OPTIMISATION OF ABRASIVE JET CUTTING BY MEANS OF TAGUCHI METHODS

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ABSTRACT: An abrasive jet based cutting system has numerous input parameters, the most important ones including jet pressure, feed speed, stand-off distance, abrasive graining, mass flow, etc. Other quantities contributing to machining efficiency are the type of utilized abrasive or the tilt of the jet. All above parameters represent input quantities of the system, each having a range of possible values. The roughness of the machined surfaces and the thickness of the cut part are output quantities of the system, their values depending on the input parameters and the influence of various disturbing factors (noises).
The paper discusses surface roughness obtained consequently to abrasive jet cutting. Optimisation of the machining system was achieved by intervening on five selected input quantities (factors), with two set points considered for each. Upon applying Taguchi methods, eventually the combination of factor set points was determined that ensures robust behaviour of the system.
KEY WORDS: abrasive jet, roughness, Taguchi methods.

1 INTRODUCTION

High pressure abrasive jet machining does not benefit from a significant tradition, as it has been used only since the 1980s. Abrasive jets appeared from the necessity of expanding the range of machinable materials, allowing the processing of materials with high mechanical characteristics.

Due to its numerous advantages, in many industrial countries this process has been employed intensively. Thus, for example in Germany abrasive jets were employed for the cutting of aluminium (41%), steel (29%), glass (22%), granite, marble and rock (21%), non-ferrous metals (7%), wood (7%), rubber (5%), titanium (5%), etc. Abrasive jet cutting devices currently hold about 35% of the total cutting machines worldwide, what proves once again the efficiency and advantages of this processing method.

An exact analysis of the mechanism of pressure abrasive fluid jet erosion is difficult, due to the multitude of individual processes which take place at the contact between the incident beam and the processed surface. The complexity of the process results from the effects of impact pressures, compression and shearing stresses, erosion and cavitation, all combined with the various properties of the processed materials.

Abrasive jet erosion is not "cutting" in the sense of carving, but a chip removal process, not unlike saw cutting. Analysis of material removed by an abrasive jet reveals chips of up to 5 μm, comparable to those generated in cutting with a diamond disk.

Machining by pressure abrasive fluid jets entails, in a first stage calibration of the fluid in the nozzle. In the second stage the fluid-abrasive mix is formed, which is sent towards the surface of the workpiece. It is extremely difficult to observe the forming process of the abrasive mix, because of the high speed of the grains (200...800 m/s) and their small dimensions. Figure 1 illustrates the stages of abrasive jet forming, and presents the main quantities contributing to the erosive process.
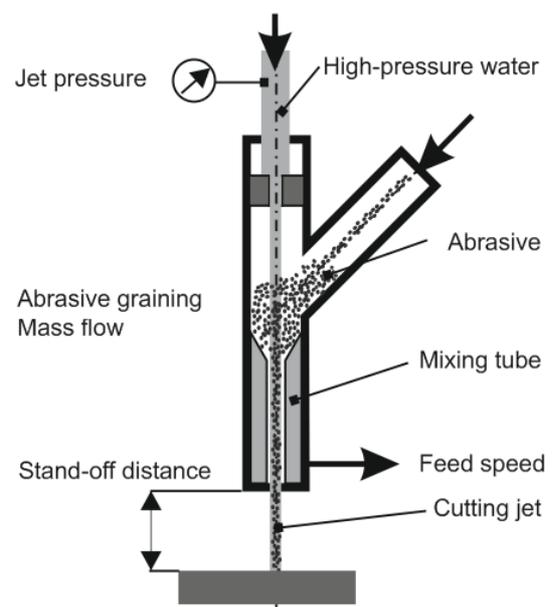

Figure 1. Principle of abrasive jet cutting

The above figure shows that the abrasive grains are transported to the mixing tube by aspiration, via the water jet. Once in the mixing tube, the grains repeatedly collide with its walls and the water jet,

being eventually included in the liquid jet. Because of these repeated collisions, the abrasive grains are continuously crushed, so that they have significantly smaller dimensions when leaving the mixing tube and hitting the workpiece.

