Annals of the Academy of Romanian Scientists
Series on Engineering Sciences
ISSN online 2066 – 8570 Volume **8**, Number **2**/**2016**

ABRASIVE ABSORPTION STUDY IN AWJ CUTTING

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Rezumat. *Cercetarea se referă la procesul de formare a jetului hidro abraziv şi la influenţa factorilor care determină comportamentul acestuia de la ieşirea din duză până în momentul impactului cu piesa, în scopul obţinerii unei configuraţii optimizate pentru întregul proces de prelucrare. Obiectivele sunt acelea de a creşte calitatea suprafeţelor prelucrate, de a mări productivitatea şi de a reduce costurile de producţie. Studiul evidenţiază modelul de formare a jetului prin absorbţia de aer şi abraziv. Rezultatele obţinute confirmă importanţa configurării exacte a cantităţii de abraziv introduse în jet, prin modificarea parametrilor procesului.*

Abstract. *This paper studies the forming process of the hydro abrasive jet and the factors that determine its behaviour after leaving the nozzle until the moment of impact with the piece, in order to obtain an optimized configuration of the processing. The objectives are those of obtaining optimal surfaces in terms of quality, increased productivity and reduced costs. The paper specifies the model of the jet forming through air and abrasive absorption. The obtained results have confirmed the importance of exactly configuring the abrasive quantity in the jet through modifying the size of the abrasive grains and the attraction force required for their absorption.*

Keywords: abrasive absorption, abrasive flow rate, hydro abrasive jet density

1. Introduction

The hydro abrasive process managed to impose a high standard amid unconventional technologies, being safe, precise, fast and economic. The continuing development of this process is based on the optimization of the manufacturing process, achieved through the study of complex fluid phenomena that occur from taking the water from the grid until it's transformed in an extremely powerful manufacturing tool, versatile and accurate.

The forming phenomenon of the hydro abrasive jet in the jet cutting machines is considered a complex one with many variables. The water enters in the cutting head at a pressure between 300 MPa and 600 MPa, being directed through an orifice with a diameter d = [0,03 ÷ 0,3] mm, made in a nozzle of extremely hard materials: sapphire, ruby or diamond. The fluid pressure pushed through the nozzle orifice creates a hydraulic coherent jet with a theoretical speed between

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700 m/s and 1000 m/s. This jet passes through the mixing chamber gathering in his composition abrasive particles together with an amount of air. This paper studies the influence of the water jet nozzle size inside the cutting head on the amount of abrasive incorporated in the jet as well as the influence of the fluid pressure, so the speed with which it runs through the mixing chamber, on the amount of abrasive incorporated.

The modelling equations of the behaviour of the jet have an important experimental component because the Rayleigh-Weber linear theory can't explain exactly the initial moment of the jet disintegration into drops and their number. These calculations however are essential and necessary for the correct sizing of the mixing chamber and the abrasive absorption tube. With the formation of droplets the behaviour of the fluid changes radically, this may or may not adhere to the tube walls forming sliding strips on the walls or not, depending on the nature of the fluid and its parameters [2].

Determining the size of each zone and the correct sizing of the cutting jet represents a problem of maximum importance for the hydro abrasive jet process. It results the need of corroborating the input data (jet pressure, flow, quality of the fluid), the intermediate data (nozzle shape, nozzle material nozzle size) and output data (sizing of the mixing chamber, focusing tube length, abrasive feeder size, etc.).[5]

The different design of the components that facilitate the entry of the flow of water in the nozzle that creates jet, determinates various effects in the exit speed of the nozzle, depending on the pressure and water flow. Research has shown that a greater length of the entry tube is preferred over a shorter length. At pressures less than 200 Mpa the ellipsoidal shape offers superior results over a hyperboloid shape at the nozzle entry.

The fluid under pressure reaches the nozzle made of a very hard material (ruby, sapphire, diamond). According to Bernoulli's law at the exit of the nozzle the fluid enters in the mixing chamber with a very high speed (up to 1000m/s).The liquid develop into a fluid whose composition has 3 stages: liquid (water that exits the nozzle), solid (the abrasive which is basically absorbed in the composition of the fluid through the Venturi effect, in the mixing chamber), gas (air enters the fluid composition with the abrasive particles).

