EXPERIMENTAL RESULTS CONCERNING THE VARIATION OF SURFACE ROUGHNESS PARAMETER (R_a) AT PLASMA ARC CUTTING OF A STAINLESS STEEL WORKPIECE

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Abstract: This paper present some experimental results concerning the surface roughness variation at plasma arc cutting, in case of processing a stainless steel workpiece. Thus, some experimental tests were made in an industrial enterprise, on a CNC plasma cutting equipment, *KOMPACT3015-HPR130*, in order to analyze the surface roughness parameter obtained during the cutting process. In order to establish an empirical model of the surface roughness obtained during the plasma cutting process the experimental tests were made using different cutting conditions. To measure the surface roughness, we used the *HANDYSURF E-35A/B* apparatus that exist in the Department of Machine Manufacturing Technology witch allows measuring of 18 types of surface roughness parameters. In this paper, we used only the R_a surface roughness parameter in order to be studied. Due to the fact that this apparatus can be connecting to a computer, the profile of the machined surface could also be analyzed.

Key words: Plasma cutting, surface roughness parameter, stainless steel workpiece.

1. INTRODUCTION

The plasma arc machining (PAM) are complex processes that are used in the machine manufacturing field due to their possibilities to process some hard and very hard materials (alloys), with maximum of technical and economical efficiency (Mihăilă, 1999), (McGeough, 2002). Thus, stainless steels, manganese steels, titanium alloys, copper, magnesium, aluminum and theirs alloys, cast iron and chemical industry toxic waste (by transforming into the marketable products) can be worked.

This method can be used with both economical and technical advantages, but this involves the development of full studies and amply theoretical and experimental researches among all the technological system's links, in order to establish (chose) the optimal processing variant. In the machine manufacturing industry, the *plasma*, as a "*tool*", is used especially in cutting operations, coating, welding, melting, and assistance of the mechanical processing operations such as: turning, threading, drilling, grooving etc., in order to improve the machinability of various materials (Mihăilă, 1999).

In Romania, ample researches concerning the utilization of thermal plasma in the machine manufacturing engineering were made at The Institute of Technological Research for Machine Manufacturing Bucharest, at some of the technical universities such as Polytechnic University Bucharest, Polytechnic University Timisoara etc. Important researches were also developed and finalized with doctoral thesis by: Liliana Popa (1997), Cyril Baudry (2003), Câneparu Puiu (2007), Cristian Făgărăşan (2009) etc. At international level, the increased interest, over the time, shown by the researchers around the world, can be observed easely by the number of published articles into the *COMPENDEX* database, articles concerning the plasma cutting process (Ilii et alt., 2007).

2. THE AIM OF THE WORK

In this study, AISI 304 stainless steel has been cut by plasma arc and the variation of R_a surface roughness parameter occurred after cutting has been investigated. Our intention was to study the effects of plasma arc cutting parameters, such as cutting speed *v [mm/min]*, material thickness *g [mm]* and current intensity of plasma arc *I [A]* on the surface roughness variation of a stainless steel plate.

3. PLASMA ARC CUTTING. OPERATING PRINCIPLE

The plasma process for cutting was developed approximately thirty years ago, for metals difficult to be cut by classic operations, and uses a high energy stream of dissociated, ionized gas, known as *plasma*, as the heat source.

According to the Welding Handbook, „the plasma arc cutting process severs metal by using a constricted arc to melt a localized area of a workpiece, removing the molten material with a high-velocity jet of ionized gas issuing from the constricting nozzle". In today's industry it is a widely used process to cut different metals and, combined with computer numerically controlled (CNC) machines, to cut alloy plate into desired shapes and prepare weld angles.

Metal plasma cutting devices are widely used in industry, and recent developments of torch design together with the use of oxygen as plasma producing gas allow improvement in cutting quality (Gage, 1959). Because of its oxidizing properties, oxygen leads to more regular surfaces inside the kerf with a better evacuation of the molten metal and less dross formation beneath the workpiece with increased cutting speeds (Teulet & Girard, 1996).

