waterjet cutting process are in insufficient knowledge of the abrasive waterjet technique as well as due to absence of sufficiently reliable practical data and knowledge about the parameters influencing the work process itself.

Process of abrasive waterjet cutting can describe by next parameters:

- Cutting rate, R

$$R = v \cdot s \quad (1)$$

- Specific power consumption, P_s

$$P_s = \frac{P}{Q} \quad (2)$$

where v -cutting speed, s -material thickness, P -pump power, Q -material removal rate.

In table 3 are shown cutting rate and specific power consumption of abrasive waterjet cutting.

Cutting rate and specific power consumption. Table 3.

Material	Cutting rate $R(\text{cm}^2/\text{min})$	Specific power consumption P_s (kW/cm ³ /min)		
		Pump 15 kW	Pump 20 kW	Pump 30 kW
Special steel	10-20	6.2-30	8.3-40	12.5-60
Titanium	10-25	5-30	6.7-40	10-60
Copper	15-30	4.2-20	5.5-27	8.4-40
Brass	20-50	2.5-15	3.3-20	5-30
Aluminium	20-50	2.5-15	3.3-20	5-30
Lead	80-120	1-3.7	1.4-5	2-7.5
Glass	100-200	0.6-3	0.8-4	1.2-6
Plexiglas	120-300	0.4-2.5	0.5-3.3	0.8-5
Rubber	200-400	0.3-1.5	0.4-2	0.6-3
Fibreglass	120-300	0.4-2.5	0.5-3.3	0.8-5
Ceramics	100-300	0.4-3	0.5-4	0.8-6
Natural stone	50-300	4-6	5.5-8	8-12
Cut width 0.5-1.2 mm				

By these parameters we can determine principal parameters of abrasive water jet cutting process. On the basis of the cutting rate, R , and the specific power consumption, P_s , we can estimate

- Cutting speed, v .

$$v = \frac{R}{s} \quad (3)$$

- Material removal rate, Q .

$$Q = \frac{P}{P_s} \quad (4)$$

- Cut width, s_r .

$$s_r = \frac{Q}{R} \quad (5)$$

- Volume of removed material, V

$$V = s \cdot s_r \cdot \ell \quad (6)$$

- Time to make the cut, t_g

$$t_g = \frac{\ell}{v} = \frac{V}{Q} \quad (7)$$

where s -material thickness, P -laser power, ℓ -length of cut.

5. COST OF WATERJET CUTTING

Three categories make costs of waterjet cutting: investment costs, operating costs, and labor costs. Investment costs are associated with the equipment purchase. It is the initial price of the equipment amortized over a specific amount of time. Since investment costs are fixed, they occur whether the machine is working or idle. The investment cost of a machine is a function of the power of the pump, the size of the workpiece and the number of axes required to manipulate the workpiece around while performing the operation. While the investment cost of a waterjet machines is high, improved productivity and product quality, often make a system economical, especially for companies that produce a wide range of parts. Operating costs are associated with operating the process, including electrical energy consumption, water consumption, abrasive consumption, wearing parts consumption, and maintenance and repair. These costs occur only when the machine is operating. The pump is the determining factor in the operating costs. The key parameter that controls cutting speed is the water orifice diameter or the cutting water flow rate. The other two parameters that greatly influence the speed are the system pressure and the abrasive flow rate.

The optimum abrasive flow rate can be related to the cutting water flow rate. Labor costs are associated with running the machine, including the time to handle raw material, finished parts and remnants. It must know the hourly cost of an operator, the percentage of time allotted for machine setup, and the percentage of time an operator actually attends the machine. Costs of abrasive waterjet cutting can be calculated in exactly the same way as for conventional machining, i.e. based on investment, operating and labor costs.

Cost per hour of abrasive waterjet cutting can be calculated by equation:

$$C = C_i + C_o + C_p \quad (8)$$

where C (EUR/h) – waterjet cutting cost per hour, C_i (EUR/h) – investment cost, C_o (EUR/h) – operating cost, C_p (EUR/h) – labor cost.

Or by equation in form:

$$C = \frac{I}{D \cdot L_a} + c_e \cdot E + c_w \cdot Q_w + c_a \cdot Q_a + \frac{c_n}{L_n} + \frac{c_m}{L_m} + \frac{M}{L_a} + C_p \quad (9)$$

where I (EUR) – capital investment cost of abrasive waterjet machine, D (year) – depreciation period, L_a (h/year) – machine utilization, c_e (EUR/kWh) – unit cost of electrical energy, E (kW) – electrical power consumption, c_w (EUR/m³) – unit cost of water, Q_w (m³/h) – water consumption, c_a (EUR/kg) – unit abrasive cost, Q_a (kg/h) – abrasive consumption, c_n (EUR/part) – water orifice price, L_n (h/part) – water orifice lifetime, c_m (EUR/part) – abrasive nozzle price, L_m (h/part) – abrasive nozzle lifetime, M (EUR/year) – maintenance costs per year. The cost per meter of abrasive waterjet cutting is established as:

$$C' = \frac{C}{v} \quad (10)$$

where C' (EUR/m) – cost per meter of waterjet cutting, v (m/h) – cutting speed.

Table 4 show cost calculation example of cutting by abrasive waterjet machine "PTV Hostivice". The technical characteristics are: high pressures pump 37 kW, 3.73 l/min, 413 MPa, water orifice diameter 0.33 mm, abrasive nozzle diameter 0.76 mm, table size 2000 x 4000 mm.

Cost calculation example. Table 4.

Capital investment	$I=120\,000$ EUR
Depreciation period	$D=5$ years
Machine utilization	$L_a=4000$ h/year
Investment cost	$C_d=6$ EUR/h
Electrical power consumption	$E=45$ kW
Unit cost of electrical energy	$c_e=0.105$ EUR/kWh
Cost of electrical energy	$C_e=4.725$ EUR/h
Cutting water consumption	$Q_{cw}=0.24$ m ³ /h
Cooling water consumption	$Q_{qw}=0.90$ m ³ /h
Unit cost of water	$c_w=0.5$ EUR/m ³
Cost of water	$C_w=0.57$ EUR/h
Abrasive consumption	$Q_a=21.6$ kg/h
Unit cost of abrasive	$c_a=0.7$ EUR/kg
Cost of abrasive	$C_a=15.12$ EUR/h
Water orifice wear cost/hour	$C_n=0.078$ EUR/h
Abrasive nozzle wear cost/hour	$C_m=0.78$ EUR/h
Cost of wearing parts per hour	$C_r=0.858$ EUR/h
Maintenance cost per year	$M=5000$ EUR/year
Maintenance cost	$C_m=1.25$ EUR/h
Labor cost	5 EUR/h
Cost per hour of cutting	33.523 EUR/h

6. CONCLUSION

Abrasive waterjet machining is an advance process capable of producing high precision parts. Application of abrasive water jet cutting increase the accuracy and the productivity. Abrasive waterjet cutting is now the most cost effective method to cut steels and other materials.

Technological problems are in absence of sufficiently reliable practical data and knowledge about the parameters influencing the work process itself. Some results of the research referring to the determination of principal parameters by abrasive waterjet cutting are shown. Cost per hour of abrasive waterjet cutting is calculated based on investment, operating and labor costs.

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