IJE TRANSACTIONS C: Aspects Vol. 29, No. 9, (September 2016) 1307-1313

International Journal of Engineering

Journal Homepage: www.ije.ir

Prediction and Optimization of Mechanical Properties of St52 in Gas Metal Arc Weld Using Response Surface Methodology and ANOVA

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PAPER INFO

Paper history:
Received 05 June 2016
Received in revised form 01 July 2016
Accepted 20 July 2016

Keywords:
Gas Metal Arc Weld
Response Surface Methodology
ANOVA
St52
Tensile Strength

ABSTRACT

Many researchers have developed algorithms to predict welding parameters. The variety of welding types is broad because the confine mixture of pressure and temperature could be selected. This paper introduces a response surface methodology (RSM) for optimization and prediction of the influence of Ar and CO_2 gases and electrical current on tensile strength of St52's gas metal arc weld (GMAW) line. After doing experiments the optimum levels of input variables for achieving high tensile strength and contribution of parameters have been obtained by RSM and ANOVA; respectively. In this study the maximum error is 0.44%. Thus it can be concluded that, RSM is one of the best methods and can be used to predict the output parameters and save the time and cost of additional experiments.

***doi**: 10.5829/idosi.ije.2016.29.09c.17*

1. INTRODUCTION

Gas metal arc welding (GMAW), sometimes referred to its subtypes as metal inert gas (MIG) welding or metal active gas (MAG) welding, is a welding process in which an electric arc forms between a consumable wire electrode and the work piece metal (s), causing them to melt and join. The mechanical properties of welding are very important aspect of manufacturing. Because of high quality, gas metal arc welding (GMAW) is one of the best processes in manufacturing due to its high speed and both manual and automatic modes of welding for wide range of ferrous and nonferrous metal parts [1]. St52 is most commonly used for structural assemblies where good weld ability and tensile strength are advantages. The quality of welding work pieces is influenced by input parameters. Because of variety of input parameters the control and optimization of welding process is very difficult then optimization of any welding process is a costly and time consuming task, due to many kinds of non-linear events involved.

One of the most widely used methods to solve this problem is response surface methodology (RSM), because it is easy to estimate and apply, even when little is known about the process. In RSM the experimenter tries to approximate the unknown mechanism with an appropriate empirical model. Identifying and fitting from experimental data, a good response surface model requires some knowledge of statistical experimental design fundamentals, regression modeling techniques and elementary optimization methods [2].

In this research by control of shielding gas percentages (18% CO_2+82% Ar, 2.5% CO_2+97.5% Ar and 100% Ar) and electrical current (155 A, 125 A and 95 A), the tensile strength of St52 was obtained from experimental tests. In the other word we had two factors with three levels. These levels had been confirmed in the previous studies. Then using ANOVA and RSM in Minitab software, the effect of input parameters was investigated on St52 tensile strength. After that, the best value of shielding gas percentage and electrical current was predicted for achieving higher strength.

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Please cite this article as: A. Doniavi, A. Hosseini, G. Ranjbary, Prediction and Optimization of Mechanical Properties of St52 in GMAW Using Response Surface Methodology and ANOVA, International Journal of Engineering (IJE), TRANSACTIONS C: Aspects Vol. 29, No. 9, (September 2016) 1307-1313

