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CORRELATIONS BETWEEN THE VALUES OF SOME SURFACE ROUGHNESS PARAMETERS WHEN ABRASIVE JET MACHINING

Laurenţiu SLĂTINEANU[1], Oana DODUN[2], Margareta COTEAŢĂ[3], Gheorghe NAGÎŢ[4], Adelina HRIŢUC[5], Irina BEŞLIU-BĂNCESCU[6], Adriana MUNTEANU[7]

1) Prof., Ph.D., Department of Machine Manufacturing Technology, "Gheorghe Asachi" Technical University of Iași, Romania
2) Prof., Ph.D., Department of Machine Manufacturing Technology, "Gheorghe Asachi" Technical University of Iași, Romania
3) Lecturer, Ph.D., Department of Machine Manufacturing Technology, "Gheorghe Asachi" Technical University of Iași, Romania
4) Prof., Ph.D., Department of Machine Manufacturing Technology, "Gheorghe Asachi" Technical University of Iași, Romania
5) Master Student, Department of Machine Manufacturing Technology, "Gheorghe Asachi" Technical University of Iași, Romania
6) Lecturer, Ph.D., Department of Mechanics and Technology, "Ştefan cel Mare" University of Suceava, Romania
7) Assoc. Prof., Ph.D., Department of Machine Tools and Tools, "Gheorghe Asachi" Technical University of Iași, Romania

Abstract: *Abrasive jet machining is part of the broader group of unconventional machining processes based on using the effects of impact between moving particles with the workpiece surface. In some experiments aimed at establishing empirical mathematical models to highlight the influence of process input factors on the values of surface roughness parameters, it was found that there are possible correlations between the values of surface roughness parameters taken into account. Usually, in the classical machining processes, it is preferred to use empirical mathematical models of the power function type. Starting from the hypothesis of a correlation between the values of some roughness parameters of the surfaces obtained by abrasive jet machining and preferring this time the use of empirical mathematical models selected by the computer program as more appropriate to the experimental results, graphical representations were made to illustrate the influence of the values of the angle of inclination of the abrasive jet, of the distance between the nozzle of orientation of the abrasive jet to the workpiece and respectively of the average size of the abrasive particles on the values of the considered surface roughness parameters. These results, together with the determination of the values of some correlation coefficients, confirmed the existence of good correlations between the values of the surface roughness parameters taken into consideration.*

Keywords: *abrasive jet machining, experimental research, surface roughness parameters, empirical mathematical models, correlation parameter.*

1. INTRODUCTION

Abrasive jet processing is part of the wider group of unconventional machining processes in which the abrasive particles are directed to the workpiece with the help of fluids. If in the case of abrasive water jet processing water is the liquid used to transport the abrasive particles, in the case of abrasive machining, air or another gas can be used to transport the abrasive particles to the workpiece surface [1–4].

In principle, abrasive jet processing is based on the effect generated by abrasive particles that have relatively high speeds at the impact with the surface of the workpiece. Concerning the kinetic energy of the abrasive grains and to the objective pursued, it is mentioned the existence of some drilling and cutting processes, procedures of making inscriptions, channels, processes of removing oxides or other undesirable substances on the surfaces of workpieces made of different materials, processes of calibration and cleaning of electronic components, etc.

It is found that the abrasive jet machining processes are used both in the case of workpieces made of metallic materials and some workpieces made of plastics, composite materials, cellulose, materials used in civil constructions, etc.

The results of using abrasive jet processing depend on the nature and properties of the workpiece material, on the dimensions and nature of the abrasive particle material, on the characteristics of the gas jet carrying the abrasive particles. One of the results followed in the case of abrasive jet machining can be the values of surface roughness parameters.