Particularly significant is the form of the grains utilized in abrasive jet machining. Grain shape should be as compact and close to spherical as possible, as illustrated in Figure 2 [1].
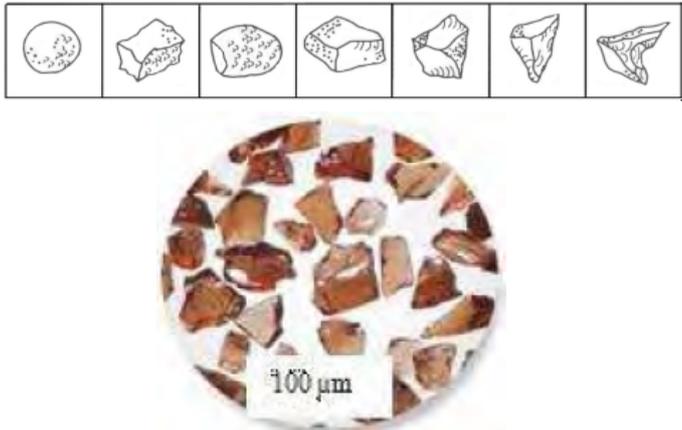
Figure 2. Recommended abrasive grain shapes

Pressure abrasive fluid jet machining holds numerous advantages, including [2]:

• edges of special quality, which do not require subsequent deburring;
• the cut contour can be complex, such as zigzag lines, narrow bridges and interior contours;
• depending on the jet diameter, a very narrow cutting gap is generated, thus allowing for significant material savings;
• sharpening and re-sharpening of tools is eliminated (abrasive grains are not reused after cutting);
• an initial tracing of the contour to be cut on the surface of the workpiece is not required;
• this type of machining lends itself to automation;
• high cutting productivity;
• minimum machining costs, due to the low cost of water, abrasives, etc.

In relation to the latter advantage, Table 1 features the hourly costs of an abrasive jet cutting installation.

Table 1. Costs generated by abrasive jet erosion

|	[%]
Labour	35
Machine (amortisation in 5 years - 10^4 hours)	25
Abrasives	15
Nozzle	10
Pump maintenance	10
Energy	5
Total	100

When leaving the mixing tube, the abrasive jet is characterised by four important properties: speed, coherence, density and symmetry. Speed is the most important characteristic of a jet, as it determines its cutting capacity. A higher speed improves capability of the jet to perform as a cutting tool.

Jet speed depends also on the stand-off distance; evidently jet speed decreases as the workpiece surface is located at a greater distance. Figure 3 presents jet speed variation versus stand-off distance, for a pressure of 200 MPa and an initial jet diameter of 0.2 mm [3].
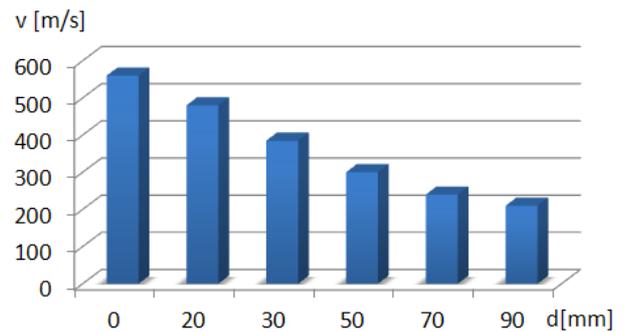
**Figure 3.** Jet speed versus stand-off distance

As the jet penetrates the material, its kinetic energy decreases continuously, causing a curved trajectory of the cut (Figure 4). This disadvantage can be compensated by increasing jet speed v, or by decreasing the feed speed w_a. In general, a cut of high quality requires adequate correlation of jet speed, workpiece thickness and material.
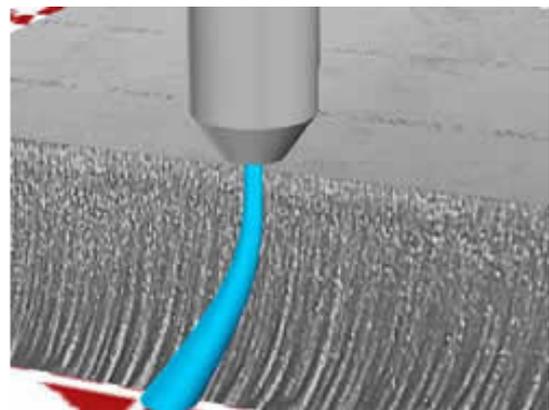
Figure 4. Curved trajectory of the cut

Jet feed speed w_a is particularly important for the quality of the cut. A higher feed speed reduces machining quality, and in some situations, when certain critical values are exceeded, the jet is deviated and cutting does not occur.

