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Evaluation of the surface profile obtained by abrasive jet machining

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Abstract. The abrasive jet machining is a machining method based on the effects generated by the action of the abrasive particles sent to the workpiece surface to be machined by means of a high pressure gas jet. Essentially, the obtained surface could be considered as constituted by chaining microcraters resulted as a consequence of the abrasive particles action. Taking into consideration the possible influence exerted by some abrasive jet machining process input factors, an experimental research was developed. By mathematical processing of the experimental results, empirical mathematical models were determined to highlight the influence exerted by the average dimension of the abrasive particles, the distance between the nozzle and the flat surface of the test piece and the impact angle on the surface roughness parameter Rz. In order to evaluate the similarities between distinct zones of the machined surface profile, the value of the Pearson’s coefficient was also determined.

1. Introduction
The abrasive jet machining (AJM) method is included in the larger group of nonconventional machining methods. Essentially, the abrasive machining method is based on the effects generated on the workpiece surface by the abrasive particles included in a high velocity gas jet [1, 2, 3]. One could identify AJM processes such are the abrasive drilling, cutting, grooving, chamfering and cleaning, removal of certain types of spots or various layers adhered in time on documents, museum objects or even on buildings walls etc. Generally, the equipment for AJM are not very complex, they including suppliers of compressed gas, tubes for transporting the gas at high pressure, filters, pressure regulators, abrasive powder suppliers, subsystems for the abrasive jet control, for holding the nozzle and directing the abrasive jet to the workpiece surface, for ensuring the controlled trajectories between the nozzle and the workpiece, hood, exhaust etc.

Sometimes, the AJM is used to diminish the height of the surface asperities or to finish the surfaces, while in other situations the objective of the AJM could not be connected with the necessity of obtaining a certain value for the surface roughness parameters (as in the case of abrasive jet cleaning, writing etc.).

The concept of surface roughness refers to the surface deviations characterized by a ratio between pitch and height lower than 50. In the manufacturing engineering, the surface asperities that constitute the roughness are the results of applying various machining techniques. They could be classified in asperities of third order, being materialized by rhythms, periodic strikes and that may occur due to the
existence of the feed movements, and, on the other hand, asperities of fourth order, that have not a periodical character and are the results of tool actions, or holes, pores, metal scrap etc.

In defining the surface roughness parameters, an important concept is the surface profile; the concept takes into consideration the profile resulted as the intersection between the investigated surface and an established section plan. The roughness profile could be considered as a surface profile modified by removing the components characterized by high wave length.

There are many possibilities of analyzing the surface profile, for example by using distinct evaluation parameters: amplitude parameters, amplitude parameters that consider also the average of the ordinates, pitch parameters, hybrid parameters, curve and parameters associated to certain curves.

The analysis of the surface profile could offer some information concerning the values of the surface roughness parameters, but it could also show how the surface asperities were generated. During the machining processes, there are distinct factors able to affect the values of the machined surface roughness parameters. For example, in the case of the AJM, such factors could be the dimensions and the shapes of the abrasive particles, the position of the abrasive jet to the workpiece surface, the pressure and the speed of the compressed gas, the mechanical properties of the workpiece surface layer etc.

Over the last decades, the researchers were interested in obtaining scientific information concerning the roughness of the surfaces obtained by AJM.

Thus, Haj Mohammad Jafar et al. proposed a numerical model to predict the surface roughness when using the AJM of brittle materials in producing micro-scale features. In the case of a test pieces made of borosilicate glass, they appreciated that the average error of the numerical model was of 29 % [4, 5].

The influence exerted by some process input factors on the values of the surface roughness parameters in the case of the AJM of the composite materials was investigated by Arunkumar et al. [6]. They appreciated that some of the factors that are able to affect the surface roughness are the time and cutting speed, the traverse rate, the feed rate.

Jagannatha et al. studied the influence exerted by the temperature of hot air jet on the surface roughness parameter Ra [7]. The analysis of variance (ANOVA) method and the Taguchi method were used to identify the significant influence factors and to find the optimal combination of the process input factors that ensure the convenient development of the abrasive hot air jet machining of the test pieces made of glass.

![Figure 1. Surface profile obtained by means of the surface roughness meter Surtronic 25.](image-url)
The objective of the research presented in this paper was to highlight some authors’ considerations concerning the profiles of the surfaces obtained by AJM and the factors that could influence the surface roughness.

2. Theoretical considerations

As above mentioned, the surface obtained as a result of applying the AJM could be essentially considered as a result of actions exerted by the abrasive particles on the workpiece surface.

Supposing an abrasive jet directed along an inclined direction to the workpiece surface, it is expected that if the abrasive particles strike the workpiece surface with sharpen edge adequately positioned, a cutting phenomenon could develop and a removal of small quantities of the workpiece material could be observed.

