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Study of the influence of the technological parameters of the air-plasma surface gouging on some quality characteristics in the surface layer

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Abstract. *The efficient use of resources on the basis of the development of scientific and technical progress requires widespread implementation of new technologies for processing of metals, such as plasma, cathode-ray, detonation and other methods that allow to increase the lifetime of machines operation and reduce the materials and energy consumption throughout production.*
One of the new highly productive methods for obtaining a high-quality surface is the plasma surface processing (gouging) of metals. It is one of the most effective methods for surface processing applied in modern metal-processing facilities. Unlike other methods for surface processing this method includes the use of an electric arc and the produced plasma has a temperature which reaches tens of thousands degrees Celsius. At such temperature, not only structural grade steel alloys can be processed, but in-fact all types of metals.
The aim of this paper is to investigate the relation between the technological parameters of the process air-plasma surface gouging and the quality characteristics of the obtained surface layers. The relations between technological parameters of the process air-plasma surface gouging of metals and quality parameters were obtained by using rotatable design of experiments and regression analyses techniques.

Keywords: air - surface plasma cutting, welding, air-plasma surface gouging

1 Introduction

The aim of this paper is to establish the technological capabilities of the method of air-plasma surface gouging by applying the method of experiment planning and the method of the mathematical statistic to experimentally optimize the operation parameters and create new methods and means ensuring the improvement in the quality and efficiency of the process.

For the purposes of the study, first the possibilities for a purposeful change of the speed characteristic of the process and the quality parameters of the surface after air-plasma surface gouging are studied depending on the main variables controlling the process –the type of the material being processed and the gouging mode. All this requires conducting a large number of studies in order to determine the relation between the variables controlling the process and the quality of the surface obtained by air-plasma surface gouging. **(Grill A., 1994; Conrads H, 1994)**.

The analysis of the scientific publications has revealed that currently there is not enough data for the building an analytical models, because of non-linear dependencies between the components of the studied technological system. This means that the statistical and experimental approach should be applied to investigate actual relations of the studied processing system by purposeful, precisely determined and pre-planned activities**.** (**Korzec D, 1996; Hollahan J., 1974)**

2 Experimental regression study of the relation between the technological parameters of the process of plasma surface gouging and some quality characteristics of the surface layer

2.1 Subject of the study

The subject of the study is the air-plasma surface gouging of specimens made of steel C45 with dimensions: 60x70mm; δ=8mm, according to the BDS EN 10025-2:2005.

Table 1 and 2 illustrate, respectively, the chemical composition and mechanical characteristics of steel C45 **(Rutscher A and Deutsch H., 1983).**

Table 1. Chemical composition of the C45 steel

Chemical elements	C	Mn	Ni	Si	S	P	Cr	Cu
C45	0,42-0,50	0,5-0,8	up to 0,3	0,17-0,37	up to 0,3	up to 0,3	up to 0,25	up to 0,3

Table 2. Mechanical characteristics of the C45 steel

Tensile strength, Rm, MPa	Yield strength, Re, MPa	Fracture elongation, A,%	Impact strength, KCV, kJ/m2	Reduction of area, Z,%
598	353	16	490	40

The hardening capacity of steel is determined by the formula: **(Rossnagel S M, 1990)**

$$\text{Ceq} = \text{C},\% + \frac{Mn}{6},\% + \frac{Cr+Mo+V}{5},\% + \frac{Ni+Cu}{15},\% \ [\%] \qquad (1)$$

After the values of the chemical elements are substituted in formula (1), the value of Ceq obtained is 0,55÷0,68%.

Therefore, the carbon equivalent of the chosen steel is from 0,60÷0,70% and is within the range between medium carbon steel and high carbon steel **(Rossnagel S M, 1990).** During plasma surface cutting there is a probability of cracks appearing in the thermal affected area.

