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Predictive Model for Tensile Ductility and Optimization of Process Variables for Arc-Welded and Tempered Micro-alloyed Steel

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***Abstract*— The over reliance on trial and error technique by many engineers/welders in the selection of optimum conditions of welding and heat treatment process variables to maximize the mechanical properties of steel weldment for enhanced performance in service has always been a huge challenge. Therefore, to avoid this time consuming practice, which most often do not produced welds with satisfactory quality in terms of fitness for service and cost. This research study has therefore, provides a systematical approach in developing an appropriate mathematical relationship between the process and response variables, with an optimization method for finding the welding and heat treatment process variables to maximize tensile ductility of the arc-welded and tempered micro-alloyed steel. The response surface methodology based on optimal design was employed to model and optimize the process variables. The results of the analysis of variance of the developed model for percent elongation indicated that it is statistically significant at p<0.0001. The regression coefficient (R2) and adjusted coefficient (R2adj.) values of 97.77% and 95.76% respectively, indicate that the developed model can adequately approximate the actual response data in the design space, and a proof that it is valid. Predicted and experimental results of the validation tests were found to be in reasonable agreements. This implies that the optimization technique adopted was reliable. The optimum input values of the process variables that resulted in maximum percent elongation of 29.523% in the micro-alloyed steel weldment were welding current setting of 101.408amps, tempering temperature of 4500C and soaking time of 120.0003 minutes.**

***Index Terms*— Micro-alloyed steel. welds, optimization, percent elongation..**

I. INTRODUCTION

Welding is a term used to describe a wide range of processes for joining metals/alloys or plastics by fusion or coalescence of the interface. It involves bringing two surfaces together under condition of pressure or temperature which allows bonding to occur at the atomic level. Usually, this is accompanied by diffusion or mixing across the boundary, so that in the region of the weld an alloy is formed between the two pieces that have been joined. The economics inherent in welding are helping to offset increase in the prices of material and cost of labour. In addition, the shortened production cycles made possible by welding, have helped to accelerate the pace of construction. All metals can be welded but not by the same welding process. Micro-alloyed steel present a good combination of strength and ductility (Villalobos *et al.,2018*). It can be welded by all the conventional welding processes due to its low carbon equivalent values. Adopting the appropriate welding procedure should result in welds with mechanical properties meeting the same requirements for strength, toughness and ductility as the based metal, and at the same time free from welding defects likely to cause premature failure of welded components in service. Although, in true sense, welded joints having the same matching properties with the parent metal can rarely be achieved because of the thermal gradient introduced in the welded metal due to the localize heating, leading to uneven cooling cycles. This differential in heating and cooling cycles has significant effects on the final transformation products formed at the different zones of the steel weldment. In the light of the forgoing, many seasoned researchers have suggested the application of post weld heat treatment in order to produceweldment with the desired microstructure and required mechanical properties for improved performance, and also to reduce the risk of brittle failure in service as a result of the lock in welding residual stresses in the welded component. Selecting the appropriate welding current and heat treatment variables that could be utilized to improve the mechanical properties of steel weldment to meet service requirement has always been a huge challenge to the engineers and welders. Most engineers and other practitioners do rely on trial and error technique to select welding and heat treatment variables to produced welded joints,which is time consuming and most often do not produced welded joint with satisfactory weld quality. Based on this, several statistical tools has been developed and used in improving and optimizing products and processes. One of such tools is the response surface methodology.

Theresponse surface methodology (RSM) have been extensively used in many experimental research activities in the field of engineering sciences, biological sciences, food sciences etc., to develop an appropriate approximating relationship between the response and the process variables, and optimization methods for finding the values of the process variables that produced desirable values of response (Edoziuno*et al., 2020*; Palanivel*et al., 2010*; Bradley 2007).With the high level of confidence in which developed models predicted results has closely agreed with experimental results, it is believed that in the near future the

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RSM will gain wide application in many other fields.Empirical modelling is important because it allows some rather expensive and repetitive runs of experimentation to be avoided (Turner and Perre, 1994). Thereby reducing the huge cost that could have been incurred if several experimental trial runs were to be performed.

Several investigators have used RSM to developed models for predicting the mechanical properties of many welded metallic materials, and conducted optimization to find the best welding conditions to maximize the mechanical properties of interest.

