Study Of Thermal Effect On The Weld Bead Geometry During Fusion Welding

Lecturer Dr. Salah Sabeeh Abed-Alkareem
Department of Machines and Agricultural Equipment
University of Baghdad
(Dr.salah2007@yahoo.com)

Abstract :

This work aims basically to study the thermal effect caused by the weldment surface temperature and welding speed on the main features of weld geometry (bead width and penetration) during fusion welding (GMAW) type TIG for hot rolled low carbon steel type AISI 1025 sheets with 4 mm thickness. Design of Experiment (DOE) with Response Surface Methodology (RSM) is used to predict the influence of these input parameters on the weld bead width and penetration. Mathematical models for the responses are obtained in terms of these welding parameters. Statistical analyses of Variance (ANOVA) are also utilized to verify the adequacy of these models. The results of these quadratic models indicated that both weld bead width and penetration increase with increasing the weldment surface temperature and welding speed. In order to reach the optimum bead width and penetration, numerical optimization is achieved for obtaining better shape of the weld bead geometry. A good agreement is found between the results of these models and optimization with experimental data at confidence level of more than 90%.

Keywords: Temperature, Welding Speed, Fusion Welding, Bead geometry, Modeling, ANOVA.

دراسة التأثير الحراري على الشكل الهندسي في بركة اللحام ألانصهاري

د.م صلاح صبيح عبد الكريم / جامعة بغداد – كلية الزراعة
قسم المكائن والالات الزراعية

الخلاصة

يهدف هذا البحث أساسا" إلى دراسة التأثير الحراري الناتج من درجة حرارة سطح منطقة اللحام وسرعة اللحام على السمات الأساسية لشكل بركة اللحام الهندسي (عرض درزة اللحام والنفاذيه) أثناء عملية اللحام ألانصهاري (لحام القوس المعدني الغازي) لصفائح من الصلب المنخفض الكاربون نـــوع (AISI 1025) بسمك (4 mm). تم استخدام التصميم التجريبي (DOE) مع طريقة السطح المستجيب (RSM) لتنبأ تاثيرهذه العوامل الداخلة على عرض درزة اللحام والنفاذيه. تم الحصول على نماذج رياضية للاستجابات بدلالة متغيرات اللحام. استخدمت أيضا" التحليلات الإحصائية للتباين (ANOVA) للتحقق من ملائمة هذه النماذج . أظهرت نتائج هذه النماذج التربيعية بأن كلا" من عرض درزة اللحام والنفاذية يزداد بزيادة درجة حرارة سطح منطقة اللحام وسرعة اللحام. لغرض الوصول الى امثل عرض لدرزة اللحام والنفاذية ، تم أنجازألامثلية العددية لغرض الحصول على أفضل شكل هندسي لبركة اللحام . وجد توافق جيد بين نتائج هذه النماذج وامثليتها مع النتائج العملية بنسبة موثوقية أكثر من 90 % .

1. INTRODUCTION

Welding is a process with sharply local heating to high temperature and rapid cooling afterwards, during which the temperature highly depends on the time and location, while the mechanical properties of the material varies with the existing temperature, and melting, phase changing and latent heat. To sum up, the weld induced temperature field analysis is a typical nonlinear transient heat transfer issue. During the welding process, the temperatures of different parts of the weldment vary immensely due to the local heating. Consequently, heat transfer occurs both inside the weldment and between the weldment and surrounding. Heat transfer mechanisms can be grouped into three broad categories: conduction, convection and radiation[1]. Previously, many studies have been conducted on screening experiments, modeling, and optimization of welding processes, employed regression analysis in order to induce a linear model between the welding process parameters and weld bead geometry parameters [2 – 10] .While other researchers have used other techniques to develop nonlinear models of the welding process [11,12].

Today, the Gas Metal Arc Welding (type TIG), has played a crucial role in modern manufacturing, such as automobile, aircraft, and high-pressure packing. This process is mainly used for construction, maintenance, and production tasks using steel alloys. The advantages to GMAW are position capability, metallurgical benefits and good quality weld metal deposit. However, the setting of weld parameters requires considerable skill and typically done by the experts. Mechanical properties of weld joint are mainly depend on bead geometry and weld microstructure, which are affected by the metal transfer modes and arc stability in GMAW. The process parameters also affect on the metal transfer modes and arc stability. Thus, establishment of a relationship between weld quality features and the process parameters is necessary. Various statistical techniques, such as regression analysis and Taguchi method are widely used for the mathematical model development in GMAW. Design of Experiments (DOE) has been used extensively in various industries to model and optimize manufacturing processes. In addition, RSM is a powerful technique not only for the prediction of the interested system's responses but also to find the optimum process parameter setting to achieve the desired quality of the optimized process. The conventional experimental design method DOE focuses mainly on the mean of the performance characteristic, whereas RSM method takes the variance into consideration for the model development, since the soft computing techniques, such as Artificial Neural Network (ANN), Genetic Algorithm (GA), Fuzzy Logic (FL) and their combinations provide an alternative solution for predictive learning and modeling of weld bead geometry [13].

In this study, the weld quality depends mainly on two input parameters, namely the welding speed and the temperature measured at the top surface of weldement. These parameters, if not carefully controlled, might result the damage of welding area. Accordingly, the aim of this research is first to obtain mathematical predicted models to link between both the bead width and penetration (responses) with the input parameters applying the Design Expert Software with the RSM technique. The resulted mathematical models will be then statistically analyzed to determine the significance of these input parameters individually in addition to their interactions with the output parameters. An optimization process for the input parameters will be then achieved for the input parameters and responses to obtain their optimum values for the weld geometry.

1.1 Design of Experiment (DOE) Technique

Nowadays, DOE has been more widely used in quality control, manufacturing, and system engineering disciplines for design or development of a new product and redesign of an existing product [14]. Due to the highly competitive global industry, companies need to understand the impact of both operational and environmental variables and their interactions on system or product performance. Therefore, mathematical model–based optimization employing DOE is a powerful design technique for use by system analysts, engineers, and designers. Compared to many methods, DOE is a more efficient method among optimization models in terms of number of required experiments. Its applications and computations are also moretime efficient [15].

Normally the use of DOE technique is combined with RSM and ANOVA statistical tests, as illustrated in the flow chart shown in **Figure.1** [16].

