# Study the Effect of Welding Parameters on the Residual Stresses Induced by Submerged Arc Welding process

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## Abstract:

Welding residual stress has influences on fatigue, fracture, and corrosion. It is therefore important to explore the welding factors effect on the residual stresses. In this work, four welding factors (current, arc voltage, welding travel speed and included angle) were used to weld low carbon steel (ASTM A516 Grade 60).The experiments included welding of (60) pieces with dimensions of (300 x 150) mm and 10 mm thickness that were conducted based on the design matrix founded by using design of experiment (DOE) software (DESIGN EXPERT 10) with response surface methodology (RSM) technique. The X-Ray diffraction (XRD) method was used to measure the residual stress, which was then modeled and optimized in terms of the welding factors using (RSM) technique. The data showed that the welding travel speed and arc voltage have a significant influence on the residual stress. It was found that the optimum solution for minimum residual stress was at 450 Amp welding current, 34 volt arc voltage, 38 cpm welding speed, and $60^0$ included angle. Where, the optimum value of residual stress was (-88.4 MPa). Finally, the predicted and experimental results of residual stress were in agreement with a maximum error of 1.8%.

**Key words:** SAW, Residual Stress, Welding parameters, DOE, RSM

## 1. Introduction

Submerged Arc Welding (SAW) is the process of arc welding that utilizes an arc among the metals and consumable bare wire electrode. The arc and weld pool are covered by a granular flux. This welding process is commonly utilized for large items, such as shipbuilding, large diameter pipes, pressure vessels, petroleum storage tanks, and structural components for bridges and buildings [1]. Residual stress is induced by the restraints of the base metal on the shrinkages of the hot weld metal when it cools, and by differences in phase transformations behavior of three regions (Fusion zone, HAZ zone and Parent zone) [2]. Welding residual stress has influences on fatigue, fracture, and corrosion, and high temperature damage behavior in pressure vessel, petroleum storage tanks and piping components. The procedures of welding can be developed to reduce the weld residual stress effects on the structural integrity [3]. The transverse weld cracks occurred in the area of the maximum residual stresses for both the SAW and flux cored arc welding (FCAW) processes [4]. Thermal conductivity had a significant effect on the transient temperature distribution in the welded joint, large tensile longitudinal residual stresses exist close the welding bead, while low transverse residual stresses were close the weldments. Both of longitudinal and transverse residual stresses reduced with the conductivity increasing [5]. The appropriate selection of filler metal affected the stress values in the weld and the position peak residual stress in the base metal. Low transformation temperature of weld metals can produce compressive residual stress in the weld bead [6]. The type of groove has a significant effect on the distribution of welding residual stress, width of sensitization region and angular distortion [7]. Many researchers in the field of SAW process have attempted to develop mathematical models of SAW using various computer software, such as, Taguchi technique, factorial design and finite element analysis by ANSYS to study the effect of SAW welding factors on the mechanical properties of welded joint and weld bead geometry [8-10]. A limited work has considered the use of groove angle (included angle) during SAW process. Also, afew researches used response surface methodology (RSM) technique by design of experiment (DOE). Where, RSM is a combination of statistical and arithmetical techniques, which are used for modeling, problem analyzing and optimizing the output depending on the input factors.Therefore, the aim of this work is to investigate experimentally the influence of welding factors (current, voltage, welding travel speed and included angle) on the residual stresses induced during the submerged arc welding process. Then, an empirical model will be developed for residual stress of the submerged arc welded joint using RSM technique by DOE software within the specified levels of the used parameters.

## 2. Experimental Work

### 2.1 Used Materials

The essential materials used in the present work were low carbon steel plates **(ASTMA516Grade 60)** plate steel with thickness of 10 mm, which is used for manufacturing boilers, pressure vessels and tanks for petroleum industries. The plates were welded using AWS EM12K wire (4 mm diameter) and AWS F60-EM12K flux (0.8 basicity index). Thechemical compositions of used and nominal **(ASTMA516Grade 60 for thickness less than 12.5 mm**)are shown in table (1) and their mechanical properties are depicted in table (2) for conformity and comparison purposes. Table (3) shows the chemical composition of **AWS EM12K**. [11]

**Table (1):** Chemical compositions of used and nominal ASTM A516 Grade 60 plate steels.

| *Material (wt %)* | *%C* | *%Mn* | *%Si* | *%P Max.* | *%S Max.* |
|---|---|---|---|---|---|
| *Used* | 0.17 | 0.9 | 0.19 | 0.03 | 0.03 |
| *Nominal For (t ≤ 12.5 mm)* | 0.21 Max. | 0.60 to 0.90 | 0.15 to 0.40 | 0.035 | 0.035 |

**Table (2):** Mechanical properties of used and nominal ASTM A516 Grade 60 plate steels

| *Material* | *Tensile strength (MPa)* | *Yield strength (MPa)* | *Elongation (%)* |
|---|---|---|---|
| *Used* | 430 | 295 | 31 |
| *Nominal* | 415 - 550 | 220 Min. | 25 Min. |

**Table (3):** Nominal chemical composition of AWS EM12K wire

| *%C* | *%Mn* | *%Si* | *%S* | *%P* | *%Cu* |
|---|---|---|---|---|---|
| 0.05 to 0.15 | 0.80 to 1.25 | 0.10 to 0.35 | 0.030 | 0.030 | 0.35 |

## 2.2 SAW Conditions

To study the influence of welding factors on the residual stress induced by SAW process, four input factors (welding current, arc voltage, welding travel speed and included angle) were used as separate factors with two levels (Table 4). The levels were selected based on the practical experience and experimental data reported previously.