The plasma arc cutting process is ilustrated in figure 1; it is a process where an open arc can be constricted by passing through a small nozzle, from the electrode to the workpiece. The gas used is typically air and it combines with an electrical current to create a high temperature plasma arc. For cooling, it is often used a secondary gas or cooling with water.

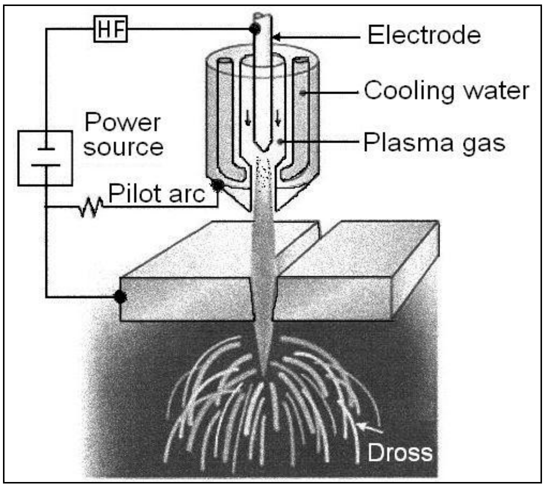


Fig. 1. Plasma arc cutting principle (Bâlc, 2001), (Miloş, 1996), (Ciobanu, 2003), (Dulău&Oltean, 2005)

How it works. The cutting procedure begins with arc ignition, which is a process consisting of several steps. It starts with igniting a *pilot arc*, an arc discharge between the electrode (cathode) and nozzle. Ignition of this pilot arc can be done in two different ways: one is with a short HF pulse applied to the electrode-nozzle gap, another is retract starting. The most common form of retract starting uses the pressure of the air supplied to the torch to drive back a piston to which the electrode is ultimately connected. The electrode and nozzle start out in contact with an electric current running through them. When the electrode retracts a pilot arc is created.

Once the pilot arc is created, the gas flow blows the pilot arc out of the nozzle thus creating an arc loop protruding out of the nozzle. If the work-piece is in position (typically within 5–15mm from the end of the nozzle), the arc will attach to the work-piece, the power supply will sense arc transfer and the nozzle will be removed from the circuit. The workpiece becomes the anode, and the main current establishes in the electrode-work gap (Nemchinsky, 1998).

There are two methods to begin the cutting process:

- ♦ piercing the plate or
- ♦ starting from the edge of the plate.

The plasma cutting technique has been improved over the time and their evolution can be summarized: 1954 – air plasma cutting, 1962 – dual flow plasma arc, 1965 – water shield plasma cutting technology, 1968 – water injection plasma cutting, 1977 – underwater plasma cutting, 1992 – hight tolerance plama cutting or so colled hight definition plasma cutting or hight precision plasma cutting.

3. EXPERIMENTAL PROCEDURE

The experimental tests were made in an industrial enterprise on a CNC plasma cutting equipment, "*KOMPACT3015-HPR130*". An austenitic stainless steel sheet metal workpiece, AISI 304 (X5CrNi18-10), was cut using different cutting conditions, in order to establish an empiric model of the obtained surface roughness (R_a) and also to determine what parameter has the most influence on the R_a parameter.

Our intention was to study the influence exerted by the plasma cutting machining working parameters (working speed, material thickness, and current intensity of the plasma arc) on the quality of the cut, more precisely on the obtained surface roughness. The plasma cutting equipment, *KOMPACT3015-HPR130*, witch was used in order to make the experiments, include the following main components: A – power supply; B – control stand; C – the gas console (oxygen, azoth, air); D – valves assembly; E – plasma torch.