The mass flow of the abrasive grains is a further significant parameter for assessing the cutting capacity of the abrasive jet. Figure 5 presents the dependency of cut material thickness on the abrasive mass flow [4].
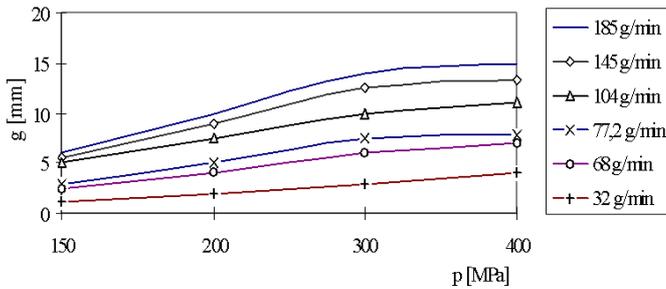
Figure 5. Influence of abrasive mass flow on cut thickness

Erosion cutting by abrasive jets is achieved consequently to the cumulated effect of two phenomena [2]:

• cutting and scraping carried out by each abrasive grain, during the first part of the machining process, as long as each grain still has sharp tips and cutting edges;

• plastic deformation of the material during the second part of the machining process, once the grains have lost their cutting capability. In this phase the remaining kinetic energy of the abrasive is still great enough to exceed to flow limit of the material, and thus in time to cause the removal of the tooling allowance.

Because of these two successive phenomena the quality of the cut surfaces is not uniform along the entire machined depth. A first area with numerous narrow striations can be observed, followed by an area with wider scratches (Figure 6). The depth of the first area, with a better roughness, depends directly on the speed of the abrasive jet.

It is known that as each abrasive grain penetrates deeper into the machined material, the quality of the cut decreases. Hence it is recommended to select the set points for the working parameters (pressure, graining, mass flow, feed speed) consequently to thorough experimental study. The thickness of the material that can be cut while ensuring acceptable quality needs to be determined by experiment-based multi-criteria optimisation.

Figure 6. Width variation of the trace left by an abrasive grain

Following analysis of the abrasive jet erosion process and knowing the main factors that contribute to obtaining surfaces of acceptable quality, further on a novel approach to ensuring machined surface quality is presented, based on the concept of *robust design* of these technological systems. This approach allows implementation of quality by conducting specially designed experiments of short duration, at low costs and with minimum material consumption.

The fundamental difference to classical R&D of a system consists in the pragmatism of robust design that does not aim at identifying and eliminating the causes responsible for non-quality, considered "noises", but only render the system insensitive to their action.

2 EXPERIMENTAL SET-UP

Experimental studies for the robust optimisation of pressure abrasive jet machining were conducted on a Maxiem 1530 machine. Such a piece of equipment allows the cutting of workpieces of up to 3099 mm x 1575 mm, at a maximum available pressure of 3450 bar and a maximum feed speed of 9 m/min. The dimensional precision ensured by this machine is of 0.05 mm [5].

The main parameters that contribute to attaining the goals of abrasive jet cutting are the pressure provided by the equipment, feed speed, stand-off distance, abrasive graining and mass flow. Other quantities impacting on machining efficiency are the type of the utilized abrasive and the tilting angle of the jet [6]. All enumerated parameters represent input quantities of the system, each having a range of possible values.

Experimental research consisted of cutting workpieces made from an aluminium alloy with the following composition: Al: 92.02%; Cu: 1.65%; Mg: 2%; Cr: 0.23%; Zn: 4%; Mn: 0.1%. The roughness (R_a) of the surface was measured after testing.

The data sets obtained upon experimenting and measuring were processed by dedicated software, *LappMaster*, developed by the authors, which yielded the optimum set-points of the tested controllable input factors.

3 EXPERIMENTAL DESIGN

Robust design of manufacturing systems is a major contribution brought by Japanese quality expert Genichi Taguchi to the set of instruments available in industry for quality analysis and improvement. Robustly designed processes ensure a constant quality, by reducing the scattering of the values

measured for the quality characteristic. Significantly for this method, this desideratum is achieved without eliminating the causes responsible for variability, namely by rendering the process insensitive to the influence of such uncontrollable factors (noise factors).

Robust design is a method to reduce the interval of variability of the quality characteristics, by providing the methodology for systematically obtaining solutions that render manufacturing processes less sensitive to disturbing causes. This type of design can be utilized for optimising product development, as well as for conceiving new manufacturing processes.

According to Taguchi's strategy non-quality can be eliminated without eliminating the disturbing factors from the system, but by adequately combining the set-points of the input factors.

The method used to optimize the pressure abrasive jet cutting process was the *method of fractioned orthogonal factorial arrays of experiments* devised by G. Taguchi. This method entails a planned approach, aimed at studying and establishing the links between the controllable input factors of a system and the obtained effects. The method identifies the combination of set-points of the input parameters of the system that reduce the effects of parasite causes, without however addressing these directly.

From the numerous input quantities affecting the pressure abrasive jet cutting process five factors were selected considered to have a major contribution to the machining process. Table 2 presents these factors, each being assigned two set-points during experiments.

