PLASMA CUTTING OPTIMIZATION BY USING THE RESPONSE SURFACE METHODOLOGY

Pedro Ferreira[1], Ivo Melo[1],
António Gonçalves-Coelho[2], António Mourão[2]

[1] Faculty of Science and Technology, The New University of Lisbon
[2] UNIDEMI, Faculty of Science and Technology, The New University of Lisbon
email: goncalves.coelho@fct.unl.pt

ABSTRACT

Optimizing a plasma cutting operation is typically a trial-and-error process that is usually inspired in recommendations given by manufacturers of plasma cutting tools and consumables. Those advices reflect the point of view of the manufacturers' business and may not lead to the most cost-effective solution on the users' point of view — even if technically sound. In addition, trial-and-error does not allow for the systematization, for further usage, of the new knowledge acquired by the users. The present paper contains a contribution for the change of the current state of affairs through the use of the response surface methodology (RSM). A genuine industrial case study is presented, where a gain of 35 to 65% in cutting speed was attained depending on the processed steel, with a cost reduction of around 28%.

KEYWORDS: Plasma Cutting, Process Optimization, Response Surface Methodology, Design of Experiments, Cost Engineering

1. INTRODUCTION

Plasma cutting is an industrial process that is essentially controlled by the operators' empirical mind-set, which is typically inspired in recommendations given by the manufacturers of the cutting torches that are to be used. Those recommendations, however, reflect the point of view of the manufacturers' business, which includes not only selling the cutting torches but also the consumables. Yet, the manufacturers' recommendations usually lead to solutions that are technically sound in terms of cutting quality, but do not necessarily correspond to the most cost-effective solutions on the user's point of view.

As a result, the user customarily attempts to optimize the cutting operations by trial-and-error every time it is needed to setup the existing equipment for a new different task. This procedure is relatively efficient when used by experienced operators, but it is not a quantified optimization process. Therefore, it does not allow for the systematization for further usage of the knowledge that was acquired in this manner. This shortcoming can be avoided through the use of design of experiments (DoE), as a means of attaining empirical mathematical expressions that can be used to predict the optimal process parameters in never yet performed cutting operations.

In an industrial point of view, general contributions for the systematization of knowledge on the plasma cutting process appear to be out of question since plasma torches and respective nozzles come in a wide range of sizes. Additionally, the topology of complete plasma cutting systems varies from the simple hand-held torches to complex CNC machines of different shapes and sizes. Therefore, the best contributions relate to usual plasma cutting operations by using specific cutting systems.

The contribution contained in this paper relates to the use of a plasma cutting system that was built with the following components:
- ESAB SUPRAREX SXE-P 6500 flame cutting machine with CNC controller;
- ESAB PT 600 plasma torch;
- ESAB ESP-200 plasma cutting power source;
- 5x33 m cutting table composed by 22 Sideros Engineering Sirius 3x5 m modules with gas exhausting system.

The above described system is being used by a maker of agricultural machinery and heavy road transport vehicles to cut different grades of carbon and alloy steel plate with thickness in the range 5-30 mm to produce the components that are required for making welded structural members of his industrial products.
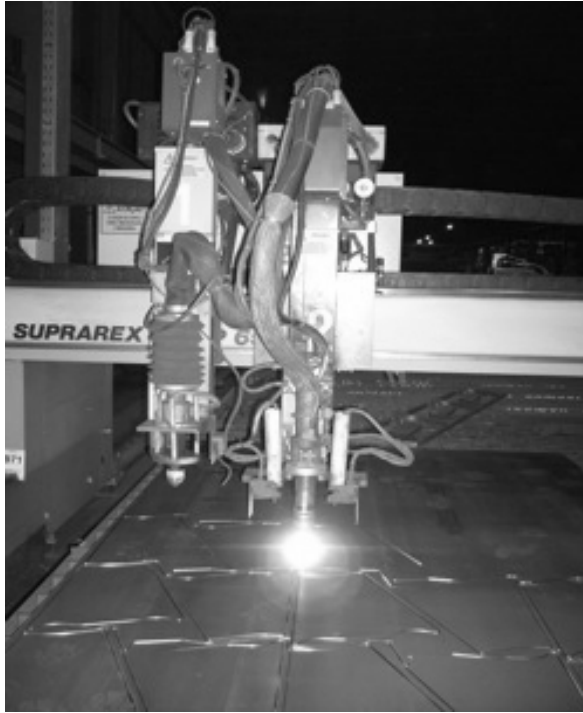
Fig. 1. The plasma cutting system

Fig. 1 shows the plasma cutting system at the host company, processing some of the 15 mm thick QstE-380 alloy steel plate parts, which productivity optimization is detailed in this paper. As one can see, the nesting of the parts is such that the number of the required piercing operations is kept to a minimum, in order to improve the torch consumables life.