The model was planned by adopting full factorial experimentation procedure. In this model, the cutting speed *v [mm/min]*, the material thickness *g [mm]* and the current intensity *I [A]* were varied at different levels and the orifice size of the plasma torch, the plate to torch distance (standoff distance), the plasma flow rate and the material type was kept constant. Thus, three process parameters were varied at two levels. In table 1, the range of different process parameters and factor levels used for this study are shown.

Table 1. Process parameters and their levels

Symbol	Parameters	Units	Level 1	Level 2
v	cutting speed	[mm/min]	1000	1800
g	material thicknes	[mm]	4	6
I	current intensity	[A]	45	130

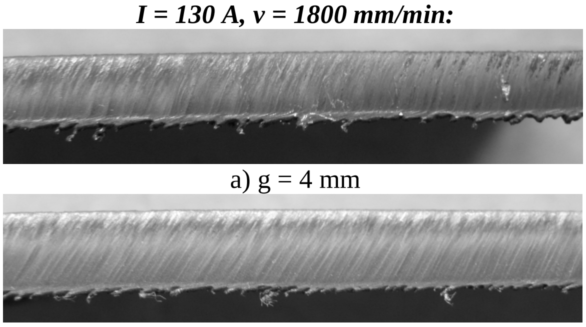
The experimental results, respectively the roughness values obtained, are given in Table 2. The roughness values represent the average of 3 point measurements both on the entry of the plasma jet, at the middle part of the cut and of the out of the plasma jet.All the cutting data presented in table 2 are for standoff distance of 3 mm, jet impact angle of 90^o, N_2 Plasma / N_2 Shield as gas producing plasma and gas cooling.

Table 2. Full factorial experimental plan - 2^3 & cutting data

Exp. no.	v [mm/min]		g [mm]		I [I]		v*g	v*I	g*I	R_a [µm]		Residue	
	Level	Value	Level	Value	Level	Value	Level	Level	Level	R_a	R_a ~	r	r^2
1.	1	1000	1	4	1	45	1	1	1	3,66	3,71	-0,05	0,00289
2.	1	1000	2	6	1	45	2	1	2	4,72	4,67	0,05	0,00289
3.	1	1000	1	4	2	130	1	2	2	1,77	1,72	0,05	0,00289
4.	1	1000	2	6	2	130	2	2	1	1,86	1,91	-0,05	0,00289
5.	2	1800	1	4	1	45	2	2	1	1,93	1,88	0,05	0,00289
6.	2	1800	2	6	1	45	1	2	2	4,30	4,35	-0,05	0,00289
7.	2	1800	1	4	2	130	2	1	2	2,40	2,45	-0,05	0,00289
8.	2	1800	2	6	2	130	1	1	1	4,23	4,18	0,05	0,00289
												Σr^2 =	0,02311

In figure 2...4 are presented some examples of stainless stell workpieces cut by plasma at different conditions. Thus, it was observed a resolidified layer along the cut edge, the presence of drag lines and dross formation at the inferior part of the plate.

I = 130 A, v = 1800 mm/min:

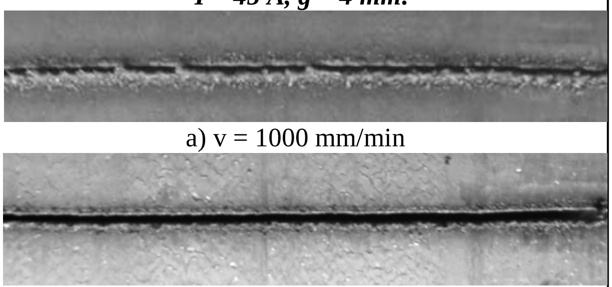


a) g = 4 mm

b) g = 6 mm

Fig. 2. The appearance of the cut edge of AISI 304 stainless steel, cut at: I = 130 A and v = 1800 mm/min

I = 45 A, g = 4 mm:

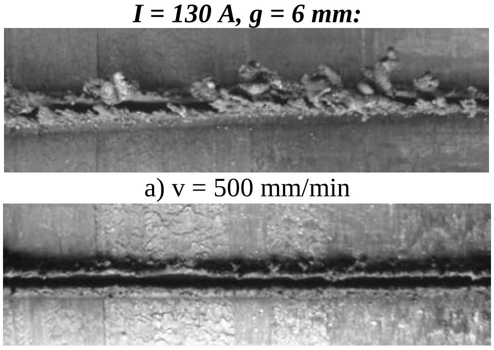


a) v = 1000 mm/min

b) v = 1800 mm/min

Fig. 3. The appearance of the cut edge of AISI 304 stainless steel, cut at: I = 45 A, g = 4 mm

I = 130 A, g = 6 mm:



a) v = 500 mm/min

b) v = 1000 mm/min

Fig. 4. The appearance of the cut edge of AISI 304 stainless steel, cut at: I = 130 A, g = 4 mm

Experiments have shown that the dross varies in quantity and the degree of adherence to the plate, depending on the cutting speed in relation to the cutting power and the composition of the base material. Thus, dross forms at low speeds and also at high speeds.

Low-speed dross tends to form in discreet and readily removable pieces (with low adherence to the plate). *High-speed dross* tends to form a continuous bead, it is very adherent to the plate, requiring grinding to be removed. Also, dross, which remains on the bottom edge, generally indicates an unoptimized cutting procedure

The quality of the cut surface was evaluated according to the roughness indexes R_a, which were determined with a profilograph – profilometer: HandySurf E–35A/B portable surface finish measuring instrument. This apparatus it allows the measuring of 18 types of surface roughness parameters. In this study, we used only the R_a surface roughness parameter. According to JIS B0601-2001, the length of 4 mm was taken at the basis.

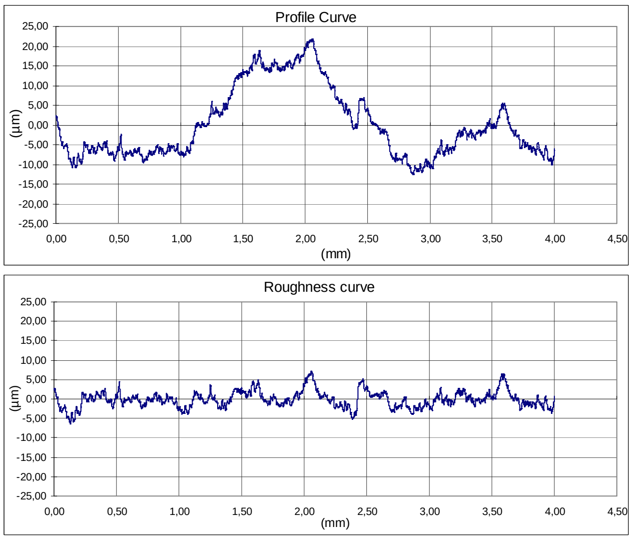


Fig. 5. Profile & roughness curve obtained for AISI 304 cut at: v = 1000 mm/min, I = 130 A, g = 6 mm

Due to the fact that this apparatus can be connected to a computer, the profile of the machined surface could also be studied. An example of the roughness profile obtained with this apparatus is presented in figure 5, were the obtained surface roughness R_a parameter is 1,63 μm, value measured in 3 points, at the superior part of the cut, at the middle part and at the inferior part of the cut.

4. MATHEMATICAL MODELLING OF SURFACE ROUGHNESS PARAMETER

By the mathematical processing of the experimental results by means of the software based on the method of the smallest squares (DataFit version 6.1), we have determinate the following empirical relation, considerated as the most adequate relation for the studied model:

$$R_a = a \cdot (x_1)^b \cdot (x_2)^c \cdot (x_3)^d \qquad (1)$$

Were, the Coefficient of Multiple Determination (R^2) = 0,8838323199; the equation ID is that presented in relation (1) and the regression variable results are given in Table 3.