It is currently accepted that the concept of *surface roughness* refers to the set of surface microirregularities for which the ratio between length and height is less than 50. Along with shape and corrugation errors, the values of roughness parameters provide information on the geometry of the machined surface. It is considered that as a result of the application of a certain machining process, there will result in geometric deviations of order 3 (consisting of periodic ridges and striations and which

* Corresponding author: Adelina Hriţuc, "Gheorghe Asachi" Technical University of Iaşi, Blvd. D. Mangeron, 39A, 700050 Iaşi, Romania,
Tel.: +40751640117,
E-mail addresses: *slati@tcm.tuiasi.ro* (L. Slătineanu), *oanad@tcm.tuiasi.ro* (O. Dodun), *mcoteata@tcm.tuiasi.ro* (M. Coteaţă), *nagit@tcm.tuiasi.ro* (G. Nagîţ), *hrituc.adelina3295@yahoo.com* (A. Hriţuc), *irina.besliu@usm.ro* (I. Beşliu-Băncescu), *adycypmunteanu@yahoo.com* (A. Munteanu)

can be generated by the feed movement specific to mechanical machining processes by cutting) and geometric deviations of order 4 (these being due to traces of the tool, the existence of gaps in the workpiece material, the snatching of material from the workpiece as a result of the action of cutting tools, etc.).

Although in the mechanical drawings of the parts only values of the roughness parameter *Ra* in most cases and in rarer situations values of the roughness parameter *Rz* are inscribed, the specialists concluded that to have more complete information on the roughness of a surface machined it is necessary to take into account a larger set of roughness parameters. Thus, four groups of roughness parameters have been standardized, they being defined by taking into account a so-called *surface profile*: amplitude parameters, which follow aspects of prominence and the gap between two asperities, amplitude parameters that take into account ordinate averages, step parameters, hybrid parameters, curves and parameters associated with a curve.

To identify the possible correlations between the different parameters for roughness assessment, Korzynski et al. measured the values of 28 such parameters when applying slide diamond burnishing on test pieces made of steel 317Ti, as a result of performing 11 experimental tests [5]. They formulated the conclusion that for a comprehensive evaluation of the texture state of the machined surface it is sufficient to determine the values of 10 representative roughness parameters.

Researchers in the field of abrasive jet processing have looked at how different factors influence the values of the parameters used to evaluate the roughness of machined surfaces.

Thus, Dharmendra showed an increase in the value of the surface roughness parameter when the size of the abrasive particles increased [6].

Kusdarjanti et al. developed an investigation concerning the influence of the sandblasting time on the values of the surface roughness parameter at the processing of a denture framework made of an alloy cobalt-chromium [7]. They appreciated that a fairly smooth surface can be obtained in a process of about 2–3 minutes.

Previous experimental research has led to the identification of empirical mathematical models of the power function type to highlight the influence exerted by the values of input factors in the process of abrasive jet machining on the values of roughness parameters [8].

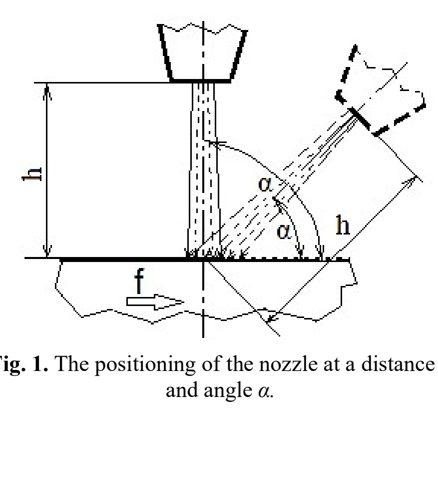

Fig. 1. The positioning of the nozzle at a distance *h* and angle *α*.

The researches whose results are presented in the article aimed at highlighting the influence exerted by different factors on the values of some surface roughness parameters and respectively revealing a possible correlation among these parameters, in the case of the abrasive jet machining of test pieces made of different materials, namely a common steel, aluminum, and glass.