Productivity can be regarded as being the ratio between production speed and cost. For plasma cutting, productivity can be defined by an expression of the type

$$P = \frac{V_C}{C_L}, \qquad (1)$$

where V_C is the cutting speed and C_L the cutting cost per unit length. Both V_C and C_L depend on several process variables and productivity can be improved either by increasing the cutting speed, or decreasing the cutting cost per unit length, or both.

For a given torch, the main process variables in plasma cutting are the voltage, V, the current, I, the cutting speed, V_C, the pressure of the cutting gas, P_C, and the pressure of the protection gas, P_P. There are four major factors for the production cost in typical plasma cutting operations: electrical power, gases, torch consumables, and labour [1].

Since there was no time available for the experimental determination of the torch consumables lifetime, it was decided not to consider their cost in this work. Additionally, the labour cost was not taken in account because it is regarded a fixed cost by the host company.

Therefore, the total cost per unit length of cutting is given by

$$C_L = C_E + C_{O_2} + C_{air}, \qquad (2)$$

were C_E, C_{O_2} and C_{air} are respectively the cost per unit length of the electrical power, the cost of the cutting gas and the cost of the compressed air that is used as protection gas. All the costs are expressed in €/m, and it is worth to notice that the cost of the piercing gas (N_2) was not included due to its very small contribution for the total production cost.

The estimated electrical power cost per unit length (in €/m) for cutting the 15 mm thick QstE-380 alloy steel plate with the ESAB PT 600 plasma torch is given by [2]:

$$C_E = \frac{V \times I}{244,9 \; V_C} . \qquad (3)$$

with V in Volt, I in Ampere, and V_C in mm/min.

The consumption of gases — and therefore their cost — basically depends on the feeding pressure and the torch nozzle size. The estimated costs for cutting the 15 mm thick QstE-380 alloy steel plate with the ESAB PT 600 plasma torch — fitted with a Centricut C47-031 nozzle and a Centricut C96-1024 electrode for all the experiments — are given by [2]:

$$C_{O_2} = \frac{53{,}012\sqrt{P_C}}{V_C} \qquad (4)$$

$$C_{air} = \frac{5{,}769\sqrt{P_P}}{V_C} \qquad (5)$$

with P_C and P_P in bar, and V_C in mm/min.

From Eq. (2) to Eq. (5), one can conclude that

$$C_L = \frac{1}{V_C}\left(\frac{V \times I}{244,9} + 53{,}012 \sqrt{P_C} + 5{,}769 \sqrt{P_P} \right) \quad (6)$$

Combining Eq. (6) with Eq. (1), we have,

$$P = \frac{V_C^2}{\dfrac{V \times I}{244,9} + 53{,}012 \sqrt{P_C} + 5{,}769 \sqrt{P_P}} \qquad (7)$$

Eq. (7) shows that the cutting process productivity increases with the square of the cutting speed when the other parameters are kept constant. However, the maximum cutting speed is limited due to quality concerns.

—> Cutting direction —>

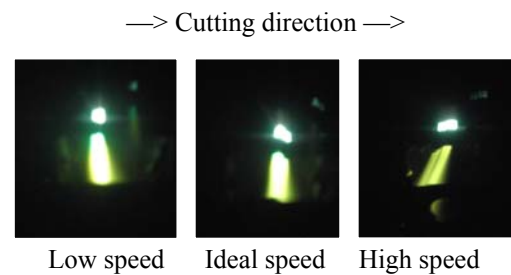Low speed   Ideal speed   High speed

Fig.2. The right cutting speed

In fact, the plasma jet must blow as close to the perpendicular to the workpiece surface as possible, if one wants to attain a smooth cut face with a striated pattern, the striae making a right angle with the upper surface of the plate. Fig. 2 illustrates this condition,

which the experience shows that leads to the best surface quality for the cut face.