The abrasive particles and air molecules are taken into the jet composition, accelerated and pushed chaotically towards the middle of the jet. Crashes between them and the water molecules lead to phenomena that oppose stability and consistency of the jet. That is way he is directed through the focusing tube, tube that basically supports the broadening of the jet, stopping particles to disperse, redirecting them towards the inside. The jet interaction with the focusing tube walls leads to the appearance of some large friction forces, wear of the walls and the decreasing of the jet speed. [9]

An abrasive jet generating system has the following requirements: optimal acceleration of the abrasive particles, providing a sufficient kinetic energy of the abrasive jet, low wear of the component parts, high performance and functionality.

The functions of an abrasive generating system are: acceleration and jet speed increase, abrasive absorption, and coherent jet projection towards the work piece.

The acceleration and speed increase of the jet are made accordingly to Bernoulli's law. It is based on the water going from a very high pressure and low speed to a very high speed and low pressure. This is obtained by adding a nozzle, in the high pressure network. The inner diameter should be between 0.03 mm and 0.3 mm, having extremely well finished surfaces to obtain the jet coherence.

2. Theoretical considerations

The water from the supply network is brought to a very high pressure with the help of pressure amplifiers, pressure spikes being attenuated by an accumulator. This sends towards the flow generating system water at a constant high pressure, through tubes.

The flow generating system receives water at a constant high pressure which it transforms into a high speed jet applying Bernoulli's law (1)

$$p_{at} + \frac{\rho_a}{2} V_j^2 + \rho_a g h_1 = p + \frac{\rho_a}{2} V_t^2 + \rho_a g h_2 \quad (1)$$

where: p_{at} is the atmospheric pressure [Pa];

p is the fluid pressure at the entrance to the nozzle [Pa];

ρ_a is water density [kg/m^3];

V_j is the velocity of the jet at the exit of the nozzle orifice [m/s];

V_t is the flow velocity of high pressure water [m/s];

$h_1 = h_2$ is the distance to the reference plane [m].

Considering: $h_1 = h_2$, $V_j >> V_t$, $p >> p_{at}$, relation (1) become:

$$\frac{\rho_a}{2} V_j^2 = p \quad (2)$$

$$V_j = \sqrt{\frac{2p}{\rho_a}} \quad (3)$$

where μ is a factor specific to each installation dependent on friction losses, turbulence, compressibility, the water pressure and the nozzle shape [1], [9], [10], [12].

2.1. Abrasive absorption

Transforming the water jet in abrasive water jet is made by absorption of the abrasive and the air, finally forming a fluid with supersonic speeds, whose tri-phase composition is the major component cutting of AWJ system.

The process of abrasive absorption in the jet is a complex one, determined by the following factors: the pressure of the flow of liquid from the pipes, *p* [Pa]; the diameter of the nozzle that forms the jet, *d* [mm]; the velocity of the jet at the nozzle exit, V_j [m/s]; the mass flow of the jet at the entry in the mixing chamber, , Qm_j [g/s]; the diameter of the abrasive particles, *D* [mm]; the density of the abrasive ρ_{ab} [g/cm^3]; the mass flow of the jet at the exit from the mixing chamber Qm_e [g/s]; the speed at the exit from the mixing chamber, V_{je} [m/s]; the speed of the jet at impact, V_f [m/s]. The following hypotheses have been made: the initial speed of the abrasive, $V_{0ab} = 0$, the friction and gravitational forces, encountered by the abrasive particles crossing through the feeding tube, are null, the shape of the particles is considered spherical, the influence of the cavitation phenomena and turbulence has not been taken into consideration, the transformations which happened in the jet because of the air molecules implosion, under the action of the pressure inside the interior of the jet, have not been considered. Throughout, from the nozzle exit until the impact with the piece the behaviour of the jet has been considered ideal without taking into consideration the friction inside the jet.

The jet has three regions at the exit from the nozzle. (Fig. 1) [2], [15].

