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ABRASIVE WATER JET CUTTING - TECHNIQUE, EQUIPMENT, PERFORMANCES

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ABSTRACT: This article presents aspects regarding an innovative nonconventional technology: abrasive water jet cutting. There are presented aspects regarding technique of abrasive water jet cutting (principle, parameters, and theoretical considerations about them), equipment (with emphasis on very high pressure pump) and performance of this technology (materials possible to be cut, cutting parameters for some materials). There are presented also results (theoretical aspects, specific techniques, cutting results) regarding other than cutting technological operations possible to be performed with abrasive water jet: drilling with abrasive water jet. Many of those presented in this article are results from research activity of the authors or from doctoral thesis.
KEY WORDS: water jet, cutting, technology.

1. INTRODUCTION

The technique of cutting materials using high pressure water jets was first time patented in 1968 by Dr. Norman Franz, researcher at University of Michigan, USA. He selected the company Ingersoll – Rand to manufacture the prototype of a water jet cutting equipment, as this company was skilled in manufacturing of high pressure pumps used in various industrial applications. First industrial equipment was installed at a furniture manufacturing company – ALTON BOXBOARD Co. – which used it to cut wood panels with 10 mm thickness. From this date the company manufactured thousands of water jet cutting equipment. Today, the company soled this division to other company – Flow Systems – which is world number one in manufacturing high pressure water jet pumps and equipment.

High pressure abrasive water jet technology has a relative recent history, its development starting in early ‘80s of 20th century. This technology was developed to broaden the range of materials possible to be cutted by water jet technology mainly for materials with high mechanical characteristics. Bellow is presented a classification of high pressure / high speed water jets used in cutting and cleaning technologies. Water jets can be classified by the following criteria [1]:

- **Pressure**
  - Low pressure water jets ($p < 150$ MPa);
  - High pressure water jets (150 MPa $<p<$ 550 MPa)
- **Continuity**
  - Continuously water jets ;
  - Discontinuously water jets: single impact jets, multiple impact jets
- **Number of phases**
  - Single phase jets (only water);
  - Two phases jets (water + additives);
  - Three phases jets (water + abrasive particles + air);

Regarding above classification, the difference between continuously and discontinuously jets is that discontinuously jets are obtained by means of mechanical mechanisms or other kind of external mechanisms. Here it is not considered the internal discontinuity of water jets due to pressure and flow variations (drops formed at the external layer of a water jet). **The abrasive water jets,** considering the number of phases criteria, have **three phases jets**, formed from water, abrasive particles and air. These jets are obtained **by injection** of abrasive particles in an formed water jet, when air is inserted together with abrasive particles.

Today, the abrasive water jet technology is a very competitive nonconventional cutting technology used in a very large area of industrial applications.

2. ABRASIVE WATER JET TECHNIQUE

2.1. Water jet technique

Water jet is the result of passing a water flow through a nozzle at high pressure, about 100 ... 400 MPa. The structure of a water jet from velocity and pressure distribution point of view is presented in Figure 1.

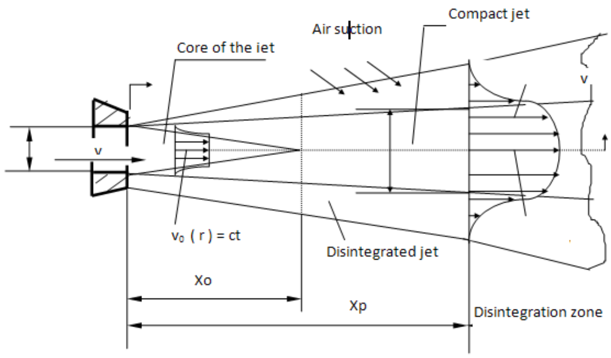

Figure 1. Structure of a high pressure water jet

The zones from above figure have the following characteristics:

- Inside the **initial zone**, length x_0, the radial distribution of velocity (v_0) is constant and the value is the same as those of exit from the nozzle; the length of the zone depend on the pressure and the diameter of the nozzle (d_0);
- Inside the **principal zone**, length x_p, dynamic parameters of the jet (velocity and pressure) varies on

radial and axial directions; hence the velocity decreases up to value $v(x,r) < v_0$ and the density of the core of the jet decreases;

- **Disintegration zone** starts from the point where we have not a core of the jet anymore.