2.2 Inputs (regime factors)

The behavior of the studied subject is determined by a large number of variables. The most significant regime factors that can be varied and controlled during the experiment are shown in Table 3. The remaining regime factors are set to be with constant values, according to the process best conditions.

Table 3. Values and variation intervals of the regime factors during air-plasma surface gouging

FACTORS		Levels of variation		
		Lower level	Medium level	Upper level
		–1	0	+1
X1	Magnitude of the current I, A	30	40	50
X2	Distance between the nozzle and the surface h, mm	2	3	4
X3	Gouging speed rate Vp, m /min	1,4	1,5	1,6

2.3 Outputs (parameters)

The investigated parameters are some important quality characteristic of the studied specimens. In the studied process of air-plasma surface gouging on the quality of the surface, the investigated parameters are the macro and microhardness (HV5 and HV0,05) measured, ten-point mean roughness (Rz), the depth of the metal layer removed (b) and the residual stress and strains on a surface.

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2.4 Selecting experimental design type

The designing of the experiment is a procedure of choosing the number and conditions for conducting the experiments, which are necessary and sufficient for obtaining the searching results. **(Natsu W. at all, 2006; Eubank P.T., 1993)**

When choosing a concrete design of experiment, some compromise should be made with the requirements for: precision of the mathematical description of the process; assurance simplicity in the processing the experimental data; the minimum required number of trials, etc. The design of the experiment for the building a regression model from second order was chosen. It has following equation:

$$Y = \beta_0 + \sum_{1 \le i \le k} \beta_i X_i + \sum_{1 \le i \le j \le k} \beta_{ij} X_i X_j + \sum_{1 \le i \le k} \beta_{ii} X_i^2 \qquad (2)$$

where: Y is the actual value of the response;

$\beta_i, \beta_{ij}, \beta_{ii}$ - the actual value of the coefficients;

κ – the number of factors

3 Experimental study

The plasma surface gouging is a process during which the metal in the area of the processing is heated to high temperatures and is molten along the line of processing by a powerful arc discharge located on a small area and the metal layer is vaporized under the action of the high-speed gas flow. The process of surface gouging consists of several processes taking place simultaneously: heating the metal; burning the metal and blowing the metal by the same jet. Purified atmospheric air, without moisture or dust, is used as a combustion gas. **(Hopwood J., 1992; Popov O (ed), 1995)**

The air plasma surface gouging is performed using Steel Cut – L - ZNC-1500L system. The equipment used is shown in Figure 1.

The surface quality is determined by the properly selected gouging mode and the air purity. The parameters of the mode of air-plasma surface gouging are the following: **(Popov O (ed), 1995)**

- Nozzle diameter, dn=1,0 mm;
- Current, I=30 A;
- Consumption of plasma-forming gas(air), Q=8 l/min;
- Voltage, U=230 V;
- Distance between the plasmotron and the plate, h=3,0 mm;
- Feed rate, Vp=1,4 m/min;
- The cut width, b=2,0 mm;
- The burner is tilted at an angle of 45°.

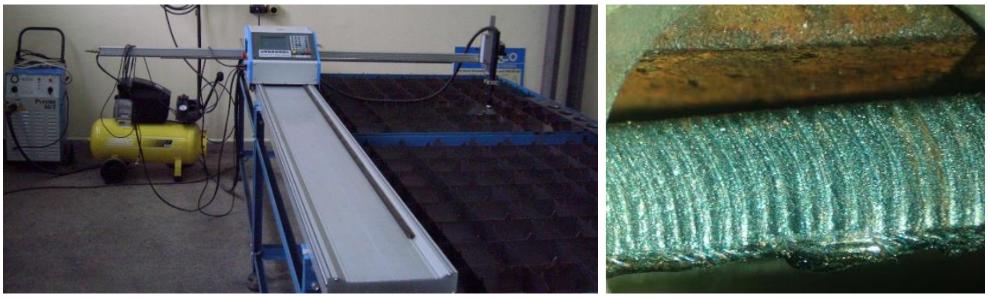

Fig. 1. A system of the type SteelCut – L and specimen surface made of steel C45 after gouging

The system of plasma cutting and gouging is fully automated and allows the processing of flat surface, as well as rotary parts. The degree of precision is according to DIN EN ISO 9013. The precision of repetitiveness is: ± 0,05 mm.