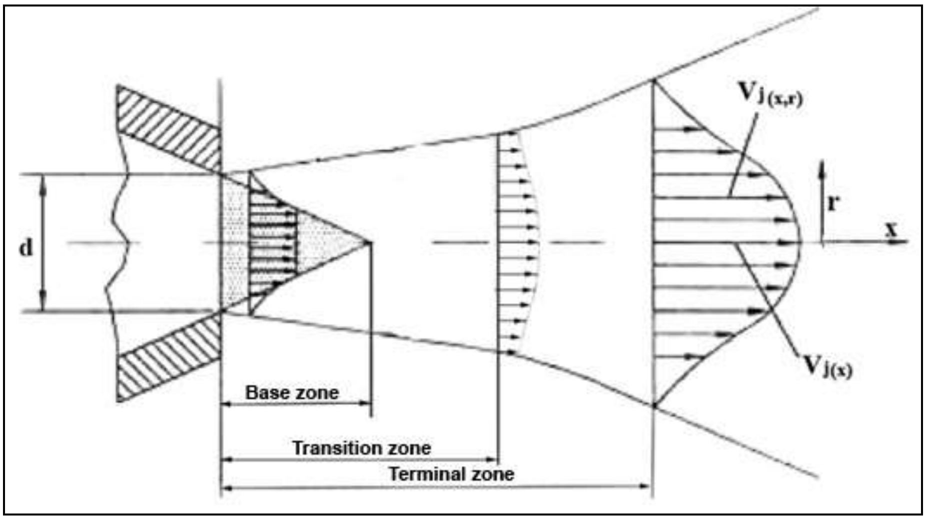

Fig. 1. The areas of the water jet at the exit from the nozzle.

The base zone is the zone with a constant pressure on axial direction. The length of this zone depends on the nozzle radius and its form, respectively the crossing angle between the jet diameter and the pipe.

The transition zone represents a zone in which the friction forces with the air decrease the jet speed. Also, attraction and incorporation of molecules in the jet, their implosion caused by high pressure, creates a phenomena of turbulence that leads to the increase of the jet diameter as well as the decrease of the speed on the edges ($L_t = 5{,}33 \cdot L_b$) [3], [4], [5]. The dynamic measures vary across the axial and radial direction. Terminal area is the area where the jet tends to lose its cohesion. At the exit of the nozzle, the jet moves at a speed $V_j = 700 \div 1000$ [m/s], incorporating the air molecules found in close proximity, creating in wider space of the mixing chamber a decrease of normal pressure $p_{n.}$

Absorption of air and abrasive in the formed jet, reduce its speed, contributing to increase the diameter of the jet. The presence of focusing tube, after the mixing chamber, forces the jet to retain cohesion, allowing its precise targeting.

The velocity of the jet at a distance r from its axis (Fig. 1.) is determined as [5]:

$$V_j(xr) = V_j(x)\left(1 - \frac{2r}{d_j(L_i)}\right)^{\frac{1}{7}} \tag{5}$$

where:

$V_j(x)$ it is the maximum speed in the centre (axis) of jet [m/s];

r is the distance from the centre of the jet for what is calculated $V_j(xr)$, [mm];

d_j (L_i) is the diameter of the jet in the mixing chamber at distance L_i from exit of the nozzle [mm].

The absorption of air in jet, modify its density [6], [7], [13].

$$\rho_j(L_{bi}) = \left(1 - a_1 \frac{L_{bi}}{d}\right)\rho_a \tag{6}$$

$$\rho_j(L_{ci}) = \left[\frac{L_{ci}}{d\left(2.7\frac{L_{ci}}{d} - 20\right)} + \frac{8d}{L_{ci}}\right]\rho a \tag{7}$$

where:

ρ_j (L_{bi}) is jet density in basic zone, calculated for dimension L_{bi} [g/cm^3];

ρ_j (L_{ci}) is jet density in transition zone, calculated for dimension L_{ci} [g/cm^3];

a_1 is a coefficient that takes into account the report L_i/d (report that defines the content of air in jet).