In figure 2 it is presented a water jet obtained on a experimental water jet cutting equipment from ICTCM. The characteristics of this water jet are: pressure 230 MPa, nozzle diameter 0.20 mm. In this picture, it can be observed the length of the principal zone of the jet, and the disintegration of the jet (dimmed white layer on outside part of the jet) due to injection and friction with the air.

Figure 2. View of a high pressure water jet (230 MPa)

Most important from application point of view, is the length of principal zone (x_p), inside which are cut materials.

In figure 3, the values experimentally determined are represented for water jet force at different pressures. The values are determined using an experimentally device placed perpendicular on jet direction.

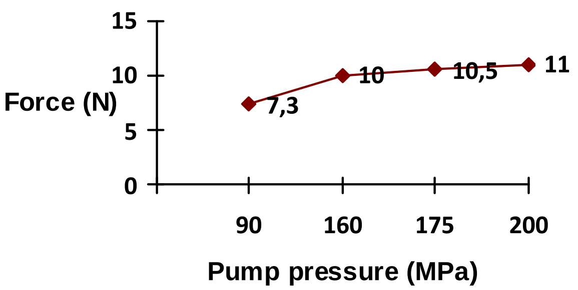

Figure 3. Water jet force

Experimental results of a water jet force at different distances from nozzle exit are presented in Figure 4. It can be observed that, for a nozzle diameter of 0.2 mm, a pressure of 200 MPa and a water flow of 1.2 l/min, the length of principal zone (x_p) is about 90 mm.

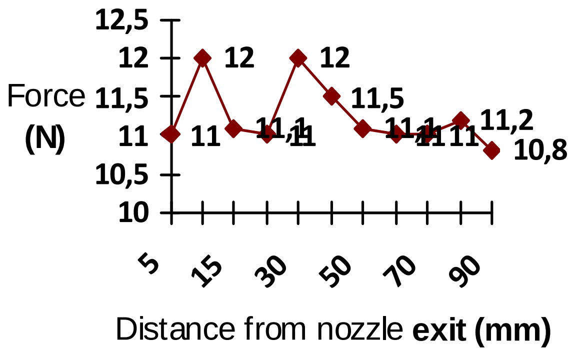

Figure 4. Variance of the water jet force with distance from nozzle exit (nozzle diameter 0.2 mm)

The length x_p can be determined introducing the water jet length quotient (k), expressed by the following formula:

$$k = x_p / d_0 \quad (1)$$

The authors experimentally determined values for the quotient k measuring the force of different water jets (e. g. in Figures 3 and 4). Considering that at the end of principal zone the force of the water jet decreases with 70%, the authors determined the following experimental values for k quotient. Hence, for pressures in range 170 ... 230 MPa and nozzle diameters of 0.15 ... 0.30 mm, the water jet length quotient can be determined with the following formula:

$$k_{170...230} = 250...520 \quad (2)$$

The velocity of a water jet, considering Bernoulli's law, can be determined by the following formula:

$$v_0 = \mu \cdot \sqrt{\frac{2P}{\rho(P)}} \quad (3)$$

- p_1 - pressure before the water exit the nozzle ;
- v – water jet velocity at exit point from the nozzle;
- ρ – density of the water at the pressure p_1;
- μ - quotient counting energy looses at input.

In Figure 5 it is represented variation of μ quotient with pressure for carbide water nozzles determined by the authors on an experimental water jet equipment presented in next chapter.

