STUDY OF PROCESS PARAMETERS IN PLASMA ARC MACHINING PROCESS

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In

PRODUCTION AND INDUSTRIAL ENGINEERING

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, "**STUDY OF PROCESS PARAMETERS IN PLASMA ARC MACHINING PROCESS**", in partial fulfilment of the requirements for the award of degree of Master of Engineering in Mechanical Engineering with specialization in **PRODUCTION AND INDUSTRIAL** submitted in **Mechanical Engineering Department** of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Dr. V.K.SINGLA** and **Mr.D.K.Maurya** other researcher's works which are duly listed in the reference section. The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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ABSTRACT

Plasma arc cutting (PAC) is a widely used industrial process for the cutting of different types of metals in several operating conditions. PAC is considered a challenging technology compared to its main competitors: oxy-fuel and laser cutting, in particular for cutting of mild steel in the thickness range 8-40 mm. PAC of mild steel thin plates through a Cebora HQC Plasma Prof 164 plasma source, operating in the range 25-120 A, with a Cebora CP250G plasma torch have been studied. PAC of mild steel thin plates (thickness in the range 1-3 mm) are characterized by low current levels (25-45 A) and the use of O_2 both as plasma gas and secondary gas. The aim of the work is the optimization of PAC of mild steel thin plates, both in terms of cut quality and performances of the consumables, to achieve cut quality standards and productivity levels usually obtainable through laser cutting processes. The first part of the work points out the main critical aspects of the considered cutting process, concerning both the obtained qualitative standards and the performances of the consumables, in particular of the nozzle, in terms of its service life. In the second part of the work, the optimization the process has been carried out through the simultaneous planning and analysis of experimental tests and numerical simulations. Experimental tests have allowed a better design of consumables, in particular nozzle, electrode and diffusers, and to optimize current profiles, in particular pilot arc current levels; while modeling and numerical simulation have allowed a better understanding of the physical phenomena concerning the critical aspects initially pointed out and to detect successful design solutions. The integration of the results of these two activities has allowed overcoming the critical aspects initially pointed out, improving plasma jet constriction and reducing plasma jet instabilities, leading to a better cut quality and performances of the consumables.

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CHAPTER 1

INTRODUCTION

Because of the growing need for manufacturing functional metallic parts, rapid Manufacturing processes have become the focus of increasing research and development. Manufacturing processes based on material removal (i.e., drilling, milling, turning, and Cutting) have been used for many years. According to Xiong (2008), the surface quality And accuracy of the parts are lower in direct metal prototyping when compared to. Machining. The recent advancements in manufacturing technology have enabled Manufacturers to make parts and products faster, with better quality, and more Complexity. Laser, water jet, and plasma techniques represent some of these newly Established technologies in part manufacturing. The process of plasma cutting was introduced in 1950. Since then, the Manufacturing industries are using this process extensively because of its wide Applications. In spite of its development, the field was given little attention by the Researchers. The different processes included in the plasma cutting process are plasma material Interaction, process control, thermal plasma generation, liquid metal removal, Etc. In the process of plasma cutting, a transferred electric arc is established between the Negative electrode and the work piece within the cutting torch. The arc that is generated has to be narrow so that the power density is enough and the heat diffusion takes place Very rapidly across the metal plate thickness. For cutting with plasma an adequate amount of power and force should be transferred to the work piece. Then, the work piece melts and the metal that is melted is removed from the cut. By definition, plasma means a low-ionized gas, in which the individual atoms get ionized. In other words, plasma is a gas that is heated to a higher temperature and is ionized so as to become electrically conductive (Farnum, 2006).. Another process of plasma is plasma gouging. This process removes metal to a controlled depth and width. Among several plasma applications, the cutting Application is superior. The major difference between PAC and plasma arc welding (PAW) is the Velocity of the orifice gas. (In some cases, a shielding gas as well as a cutting Or orifice gas may be used. The shielding gas prevents oxidation of the cut surface.), the higher velocity gas used I PAC removes or blows away the molten material. The PAC process can be used to cut any electrically conductive metal if its Thickness and shape permit full penetration by the plasma

1. VARIOUS TYPE OF PLASMA ARC CUTTING

1.1 Conventional PAC

In conventional PAC, the arc is constricted by a nozzle only; no shielding gas is added. Generally, the cutting gas is tangentially injected around the electrode The swirling action of the gas causes the cooler (heavier) portions of the gas to move radially outward, forming a protective boundary layer on the inside of the nozzle bore. This helps prevent damage to the nozzle and extends its life. Electrode life is also improved. Since the arc attachment point (cathode spot is forced to move about and distribute its heat load more uniformly.

1.2 Air PAC

Air PAC was introduced in the early1960s for cutting mild steel. Oxygen in the air provides additional energy from the exothermic reaction with molten steel, boosting cutting speeds about 25percent. Although this process can also be used to cut stainless steel and aluminum, the cut surface will be heavily oxidized and thus can be unacceptable for some applications.

1.3 Dual-flow PAC

Dual-flow PAC is a slight modification of conventional PAC It incorporates most of the features of conventional PAC but adds a secondary shielding gas around the nozzle. The cutting gas is usually nitrogen; the shielding gas is selected according to the metal to be cut. Cutting speeds are

Slightly better than those of conventional PAC on mild steel, but the cut quality is not acceptable for some applications. Cutting speed and quality on stainless steel and aluminum are essentially the same as with conventional PAC.

1.4. Water Injection PAC

In the water injection PAC method, water is introduced inside the nozzle to provide additional arc constriction two modes of water injection have been developed:

1. Radial injection - the water impinges the arc with no swirl component

2. Swirl injection - the water is introduced as a vortex swirling in the same direction as the cutting gas.

The increased arc constriction provided by the water improves cut square-ness and increases cutting speed. The water also protects the nozzle, since it provides cooling at the point of arc constriction.

The water protects the bottom half of the nozzle from the intense radiation, allowing complete insulation of the nozzle, so damage resistance is improved. This approach allows enough freedom in torch design to ensure component durability, cut quality, and high cutting speed.

1.5. Underwater PAC

Underwater PAC is suited to numerically controlled (NC) shape cutting and produces a noise level of 85 dBA or less under normal operating conditions. In comparison, conventional PAC typically produces noise levels in the range of 105 to 115 dBA. Underwater cutting also nearly eliminates ultraviolet radiation and fumes. Steel plate being cut is supported on a cutting table with the top surface of the plate 2 to 3 inches under water. Advice that locates the submerged top surface of the metal is vital to the fully automated underwater PAC process. Height control is maintained by a sensor that monitors arc voltage. Cutting speed and quality are comparable to those attained with water injection PAC. Note that it is hazardous to cut aluminum under water. Hydrogen generated by the process can be trapped under the plate, creating the potential for explosion.

1.6 PLASMA SET UP

Fig.1 Plasma arc cutting table with moving torch.

Fig.2 Plasma arc cutting set up.

Courtesy by: ENEXCO TEKNOLOGIES INDIA LTD. GURGAON

1.7 APPLICATIONS

The machining technologies based on the thermal effect of plasma have an important place in the field of unconventional technologies.at present the plasma arc machining represent one of the most modern machining technologies used in the industry domains such as :machines manufacturing,electronics,aeronautics, etc. due to its advantages ,to the fact that it allows maching of the high alloy refractory and stainless steel with maximum productivity, to the automation capacity ,to the low expenses towards traditional techniques, and also due to the quality obtained of the surface material.

Plasma cutting is used to cut particularly those nonferrous and stainless metals that cannot be cut by the usual rapid oxidation induced by ordinary flame torches. Plasma cutting can be used for stack cutting, plate beveling, and shape cutting and piercing. With some modifications, plasma arc cutting can be used under water.) Plasma arc cutting finds applications in many industries such as shipyard, chemical, nuclear and pressure vessel. It is used for removing gates and risers in foundry. It cuts hot extrusions to desired length. It is used to cut any desired pipe contour. It is also employed for gouging applications. It finds use in the manufacture of automotive and railroad components.

It cuts carbon steel up to 10 times faster than oxy-fuel cutting, with equal quality more economically It leaves a narrower kerf Plasma cutting being primarily a melting process can cut any metal. Arc plasma torches give the highest temperature available from many practicable sources. The energy seems to be unlimited in this method.

CHAPTER 2

PROCESS VARIABLES

2.1 Gases

At least two separate (and possibly three) flows of gas are used in PAC

- Plasma gas – flows through the orifice and becomes ionized
- Shielding gas – flows through the outer nozzle and shields the molten weld from the atmosphere
- Back-purge and trailing gas – required for certain materials and applications.

These gases can all be same, or of differing composition.

2.2 Key process variables

- Current: 40 to 80A.
- Cutting speed: 200-3000mm/min.
- Gas flow rate (This critical variable must be carefully controlled based upon the current, orifice diameter and shape, gas mixture, and the base material and thickness.)
- Torch height: 2.54-7.72mm
- Cutting oxygen pressure: 1.2Mpa
- Preheat oxygen pressure: 1.0Mpa.

2.3 Other plasma arc processes

Depending upon the design of the torch (e.g., orifice diameter), electrode design, gas type and velocities, and the current levels, several variations of the plasma process are achievable, including:

- Plasma arc cutting
- Plasma arc gouging
- Plasma arc surfacing

CHAPTER 3

LITERATURE VIEW

Joseph C. Chen & Ye Li & Ronald A. Cox in (2009)

Studied the use of Taguchi parameter design to optimize the roundness of holes made by an aging plasma-cutting machine. An L9 array is used in a Taguchi experiment design consisting of four controllable factors, each with three levels. With two non-controllable factors included in the setting, we conduct 36 experiments, compared to the 81 parameter combinations (four factors, three levels or 34) required in a traditional DOE setting. Therefore, using the Taguchi method significantly reduces the time and costs of a quality improvement process. Conducted for two response variables—bevel magnitude and the smallest diameter deviation of the hole—the Taguchi experiments gave the optimal combination A1B2C1D3 (small for tip size, 93 in/min for feed rate, 100 V for voltage, and 63A for amperage.