After conducted experiments, Yanaida proposed the following relation for d_j (L_i) [3]:

$$d_j(L_i) = 0.24d\sqrt{L_i} \tag{8}$$

Jet diameter increases proportionally to the square root of the length at which it is measured.

Flow regime can be laminar, of the transit or turbulent, depending on the value of Reynolds number. In fact, the fluid is viscous, air is compressible, and the system made to achieve a minimum entropy state. In such a system, Reynolds number, *Re*, is:

$$\mathrm{Re}_j = \frac{\rho_j (L_i) V_j d_j (L_i)}{\mu} = \frac{V_j d_j (L_i)}{\nu} \quad (9)$$

where:

> Re_j is Reynolds number, corresponding with focusing sector, considering water a viscous liquid;
>
> μ is the dynamic viscosity of the fluid [Pa·s];
>
> ν is the kinematic viscosity of the fluid [m^2/s];
> V_j is jet velocity [m/s].

For *Re* < 2000, the flow is laminar. For turbulent flow, where *Re* > 4000, can be noted random and irregular fluctuations of fluid velocity, caused by the local mixing or internal fluid turbulence which, usually, has low viscosity and high density.

Results that starting from mixing chamber, occurring vortices and secondary flow directions leading to losses speed according to relations (4), (5) and to pressure drop due to multiple factors (absorption of air and abrasive at the entrance and exit of nozzle, as well as, at entrance and exit of focusing tube) Fig. 2.

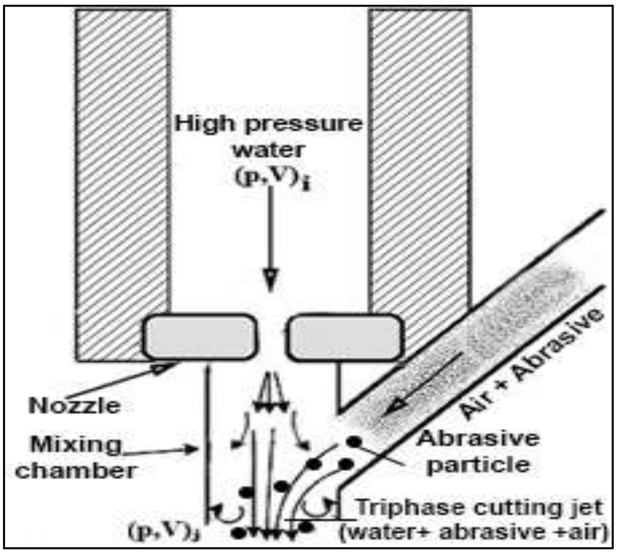

Fig. 2. Abrasive absorption

The absorption of particles of the abrasive in fluid has no analytical solution, only approximations of the curves resulting from experimental research.

Pressure drop at distance L_i of the exit of the nozzle can be calculated from the relationship (10):

$$\Delta p = k \frac{\rho_j (L_i) v^2}{2} \quad (10)$$

where k is a pressure loss coefficient (k = 0,05 for each component that loses pressure) [8].

It is considered that the particles are driven in the fluid, having a negligible initial speed, being accelerated to a fluid velocity. The particle shape is considered spherical, with a smooth surface, so that not develop resistance forces to movement in the fluid.

The entrance into the fluid is approximated as being slow and laminar. In these conditions, the absorption force F_{tr} applied by the fluid on each particle can be calculated by the relationship [16]:

$$F_{tr} = F_{av} + F_{ip} \quad (11)$$

where:

F_{tr} is the force through a particle of abrasive is attracted towards the centre of the fluid [N];

F_{av} is the force of attraction manifested between particles and fluid, due to viscosity [N];

F_{ip} is the force that occurs due to particle inertia [N].

$$F_{tr} = C_D \frac{\pi\rho}{8} d^2 w^2 + \frac{\pi\rho}{12} d^3 \frac{dw}{dt} \quad (12)$$

where:

C_D is a coefficient of particle movement resistance;

d is the diameter of the abrasive particle, considered spherical [mm];

w is the relative velocity of the particle to the fluid. [m/s].

At the entrance of the jet in the mixing chamber, the pressure inside is equivalent to the normal pressure p_n [14].

