

OPTIMIZING THE QUALITY OF PARTS MANUFACTURED BY THE AUTOMATED PLASMA CUTTING PROCESS USING RESPONSE SURFACE METHODOLOGY

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Reviewed, accepted 9/18/09 **Abstract**

Automated plasma cutting is an effective process for building complex two-dimensional metallic parts in a short period of time. Because the plasma cutting machine has several factors or input variables to control (e.g., current, cutting speed, torch height) and a variety of part quality characteristics or response variables to satisfy (e.g., flatness, clean cut, bevel angle), it is very difficult to find an overall optimum machine setting. In this research, response surface methodology and desirability functions are used to simultaneously optimize 18 part quality characteristics. Final results identify an optimal machine configuration that facilitates the fabrication of parts with close-to-perfect quality for all responses considered.

Keywords: Plasma cutting, Regression model, Desirability function, Optimization, Experimental design, Rapid Manufacturing

Introduction

In recent years, plasma CAM has combined the plasma cutting technology (Kirkpatrick, 1998) with the computer numerical control (CNC) system to cut parts with very complex patterns in a short period of time. In the plasma CAM system, a 2-D geometry drawn in its CAD environment or in other commercial CAD system is used to generate the cut path. Then, the cut path controls the movement of the plasma torch installed on a robotic XY table. Parts up to one inch thick and with high complexity can be cut rapidly. However, quality of the parts is not always high. Several frequent problems with fabricated parts, especially after continuous use of the machine, result in deformation of the sheet metal, bad cut, accumulation of metal residuals underneath the work piece, inaccurate dimensions, and cut sloppiness. Preliminary experiments revealed that part quality is directly related to the machine setting.

In this study, Response Surface Methodology (RSM) was used to explore the relationships between machine input variables (explanatory variables) and quality of cut parts from the plasma CAM operation. The contribution of this paper is to (1) provide practitioners and future researchers with mathematical models that define which input variables are the ones related to relevant process quality characteristics, and (2) recommend an optimal setting for the plasma cutting machine to obtain better quality parts with minimum process interruption, and thus lower costs.

The rest of the paper is organized as follows. In section 2, the plasma cutting process is briefly explained. Section 3 describes RSM and the design of experiment (DOE) performed, including a description of explanatory variables and studied levels, responses and their measurement tools and methods, and the class of design of experiments (DOE) implemented. The mathematical models that relate explanatory variables and responses are reported in section 4. Desirability function and overall optimum setting are presented in section 5. Model validation is explained in section 6. Conclusions are shown in section 7.

2. Plasma cutting process

As shown in Figure 1 (Thermal Dynamics 1Torch™ Instruction Manual, 2007), a cool gas enters Zone B of the plasma cutting torch, where a pilot arc between the electrode and the torch tip heats and ionizes the gas. The main cutting arc then transfers to the work piece through the column of plasma gas in Zone C. By forcing the plasma gas and the electric arc through a small orifice, the torch delivers a high concentration of heat to a small area. The stiff, constricted plasma arc is shown in Zone C. Direct current (DC) straight polarity is used for plasma cutting, as shown in the illustration. Zone A channels a secondary gas that cools the torch. This gas also assists the high velocity plasma gas in blowing the molten metal out of the cut allowing for a fast, slag-free cut (Thermal Dynamics 1Torch™ Instruction Manual, 2007).