Table 3. Regression Variable Results

Variable	Value	Standard Error	t-ratio	Prob(t)
a	25,69294	118,54386	0,21673	0,83902
b	-0,31573	0,58314	-0,54143	0,61695
c	0,64720	0,85979	0,75274	0,49348
d	-0,22636	0,32681	-0,69263	0,52665

Thus, the relation (1) becomes:

$$R_a = 25{,}69294 \cdot v^{-0{,}31573} \cdot g^{0{,}64720} \cdot I^{-0{,}22636} \qquad (2)$$

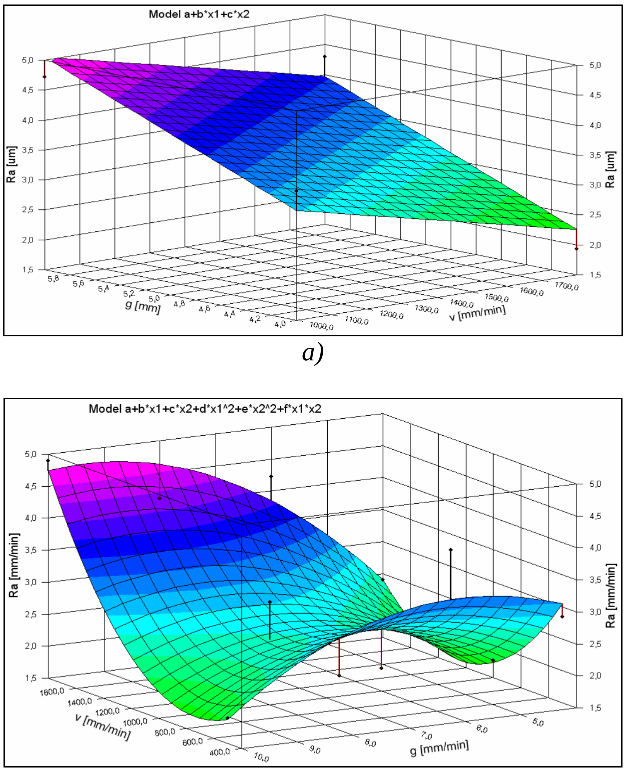
As it can be seen, the relation 2 represents a power function type, which means that, the coefficients of parameters give us an image of which parameter influence the most on the value of the obtained R_a parameter.

Thus, taking into consideration the empirical model obtained for the R_a – roughness parameter and studying the size of the exponents (see relation 2), we can observed that the material thickness, *g*, has the most influence on the R_a parameter followed by the *v* – cutting speed and the current intensity *I* of the plasma arc.

Figure 6 present the response surface model for R_a as a function depending on the cutting speed, *v*, parameter and material thickness, *g*, also, both casses: a – plasma processing at a current intensity of 45 amps and b - plasma processing at a current intensity of 130 amps.

The theoretical matrix model able to highlight the effects of the parameters considered for this study (cutting speed, material thickness and plasma arc current intensity) and factors interaction also, is that presented into the relation 2.

In numerical form, the relation 2 becomes the relation 4.



a)

b)

Fig. 6. The response surface model for R_a = f(v, g) when:
a) I = 45 A constant, R^2 = 0,9052061756
b) I = 130 A constant, R^2 =0,8272739362

$$\begin{aligned} Y = \;& M + \\ & + \begin{bmatrix} E_{v_1} & E_{v_2} \end{bmatrix} \cdot [A_v] + \\ & + \begin{bmatrix} E_{g_1} & E_{g_2} \end{bmatrix} \cdot [A_g] + \\ & + \begin{bmatrix} E_{I_1} & E_{I_2} \end{bmatrix} \cdot [A_I] + \\ & +^t [A_v] \cdot \begin{bmatrix} I_{v_1,g_1} & I_{v_1,g_2} \\ I_{v_2,g_1} & I_{v_2,g_2} \end{bmatrix} \cdot [A_g] + \\ & +^t [A_v] \cdot \begin{bmatrix} I_{v_1,I_1} & I_{v_1,I_2} \\ I_{v_2,I_1} & I_{v_2,I_2} \end{bmatrix} \cdot [A_I] + \\ & +^t [A_g] \cdot \begin{bmatrix} I_{g_1,I_1} & I_{g_1,I_2} \\ I_{g_2,I_1} & I_{g_2,I_2} \end{bmatrix} \cdot [A_I] \end{aligned} \qquad (3)$$