Because of the high speed of the jet that passes through the mixing chamber with V_j (L_i), having a mass flow Qm_j, in the jet is incorporated an amount of air, resulting, in the mixing chamber, a pressure drop with the value:

$$\Delta p_{cam} = p_n - p_{cam} \quad (13)$$

where:

p_{cam} is the pressure in the mixing chamber when crossing jet [MPa];

p_n is the normal pressure [MPa].

On the other hand, the pressure drop in the mixing chamber Δp_{cam} may be considered [5]:

$$\Delta p_{cam} = p_{ab} \tag{14}$$

where:

p_{ab} represents the pressure needed to transport the abrasive [MPa].

Relationship (14) can be developed [5]:

$$\Delta p_{cam} = a \frac{dm_{ab}}{dt} \frac{dQ_{ab}}{dt} \tag{15}$$

where:

a is the coefficient of losses, occurring from transport of the abrasive;

Q_{ab}/dt is specific flow of abrasive, transported in unit time [l/min^2];

dm_{ab}/dt is mass of abrasive, transported in unit time [g/s].

A greater difference in pressure leads to aspiration of a larger amount of abrasive, in unit time.

The pressure difference increases with increasing water pressure and decreased of the volume of air in the room.

The volume of air aspirated into the jet, that determines the pressure in the mixing chamber p_{cam} şi Δp_{cam}, depends on several process parameters, including constructive parameters of the processing head: nozzle design and mixing chamber design, diameter and slope of aspiration hose.

Aspired air volume increases approximately linearly with the square root of water pressure before passing through the nozzle. Also increases with the length of the mixing chamber.

A specific calculation relation of air flow aspirated in jet is [9]:

$$\frac{dQ_{aer}}{dt} = a_1 \sqrt{p} \tag{16}$$

where a_1 is a coefficient that takes into account of the characteristics of the cutting jet head.

1.1. Focusing and injection of hydro abrasive jet

Focusing tube or mixing tube, is a component of great importance in processing with hydro abrasive jet.

It is characterized by the following parameters [10]: lenght L [mm], inner diameter D [mm], the pressure at the entry of focusing tube p_{je} [MPa], jet speed at the entry of the tube V_{je} [m/s], the pressure at the outlet of the focusing tube p_f [MPa] and jet speed at the exit of the tube V_f [m/s] (Fig. 3).

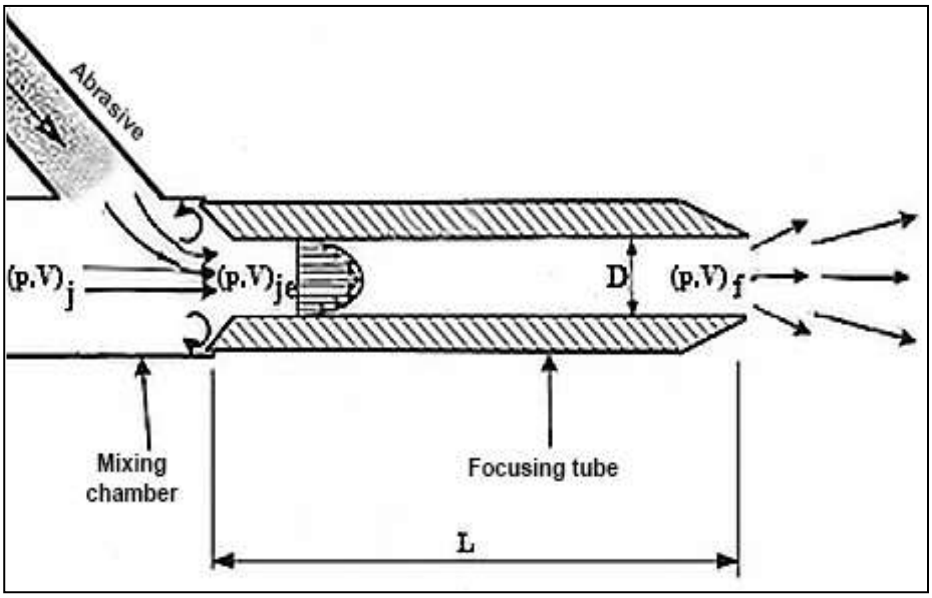

Fig. 3. Focusing process

Jet forming system is one to which may be applied the conservation laws of moments [11]. It can be written as:

$$\sum \frac{dm}{dt} V(initial) = \sum \frac{dm}{dt} V(final) \quad (17)$$

$$\frac{dm_w}{dt} V_j = \frac{dm_{air}}{dt} V_f + \frac{dm_w}{dt} V_f + \frac{dm_{ab}}{dt} V_f \quad (18)$$