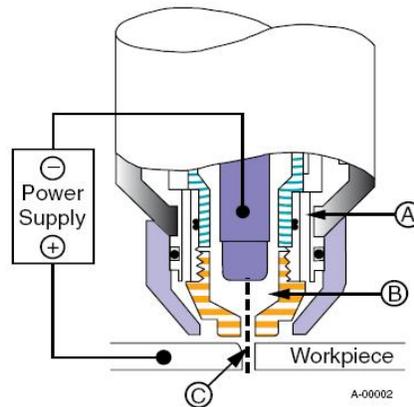


Figure 1. Structure of the Plasma Cutting System

3. Response Surface Methodology

RSM is a collection of statistical and mathematical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize the value of the response (Montgomery, 2004). RSM helps in building predictive polynomial models to relate design variables (factors or explanatory variables) to system responses (response variables) by using design of experiments and regression techniques (Mc.Clurkin and Rosen, 1998). RSM is then a tool for relating outputs to relevant inputs, which can be used to perform sensitivity analysis. (Bauer et al., 1999). In some cases, RSM requires a sequential procedure, that is, several DOE, regression analysis, and optimization steps are performed to arrive to an optimal response value. The graphical perspective of the problem for the case with two explanatory variables and one response motivated the invention of the term Response Surface Methodology (Myers and Montgomery, 2002).

3.1. Factors or Input Variables for the DOE

Based on preliminary experiments and Plasma CAM machine manuals (Thermal Dynamics 1Torch™ Instruction Manual, 2007 and Plasma CAM manual, 2001), the input variables shown in Table 1 seem to be the most influential on part quality. Therefore, these are the ones included in the DOE studied in this paper. Table 1 also shows the levels selected and the units of measurement for each variable considered.

Table 1. Factors or Input Variables Considered in the DOE

Factor Code	Factor name	Level 1: Low	Level 2: Center	Level 3: High	Units
A	Current	40	60	80	Amperes (A)
B	Pressure	60	75	90	Psi
C	Cut speed	10	55	100	Ipm
D	Torch height	0.1	0.2	0.3	Inches
E	Tool type	A (E_1)	B (E_2)	C (E_3)	
F	Slower on curves	0	2	4	
G	Cut Direction	Vertical (G_0)		Horizontal (G_1)	

Cutting power was determined by the current, as voltage was constant. Low values for pressure prevent the operation of the machine and excessive pressure may result in defective cuts. The cut speed is the speed at which the torch moves in the X-Y plane while the torch is cutting. Preliminary experiments showed that pressure, cut speed, and current seem to be related. Torch height is the distance between the tip of the torch and the work piece, whereas tool type refers to the type of tip used for cutting. Tool tips vary based in cutting power. Tool type A (factor E_1), tool type B (factor E_2), and tool type C (factor E_3) are recommended for 40A, 60A, and 80A, respectively.

The machine has the ability to slow down around the corners of the part to obtain a finer cut. Then, the factor slower on curves (i.e. factor F) is considered in the experiment. If the setting for factor F is greater than 0, the machine reduces its cutting speed for curves and circles. Factor G is the direction in which the cut is made. Two types of cuts were considered in the experimental design: Y-direction (vertical) cuts (Factor G_0) and X-direction (horizontal) cuts (Factor G_1). Each work piece is cut first in one direction, and then rotated 90 degrees around the point to perform the other cut.

3.2 Response Variables for the DOE

To produce high quality parts in all aspects, 18 quality responses were measured and considered in the DOE, as shown in Table 2. In this section, these responses along with tools and assessment methods are explained. All cuts were made on stainless steel sheet metal of 0.25 inch thickness. The geometry of the resulting cut parts is presented in Figure 2. It is the same for all cut parts and it contains multiple geometrical features that a typical part may have (e.g., internal curve, external curve, straight line, sharp edges).

3.2.1. Roughness

Roughness of the cut was evaluated and documented separately for three different part areas (straight line, internal curve, and external curve) to get a better assessment of this quality response. Figure 2 shows these three different areas.

Table 2. Responses Considered in the DOE

Response Code	Response Name
R1	Roughness on Internal Curve
R2	Roughness on External Curve
R3	Roughness on Straight Line
R4	Flatness
R5	Accumulation on Internal Curve
R6	Accumulation on External Curve
R7	Accumulation on Straight Line
R8	Geometry in X-Direction
R9	Geometry in Y-Direction
R10	Tool Life
R11	Bevel Angle on Internal Curve
R12	Bevel Angle on External Curve
R13	Bevel Angle on Left Side of Straight Line
R14	Bevel Angle on Right Side of Straight Line
R15	Start Point Quality for Internal Part
R16	Start point quality for External Part
R17	Cut Depth Quality for Internal Area
R18	Cut Depth Quality for External Area

