A Study on Relationship between Process Variables and Weld Penetration for Gas Metal Arc Welding (GMAW)

S. Thiru Chitrambalam[1),*], Tan Wee Ming [2)], Imran Syakir Mohammad [3)] and Shafizal bin Mat [4)]

Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia
* Tel: +6-06-234678, Fax: +6-06-331 6066,
Email: thiru@utem.edu.my

Abstract

Weld penetration is an important physical characteristic of a weldment that affects the stress carrying capacity of the weld joint. Several welding parameters seem to influence weld penetration. This paper presents the relationship between weld penetration and four direct welding process parameters of gas metal arc welding (GMAW) process on structural carbon steel. Two level, full factorial design was applied to investigate and quantify the direct and interactive effects of four process parameters on weld penetration. The upper and lower limits of the parameters were identified through trial and error methodology, and the experiments were conducted using 'bead on plate' mode. The performance of the model was then tested by using analysis of variance technique and the significance of the coefficients was tested by applying student's 't' test. Commercial computer programs were used for both physical and statistical analysis of weld specimens after experimentation. The main and interactive effects of different welding parameters are studied by presenting it in graphical form.

Keywords: Weld Penetration, Design of Experiments, Factorial Design.

1. Introduction

Welding technology has obtained access virtually to every branch of manufacturing; to name a few, rail, building construction, pipelines, automobiles and etc. As the manufacturing technology grows exponentially in the last few decades due to the advent of high speed micro computers based fully automated fabrication processes, welding technology also needs constant upgrading due to its widespread applications. However, to consistently produce high quality of welds, arc welding requires experienced welding personnel at the same time. One reason for this is the need to properly select welding parameters for a given task to provide the best weld quality which can be identified by its micro-structure and the amount of spatter and relied on the correct bead geometry size (M.P. Jain, 2002). Unfortunately, a common problem that has been faced by the manufacturer is the control of the process input parameters to obtain a good welded joint with the required bead geometry and weld quality with minimal detrimental residual stresses and distortion.

Traditionally, it has been necessary to determine the weld input parameters for every new welded product to obtain a welded joint with the required specifications. To do so, requires a time-consuming trial and error development effort, with weld input parameters chosen by the skill of the engineer or the machine operator. Then welds are examined to determine whether they meet the required specifications. Finally, the weld parameters may be determined to produce a joint which closely meets the requirements. Nevertheless, a pre-specified weld bead can often be produced with various parameters combinations (A.C. Underwood, 1980, R. L. Klien, 1984). In other words, there is often a more ideal welding parameters combination, which can be used if it can only be determined. This paper presents the investigation made on GMAW process with mild steel as the base metal to analyse the effect of welding parameters viz. the welding current, voltage, welding speed and welding feed angle on one of the most important factors of bead geometry and shape relationships of GMAW welds-the weld penetration.

2. Literature Review

The gas metal arc welding (GMAW) is increasingly employed for fabrication in many industries. The process is versatile, since it can be applied for all position welding, can be easily automated and integrated into the robotized production centers. These advantageous features of this process have motivated many researchers to study the GMAW process in detail. GMAW is an arc welding process that uses an arc between a continuously-fed filler metal electrode and the weld pool. The process is used with shielding from an externally supplied gas and without the application of a pressure. It is also known as MIG welding or MAG welding where MIG (Metal Inert Gas) welding refers to the use of an inert gas while MAG (Metal Active Gas) welding involves the use of an active gas (i.e. carbon dioxide and oxygen). A variant of the GMAW process uses a tubular electrode filled with metallic powders to make up the bulk of the core (metal core electrode). Such electrode may or may not require a shield gas to protect the molten weld pool from contamination. All commercially important metals such as carbon steel, high-strength low alloy steel, stainless steel, aluminium, copper, titanium and nickel alloys can be welded in all position with GMAW process by choosing appropriate shielding gas, electrode and welding variables.