Theoretical values obtained by solving the matrix model R_a~, for the 8 experimental points and the experimentally determined values of R_a are centralized in Table 2. Theoretical and experimental points corresponding to R_a and R_a~ are represenred in Figure 7. Studying the graph shown in Figure 7, it can be observed a relative small amount for the residue (r^2), meaning that the teoretical model is very close to the experimental one.

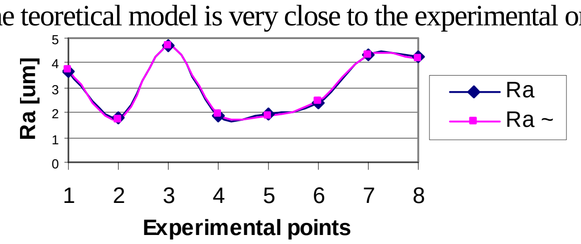


Fig. 7. R_a and R_a ~ values for AISI 304

$$
\begin{aligned}
R_a \sim= \; & 3{,}10875 + \\
& +\left[-0{,}10625 \quad 0{,}10625\right]\cdot[v] + \\
& +\left[-0{,}66875 \quad 0{,}66875\right]\cdot[g] + \\
& +\left[0{,}54375 \quad -0{,}54375\right]\cdot[I] + \\
& +^{t}[v]\cdot\begin{bmatrix}0{,}385125 & -0{,}385125\\ -0{,}385125 & 0{,}385125\end{bmatrix}\cdot[g] + \\
& +^{t}[v]\cdot\begin{bmatrix}0{,}64375 & -0{,}64375\\ -0{,}64375 & 0{,}64375\end{bmatrix}\cdot[I] + \\
& +^{t}[g]\cdot\begin{bmatrix}-0{,}18875 & 0{,}18875\\ 0{,}18875 & -0{,}18875\end{bmatrix}\cdot[I]
\end{aligned}
\qquad (4)
$$