Kumar and Gandhinthan (2020) while reviewing the application of Taguchi method in optimization of the process parameters to maximize tensile strength and percent elongation of MIG welded AISA 1018 mild/low carbon steel joints, concluded that increased in welding speed increases tensile strength. Pandya and Menghani (2018) in theirconfirmation tests for the developed models for evaluating the tensile properties of AA6061-T6 aluminium alloy welded to pure copper using friction stir process. They established that the percent error between the predicted and experimental values are within -3.55 to +4.85%. Shamsudeen and RajaDhas (2018) showed that the optimal values of input parameters to maximize the tensile strength and hardness of friction stir welded AA 5052-H32 aluminium alloy are pin profile (tapered square), rotational speed (600rpm), welding speed (60mm/min) and tool tilt angle (1.9^0). They also, showed that the developed models can effectively estimate the responses at a confidence level of 95%. Balasubramanian (2015) developed mathematical model equations for pulsed tungsten inert gas welding of titanium sheets and concluded that the mathematical relationships developed can be employed easily in automated welding in the form of a program, for obtaining the desired weld bead dimensions. Vishnu and Sujith (2014) developed an empirical relationship to predict the tensile strength of friction welded AISI 1035 steel rods, and optimized the independent parameters to maximize the output parameter (tensile strength).The analyzed model gave a confidence level of 95%. They also showed that the optimum conditions that can be utilized to attain a maximum tensile strength of 548.6767 MPa in the welded steel rods are 28.9394 MPa/s of pressure time, 29.5455 MPa/s of upset pressure/time and 24.3636 MPa/s of rotational speed. Sapkal and Teslang (2012) applied Taguchi technique to optimize the input parameters(welding current, voltage and welding speed) to obtained maximum depth of penetration on mild steel. Haragopal*et al.* (2011) optimized the process variables for enhancingthe mechanical properties of aluminum alloy joints produced using metal inert gas process. The experiments was conducted according to L9 orthogonal array. It was concluded that current was the most significant factor on ultimate tensile strength and pressure for impact energy. Padmanabhanand Balasubramanian (2011) optimized the pulsed tungsten inert gas parameters in using GRA to achieve maximum tensile strength on AZ31B magnesium alloy. Hakan*et al.* (2010) carried out optimization of friction stir welding process to find out the optimum input factors to obtain the desired tensile strength and elongation using the Taguchi based Grey relational analysis.

Therefore, the present research work is aimed at developing anempirical model for predicting tensile ductility (percent elongation) of arc-welded and tempered micro-alloyed steel,and optimizingthe welding and heat treatment process variables to obtain welds with optimal response value in the experimental domain. Tensile ductility refers to the capacity of a material to undergo appreciable deformation under tension before failure. It is usually expressed quantitatively as percent elongation. Adequate ductility is an important engineering consideration, because it allows the material to redistribute localized stresses (Dieter 1988).

II. Materials and Methods

The materials and equipment used in the research study were: Micro-alloyed steel plate (5mm thickness), shielded metal-arc welding machine, electrode (E7018), electrode drying oven, stop watch, digital multimeter, metallurgical cut-off wheel and tensometer. The chemical composition of the micro-alloyed steel are shown in Table 1.The full details of the experimental procedures are presented in Adzor (2020).

Table 1: Elemental composition of test material (wt%)

Composition Material	C	Si	P	S	Ti	AL	Cr	Mn	V	Nb	Zn	Cu	N	Ca	Fe
Micro-alloyed steel	0.15	0.40	0.05	0.03	0.01	0.02	0.08	0.35	0.12	0.03	0.002	0.16	1.1	0.001	97.00

2.1Design matrix and response surface methodology

After careful screening of the vital factors (welding current, soaking time temperature).The optimal (custom) design was chosen because of it flexibility in accommodating different number of levels for each factor and also, placing equal emphasis on estimating main effects and interactions.The independent design variables with the corresponding design levels based on optimal design used in the research study are listed in Table 2. The maximum and minimum values for each of the independent variables were chosen based on preliminary studies carried out. The welding current range (90-102 ampere) selected for this study was based on the current range specified for the electrodes by the manufacturers. The tempering temperature range ($250\text{-}450^0$C) and soaking time (60-120 min.) were selected so as not to cause excessive decrease in hardness and strength of the micro-alloyed steel weldment while improving tensile ductility(percent elongation). The whole design consisted of 20 experimental runs as listed in Table 3. The experiments were performed at all the design points in randomized order.Each factor was replicated more than once in order to obtain a more stable average result. The RSM design on the three factors were generated with the aid of Design-Expert version10 software (2016).