Y. F. Hsiao, Y. S. Tarng, and W. J. Huang (2008)

Optimized the parameters of plasma arc welding (PAW) by the Taguchi method with Grey relational analysis is studied. The Grey relational grade is used to find optimal PAW parameters with multiple response performance characteristics. The welding parameters (welding current, Welding speed, plasma gas flow rate, and torch stand-off) are optimized with consideration of the multiple response performance characteristics (the penetration of root, the weld groove width, and the weld pool undercut). As a result, the improvement percentage of the Grey relational grade with the multiple performance characteristics is 31.8%. It is shown that the multiple response performance characteristics are greatly improved through this study.

S. S. Mahapatra & Amar Patnaik Int J Adv Manuf Technol (2007)

Studied Wire electrical discharge machining (WEDM) is extensively used in machining of conductive materials when precision is of prime importance. Rough cutting operation in WEDM is treated as a challenging one because improvement of more than one machining performance measures viz. metal removal rate (MRR), surface finish (SF) and cutting width (kerf) are sought to obtain a precision work. Using Taguchi's parameter design, significant machining parameters affecting the performance measures are identified as discharge current, pulse duration, pulse frequency, wire speed, wire tension, and dielectric flow. It has been observed that a combination of factors for optimization of each performance measure is different.

John Kechagias , Michael Billis , Stergios Maropoulos (2010)

An optimization of the cutting parameters during CNC plasma-arc cutting of St37 mild steel plates is attempted using robust design. The process parameters tested were plate thickness, cutting speed, arc ampere, arc voltage, air pressure, pierce height, and torch standoff distance. An orthogonal matrix experiment [L18 (21 × 37)] was conducted and the right bevel angle was measured and optimized according to the process parameters using an analysis of means and an analysis of variances.

FUJIMOTO Ryoichi: Manager, Quality Assurance Department, Aero-Engine & sales operation (2003).

There is available a design method for a product which is robust and can fulfill its function without failure under any service conditions and environmental conditions. This method is called a robust method or Taguchi's Methods in the U.S.A. and is called quality engineering in Japan. Taguchi's Methods have received much attention in the U.S.A. since the 1980s as an engineering development method developed in Japan, and were imported back into Japan in the 1990s. Many

successful results obtained by the application of the Methods such as q elimination of various quality nonconformities, w reduction in failure and cost by half, e dramatic improvement in machining accuracy and production efficiency, and r reduction in development lead time by half have been reported successively. Nowadays, therefore, many Japanese companies use the Me

Fang Yi-Chin1, Tzeng Yih-Fong and Li Si-Xiang JOURNAL OF PHYSICS D: APPLIED PHYSICS (2008)

The paper proposes a hybrid approach, integrating a combination of Taguchi methods, principal component analysis (PCA) and fuzzy theory for the extended optimization of multiple quality characteristics in optimization experiments of non-image optics; a miniature light emitting diode pocket-sized projection display system is demonstrated in this research as an optimization sample. Traditionally, the performance of projector optics can be evaluated by modulation transfer function and its optimization method is DLS (damped least square). Comparatively, light efficiency and uniformity play a part in non-image optics where the optimized method is based on the concept of non-sequential rays; for example, in the optical engine of a projector, which demands better light efficiency and uniformity. The DLS method is occasionally employed in the optimization of non-image optics such as optical engines, but it is sometimes sensitive to the number of rays employed and some over-optimization problems. In this research we propose as an alternative method to optimize in an extended way the optical engine of a miniature projector. Control factors were checked and then repeatedly examined before the experiments started. In the experiment, optimization works through an L18 orthogonal array. Finally, this proposed optimization work shows good success for the optimization of non-image optical engines because this method is less sensitive to the number of non-sequential rays. Compared with the initial design, the optimized parameter design is able to improve the luminous flux by 11.46 dB, the illumination uniformity by 3.14 and the packing size by 1.125 dB.

G. Hong, A.S. Holmes, M.E. Heaton (2004)

The thick photo resist SU8, by virtue of its good mechanical durability, water impermeability and dielectric properties on polymerization, is widely used as a resin for making high aspect ratio, functional MEMS device structures and packaging parts. However, the difficulty associated with removal, stripping or re-patterning of the polymerized SU8 remains a serious issue. This paper presents a novel process, based on O2/SF6 plasma etching, for patterning or removal of fully cross-linked SU8. The Taguchi methodology is used to optimize the O2/SF6 mix for a high etch rate and low under cut.

S Ramakrishnan, V Shrinet, F B Polivka, T N Kearney and P Koltun J. Phys. D: Appl. Phys. 33 (2000)

Reported the results of a study on the influence of oxygen in the plasma gas used in the plasma arc cutting process on cuts obtained in mild steel plates. Experimental results of shapes of kerfs and the leading edges of the cut front formed while cutting a 6 mm mild steel plate at 100 A with nitrogen, air and oxygen as plasma gases are presented. These results are discussed in the light of the overall energy balance of the process. It is found that the exothermic reaction of oxygen in the plasma gas with the iron in mild steel enables the cutting of mild steel at higher speeds with both air and oxygen than the maximum cutting speed attainable with nitrogen. A comparison of the melting rates for oxygen with those of air reveals that although oxygen can produce more exothermal energy by oxidation, oxygen is not superior to air in melting metal near the bottom of the kerf formed at high cutting speeds.

Abdulkadir Gullu and Umut Atici (2005)

In this study, AISI 304 stainless steel and St 52 carbon steel have been cut by plasma arc and the variations of structural specifications occurred after cutting has been investigated. According to the experimental results, it has been seen that burning of particulars and distribution amount were increased when the cutting was performed using the speeds which are upper or lower limits of the ideal cutting speeds proposed by the manufacturer of the machine tool. Moreover, it was determined that the hardness from the outer surface to the core decreased, while the hardness near to the outer surface which affected by the high temperature occurred during cutting increased.

W. J. Xu, J. C. Fang, Y. S. Lu October (2002)

To reduce the kerf width and to improve the kerf quality, the hydro-magnetically confined plasma arc was used to cut engineering ceramic plates. By experiments and analyses, the characteristics of the hydro-magnetic confined plasma arc were explored and the effects of secondary confinement on cutting quality, arc properties, and optimal process parameters were determined. By using this new method, the authors achieved better cutting quality and higher cutting speeds. Also, the possibility to reduce the heat load of the nozzle and thus enhance its service life and process stability was studied. When the nozzle diameter is 3 mm, the kerf width of the Al_2O_3 ceramic plate of 6 mm thickness is less than 4.6 mm, while the cutting speed reaches to 0.9–1.2 m/min

L. J. Yang (2001)

Measured Surface hardening of steel components is traditionally done either by oxy-fuel, induction or laser hardening. Plasma arc is a new hardening technique which makes use of a small controlled stream of ionized gas to heat the material to its austenitising temperature. The heat is conducted rapidly into the bulk of the specimen causing self-quenching to occur and the formation of martens tic structures. This paper describes the optimization of the processing parameters for maximum hardened depth of ASSAB 760 (equivalent to AISI 1045) steel specimens of 6 mm thickness by using a Microplasma-50 plasma arc machine with the Taguchi method. A 4-factor 3-level (L9) orthogonal array (OA) was used in the experiment.

Wei-long Liu, Shu-huei Hsieh, Wen-jauh Chen, Pei-i Wei, Jiing-herng Lee (2009)

Used Taguchi method to obtain the optimum electro deposition parameters for the synthesis of the $CuInSe_2$ thin film for solar cells. The parameters consist of annealing temperature, current density, $CuCl_2$ concentration, $FeCl_3$ concentration, H_2SeO_3 concentration, TEA amount, pH value, and deposition time. The experiments were carried out according to an $L_{18}(2^1 3^7)$ table. An X-ray diffract meter (XRD) and a scanning electron microscope (SEM) were respectively used to analyze the phases and observe the microstructure and the grain size of the $CuInSe_2$ film before and after annealing treatment. The results showed that the $CuInSe_2$ phase was deposited with a preferred plane (112) parallel to the substrate surface. The optimum parameters are as follows: current density, 7 mA/cm^2; $CuCl_2$ concentration, 10 mM; $FeCl_3$ concentration, 50 mM; H_2SeO_3 concentration, 15 mM; TEA amount, 0 mL; pH value, 1.65; deposition time, 10 min; and annealing temperature, 500°C

P. Saravanan, V. Selvarajan, D. S. Rao, S. V. Joshi, G. Sundararajan (2000)

Detonation gun (D-gun) spraying is one of the most promising thermal spray variants for depositing high quality wear resistant coatings. Of all the ceramic materials that can be D-gun sprayed, alumina (Al_2O_3) is the most widely established and these coatings have already gained industrial acceptance for diverse applications. The present study deals with a statistical design of experimental study of the D-gun spraying of Al_2O_3 powder. Coating experiments were conducted, using a Taguchi-full factorial (L_{16}) design parametric study, to optimize the D-gun spray process parameters. Four selected important spraying parameters were considered in their upper and lower levels of the predefined range according to the test matrix, in order to display the range of processing conditions and their effect on the coating quality.

Angus Jeang, Chien-Ping Chung, Chung-Wei Chen, Huan-Chung Lialculated. (2009)

As quality values failed to meet customers' requirements when the hot-bar soldering process (HBSP) was first introduced in the electronic manufacturing service (EMS) company, it is the intention of this study to combine quality function deployment (QFD) and the Taguchi method to analyze the produced quality characteristics and to optimize the process parameters. The product from HBSP is a gate board that transmits vertical signals in thin film transistor liquid crystal display (TFT-LCD) modules. To produce a gate board through HBSP, a film of flexible printed circuit (FPC) is soldered onto the pad of a printed circuit board (PCB) with the hot-bar (HB) which is heated by a pulse heater.