2.1. Bead Geometry and Shape Relationship

In arc welding, the weld quality is greatly influenced by the welding parameters. The welding process parameters are strongly related to the geometry of the back-bead, a relationship is thought to be very complicated. Weld bead geometry and shape relationship of girth welding for coated electrodes are significantly influenced by several process variables, such as arc-voltage, welding current, metal disposition rate, arc-travel rate, electrode work angle etc., which affect the quality, productivity and the cost effectiveness of the entire pipeline (Widgery 1999, Widgery 2002, Jain 2002). The relationship between the process variables and bead geometry is complicated due to the number of variables and their interrelationship involved. Thus, in predicting the weld bead shape geometry and hence to get better control over the weld quality and the optimum utilization of the resources, optimal welding conditions among the welding parameters have to be ascertained. Repeated experiments are needed in order to determine the optimal welding conditions among the welding process parameters

Investigations into the relationship between the welding process parameters and bead geometry began in the mid 1900s and regression analysis was applied to welding geometry research by (Lee, 2000 and Raveendra, 1987). Many efforts have been carried out for the development of various algorithms in the modeling of arc welding process. In the early days, arc welding was carried out manually so that the weld quality can be totally controlled by the welder ability. It has been reported (McGlone and Chadwick, 1978) that a mathematical analysis correlating process variables and bad geometry for the submerged arc welding of square edge close butts. Similar mathematical relationship between welding variables and fillet weld geometry for gas metal arc welding (GMAW) using flux cored wires have also been reported. (Chandel, 1988) first applied this technique to the GMAW process and investigated relationship between process variables and bead geometry. These results showed that arc current has the greatest influence on bead geometry, and the mathematical models derived from experimental results can be used to predict bead geometry accurately. Nearly 90% of welding in world is carried out by one or the other arc welding process; therefore it is imperative to discuss the effects of welding parameters on the weld ability of the materials during the arc welding.

Welding personnel with great experience in arc welding is required in order to consistently produce high quality welds. This is due to the urgency of selecting the welding parameters properly for a given task in order to get a good weld quality which is identified by its micro-structure and the amount of spatter, and relied on the correct bead geometry size. Thus, the use of the control system in arc welding can eliminate much of the “estimation” often engaged by welders to specify welding parameter for a given task. In addition of specific importance is the development of mathematical models that can be employed to predict welding parameters about arc welding process with respect to the work piece and bead geometry to develop and integrate into a robotic welding system due to its versatility. Besides, other factors such as the type of base metal, the welding process and the geometry of the welded parts will determined the optimal welding conditions. As a result, an enormous amount of data is needed in order to obtain best welding conditions. It is impossible in continuous butt-welding to check whether each back-bead of the welded part has been formed in the desired bead size. Also, working conditions do not allow for the installation of the costly vision sensors in every area. Therefore, geometry prediction system is needed in order to predict the size of the back-bead without the use of separate measuring systems. Investigations and attempts have been made by many researchers (Zacharia 1988, Kim et al. 1996, Pandey 2001, Murray 2002) for predicting and analyzing the effect of welding parameters on the bead shape geometry and shape relationships by developing mathematical models.

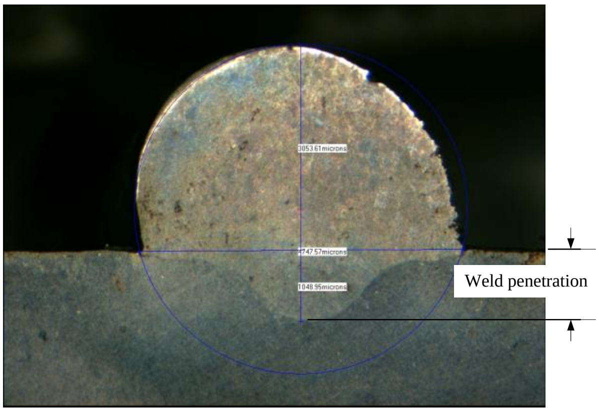

Figure 1: Weld penetration

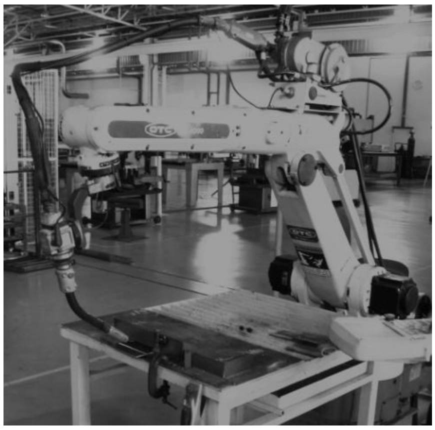

Figure 2: Experimental set up

Statistical models were developed in present for analyzing and predicting the effects of welding current, arc travel rate, auxiliary plasma gas flow rate, and the electrode angle on bead geometry and shape parameters (weld penetration, bead width, and height of reinforcement, weld penetrations shape factor and weld reinforcement form factor). Welding parameters such as the open circuit voltage (V), welding current (I), welding speed (arc travel rate) (S), and electrode feed angle (welding angle) (A) on the bead geometry and shape relationship are used for estimating the individual and interaction effects within the designed limit of the parameters in these models.