2. INITIAL CONSIDERATIONS

Within the Department of Machine Manufacturing Technology from the "Gheorghe Asachi" Technical University of Iaşi, there are several instruments that allow determining the values of surface roughness parameters, and these devices have been used in doctoral research in the field of abrasive jet machining [8]. Some of the surface roughness parameters considered were:

- The arithmetic mean deviation *Ra* of the evaluated profile, defined as an arithmetic mean of the absolute values of the $z(x)$ ordinates within a basic length l and which is determined using the following relation:

$$R_a = \frac{1}{l}\int_0^l |z(x)|dx \cdot \quad (1)$$

- The quadratic mean deviation *Rq* of the evaluated profile, defined as a quadratic mean of the values of the $z(x)$ ordinates within the limits of the basic length l:

$$Rq = \sqrt{\frac{1}{l}\int_0^l Z^2(x)dx} \cdot \quad (2)$$

The two parameters mentioned above are part of the group of *amplitude parameters that take into account the average of the ordinates*;

- The parameter *Rz*, which, according to some previous standards, was called the height of the profile irregularities in ten points and was defined as a difference between two arithmetic means, one corresponding to the ordinates of the highest five prominences and the other - the ordinates of the lowest five goals of the actual profile, to a straight line parallel to the mean line, but which does not intersect the actual profile, for a certain length;

- Maximum height of *Ry* profile; according to the SR ISO 4287 standard, currently this size has been assigned the symbol *Rz* and is determined as a sum of the largest of the heights of the profile protrusions and the largest depth between the goals of the profile, within the limits of a basic length.

3. EXPERIMENTAL CONDITIONS

The experimental tests were performed using sandblasting equipment. Three materials with distinct mechanical properties were used for the specimens: common steel (1.0038), technical aluminum, glass. The surface exposed to the action of the abrasive jet was $20 \times 40 = 800$ mm^2.

Following first of all the influence exerted by the average size *g* of the abrasive particles, by the distance *h* between the front surface of the blasting gun nozzle and the workpiece and respectively by the angle *α* between the direction of the abrasive jet axis and the flat surface

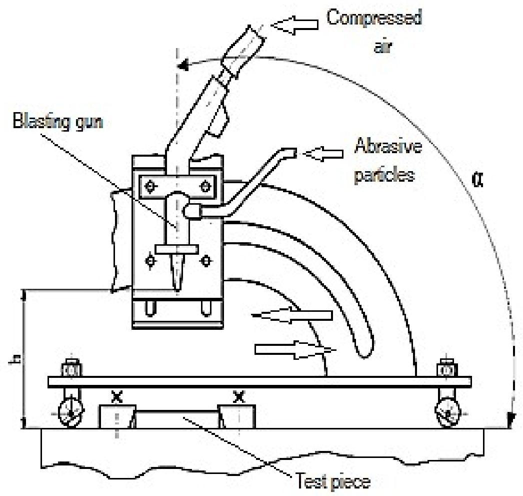

Fig. 2. Device for abrasive jet machining of test pieces made of different materials (adapted from [8]).

of the test piece, the device presented in Fig. 2 was used. This device ensures conditions for positioning the blasting gun to ensure the values established for the parameters *h* and *α*. As an abrasive material, sand with a somewhat constant granulation was used, obtained by sieving with distinct sieves.

All the test pieces made of the three materials mentioned above were subjected to the action of the abrasive jet for 30 seconds. To obtain an approximately uniform removal of material from the test piece surface, an alternative rectilinear manual movement of the blasting device was used at an approximately constant speed and along a trajectory that allowed the abrasive particle to process half of the upper surface of the test piece.

To reduce the duration of the experimental tests, experiments were performed according to the requirements of a full factorial experiment with 3 independent variables at two levels of testing. It was decided to adopt only two levels of testing considering that there is a monotonous dependence (without maxima and minima) of the values of the surface roughness parameters followed by the values adopted for the independent variables.