Tawfik T. Ajaal, Reginald W. Smith (2009)

The Taguchi method of experimental design is very well suited to improving the production process of synthetic bone grafts for several reasons. Firstly, the effect of many different process variables can be examined simultaneously, which ensures that beneficial factor combinations are not overlooked. Secondly, it is very efficient and easy to apply, so that it does not require large amounts of time or resources to conduct a given set of experiments. This makes it possible to conduct a series of experiments that result in continuous process improvement. Finally, using a Taguchi signal-to-noise ratio permits the concurrent optimization of the process and the reduction of process variability.

Yih-fong Tzeng, Fu-chen Chen (2007)

Described the application of the fuzzy logic analysis coupled with Taguchi methods to optimize the precision and accuracy of the high-speed electrical discharge machining (EDM) process. A fuzzy logic system is used to investigate relationships between the machining precision and accuracy for determining the efficiency of each parameter design of the Taguchi dynamic experiments. From the fuzzy inference process, the optimal process conditions for the high-speed EDM process can be easily determined as $A_1B_1C_3D_1E_3F_3G_1H_3$. In addition, the analysis of variance (ANOVA) is also employed to identify factor B (pulse time), C (duty cycle), and D (peak value of discharge current) as the most important parameters, which account for about 81.5% of the variance.

J. L. Lin, K. S. Wang, B. H. Yan, Y. S. Tarng (2000)

Used Taguchi method with fuzzy logic for optimizing the electrical discharge machining process with multiple performance characteristics has been reported. A multi-response performance index is used to solve the electrical discharge machining process with multiple performance characteristics. The machining parameters (the work piece polarity, pulse-on time, duty factor, open discharge voltage, discharge current and dielectric fluid) are optimized with considerations of the

Nihat Tosun, Can Cogun, Gul Tosun (2004)

Presented an investigation on the effect and optimization of machining parameters on the kerf (cutting width) and material removal rate (MRR) in wire electrical discharge machining (WEDM) operations. The experimental studies were conducted under varying pulse duration, open circuit voltage, wire speed and dielectric flushing pressure. The settings of machining parameters were determined by using Taguchi experimental design method. The level of importance of the machining parameters on the cutting kerf and MRR is determined by using analysis of variance (ANOVA). The optimum machining parameter combination was obtained by using the analysis of signal-to-noise (*S*/*N*) ratio.

CHAPTER 4

PROBLEM FORMULATION

STUDY OF PROCESS PARAMETERS IN PLASMA ARC MACHINING PROCESS

Input Parameters

1. Current: 40 to 80A

2. Cutting speed: 200-3000mm/min

3. Torch height: 2.54-7.72mm

4. Cutting oxygen pressure: 1.2MPa

5. Cutting oxygen pressure :< =1.0MPa

6. Cutting pressure 0.4 to0.5Mpa

7. Work temperature :< =50 C

Output parameters

1. Material removal rate

2. Surface roughness

3. Microstructure

CHAPTER 5

TAGUCHI DESIGN

5.1. Taguchi design overview

Dr. Genichi Taguchi is regarded as the foremost proponent of robust parameter design, which is an engineering method for product design that focuses on minimizing variation and or sensitivity to noise. When used properly, Taguchi design provides a powerful and efficient method for designing products that operate consistently and optimally over a variety of conditions. In robust parameter design the primary goal is to find factor settings that minimize response variation, while adjusting (or keeping) the process on target. After you determine which factors affect variation, you can try to fine settings for controllable factors that will either reduce the variation, make the product insensitive to changes in uncontrollable (noise) factors, or both, a process designed with this goal will produce more consistent output. a product designed with this goal will deliver more consistent performance regardless of the environment in which it is used. Engineering knowledge should guide the selection of factors and responses [3]. Robust parameter design is particularly suited for energy transfer processes; for example, a car's steering wheel is designed to transfer energy from the steering wheel to the wheels of the car. You should also scale control factors ad responses so that interactions are unlikely. When interactions among control factors are likely or not well understood, you should choose a design that is capable of estimating those interactions. Minitab can help you select a Taguchi design that does not confound interactions of interest with each other or may require preliminary experimentation. The noise levels selected should reflect the parameter design uses Taguchi designs (orthogonal arrays), which allow you to analyze many factors with few runs. Taguchi designs are balanced, that is no factor is weighted more or less in an experiment, thus allowing factors to be analyzed independently of each other. Minitab provides both static and dynamic response experiments.

- In a static response experiment, the quality characteristic of interest has a fixed level.
- In a dynamic response experiment, the quality characteristic operates over a range of values and the goal is to improve the relationship between an input signal and an output response.

- An example of a dynamic response experiment is an automotive acceleration experiment where the input signal is the amount of pressure on the gas pedal and the output response is vehicle speed. You can create a dynamic response experiment where the input signal is the amount of pressure on the gas pedal and the output response is vehicle speed. You can create a dynamic response experiment by adding a signal factor to a design- see creating a dynamic response experiment by of robust experimentation is to find an optimal combination of control factor settings that achieve robustness. Against (insensitivity to) noise factors, Minitab calculates response tables, linear model results, and generates main effects and interaction plots for:
- Signal-to-noise radios (S/N rations, which provide a measure of robustness) vs. the Control factors.
- Means (static design) or slopes (dynamic design vs. the control factors
- Standard deviations vs. the control factors.
- Natural log of the standard deviations vs. the control factors.

Use the results and plots to determine what factors and interactions are important and evaluate how they affect responses. To get a complete understanding of factor effects it is advisable to evaluate S/N ratios, means (static design), slopes (dynamic design), and standard deviations, Make sure that you choose an S/N ratio that is appropriate for the type of data you have and your goal for optimizing the response.

5.2. What is a Taguchi Design?

A Taguchi design, or an orthogonal array, is a method of designing experiments that usually requires only a fraction of the full factorial combinations. An orthogonal array means the design is balanced so that factor levels are weighted equally. Because of this, each factor can be evaluated independently of all the other factors, so the effect of one factor does not influence the estimation of another factor, in robust parameter design, you first choose control factors and their levels and choose an orthogonal array appropriate for these control factors. The control factors comprise the inner array. At the same time, you determine a set of noise factors, along with an experimental design for this set of factors. The noise factors comprise the outer array. The experiment is carried out by running the complete set of noise factor settings at each combination of control factor settings (at each run).

The response data from each run of the noise factors in the outer array are usually aligned in a row, next to the factors settings for that run of the control factors in the inner array. For an example, see Data for Analyze Taguchi Design. Each column in the orthogonal array represents a specific factor with two or more levels. Each row represents a run; the cell values indicate the factor settings for the run. By default, Minitab's orthogonal array designs use the integers 1, 2, 3....to represent factors levels. If you enter factor levels, the integers 1, 2, 3...will be the coded levels for the design. The following table displays the L8 (2**7) Taguchi design (orthogonal array_. L8 means 8 runs. 2**7 means 7 factors with 2 levels each. If the full factorial design were used, it would have 2**7= 128 runs. The L8 (2**7_ array requires only 8 runs-a fraction of the full factorial design. This table array is orthogonal; factor levels are weighted equally across the entire design. The table column represent the control factors, the table rows represent the runs. (Combination of factor levels), and each table cell represents the factor level for that run.

L8 (27) Taguchi Design**

Table No.5.1

	A	B	C	D	E	F	G
1	1	1	1	1	1	1	1
2	1	1	2	2	2	1	1
3	2	2	1	1	2	2	1
4	2	2	2	2	1	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

In the above example, levels 1 and 2 occur 4 times in each factor in the array. If you compare the levels in factors A with the levels in factor B, you will see that B1 and B2 each occur 2 times in conjunction with A1 and 2 times in conjunction with A2. Each pair of factors is balanced in this manner, allowing factors to be evaluated independently. Orthogonal array designs focus primarily on main effects. Some of the arrays offered in Minitab's catalogue permit a few selected interactions to be studied. See Estimating selected interactions. You can also add a signal factor to the Taguchi design in order to create a dynamic response experiment. A dynamic response experiment is used to improve the functional relationship between an input signal and an output response. See creating a dynamic response experiment.

5.3 RESERCH METHODOLOGY

Since the introduction of the plasma arc cutting process in the 1950s, there has been a steady growth in its use in the metal fabrication industries for profile cutting of metallic sheets and plates. Despite superior industrial developments that have taken place, the process has received very little attention from the scientific community on any of the scientific aspects of the process, including thermal plasma generation, plasma- material interaction, liquid metal removal, and process control. The different activities that are employed in this research are categorized into two groups: analytical research and experimental research. These activities are dependent on one another. The theoretical study and experimental research are done simultaneously as shown in Fig 3.