3. Design of Experiments and Developing the Design Matrix

Two level, full factorial design of (24 = 16) sixteen runs was selected for determining the effect of four independent direct welding process parameters on weld penetration shown in Figure 1. The main disadvantages of the general experimental approach of keep on varying one control parameter at a time are a) needs more trial runs and b) does not provide any information about the interaction between the selected parameters. For factorial design, the most important part is the selection of the independent direct parameters which could affect the response and later the range of the parameters.

Table 1: Process control variables and their limits

Parameters	Units	Symbol	Limits	
			Low (-)	High (+)
Open circuit Voltage	Volts	V	18	26
Welding Current	Amps	I	180	260
Welding Speed	cm/min	S	24	46
Welding Angle	Degree	A	90	145

For the current investigation four parameters were selected based on the available literature such that they have been proven to be affecting the weld penetration largely. The low and high levels of the parameters were selected on Trial and Error basis so that they can keep equilibrium between the wire feed rate and the burn off rate as well as keeping the welds free from all the visible welding defects such as undercut, non uniform width, extreme spattering, porosity, overlap, extreme convexity and macro cracking. The rest of parameters other than the selected were kept constant. Welding parameters were coded as (+) and minus (-) for high and low level respectively for manual data processing for rechecking the software based results. The selected process control variables and their respective limits are given in Table 1.

4. Experimental Setup

For the experiments, flat position "Bead on plate" technique was employed on SS41 carbon structural steel plate with a specification of 180mm (width) x 100mm (length) x 20mm (thickness). The top surfaces of the test plates were cleaned mechanically to remove any oxide layer and any source of hydrogen. AWS ER70S-6 (0.8mm) mild steel flux cored wire was used as consumables and the experiments were carried out using MIG robotic arm welding (OTC DR-4000) welding machine under the shield of 80% Ar and 20%CO2 gas mixture supplied at the rate of 16 litre/min. The experimental set up is shown in Figure 2.

Table .2: Design Matrix and Responses

`	Exp. Sequence	Design Matrix V	I	S	A	P (µm)
1		-	-	-	-	233.10
2		+	-	-	-	1515.15
3		-	+	-	-	1048.95
4		+	+	-	-	1973.58
5	R	-	-	+	-	209.79
6	A	+	-	+	-	1313.70
7	N	-	+	+	-	1289.82
8	D	+	+	+	-	1229.38
9	O	-	-	-	+	357.42
10	M	+	-	-	+	1833.79
11		-	+	-	+	1352.00
12		+	+	-	+	2004.66
13		-	-	+	+	69.93
14		+	-	+	+	1090.92
15		-	+	+	+	1421.91
16		+	+	+	+	1297.40

Prior to the experiments, trial runs were conducted to determine the workability of the machine. Two sets of experiments were conducted as per design matrix at random to avoid systematic error creeping into the system. The data was collected once the equilibrium between the wire feed rate and the burn off rate is established and about 300 mm weldment was deposited. The finished welded plates are cross-sectioned at their mid-points using a band saw to obtain its' bead geometry. The polished weld surfaces were etched with 5% nital (nitric acid + ethanol) solution. The plates are dipped into the solution for 7seconds and then washed with running water before blow drying. The weld bead geometry was traced using an optical profile projector and the bead dimensions, i.e. depth of penetration, height of bead and also bead width were measured. With the digital planimeter, the areas of the parent metal melted and he metal forming reinforcement are measured and percent of dilution is calculated. The average value derived from the measured penetration from the two sets of experiments and presented in Table 2