2. LITERATURE

In recent years, many researchers have investigated the relationship between the input parameters and output variables. There are many optimization methods like GA, PSO, Taguchi, grey relational and etc, that their applications will be referred in the following studies. The correlation between welding parameters and bead geometry of 3F fillet joint (a vertical weld done using a fillet joint) welded by GMAW in downhill position has been investigated by Tham et al. [3]. A calculator has been developed to display the values of weld bead geometry for any value of welding parameter and vice versa. The comparison between genetic algorithm (GA) and RSM has been done by Correia et al. [4]. The situation was to choose the best values of three control variables (voltage, wire feed rate and welding speed) based on four quality responses (deposition efficiency, bead width, depth of penetration and reinforcement). It was found from their investigation that GA can be a powerful tool in experimental welding optimization, even when the experimenter does not have a model for the process. However, the optimization by GA technique requires a good setting of its own parameters, such as population size, number of generations, etc. Otherwise, there is a risk of an insufficient sweeping of the search space. RSM technique found a better compromise between the evaluated responses than GA [4]. Besides, RSM generated models can be useful in further investigations of the search space, avoiding the experiments with undesired predicted responses. Micro-Macro-characterization and modeling of mechanical properties of gas metal arc welding (GMAW) DP600 steel has been done by Ramazani et al. [5]. Kubiak et al. [6], have done laser and GMAW welding process with experimental verification. They concluded that application of Kriging method in the numerical analysis allows to specify Yb:YAG laser power distribution in more precise way by reproduction of the real thermal load depending on the laser profile obtained for specified industrial laser. From performed analysis it can be observed that two heat sources in hybrid welding process are cooperating in a single welding pool. The geometry of the weld at the top surface mainly depends on the arc heat source. Laser beam heat source determines the weld penetration depth, thus at lower parts the weld is more laser-like. Process parameter optimization of lap joint fillet weld based on FEM–RSM–GA integration technique has been carried out by Islam et al. [7]. This method is able to search for optimum set of process parameters for minimum distortion while ensuring sufficient weld penetration. In this optimization problem, a straightforward solution approach was to run all possible combinations and select the best one as optimum solution. In this approach, obviously the number of combinations will be very large and it would be computationally inefficient and infeasible to try to run all combinations. Using RSM and GA, they achieved optimum results with 75 FE simulations. So, the method was certainly effective for this case study. Zhang et al. [8] have investigated the effect of fluid flow in the weld pool on the numerical simulation accuracy of the thermal field in hybrid welding (Laser and GMAW-P hybrid welding). They found that the convective heat transfer caused by fluid flow has a significant effect on the temperature distribution in the hybrid welding, thus on the thermal cycles, and the coupled model of fluid flow and heat transfer obviously improves the calculation accuracy of thermal cycles.

Xueping et al. [9] have done a numerical analysis of arc plasma behavior in double-wire GMAW and concluded that with the same welding parameters, the pressure on the work piece is less in double wire-GMAW than that in single wire-GMAW and it decreases the occurrence of undercut and humping. The magnetic flux density distribution presents circular in SW-GMAW but elliptic in DW-GMAW. The electromagnetic force deflects to the middle of double welding wires and the maximum value is larger than that in SW-GMAW because of the inter-attraction of double arcs. With the increase of welding current, both inclined angle and maximum arc temperature increase significantly. In addition, the distribution of heat flux on the work piece changes from double-peak to single-peak. As it can be seen in the literature [10-18], other researchers have studied the effects of input parameters on GMAW, using different methodologies. The mentioned researchers have not used RSM in their works for optimization of GMAW. Another method of optimization is particle swarm optimization (PSO). The system is initialized with a population of random solutions. Over several years, PSO has been successfully used in different fields such as objective function optimization, artificial neural network training, fuzzy system control, and other related areas. To improve the performance of the BPNN, GA was adopted to optimize the initial values including the weight factors and thresholds of BPNN by Ai et al. [19]. The collecting experimental results have been utilized to establish the relationship between the welding process parameters and weld bead assessment parameters by GA-BPNN. Based on the predicted results from GA-BPNN, the optimal objective of the weld bead integrity and weld area was formulated and the process parameters were optimized by PSO with the objective function. Nondagopal and et al. [20] have investigated the mechanical properties and optimization of gas tungsten arc welding (GTAW) parameters on dissimilar metal titanium (6Al–4V) and aluminium 7075 by Taguchi and ANOVA techniques and concluded that the maximum tensile strength for the welded sample is 342.20 MPa and the maximum hardness value for the welded sample is 183.10 Hv. Optimisation of laser welding parameters for welding of P92 material using Taguchi based grey relational analysis has been done by Shanmugarajan et al. [21]. They concluded that (1) Taguchi based optimisation of laser welding parameters for autogenous laser welding of P92 material has shown that for the given conditions, 3 kW laser power, 1 m/ min welding speed and positioning the focal plane of the laser at 4 mm from the surface of the base material have evolved as the optimal parameters. (2) From ANOVA, amongst the parameters experimented, welding speed has the most significant contribution with 74.39% followed by laser power with 14.63% and focal length with 10.97%. (3) Microhardness survey across welds with optimised parameter did not indicate any softening in the HAZ/BM boundary and microstructural analysis did not reveal any deleterious phases, which confirms that the parameters obtained through optimisation are valid.