The typical shape of the products is shown in Fig. 3, where one can see that the cut path is basically composed by straight lines linked by rounded corners. The cutting speed should be slowed down in the curved zones in order to ensure the quality of the cut face. The CNC controller automatically performs the required speed decrease, but this fact was not considered in our analysis since the length of the curves roughly represent 5-10% of the total length of the torch path for the typical workpieces.
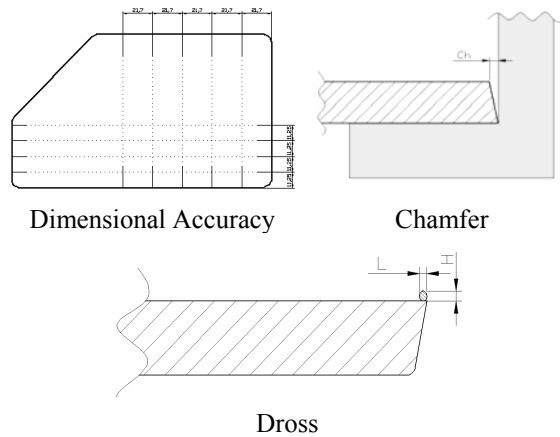

Dimensional Accuracy   Chamfer

Dross

Fig. 3. Quality control requirements

Attention should also be paid to other quality features, especially the dimensional accuracy, the cut face chamfer and the characteristics of the dross of the fabricated parts, as illustrated in Fig. 3.

The dimensional accuracy largely depends on the kerf size, which in turn depends on the process variables. From the previous experience of the host company, one can conclude that the kerf size variation is small for the cutting operations under analysis. Moreover, the kerf size variation can always be corrected by imposing a kerf offset in the CNC controller, and the required offset can be easily determined by a simple, previous experiment. As regards to the chamfer and the dross characteristics, the previous experience of the host company is that it is not difficult to fulfil the *de facto* standards for a wide range of each one of the considered process variables, as noticed elsewhere [2]. Since both the kerf size and the cut face quality seems that are not difficult to control, our analysis could be simplified to focus on the main factors of productivity: cutting speed and costs of electrical power and gases.

2. THE PROCEDURE

Our experimental research was based in a design of experiments (DoE) implementing a central composite design (CCD) scheme [3].

The physical values and the corresponding coded levels of the considered process variables were chosen taking in account the typical values for cutting operations of this kind that can be found in the technical literature, the empirical knowledge of the operators, and the preparatory runs. These values are expressed in Table 1.

Table 1. Physical values and coded levels for CCD

I [A]	V [V]	P_C [bar]	P_P [bar]	Level
120	130	2,1	0,5	-2
140	138	2,5	0,7	-1
160	145	2,8	1	0
180	153	3,2	1,2	1
200	160	3,5	1,4	2

Table 2 contains the values of the experimentally determined optimum cutting speed, V_C (according to the previously detailed method, and the cutting cost per unit length was calculated through Eq. (6). Table 2 also contains the value levels of the process variables for each one of the 26 experimental runs that were performed in industrial production conditions.

Table 2. The results of the experiment

Run no.	I [A]	V [V]	P_C [bar]	P_P [bar]	V_C [mm/min]	C_L [€/m]
1	-1	-1	-1	-1	1311	0.128
2	-1	-1	-1	1	1330	0.127
3	-1	-1	1	-1	1368	0.131
4	-1	-1	1	1	1387	0,130
5	-1	1	-1	-1	1254	0,141
6	-1	1	-1	1	1235	0,144
7	-1	1	1	-1	1311	0,143
8	-1	1	1	1	1235	0,153
9	1	-1	-1	-1	1748	0,109
10	1	-1	-1	1	1748	0,110
11	1	-1	1	-1	1843	0,109
12	1	-1	1	1	1805	0,112
13	1	1	-1	-1	1634	0,123
14	1	1	-1	1	1634	0,124
15	1	1	1	-1	1767	0,120
16	1	1	1	1	1691	0,126
17	-2	0	0	0	1064	0,155
18	2	0	0	0	1843	0,115
19	0	-2	0	0	1539	0,116
20	0	2	0	0	1330	0,150
21	0	0	-2	0	1254	0,141
22	0	0	2	0	1501	0,133
23	0	0	0	-2	1501	0,125
24	0	0	0	2	1482	0,128
25	0	0	0	0	1463	0,129
26	0	0	0	0	1425	0,133

The results of the experiment were processed trough the response surface methodology (RSM) [3] and the obtained phenomenological expression for the cutting speed was found to be:

$$V_C = 1444 + 298,21\ I - 49,88\ V + 41,96\ P_C,$$

$$R^2 = 0,964 \tag{8}$$

One can see that the optimum cutting speed depends on all the process variables but the protection

gas pressure, as expected. However, P_P was included in our plan of experiments because we were interested in accessing its influence in the quality responses. One can also notice that both the current and cutting gas pressure are important, because they increase the specific energy and the flow of the plasma jet, respectively. At last, one can remark that the negative coefficient of the arc voltage is due to the fact that the distance from the torch nozzle to the workpiece must increase with the increasing of the voltage, thus contributing to the dispersion of the plasma jet, which in turn calls for a lower cutting speed.