The proper values of the surface roughness parameters were subsequently measured using the surface roughness meter Mitutoyo Surftest SJ-201P. This apparatus allows the determination of the values of the roughness parameters *Ra*, *Rq*, *Rz,* and *Ry*, defined as shown in the previous chapter.

Both the values of the independent variables and the results of the roughness measurements were mentioned in Table 1.

4. PROCESSING THE EXPERIMENTAL RESULTS

The experimental results were mathematically processed using specialized software, based on the use of the least-squares method [9].

The software provides conditions for determining some mathematical empirical models of the polynomial type of degree 1 and 2, power type function, exponential function, hyperbolic function. The evaluation of the adequacy of an empirical mathematical model to the experimental results considered was made using the so-called Gauss's criterion. According to Gauss's criterion, an empirical model is all the more appropriate to the experimental data the smaller the sum of the squares of the differences between the ordinates of the points established by the empirical mathematical model adopted and the ordinates of the points corresponding to the experimental results.

By taking into account the arguments mentioned above, in the case of steel test pieces, the following exponential function was reached for the roughness parameter *Ra*:

$$Ra = 1.877 g^{0.249} h^{-0.0955} \alpha^{0.0910}, \quad (3)$$

Gauss's criterion having in this case the value $S_G = 0.81601$.

Usually, in the specialized literature, it is preferred to use empirical mathematical models such as power type functions. This situation was reached primarily due to the ease of processing and interpretation of the experimental results.

By logarithmizing the power type functions, linear relations were reached, easier to represent graphically and to analyze. At the same time, the values of the exponents attached to the variables in the power type functions allowed to obtain a direct image on the intensity of the influence exerted by one of the input factors (by one of the independent variables) on the value of the output parameter (one of the surface roughness parameters, in this case).

For example, the exponent with the highest absolute value highlights the fact that the input factor to which it is attached exerts the most intense influence, in relation to the intensities of the other factors. Also, a positive value of this effect shows that an increase in the value of the input factor causes an increase in the value of the output parameter, while in the case of a negative value of the exponent, we will have a decrease in the value of the output parameter when the value of the process input factor increases.

According to the determined mathematical model, increasing the average values of the abrasive particles dimension *g* and the angle *α* of jet axis inclination leads to an increase in the value of the surface roughness parameter *Ra*, while the increase in the distance *h* results

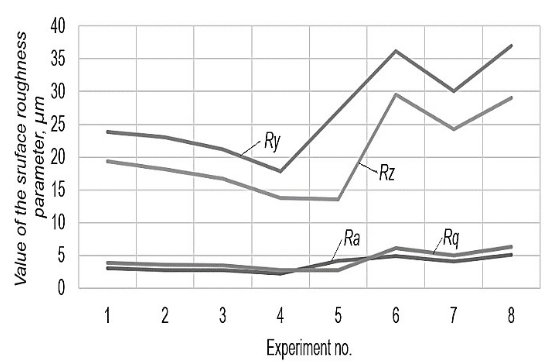

Fig. 3. Values of the surface roughness parameters in the case of steel test pieces for all the eight experiments.

in a decrease in the value of the roughness parameter *Ra*. Of the three input factors in the process (average dimension *g* of abrasive grains, distance *h,* and angle *α*), the strongest influence is exerted by the average dimension *g*, because in the empirical mathematical model of power type function, this input factor is associated the highest absolute value of the exponent, to the values of the exponents attached to the other input factors.

It can be seen that in the case of steel test pieces, Gauss's criterion has a higher value if the power type function is used to the other types of empirical mathematical models (a polynomial type of degree 1 or 2, exponential function, hyperbolic function). This means that the mathematical model of the power type function is more appropriate to the experimental results considered than the other types of empirical mathematical models.

In the case of steel test pieces and when following the value of the roughness parameter *Rq*, the specialized software highlights the fact that the most adequate mathematical model is the following exponential function:

$$Rq = 2.549 \cdot 1.314^{g} \cdot 1.0023^{h} \cdot 1.0024^{\alpha}, \quad (4)$$

for which Gauss's criterion has the value S_G =1.076146.