For conducting the DOE approach and regression analysis, a commercial statistical software (MINITAB 12) was used to develop different mathematical models to establish the relationships between welding input parameters and the response parameter. The coefficients obtained were used to construct the model for weld bead geometry outputs especially the weld penetration. From the analysis, a tabulated value of 95% confidence level was only to be considered as adequate. The associated “p”value for this model is lower than 0.05; i.e. $\alpha = 0.05$ or 95% confidence level. The values of the regression coefficients give an idea as to what extent the factors after the responses. Insignificant coefficients were eliminated without sacrificing much of the accuracy to avoid cumbersome mathematical labour. The data was processed again by using the same commercial statistical software to plot the main, interaction effects between two direct process parameters and also to plot the surface plots as well.

5. Analysis of the results and discussion

The analysis of variance (ANOVA) results performed on different regression functions denoted that the set of curvilinear models is the best representative for the actual GMAW process. The level of significance of a particular parameter is assessed by the magnitude of the “p” value associated with it. The main relationships between weld penetration with arc voltage, welding current, welding speed and welding angle are shown in Figure 3. Response surfaces due to the interaction of two selected parameters are given in Figures 4, 5 and 6. The insignificant main effects and interaction effects have been dropped from consideration and it can be seen from Figure 3, that apart from the welding angle, the open circuit voltage, welding current and the welding speed have much more significant influence over weld penetration

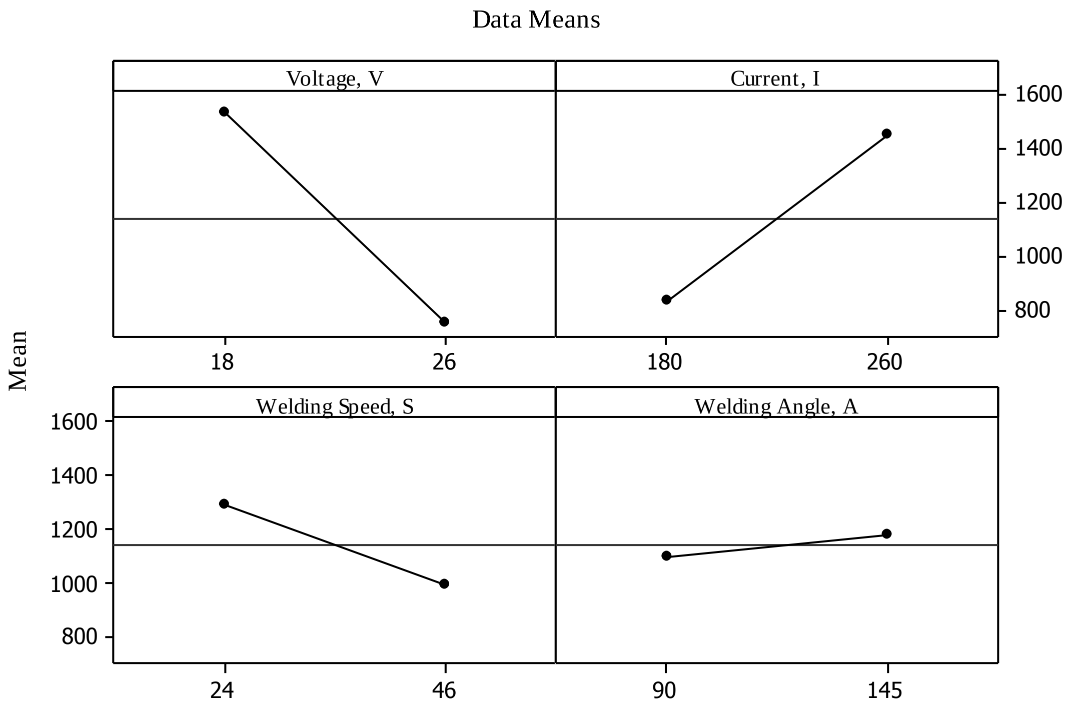

Figure 4. The effects of flank wear on cutting and feeding forces

The effect of crater wear on the cutting and feeding forces is explained the following: the rake plane is the plane where chip flows. Due to the plane angle, chip flow is deflected so that chip is compacted. The consequences, it is harder than that of the raw material. The chip flow grinds the surface of rake plane and also it transfers heat, so that the rake plane experiences wear. The wear is called as crater wear. Because of the wear, it increases friction coefficient of the rake surface. Cutting and feeding forces tend to increase proportionally to the roughness. Correlation between crater wear and cutting and feeding forces is illustrated in Figure 5.