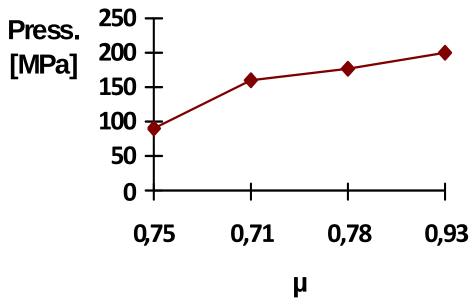

Figure 5. Values for μ quotient (for carbide nozzles)

Another specific aspect of high pressure water jets is the **density of the water.** If, for low pressures (up to 100 MPa) the water is incompressible, at pressures above 150 MPa the water is compressible. The density of water can be calculated with the following formula:

$$\rho / \rho_0 = 1 / [1 - (\beta \cdot p)] \qquad (4)$$

- p - pressure;
- ρ – water density at current pressure;
- ρ_0 – water density at atmospheric pressure (0,1 MPa) ;
- β – water compressibility module.

In formula 4 can be observed that there is a linear dependence between density and pressure, if we consider that water compressibility module β is constant . In fact it is not constant it varies with pressure [2] .

In Figure 4 it is presented variation of water density with pressure for two cases:

- β (water compressibility module) is constant with pressure increase ;
- β (water compressibility module) is not constant with pressure increase : it decreases. ;

The values are obtained during tests performed on a experimental water jet equipment in ICTCM laboratory. Looking closer to the values from Figure 6 it can be concluded that, from practical point of view, the water density increases linear with pressure increase up to 200 MPa, and not linear for pressures between 200 ... 400 MPa.

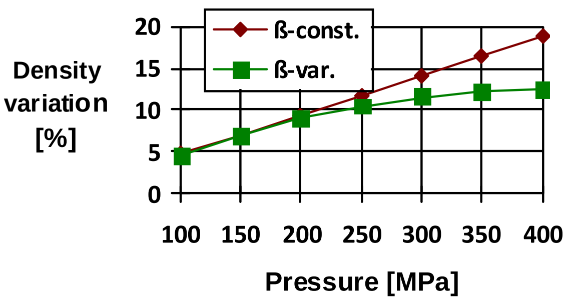

Figure 6. Variation of water density vs. pressure

Considering values of water density and μ quotient from Figures 3 and 4, the values for velocity of water jet (for pressure between 100 … 450 MPa) calculated with formula 3 are:

$$v_0 = 328 \ldots 786 \quad (m/s) \qquad (5)$$

It can be observed that the water jet velocity, for pressures used for cutting (200 ... 450 MPa), is grater than the velocity of sound in air ($v_s = 347$ m/s).

2.2. Abrasive water jet technique

Abrasive water jet is a polyphasic fluid where the constituents do not react chemically each other. The phases of this fluid are:

- A liquid phase represented by the water (with the largest mass participation);
- A solid phase represented by abrasive particles;
- A gaseous phase represented by the air introduced in fluid due to method of introduction of abrasive particles in water jet: injection.

The mechanism of abrasive water jet forming it is not up to this moment theoretically explained due to the big number of independent parameters which participate.

However, it can be explained the mechanism of a abrasive water jet forming, as it is represented in figure 7 [3] .

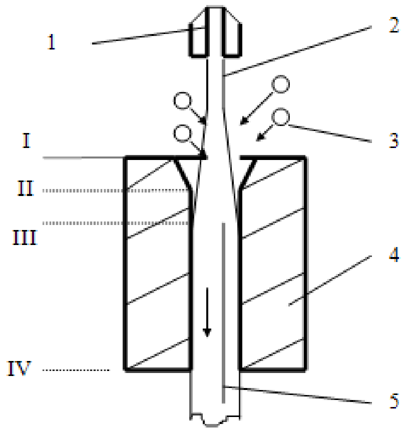

Figure 7. Abrasive water jet forming mechanism

- 1 – water jet nozzle;
- 2 – formed water jet;
- 3 – abrasive particle;
- 4 – water – abrasive particles focus;
- 5 – formed abrasive water jet.