Table 2.Factorsand levels for optimal design

Variable	**Unit**	**Level**			
		1	2	3	4
Current	amp.	90	94	98	102
Soaking time	min.	60	90	120	
Temperature	^{0}C	250	350	450	

Table 3: Experimental design for the welding and heat treatment of micro-alloyed steel

Run	Factor 1 Current (amps)	Factor 2 Soaking Time (min)	Factor 3 Temperature (^{0}C)	Response 1 Elongation (%)
1	102	120	450	
2	90	120	450	
3	94	120	350	
4	94	90	450	
5	90	90	350	
6	102	120	250	
7	94	120	350	
8	94	90	450	
9	98	60	350	
10	90	120	250	
11	102	120	350	
12	102	90	350	
13	98	60	250	
14	102	90	350	
15	94	120	350	
16	90	90	250	
17	90	60	350	
18	98	90	250	
19	102	60	450	
20	90	90	450	

III. RESULTS AND DISCUSSION

The results of the research work are presented in Tables 4 and Figures 1-5.Table 4 shows the percent elongation values with the corresponding welding and heat treatment process variables.Through multiple regression analysis on the experimental data, the predicted response (percent elongation) was expressed by the second-order polynomial equation in terms of coded values (Equation 1).

Table 4: Design matrix and corresponding percent elongation

Run	Current (ampere)	Soaking Time (min)	Temperature (^{0}C)	Elongation (%)
1	102	120	450	29.8
2	90	120	450	27.4
3	94	120	350	25.9
4	94	90	450	27.5
5	90	90	350	24.5
6	102	120	250	26.5
7	94	120	350	25.9
8	94	90	450	27.5
9	90	60	250	22.8
10	90	120	250	25.2
11	102	120	350	26.9

12	102	90	350	26.7
13	98	60	250	23.6
14	102	90	350	26.7
15	94	120	350	25.9
16	90	90	250	24.5
17	98	60	350	25.6
18	98	90	250	25.7
19	102	60	450	29.3
20	90	90	450	26.8

3.1 Statistical analysis of predictive model

The statistical testing of the model was performed in the form of analysis of variance (ANOVA). The ANOVA for the fitted quadratic polynomial model of percent elongation is shown in Table5. The quadratic regression model shows the value of coefficient determination (R^2) of 97.77%.This implies that the model was able to explain 97.77% of the results. Bradley (2007) posited that when the R^2 value is closer to 1 (100%), the better the estimation of the regression equation fits the actual data. Themodel adequacy precision value of 24.322indicates a very strongcorrelation between the response and the independent variables. The significance of the model was also judged by F-test. The high model F-value (F= 48.68) greater the P-value is a further demonstration of it significant. The adjusted R^2 of 95.76%, implies that only 4.24% of the total variations was not explained by model. However, the relatively lower value of coefficient of variation (CV = 1.28%) in Table 5.1validate the precision and reliability of the experiments carried out.

Table 5: ANOVA result for percent elongation model

Source	Sum of Square	Df	Mean Square	F value	P-value Prob>F	
Model	47.11	9	5.23	48.68	< 0.0001	Significant
A-Current	9.69	1	9.69	90.14	< 0.0001	
B-Soaking time	3.85	1	3.85	35.78	< 0.0001	
C-Temperature	25.11	1	25.11	233.53	0.6049	
AB	0.031	1	0.031	0.29	0.4560	
AC	0.63	1	0.63	5.88	0.0357	
BC	0.63	1	0.63	5.84	0.0362	
A^2	0.050	1	0.050	0.46	0.5124	
B^2	0.013	1	0.013	0.12	0.7378	
C^2	3.64	1	3.64	33.84	<0.0002	
Residual	1.08	10	0.11			
Lack of Fit	1.08	5	0.22			
Pure Error	0.000	5	0.000			
Cor Total	48.19	19				
R-Squared = O.9777			Adj R-Squared = 0.9576			
Predicted R-Squared = 0.6771			Adequate Precision = 24.322			