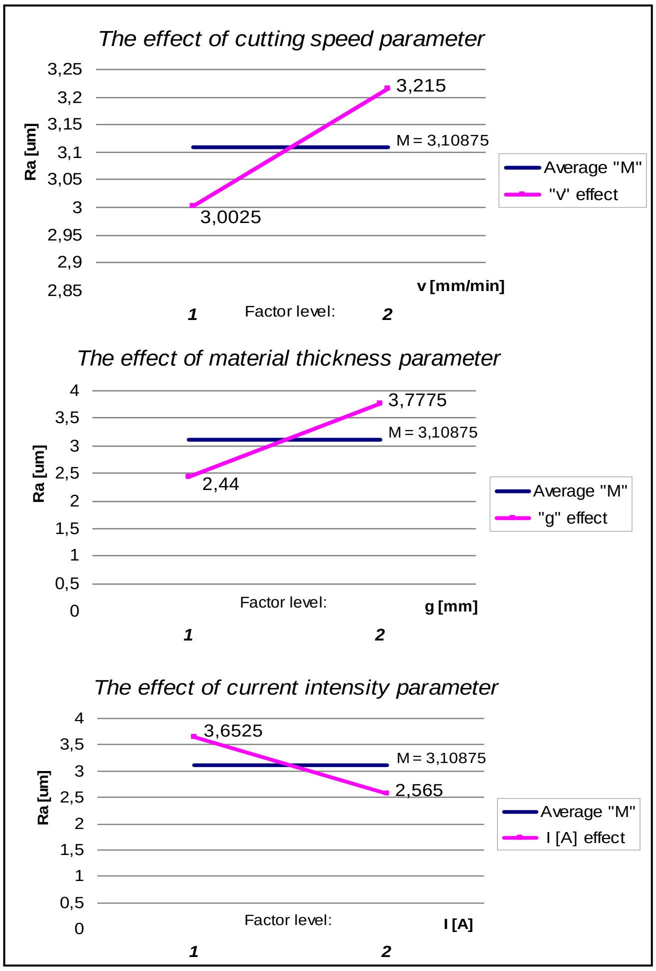


Fig. 8. The average effect results of cutting speed, material thickness and current intensity parameters

After analyzing the model presented in relation 4, and the graphs shown in figure 8, regarding the effects of the *v*, *g* and *I* factors, we can conclude that a small value for the R_a roughness parameter can be obtained when the cutting process take place with the *cutting speed parameter*, v [mm/min] and material thickness parameter g [mm], *at first level* (v = 1000 mm/min and g = 4 mm) and the *current intensity* parameter I [A] at *level 2* (I = 130 A). In this case of processing, R_a=1,77 µm.

Taking into considerations the interactions between factors (Fig.9), namely (*v*g*), (*v*I*) and (*g*I*), we can conclude that, at plasma arc cutting, in order to obtained a small value for the R_a roughness parameter, the cutting process must be conducted with the follwing combinations: v_2g_1, v_1I_2, g_1I_2.

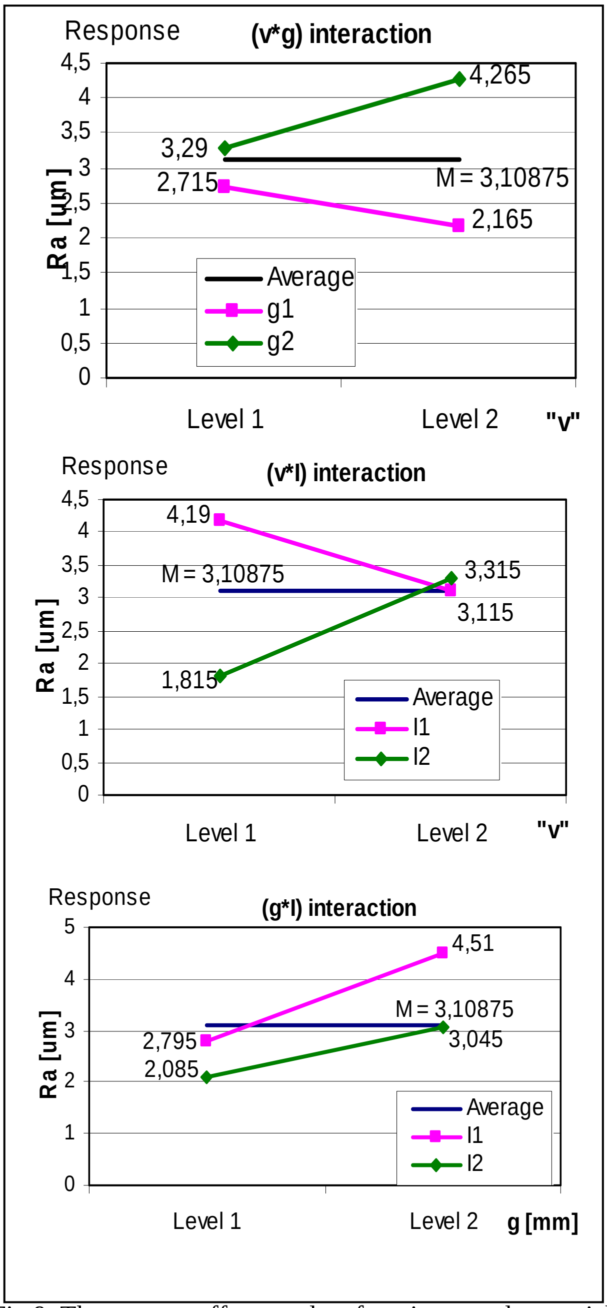


Fig.9. The average effect results of cutting speed, material thickness and current intensity parameters