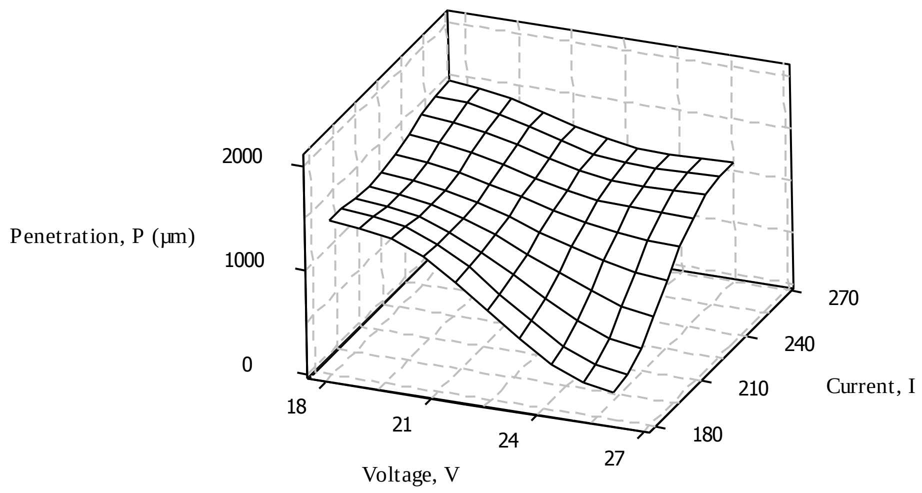

Figure 4: Response surface due to interaction of welding voltage and welding current with penetration

Welding current is an influential variable in arc welding process which controls the electrode burn off rate, the depth of fusion and geometry of the weldment. Increasing the welding current is expected to increase the intensity of convective fluid flow because higher current density and heat flux will enhance the driving forces for fluid flow, which in turn will influence the penetration profile. Welding speed has a negative main effect on penetration (Figure 3). From the response surface plot shown in Figure 5 indicated an inverse trend for weld penetration with the arc travel rate (welding speed). This trend also is in total agreement with most of the published results. Increase in welding speed reduces the melting rate of the base metal as the arc passes the area under influence faster and hence heat penetration and hence the depth of fusion is also becoming lesser. The trend is consistent at both low and higher level of welding speed as shown in Figure 5. The penetration decreases due to the pressure of the large amount of weld pool beneath the electrode, which will cushion the arc penetrating force. This could obviously be attributed to the reduced line power per unit length of weld bead as welding speed increases. Also, at higher welding speeds, the electrode travels faster and covers more distance per unit time. The combined effects of lesser line power and faster electrode travel speed results in decreased metal deposition rate per unit length of weld bead. Hence, penetration and reinforcement decrease as welding speed increases. By comparing of the all cutting and feeding forces data, it can be concluded that the flank wear produces bigger effect on the increase of cutting force than that of crater wear. However, feeding forces produced by flank as well as crater wears relatively unchanged. (Figure 6).

Welding angle has statistically positive effect on weld penetration (Figure 6). Since the angle determines the pints of application and direction of the arc force and hence the weld pool motion, the relative angular position between electrode and base plate alters the weld pool shape and the penetration. Changing of electrodes from perpendicular (90°) to forehand position (for example, in this case is 145°) makes the weld bead shallower which resulted in wider weld beads with less penetration. Besides, narrow bead and deep penetration are a result of the application of backhand technique as well