3. RESPONSE SURFACE METHODOLOGY

The procedure of RSM consists of the following steps [2, 14]:

1) Design of experiments (DOE)
2) Development of approximate model
3) Optimization of approximate model
4) Representation of direct and interactive effects of the process parameters through two and three dimensional plots and determination of the optimized results

In step 2, the polynomial function is usually assumed to be the approximate model for the response surface in order to simplify the procedure, when the number of experiments is *n*, a second order model can be expressed by the following matrix equation:

$$Y = X\beta + \varepsilon \tag{1}$$

$$\mathrm{y} = \begin{bmatrix} y_1 \\ y_2 \\ \cdot \\ \cdot \\ y_n \end{bmatrix}, \mathrm{x} = \begin{bmatrix} 1 & x_{11} & \dots & x_{1m} \\ 1 & x_{21} & \dots & x_{2m} \\ . & . & \dots & . \\ . & . & \dots & . \\ 1 & x_{n1} & \dots & x_{nm} \end{bmatrix}, \beta = \begin{bmatrix} \beta_1 \\ \beta_2 \\ . \\ . \\ \beta_n \end{bmatrix}, \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \cdot \\ \cdot \\ \varepsilon_n \end{bmatrix} \tag{2}$$

where *y* is the response vector, *x* is the design variable matrix, *β* is the regression coefficient vector, *ε* is the random error term and *m* is the number of design variables. The details of this method are well described elsewhere [2].

4. EXPERIMENTAL METHOD

In this study an attempt is made to explore the influence of two elements: proportion of shielding gasses Ar and CO_2 and electrical current on welding of St52's tensile strength through GMAWand using Er70S-6 electrode. Because high tensile strength of weld line is considered as best quality property of welding, it is used as response variable in this research. So by control of shielding gas percentages (18% CO_2+82% Ar, 2.5% CO_2+97.5% Ar and 100% Ar) and electrical current (155 A, 125 A and 95 A) and then according to tensile tests, at first in experimental form and then using DOE method by Minitab software the effects of these factors on tensile strength have been examined. Full factorial design of experiments has been used to cover all of states. In statistics, a full factorial experiment is an experiment whose design consists of two or more factors, each with discrete possible values or "levels", and whose experimental units take on all possible combinations of these levels across all such factors. Such an experiment allows the investigator to study the effect of each factor on the response variable, as well as the effects of interactions between factors on the response variable. In this paper, we have two factors with three levels. The results of experiments and DOE have been shown in Tables 1 and 2.

Comparison of three different levels based on increasing electrical current and Ar are shown in Figures 1 and 2, respectively. According to the figures by increasing electrical current and Ar percentage, the tensile strength decreases intensively because in the same temperature the heat coefficient of Ar is lower than CO_2.

5.RESULTS AND DISCUSSION

5. 1. Regression Models for Prediction of Tensile Strength

According to test results, suitable models have been provided for estimation of tensile strength with reliability of 95%. Analysis of variance has been done for modeling and coefficients of variables. Finally the adequacy of modeling has been investigated by residual diagrams.