If in this situation a power type function is preferred, the following empirical mathematical model will be determined:

$$Rq = 2.531 g^{0.225} h^{0.0509} \alpha^{0.1044}, \quad (5)$$

for which the Gauss's criterion has the value S_G = 1.076154.

It can be seen that the empirical mathematical model constituted by the exponential function is in this case more adequate to the experimental results since the value of Gauss's criterion for the empirical mathematical model of exponential type function is less than the value of the same criterion in the case of power type function.

Subsequently, for each type of material and roughness parameter, there will be indicated the empirical mathematical models most adequate to the experimental results among the five such mathematical models considered by the specialized software, mentioning each time the value of the Gauss's criterion.

As described above, the following empirical mathematical models were arrived at;

- in the case of steel test pieces:

$$Ry = 18.980 \cdot 1.391^{g} \cdot 0.997^{h} \cdot 1.0009^{\alpha}, \quad (6)$$

the Gauss's criterion having the value S_G=11.84307;

$$Rz = 13.238 \cdot 1.285^{g} \cdot 0{,}997^{h} \cdot 1{,}0023^{\alpha}, \quad (7)$$

the Gauss's criterion having the value S_G = 22,82357;

- in the case of aluminum test pieces;

$$Ra = 1.983 \cdot 1.909^{g} 1.003^{h} 1.0022^{\alpha}, \quad (8)$$

the Gauss's criterion having the value S_G = 0,2973531,

$$Rq = 2.493 \cdot 1.895^{g} \cdot 1.0031^{h} \cdot 1.0021^{\alpha}, \quad (9)$$

the Gauss's criterion having the value S_G=0.5275425,

$$Ry = 13.242 \cdot 1.908^{g} \cdot 1.0052^{h} \cdot 1.0023^{\alpha}, \quad (10)$$

the Gauss's criterion having the value S_G=42.28193

$$Rz = 12.431 \cdot 1.791^{g} \cdot 1.0038^{h} \cdot 1.0015^{\alpha}, \quad (11)$$

the Gauss's criterion having the value S_G=11.62072;

- in the case of glass test pieces;

$$Ra = 2.695 \cdot 1.598^{g} 0.998^{h} 1.0031^{\alpha}, \quad (12)$$

the Gauss's criterion having the value S_G=0.1754163.

$$Rq = 3.384 \cdot 1.592^{g} \cdot 0.9985^{h} \cdot 1.0030^{\alpha}, \quad (13)$$

the Gauss's criterion having the value S_G = 0.2705742.

$$Rz = 16.947 \cdot 1.479^{g} \cdot 0.998^{h} \cdot 1.002^{\alpha}, \quad (14)$$

the Gauss's criterion having the value S_G = 7.824401,

$$Ry = 74.231 + 16.014g - 1.509g^2 - 8.123h + 0.163h^2 + 0.745\alpha - 0.00651\alpha^2, \quad (15)$$

the Gauss's criterion having the value S_G = 33.96108.

Table 1

Experimental conditions and results

Exp. no.		1	2	3	4	5	6	7	8
Average dimension *g*, mm		0.35	0.35	0.35	0.35	1.6	1.6	1.6	1.6
Distance *h*, mm		10	10	40	40	10	10	40	40
Angle *α*, degree		15	90	15	90	15	90	15	90
Test piece material	**Roughness parameter**	**Average values of the surface roughness parameters, μm**							
Steel	*Ra*	3.04	2.78	2.75	2.19	4.21	4.86	4.02	5.09
	Rq	3.88	3.54	3.47	2.78	2.70	6.15	4.97	6.31
	Rz	19.31	18.13	16.71	13.77	13.58	29.56	24.27	29.08
	Ry	23.84	23.01	21.19	17.84	26.96	36.16	30.00	37.02
Aluminum	*Ra*	2.75	2.78	2.60	2.05	3.94	5.50	3.64	5.83
	Rq	3.69	3.52	3.25	4.79	8.14	7.83	7.46	10.40
	Rz	18.48	16.73	15.65	22.54	36.16	33.34	35.57	46.89
	Ry	21.56	18.43	18.11	29.08	46.11	42.10	41.10	66.46
Glass	*Ra*	3.67	4.10	2.95	3.95	5.77	6.99	5.67	7.70
	Rq	4.61	5.09	3.70	4.75	6.99	8.78	7.02	9.81
	Rz	22.13	24.09	18.01	20.77	30.51	36.60	30.06	42.17
	Ry	29.12	32.41	24.56	23.68	38.78	39.56	40.63	55.85