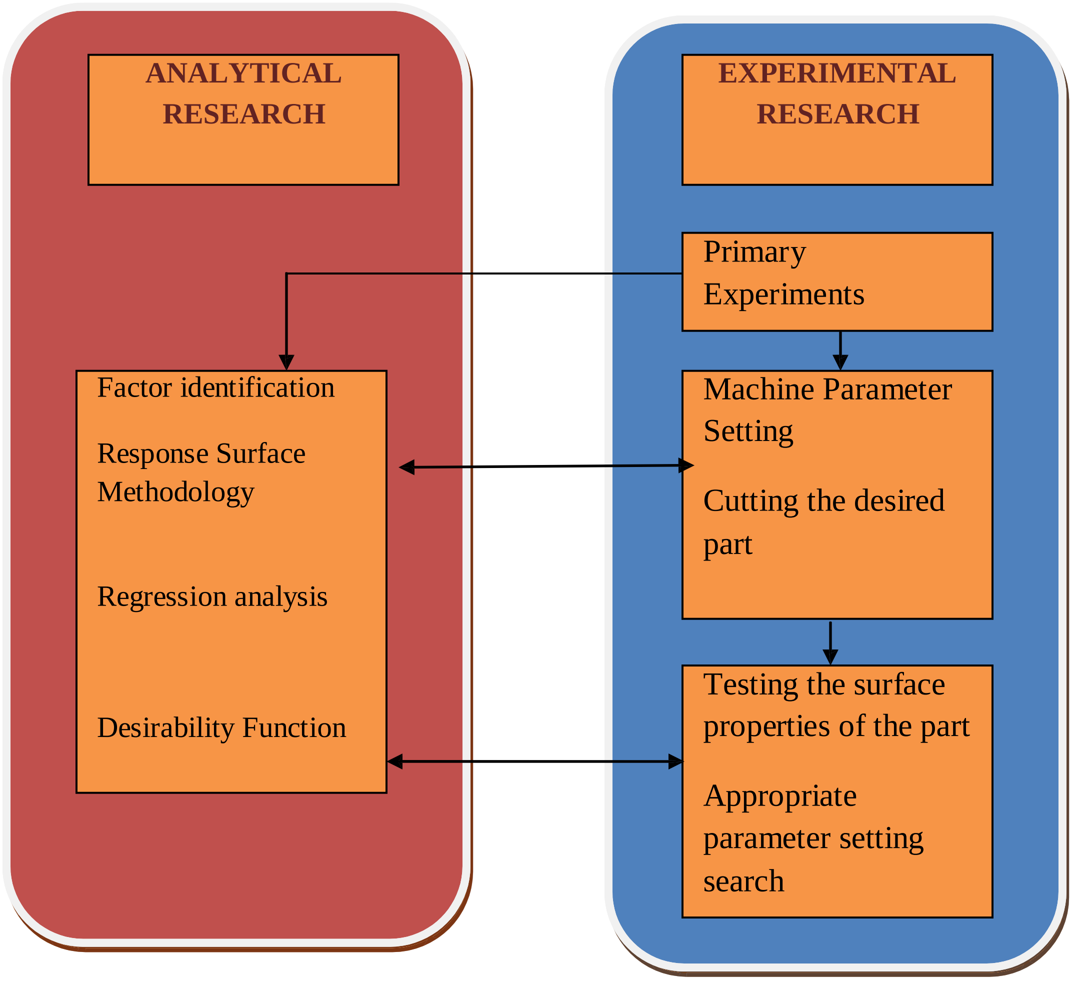

Fig 3. Research Methodology

5.4 Experimental Research

In the experimental research, many parts were fabricated. In addition, as part of the research, numerous experiments were conducted to find better surface quality of the cut. These include experiments with machine parameter variation (e.g., cutting pressure, voltage, cut height etc). The primary reason for experimental research was to discover or identify the factors that most affected the part quality. Primary settings for factors in

Conducted experiments in this stage were assigned through the one-factor-at-a-time method.

5.5 Analytical Research

The analytical research was designed by applying a goal hierarchy plot (Barton R.R., 1999). Goal hierarchy plot contains several goals. The general goals occur at higher levels of the plot. Fig 7 shows the hierarchy plot for the Plasma CAM operation. In this research, the top-level goal (finding the appropriate set of parameters for a better cut quality) was satisfied by accomplishing a 2nd level sub-goal by identifying the responses (i.e., cut quality, accumulation underneath the work piece, flatness and dimensions of the part). To achieve the 2nd level sub-goal, identification and control of effective factors on any item of desirable specification were necessary. Factor identification and control are shown in the 3th level sub-goal. The lowest-level sub-goal (level 4), Design of Experiments, theoretical studies, and response surface methodology, helps to achieve the 3rd level sub-goal. In practice, first by studying the related literature and theories and by designing and conducting experiments, the factors related to the 3rd level sub-goal are identified. The results were obtained using Response Surface Methodology. So, they occupied the 4th level in our hierarchy plot.

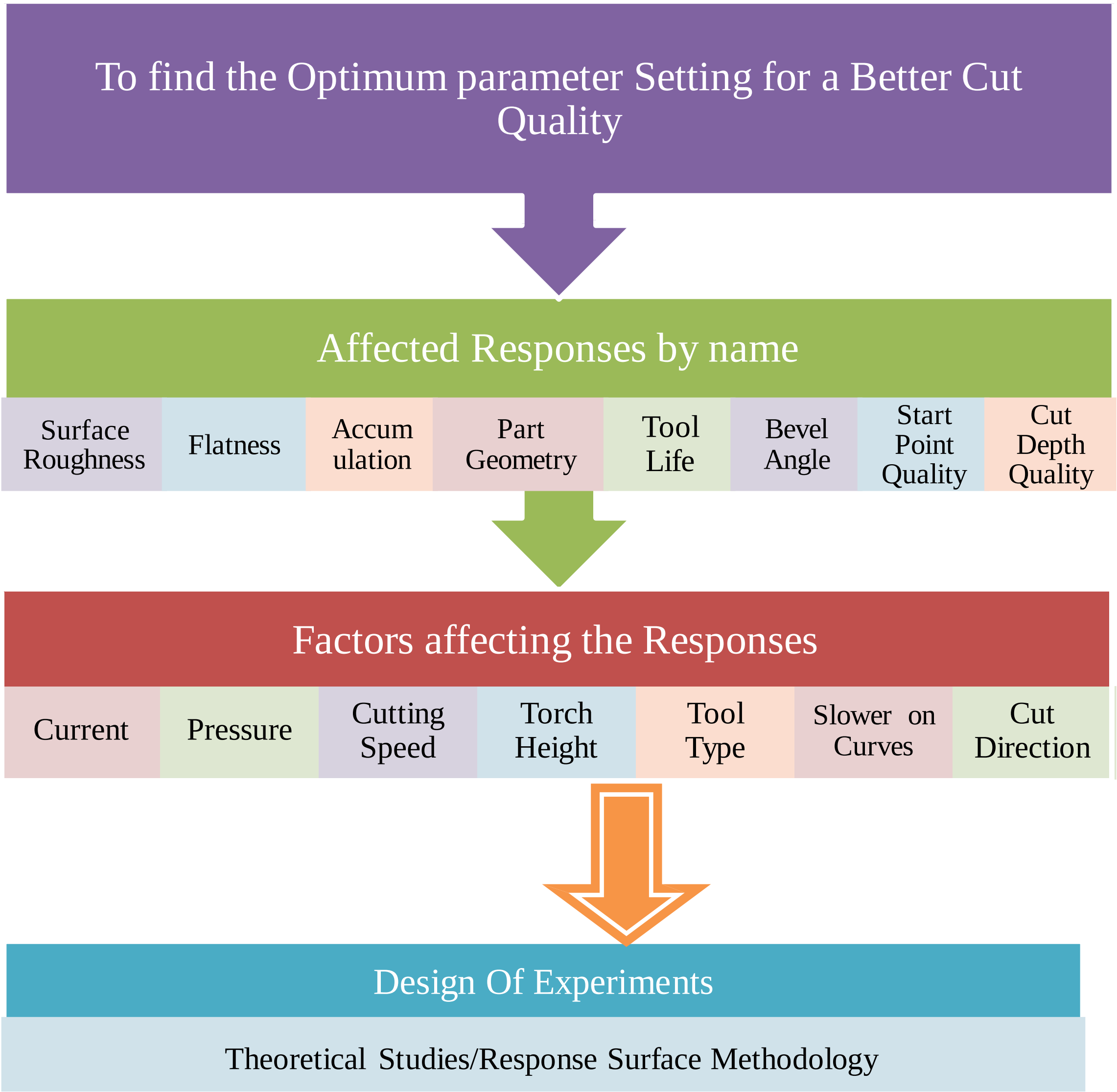

Fig 4. Goal Hierarchy Plot

CHAPTER 6

INDEPENDENT AND DEPENDANT VARIABLES

6.1 Factor Identification and Classification

Previous research and preliminary experiments helped to identify the factors for the experiments and also to find the appropriate parameters for a better cut quality. For this purpose seven factors are selected for our new experiment. Based on the preliminary experiments and the Plasma CAM machine manuals, the following variables seem to be the most influential factors on the part quality: current, pressure, torch height, slower on curves, tool type, and cut direction.

A: Current

This factor was among the suggested variables by the Plasma developers (Thermal Dynamics 1Torch™ Instruction Manual, 2007). Cutting power is dependent only on the type and thickness of the material being cut. The amount of variation allowed by the Cut Master™ 101 was 20A to 80A. The 20A to 40A range was used for drag tip cutting where the torch tip touches the work piece on thin plates of quarter inch Thick mild steel.

The 40A to 80A range was employed for standoff cutting, where the torch tips do not touch the work piece. The discrete range used for investigation was 40A, 60A, and 80A. Typical results from insufficient cutting power proved to be cuts that did not penetrate all the way through the thickness of the work piece. Whereas, typical results from too much cutting power were kerf width too great, excessive dross build up due to extreme heat, and poor cut surface quality (Thermal Dynamics 1Torch™ Instruction Manual, 2007).

B: Pressure

Pressurized air serves two purposes in plasma cutting. The primary purpose is to supply gas to fuel the plasma reaction, and the secondary purpose is to blow melted material away while cooling the tip. Pressure was determined as a variable affecting quality by the Plasma CAM machine Manual. According to Wichern et al. (2005), the pressure during testing affects the roughness. Operating pressure range as given by the user manual was listed as 60 psi to 75 psi; less than 60 psi triggered a safety in the Cut Master™ 101 and prevented operation. A maximum pressure input of 125 psi was also listed. Operating pressure was found to be 70 psi for all cutting power levels (Thermal Dynamics 1Torch™ Instruction Manual, 2007). A combination of operating range and experimentation determined that the discrete range used for investigation was 60 psi, 75 psi, and 90 psi. Insufficient pressure results in the Cut Master™ 101 operation prevention for safety purposes. Typical results from excess pressure were poor cut surface quality, excessive top spatter, and poor bevel angle (Thermal Dynamics 1Torch™ Instruction Manual, 2007).