The quality inspection for the workpieces fabricated during the 26 runs was performed and the results are displayed in Table 3.

Table 3 – Results of the quality inspection

Run no.	Chamfer [mm]	Dross sec. [mm²]	Kerf size [mm]
1	1,38	3,000	4,30
2	1,20	5,280	4,33
3	1,18	1,900	4,31
4	1,17	1,980	4,23
5	1,61	3,640	4,58
6	1,51	8,000	4,38
7	1,42	1,980	4,53
8	1,24	1,980	4,64
9	1,45	0,03	4,4
10	1,33	0,25	4,2
11	1,25	1,3	4,4
12	1,13	0,42	4,1
13	1,43	0,040	4,40
14	1,28	0,100	4,25
15	1,20	0,720	4,40
16	1,13	0,600	4,29
17	1,22	10,340	4,35
18	1,42	0,02	4,6
19	1,09	1,120	4,11
20	1,57	2,800	4,66
21	1,46	2,380	4,69
22	1,20	0,600	4,52
23	1,51	0,320	4,50
24	1,31	0,120	4,21
25	1,28	1,800	4,47
26	1,36	2,450	4,37

In what to the chamfer concerns (see definition in Fig. 2), one can see from Table 3 that the mean value is 1,29 mm with a standard deviation of 0,15 mm. This is quite acceptable for 15 mm thick steel parts that are intended for welded construction.

As for the dross, the mean area of their cross section is 1,55 mm² with a standard deviation of 2,49 mm². The high standard deviation is due to the significant mean cross section of the dross that was obtained in runs no. 2, 6 and 17, all the other values being acceptable according to the *de facto* standard in use at the host company.

Finally, the kerf size has a mean value of 4,36 mm with a standard deviation of 0,16 mm. This is acceptable by the *de facto* standard and allows for easy compensation by the CNC cutting system through the use of the automatic kerf offset function, so that the required dimensional accuracy can be attained.

The phenomenological expressions are:
- For the chamfer, Ch:

$$Ch = 1,32 + 0,07\ V - 0,083\ P_C - 0,056\ P_P - 0,061\ I \times V, \quad (9)$$

$$R^2 = 0,821$$

- For the dross mean section, D:

$$D = 2,125 - 1,872\ I + 0,720\ I^2 - 0,543\ P_C + 0,918\ I \times P_C, \quad (10)$$

$$R^2 = 0,928$$

- For the kerf size, K:

$$K = 4,42 + 0,092\ V - 0,063\ P_P,$$

$$R^2 = 0,697 \quad (11)$$

The interpretation of the polynomials above can be found elsewhere [4], but, the most interesting conclusion that one can extract here is that the cross examination of Tables 2 and 3 reveals that runs no. 9, 10, 11, 12 e 18 are characterized by high productivity (high cutting speed at a low cost) and suitable quality of the cut faces.

Fig. 3 depicts the values of the ratio V_C/C_L for each run. The figure shows that it is possible to obtain more productivity than the one that was current at the time. In fact, one can see that runs no. 9, 10, 11, 12 and 18 lead to productivities that are greater than 100%.
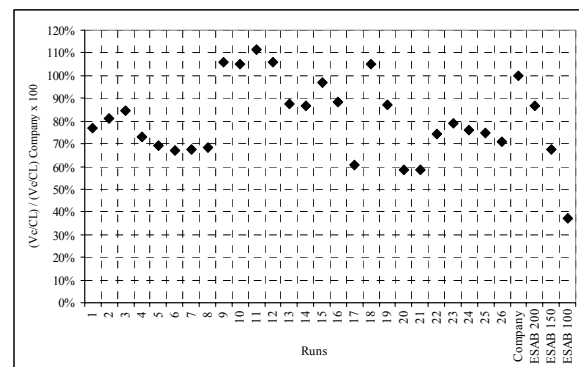

Fig. 3. V_C/C_L for each run, relative to the current at the time in the host company

The last four points at the right side of Fig. 3 relate to some additional tests that were done for comparison, and show the productivity attained with the traditional set of values for the process variables, as well as with the sets of values recommended by a vendor for processing the 15 mm thick QstE-380 alloy steel plate. Those values are presented in Table 4.