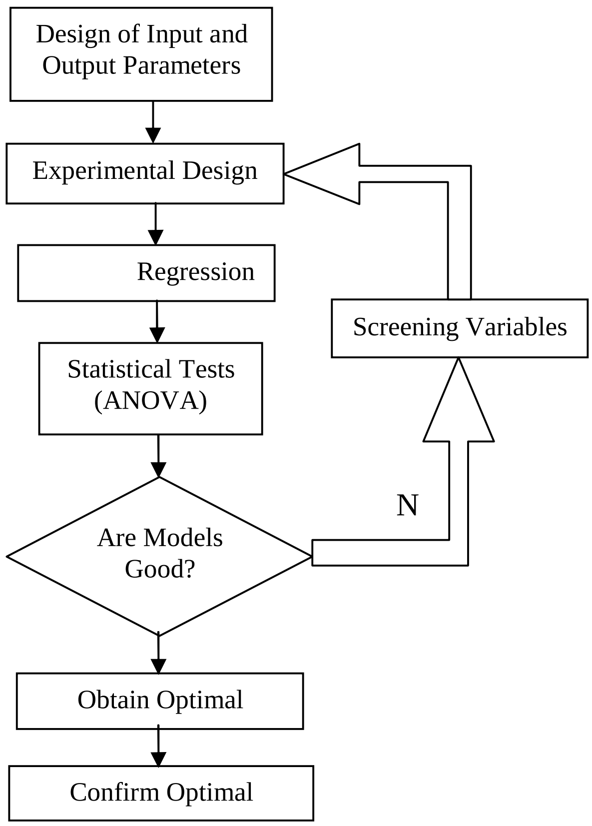

Fig. (1) Flow Chart Procedure of Response Surface Methodology

1.2 Approach of Response Surface Methodology

Generally, the procedure that could be used to find the optimum weld parameters is response surface methodology RSM [17] is defined as a group of statistical and mathematical techniques useful in modeling, improving, and optimizing processes. The general approach of RSM for process optimization [18]includes: Conducting screening experiments; moving the experimental region near the optimal point. The best condition from this step is called “the near-optimal condition”; developing a model within a relatively small region around the optimal point; and finding the optimal settings for process parameters that maximize or minimize the objective function. Due to few studies have been carried out by using the RSM technique for modeling and optimization the weld bead geometry, therefore, the RSM technique was used in the present study to model and optimize both weld bead width and penetration as main responses in terms of welding speed and temperature as main process parameters.

1.3 Weld Bead Geometry in Arc Welding Process

Bead geometry in the arc welding process is an important factor in determining the mechanical characteristics of the weld. Bead geometry variables, such as bead width, and penetration depth are greatly influenced by welding process parameters, such as welding current, welding voltage, welding speed, heat input, temperature and shielding gas. The selection of the appropriate welding process parameters is required in order to obtain the desired weld bead geometry, which greatly influences weld quality, leading to costly and time-consuming experiments to determine the optimum welding process parameters due to the complex and nonlinear nature of the welding process. Therefore, a more efficient method is needed to determine the optimum welding parameters. The typical main features of geometry of the weld bead are shown in **Figure.2**.

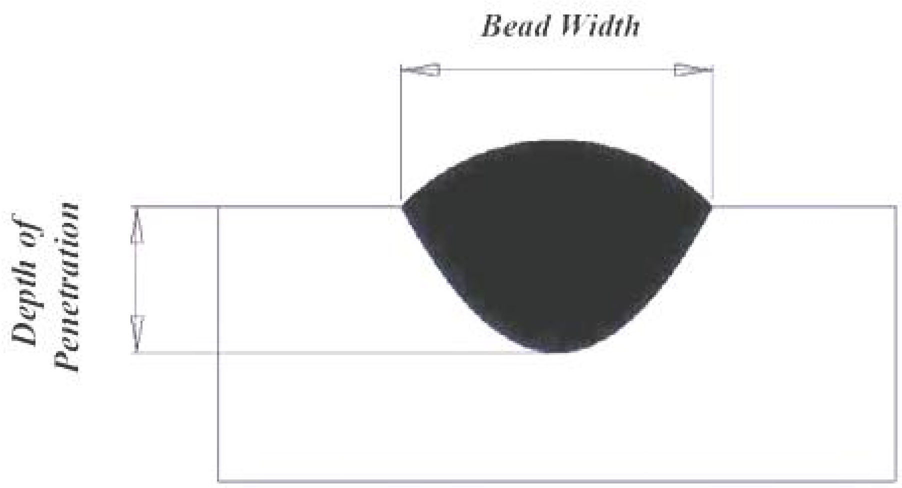

Fig.(2): Typical main Features of Weld Bead Geometry.

2. EXPERIMENTAL WORK

In previous work [19], the test specimens with dimensions of 200 x 60 x 4 mm thick were first prepared form the hot rolled low carbon steel type AISI 1025 and then welded at different welding speeds in a TIG process with a butt-welded joint design. During the welding, the maximum temperature was measured at the top surface of the weldment by an infra red sensor attached to the welding gun, depending on the radiation from the surface. The surface temperature was measured at five different measurement points located anywhere in the coordinate system whose origin is located at the arc center. The welding process was repeated three times for the same welding conditions at the centerline of the base metal, and Ar gas was used for shielding purpose.

After welding was done, the experimental weld bead sizes were obtained by examining the microstructures of the weld sections, which were prepared by cutting and polishing the weldment. The weld pool boundary was obtained by measuring the dendrite area of the microstructure expose to 3% Nital to measure the weld bead width and penetration. Therefore, in order to model and optimize the resulted experimental data obtained for the bead width and penetration (as responses) of the bead geometry, the weldment surface temperature and welding speed were only chosen as input parameters for this purpose, as shown schematically in **Figure.3**. To achieve the modeling and optimizing techniques, the Design of Experiment procedure was decided necessary to be applied in the present research.

In this procedure, a design matrix was used to include the values of input parameters (welding speed and surface temperature) together with the experimental measurements taken from the above mentioned work for the bead width and penetration of bead geometry of the welded sheet from low carbon steel type AISI 1025 in hot rolled condition using TIG welding process. **Table 1** lists these input parameters at two levels. RSM was applied for modeling purpose, using a central composite rotatable design for 2^2 factors, with 5 central points and $\alpha = \pm 2$. The experimental design matrix (5 center points) includes 13 runs carried out randomly at different code levels of −2, −1, 0, +1, and +2. Therefore, welding speed and temperature are used in the experimental design matrix, as input parameters in terms of actual factors with the experimental measured values of bead width and penetration as listed in **Table 2**. The software DESIGN EXPERT 8 was employed to obtain the model and results of predicted model were determined at more than 90% confidence level.