TABLE 1. The values of input parameters

Electrical current (A)	Percentage of gas	Number of work pieces
95	82% Ar+18% CO_2	1
125	82% Ar+18% CO_2	2
155	82% Ar+18% CO_2	3
95	97.5% Ar+2.5% CO_2	4
125	97.5% Ar+2.5% CO_2	5
155	97.5% Ar+2.5% CO_2	6
95	100% Ar	7
125	100% Ar	8
155	100% Ar	9

TABLE 2. The results of DOE

RUN ORDER	STD ORDER	Ar	I	Tensile strengh
1	4	97.5	95	614.44
2	13	97.5	95	616.25
3	11	82	125	623.00
4	14	97.5	125	629.19
5	3	82	155	624.05
6	9	100	155	476.00
7	16	100	95	598.47
8	2	82	125	624.22
9	12	82	155	626.70
RUN ORDER	**STD ORDER**	**Ar%**	**I**	**Tensile strengh**
1	10	82	95	620.00
2	17	100	125	473.93
3	6	97.5	155	496.05
4	15	97.5	155	510.70
5	5	97.5	125	627.88
6	18	100	155	478.00
7	1	82	95	624.37
8	8	100	125	454.88
9	7	100	95	596.95

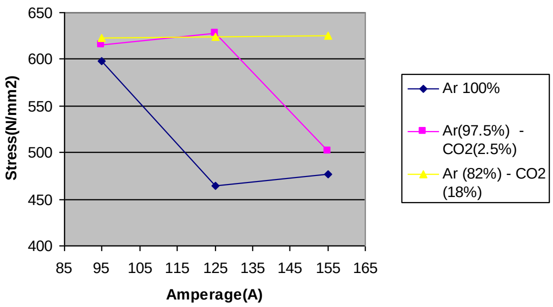

Figure 1. The effect of electrical current on tensile strength

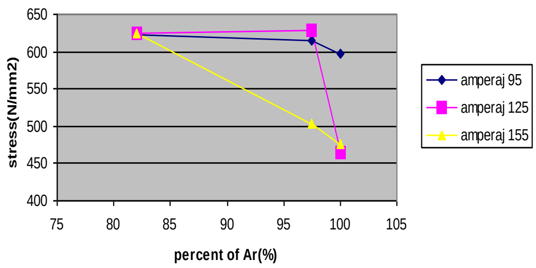

Figure 2. The effect of Ar percentage on tensile strength

The second order model coefficients and the adequacy of them have been shown in Table 3. According to this table the primary model for coding data is:

$$s = 581.542 - 55.34(Ar) - 38.248(I) - 14.038(Ar)^2 + 1.315I^2 - 30.975(Ar) * (I) \quad (2)$$

ANOVA table helps to select suitable coefficients in Equation (2). P and T values should compare with statistic tables for T and P. Firstly the values in ANOVA should be less than statistic table values. Secondly P values should be less than 0.05 to be accepted as a valid coefficient.

According to Table 3, percent of Ar*Percent of Ar and Amperage*Amperage will be removed from Equation (2). Then the final model for coding variables is:

$$S = 5810542 - 55.34(Ar) - 38.248(I) - 30.975(Ar) * (I) \quad (3)$$

Analysis of variance (ANOVA) and residual versus order diagrams for checking of modeling efficiency have been shown in Table 4 and Figure 3, respectively. According to ANOVA table, it has been claimed that the modeling of tensile strength is attributable and reliable.

The efficiency of modeling can be realized from Figure 3. The normal probability plot is in linear form. The residual versus order plot shows that the randomizing has been done well and there is not a meaningful relationship between residuals. The residual histogram is not attributable because the number of tests is low. Residual versus time shows that there is not any meaningful sequence among residuals. The residuals are dispersing. According to Figure 4 it can be seen that the tensile strength decreases with increasing the electrical current and percentage of Ar but due to the slope of the graph, it can be seen that the impact of changes in the amount of argon gas is higher than the amperage changes. The experimental results have been shown with points.