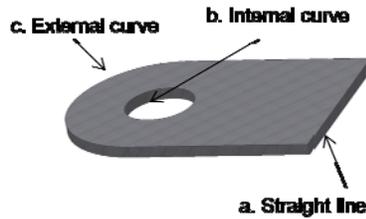


Figure 2. Part Geometry

Because of the complexity and size of the part, standard surface roughness measurement tools were not applicable. Instead, a rating system was designed to grade the surface quality. The rating system scale was between 1 (very rough surface) and 10 (perfect surface finish). For each value in the scale, a different representative object was assigned. For measuring roughness, each area of the cut part was compared to the area of the representative objects to find the object most similar to the cut part. This method was performed by three researchers and the median of their grades was recorded.

3.2.2 Part Flatness

Flatness of the work piece was measured to identify part deformation. A surface variation measurement gauge was used for measuring part flatness. This tool gives the values and the variation in the surface when the surface is moved smoothly under the gauge (Figure 3).

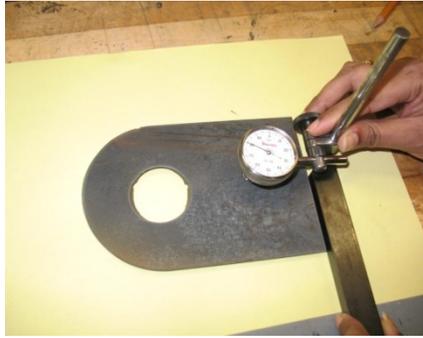


Figure 3. Flatness Measurement Gauge

For measuring part flatness, the gauge knob touches the part and it gives an original flatness value at that place. Then, the top surface of the part is moved all along the knob and the flatness values may differ from the original value if the work piece is not flat. Maximum flatness variation is recorded as the degree of deformation (e.g., 0 means perfect flat).

3.2.3 Accumulation underneath the Work Piece

Accumulation of metal underneath the part occurs after the cutting process. It is expected that a perfect cut not leave any residuals. For a better assessment of this response, accumulation was also measured and documented separately for three areas of the part (straight line, internal curve, and external curve). Similar to the case for roughness response, standard measurement mechanisms were not applicable for measuring accumulation. Instead, a rating system was designed to rate the unwanted accumulations. The rating system scale was between 1 (too much accumulation) and 10 (no accumulation) and for each scale value a representative object was defined (Figure 4). Part accumulation was assessed by three researchers and the median of their grades was recorded.



Figure 4. A Perfect Cut (Part 52) vs. a Part With Residuals (Part 61).

3.2.4 Dimensional accuracy

The change in dimensions after the cutting process was another measured response. The measure was taken in the two dimensions: X (length) and Y (width). An electronic caliper with accuracy of 0.001" was used to measure the dimensions of the fabricated part. For measuring dimensional accuracy, the part was placed in the caliper jaws and the actual reading was recorded as shown in the caliper.

3.2.5 Tool Life

Based on a preliminary experiment, the tool life, which is the tip of the torch, seemed to have an important role in part quality. In this experiment, tool life was not considered as a factor. However, it was measured as a response to evaluate its correlation with the other responses collected. Tool life was measured by counting the number of parts that are cut with the tool. Since cutting length for all parts was equal, tool life could also be measured in terms of cut lengths. Furthermore, it is possible to measure tool life in time units (e.g., in seconds or minutes) and consider also cutting speeds.

3.2.6 Bevel Angle Response

The ideal bevel angle (i.e. the angle between the surface of the cut edge and top surface of the part) is zero. However, this is not always the case. The bevel angle is measured for internal curve, external curve, and straight line. In the straight line area of the part, the bevel angle varied in two sides. Therefore, the bevel angles on left side and right side of a straight line were considered as two different responses. For the internal and external curve, a single bevel angle is measured for each part. The bevel angles were measured using a protractor with a sliding scale and keeping the scale parallel to the side (Figure 5). As shown in Figure 5, to read the bevel angle one edge of the angle measuring apparatus touches the top side of the part, whereas the other edge touches the part's cut edge.

