Hydroabrasive Machining Process Optimization through Statistical Analysis and Robust Design

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Abstract
Hydroabrasive jet cutting process has demonstrated its application need, thanks to the flexibility and simplicity. The objective of this research is optimization of the processing with hydroabrasive jet through the use of robust design of manufacturing processes. Implementing the method in parameterization of abrasive jet cutting, like statistical analysis performed, demonstrates the applicability of the proposed solution, namely, increasing of hydroabrasive processing efficiency by using robust design. Parameters proposed to be enhanced are dimensional accuracy and surface roughness, resulting from the processing with hydroabrasive jet. Parameters of process influence is changed in order to optimize, revealed the importance of their values correct elections and interdependence between them. The obtained results have confirmed the importance of exactly configuration of these input parameters, based on statistical analysis and robust design.

Keywords
abrasive water jet cutting, robust design, hydro abrasive process optimization

1. Introduction

The advantages that put hydroabrasive technology in the forefront of special technologies are: the variety of processed materials, reduced processing costs, low environmental impact, high flexibility, easy programing, fast processing, keeping the same material properties caused of low temperature processing. All of these advantages lead to the necessity of thorough research and quick resolution of the existing problems in hydroabrasive erosion: relatively low (0.1 mm) dimensional accuracy of products and the emergence of defects (streaking, microcraters, high roughness) on the machined surface. All the abrasive jet cutting machines have a series of parameters which define the entire technological operation.

In this study there are considered the following parameters: water pressure (p) which determines the speed of impact (V_i), traverse speed (V_t) who determine cutting depth (a) and work time (t), the distance between the end of mixing tube and the workpiece (L), as well as mixing tube diameter (d_t), who determine the abrasive jet diameter (D) on exiting of the tube.

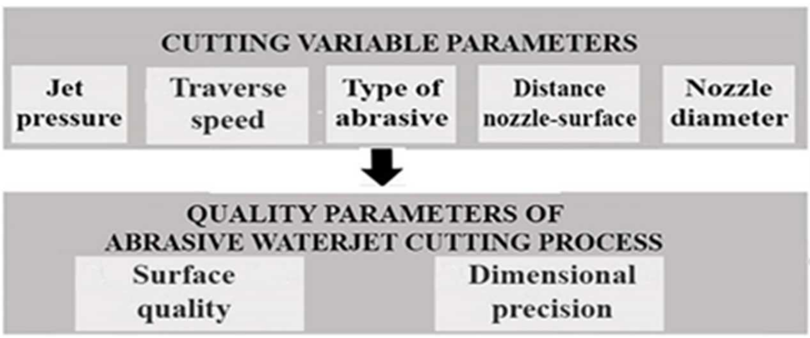

Fig. 1. Abrasive water jet cutting process

Control and choosing the correct values of these factors leads to the optimization of the abrasive jet cutting by achieving a minimum surface roughness results, and a maximum dimensional accuracy.

2. Theoretical Considerations

The easiest to set up, with the greatest impact on the technological process, is traverse speed (V_t) [1, 2, 3]:

$$V_t = \frac{R_m}{d_t a} \tag{1}$$

where: - V_t is traverse speed of the abrasive jet in cutting process [mm/s];
- R_m is the rate of removal unit volume of material [mm^3/s];
- d_t is diameter of mixing tube [mm];
- a is the depth of cutting, made in the material area [mm].

Choosing traverse speed values (V_t) is conditioned by cutting achievement so that the depth of cut exceed the thickness of the workpiece (h) and to realization of rate of removal unit volume of material (R_m) who allowing complete cutting, during transition. Cutting in two or more passes have the disadvantage of the occurrence of some problems to evacuation of abrasive jet, leading to dimensional errors

It is considered the rate of removal unit volume of material:

$$R_m = \frac{1}{2} I_m V_j^2 M_s \tag{2}$$

where: - I_m is the impulse given to the abrasive in unit time [gm/s];
- V_j is the velocity of the jet at the place of impact [m/s];
- M_s is specific machinability of material.

$$V_j = \mu\xi \sqrt{\frac{2p}{\rho_a}} \tag{3}$$

where: - μ is a coefficient of acceleration according to opening for high-speed ring;
- ξ is a coefficient which takes into account the characteristics of abrasive, the degree of grinding, friability and structure;
- p is pressure of jet in mixing tube[MPa];
- ρ_a is abrasive jet density [g/mm^3].