Considering the insignificant air mass and the speed of the abrasive particles and the molecules of water equal to the output speed of the focusing tube V_f, it results:

$$\frac{dm_w}{dt} V_j = \left(\frac{dm_w}{dt} + \frac{dm_{ab}}{dt} \right) V_f \quad (19)$$

$$V_f = \frac{\frac{dm_w}{dt}}{\left(\frac{dm_w}{dt} + \frac{dm_{abr}}{dt} \right)} V_j \quad (20)$$

Relationship (20) is one approximate; starting conditions are different from real ones. The particle was considered a sphere with smooth surface, so without friction and without loss of moment that occurs when rolling a non-spherical particle.

Likewise, not taking into account the collisions with the walls of the tube and any collisions between particles, who fragmenting and decreasing them, changing the entire process. It was not taken into account the loss of speed caused by changing the jet density and of the loss of speed due to the distance of the nozzle.

For this reason, the analytical data must be confirmed by experiments.

Momber and Kovacevic correct the relationship (20), applying a set of experiments that led to the relationship (21) of the real speed of the particles to the exit of the focusing tube [12]:

$$V_i = A\frac{\frac{dm_w}{dt}\sqrt{\frac{p_j}{\rho_j\left(L_i\right)}}}{\frac{dm_w}{dt}+\frac{dm_{abr}}{dt}}\left[1-e^{\frac{-BL}{d}\left(\frac{\rho_j\left(L_i\right)}{2\rho_{abr}+\rho_j\left(L_i\right)}\right)}\right] \tag{21}$$

where:

V_i is the velocity of jet at a distance L_i;

A and *B* are parameters that depend on the design of parts of the cutting head;

d is the particle diameter of the abrasive.

$$V_f = A\frac{\frac{dm_w}{dt}V_j}{\frac{dm_w}{dt}+\frac{dm_{abr}}{dt}}\left[1-e^{\frac{-BL}{d}\left(\frac{\rho_f}{2\rho_{abr}+\rho_f}\right)}\right] \tag{22}$$

Equation (22) shows the dependence on the jet exit speed of the focusing tube (V_f), on variation in mass of the water who enters in the mixing chamber per unit time (dm_w/dt), on variation of abrasive mass that is absorbed per unit time (dm_{abr}/dt), on variation of jet density ρ_j (L_i) depending on its distance from the nozzle, on the abrasive characteristics (density ρ_{abr} and the diameter of the abrasive granules *d*), on positioning from the nozzle (length *L*), as well as parameters A and B, who depend on the constructive form of the cutting head.

3. Experimental results

The research was conducted on a machine Maxiem 1530.

Were used high pressure p_1 = 345 MPa and low pressure p_2 = 180 MPa.

Were used sapphire nozzle with d_d = 0.28 mm and d_d = 0.08 mm.

In the first case, the focusing tube has the length *of* $L \approx 100 \cdot D$ = 75 mm, where the focusing tube diameter is $D \approx 3 \cdot d_d$ = 0.84 mm.

For the second nozzle was used a focusing tube with the length of *L* = 25 [mm].