TABLE 3. Estimated regression coefficients

Term	Coef.	SE Coef.	T	P-value
Constant	581.542	19.04	30.539	0.000
Percent of Ar	-55.342	10.43	-5.306	0.000
Amperage	-38.248	10.43	-3.677	0.003
Percent of Ar*Percent of Ar	-14.038	18.07	-0.777	0.452
Amperage*Amperage	1.315	18.07	0.073	0.943
Percent of Ar*Amperage	-30.975	12.77	-2.42	0.032

TABLE 4. Analysis of variance

Term	Coef.	SE Coef.	T	P-value
Constant	581.542	19.04	30.539	0.000
Percent of Ar	-55.342	10.43	-5.306	0.000
Amperage	-38.248	10.43	-3.677	0.003
Percent of Ar*Percent of Ar	-14.038	18.07	-0.777	0.452
Amperage*Amperage	1.315	18.07	0.073	0.943
Percent of Ar*Amperage	-30.975	12.77	-2.42	0.032

To better understand how tensile strength changes by changing the input variables, three-dimensional curved surface is shown in Figure 5. As it can be seen from Figure 5, the maximum amount of tensile strength is obtained when Ar gas percentage is 82% and electrical current is 155 A and the minimum amount of tensile strength is obtained when Ar gas percentage is 100% and electrical current is 155 A.

5. 2. Numerical Optimization of the process

Input variables for desired condition have been shown in Table 5.

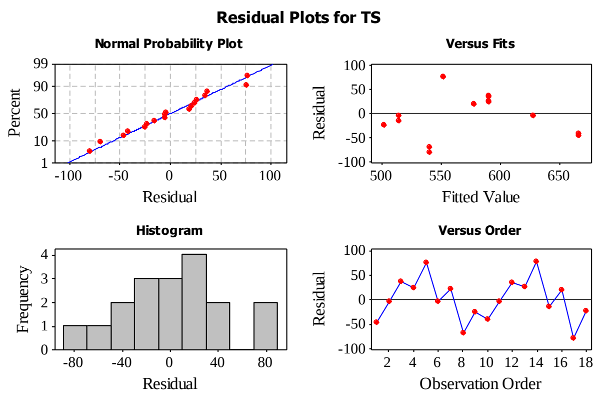

Figure 3. Diagrams for checking of modeling efficiency

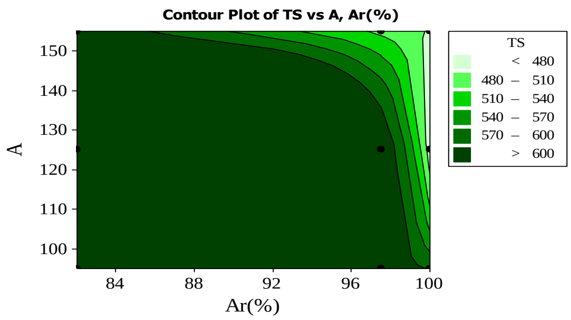

Figure 4. Contour plot of tensile strength versus amperage and percentage of Ar

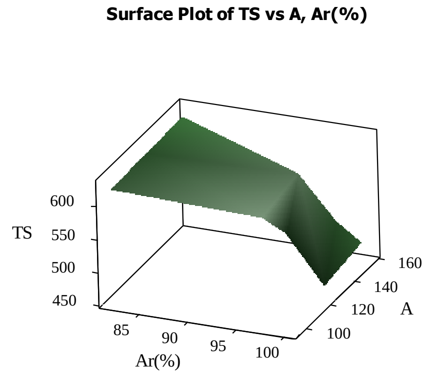

Figure 5. Surface plot of tension strength versus amperage and percentage of Ar.

The output of Minitab software has been shown in Figures 6 and 7. According to Figure 7 and Table 6 the optimum value for tensile strength of weld line, optimum amount of electrical current and percentage of Ar has been obtained. In the other words, the values in Figure 7 have been applied in Table 6. These figures show that both electrical current and percentage of Ar have opposite effect on tensile strength.

The evaluation of modeling and optimization has been done by five experiments that is shown in Table 7. According to Table 7, there is a good accordance between the experimental and predicted values. The maximum error is 0.44 %.