It is seen from equations (1), (2) and (3) interdependence of the determinants factors during the processing with hydroabrasive jet, namely: traverse speed V_t, the diameter of mixing tube d_t, the abrasive jet pressure in mixing tube p and abrasive characteristics ξ. The correct choice of one of these factors s obviously conditioned by the correct choice of all factors, resulting so, the necessity of statistical survey of the phenomenon. Generalization of a method for determining them in interdependent condition, allow operators, the use of abrasive jet cutting technology to a high potential.

Abrasive powders used in processing abrasive jet cutting tool is actually used for processing action. Abrasive particle is one that removes the material is directly in contact with the workpiece. Jet speed, momentum and energy that provides abrasive particle determines the cutting speed. The type and the quantity thereof contained in the abrasive jet cutting influences the process.

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 [4] of the exit of the nozzle, can be calculated from the relationship (4):

$$\Delta p = k \frac{\rho_j (L_i) \nu^2}{2} \tag{4}$$

where: - k is a pressure loss coefficient (k = 0,05 for each component that loses pressure);
- Δp is pressure drop at distance L_i [Pa];
- L_i is distance between nozzle and measured point [mm];
- ν is the kinematic viscosity of the fluid [m^2/s].

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 [5, 6, 7, 8]:

$$F_{tr} = F_{av} + F_{ip} \tag{5}$$

where: - F_{tr} is the force through a particle of abrasive is attracted towards the center 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].

$$F_{tr} = C_D \frac{\pi\rho}{8} d^2 w^2 + \frac{\pi\rho}{12} d^3 \frac{dw}{dt} \tag{6}$$

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]

From relationship (4), (5) and (6) it seen the influence of distance between nozzle and work piece (L) on cutting process and also the influence of this distance on other process parameters .

Robust design uses statistically planned experiments to measure and control parameters. For combination of parameter in experiment, output measurements are verified by monitoring the effects of process variation. The estimates of effects of parameters variation are used to predict the response of process to any combination of the parameter levels. Statistical analysis is based on the mean and the standard deviation to determine the parameters level combination to which the answer is optimal.

A complete parameter design experiment consists in defining parameters of variance, their level and matrices of appropriate selected experiments plan. Since surface roughness (R_a) results from processing must be as small, the used criterion is the minimization [9].

The formula used for minimization roughness Ra is calculated using average roughness compiled with minimum effects caused by chosen parameters

$$Ra = Ra_{med} + \sum_{i=1}^{n} minE_i \tag{7}$$

where: - Ra is arithmetic average of the absolute values of vertical deviation appeared on the machined surface [μm];
- Ra_{med} is arithmetic average of the measured Ra in all experiments [μm];
- E_i is the response of each combination of parameters.

For verification was used Taguchi method [10, 11]. The optimal combination of parameters is made using criterion of minimization of signal-noise ratio:

$$\frac{S}{N} = -10 \log(s^2 + \bar{y}^2) \tag{8}$$

where: - S/N is ratios depending of parameters values (performance indicator);
- s is standard deviation of data;
- y is arithmetic average of data.

3. Experimental Results

The research was conducted on a machine Maxiem 1530 (Fig. 2). Were used high pressure p_1 = 345 MPa and low pressure p_2 = 180 MPa. Were used saphire nozzle with d_t = 0.28 mm and d_d = 0.08 mm. In the first case, the focusing tube was the length $L \approx 100 \cdot D$ = 75 mm, where the focusing tube diameter is D ≈ 3·d_d, = 0.84 mm.

For the second nozzle was used a focusing tube with length L = 25 [mm]. Were used three types of garnet abrasive: Mesh 60, Mesh 80 and Mesh 100, with following characteristics (Table 1).

Table 1. Properties of used abrasives

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

The used material is alloyed austenitic stainless steel X5CrNiMo17-12-2 with following properties: Hardness Rockwell B, H_B = 80; machinability, M = 82.5; modulus of elasticity, E = 193 GPa. Have been made three different measurement for each combination, with thickness $h \in \{6, 4, 2\}$ mm, and lenght of cut l = 100 mm.