When the surface is gouged, extremely precise result is obtained and no continuous treatment of the area processed is necessary after the process itself is completed. The quality gouging is especially ap-

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plicable to fine contours, thin networks and small outlets and channels. The outlets have an angle deviation between 2° and 4°, in compliance with the DIN EN ISO 9013 standard. According to this standard, the results attained because of the deviation are spread up into categories. The precision of the categories decreases with the increase of the number of the category. In most cases, the deviation is approximately 2°.

3.1 Design matrix of the experiment

One of the simplest experimental designs in terms of the number of trials is suggested by Rotational invariance designs (so called Rotatable designs). From mathematics, it is known that a function defined on an inner product space have rotational invariance if its values does not change when arbitrary rotations are applied to its arguments. It turns out that type of designs may be used, as their number of trials is equal to or a little bigger than the number of the coefficients in the regression model. **(Hung N.P., 1994; Muller F., 2001)**

The structure of the design matrix is shown on Table 4) and the matrix of the errors for plans is analyzed in detail. It turns out, that in the information matrix uneven moments different from zero may appear. As a result, such experimental design plans turn out to be asymmetrical.

Table 4. The design experimental matrix chosen in the air- plasma surface gouging.

№	X_1	X_2	X_3	$X_1.X_2$	$X_1.X_3$	$X_2.X_3$	X_1^2	X_2^2	X_3^3	Y1	Y2	Y3	Y4
1	-1	-1	-1	1	1	1	1	1	1	502	605	152	2,09
2	1	-1	-1	-1	-1	1	1	1	1	480	583	130	1,83
3	-1	1	-1	-1	1	-1	1	1	1	450	553	100	1,57
4	1	1	-1	1	-1	-1	1	1	1	445	548	95	1,62
5	-1	-1	1	1	-1	-1	1	1	1	470	573	120	2,27
6	1	-1	1	-1	1	-1	1	1	1	430	533	80	1,52
7	-1	1	1	-1	-1	1	1	1	1	509	612	159	1,90
8	1	1	1	1	1	1	1	1	1	438	541	88	1,59
9	-1,682	0	0	0	0	0	2,829	0	0	500	603	150	2,08
10	1,682	0	0	0	0	0	2,829	0	0	445	548	95	1,64
11	0	-1,682	0	0	0	0	0	2,829	0	475	578	125	1,92
12	0	1,682	0	0	0	0	0	2,829	0	457	560	107	1,52
13	0	0	-1,682	0	0	0	0	0	2,829	477	580	127	2,10
14	0	0	1,682	0	0	0	0	0	2,829	479	582	129	1,89
15	0	0	0	0	0	0	0	0	0	499	602	149	1,96
16	0	0	0	0	0	0	0	0	0	494	597	144	2,00
17	0	0	0	0	0	0	0	0	0	496	599	146	2,00
18	0	0	0	0	0	0	0	0	0	498	601	148	1,95
19	0	0	0	0	0	0	0	0	0	497	600	147	1,96
20	0	0	0	0	0	0	0	0	0	511	614	151	1,97

In the result section of the article, four groups of diagrams with response surfaces are presented. They illustrating the manner of amendment in: macro and microhardness; the maximal height of the grooves and the maximal depth of the removed layer of specimen (У), as a function of the operating current (x1); the distance between the surface and the electrode (x2) and the speed of the burner movement (x3). X1, X2 and X3 are given as non-dimensional variables (or so called coded values).