C: Cut Speed

The cut speed is the speed at which the torch moves in the X-Y plane while the torch is cutting. Cut speed varies depending on material type, material thickness, and input power. Material thickness and type were constant and then cut speed was dependent only on input power. Both the cut speed and input power are input variables for the Plasma CAM system. The Plasma CAM user manual states that the cut speed may vary by as much as 50% of the given value, i.e., 110 (Thermal Dynamics 1Torch Instruction Manual, 2007). Therefore, the feasible range of speeds was found to be in between 10 ipm and 100 ipm (inches per minute). Typical results from high cut speed were high speed dross, poor bevel angle, and cuts that did not go completely through the thickness. Typical results from low cut speed were slow speed dross, unstable arc, and loss of arc (Thermal Dynamics 1Torch™ Instruction Manual, 2007).

D: Torch Height

Torch Height is the distance between the tip of the torch and the work piece. Standoff distances of 1/8 inch to 3/8 inch were proposed in the 1Torch™ instruction manual. The feasible range of torch height was found to be in between 0.1 inch and 0.3 inch. A typical result from cutting too close was that the tip would touch the work piece thus triggering a safety built into the Cut Master™ 101, which would drop the current to 40A.Typical results from cutting too far away were excessive top spatter, poor bevel angle, and cuts that did not go completely through the thickness.

E: Tool Type

Tool type referred to the type of tip used for cutting. The 1Torch™ came with several tip options which differ based on cutting power. The cutting power range used was 40A to 80A and tips were obtained for that entire range. The available tools for this research were 40A tip, 60A tip, and 80A tip.

F: Slower on Curves

The machine has the ability to slow down when going around corners, for a better cut. If slower on curves is greater than 0, then the machine reduces its speed when cutting curves and circles. This means that straight cuts use different speeds than circular, semi- circular or curved cuts. The larger the number, the more it slows. The range for this factor was identified by experimentation. The range that is observed for this variable is 0 to 4 (Plasma CAM manual, 2001).

G: Cut Direction

Cut direction is simply the direction in which the cut is made. Two types of cuts were considered for comparison. These were Vertical-direction cuts and Horizontal direction cuts. In other words, we cut a part first in one direction and then we rotate the part 90 degrees around the point and made the other cut.

6.2 Noise factors

According to Arvidsson and Gremyr (2008) noise factors are those forces that cause deviation from target and are out of the control of the experimenter. These factors are simply sources of variation and have an effect on the response but their affect was uncontrollable. The noise factors in this experiment were temperature and humidity of the air. This was because the sheet metal gets heated up to different temperatures since the runs were done continuously. This was uncontrollable. So, we considered it as a noise factor. According to Suwanprateeb. J (2007), direct contact of the metal with the water or exposure to humidity degrades the material’s mechanical and physical properties. The humidity in the air also affects the sheet metal and it is uncontrollable.

Selection of Experimental Region

The optimization started by conducting an investigation on the conditions that are essential for a better cut quality. For this purpose many experiments were conducted. The seven variables or factors and the levels that are potentially affecting the parts quality are shown in the following Table 1. Design Expert Software was used in this research for planning the experimental design

Table 6.1. Summary of the variables and their levels.

A.Current	**Amps**
Level 1:	40
Level 2:	60
Level 3:	80
B. Pressure	**MPa**
Level 1:	0.41
Level 2:	0.51
Level 3:	0.62
C. Cut speed	**mm/min**
Level 1:	254
Level 2:	1270
Level 3:	2540
D. Torch height	**mm**
Level 1:	2.54
Level 2:	5.08
Level 3:	7.63
E. Tool type	
Level1: (E_0)	a
Level2: (E_1)	b
Level3: (E_2)	c
F. Slower on curves	
Level 1:	0
Level 2:	2
Level 3:	4
G. Cut Direction	
Level1:(G_0)	Vertical
Level2:(G_1)	Horizontal

Three levels are considered for six of the factors (1= low, 2 = medium and 3 = high), and 2 levels are considered for the cut direction (horizontal and vertical directions). The Response Surface function curvature is also looked. So, this is the best way to fit a regression model which relates the response to the factor levels. Two replicates were used For DOE. The number of runs for a full factorial experiment is $3^6 \times 2^1 \times 2$ (replicates)

2916. The Orthogonal Array approach was used to reduce the number of runs and still obtains the maximum information which allows easy interpretation of results. Among the Orthogonal Array approaches, an L- 18 Orthogonal Array is selected and augmented with 71 additional runs to estimate the two factor interactions. All 89 experiment settings were shown in Appendix A.

Mixed levels of factors are present in this research (i.e., six of them are at 3-levels and one is a 2-level). During interpretation of the results, we are considering only two factor interactions were considered, as higher factor interactions are difficult to interpret and are assumed as negligible.

There was a possibility of missing data as some of the responses cannot be measured if the part wasn't cut. There are two approaches in missing data analysis. They are:

1. **Approximate Analysis**: In this type of analysis, the missing observation is estimated and the analysis of variance is performed with that data as it were the real data. The error degrees of freedom are reduced by one for each missing observation.

2. **Exact Analysis:** In this analysis, the missing data makes the design unbalanced. The fitted values for the observation are found from the solution to the normal equation and the ANOVA is done through a general regression significance test. This Research uses the Minitab software that excludes the missing observations from the row they are in and accordingly the regression model is adjusted.

6.3 General Equipment for Measuring Responses

6.3.1 Measuring Tool for Surface Roughness

Due to the complexity and size of the part, available surface roughness (finish) standard mechanisms were not applicable. Instead, a rating system was designed to rate the surface quality. The rating system scale was between 1 (very rough surface) and 10 (perfect surface finish). For each rate, a representative object was found.

6.3.2 Measuring Method

To measure surface roughness, each area of the part was compared to representative objects, to find the most similar one. The surface quality of each part was evaluated by three researchers and a medium rating was used for the optimization calculations.

6.3.3. Surface Variation Tool

A surface variation measurement gauge was used for measuring the flatness. This tool gives the values and the variation in the surface when the surface is moved smoothly under the gauge. The tool was produced by Starrett.

6.3.4. Electronic Vernier Caliper

An electronic caliper was used for measuring the dimensions of the part. Dimensions are measured by placing the part in between the knobs and the caliper reads the dimensions in inch or mm.

6.3.5 Protractor with a sliding scale

A protractor with a sliding scale was used for measuring the bevel angles of the part. The protractor was a normal one with a scale which slides at its back. The measurement was taken by keeping the scale parallel to that side where the angle had to be measured and the protractor reads the angle.

6.4 Mechanical and Physical Part properties

6.4.1 Part geometry

Stainless steel sheet metal with 0.25 inch thickness was selected as the part type for the experiments. The part was 4x4 inch in vertical and horizontal direction. It has a semicircle of radius 2 inches and an inner circle of radius 1.5 inches.

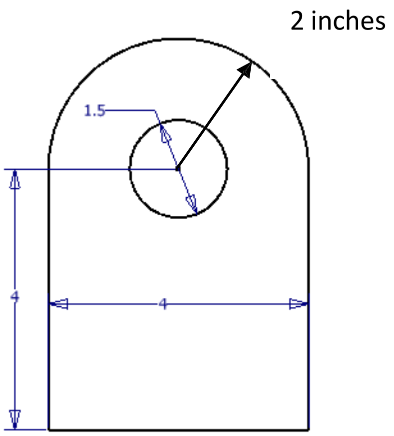

Fig 5. Geometry of the experimental parts in inches

6.4.2 Surface Roughness Responses

Many new technologies are being used for surface quality evaluation. Alabi (2007) and his team used Fractal Analysis to characterize the surface finish quality of the machined work -piece. They proposed a process monitoring approach for measuring surface quality. This process monitoring assists the work piece quality in machining. The machined surface quality is correlated after broaching with the output signals which are obtained from cutting forces, vibration, acoustic emission, and multiple sensors. The machined surface quality is estimated in terms of burr formation, surface anomalies, geometric accuracy and chatter marks. Factors such as tool settings, coolant conditions and cutting speed are set in the form of an orthogonal array based on the cutting condition variations. At every level of tool wear each orthogonal array is repeated. The geometric deviation, burr formation and even the chatter marks to a small extent of the machined profile are detected by the cutting force signals which are sensitive to detect. To develop appropriate techniques for qualitative and quantitative evaluation of the machined surface quality, the output signals time and frequency domain analysis is carried out (Axinte etal., 2004).

Cutting conditions: work piece: Inconel718; v ¼ v1; tool setting: roughing and burnishing taken from the paper by Axinte et. al, 2004. p.no.1103.
tool segments; coolant off; tool with all teeth uniformly worn at VB= 0.25 m.

In the research by Axinte et al. (2004) the response was measured for three

different areas.

1. Straight Line
2. Internal Curve
3. External Curve

6.4.2.1 Straight Line Response

The straight line on the part was selected as one of the areas for measuring the response variable surface roughness. This was measured using rating system described in

6.4.2.2 Internal Curve Response

There was an internal curve in the model which was one of the responses for surface roughness. This response was also measured with the rating system.

6.4.2.3 External Curve Response

There was an external curve in the model and it was selected as one of the responses. It was measured with the rating system. Because of lack of access to the tool the measuring method for surface roughness used by Axinte et al.(2004) was not used in this research.

6.4.2.4 Flatness Response

Among many methods that are available for measuring flatness, Marsh et al. (2006) used interferometric measurement to determine the Flatness of a work piece in ultra-precision fly cutting. This cutting process was characterized by depths of cut that ranges from 25 micrometer to 1 micrometer or less for finishing cuts (Marsh et. al. 2006). The model used in this research was an important and useful tool for improving the resultant flatness of the fly cutting operation and was based on the work piece geometry and spindle speed. The results imply that the spindle speed that was preferred for the ultra

Precision fly cutting should be chosen in a way that the structural resonance dominance should not occur at an integer multiple of the spindle speed. The process condition’s exact phasing of the trial work pieces can be verified by the inspection of interferometer (Marsh et al., 2006).