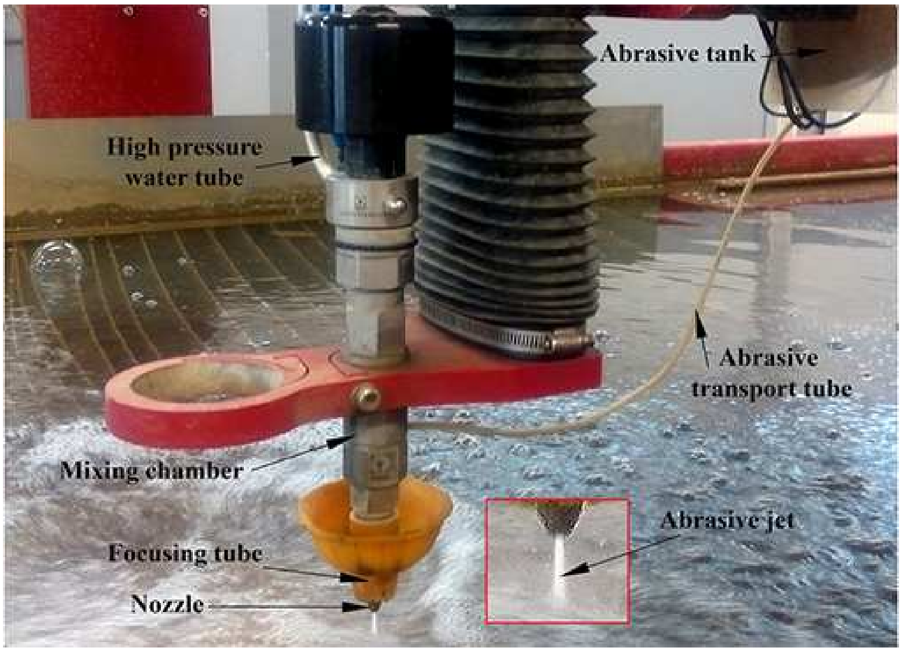

Fig. 2. Abrasive water jet cutting system Maxiem 1530

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. Further, samples were made with a mini jet head cutting, with orifice diameter d_t = 0.08 mm. The used software for AWJ setting and cutting was Intelli-Max Make, version 23.0, release date: 26.08.2015. In Table 2 is shown the two levels of variance for input parameters.

The plan of experiments is presented in Table 3.

Table 2. Parameters values used in experiments

Parameters	Pressure [MPa]	Orifice diameter [mm]	Type of garnet [Mesh]	Distance between end of tube and workpiece [mm]	Traverse speed [mm/s]
	A	B	C	D	E
Level 1	345	0.08	60	1	60
Level 2	180	0.28	100	2	90

Table 3. Matrix of experiments and their results

	A	B	C	D	E	Measurement			Arithmetic mean (y)	Standard deviation (s)	S/N
						1	2	3			
1	1	1	1	1	1	1.856	1.745	1.654	1.7516	0.1011	-4.8835
2	1	1	1	2	2	2.349	2.238	2.156	2.2476	0.0968	-7.0427
3	1	2	2	1	1	2.981	2.764	3.89	3.2116	0.5973	-10.282
4	1	2	2	2	2	3.368	3.086	4.131	3.5283	0.5406	-11.052
5	2	1	2	1	2	3.777	4.126	3.732	3.8783	0.2156	-11.786
6	2	1	2	2	1	2.173	2.993	3.449	2.8716	0.6465	-9.3775
7	2	2	1	1	2	4.789	3.781	4.562	4.3773	0.5287	-12.887
8	2	2	1	2	1	4.345	4.653	4.867	4.6216	0.2624	-13.31

In classical method is calculated the average response for each factor and for each level. The calculated responses is shown in Table 4, where in row 1 is average response and in row 2 is shown the average effect.

Table 4. The average response and calculated effect of combined parameters

	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
1	2.6848	3.9372	2.6873	3.9345	3.2495	3.3725	3.3048	3.3173	3.1141	3.5079
2	-0.626	0.626	-0.623	0.623	-0.06	0.06	-0.07	0.07	-0.196	0.196

Using equation (7) is obtained Ra = 1.7965 [μm] and parameters value combination: 11111.

With Taguchi method is calculated the response for every ratio S/N and the resulted effect shown in Table 5, where in row 1 is average S/N response and in row 2 is shown the average effect.

Table 5. The average response of S/N and calculated effect of combined parameters

	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
1	-8.315	-11.84	-8.272	-11.88	-9.53	-10.62	-9.961	-10.21	-9.463	-10.692
2	1.7625	-1.7625	1.8052	-1.8052	0.55	-0.55	0.1	-0.1	0.61438	-0.61438

With Taguchi method, the optimal combination of input parameters is 11111.

4. Conclusions

The researches lead to next conclusions:

- Increasing the pressure influence positively the surface quality;
- Using a smoother abrasive get a smaller surface roughness;
- Microprocessing with orifice diameter very small lead to increasing the surface quality;
- Increasing distance between exit orifice and workpiece negative influence the roughness;
- With increasing traverse speed, increase surface roughness;
- For a combination of parameters can be predicted obtained roughness.

In this paper was demonstrated the possibility of creating a modern instrument to consider the factors that influence the processing in order to optimize certain criteria that interested, with minimum experiments and its implementation on the computer could lead to significant gains.

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Received in November 2016