Table 5.1: Statistical summary of the model for percent elongation

Std. Dev.	0.33	R-Squared	0.9777
Mean	26.34	Adj R-Squared	0.9576
C.V. %	1.24	Pred R-Squared	0.6771
PRESS	15.56	Adeq Precision	24.322
-2 Log Likelihood	-1.70	BIC	28.25
		AICc	42.74

In terms of coded and actual factors, the prediction of percent elongation is expressed by equation (1).

$$\%Elongation=+25.60+0.98*A+0.62*B+1.59*C-0.073*AB+0.34*AC-0.35*BC+0.13*A^2-0.054*B^2+0.88*C^2 \quad (1)$$

3.2 Graph of predicted versus actual results

Figure 1 shows the plot of predicted versus actual values for percent elongation. The graph indicates that there is strong correlation between the predicted and actual results. The closeness of the predicted and actual values along the regressed diagonal line justified the correlation of these values. Closer points along the diagonal line indicate more significant model fits and is associated to high R^2 value (Sympa, 2014). Therefore, the high values of R^2 and adjusted R^2 in Table 5 validate the model significant and its predictive capacity. In addition, the high values of R^2 and adjusted R^2 of the model indicated that only 4.24% of the variation that was not explained by the model.

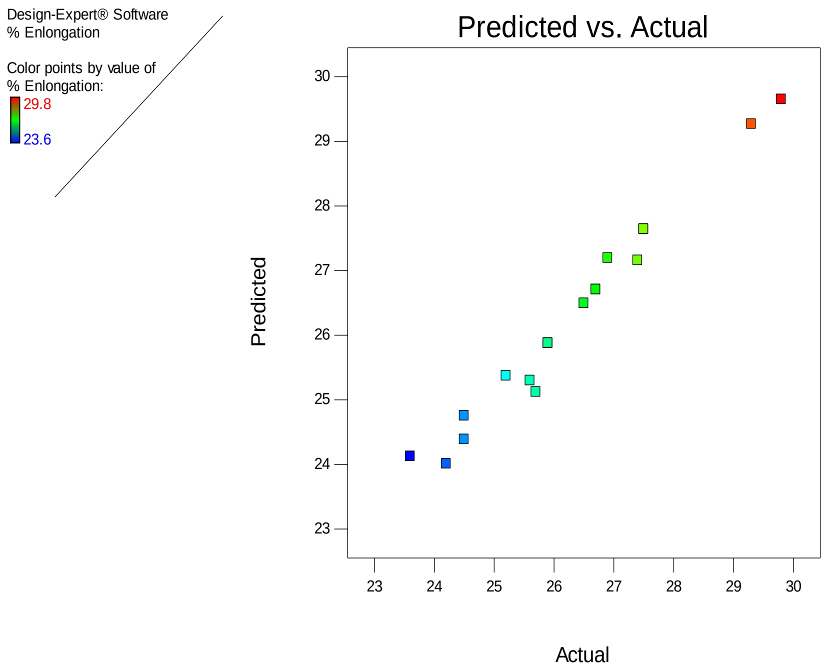

Fig. 1: Plot of predicted versus actual value of percent elongation

3.3 Perturbation plot results

The perturbation plot helps to compare the effects of all the variable factors at a particular point in the design space. The response is plotted by changing only one factor over its range while holding all the other factors constant. The plot is used to find the factors that affect the response most (Design-Expert Stat-Ease, 2018). Figure 2: shows the perturbation plot of welding current, soaking time and temperature on percent elongation. The nature of the curvature displaced by the individual factor shows that the three factors affected the response (percent elongation) although at different degree. However, the results of the analysis of variance (Table 5) depicts that welding current and soaking time had profound influence on the response based on their lower probability values (P<0.0001). Whereas temperature showed no influence on the response as indicated by P>0.1.