Table 4. Sets of values of the comparison tests

	I [A]	V [V]	P_C [bar]	P_P [bar]	V_C [mm/min]	C_L [€/m]
Comp.	200	135	2,7	0,6	1750	0,115
ESAB 100	200	139	2,8	0,8	1651	0,126
ESAB 200	150	151	3	1,2	1397	0,136
ESAB 300	100	159	3,2	0,8	965	0,171

3. VALIDATION OF THE MODEL

Since the main goal of our work was to find out the cutting conditions that lead to improved productivity, for the validation runs we used particular combinations of the process variables that could lead to an improved value for V_C/C_L. This was done by analysis of Eq. (7) and Eq. (8) using the following rationale:

a) The used combinations for the process variables should be such that the cutting speed is high, typically more that 1800 mm/min, since the previous runs showed that this would lead to a best productivity than the one that was attained by the host company before this research program.

b) The voltage should be kept as low as possible, in order to favour the cost.

c) The protection gas pressure, P_P, should be kept low since it does not affect the setting of the cutting speed. Even though the influence of this pressure is not important for the setting the value of V_C, low pressure definitely helps improving the productivity.

d) The pressure of the cutting gas, P_C, does not significantly affect the setting of the cutting speed. However, it should be kept as low as possible because of its influence on the cutting cost.

Table 5 below contains the results of the validation runs (runs A to G), from which one can conclude that our model for the estimation of the optimum cutting speed for improved productivity is well behaved. In fact, the differences that were found between the values attained in the validation runs and the values predicted by the model belong to the range -2,25% to -10,3%

It is worth to notice that the productivity values that were obtained by estimation through the model are always lower that the ones that were attained trough the experimental runs, which means that our model is consistently conservative.
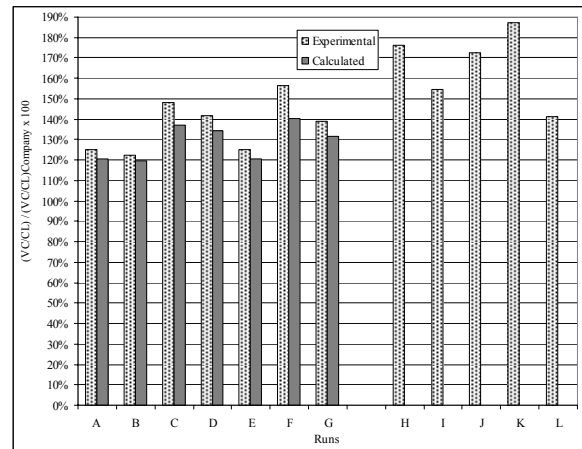

Fig.4. Possible gain in productivity relative to the current one in the host company

In fact, Fig. 4 above shows that the productivity obtained through the validation runs (A to G) allowed attaining improvements up to 155% (the case of run no. F), whereas the model only predicts 140% with the set of values of process variables for the same run.

4. LOOKING FOR A EVEN BETTER PRODUCTIVITY

The results of the validation runs suggest that the range of the voltage V that has been used in the DoE could be made wider, especially in what the lower voltage values concern. At the time that the DoE presented in Tables 1 and 2 was performed there was no time to schedule a different, entire DoE plan with an extended range for the voltage.

Anyway, we have done a small number of additional runs with a voltage of 125 V, as shown in Table 6 and Fig. 4 (runs H to K) in order to confirm our speculation.

Table 5. Results of the validation runs

Run	I		V		P_C		P_P		V_C [mm/min]			C_L
	[A]	Level	[V]	Level	[bar]	Level	[bar]	Level	Experiment.	Estimated	Diff.	[€/m]
A	200	2	138	-1	2,8	0	0,7	-1	1980	1910	-3,5%	0,104
B	200	2	138	-1	2,8	0	0,5	-2	1952	1910	-2,2%	0,105
C	200	2	130	-2	2,8	0	0,5	-2	2117	1960	-7,4%	0,094
D	200	2	130	-2	3,0	0,5	0,5	-2	2090	1981	-5,2%	0,097
E	190	1,5	130	-2	2,8	0	0,5	-2	1925	1856	-3,6%	0,101
F	200	2	130	-2	2,5	-0,86	0,5	-2	2145	1924	-10,3%	0,090
G	200	2	130	-2	2,3	-1,43	0,5	-2	2007	1900	-5,3%	0,095