The high pressure water jet 2 passes thru a zone called mixing chamber between nozzle 1 exit and entrance in focus 4. In this area the pressure is negative due to very high velocity of water jet.

Abrasive particles 3 are sucked in water stream due to this negative pressure, in area ranging between points I and II. In area between points II and III the abrasive particles are forced to move in the direction of the water stream, but the velocity of them is low. If the abrasive jet should exit from focus in point III, the velocity is too low and the efficiency should be low also.

Between points III and IV the abrasive particles velocity is increased but this will never reaches the velocity of water jet. If the length of this zone is too big, the velocity of particles will be decreased due to friction with focus walls.

Because there are so many parameters, it is difficult to theoretically determine the length of focus 4. Hence the length of focus is experimentally determined by the focus manufacturers, in order to increase as much as possible the velocity of abrasive particles.

Usually the ratio between focus diameter and its length is (25 … 50).

In figure 8 is presented an abrasive water jet cutting head from an experimental equipment of ICTCM.

Similar to water jet, it was determined the force of an abrasive water jet (the experimental device is similar).

Comparatively (see Figure 9), the forces of a water jet (WJ) and abrasive water jet (AWJ) do not vary too much.

Keeping identical values for common parameters (pressure, water flow, nozzle diameter) the authors determined experimental values for these forces.

Figure 8. Abrasive water jet cutting head (ICTCM)

Hence, for a pressure of 200 MPa, water flow of 1.2 l/min and a nozzle diameter of 0.2 mm, the experimental values for forces are:

$$F_{WJ} = (10.8 \ldots 12.0)\ \text{N} \quad (6)$$
$$F_{AWJ} = (7.0 \ldots 8.0)\ \text{N} \quad (7)$$

It can be observed that the force of a water jet is 35 ... 36 % bigger than an abrasive water jet.

Regarding the variance of jet force with the distance from exit point, the force is constant in principal zone for AWJ also. In Figure 9 bellow are represented the forces for water jet and abrasive water jet as described above. It can be observed that, for different diameters of focus the force of abrasive water jet increases slightly.

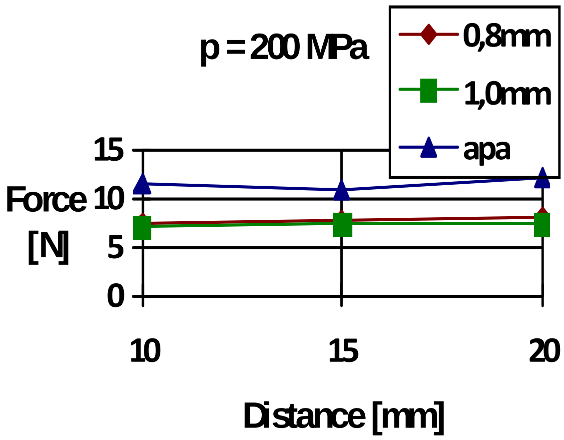

Figure 9. Comparison of AWJ and WJ forces

3. ABRASIVE WATER JET CUTTING (EXPERIMENTAL) EQUIPMENT

Experimental results presented in this paper are obtained from a cutting equipment presented in Figure 10 bellow.

The equipment is composed from 2 main functional assemblies:

- low pressure hydraulic group
- high pressure group.

Figure 10. Abrasive water jet cutting equipment (ICTCM)

Low pressure hydraulic group has the following technical characteristics:

- Working pressure: 20 MPa;
- Maximum pressure: 31.5 MPa;
- Oil flow: Q = 60 l/min;
- Oil tank capacity: 500 l;
- Electric motor:
  - Power 22 kW;
  - Speed 1000 r/min.

High pressure group increases the pressure of water from supply pressure to working high pressure. The main part of this group is high pressure pump / amplifier.

In Figure 10 it can be observed that the equipment has two high pressure pumps which can work together or individually. There are components which are parts of high pressure group: check valves, a safety valve, hydraulic accumulator, filters.