By taking into account these empirical mathematical models, the graphical representations from the Figs. 4, 5, 6, and 7 were elaborated.

The analysis of the empirical mathematical models and of the graphic representations elaborated by taking them into account shows that the factor that exerts the strongest influence on the sizes of the values of the studied roughness parameters is the average dimension *g* of the abrasive particles. As expected, an increase in the particle average dimension *g* leads to an increase in the values of the surface roughness parameters that take into account the asperities heights.

In second place from this point of view is the size of the angle α of inclination of the abrasive jet axis, but the statement is valid only in the case of steel and glass, in the case of aluminum the second factor in terms of influence being the distance *h* between the front surface of the nozzle and the surface of the test piece. This can be explained by the higher plasticity of aluminum, compared to the higher hardness and brittleness of steel and glass.

Even the steeper slope of the *Ra* parameter variation in the case of aluminum, at the increase in the size of the average dimension *g* of the abrasive particles could also be connected to the higher plasticity characteristics in the case of aluminum specimens.

The sets of values of surface roughness parameters determined for three materials with quite different physical-mechanical properties were further used to investigate the possibility that there are certain correlations between these series of values. A suggestion in this sense is given by the graphical representation in figure 3, in which some similar sensations of variation of the values of the roughness parameter *Ra* could be observed for the 8 experimental tests performed.

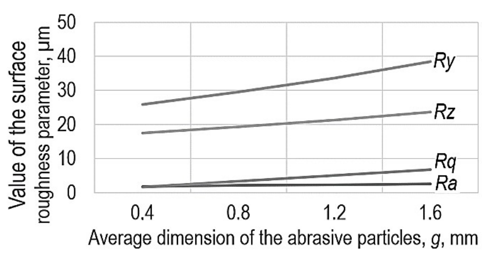

Fig. 4. The influence exerted by the average dimension *g* of the abrasive particles on the sizes of the surface roughness parameters *Ra*, *Rq*, *Ry,* and *Rz* in the case of test pieces made of steel (h = 10 mm, α = 90 º).

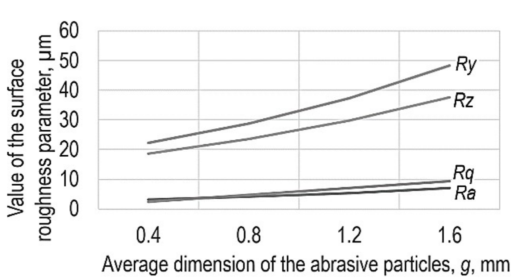

Fig. 5. The influence exerted by the average dimension *G* of the abrasive particles on the sizes of the surface roughness parameters *Ra*, *Rq*, *Ry,* and *Rz* in the case of test pieces made of aluminum (h = 10 mm, α = 90 º).

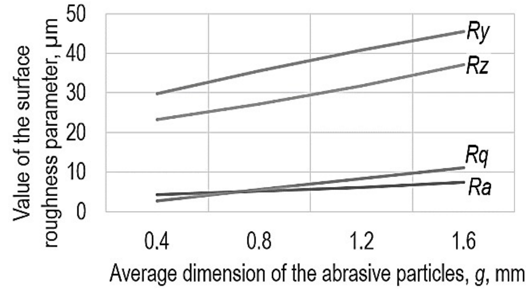

Fig. 6. The influence exerted by the average dimension *g* of the abrasive particles on the sizes of the surface roughness parameters *Ra*, *Rq*, *Ry*, and *Rz* in the case of test pieces made of glass (h = 10 mm, α = 90 º).