The plasma arc cutting is a very complex process and therefore there is a lot of information that must be considered; in order to obtain good results (quality, productivity, low cost etc) and be able to solve different problems concerning the cutting process, the engineer/machinist must have all the necessary information, to well know the cutting process, what are the parameters involved, their influences, working conditions etc; this will minimize also the time for analysis and set the optimal working conditions.

Plasma cutting offers productivity and cut quality benefits for some applications. It has the ability to cut thin materials with minimal distortions.

Table 4. Analysis of model variance

Factors/ Interactions	Sum of squared deviations from the average S	Degree of freedom	Dispersion	F_{exp} (= V_i/V_R)	$F_{theoretic}$ (F_t) pentru α = 0,70	Significant (Yes if $F_{exp}>F_t$)
v	S_v = 0,756	$ngl_v = 1$	V_v = 0,756	F_{exp} = 3,812	v_1=1; v_2 = 1 F_t = 3,852	Nu
g	S_g = 0,162	$ngl_g = 1$	V_g = 0,162	F_{exp} = 0,819	v_1=1; v_2 = 1 F_t = 3,852	Nu
I	S_I = 0,530	$ngl_I = 1$	V_I = 0,530	F_{exp} = 2,673	v_1=1; v_2 = 1 F_t = 3,852	Nu
v*g	$S_{(v*g)}$ = 0,2178	$ngl_{v*g} = 1$	V_{v*g} = 0,2178	F_{exp} = 1,098	v_1=1; v_2 = 1 F_t = 3,852	Nu
v*I	$S_{(v*I)}$ = 0,4418	$ngl_{v*I} = 1$	V_{v*I} = 0,4418	F_{exp} = 2,226	v_1=1; v_2 = 1 F_t = 3,852	Nu
g*I	$S_{(g*I)}$ = 0,0338	$ngl_{g/I} = 1$	V_{g*I} = 0,0338	F_{exp} = 0,170	v_1=1; v_2 = 1 F_t = 3,852	Nu
Rez.	S_R = 0,20	$ngl_{rez} = 1$	V_R = 0,20			
Total	S_T = 10,996	7				

5. CONCLUSIONS

A plasma cutting device is used to convert electrical power into thermal energy through a high temperature plasma jet which melts and ejects the molten metal out of the kerf. An electric arc is established in a gas flow through a nozzle of a few milimeters diameter in order to obtained a ferry thin jet

The plasma proces is suitable for electrically conducting materials of thickness from 1 to 600 mm.

The plasma cutting process may be used to cut any conductive material, including carbon steel, stainless steel, aluminium, cooper, brass, cast metals and exotic alloys.

In case of processing an austenitic stainless steel workpiece AISI 304, by the mathematical processing of the experimental results by means of the software based on the method of the smallest squares, we have determined that the material thickness, *g [mm]*, has the most influence on the R_a roughness surface followed by the cutting speed parameter *v [mm/min]* and the current intensity *I [A]*. The optimal cutting condition in this case is when v = 1000 mm/min, g = 4 mm and I = 130 A; R_a = 1,77 µm.

Analysis conducted by Sndecor test for a 10% risk, show that all the factors have an influence on the final results of the cut, less the material thickness which has a lower influence on the R_a parameter.

Also, all the interactions considered in this study (v*g, v*I and g*I) have a significant influence on system response (R_a surface roughness parameter).

Order, depending on the degree of influence, is the following:

- v*I – significance level 1;
- v*g – significance level 2;
- g – significanve level 3;
- I – significance level 4;
- g*I – significance level 5;
- v – significance level 6.

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