The high pressure group has the following technical characteristics:

- Maximum pressure: 400 MPa;
- Water flow: 1.2 l/min;
- Amplification ratio: 34:1;
- Nominal diameter: 2.0 mm;
- Filtration finesse: 15 µm.

The equipment has also a high pressure measuring system which has as main part a high pressure sensor connected with a data acquisition system.

4. PERFORMANCES OF ABRASIVE WATER JET CUTTING TECHNOLOGY

4.1. Abrasive water jet cutting

Abrasive water jet cutting process is influenced by many specific parameters which influence quality, efficiency and the cost of process [4].

The influence parameters of the abrasive water jet processing are:

a. Process parameters (specific to AWJ processing);

b. Result/effect parameters (describe the effect of abrasive water jet on workpiece).

Process parameters are:

- Hydraulic parameters: pump pressure, nozzle diameter, water flow;
- Processing parameters: cutting speed, number of passes, cutting distance (between focus tube tip – cut piece);
- Abrasive particles mixing and acceleration parameters: focus inner diameter and length;
- Abrasive particles specific parameters: mass flow, diameter/dimension off abrasive particle, hardness, shape.

Result parameters express the result of processing; they are the following (see Figure 11):

- Cut width in upper zone of the workpiece (bs);
- Cut width in down zone of the workpiece (bi);
- Cut tilt (It);
- Angle of the flank (ϕ_F);
- Smooth zone high (h_a);
- Wavy zone high (h_v)

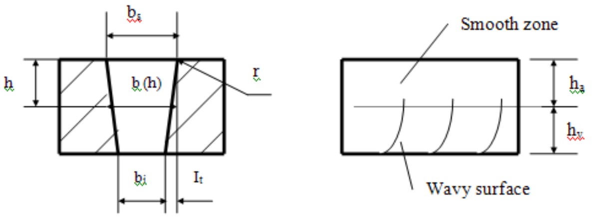

Figure 11. Geometry of AWJ cut

In Table 1 are presented results of materials cut with abrasive water jet on the experimental equipment from Figure 10.

In figure 12 (a, b) there are presented examples of materials cut with abrasive water jet.

Figure 12-a. – Stone, granite and marble cut with AWJ

Figure 12-b. Stainless steel (6 mm) and marble (20 mm) cut with AWJ

In figures bellow there are presented **influence of some process parameters** on cut efficiency, mainly on cut depth.

In Figure 13 it is presented the influence of pressure e on process efficiency. It can be observed that the efficiency of the process, represented by the cut depth, increases with increase of pressure, regardless the material.

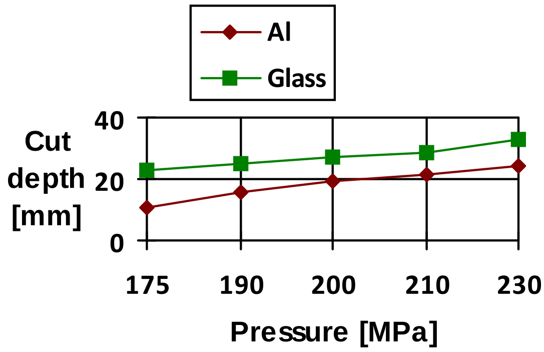

Figure 13. Influence of pressure on process efficiency

In Figure 14 it is presented the influence of cutting speed on process efficiency. It can be observed that an increase in cutting speed decrease the cut depth hence the process efficiency.

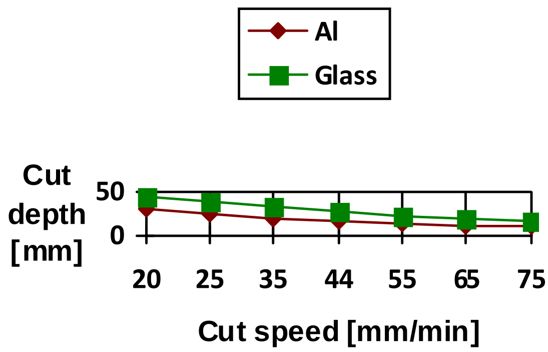

Figure 14. Influence of cutting speed on process efficiency

Figure 15 shows the influence of distance between focus tube and part to be cut on process efficiency. General influence is to decrease the process efficiency with increase of distance almost linear.