Other particles could not have sufficient kinetic energy and they could generate a chip which could not be completely detached from the workpiece surface layer. If the particles are directed along a trajectory perpendicular to the workpiece surface, small cavities corresponding to the sharp edges of the abrasive particles could be generated.

When the workpiece material has a high plasticity and the abrasive particles strike the workpiece surface with their rounded zones (that is not able to generate cutting processes), the results could be the generation of small cavities obtained by the plastic deformation of the workpiece surface layer. If the workpiece material is fragile, some of the above-mentioned actions of the abrasive particles could also determine the initiation of microcracks, whose joining could contribute also to the material detachment from the workpiece material.

It is expected that the surface affected by the action of the abrasive particles could contain a chaining of small microcavities resulted in one or in many of the above-mentioned ways.

The microcavities depths and shapes generated on the workpiece surface could be affected by some main groups of factors; the results of a systemic analysis concerning the influence exerted by the AJM process input factors on some output parameters are presented in figure 2.

A theoretical question could be if there is a certain correlation between distinct zones of the profiles corresponding to the surface obtained by AJM. This means to answer the question if certain similarities could exist between the distinct zones of the surface affected by the action of the abrasive machining jet.

![Diagram](image)

**Figure 2.** Result of the systemic analysis of the AJM process.
3. Experimental conditions and results

In order to test some of the above mentioned hypotheses, an experimental research was performed [8, 9].

Test pieces made of aluminium with a surface of 40x40 mm² were cut from a plate of 3 mm thickness. A blasting gun type 650R (Prodif Air comprimé – France) was used to generate the abrasive jet. A compressor ensured a pressure of 0.6 MPa to the gas for transporting the abrasive particles (sand with two average dimensions of the particles). A simple device was used to move the blasting gun over the test piece and at a pre-established distance from the flat surface of the test piece. The surface roughness meter Surtronic 25 allowed determining of the values of the surface roughness parameter $R_z$ and was used to elaborate the profilogram corresponding to the investigated surface (fig. 2). One took into consideration the value of the surface roughness amplitude parameter $R_z$ (maximum height of the profile) appreciating that this parameter offers a good image concerning the surface profile, compared with the surface parameter $Ra$ (arithmetical mean deviation of the assessed profile), which is classified as a parameter based on the ordinates average). An image of the microeffects generated by the AJM could be obtained by means of the electron scanning microscope; two such images, corresponding to two different magnifications and obtained by means of the electron scanning microscope Tescan Vega II LMH could be observed in figure 3. To determine some mathematical empirical models, the experimental research was organized in accordance with the principles specific to a full factorial experiment with three independent variables at two variation levels. As the independent variables, one considered the average dimension $g$ of the abrasive particles, the distance $h$ between the nozzle and the test piece surface and the impact angle $a$. The two values of these process input variables were $g_{\text{min}}=0.35$ mm, $g_{\text{max}}=1.6$ mm, $h_{\text{min}}=10$ mm, $h_{\text{max}}=40$ mm, $a_{\text{min}}=15^\circ$, $a_{\text{max}}=90^\circ$.

The experimental results were included in table 1.

Table 1. Experimental conditions and results.

| Sizes values | Experiment no. |
|--------------|----------------|
|              | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
| $g$, mm      | 0.35 | 0.35 | 0.35 | 0.35 | 1.6 | 1.6 | 1.6 | 1.6 |
| $d$, mm      | 10  | 10  | 40  | 40  | 10  | 10  | 40  | 40  |
| $a$, degrees | 15  | 90  | 15  | 90  | 15  | 90  | 15  | 90  |
| $R_{z1}$, µm | 19.09 | 16.99 | 17.00 | 23.30 | 39.12 | 28.42 | 36.36 | 49.05 |
| $R_{z2}$, µm | 17.45 | 16.14 | 13.72 | 23.77 | 34.28 | 38.42 | 36.85 | 47.20 |
| $R_{z3}$, µm | 18.90 | 17.05 | 16.22 | 20.55 | 35.07 | 33.18 | 33.51 | 44.41 |
| Average value $R_z$, µm | 18.48 | 16.73 | 15.65 | 22.54 | 36.16 | 33.34 | 35.57 | 46.89 |

Figure 3. Image of the surface affected by the action of the abrasive particles (test piece no. 2; $a$ – 75x magnification; $b$ – 2500x magnification).
Specialized software [10] was used to mathematically process the experimental results. This software offers the possibility of selecting a certain type of empirical function among five such available functions (polynomial of first and second degree, power function, exponential function, hyperbolic function), by taking into consideration the so-called Gauss’s criterion. The value of the Gauss’s criterion could be calculated as the sum of the least squares of differences between the measured values and the values determined by considering a certain type of function.

In accordance with the use of the above-mentioned specialized software, the adequate empirical mathematical model corresponding to the experimental results was an exponential function:

\[ R_z = 12.431 \cdot 1.791^g \cdot 1.0038^h \cdot 1.0015^\alpha, \quad (1) \]

for which the value of the Gauss’s criterion is \( S_G = 11.62072 \).