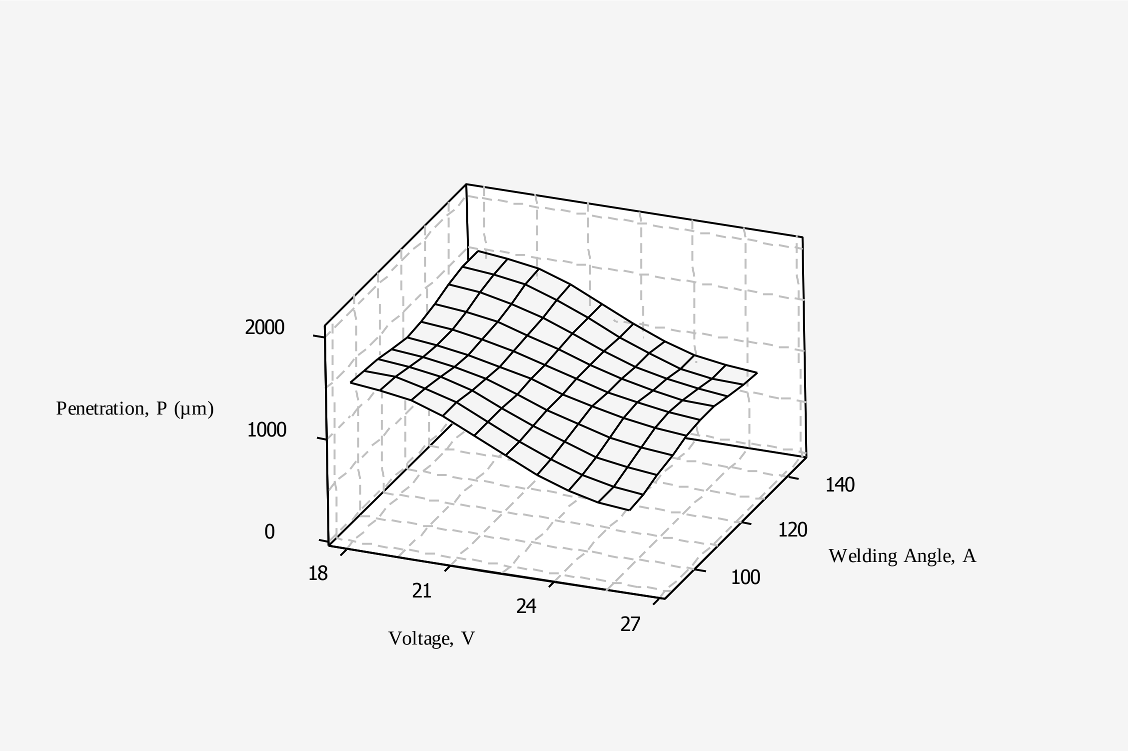

Figure 5. The effect of crater wear on the cutting and feeding forces

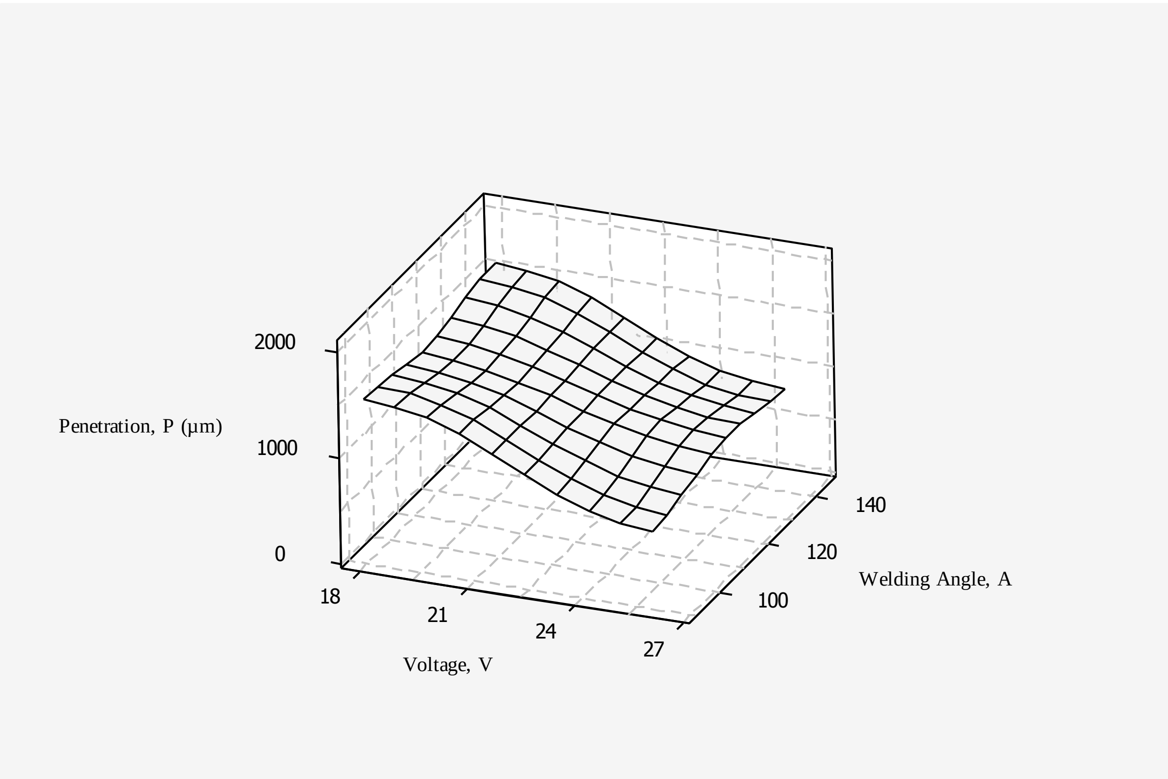

Figure 6. Curves comparison between cutting and feeding forces produced by flank, crater and normal geometry of tool

6. Conclusions

The following are the conclusions drawn from this analysis:

a) . A Mathematical model has been developed to predict weld penetration as a function of parameters that can be measured and controlled independently in gas metal arc welding (GMAW)
b) The model can be used to calculate other weld responses which depend on weld penetration.
c) The two level, full factorial design is found to be very effective tool for quantifying the main and interaction effects of direct independent welding process parameters on weld penetration.
d) It was observed that welding current is the most significant parameter affecting the weld penetration and that the open circuit voltage and welding speed's interactions on weld penetration were found to be statistically significant and the interactions are well represented by the response surfaces developed.
e) Welding angle is also found to be statistically significant, influencing on welding penetration in a lower scale as compared to the welding current.
f) Both open circuit voltage and welding speed have influenced in an inverse relationship with weld penetration while the welding angle although has direct linear relationship with penetration however in much lower scale

References

M.P.Jain, (2002), Welding & NDT of oil & gas pipelines-productivity & quality issues, *National seminar on cost effective welding & productivity*, Indian welding society (IWS), New Delhi, India, 115.