3.2.7 Start point quality

It is sometimes difficult to pass the part's boundary at the start point of the cutting path, thus creating a defective part. To identify the causes of this phenomenon, the quality of the start point are measured for both the internal and external areas of the parts. Visual inspection was used for evaluating the quality of the start point. Different objects with diverse defects (e.g. large, deformed hole, no start points) were rated from 1 to 10, and used as a comparison scale. For measuring this response, the start point quality for the internal and external areas of the part was rated and recorded by comparing it with a representative object in the scale.



Figure 5. Bevel Angle Measurement

3.2.8 Cut Depth

Preliminary experimentation showed that it was not always possible to cut material by using certain machine settings, as depicted in Figure 6. It was observed that a part's boundary is half way cut or not cut at all during these defects. By measuring cut depth for the part's internal and external areas, it was possible to identify the factors leading to infeasible cuts.



Figure 6. Cut and not Cut Samples

Since no tool can be used to measure these responses, a rating system was used to measure the cut depth. The scale ranged from 1 to 10, where the lowest number (1) indicated a minor scratch on the sheet metal's surface and the highest number (10) indicated a complete cut. The cut depth at internal and external edges of the part was measured and rated by comparing the experimental part with standard parts defining the representative scale.

3.3 Design of Experiments Selected

Experimental design has been implemented to characterize how seven Plasma CAM machine factors (input variables) affect the quality and geometrical accuracy of 18 response variables. As previously summarized in Table 1, three levels are considered for six of the factors and two levels are considered for the cut direction (horizontal or vertical). The Orthogonal Array approach was used to reduce the number of runs and still obtain the maximum information from the experiment. Among the Orthogonal Array approaches, an L- 18 Orthogonal Array is selected and augmented with 71 additional runs to estimate the two factor interactions (end with no aliases for the model with two-factor interactions). Thus, the total number of different runs performed in this experiment is 89. Design-Expert software was used to generate this design.

4. Mathematical Models

After conducting all runs of the experiment, the surface quality and geometrical accuracy responses of the fabricated parts were determined. The experimental design in this research has two characteristics that require careful analysis, including missing observations and categorical variables. Missing observations occurred because some of the responses could not be obtained, e.g. parts weren't cut due to infeasible machine settings. The literature reports two approaches for analyzing experiments with missing data, as follows:

1. **Approximate Analysis:** In this type of analysis, the missing observation is estimated and the analysis of variance is performed considering the estimated data as if they were real data. The error degrees of freedom are reduced by one for each missing observation (Montgomery, 2004).
2. **Exact Analysis:** In this analysis, the missing data point makes the design unbalanced. The analysis of variance can be done through a general regression significance test. This research used Minitab statistical software, which excludes missing observations and adjust the regression model accordingly.

Tool type (Factor E) and cut direction (Factor G) were the two categorical variables in this experiment. If in the regression model the categorical variables were treated as numerical ones, results would be misleading. Therefore, categorical variables were accurately described through dummy (indicator) variables. Indicator variables can take on only two values, either zero or one. A value of one indicates that the observation belongs to the encoded category, and zero

otherwise. For example, the three levels of the categorical variable tool type (E_1, E_2, and E_3) are encoded with three indicator variables. Then, a experimental run using tool type A can be represented as (1,0,0), one with tool type B as (0,1,0) and one with tool type C as (0,0,1). The reader should note that for the regression model, one of the indicator variables may be excluded without loss of information. In this study, the third indicator variable is excluded and then the level E_3 of the categorical variable becomes the base or reference level to which the other two levels are compared. In the same way, the input variable “Cut direction” has two levels (G_0 and G_1). A vertical cut is represented as (1,0) whereas a horizontal cut is represented as (0,1). By dropping G_1 from the regression model, the contribution (i.e. positive or negative) of the vertical cut can be measured from the regression coefficient for variable G_0. If the desired value for a response variable is a high one, then the level of the categorical variable which gives the higher response value is preferred (Montgomery, 2007).