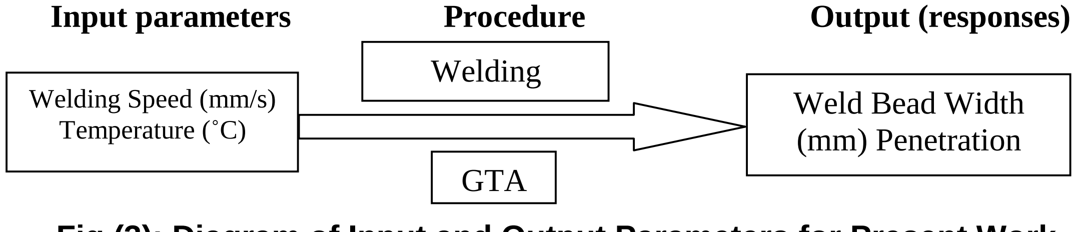

Fig.(3): Diagram of Input and Output Parameters for Present Work.

Table 1: Selected Input Parameters Used in Present Work

Input parameter	Unit	Low Level - 1	High Level + 1	-alpha	+alpha
Welding speed	mm/sec	4	8	2	10
Temperature	°C	725	875	650	950

Table 2: Design Matrix Used for Input Parameters and Measured Responses.

Standard No.	Run No.	Type of point	Welding speed (mm/sec)	Temperature (°C)	Bead width (mm)	Penetration (mm)
1	11	Factorial	4	725	7	2.25
2	13	Factorial	8	725	8	2. 5
3	5	Factorial	4	875	8.5	3
4	8	Factorial	8	875	9	3.5
5	10	Axial	2	800	8	2.5
6	3	Axial	10	800	10	4. 5
7	2	Axial	6	650	7	2. 5
8	1	Axial	6	950	10	6
9	9	Center	6	800	9	3.5
10	7	Center	6	800	9	3.5
11	6	Center	6	800	9	3.5
12	4	Center	6	800	9	3.5
13	12	Center	6	800	9	3.5

3. RESULTS AND DISCUSSION

3.1 Modeling of the Bead Width

The average responses obtained for both bead width and penetration were used in calculating the models of the response surface per response using the least-squares method. For bead width prediction, a reduced cubic model in coded terms was analyzed with backwards elimination of insignificant coefficients at an exit threshold of alpha = 0.1. Some coefficients were removed in order to obtain a formula with actual factors rather than coded ones.

Table (3) shows the statistical analysis of variance produced by the software for the remaining terms. The model is significant for more than 90% confidence. It is noted that the welding speed **(A)**, temperature **(B)**, and the interaction of welding speed and squared temperature**(AB2)** terms are all significant, while the interaction of weelding speed and temperature **(AB)** and squared temperature **(B2)** terms had no significant effect on the bead width. The lack of fit test indicates a good model. This model illustrates that only the three terms **(A, B** and **AB^2)** have the highest impact on bead width. The final equation in terms of coded factors is :

$$\textbf{Bead width} = +8.43 + 0.50 * A + 0.77 * B + 0.063 * A * B + 0.018 * B^2 + 0.19 * A * B^2 \quad \ldots\ldots\ldots\ldots (1)$$

And, the final equation in terms of actual factors is :

Bead width = - 61.27709 + 10.58333 * Welding speed + 0.16273 * Temperature - 0.026250 * Welding speed * Temperature - 9.68450E-005 * Temperature^2 + 1.66667E - 005 * Welding speed * Temperature^2 …………………… (2)

Table 3: Results of Variens Analysis (ANOVA) for Bead Width Model.

Source	Sum of squares	df	Mean square	F value	p-value Prob > F
Model	11.04	5	2.21	154.74	< 0.0001 significant
A-Welding speed	2.00	1	2.00	140.11	<0.0002
B- Temperature	7.13	1	7.13	499.50	<0.0001
AB	0.016	1	0.016	1.09	0.3302
B^2	7.850E003	1	7.850E003	0.55	0.4825
AB^2	0.094	1	0.094	6.57	0.0374
Residual	0.100	7	0.014	-	-
Lack of Fit	0.025	3	8.308E-003	0.44	0.7352 not significant
Purr Error	0.075	4	0.019	-	-
Core Total	11.14	12	-	-	-
Std. Dev. = 0.12			R-Squared = 0.9910		
Mean = 8.44			Adj R-Squared = 0.9846		
C.V. % = 1.42			Pred R-Squared = 0.9720		
PRESS = 0.31			Adeq Precision = 37.987		

Looking at the normal probability plot in **Figure.(4)** or the bead width data, the residuals that generally fall on a straight line implying errors are normally distributed. Also, according to **Figure.(5)** that depicts the residuals versus predicted responses for bead width data, it is seen that no obvious patterns or unusual structure, implying models are accurate.