A.C. Underwood, (1980), 'Automated Welding will Meet the Desperate Need for more Pipelines in the United States', *Welding Design & Fabrication*, pp.134-135.

R. L. Klien, (1984), *Pipelines Design*, construction and operation.2, New York, Construction press, 3-4.

Sunil Pandey, (2002) New Technologies in Shielded metal Arc welding and Gas Metal Arc Welding. *National Welding Seminar*, Indian Institute of Welding (IIW), Chennai, India.

Sunil Pandey et al., (2003) 'Surface modification of steels using plasma enhanced shielded metal arc welding process (PESMAW)', *Indian Welding Journal*, pp.27-30.

J. I. Lee, K. W. Um, (2000) 'A prediction of welding process parameters by prediction of back-bead geometry', *Journal of Materials Processing Technology,* Vol.108, pp.106-113.

R. S. Chandel, et al., (1997) 'Effect of Increasing Deposition Rate on the Bead Geometry of Submerged Arc Welds, *Journal of Materials Processing Technology*, 124-128.

D. S. Nagesh, G. L. Datta, (2002) 'Prediction of Weld Bead Geometry and Penetration in Shielded Metal-Arc Welding using Artificial Neural Networks', *Journal of Materials Processing Technology*, Vol.123 (2), pp.303-312.

S. Kim, J. S. Son, et al., (2003), 'A Study on Relationship between Process Variables and Bead Penetration for Robotic CO_2 Arc Welding', *Journal of Materials Processing Technology*, Vol.136 (1-3), pp.139-145.

Widgery, D.J., (1999), 'Line pipe welding beyond 2000', *Svetsaren*, *Esab welding and cutting Journal*, Vol.3, pp.8-11.

S. Kim, J. S. Son, et al., (2002), A Study on Prediction of Bead Height in Robotic Arc Welding Using a Neural Network', *Journal of Materials Processing Technology*, Vol. 130-131, 20 , pp. 229-234.

S. Kim I et al., (1996) 'An Investigation of a Mathematical Model for Predicting Weld Bead Geometry', *Canadian Metallurgical Quarterly*, Vol. 35, PP.385-392.