A regression equation was adjusted for each of the 18 quality responses. The interaction between categorical and numerical variables was neglected, as it would become difficult to interpret the results. The process of adjusting a linear regression model for each response was repeated as necessary until only significant interactions and significant factors (or non significant factors with significant interactions) are in the models. Minitab vs. 15 was used to obtain the regression models (mathematical models) and generate the residual plots to check models adequacy. Sections 4.1 – 4.8 show the regression models, the computed p-value for the factors included and the R-squared statistics. The R-squared statistic measures the proportion of variability in the response variable explained by the factors and interactions considered in the model and consequently high R-squared values are desirable. A significance level of 0.2 was used to determine statistical significant factors and interactions. Practical studies using similar significance levels are Caley et al., (2007), Stanzel et al., (2008), and Azarov et al., (1985).

4.1 Roughness Responses

4.1.1 Roughness on Internal Curve (R1):

The significant factors were “Pressure” (B, p-value 0.00); “Vertical cut direction” (G_0, p-value 0.022); “Cut speed²” (C*C, p-value 0.001); and the interaction between “Pressure” and “Cut speed” (BC, p-value 0.001). Another factor included in the model below is “Cut speed” (C, p-value 0.609). Regression model R-squared is 0.624 and adjusted R-squared is 0.583.

$$R1 = 12.8 - 0.101 B - 0.0209 C - 0.896 G_0 - 0.000817 C * C + 0.00185 B * C$$

4.1.2 Roughness on External Curve (R2):

The significant factors were “Pressure” (B, p-value 0.019); “Tool type A” (E_1, p-value 0.035); “Vertical cut direction” (G_0, p-value 0.006); “Cut speed²” (C*C, p-value 0.012); and interaction between “Pressure” and “Cut speed” (B*C, p-value 0.049). Regression model R-squared is 0.601 and adjusted R-squared is 0.549.

$$R2 = 11.3 - 0.0626 B + 0.0141 C - 0.927 E_1 - 1.15 G_0 - 0.00062 C * C + 0.0011 B * C$$

4.1.3 Roughness on Straight Line (R3):

The significant factors were “Cut speed” (C, p-value 0.00); “Torch height” (D, p-value 0.00); “Cut speed²” (C*C, p-value 0.026); and interaction between “Cut speed and Torch height” (C*D, p-value 0.032). Regression model R-squared is 0.501 and adjusted R-squared is 0.46.

$$R3 = 3.83 + 0.105 C + 15.5 D - 0.000458 C * C - 0.189 C * D$$

4.2 Flatness (R4):

The significant factor was “Tool type A” (E_1, p-value 0.004). Regression model R-squared is somewhat low since it is 0.149 and the adjusted R-squared is 0.133.

$$R4 = 0.0235 + 0.00897 E_1$$

4.3 Accumulation Responses

4.3.1 Accumulation on Internal Curve (R5):

The significant factors were “Cut speed” (C, p-value 0.00); “Tool type A” (E_1, p-value 0.061); “Tool type B” (E_2, p-value 0.029); and “Cut speed²” (C*C, p-value 0.00). Regression model R-squared is 0.762 and adjusted R-squared is 0.743.

$$R5 = 2.05 + 0.182 C + 0.902 E_1 + 1.09 E_2 - 0.00119 C * C$$

4.3.2 Accumulation on External Curve (R6):

The significant factors were “Pressure” (B, p-value 0.253); “Cut speed” (C, p-value 0.00); “Slower on curves” (F, p-value 0.103); “Tool type B” (E_2, p-value 0.033); “Cut speed²” (C*C, p-value 0.00); and the interaction between “Pressure” and “Slower on curves” (B*F, p-value 0.097). Regression model R-squared is 0.706 and adjusted R-squared is 0.668.

$$R6 = -1.01 + 0.040 B + 0.200 C + 1.69 F + 1.21 E_2 - 0.0013 C * C - 0.023 B * F$$

4.3.3 Accumulation on Straight Line (R7):

The significant factors were “Cut speed” (C, p-value 0.00) and “Cut speed²” (C*C, p-value 0.00). Regression model R-squared is 0.656 and adjusted R-squared is 0.642.