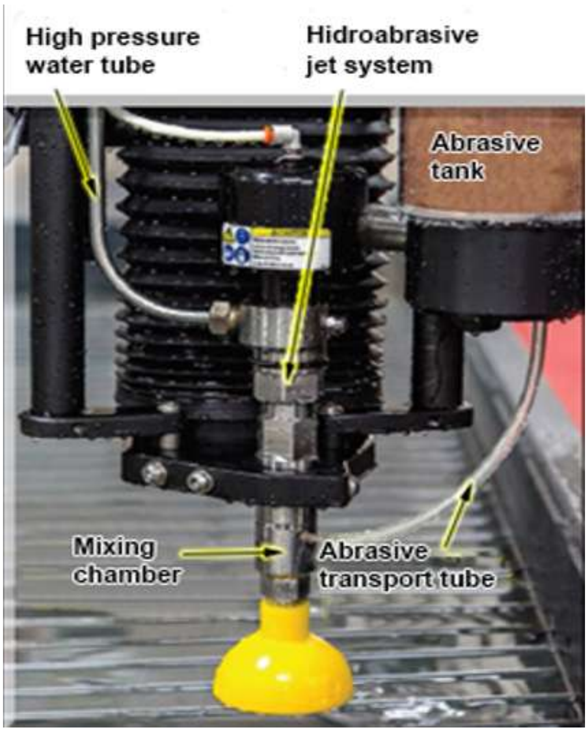

Fig. 4. Maxiem hidroabrasive system.

In Fig. 4 is shown the abrasive feeder of Omax Corporation, Maxiem 1530 model. Abrasive reaches the tank, filtered and pushed by compressed air, after being discharged in a warehouse. From the tank, the abrasive is aspirated into the mixing chamber through a transparent plastic tube. The plastic tube must be perfectly dry, not slippery on the inside or abrasive blocked, strengthened on tube walls, because the pressure difference between the pressure inside the mixing chamber and normal pressure has moderate values.

Were used three types of garnet abrasive: Mesh 60, Mesh 80 and Mesh 100 with the following characteristics (Table 1).

Table 1. Properties of used abrasives

No.	*Type of abrasive*	*Grain size [mm]*	*Density [g/cm³]*	*Hardness[Mohs]*	*Purity*
1.	Garnet Mesh 60	250	2.24	>8	>80%
2.	Garnet Mesh 80	180	2.30	>8	>80%
3.	Garnet Mesh 100	150	2.40	>8	>80%

The used material is alloyed austenitic stainless steel X5CrNiMo17-12-2 with the following properties: Hardness Rockwell B, H_B = 80; machinability, M=82.5; modulus of elasticity, E = 193 GPa; thickness h = 10 mm; length of cut l = 100 mm.

The setting parameters are shown in Fig. 5.

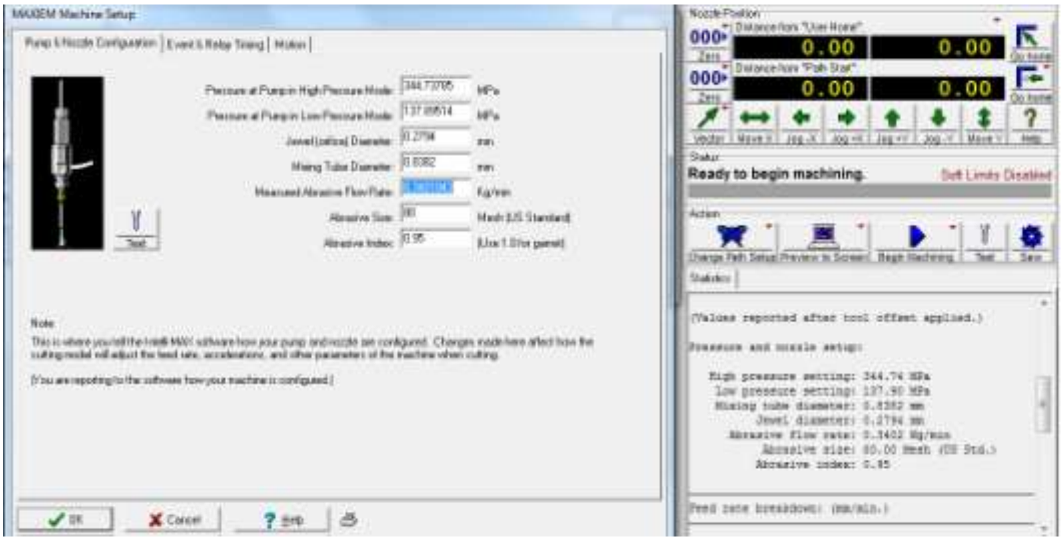

Fig. 5. Maxiem 1530 equipment configuration window.