As the accuracy in micro inches was not needed in this research, the method designed above was not used. In this experiment, flatness of the work piece was measured with the tool mentioned in Fig 10 to identify the part deformation.

6.4.3.1 Measuring Tool

A surface variation measurement gauge was used for measuring the flatness. This tool gives the values and the variation in the surface when the surface is moved smoothly under the gauge. A surface variation tool is shown in Fig 8.

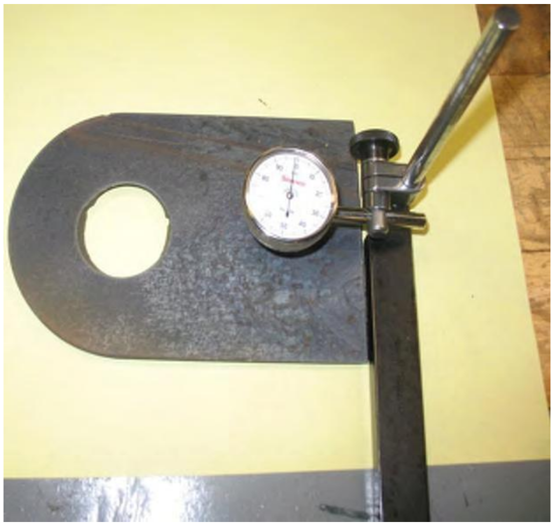

Fig 6.**Surface Variation Measurement Tool**

6.4.3.2 Measuring Method

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

6.4.4 Accumulation underneath the Work piece

The accumulation of the metal takes place after the cutting process underneath the part. Obviously, a perfect cut would not leave any residuals. For better understanding of the system performance, this response was measured for three different areas of the part independently:

a. Straight line

b. Internal curve

c. External curve

Measuring Tool

Similar to roughness response, the available surface roughness (finish) standard mechanisms were not applicable for this response. Instead, a rating system was designed to rate the unwanted accumulations. The rating system scale was between 1 (too much accumulations) and 10 (zero accumulations). For each rate a representative object was defined.

Measuring Method

To measure the amount of accumulation underneath of the three different areas of the part, it was compared to representative objects to find the most similar one. The evaluation was conducted by three researchers and a medium rating was used for the optimization calculations.

6.4.5 Dimensions of the part Responses

The change in the dimensions of the part after the cut was another response that was measured. This was done simply by using an electronic caliper. The measure was for two dimensions in X (length) and Y (width) directions.

Measuring Tool

An electronic caliper with accuracy of 0.001 was used as a tool to measure the dimension Of the fabricated part

Measuring Method

The part was placed in between the jaws and the actual reading was taken as shown by the caliper.

6.4.6 Bevel Angle Response

The ideal bevel angle, the angle between the surface of the cut edge and the top surface of the part, for a part fabricated by the plasma cutting process was zero. However, it was not always the case. The bevel angle was measured for the internal curve, external curve, and also for the straight line.

6.4.6.1. A Straight Line

In the straight line area of the part, the bevel angle varied in two sides. Therefore, the bevel angle on left side of a straight line and the bevel angle on right side of a straight line were considered as two different responses.

6.4.6.1.b Internal Curve

A single bevel angle for the internal curve was measured for each part.

6.4.6.1.c External Curve

A single bevel angle for the external curve was measured for each part.

6.4.6.2 Measuring Tool

The bevel angles were measured using a protractor with a sliding scale and by keeping the scale parallel to the side. The measuring tool is shown in the Fig 9.

Fig 7. Protractor with a sliding scale

6.4.6.3 Measuring Method

As shown in Fig 7, one edge of the angle measuring apparatus touches the top of the part and its other edge touch the part's cut edge. Then, bevel angle is read.

6.4.7 Tool Life

According to Coelho et al. (2004), the cutting edge geometry plays a significant role on the insert performance, thus affecting the tool life. The tool life was measured by the number of cuts it had cut. It was included in the responses to identify its correlation with the responses.

6.4.8. Start Point Quality Response

Sometimes the start point of the cutting path was incorrectly passing the part's boundary and creating a defective part. To identify the causes of this phenomenon, quality of the start point for both internal and external areas of the parts was measured.

6.4.8.1 Measuring Tool

A visual inspection was used for evaluating the quality of the start point. Different objects with diverse defects (from a big deformed hole to no start point) were rated 1 to 10 and used as a comparison scale. One of the pieces is shown in the Fig 8.

Fig 8. Part used in the comparison scale

6.4.8.2 Measuring Method

The start point quality for the internal and external areas of the part were compared with representing scale objects and rated (1 for a big extra cut and 10 for no start point sign on the part).

6.4.9 Cut Depth

Preliminary experiments showed that the combinations of settings did not always end with a cut (Fig 9). Sometimes a part's boundary was half way cut or not cut at all. By measuring the cut depth as a response for both part's internal and external areas, it was possible to identify the affecting factors for cut depth.

Fig 9. **Cut and not cut samples**

Measuring Tool

A rating system was used to measure the cut depth. Representative scales were 1 for a Minor scratch on the sheet metal's surface to 10 for a complete cut.

Measuring Method

Cut depth for internal and external edges of the parwas evaluated and rated based on on the status of the cut in those areas.

CHAPTER 7

RESULTS AND DISCUSSION

7.1 Mathematical Models

Tool type and cut direction were the two categorical variables which were considered in the design. If the categorical variables were treated as numerical variables then the results would be difficult to interpret or misleading. Therefore, this categorical variable problem was solved by creating dummy variables and the categorical variables were transformed into indicator variables. These indicator variables can take on only two values, either zero or one. The value one indicates the observation belongs in that category, a zero means it does not. In Regression, the indicator variables are used by leaving one of the indicator variables from the Regression model. This indicator variable becomes the base or reference level to which the other levels are compared. If the response value desired is higher, then the indicator variable which gives the higher response value was preferred (Montgomery, 2002).

After conducting all runs of the experiment, the surface quality and geometrical accuracy responses of the fabricated parts were determined. Response Surface Regression was used and the interaction between categorical and numerical variables was neglected as it would become difficult to interpret the results. The data set from the DOE

Was used to develop an optimization plot, residual plots and mathematical models to show the response behaviors versus the factors. There are two ways to interpret the significant factors and interactions if the factor was not significant and the interaction was significant. They are:

1. Neglecting the interaction effect in the model if the factor was not significant.

2. Including the factor in the model if the interaction effect was significant.

The second approach was used so that the R-squared value was high enough. The factor in the model was included if the interaction effect was significant and the factor effect was not significant.

The Regression analysis was used until the whole model become significant and the regression equation was developed. The resulting models are shown in the appendix B. Mintab 15 software was used to obtain the results and the plots, such as optimization plot, interaction plots, and main effects plot. The P-values were looked at and values which are more than 0.2 were not considered. 80% confidence interval was used in this research as this confidence interval has been used in real life applications (Caleyo et al., 2007, Stanzel et al., 2008, & Azarov et al., 1985). This means that the confidence interval will contain the true mean, 80% of the time. The interaction effects were also taken into account. Then, the equations were developed for all the 18 responses. For the roughness on Internal Curve response, the Regression coefficients and the ANOVA are shown. For the remaining responses, the Regression coefficients and ANOVA are shown in the Appendix. All the Responses and their designations are shown in the following Table 3.

Table 7.1. **The Response table and their desired value**

No	Name of the Response	Designation	Target Value
1	Roughness on Internal Curve	R1	10
2	Roughness on External Curve	R2	10
3	Roughness on Straight Line	R3	10
4	Flatness	R4	0
5	Accumulation on Internal Curve	R5	10
6	Accumulation on External Curve	R6	10
7	Accumulation on Straight Line	R7	10
8	Geometrical Accuracy in X-Direction	R8	4.0 in
9	Geometrical Accuracy in y-Direction	R9	6.0 in
10	Tool Life	R10	Max
11	Bevel Angle on Internal Curve	R11	0
12	Bevel Angle on External Curve	R12	0
13	Bevel Angle on Left Side of Straight Line	R13	0
14	Bevel Angle on Right Side of Straight Line	R14	0
15	Start Point Quality for Internal Part	R15	10
16	Start Point Quality for External Part	R16	10
17	Cut Depth Quality for Internal Feature	R17	10
18	Cut Depth Quality for External Feature	R18	10

7.2. Roughness Responses

7.2.1 Roughness on Internal Curve (R1):

The significant factors for this response were identified through Regression analysis. the results are shown below and also in the appendix B.