$$R7 = 2.72 + 0.189 C - 0.00129 C * C$$

4.4 Dimensional Responses

4.4.1 Geometry in X-Direction (R8):

The significant factors were “Cut speed” (C, p-value 0.134); “Torch height” (D, p-value 0.0000); “Slower on curves” (F, p-value 0.303); “Tool type A” (E_1, p-value 0.004); “Tool type B” (E_2, p-value 0.121); the interaction between “Cut speed” and “Torch height” (CD, p-value 0.0031); and the interaction between “Cut speed” and “Slower on curves” (CF, p-value 0.108). Regression model R-squared is 0.585 and adjusted R-squared is 0.52.

$$R8 = 4.05 - 0.000533 C - 0.283 D - 0.00280 F - 0.0210 E_1 + 0.0114 E_2 + 0.00305 C * D + 0.000086 C * F$$

4.4.2 Geometry in Y-Direction (R9):

The significant factors were “Current” (A, p-value 0.02); “Current²” (A², p-value 0.017); and “Vertical direction” (G_0, p-value 0.10). Regression model R-squared is somewhat low since it is 0.147 and the adjusted R-squared is 0.094.

$$R9 = 6.57 - 0.0241 A + 0.046 G_0 + 0.000188 A * A$$

4.5 Tool life (R10):

Tool life is considered in the responses to identify its correlation with other responses. As shown in Table 3, most of the correlations are negative (i.e., increasing tool life decreases the

part quality). Since tools tips were replaced before they get worn, the magnitude of the correlation with other responses is low.

Table 3. Correlation between Tool Life (R10) vs. Other Responses.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
R10	0.15	-0.02	0.07	-0.06	-0.18	-0.16	-0.15	-0.1	0.1	1.0

	R11	R12	R13	R14	R15	R16
R10	0.05	-0.06	-0.1	0.03	-0.05	0.02

4.6 Bevel Angle Responses:

4.6.1 Bevel angle on Internal Curve (R11):

The significant factors were “Current” (A, p-value 0.005); “Pressure” (B, p-value 0.125); “Cut speed” (C, p-value 0.105); “Torch height” (D, p-value 0.049); the interaction between “Current” and “Pressure” (AB, p-value 0.013); the interaction between “Current” and “Cut speed” (AC, p-value 0.008); the interaction between “Current” and “Torch height” (AD, p-value 0.056); the interaction between “Current” and “Slower on curves” (AF, p-value 0.066); and the interaction between “Pressure” and “Slower on curves” (BF, p-value 0.025). Other factor included in the equation below is “Slower on curves” (F, p-value 0.332). Regression model R-squared is 0.522 and adjusted R-squared is 0.405.

$$R11 = -80.4 + 1.60 A + 0.667 B - 0.259 C - 4.91 F + 149 D - 0.0165 A * B + 0.00635 A * C - 2.17 A * D - 0.0917 A * F + 0.161 B * F$$

4.6.2 Bevel Angle on External Curve (R12):

The significant factors were “Current” (A, p-value 0.069); “Pressure” (B, p-value 0.041), “Torch height” (D, p-value 0.039); “Slower on curves” (F, p-value 0.085); and interactions between “Current” and “Torch height” (A*D, p-value 0.118); and between “Pressure” and “Slower on curves” (B*F, p-value 0.069). Regression model R-squared is somewhat low since it is 0.252 and the adjusted R-squared is 0.155.

$$R12 = -16.8 + 0.614 A - 0.458 B + 211 D - 11.4 F - 2.35 A * D + 0.164 B * F$$

4.6.3 Bevel Angle on Left Side of Straight Line (R13):

The significant factors were “Torch height” (D, p-value 0.005); “Tool type A” (E_1, p-value 0.070), and “Torch height²”(D*D, p-value 0.007). Regression model R-squared is also somewhat low since it is 0.238 and the adjusted R-squared is 0.186.