TABLE 5. Target variables of tensile strength

Res	Tar	Min	Tar	Max	Weight	Importance
Tensil strength	Max	400	650	650	1	1

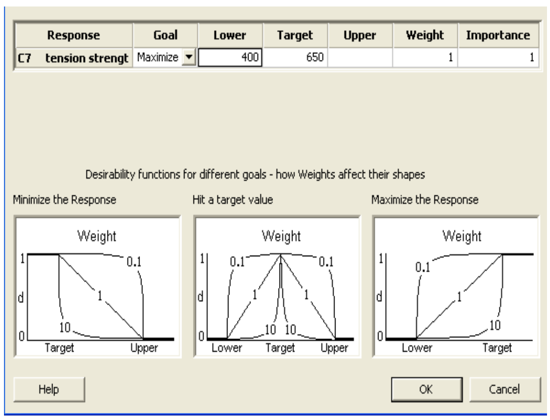

Figure 6. Desirability functions for different goals

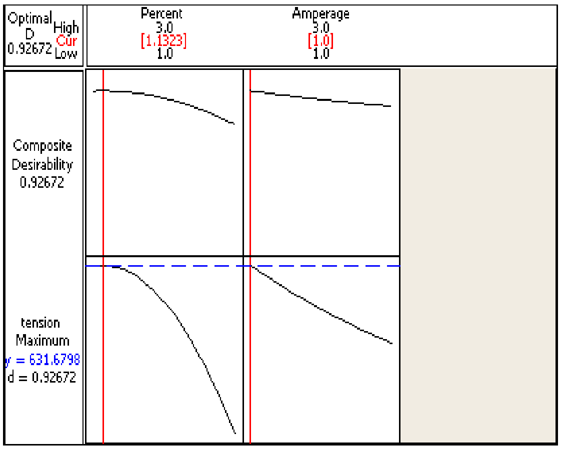

Figure 7. The optimum value for tensile strength

TABLE 6. The results of optimization

Percentage of Ar	Electrical current	Estimated value	Desirability
Ar 84.75% + CO_2 15.25%	95	631.6798	92%

TABLE 7. The evaluation of optimization

	Ar%	I	Exp. value	Predicted value	Error%
Tensile strength	Ar 84.75% + CO_2 15.25%	95	628.9	631.6798	0.44%
	Ar 84.75% + CO_2 15.25%	100	619	620.19	0.19%
	Ar 90% + CO_2 10%	125	608.9	610.4	0.24%
	Ar 85% + CO_2 15%	95	625.9	628.2	0.36%
	Ar 87% + CO_2 13%	95	623.4	620.9	0.2%

6. CONCLUSION

This study carried out an optimization and proposed a prediction model to investigate the weld line tensile strength based on electrical current and percentage of Ar gas in GMAW using RSM and ANOVA. The study not only presents a model to predict the tensile strength but also optimize the process for achieving the higher strength value. The lower the temperature difference between the weld HAZ areas is the lower tensile stress in weld line. It is due to slower heat transfer and uniform solidification. Then less temperature difference between the weld line and the surrounding area will increase weld strength. It can be achieved with increasing the amount of CO_2 percentage. In this study the maximum error between predicted and experimental values for tensile strength is 0.44%. Thus it can be concluded that, RSM is one of the best methods of optimization and it can be used to predict the output parameters and save the time and cost of additional experiments.

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P A P E R I N F O

Paper history:
Received 05 June 2016
Received in revised form 01 July 2016
Accepted 20 July 2016

Keywords:
Gas Metal Arc Weld
Response Surface Methodology
ANOVA
St52
Tensile Strength

چکیده

الگوریتم های فراوانی در مطالعات اخیر جهت پیش بینی پارامترهای موثر در فرایند جوشکاری ارائه شده است.در این مقاله با و مطالعه تاثیر مقدار گازهای آرگون و دی اکسید کربن، به پیش بینی و بهینه سازی استحکام کششی RSM استفاده از روش و RSM پرداخته شده است. پس از انجام آزمایشات سطوح بهینه پارامترهای ورودی توسط GMAW در فرایند St52 فولاد یکی از RSM بدست آمده است.در این مقاله بیشترین مقدار خطا ۰.٤٤٪ میباشد. بنابراین میتوان نتیجه گرفت ANOVA بهترین روشهای بهینه سازی در فرایندهای ساخت و تولید است که منجر به صرفه جویی در هزینه و زمان تولید خواهد شد.

doi*: 10.5829/idosi.ije.2016.29.09c.17*