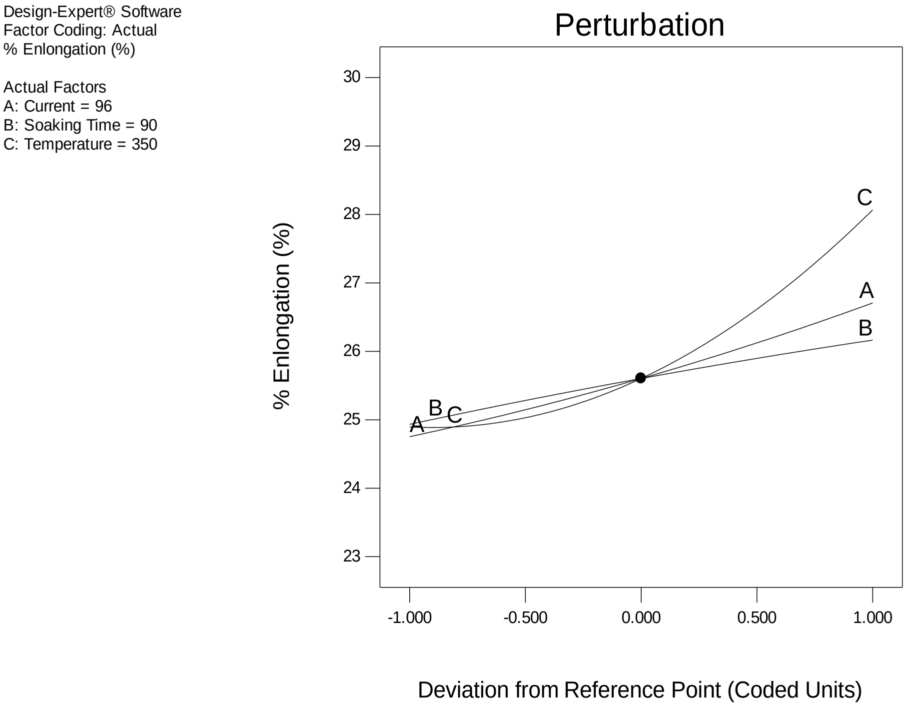

Fig. 2: Perturbation plot of welding current, soaking time and temperature on percent elongation.

3.4. 3D response surface plot result

Figure 3 showsgraphically the interaction effects of temperature and soaking time on percent elongation. The elliptical nature of the plot suggest mutual interaction existed between the two variable factors. Hazard *et al.*, (2007) reported that an elliptical plot indicates that interaction existed between the factors. The probability value ($P<0.05$) of the interaction factors (BC) as shown in Table 5 infers that the interaction factors (BC) had substantial effect on the response.

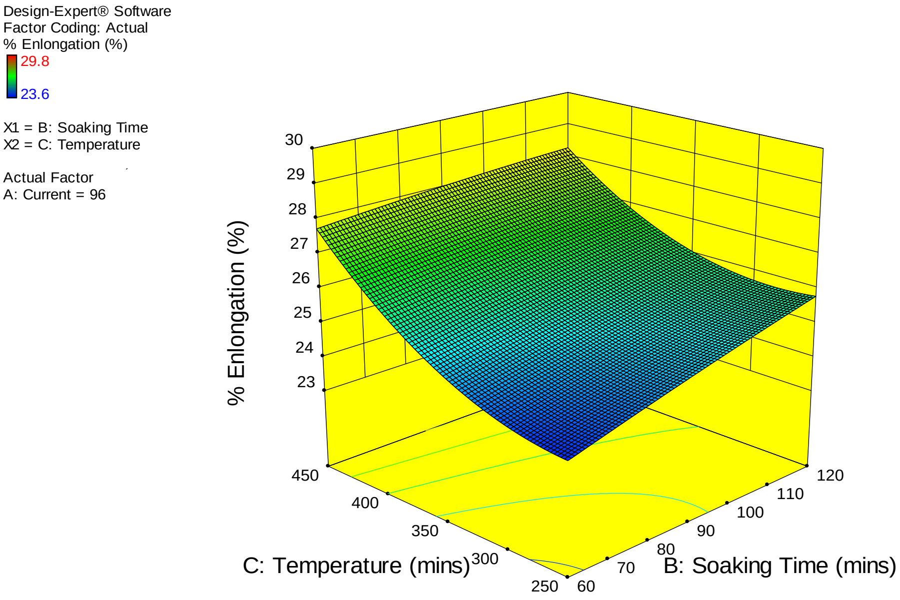

Fig. 3: 3D response surface plot of temperature and soaking time on percent elongation

Figure 4 shows graphically the interaction effect of the variable factors (welding current and soaking time) on percent elongation. The elliptical nature of the plot entails mutual interaction existed between the two variable factors. However, the probability value ($P>0.1$) of the two variable factors (AB) indicates that the interaction factors are less sensitive to the response.