Setting the AWJ machine has been executed by changing water pressure provided by the pump for the maximum value p = 345 MPa to p = 180 MPa. Samples were executed with two pressures for each type of abrasive. The abrasive flow rate was measured in Test Mode (Fig. 6) for t=5min and the obtained value was introduced in the configuration window.

Further, samples were made with a mini jet head cutting, with orifice diameter d_d = 0.08 mm. For values of abrasive flow rate, it was used the same method.

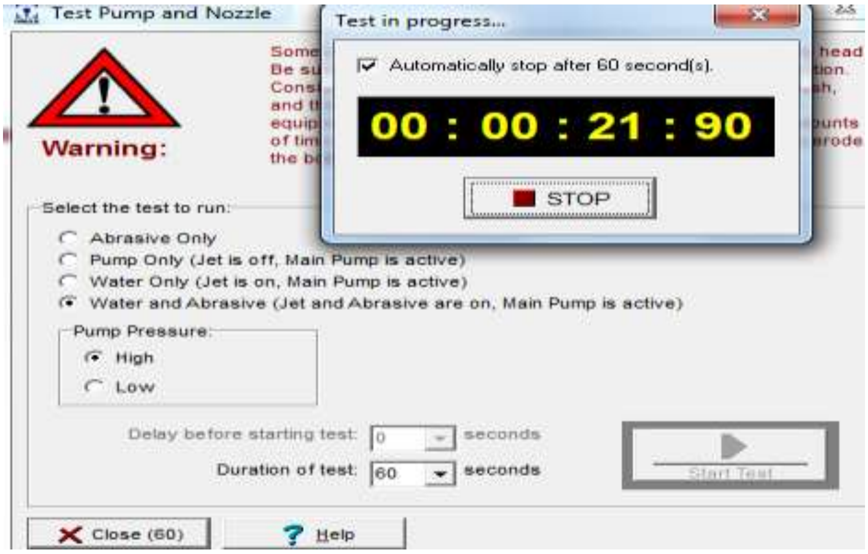

Fig. 6. Maxiem 1530 Test Mode.

The results were listed in Table 2.

Table 2. Properties of used abrasives.

Test no.	*Pressure [MPa]*	*Orifice diameter [mm]*	*Type of garnet [Mesh]*	*Measured abrasive flow rate [kg/min]*	*Used abrasive [Kg]*	*Operation time [min]*	*Estimated cost [Euro]*
1.	345	0.28	60	0.29	0.39	1.42	0.6
2.			80	0.34	0.43	1.358	0.57
3.			100	0.405	0.49	1.316	0.55
4.		0.08	60	0.015	0.18	12.34	5.14
5.			80	0.05	0.38	9.58	4.16
6.			100	0.081	0.59	7.38	3.08
7.	180	0.28	60	0.21	1.06	5.13	2.14
8.			80	0.28	1.19	4.33	1.8
9.			100	0.335	1.29	3.96	1.65
10.		0.08	60	0.009	0.41	46.1	19
11.			80	0.022	0.73	33.2	13.8
12.			100	0.058	1.36	22.5	9.82

The estimated cost is calculated for 25 Euro/hour for AWJ function. The used software for AWJ setting and cutting was Intelli-Max Make, version 23.0, release date: 26.08.2015.

Conclusions

The increase of pressure in the high pressure system, greatly influences the operating time and the amount of abrasive consumed, on the downside of their. Jet cutting process becomes more cost effective with increasing work pressure. Equipment of the latest generation, working with pump which provide a pressure, up to p = 600 MPa.

Decrease in diameter of nozzle, $d_{d,}$ leading to lower consumption of abrasive, for all that, the amount of abrasive consumption for the same operation grows, due to increase of working time. Use of heads with nozzle diameter much smaller, leads to increase in the cost of processing.

Changing the type of abrasive has a much greater influence in the case of low pressure, within the meaning of large increase of working time with increasing of particle size and decrease of nozzle diameter.

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