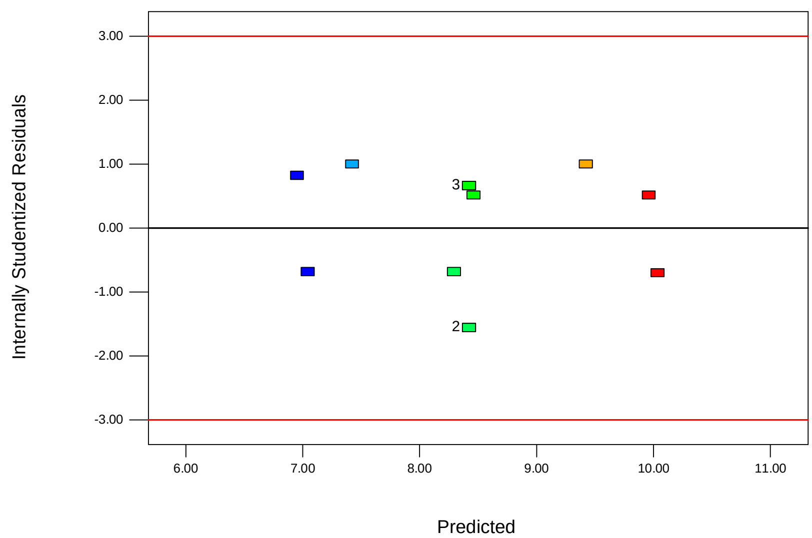

Fig.(4) : Normal Plot of Residuals for Bead Width

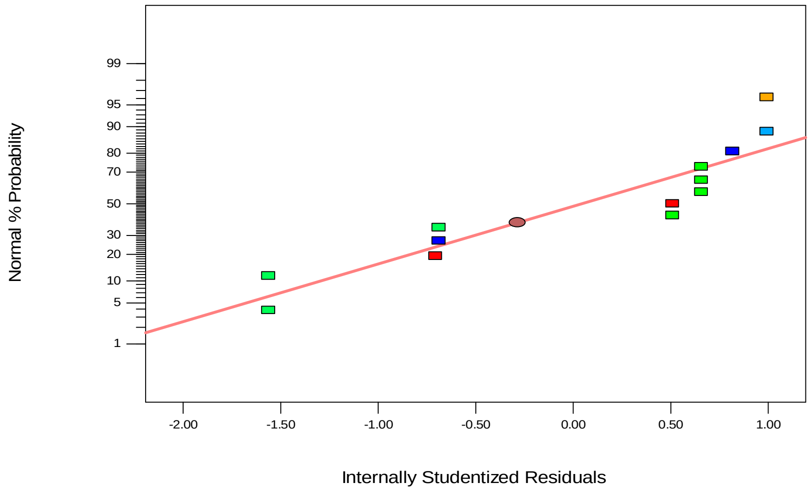

Fig.(5): Residual Versus Predicted for Bead Width.

Figure(6) exhibits that the **2-D** contour graph of welding speed and bead width as a response, and only the two-factor interaction is shown. It is noted that the increase in both welding speed and temperature causes an increase in bead width. This is most probably because higher thermal effect resulted in an increase of the fusion zone of the bead geometry with increasing both temperature and welding speed and their interaction. But, at lower values of these parameters, this thermal effect will be less effective. **Figure (7)** shows the comparison between the predicted actual bead width data versus the actual ones. Whereas, **Figure (8)** depicts the 3-D surface plot of bead width as a function of welding speed and temperature. It can be seen that the individual increase of both welding speed and temperature increases the value of weld bead width. Therefore, it can be concluded that the bead width is smaller at the lowest values of welding speed and temperature, while it is larger at the highest values of these input parameters, due to the more material fusion occurred, indicating that the thermal effect associated with speed influence has the greatest impact in the weld geometry shape. These results are found to be in agreement with the results of previous works [19, 20].

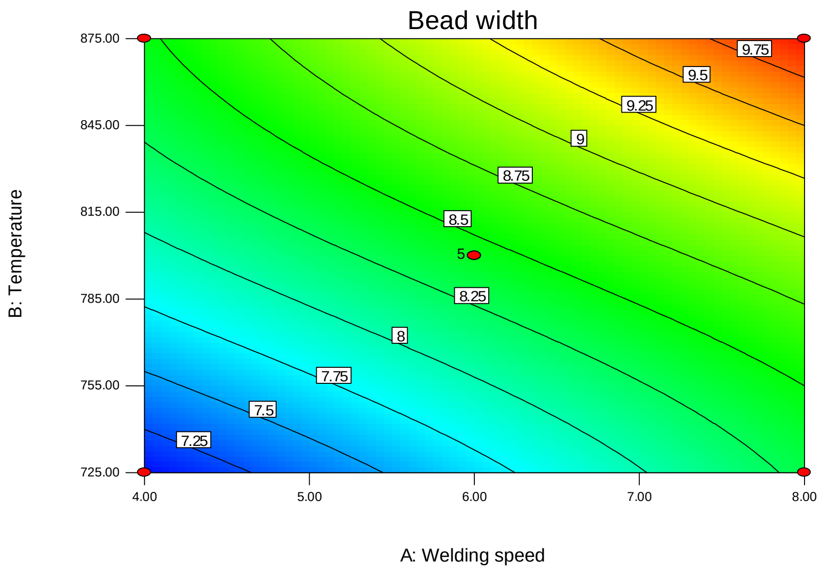

Fig.(6): 2-D Contour of Bead Width at Different Welding Speeds and Temperatures.

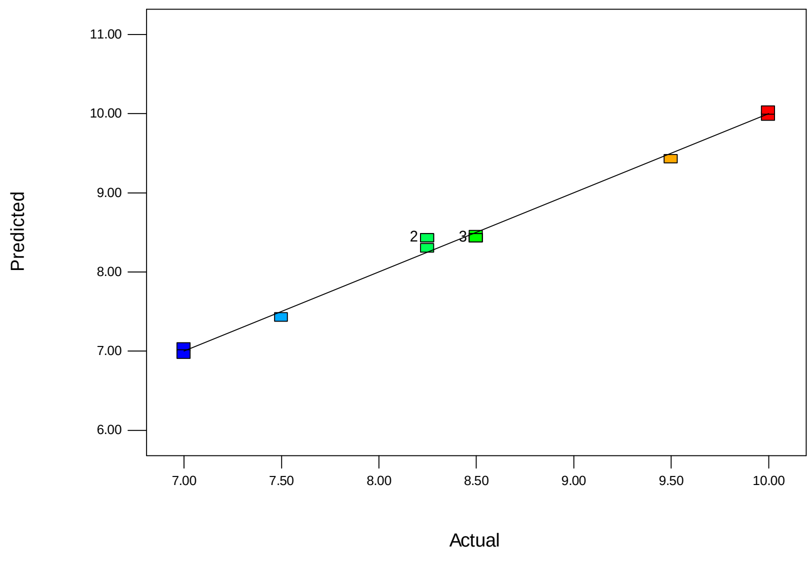

Fig.(7): Predicted Versus Actual of Bead Width.

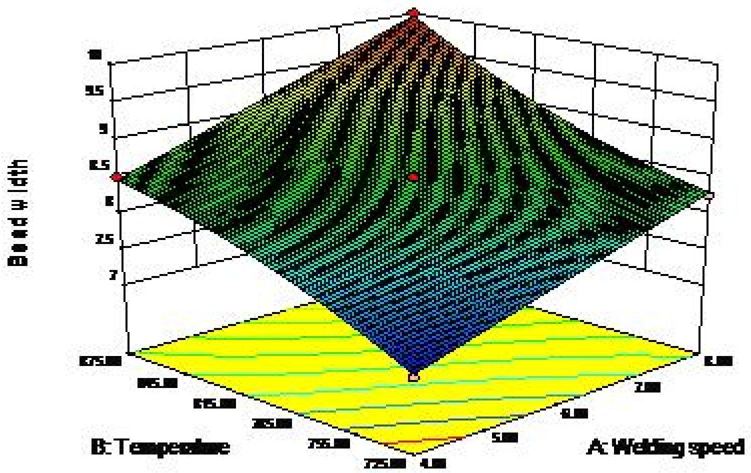

Fig.(8): 3-D Surface Plot of Bead Width at Different Welding Speeds and Temperatures.