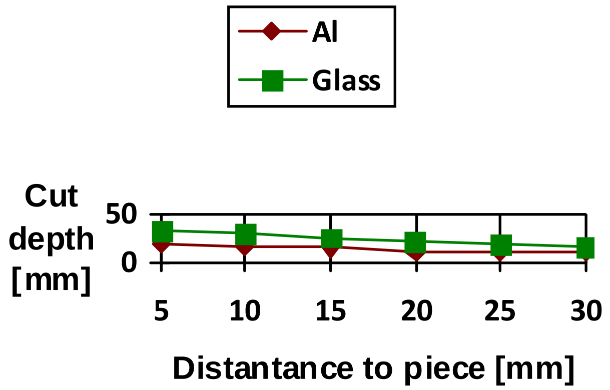

Figure 15. Influence of distance focus - piece on process efficiency

4.2. Abrasive water jet drilling

Abrasive water jet drilling is the process in which neither the cutting head nor the working part move relative each other. The abrasive jet penetrates totally the working part.

The drilling process has three phases [5, 8]:

- Impact phase (during abrasive waterjet input in piece material);
- Penetration phase when there are inverse flows of water near the hole walls until complete penetration of the hole;
- Finishing phase, when the hole walls are finished until finish of process.

In Figure 16 it is presented the geometry of a hole drilled with abrasive water jet.

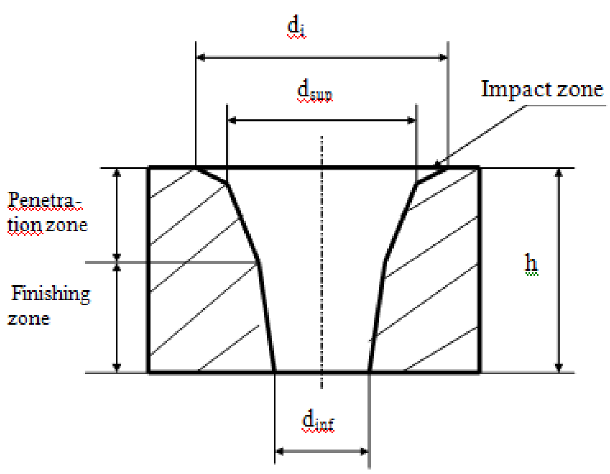

Figure 16. Geometry of AWJ drilled hole

We have for the parameters from figure the following meanings:

- d_i – equivalent diameter of the impact zone;
- d_{sup} – upper diameter of the hole
- d_{inf} – lower diameter of the hole
- h – hole depth.

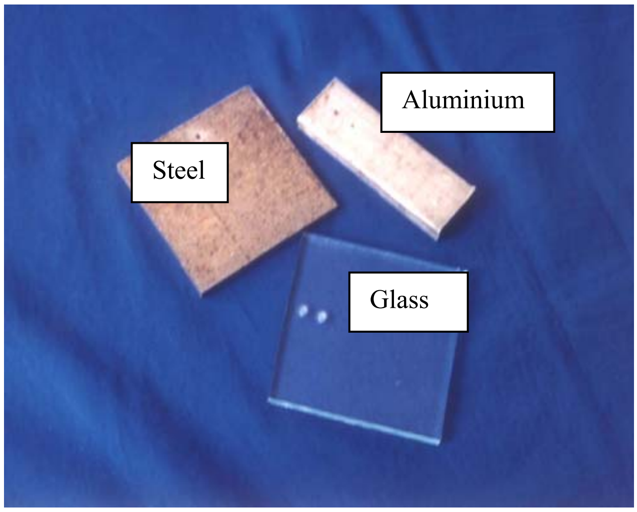

Figure 17. – Examples of materials drilled with AWJ

In figure 17, there are presented examples of materials drilled with abrasive water jet: steel, aluminium and glass.