Table . 7.2 **Roughness on Internal Curve Results for 1st iteration**

Term	Coef	SE Coef	T	P
Constant	-0.3661	13.5350	-0.027	0.979
A	0.3568	0.2092	1.705	0.102
B	-0.0439	0.3431	-0.128	0.899
C	-0.1028	0.0671	-1.532	0.140
D	15.1636	28.7841	0.527	0.604
F	-0.4454	1.1645	-0.382	0.706
E_1	-0.5707	0.6205	-0.920	0.368
E_2	-0.6880	0.5218	-1.319	0.201
G_0	-0.8133	0.4374	-1.859	0.076
A*A	-0.0012	0.0013	-0.951	0.352
B*B	0.0006	0.0023	0.254	0.802
C*C	-0.0007	0.0003	-2.868	0.009
D*D	-22.3910	49.3232	0.454	0.654
F*F	0.0894	0.1318	0.678	0.505
A*B	-0.0022	0.0013	-1.729	0.098
A*C	0.0002	0.0005	0.433	0.669

A*D	-0.1930	0.2489	-0.776	0.446
A*F	-0.0034	0.0133	-0.255	0.801
B*C	0.0021	0.0006	3.228	0.004
B*D	0.0499	0.2955	0.169	0.867
B*F	-0.0051	0.0157	-0.324	0.749
C*D	0.1539	0.1262	1.220	0.235
C*F	0.0015	0.0056	0.265	0.794
D*F	1.9858	1.8298	1.085	0.290

Table 4. Roughness on Internal Curve Results for 1st iteration continued

S = 1.29592   PRESS = 235.367

R-Sq = 77.52% R-Sq(pred) = 0.00% R-Sq(adj) = 54.02%

Table 7.3. ANOVA for Roughness on Internal Curve 1st iteration

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	23	127.423	127.4228	5.54012	3.30	0.003
Linear	8	90.573	19.5760	2.44700	1.46	0.229
Square	5	11.547	16.7318	3.34635	1.99	0.120
Interaction	10	25.303	25.3031	2.53031	1.51	0.203
Residual Error	22	36.947	36.9468	1.67940	*	
Lack-of-Fit	21	36.947	36.9468	1.75937	*	
Pure Error	1	0.000	0.0000	0.00000		
	Total	45	164.370			

With 80% confidence interval the significant factors were identified

The regression equation is

$$\mathrm{R1} = 7.89 + 0.0726\,\mathrm{A} - 0.0424\,\mathrm{B} - 0.0456\,\mathrm{C} + 2.93\,\mathrm{D} - 0.253\,\mathrm{E\_2} - 0.718 G\_0 - 0.000849\, C * C - 0.00096\, A * B + 0.00193\, B * C + 0.0828\, C * D$$

Table 7.4. Roughness on Internal Curve Results for 2_{nd} iteration

Predictor	Coef	SE Coef	T	P
Constant	7.893	4.951	1.59	0.119
A	0.07259	0.07665	0.95	0.349
B	-0.04243	0.06759	-0.63	0.534
C	-0.04558	0.04550	-1.00	0.322
D	2.929	3.789	0.77	0.444
E_2	-0.2533	0.4248	-0.60	0.554
G_0	-0.7183	0.3863	-1.86	0.070
C*C	-0.0008494	0.0002259	-3.76	0.001
A*B	-0.000961	0.001027	-0.94	0.355
B*C	0.0019292	0.0005436	3.55	0.001
C*D	0.08283	0.09380	0.88	0.382

S = 1.34497   R-Sq = 67.3%   R-Sq(adj) = 59.3%

Analysis of Variance

Table 7.4. ANOVA for Roughness on Internal Curve 2nd iteration

Source	DF	SS	MS	F	P
Regression	10	152.660	15.266	8.44	0.000
Residual Error	41	74.167	1.809		
Total	51	226.827			

Then, again the significant factors were identified and the Regression model was developed.

Estimated Regression Coefficients for R1

The Regression equation is

$$\mathrm{R1} = 7.89 + 0.0726\,\mathrm{A} - 0.0424\,\mathrm{B} - 0.0456\,\mathrm{C} + 2.93\,\mathrm{D} - 0.253\,\mathrm{E\_2}$$

$$- 0.718\,G\_0 - 0.000849\,C * C - 0.00096\,A * B + 0.00193\,B * C + 0.0828\,C * D$$

Table 7.5. Roughness on Internal Curve Results for 3rd iteration

Predictor	Coef	SE Coef	T	P
Constant	7.893	4.951	1.59	0.119
A	0.07259	0.07665	0.95	0.349
B	-0.04243	0.06759	-0.63	0.534
C	-0.04558	0.04550	-1.00	0.322
D	2.929	3.789	0.77	0.444
E_2	-0.2533	0.4248	-0.60	0.554
G_0	-0.7183	0.3863	-1.86	0.070
C*C	-0.0008494	0.0002259	-3.76	0.001
A*B	-0.000961	0.001027	-0.94	0.355
B*C	0.0019292	0.0005436	0.355	0.001
C*D	0.08283	0.09380	0.88	0.382

S = 1.34497   R-Sq = 67.3%   R-Sq(adj) = 59.3%

Analysis of Variance

Table 7.6. ANOVA for Roughness on Internal Curve 3rd iteration

Source	DF	SS	MS	F	P
Regression	10	152.660	15.266	8.44	0.000
Residual Error	41	74.167	1.809		
Total	51	226.827			

Then again Regression analysis was developed with the significant factors. The Regression analysis with the significant factors was

The Regression analysis was developed again.

The Regression equation is

$$R1 = 12.8 - 0.101\,B - 0.0209\,C - 0.896\,G\_0 - 0.000817\,C * C + 0.00185 B*C$$

Table 7.7. Roughness on Internal Curve Results for 4th iteration

Predictor	Coef	SE Coef	T	P
Constant	12.830	1.872	6.85	0.000
B	-0.10056	0.02514	-4.00	0.000
C	-0.02094	0.04065	-0.52	0.609
G_0	-0.8964	0.3794	-2.36	0.022
C*C	-0.0008168	0.0002236	-3.65	0.001
B*C	0.0018476	0.0005322	3.47	0.001

S = 1.36142   R-Sq = 62.4%   R-Sq(adj) = 58.3%

Table 7.8. ANOVA for Roughness on Internal Curve 4th iteration

Source	DF	SS	MS	F	P
Regression	5	141.568	28.314	15.28	0.000
Residual Error	46	85.259	1.853		
Total	51	226.827			

So the whole model was significant and the significant factors are pressure, cut speed, cut direction, cut speed^2 and interaction between pressure and cut speed.

In this way all the statistical significant factors for all the responses were determined.

7.2.2 Roughness on External Curve (R2):

The significant factors were pressure, cut speed, tool type, cut direction, cut speed, and interaction between pressure and cut speed. The results were shown in the appendix B.

The Regression equation is

$$\mathrm{R2} = 11.3 - 0.0626\,\mathrm{B} + 0.0141\,\mathrm{C} - 0.927\,\mathrm{E\_1} - 1.15\,\mathrm{G\_0} - 0.000624\,\mathrm{C} *$$

$$\mathrm{C} + 0.00112\mathrm{B} * \mathrm{C}$$

7.2.3 Roughness on Straight Line (R3):

The significant factors were cut speed, torch height, cut speed and interaction between cut speed and torch height. The results were shown in the appendix B.

The Regression equation is

$$\mathrm{R3} = 3.83 + 0.105\,\mathrm{C} + 15.5\,\mathrm{D} - 0.000458\,\mathrm{C} * \mathrm{C} - 0.189\,\mathrm{C} * \mathrm{D}$$

7.3 Flatness(R4)

The significant factor affecting this response was tool type. The results were shown in the appendix B.

The Regression equation is

$$\mathrm{R4} = 0.0235 + 0.00897\,\mathrm{E\_1}$$

7.4. Accumulation Responses

7.4.1 Accumulation on Internal Curve (R5):

The significant factors were cut speed, tool type and cut speed². The results were shown in the appendix B.

The Regression equation is

$$R5 = 2.05 + 0.182\,C + 0.902\,E\_1 + 1.09\,E\_2 - 0.00119\,C*C$$

7.4.2 Accumulation on External Curve (R6):

The significant factors were pressure, cut speed, slower on curves, tool type, cut speed² and the interaction between pressure and slower on curves. The results were shown in the appendix B.

The Regression equation is

$$R6 = -1.01 + 0.0403\,B + 0.200\,C + 1.69\,F + 1.21\,E\_2 - 0.00133\quad C*C$$

$$-0.0234B*F$$

7.4.3 Accumulation on Straight Line (R7):

The significant factors affecting accumulation on straight line were cut speed, cut speed². The results were shown in the appendix B.

The Regression equation is

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

7.5. Dimensional Reponses

7.5.1 Geometry in X-Direction (R8):

The significant factors affecting Geometry in X-Direction were cut speed, torch height, slower on curves, tool type and interaction between cut speed and torch height and in between cut speed and slower on curves. The results were shown in the appendix B.

The Regression equation is

$$R8 = 4.05 - 0.000533\,C - 0.283\,D - 0.00280\,F - 0.0210\,E\_1 + 0.0114$$

$$E\_2 + 0.00305 C*D + 0.000086 C*F$$

7.5.2 Geometry in Y-Direction (R9):

The significant factors affecting this response were current, torch height, cut direction, current², and torch height^2. The results were shown in the appendix B.

The Regression equation is

$$R9 = 6.71 - 0.0241\,A - 1.07\,D + 0.0448\,G\_0 + 0.000200\,A * A + 2.62\,D * D$$

7.6 Tool Life (R10):

Tool life is not a function of the factors. It was considered in the responses to identify its correlation with other responses. As shown in Table 11, most of the correlations are low and non-significant (i.e., increasing tool life decreases the part quality), however because tools (tips) were replaced before they get worn, their effects on the value of other responses are not significant.

Table 7.9 . Correlation between R10 (tool life) vs. other responses.

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

	R9	R10	R11	R12	R13	R14	R15	R16
R10	**0.1**	**1**	**0.05**	**-0.06**	**-0.1**	**0.03**	**-0.05**	**0.02**

7.7. Bevel Angle Responses

7.7.1 Bevel angle on Internal Curve (R11):

The significant factors affecting bevel angle on internal curve were current, pressure, cut speed, Torch height, slower on curves and interactions between current and pressure, current and cut speed, current and torch height, current and slower on curves, and pressure and slower on curves. The results were shown in the appendix B.

The Regression equation is

$$R11 = -80.4 + 1.60\ A + 0.667\ B - 0.259\ C - 4.91\ F + 149\ D - 0.0165\ A$$

$$*B + 0.00635 A*C - 2.17 A*D - 0.0917 A*F + 0.161 B*F$$

7.7.2 Bevel Angle on External Curve (R12):

The significant factors affecting this response were current, pressure, torch height, slower on curves and interaction effect between current and torch height and in between pressure and slower on curves. The results were shown in the appendix B.

The Regression equation is

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

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

The significant factors affecting this response were torch height, tool type, and torch height^2. The results were shown in the appendix B.