3.2 Modeling of the Penetration

In a similar approach , for taken penetration measurements, a reduced cubic model in coded terms was analyzed with backwards elimination of insignificant coefficients at the exit threshold of alpha = 0.1.

Table 4 exhibts the statistical analysis of variance (ANOVA), indicating that this model is significant for more than 90% confidence. It can be noticed that only welding speed **(A)** and temperature **(B)** are both significant. This model manifests that these two terms have the highest impact on the weld penetration. The lack of fit test indicates a good model. The final equation in terms of coded factors is :

$$\text{Penetration} = +3.38 + 0.65 * A + 0.56 * B - 0.062 * A * B - 0.036 * A^2 - 0.25 * A^2 * B \quad \ldots\ldots (3)$$

Final Equation in Terms of Actual Factors is:

$$\text{Penetration} = +17.11574 - 7.23495 * \text{Welding speed} - 0.020000 * \text{Temperature} + 9.58333E\text{-}003 * \text{Welding speed} * \text{Temperature} + 0.65760 * \text{Welding speed}^2 - 8.33333E\text{-}004 * \text{Weldingspeed}^2 * \text{Temperature} \quad \ldots\ldots (4)$$

Table 4: : Results of Variens Analysis (ANOVA) for Penteration Model.

Source	Sum of squares	df	Mean square	F value	p-value Prob > F
Model	7.98	5	1.60	32.67	< 0.0001 significant
A-Welding speed	5.01	1	5.01	102.50	<0.0002
B-Temperature	2.53	1	2.53	51.84	<0.0001
AB	0.016	1	0.016	0.32	0.3302
A^2	0.033	1	0.033	0.67	0.0661
A^2B	0.17	1	0.17	3.41	0.1072
Residual	0.34	7	0.049	-	-
Lack of Fit	0.017	3	5.607E-003	0.069	0.9735 not significant
Purr Error	0.33	4	0.081	-	-
Core Total	8.32	12	-	-	-
Std. Dev. = 0.22			R-Squared = 0.9589		
Mean = 3.35			Adj R-Squared = 0.9295		
C.V. % = 6.60			Pred R-Squared = 0.9282		
PRESS = 0.60			Adeq Precision = 17.208		

Figure(9) illustrates the normal probability plot of residuals for penetration data. It can be seen that the residuals generally fall on a straight, and they are normally distributed. **Figure.(10)** shows that no obvious patterns or unusual structure, implying models are accurate. Refer to **Figure.(11)** for **2-D** contour graph penetration at different welding speeds and temperatures, it can be noticed that increasing both welding speed and temperature generally increases the value of weld penetration. **Figure.(12)** depicts the predicted versus actual penetration data for comparison purpose. **Figure.(13)** shows the **3-D** surface plot of penetration as a function of welding speed and temperature. Accordingly, it is apparently that the rise of both welding speed and temperature caused a higher increase in the weld penetration value, since these input parameters have greatest impact on the weld penetration model. As mentioned before with the bead width model, it can be concluded that the weld penetration is also smaller at the lowest values of welding speed and temperature, while it is larger at the highest values of these parameters due to the larger penetration resulted by the more thermal effect than speed influence, forming larger fusion zone and consequently larger weld bead shape. This result comes in a good agreement with the results of previous researches [19, 21].

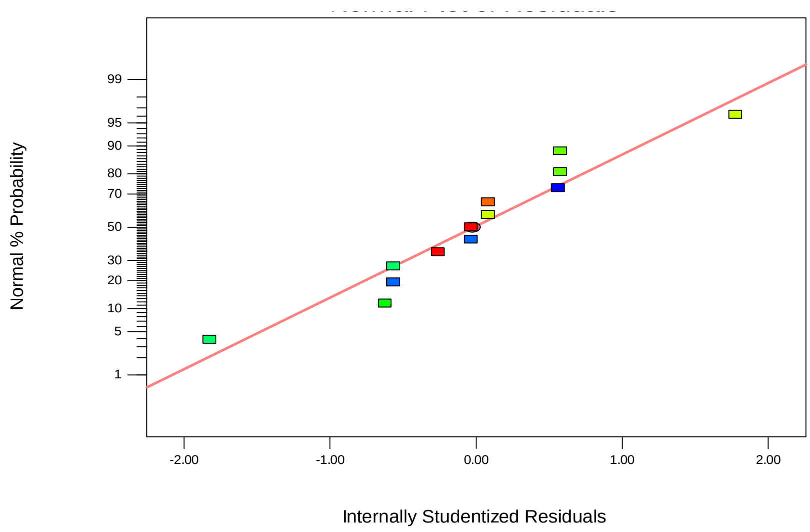

Fig.9: Normal Plot of Residuals for Penetration.

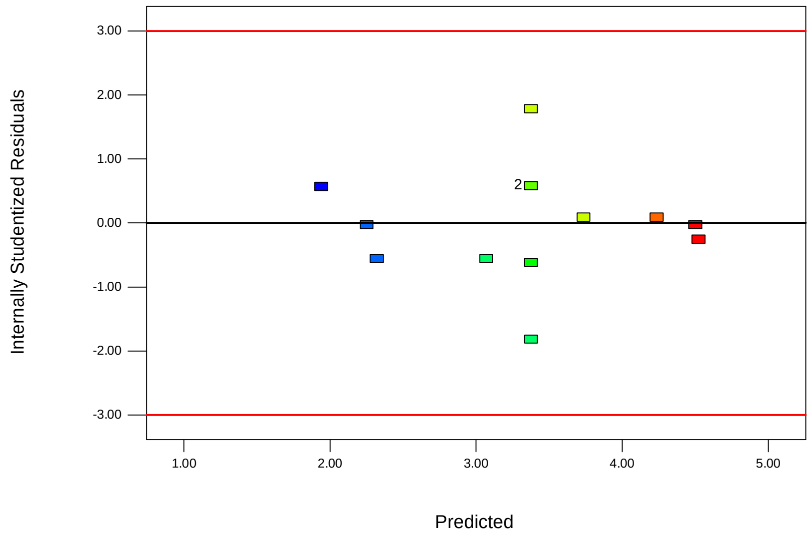

Fig.(10) Residual Versus Predicted for Penetration.