In table 2, are presented results of abrasive water jet drilling of materials from figure 17.

Figure 18 presents the influence of material on two of main parameters of abrasive water jet drilling:

- specific volume of material excavated by the abrasive water jet Vc (mm^3/s);
- the taper of the hole k (°).

The conclusions of the curves presented in figure 18 are:

- specific volume decreases with increase of tensile strength of drilled material;
- the hole taper is dependent of material toughness; for example for glass the taper is very low as it is a brittle material.

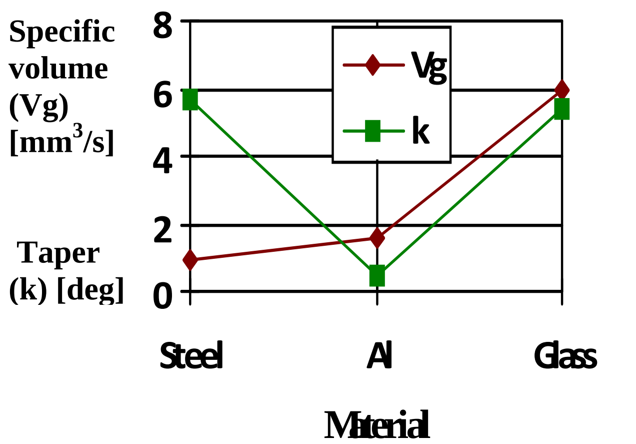

Figure 18. Influence of material characteristics on specific volume excavated and taper of the hole (ICTCM)

Table 1. Materials cut with abrasive water jet (ICTCM)

Material	Thick-ness	Cutting speed	Cut width	Cut quality		Technological aspects
				Flank aspect	Roughness	
-	(mm)	(cm/min)	(mm)	-	-	-
Aluminium AlCu 4 MgMn	5	8,0	1,5	Clean, without cracks, rounded at jet entrance	Smooth at jet entrance	
	6	7,0	1,5			
	∅20	4,5	2,5			
Brass (Cu Zn 37)	3,0	8,5	1,5	As for aluminium	As for aluminium	
	∅25	3,7	3,0			
Bronze (Cu Sn 14)	∅25	4,5	3,5	Smooth, round at jet entrance	Smooth, no waves	The cutting speed can be increased
Structural Steel (St37)	2,0	7,8	2,2	Good, flanks without cracks	Better for upper zone of the cut	In decrease the speed increase the quality of flanks
	4,0	6				
	6,0	5,5				
	∅ 6	6,1	3,0	Broken flanks		
	∅ 12	4,8				
Stainless steel (15 Cr 170)	1,25	6,5	2,5	Flanks with small cracks	Good	
	2,0	6,0				
	2,5	5,8				
Alloyed steel (41MoCr11)	∅ 20	3,0	1,8	Broken flanks	Rough	Hard to be cut

Table 2. Materials drilled with abrasive water jet (ICTCM)

Material	Thickness	Distance focus piece	Specific volume excavated	Geometric parameters of the hole			Observations
			V_g	k	d_{sup}	d_{inf}	
-	(mm)	(mm)	(mm^3 / s)	(°)	(mm)	(mm)	-
Glass	5,0	3,0	6	$5,426^0$	3,215	2,265	- pressure 200 MPa; - mixing tube:
Aluminium	10,0		1,6	$0,444^0$	2,085	1,930	- d_t = 0,8 mm; - l_t = 42 mm.
Structural steel (St 37)	5,0		0,9	$5,653^0$	2,915	1,925	- abrasive flow: 4,66 g/s; - abrasive: garnet with diameter 100...160 µm

5. CONCLUSIONS

The work presented in this paper is done at ICTCM Bucharest on experimental abrasive water jet equipment. This research work had the purpose to identify, as much as possible, specific aspects of the technology, equipment and phenomena of this technology.

It served to further developments of both equipment and technology, in order to identify all possible applications of this technology in different industries.

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