Table 6. Runs with the process variables out of the DoE domain

Run	I		V		P_C		P_P		V_C [mm/min]			C_L
	[A]	Level	[V]	Level	[bar]	Level	[bar]	Level	Experim.	Estim.	Diff.	[€/m]
H	200	2	125	-2,7	2,8	0	0,5	-2	2282	1995	-12,6%	0,085
I	200	2	125	-2,7	2,5	-0,9	0,5	-2	2117	1957	-7,6%	0,090
J	200	2	125	-2,7	2,7	-0,29	0,5	-2	2255	1983	-12,1%	0,086
K	200	2	125	-2,7	2,9	0,29	0,5	-2	2365	2007	-15,1%	0,083
L	200	2	125	-2,7	3,0	0,57	0,5	-2	2062	2019	-2,1%	0,096

As a result, both Table 6 and Fig. 4 clearly show a further improvement of productivity, due to the possibility of increasing of the cutting speed and the consequent decreasing of the cutting cost per unit length.

The best combination of the process variables was found to be the one that corresponds to run K, for which the cutting speed was 35% higher, leading to a decreasing of 28% in the cost and a increasing of 87% in the productivity. The results of the quality test is not presented here but were found as conforming to the *de facto* standards of the host company.

5. CONCLUDING REMARKS

As a result of the research work presented here, one could obtain a very significant improvement of the cutting process for the specific case of 15 mm thick QstE-380 alloy steel plate. A similar study on cutting 8 mm thick Hardox 450 alloy steel not presented here lead to an increase of 65% in the cutting speed, which in turn lead to a decrease of 29% in the cutting cost.

In spite of the significance of these results, one should notice that they do not correspond to optimum values, since the variable ranges that were used for the process variables, especially for the arc voltage, were not the most appropriate. Additionally, a genuine mathematical optimization trough Eq. (7) and Eq. (8) was not attempted and the torch consumables costs should be taken in account for even better results. Anyway, the torch consumables have been qualitatively controlled be the system's operator, who did not report any noteworthy increase in the wearing of consumables.

The technical sheets of the host company for cutting 15 mm thick QstE-380 and 8 mm thick Hardox 450 alloy steel plate were promptly modified to reflect the results of our study since our results were obtained in their typical production environment with the collaboration of their technical staff.

Beyond the delight of having the chance of researching in genuine industrial conditions, the authors of the present paper could perceive that the use of RSM has made a change in the attitude of the technical staff and systems operators of the host company, in what concerns to systematizing and quantifying the empirical knowledge that can be acquired under unmodified production conditions.

At last, the authors would like to express their believe in using small projects with students as a means to promote the Industry-University co-operation, especially with small and medium enterprises (SMEs) as it was the case of the successful project herein described.

This method allows for increasing the informal direct contacts between professors and the SMEs' technical and management staff, which is a very interesting way for promoting technology transfer. According to our experience [5], the efficiency of these projects in terms of promoting co-operation largely dependent on the manner they are conceptualized and implemented: on the one hand, the University should not regard the projects as a paid consultancy service, and should reduce her present tendency to constraint the professional contacts of professors; on the other hand, owners and managers of companies should not perceive these projects as a means to find cheap technical solutions to specific business problems. In fact, both parts must realise that they are dealing with non-profit student final projects, for which both the companies and the University are net contributors.

REFERENCES

[1] **Cook, D.**, *Operational Costs of Automated Plasma Cutting*, Welding Design & Fabrication, May 2000.
[2] **Ferreira, P., Melo, I.**, *Definição das condições de funcionamento de uma máquina de corte por plasma*, Technical Report, DEMI-FCT/UNL, Campus de Caparica, March 2006 (in Portuguese).
[3] **Montgomery, D.**, *Design and Analysis of Experiments (6th Ed.)*. John Wiley & Sons, ISBN 978-0-471-48735-7, N.Y., 1991.
[4] **Melo, I., Ferreira, P.**, *Definição das condições de funcionamento de uma máquina de corte por plasma*, Final Report, DEMI-FCT/UNL, Campus de Caparica, June 2006 (in Portuguese).
[5] **Mourão, A., Gonçalves-Coelho, A.**, *Industry-University co-operation in the product and process development: experiences with Portuguese SMEs*, 14th International Conference on Concurrent Enterprising, session "Industry-University co-operation in technology oriented research and education: case studies and best practices", Lisboa, 23-25 Junho, 2008.