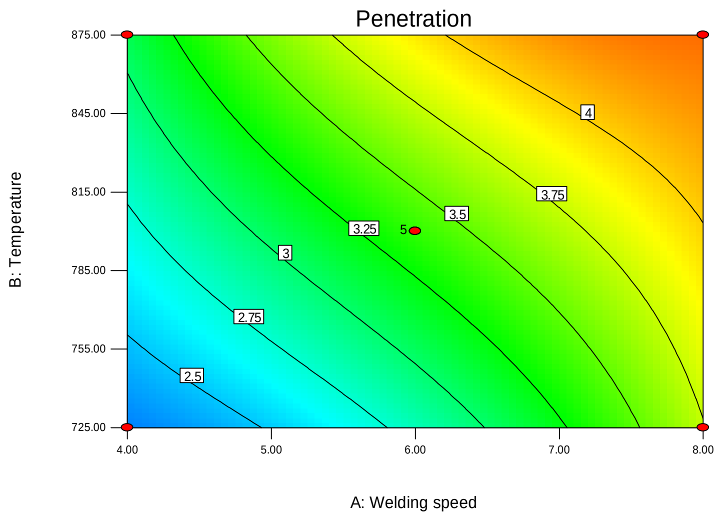

Fig.(11):2-D Contour of Penetration at Different Welding Speeds and Temperatures.

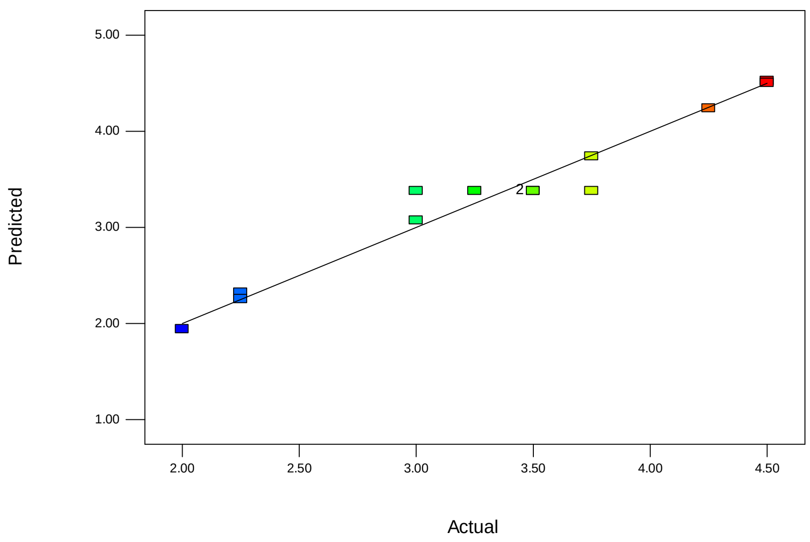

Fig.(12): Predicted Versus Actual of Penetration.

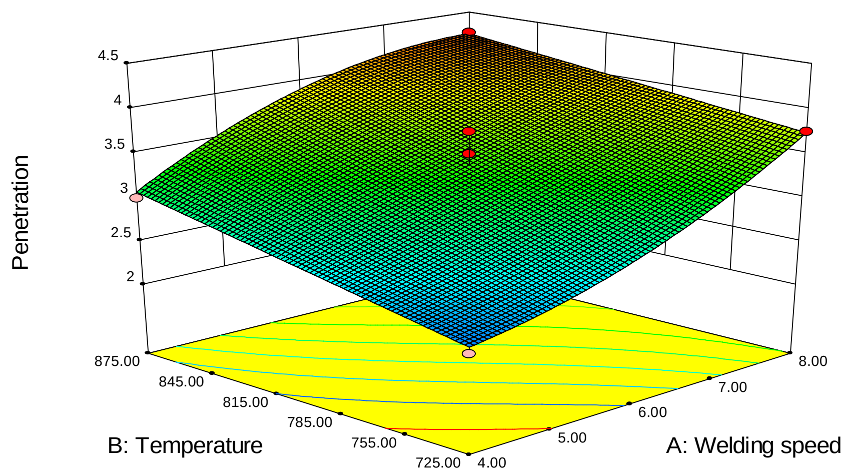

Fig.(13): 3-Dsurface Plot of Penetration at Different Welding Speeds and Temperatures.

3.3 Numerical Optimization of Weld Bead Width and Penetration

The numerical optimization was carried out by using Design of Experiment software to obtain the optimum combinations of parameters. This optimization was based on the data from the predicted models for the weld bead width and penetration, in terms of welding speed and temperature. **Table 5** lists the design summery for the two factors and two responses, showing that the models of both bead width and penetration are quadratic model. To modify the two predicted models, desirability, as an objective function, allows to properly combining all the goals. Desirability was therefore evaluated reaching to be maximized through a numerical optimization, which ranges from zero to one at the goal. In this optimization, both weight and importance were selected to be constant (i. e, weight =1 and importance =3), since the bead width and penetration have the importance and are not in conflict within each other. The aim of this optimization is to determine a good set of conditions that will meet all the goals. The ultimate goal of this optimization was to obtain the maximum response that simultaneously satisfied all the variable properties.

The constrains of each variable for numerical optimization of the weld bead width and penetration are given in **Table 6**, indicating four possible runs satisfied these specified constrains to find the optimum values for weld bead width and penetration. This table showes that all the runs gave desirability of **0.941**. **Figure 14** illustrate the **2-D** countour graph for desirability as a function of temperature and welding speed, while **Fig. 15** exhibits the **3-D** surface plot for desiability as a function of temperature and welding speed. **Figures 16** and **17** show the optimum values of the weld bead width and weld penetration, respectively. These figures illustrate that the desirability reaches the maximum value of **0.941**when the optimum value of bead width is **9.96451** mm **,** and the optimum vaule of penetration is **4.2392** mm.

Table 5: Limits of Each Varaible Used for Numeerical Optimization (Lower Weight= Upper Weight=1, Importance=3).

Types of variables	Goal	Lower Limit	Upper Limit
A: Welding speed	is in range	4	8
B: Temperature	is in range	725	875
Bead width	maximize	7	9.5
Penetration	maximize	2	6

Table 6: Optimium Values Used to Find Maximum Bead Width, Penetration and Desirability.