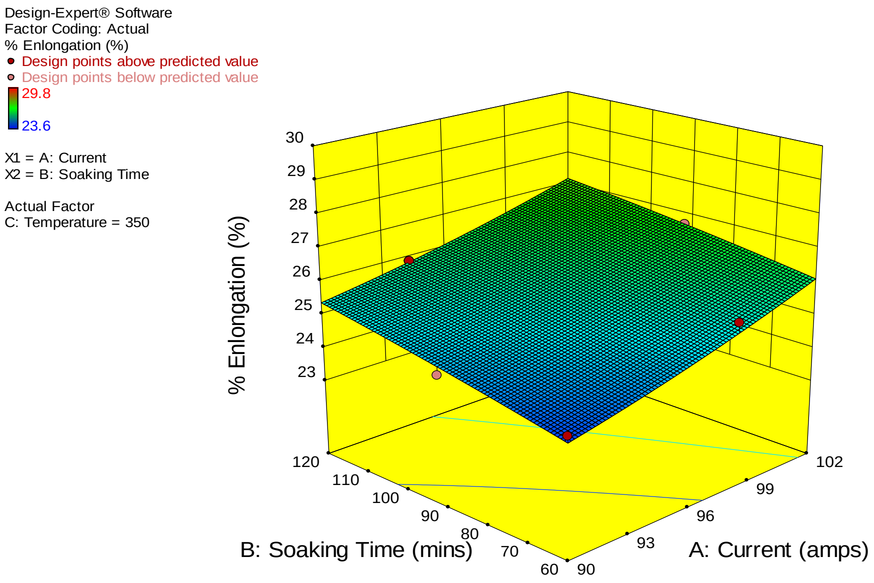

Fig. 4: 3D response surface plot of welding current and soaking time on percent elongation.

Figure 5 represents graphically the interaction effect of welding current and temperature on percent elongation. Mutual interaction between the two variable factors could be observed due to elliptical nature of the plot. The probability value ($P<0.05$) as indicated in Table 5 clearly demonstrates the sensitivity of the response to the interaction of the two variable factors.

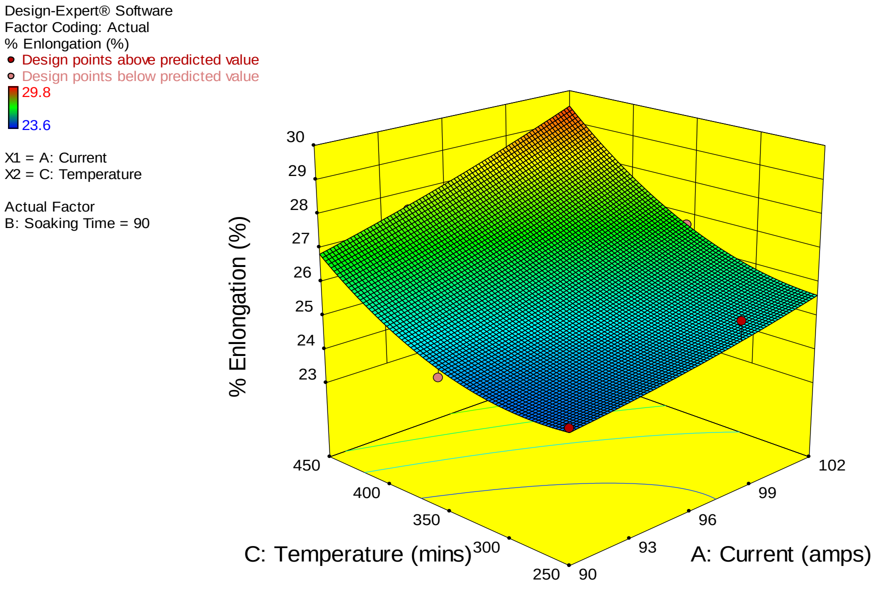

Fig. 5: 3D response surface plot of welding current and temperature on percent elongation.