$$R13 = -24.4 + 239 D - 3.98 E_1 - 552 D * D$$

4.6.4 Bevel Angle on Right Side of Straight Line (R14):

The significant factors were “Current” (A, p-value 0.259); “Pressure” (B, p-value 0.088); “Cut speed”(C, p-value 0.012); “Tool type A” (E_1, p-value 0.00); and interaction between “Current” and “Pressure” (A*B, p-value 0.062) and between “Current” and “Cut speed” (A*C, p-value 0.002). Regression model R-squared is 0.467 and adjusted R-squared is 0.396.

$$R14 = -28.1 + 0.446 A + 0.638 B - 0.353 C + 11.4 E_1 - 0.010 A * B + 0.006 A * C$$

4.7 Start Point Quality Responses

4.7.1 Start Point Quality for Internal Part (R15):

The significant factors were "Tool type A" (E_1 , p-value 0.072); "Cut speed" (C^2 , p-value 0.0177); the interactions between "Pressure" and "Cut speed" (BC , p-value 0.075); and the interaction between "Pressure" and "Slower on curves" (BF , p-value 0.239). Other factors in the equation below are "Pressure" (B , p-value 0.349); "Cut speed" (C , p-value 0.603); and "Slower on curves" (F , p-value 0.227). Regression model R-squared is somewhat low since it is 0.38 and the adjusted R-squared is 0.283.

$$R15 = 9.85 - 0.0287 B - 0.0197 C + 0.867 F - 0.679 E_1 - 0.000283 C * C + 0.000871 B * C - 0.0114 B * F$$

4.7.2 Start point quality for External Part (R16):

The significant factors were "Torch height" (D , p-value 0.079); "Pressure" (B , p-value 0.003); "Tool type A" (E_1 , p-value 0.056); "Vertical cut direction" (G_0 p-value 0.001); "Cut speed" (C^2 , p-value 0.008); the interactions between "Pressure" and "Cut speed" (BC , p-value 0.021); the interaction between "Pressure" and "Torch height" (BD , p-value 0.039); and the interaction between "Cut speed" and "Slower on curves" (CF , p-value 0.116). Other factors in the equation below are "Slower on curves" (F , p-value 0.303) and "Cut speed" (C , p-value 0.545). Regression model R-squared is 0.616 and adjusted R-squared is 0.524.

$$R16 = 17.5 - 26.9 D - 0.178 F - 0.0244 C - 0.149 B - 0.795 E_1 - 1.39 G_0 - 0.000601 C * C + 0.00123 B * C + 0.433 B * D + 0.00526 C * F$$

4.8 Cut Depth Responses

Among 89 fabricated parts, 36 were not fully cut and therefore, they were not extracted from the sheet metal. While those parts are missing data for other responses, they are usable data for fitting regression models for cut depth responses. Following are the regression models considering all the 89 observations.

4.8.1 Cut Depth Quality for Internal Area (R17):

The significant factors were "Current" (A , p-value 0.000); "Pressure" (B , p-value 0.076); "Cut speed" (C , p-value 0.000), "Torch height" (D , p-value 0.028); "Tool type A" (E_1 , p-value 0.145); "Tool type B" (E_2 , p-value 0.184); and "Slower on curves" (F , p-value 0.042).

Regression model R-squared is 0.453 and adjusted R-squared is 0.405.

$$R17 = 6.73 + 0.060 A - 0.0368 B - 0.036 C + 6.87 D + 0.88 E_1 + 0.814 E_2 + 0.315 F$$

4.8.2 Cut Depth Quality for External Area (R18):

The significant factors were "Current" (A , p-value 0.000); "Pressure" (B , p-value 0.041); "Cut speed" (C , p-value 0.000); and "Torch height" (D , p-value 0.026). Regression model R-squared is 0.525 and adjusted R-squared is 0.502.

$$R18 = 7.63 + 0.0728 A - 0.0421 B - 0.0485 C + 6.93 D$$

5. Desirability Function and Best Setting Found

Tradeoffs between the effects of the factors in the responses can be observed from the analysis of the mathematical models. Choosing a factor and increasing its value has a different impact on one or more responses, but it may not have an impact on other responses. Therefore, in order to balance these trade-offs, a multi-response optimization technique was used. Derringer and Suich (1980) suggested a technique for this kind of situations. This technique is known as Desirability Functions and it is available in Minitab 15. For more details on this technique the reader is referred to Montgomery (2004).