Solutions Number	Welding speed (mm/sec)	Temperature (°C)	Max .Bead width (mm)	Max .Penetration (mm)	Max. Desirability
1	8.00	875.00	9.96451	4.2392	**0.941 Selected**
2	7.95	875.00	9.9448	4.23872	0.938
3	8.00	871.83	9.91224	4.22862	0.930
4	7.82	875.00	9.89784	4.23597	0.929

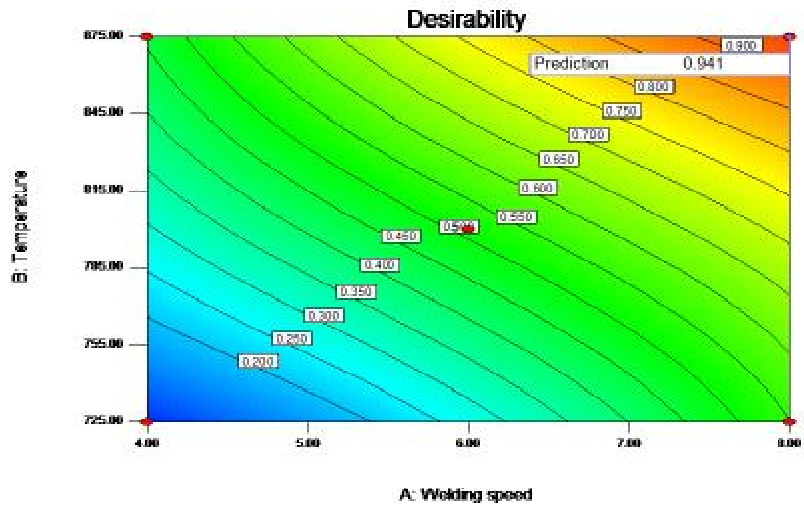

Fig.(14) : 2-D Contour Graph for Desirability as a Function of Temperature and Welding Speed.

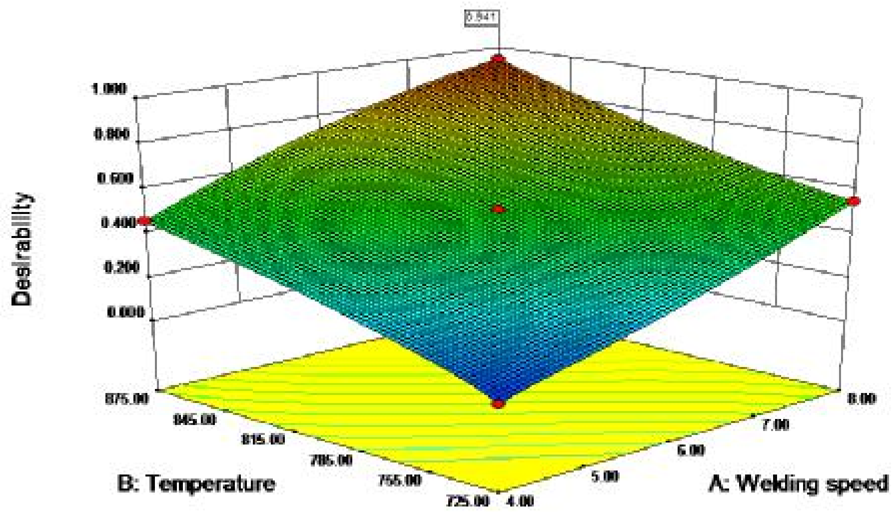

Fig. (15): 3-D Surface Plot for Desirability as a Function of Temperature and Welding Speed.

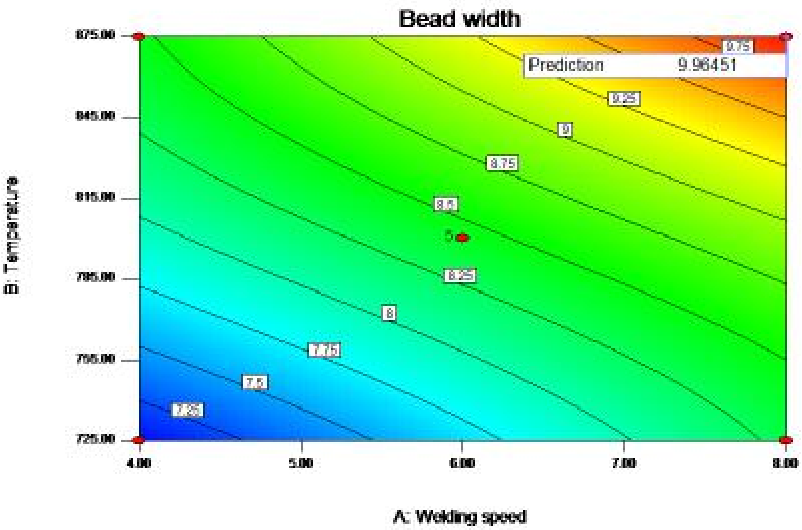

Fig.(16): The Optimum Value of Weld Bead Width.

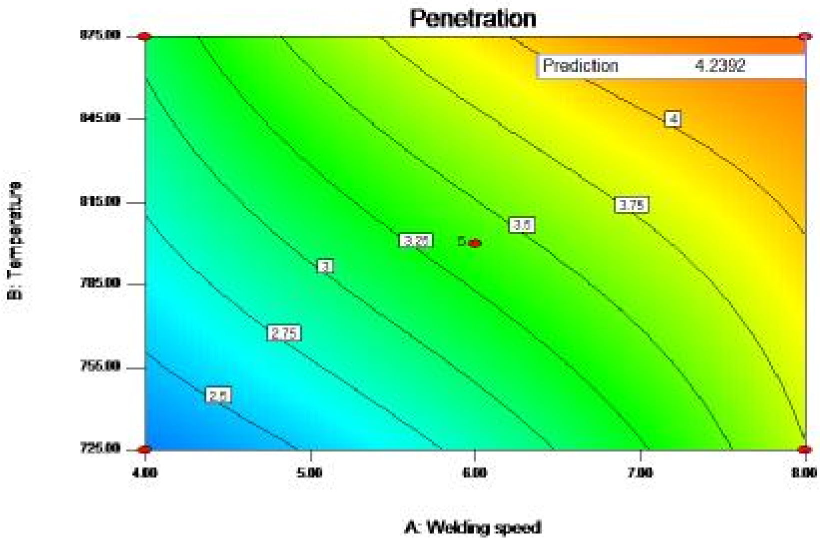

Fig. (17) : The Optimum Value of Weld Penetration

4. CONCLUSIONS

1. RSM can be used effectively in analyzing the Design of Experiment (DOE) technique to obtain the effect of input variables parameters on the geometrical features (bead width and penetration). The RSM is also used to draw the contour graphs for various responses .
2. Quadratic equations for bead width and penetration of the weld pool as a function of welding speed and heat input were developed at level of more than 90% confidence.