Table 2. Selected factors and associated set-points

Set-point	Factors				
	A	B	C	D	E
	Feed speed	Jet pressure	Stand-off distance	Abrasive graining	Mass flow
	[mm/min]	[bar]	[mm]	[µm]	[g/s]
1	50	1250	1	60	0.5
2	100	1750	1.5	90	2

If a *full array of experiments* were used, the total number of tests would be $2^5 = 32$. Such an array entails the experimental study of all possible combinations of the set-points of the considered input factors, influencing system operation. Not all tests have, however, the same practical significance, some of the runs providing more information than others. Starting from this observation, G. Taguchi has devised a set of *fractioned orthogonal factorial arrays of experiments*. These arrays allow considerable reduction of the number of test runs to be conducted, without diminishing relevance and accuracy of the yielded results.

The experiments were conducted according to an array of experiments requiring only 8 runs, each with a different combination input factor set-points.

Table 3 presents this array of experiments, indicating in brackets, next to the set-point for each factor, the respective concrete values.

Table 3. The utilized array of experiments

Run	Factors				
	A	B	C	D	E
1	1 (50)	1 (1250)	1 (1)	1 (60)	1 (0.5)
2	1 (50)	1 (1250)	1 (1)	2 (90)	2 (2)
3	1 (50)	2 (1750)	2 (1.5)	1 (60)	1 (0.5)
4	1 (50)	2 (1750)	2 (1.5)	2 (90)	2 (2)
5	2 (100)	1 (1250)	2 (1.5)	1 (60)	2 (2)
6	2 (100)	1 (1250)	2 (1.5)	2 (90)	1 (0.5)
7	2 (100)	2 (1750)	1 (1)	1 (60)	2 (2)
8	2 (100)	2 (1750)	1 (1)	2 (90)	1 (0.5)

Each run was repeated five times, and roughness R_a was measured in different areas of the machined surface. Further arithmetic mean, standard deviation and signal-to-noise ratio were computed for the measured results.

The signal-to-noise ratio (S/N) is the performance indicator that simultaneously considers the target value of the analysed quality criterion and the variability around the target. The desired value is defined as signal (expressed by $\bar{y}$ = the arithmetic mean of the measured values), while its undesired variability, to be diminished, is defined as noise, (expressed by the standard deviation s).

In certain practical applications merely determining the results of measurements may not be sufficient. In the case of pressure abrasive jet cutting, one of the aims is to machine surfaces such as to achieve a roughness as small of possible. This means imposing a sense of this quantity's evolution, in other words considering an optimisation criterion of "*smaller is better*" type. The computational relationship of the S/N ratio for a quality characteristic whose value, in order to be optimum, should tend towards a minimum, as is the case of surface roughness is:

$$S/N_m = -10 \cdot \log(s^2 + \bar{y}^2) \qquad (1)$$

Obviously, the higher the algebraic value of the signal-to-noise ratio is (maximised signal − to minimized noise), the better the performance of the machining system will be. Consequently, based on the results obtained by running the *LappMaster* programme the optimum set-points for each

analysed input factor could be established. Table 4 presents these results.

Table 4. Optimum combination of factor set-points

Factor	Factor description	Optimum set-point	Value of optimum set-point
A	Feed speed	1	50 mm/min
B	Jet pressure	1	1250 bar
C	Stand-off distance	2	1.5 mm
D	Abrasive graining	1	60 μm
E	Mass flow	1	0.5 g/s

By setting the values of the five factors to the determined points, the expected resulting signal-to-noise ratio is of -6.4276 dB, which value would generate a robust abrasive jet cutting process. This value of resulting S/N ratio was computed according to equation (2):

$$\frac{S}{N_{res}} = \frac{\overline{S}}{N} + + \sum the\ effects\ with\ the\ highest\ algebraic\ value \tag{2}$$

4   CONCLUSIONS

The paper presents a study of high pressure abrasive jet cutting, optimised by the method of robust parameter design. This approach is aimed at rendering the analysed system insensitive to the action of noise factors, by an adequate combination of the input factor set-points.

In the first stage of applying the method of fractioned orthogonal factorial arrays of experiments devised by G. Taguchi, five controllable input factors were selected, and two set-points were considered for each. Within the ensuing phase, a set of experiments were run, with a set-point assigned to each factor as provided by Taguchi's fractioned orthogonal factorial array; eventually, upon mathematical processing of the measured results a combination of optimum set-points of the analysed factors resulted. By assigning these optimum set-points to the input quantities the machining system becomes robust, and consequently the roughness of the machined surfaces will not deviate from the desired and predicted value.

5   REFERENCES

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