Frequently, in the machine manufacturing technology, in the case of the monotone variation of the output factor, the power type function is preferred. For this reason, the power type function corresponding to the experimental results was also determined:

\[ R_z = 18.635 \cdot g^{0.479} \cdot h^{0.0823} \cdot \alpha^{0.0642}, \quad (2) \]

in this case the value of the Gauss’s criterion being \( S_G = 11.62103 \).

The analysis of the mathematical model corresponding to the power type function (2) showed that among the three considered process input factors the most significant influence is exerted by the average size \( g \) of the abrasive particles, since in the empirical mathematical model (2) the exponent attached to this size has the maximum value, compared with the values of the other exponents. The increase of the average dimension \( g \) of the abrasive particles, distance \( h \) and impact angle \( \alpha \) determines an increase of the value of the surface roughness parameter \( R_z \). The low values of the exponents attached to the factors \( h \) and \( \alpha \) show a reduced influence exerted by these factors on the value of \( R_z \).

Taking into consideration the empirical mathematical model constituted by the relation (2), the graphical representation from figure 4 was elaborated.

### Figure 4. Influence exerted by the average dimension \( g \) of the abrasive particles and by the impact angle \( \alpha \) on the value of the surface roughness parameter \( R_z \) (test piece made of aluminium; \( d=25 \, \text{mm} \)).

The apparatus used in determining the values of the surface roughness parameters ensures possibilities to highlight the proper values of the ordinates used in obtaining the profilogram represented in figure 1 for a pitch of 0.0005 mm. This fact could be used to establish if there is a correlation between the values of the ordinates along the determined profile. Generally, the correlation is a way of evaluation the similarities existing between two signals. If the set of examined results belongs to the same signal, the analysis could be called the autocorrelation analysis.

The correlation could be highlighted by means of the so-called Pearson’s coefficient, defined, from practical point of view, by the relation [11]:

\[ r_{xy} = \frac{n \sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{n \sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2} \sqrt{n \sum_{i=1}^{n} y_i^2 - (\sum_{i=1}^{n} y_i)^2}}, \quad (3) \]

where \( n \) is the number of measurements included in each of the two series of measured values \( x_i \) and \( y_i \), \( i=1, 2, \ldots, n \).
The correlation coefficient could have values in the interval \([-1, +1]\). A value close to 0 proves a low correlation, while values near -1 or +1 highlight a strong correlation. To obtain an image concerning the similarities of the distinct zones of the determined surface profile, one selected the set of ordinates corresponding to the absissa values included between 0 and 1 mm, and between 1 and 2 mm, respectively. As an example of the way in which this information was extracted from the data offered by the surface roughness meter Surtronic 25, one included the first 10 of the ordinates values in the table 2.

In the above mentioned conditions, the value of the Pearson’s coefficient \(r_{xy}\) was determined. The found value was \(r_{xy}=0.275\), this meaning that a certain correlation exists, but it is low enough.

5. Conclusions

The abrasive jet machining is a machining method that could ensure low values for the surface roughness parameters. The systemic analysis of this machining method showed that there are many groups of factors that could affect the values of the surface roughness parameters. An experimental research was developed to highlight the influence exerted by the average dimensions of the abrasive particles, the distance between the nozzle and the flat surface of the test piece and the impact angle on the surface roughness parameter \(Rz\). By mathematical processing of the experimental results, empirical mathematical models were determined. One noticed that the strongest influence is exerted by the average size of the abrasive particles. Another investigated aspect aimed to establish if between the distinct zones of the machined surface profile there are certain similarities and the Pearson’s coefficient was determined. The value of this coefficient showed a low correlation between two distinct zones of the surface profile obtained by AJM. In the future, there is the intention to extend the experimental research to observe if there are correlations between the values of some distinct parameters used to characterize the surface roughness.

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**Table 2.** First 10 values corresponding to the profile ordinates valid for absissa 0 and 0-1 mm and 1-2 mm, respectively.

| Order number | Abscissa (0-1 mm) | Data set no. 1 | Data set no. 2 (1-2 mm) |
|--------------|-------------------|----------------|------------------------|
| 1            | 0.0000            | 6.830          | -20.380                |
| 2            | 0.0005            | 6.880          | -19.970                |
| 3            | 0.0010            | 7.010          | -19.540                |
| 4            | 0.0015            | 7.120          | -19.110                |
| 5            | 0.0020            | 7.220          | -18.650                |
| 6            | 0.0025            | 7.270          | -18.230                |
| 7            | 0.0030            | 7.280          | -17.890                |
| 8            | 0.0035            | 7.270          | -17.630                |
| 9            | 0.0040            | 7.240          | -17.420                |
| 10           | 0.0045            | 7.160          | -17.300                |
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