In the Desirability Function, different importance weights were given to the responses. The research group gave an importance of 4 for roughness and accumulation responses, 3 for bevel angle, 2 for start point quality and part geometry, and 1 for flatness. It was also necessary to define goals for each one of the responses. For responses measured under the rating system 0-10 (roughness, accumulation, start point quality, and cut depth quality), the goal was defined as a maximum of 10. For part geometry and bevel angle, the goal was defined as a target value corresponding to the original CAD file dimensions of the part. The chosen goal for flatness was also a target and it was set equal to 0.

After inputting the weights, the factors on each regression model, and the desired goals for all responses, the best values for the responses and the desirability indexes (D) were found. Results are reported on Table 4. The resulting composite desirability is 0.944416. Based on the Desirability Function, overall optimum point was reached in the following setting: Current 80 A, Pressure 90 psi, Cut speed 54.55 ipm, Torch height 0.297 inches, Slower on curves factor 0.3636, Tool type C, and Cut direction Horizontal.

Table 4. Best Values for the Responses from Desirability Function.

	Response	Best Value	D
R1	Roughness on internal curve	9.3898	0.932197
R2	Roughness on external curve	9.7443	0.971590
R3	Roughness on straight line	10.0138	1.00000
R4	Flatness	0.0181	0.892339
R5	Accumulation on internal curve	9.9990	0.999888
R6	Accumulation on external curve	10.6272	1.000000
R7	Accumulation on straight line	10.5197	1.000000
R8	Geometry in X-direction	3.9814	0.854725
R9	Geometry in Y-direction	6.0002	0.994658
R11	Bevel angle on internal curve	4.5917	0.826730
R12	Bevel angle on external curve	1.8111	0.922932
R13	Bevel angle on left side of straight line	-5.3500	0.827420
R14	Bevel angle on right side of straight line	2.5416	0.924133
R15	Start point quality for internal part	<i>10.1841</i>	<i>1.000000</i>
R16	Start point quality for external part	9.8297	0.981073

Responses with incomplete observations were not considered in the desirability function above. Thus, a new desirability function for cut depth responses was obtained. The best response values

and the desirability indexes for these responses were: Cut depth for internal area (R17) 9.72 (D=0.97), Cut depth quality for external area (R18) 9.67 (D=1.00).

6. Validation

Ten extra parts were made in the optimum point setting as well as in other diverse settings. Confidence intervals were computed for the differences between goals and responses at the optimal settings. Non-significant differences were found. Consequently, it was not necessary to follow a sequential procedure for RSM and the study ended with the single step of design of experiments, fit of regression models and optimization with Desirability Functions presented in this paper. Furthermore, for all settings, the responses for fabricated parts were close to the predicted values from mathematical models.

7. Conclusions

Seven affecting factors and eighteen responses make the automated plasma cutting process very complex. After performing Design of Experiments, Regression Analysis was conducted to identify the significant factors affecting each response. Mathematical models explaining each one of the responses were identified. Then, Desirability Function was used to combine the models obtained for each response and balance the trade-offs between the responses. Response Surface technique permitted the identification of the settings for seven relevant input variables that optimize the resulting quality characteristics. After analyzing the regression models, this research concludes that the effect of torch height, tool type, and cut direction plays a critical role in surface quality characteristics. In the future, cost savings may result of using tool type C, horizontal cut, and a torch height near to 0.3 inches. High values for current, pressure and slower on curves (80A, 90 psi, and 0.36) are needed to achieve quality results while an intermediate cut speed of 55 ipm is recommended. The entire study was conducted for stainless steel sheet metal with 0.25 inch thickness. A similar study can be done to investigate other popular sheet metal thickness. Also, it would be interesting to conduct a new similar study incorporating sheet metal thickness as one of the factors.

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