The Regression equation is

$$R13 = -24.4 + 239\,D - 3.98\,E\_1 - 552\,D * D$$

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

The significant factors affecting this response were current, pressure, cut speed, tool type, cut speed^2, and interaction between current and pressure and in between current and cut speed. The results were shown in the appendix B.

The Regression equation is

$$R14 = -28.1 + 0.446\,A + 0.638\,B - 0.353\,C + 11.4\,E\_1 - 0.0103\,A * B + 0.0029A*C$$

7.8. Start Point Quality Responses

7.8.1 Start Point Quality for Internal Part (R15):

The significant factors affecting this response were pressure, cut speed, slower on curves, tool type, cut speed² and interaction between pressure and slower on curves and in between pressure and slower on curves. The results were shown in the appendix B.

The Regression equation is

$$R15 = 9.85 - 0.0287\ B - 0.0197\ C + 0.867\ F - 0.679\ E\_1 - 0.000283\ C* C + 0.000871 B*C - 0.00114 B*F$$

7.8.2 Start Point Quality for External Part (R16):

The significant factors affecting this response were torch height, slower on curves, cut speed, pressure, tool type, cut direction, cut speed², and interaction between pressure and cut speed, pressure and torch height, and cut speed and slower on curves. The results were shown in the appendix B.

The Regression equation is

$$R16 = 17.5 - 26.9\ D - 0.178\ F - 0.0244\ C - 0.149\ B - 0.795\ E\_1 - 1.39 G\_0 - 0.000601 C*C + 0.123 B*C + 0.433 B*D + 0.00526 C*F$$

7.9 Cut Depth Responses

Among the 89 fabricated parts, some of the parts were not fully cut and they were not extracted from the sheet metal. While those parts are missing data for other responses, they are usable data for cut depth responses. Also, as mentioned before, a rating system was used to measure cut depth. In this response, a value of 10 (maximum quality) was given to those parts which were cut and the remaining parts which did not cut were rated with lower numbers (1-10). Since, of all the parts, 53 were cut and 36 were not cut, in the Desirability function,due to unequal length of columns, these two responses are separated. The Regression models are independently developed to identify the significant factors and their effects on these two responses.

7.9.1 Cut Depth Quality for Internal Feature (R17):

The factors affecting this response were current, pressure, cut speed, torch height, tool type, and slower on curves. The results were shown in the appendix B.

$$\mathrm{R17} = 6.73 + 0.0596\ \mathrm{A} - 0.0368\ \mathrm{B} - 0.0363\ \mathrm{C} + 6.87\ \mathrm{D} + 0.883\ \mathrm{E\_1} + 0.814\mathrm{E\_2} + 0.315\mathrm{F}$$

7.9.2 Cut Depth Quality for External Part (R18):

The factors affecting this response were current, pressure, cut speed and torch height. The results were shown in the appendix B.

$$\mathrm{R18} = 7.63 + 0.0728\ \mathrm{A} - 0.0421\ \mathrm{B} - 0.0485\ \mathrm{C} + 6.93\ \mathrm{D}$$

Current

- Geometrical Accuracy in Y-Direction
- Bevel Angle on Internal Curve
- Bevel Angle on Right side of Straight line
- Bevel Angle on External Curve
- Cut Depth Quality for Internal feature
- Cut Depth Quality for External Feature

Pressure

- Roughness on Internal Curve
- Roughness on External Curve
- Accumulation on External Curve
- Bevel Angle on Internal Curve
- Bevel Angle on External Curve
- Bevel Angle on Right side of Straight line
- Start point Quality for Internal part
- Start point Quality for External part
- Cut Depth Quality for Internal Feature
- Cut Depth Quality for External Feature

Cutting Speed

- Roughness on Internal Curve
- Roughness on External Curve
- Roughness on Straight Line
- Accumulation on Internal Curve
- Accumulation on External Curve
- Accumulation on Straight line
- Geometrical Accuracy in X-Direction
- Bevel Angle on Internal Curve
- Bevel Angle on External Curve
- Bevel Angle on Right Side of Straight line
- Start Point Quality for Internal Part
- Start Point Quality for External Part
- Cut Depth Quality for Internal Feature
- Cut Depth Quality for External Feature

Fig 10. Figure showing which factors affect which responses

Torch height

- Roughness on Straight line
- Geometry in X-Direction
- Geometry in Y-direction
- Bevel Angle on Internal Curve
- Bevel Angle on External Curve
- Bevel Angle on Left side of Straight line
- Start point Quality for External Part
- Cut Depth Quality for Internal Feature
- Cut Depth Qquality for External Feature

Tool Type

- Roughness on External Curve
- Flatness
- Accumulation on Internal Curve
- Accumulation on External Curve
- Geometrical Accuracy in X-Direction
- Bevel Angle on Left Side of Straight Line
- Bevel Angle on Right Side of Straight Line
- Start Point Quality for Internal Part
- Start Point Quality for External Part
- Cut Depth Quality for Internal Feature

Cut Direction

- Roughness on Internal Curve
- Roughness on External Curve
- Geometrical Accuracy in X-Direction
- Geometrical Accuracy in Y-Direction
- Bevel Angle on Internal Curve
- Bevel Angle on External Curve
- Start point Quality for External Part

Slower on Curves

- Accumulation on External Curve
- Geometrical Accuracy in X-Direction
- Bevel Angle on Internal Curve
- Bevel Angle on External Curve
- Start point Quality for Internal Part
- Start Point Quality for External Part
- Cut Depth Quality for Internal Feature

Fig 10. Figure showing which factors affect which responses continued

7.10 Desirability Function

Tradeoffs between the responses were observed during analyzing the mathematical models. Choosing a factor and increasing its value have an impact on one or more responses and it did not have an impact on the other responses. Therefore, for balancing the tradeoffs, a multi-response optimization technique was used. Derringer and Suich (1980) suggested a technique for this kind of approaches. They called it Desirability Function, a method that was used for tradeoff balance for the responses. The Desirability Function in this research was developed using Minitab software. In this Desirability Function, different importance weights were given to different responses: An importance of 4 for roughness and accumulation responses, 3 for bevel angle responses, 2 for start point quality responses and part geometry responses, and 1 for tool life and flatness. For roughness, accumulation, start point quality, tool life, and cut depth quality responses the goal of 10 as maximum was chosen. For part geometry and bevel angle the goal was to target (equal to CAD file dimensions). We chose the goal for flatness as 0. The results were shown below.

After incorporating all the above values, the responses and their Desirability values are given below.

R1 = 9.3898 Desirability = 0.932197

R2 = 9.7443 Desirability = 0.971590

R3 = 10.0138 Desirability = 1.000000

R4 = 0.0181 Desirability = 0.892339

R5 = 9.9990 Desirability = 0.999888

R6 = 10.6272 Desirability = 1.000000

R7 = 10.5197 Desirability = 1.000000

R8 = 3.9814 Desirability = 0.854725

R9 = 6.0002 Desirability = 0.994658

R11 = 4.5917 Desirability = 0.826730

R12 = 1.8111 Desirability = 0.922932

R13 = -5.3500 Desirability = 0.827420

R14 = 2.5416 Desirability = 0.924133

R16 = 9.8297 Desirability = 0.981073

Composite Desirability = 0.944416

The responses R11 to R15 were Bevel Angle responses and the target value for the Bevel Angle is zero. The Desirability Function gives the value which is slightly less or more than the target value. The difference between the target value and the desired value is almost equal and the difference is non-significant. So, the desirable value was good enough.

7.10.1 Desirability for Cut Depth Quality Response:

As explained in the previous section, the Desirability Function for these two cut depth responses were separately conducted as below.

R17 = 9.72 , Desirability=0.97

R18 = 9.67, Desirability=1.00

Based on the Desirability Function, overall optimum point was reached in the following setting:

Optimization Plot:

Current = 80

Pressure = 90

Cut speed = 54.55

Torch height=0.297

Slower on curves=0.3636

Tool type= C

Cut direction=Horizontal

The optimization plot was plotted to show the effect of each factor (columns) on the responses or composite Desirability (rows). The vertical red lines on the graph represent the current factor settings. The numbers displayed at the top of a column show the current factor level settings (in red). The horizontal blue lines and numbers represent the responses for the current factor level. The optimization plot was shown in the appendix C.

CHAPTER 8

CONCLUSIONS AND FUTURE RESEARCH

In this research, the optimum parameter settings were identified for the automated plasma cutting process by doing $3^{6} * 2^{1 \text{ experiments}}$ with 2 replicates and reduced the number of runs with an Orthogonal Array approach. Seven independent variables were considered for the study. Six of them were studied at three levels while the seventh independent variable, cut direction, was studied only at two levels (Horizontal and Vertical Direction). Seven affecting factors and eighteen responses make the automated plasma cutting process very complex. Without applying design of experiment it seems impossible or very difficult to perform all the runs. The entire process in this study was conducted for stainless steel sheet metal with 0.25 inch thickness.

After performing the Design of Experiments, Regression analysis was conducted to identify the significant factors affecting each response. Several mathematical models to explain each one of the responses was obtained. Then, a Desirability Function, a multi- response optimization technique, 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 parameter settings that optimize the resulting quality

Characteristics. Through experimentation, validation was again performed on the optimum parameter setting before coming to a conclusion. Finally, the independent variables which influence the most the response variable outcomes were identified. Looking upon the results, one can conclude that the effect of torch height, tool type and cut direction plays a vital role in surface quality characteristics. So, for a better cut quality one should consider these factors and proceed. The effect of factors on the responses was shown diagrammatically in Fig 15.

8.1 Future Research

A similar study can be done to investigate other popular sheet metal thicknesses. Also, that would be interesting (and costly) if one can conduct a new similar study by incorporating sheet metal thickness as one of the factors. So, one could take this in to consideration and make a related study.

As many of the responses measured were qualitative, one can use new measuring equipment and measure the responses quantitative and can make a similar study. Another study can also be made using other materials such as wood etc.

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