3.2 Results

The processing of the experimental data are made by using software programs EXPLAN **(Georgiev D. S., Slavov, S.D. 2008)** and MathCAD which allows the building regression models and response surface graph plots. The diagrams with 3D contour plots illustrating the change in the macro and microhardness, the maximal height of the roughness, and the maximal depth of the metal layer removed during air plasma surface gouging. Dependencies $Y_{1\div4}=f(X1, X2, X3)$ are presented with dimensional variables in regression equations (3÷6), but their response graphs are shown in Figure 2, 3, 4, and 5 and they are given with the real calculated values for regime parameters.

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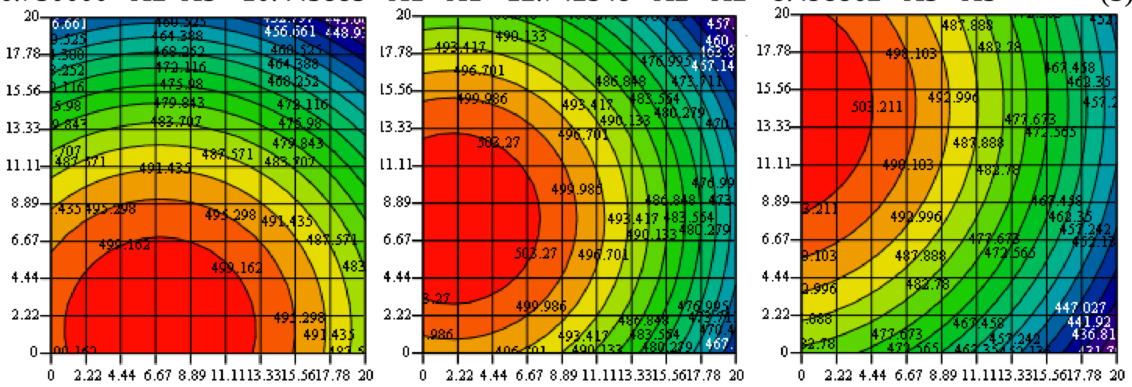
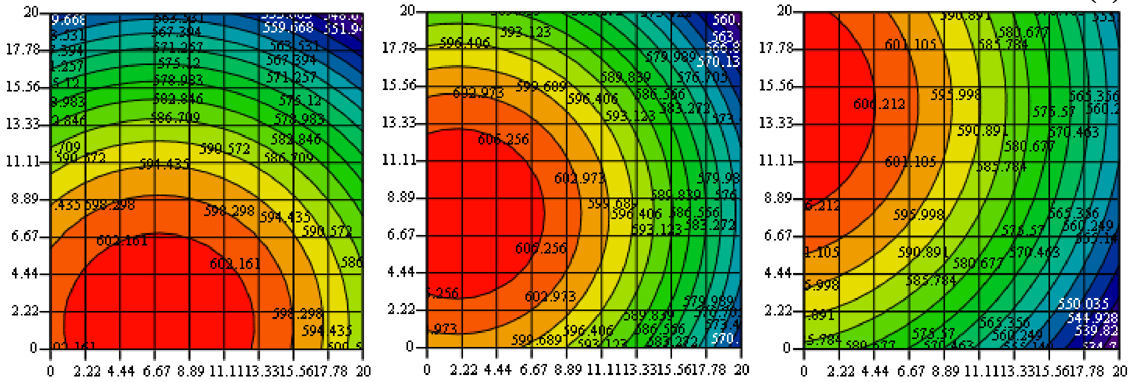
Y1 (X1, X2, X3) = 499.216867 -16.878864*X1 - 5.145890*X2 - 1.950394*X3 - 10.500000* X1*X3 + + 16.750000* X2*X3 -10.443885* X1* X1 -12.742548* X2* X2 -8.498862* X3* X3 (3)



a) HV5 = (h, I) when Vp = 1,4 m/min b) HV5 = (h, I) when Vp = 1,5 m/min c) HV5 = (h, I) when Vp = 1,6 m/min