3. The bead width equation shows that the welding speed, temperature, the interaction of welding speed and squared temperature have a great influence, and increasing of both welding speed and temperature individually increases the value of weld bead width, indicating that the bead width is smaller and larger at the lowest and highest values of welding speed and temperature, respectively.
4. The quadratic penetration equation shows that the temperature has higher effect on the value of weld penetration than welding speed, resulting that the weld penetration is smaller and larger at the lowest and highest values of welding speed and temperature, respectively.
5. The numerical optimization was carried out to investigate both welding speed and temperature effects.
6. Depending on the DOE response of optimization technique, the maximum value of bead width is **9.96451** mm, while the maximum vaule of penetration is **4.2392** mm, giving the maximum value of desirability **0.941**.

REFERENCES

1. **B . Q . Chen , M . Adak and C. Guedes Soares, "Thermo-Mechanical Analysis of the Effects of Weld Parameters in Ship Plates During Welding Process", ICSOT: Technological Innovations in Shipbuilding, 8-9 Kharagpur, India, 2011.**
2. **Kim, D. and Rhee, S., "Optimization of a gas metal arc welding process using the desirability function and the genetic algorithm", Proce. the I Mech E, Part B, J. Enginee. Manuf.,Vol. 218, No. 1, pp.35–41, 2004.**
3. **Karadeniz, E., Ozsarac, U. and Yildiz, C., "The effect of process parameters on penetration in gas metal arc welding processes", Materials and Design, Vol. 28, pp.649–656, 2007.**
4. **Correia, D. S., Gonçalves, C. V., Cunha da, S. S. and Ferraresi Jr., V. A, "Comparison between genetic algorithms and response surface methodology in GMAW welding optimization", J. Mat. Proc. Tech., Vol. 160, pp.70–76, 2005.**
5. **Ates, H., "Prediction of gas metal arc welding parameters based on artificial neural networks", Materials and Design, Vol. 28, pp.2015–202, 2007.**
6. **H. H. Na, I. S. Kim, B. Y. Kang and J. Y. Shim , "A experiment study for welding optimization of fillet welded structure", Journal of Achievements in Materials and Manufacturing Engineering, Vol. 45, Issue 2, 2011.**

7. Vinod Kumar, " Modeling of Weld Bead Geometry and Shape Relationships in Submerged Arc Welding using Developed Fluxes", Jordan Journal of Mechanical and Industrial Engineering (JJMIE) , ISSN 1995-6665 , Vol. 5, Number 5, PP. 461 – 470, 2011.

8. R. Sudhakaran , V. Vel-Murugan and P . S. Sivasakthivel, "Effect of Process Parameters on Depth of Penetration in Gas Tungsten Arc Welded (GTAW) 202 Grade Stainless Steel Plates Using Response Surface Methodology", TJER, Vol. 9, No. 1, PP. 64-79, 2012.

9. Kondapalli Siva Prasad, Chalamalasetti Srinivasa Rao and Damera Nageswara Rao, " Study on Factors Effecting Weld Pool Geometry of Pulsed Current Micro Plasma Arc Welded AISI 304L Austenitic Stainless Steel Sheets Using Statistical Approach", Journal of Minerals and Materials Characterization and Engineering (JMMCE) , 11, pp.790-799, 2012.

10. R. V. Rao, "Modeling and Optimization of Gas Metal Arc Welding (GMAW) Process", Sardar Vallabhbhai National Institute Technology (SVNIT), India, DOI:10.4018/978-1-4666-0128-4.ch014, Chapter 4, 29 pages, 2012.

11. Meng, T. K., and Butler, C ," Solving multiple response optimization problems using adaptive neural networks", International Journal of Advanced Manufacturing Technology , 13, PP. 666–675, 1997.

12. Tarng, Y. S., and Yang, W. H., "Optimization of the weld bead geometry in gas tungsten arc welding by the Taguchi method", International Journal of Advanced Manufacturing Technology, 14, pp. 549–554, 1998.

13. Sudhakaran R. ,VeL Murugan V. , Senthil Kumar K. M., Jayaram R., Pushparaj A., Praveen C.and Venkat Prabhu N, "Effect of Welding Process Parameters on Weld Bead Geometry and Optimization of Process Parameters to Maximize Depth to Width Ratio for Stainless Steel Gas Tungsten Arc Welded Plates Using Genetic Algorithm", European Journal of Scientific Research ,ISSN 1450-216X , Vol.62 No.1, pp. 76-94 , 2011.

14. DeVor, R. E., Chang, T–h., and Sutherland, J. W. " Statistical Quality Design and Control — Contemporary Concepts and Methods", New Jersey: Prentice–Hall, Inc., pp. 542–562,1992.

15. J. Antony, "Design of Experiments for Engineers and Scientists", ISBN: 0750647094, Elsevier Science & Technology Books, October 2003.

16. http://www.qualitydigest.com/june01/html/doe.html.

17. Montgomery, D. C., "Design and Analysis of Experiments: Response Surface Method and Designs", New Jersey: John Wiley and Sons, Inc., 2005.

18. Myers, R. H., and Montgomery, D. H., "Response Surface Methodology", John Wiley & Sons, Inc., pp. 9–12, 1995.

19. K. S. Boo and H. S. Cho, "Determination of a Temperature Sensor Location for Monitoring Weld Pool Sizes in GMAW", Welding Research Supplement, Vol.73, No.11, pp. 265-271, 1994.

20. Shahnwaz Alam et. al., " Prediction Of Weld Bead Penetration For Steel Using Submerged Arc Welding Process Parameters " , International Journal of Engineering Science and Technology (IJEST) , ISSN : 0975-5462 Vol. 3, No.10 , October 2011.

21. N. Okui, D. K etron, F. Bordelon, Y. Hirata, And G. Clarkearch , " A Methodology for Prediction of Fusion Zone Shape", Welding Journal , PP. 35s – 43s, February 2007 .