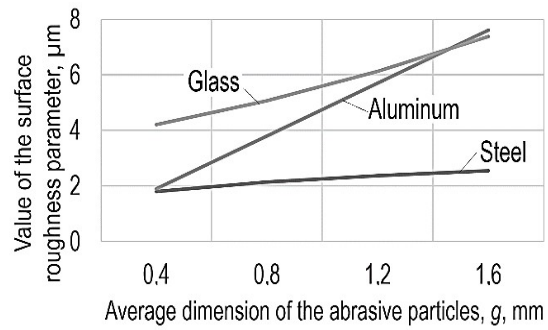

Fig. 7. The influence exerted by the average dimension *g* of the abrasive particles on the size of the surface roughness parameter *Ra* for test pieces made of steel, aluminum and glass (h = 10 mm, α = 90 º).

The values of the r_{xy} Pearson's correlation coefficients were calculated using the following relation [10]:

$$r_{xy} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - \left(\sum x_i\right)^2}\sqrt{n\sum y_i^2 - \left(\sum y_i\right)^2}}, \quad (15)$$

where n is the number of results (measurements) found in each of two sets of values x_i and y_i and i = 1, 2, …, n considered at a given time.

It is estimated that there is a good correlation between the values of the two sets of values if the correlation coefficient has a value close to 1.00 or -1.00. There is also the convention that we are dealing with a strong positive correlation when the correlation coefficient has a value between 0.5 and 1.0, an average correlation for values of the correlation coefficient between 0.3 and 0.5, and, respectively, a reduced correlation for values of correlation coefficient found between 0.1 and 0.3.

The values of the correlation coefficients for pairs of two sets of experimental results valid for two of each of the measured roughness parameters were determined using the CORRELATION function in the EXCEL software.

Table 2 thus recorded the values of the correlation coefficients determined for pairs of sets of values corresponding to two roughness parameters each. It can be seen that in the case of all pairs of values determined for two roughness parameters, there are strong correlations, all the values of the correlation coefficients being in the range 0.771–0.996.

Table 2

Values of the correlation parameters

Initial parameter	Correla-ting para-meter	Steel	Alumi-num	Glass
Ra	*Rq*	0.781	0.874	0.998
	Rz	0.771	0.844	0.991
	Ry	0.972	0.849	0.920
Rq	*Rz*	0.997	0.995	0.996
	Ry	0.901	0.987	0.930
Rz	*Ry*	0.896	0.988	0.953

The best correlation exists between the values of the roughness parameters *Ra* and *Rq*, in the case of glass, for which the correlation coefficient has a value of 0.998.

5. CONCLUSIONS

In the case of abrasive jet processing, there are several process input factors with a decisive influence on the values of the surface roughness parameters that take into account the height of the asperities generated on the machined surface.

To evaluate this influence, experimental research was performed on three different materials (steel, aluminum, and glass), determining empirical mathematical models to highlight the influence of the average size of abrasive particles, the distance between the nozzle and the test piece and the angle. of tilting the abrasive jet on the values of four roughness parameters (*Ra*, *Rq*, *Rz,* and *Ry*). Empirical models were selected from several available models using the Gauss's criterion.

The strong influence of the average size of the abrasive particles on the values of the roughness parameters was revealed.

Subsequently, the values of the correlation coefficients between the two by two values of the surface roughness parameters used were calculated, finding that there are sufficiently strong correlations between the values of the four surface roughness parameters. In the future, the use of other surface roughness parameters is considered, to identify possible correlations between the numerous roughness parameters currently used to evaluate the condition of the processed surfaces.

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