Fig. 2. Dependence between microhardness after plasma surface gouging HV5 and the technological parameters: magnitude of the current I, distance “plasmotron-metal” h and the speed of gouging Vp on the specimens

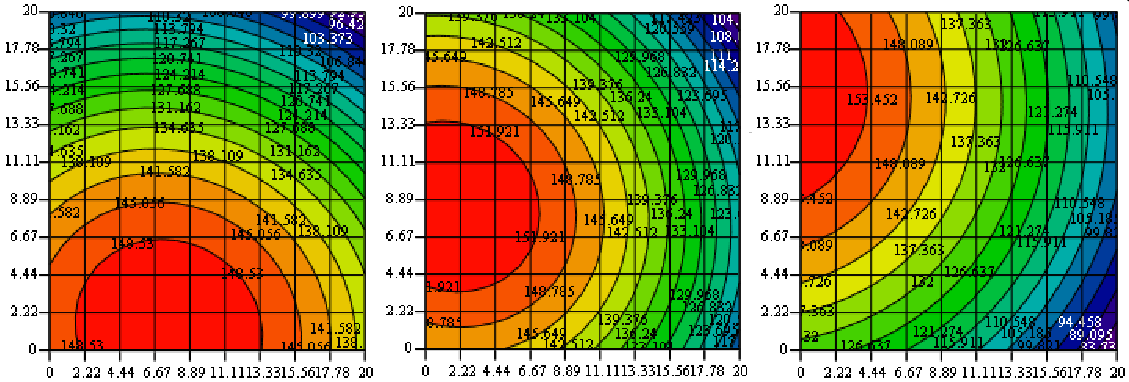
Y2 (X1, X2, X3) = 602.192488 -16.878864* X1 -5.145890*X2 -1.950394*X3 - 10.500000*X1*X3 + + 16.750000*X2*X3 -10.434047*X1*X1 -12.732710* X2* X2 -8.489024 * X3* X3 (4)



a) HV0.05= (h, I) when Vp = 1,4 m/min b) HV0.05= (h, I) when Vp = 1,5 m/min c) HV0.05= (h, I) when Vp = 1,6 m/min

Fig. 3. Dependence between microhardness after plasma surface gouging HV0.05 and the technological parameters: magnitude of the current I, distance “plasmotron-metal” h and the speed of gouging Vp on the specimens

Y3(X1,X2,X3)=147.636327-16.87886*X1-5.145890*X2-1.950394*X3-1.7500*X1*X2-10.5*X*X3+ + 16.750000* X2*X3 -9.909404*X1*X1 -12.208067*X2*X2 -7.964381*X3*X3 (5)



a) Rz = (h, I) when Vp = 1,4 m/min b) Rz = (h, I) when Vp = 1,5 m/min c) Rz = (h, I) when Vp = 1,6 m/min

Fig. 4. Dependence between ten-point mean roughness (Rz) after plasma surface gouging and the technological parameters: magnitude of the current I, distance “plasmotron-metal” h and the speed of gouging Vp on the specimens

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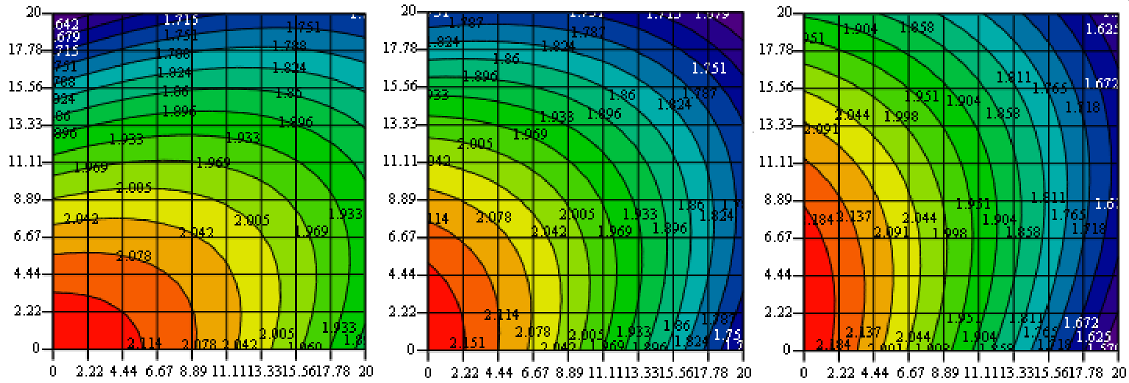
$$Y4\ (X1, X2, X3) = 1.974590 - 0.147186*X1 - 0.124686*X2 - 0.013416*X3 + 0.093750*X1*X2 - 0.106250*X1*X3 + 0.053750*X2*X3 - 0.050991*X1*X1 - 0.100501*X2*X2 \quad (6)$$