4.6 Optimization of response variables

The objective of optimization was to set the variable factors at the levels that would produce optimal response values. In other words, it was intended to minimize the difference between the measured and the predicted output parameters by minimizing errors and cost. In this way, the process parameter was calculated in such a way that the response approach the desired values. Therefore Table 6 shows the variable factors and responses at their different levels with the criteria used.

Table 6: Optimization criteria used in the study

Factorand Response	Limits		Criterion	Goal
	Lower	Upper		
Current	90	102	In range	In range
Soaking time	60	120	In range	In range
Temperature	250	450	In range	In range
Tensile strength	212	256	In range	Maximize
Percent elongation	23	29.8	In range	Maximize

4.7 Optimum conditions and response values

The determination of the appropriate welding and heat treatment conditions to be applied in the welding and heat treating of micro-alloyed steel will reduce time and cost in subsequent experimental runs or test. Therefore, Table 7 shows the optimum conditions (set of values) of the welding and heat treatment operational conditions that are appropriate in obtaining maximum response in the experimental design space. The design expert software generated three different operational conditions that would result in optimal percent elongation of the micro-alloyed steel weldment. Each set of values for the variable factors were averaged in order to obtain the final set of values for each of the variable factor. The desirability index for each of the optimum conditions generated by the design expert software was 0.803. Granato and Calado (2014) posited that if the desirability index ≥0.70, it implies that the optimum conditions chosen are appropriate and will result in optimal response.

Table 7: Optimal solution as obtained by Design Expert software based on the criterion and goal on percent elongation

Number	Current (amps)	Soaking time (min)	Temperature (^{0}C)	Percent elongation (%)	Desirability
1	101.883	120.0003	450	29.2669	0.803
2	101.883	120.0002	450	29.2349	0.803
3	101.957	120.0003	450	29.2551	0.803
Average	101.908	120.0003	450	29.2523	0.803

4.8: Validation of optimized predictive results

The optimization technique was applied to find the conditions which gave the maximum desirable mechanical properties of the tempered micro-alloyed steel weldment. The Design Expert software generated the optimum conditions of 101.908 ampere, 120.0003 minutes and 450^{0}C for welding current, soaking time and tempering temperature respectively, that would result in optimal value of percent elongation of 29.2523%. A comparison of the experimental values with the values predicted by Design Expert 10, revealed that the actual and the predicted values are very close (Table 8).The deviation of predicted values from actual values were found to be very low and quite within the acceptable range for experimental results. The observed deviation of the predicted results from the actual results could be attributed to the fact that the surface properties of the welded metal and the physiochemical interactions between the weld metal zones and the surrounding which played vital roles during the welding and heat treatment operations were not considered as criteria during optimization. The results (Table 8) revealed that the optimization achieved in the present study was reliable.

Table 8: Predicted and actual values of percent elongation at the optimum conditions.

Condition	Welding current (amps)	Soaking time (min)	Tempt. (^{0}C)	Elongation (%)	Deviation (%)
Optimum condition (Predicted)	101.908	120.0003	450	29.2523	-0.02
Optimumcondition (Actual)	102	120	450	29.8	

IV. CONCLUSION

Based on the results of the research work, the following conclusions has been drawn:

1. The empirical relationship established to predict the tensile ductility (% elongation) was found to be statistically significant as indicated by the ANOVA analysis, hence, could serve as a useful tool in engineering for evaluating the amount of percent elongation the arc-welded and tempered micro-alloyed steel would undergo in service before

fracture.

2. It was confirmed that the model predicted and experimental values were in reasonable agreement as indicated by the validation tests. This clearly, attest to the model validity.
3. The process variables settings of 101.908amps, 450^{0}C and 120.0003mins of welding current, tempering temperature and soaking time respectively, were established as the optimum conditions for achieving optimal percent elongation of 29.2523%.
4. The process variables (welding current, tempering temperature and soaking time) exhibited different degree of effects on percent elongation. However, welding current and soaking time showed the most remarkable influence on the response (percent elongation).

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