a) b = (h, I) when Vp = 1,4 m/min   b) b = (h, I) when Vp = 1,5 m/min   c) b = (h, I) when Vp = 1,6 m/min

Fig. 5. Dependence between the depth of the removed metal layer after plasma surface gouging b and the technological parameters: magnitude of the current I, distance "plasmotron-metal" h and the speed of gouging Vp on the specimens

3.3 Criteria for assessing the specimens.

In most cases, the aim of surface gouging is finishing process, especially of restored parts. The criteria for assessment of the quality of the process of air-plasma surface gouging is the obtained good quality of the treated surfaces. This involves uniformity of the marks from the processing on these surfaces, not very-high roughness (height of the asperities up to $0{,}5.10^{-3}$ m) and width of the channel within the limits from 1.10^{-3} to 4.10^{-3} m. Thus, if the treated surface need to be smoother, any following mechanical processing operation can be implement. Each trials of the experimental design plan are considered to have been successfully conducted in order the above-mentioned criteria are fulfilled.

3.4 Verifying the adequacy of the regression models.

Based on the prepared calculations by using EXPLAN and determined Fisher's criterion values (F – criterion) for the regression equations (3 ÷6), they were identified as significant and adequate and can be used to predict the resulting quality characteristics of the treated surfaces.

4 Summary

Considering conducted experimental designs, obtained results and built 3D contour plots by using obtained regression equations, the following conclusions can be made:

1. Four regression equations were obtained based on conducted experiments and statistical evaluation to reveal the relations between the technological parameters of the process of air plasma surface gouging of the C45 steel and some quality parameters of the surfaces layer. The obtained relations includes macro- and microhardness of the processed materials and the depth of the strengthened area, as well as ten-point mean roughness (Rz) and the depth of the removed metal layer (b).
2. The experimental investigation carried out on the samples that were processed by air plasma surface gouging has revealed that the regime factors having effect on the quality parameters may be classified according to their significance in the following way:
   a) The analysis of the results obtained within the range of change of the factors has revealed that the factor that has the biggest effect on microhardness, HV0.05 is the speed of the burner movement. This is due to change in the amount of heat energy directed to the surface of the sample in the course of the processing. In addition, the speed of the burner movement has also an effect on the stability of the arc burning in the process of surface gouging. At the rate of gouging at

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lower level, it is clear that the other two parameters may be changed in widest range and at the same time the optimal microhardness is preserved.

b) The next factors of significant to the hardness HV0.05 after surface cutting are the distance “nozzle-metal" h, and the magnitude of the current during the plasma surface cutting that have a strong effect on hardness. With the increase in the speed of the plasma burner movement, the area encircled by the isoline, indicating the maximal microhardness is shifted so that the distance between the plasmotron and the sample becomes smaller. At the same time, this area becomes narrower and the possibility of varying with the magnitude of the current and the distance the nozzle is limited. As can be seen from Figure 2 at the maximal rate of gouging there is also a decrease in the microhardness, which indicates that the speed chosen is high and the heat power is insufficient to do the processing.

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