**Table (4):** Used levels of welding input factors

| **Input factor** | **Levels** | |
|---|---|---|
| | **-1** | **+ 1** |
| Current (Amp.) | 350 | 450 |
| Voltage (volt) | 30 | 34 |
| Welding speed (cpm) | 35 | 45 |
| Included angle (degree) | 54° | 66° |

## 2.3 Welding Procedure

The plate was first cut to (60) pieces with measurements of (300 x 150 x 10 mm) and then surfaces were cleaned to remove the oxides and contamination by sand blasting. Milling cuter was used to make the V-groove angles (included angle) of single butt weld joint which were 48°,54°, 60°, 66°, and 72°. The experiments were conducted based on the design matrix (table 5) established by the (DOE) software with two levels of input parameters to find out their influence on the residual stresses developed in submerged arc welding. Figure (1) shows a sample of welded plate with welding parameters of run No.1. Welding machine type (EsabA2 Multitrack with the A2-A6 process controller PEK) was used in this work (Figure 2).

**Table (5):** Design matrix for actual input and output factors

| *Std. No.* | *Current (Amp.)* | *Voltage (volt)* | *Welding speed (cpm)* | *Included angle (deg.)* | *Residual Stresses (MPa)* |
|---|---|---|---|---|---|
| 1 | 350 | 30 | 35 | 54 | -37 |
| 2 | 450 | 30 | 35 | 54 | -96 |
| 3 | 350 | 34 | 35 | 54 | -107 |
| 4 | 450 | 34 | 35 | 54 | -78 |
| 5 | 350 | 30 | 45 | 54 | 28 |
| 6 | 450 | 30 | 45 | 54 | -61 |
| 7 | 350 | 34 | 45 | 54 | -42 |
| 8 | 450 | 34 | 45 | 54 | -57 |
| 9 | 350 | 30 | 35 | 66 | -20 |
| 10 | 450 | 30 | 35 | 66 | -25 |
| 11 | 350 | 34 | 35 | 66 | -62 |
| 12 | 450 | 34 | 35 | 66 | -94 |
| 13 | 350 | 30 | 45 | 66 | -24 |
| 14 | 450 | 30 | 45 | 66 | 25 |
| 15 | 350 | 34 | 45 | 66 | -51 |
| 16 | 450 | 34 | 45 | 66 | -50 |
| 17 | 300 | 32 | 40 | 60 | 52 |
| 18 | 500 | 32 | 40 | 60 | 4 |
| 19 | 400 | 28 | 40 | 60 | -113 |
| 20 | 400 | 36 | 40 | 60 | -114 |
| 21 | 400 | 32 | 30 | 60 | -30 |
| 22 | 400 | 32 | 50 | 60 | 67 |
| 23 | 400 | 32 | 40 | 48 | -101 |
| 24 | 400 | 32 | 40 | 72 | -24 |
| 25 | 400 | 32 | 40 | 60 | -57 |
| 26 | 400 | 32 | 40 | 60 | -49 |
| 27 | 400 | 32 | 40 | 60 | -51 |
| 28 | 400 | 32 | 40 | 60 | -75 |
| 29 | 400 | 32 | 40 | 60 | -80 |
| 30 | 400 | 32 | 40 | 60 | -65 |

**Figure (1):** Sample of welded plate with welding parameters of run No. 1


**Figure (2):** EsabA2 Multitrack with the A2-A6 process controller PEK

## 2.4 Measurements of Residual Stresses

In this research, the X – ray diffraction (XRD) method was used to measure the residual stress on the metal surface, since it is a vastly employed technique. XRD test was performed by Shimadzu X-ray diffractometer (XRD-6000) with Stress Analysis Attachment "SA-1101". Diffraction methods that determine residual stress essentially measure the angles at the ultimate diffracted intensity occurs when x-rays are directed on a crystalline sample. By using the angles, Bragg's law can be applied to determine the interplanar spacing of the diffraction planes. And the d spacing is measured at both a stressed case and an unstressed state; the difference of the d spacing between two cases is depended on the value of residual stress. [12]

## 2.5 Experimental Design

In the present work, a response surface methodology (RSM) technique was used to develop a mathematical model based on the experimental data. The quadratic functions of response surface should be considered, because the curvature may be insufficiently modeled by using the first-order function within the ranges of normal operating conditions. A total of 30 runs (experiments) were carried out based on thematrix of experimental design. The runs were randomly conducted according to the run order that recorded in Table (5). Different levels coded from -2 to +2, were used with each factor, whereby every utilized level adapted to an actual value corresponding to the coded value. Thus, the welding parameters (input factors) studied are current, arc voltage, welding travel speed and included angle. The matrix of experimental design used for input factors with the obtained residual stresses values which are given in Table (5). Prediction model within a 95% confidence was developed by "DESIGN EXPERT Version 10."

# 3. Results and Discussion

## 3.1 Modeling of Residual Stress

The suitable model was selected and developed using the RSM technique, and then the response characteristics were used to obtain the regression equations to the model. The experimental data (Table 5) were used to develop the regression equations which were plotted to explore the influence of process parameters on the different response characteristics. The analysis of variance (ANOVA) for response surface quadratic model for residual stress was performed to statistically analyze the results, as given in table (6). The model F-value of 11.71 in the table reveals the model significance. Values of "Prob> F" lesser than 0.05 explain that the model terms are considerable. In this state, B, C, D, $A^2$, $B^2$ and $C^2$ are significant terms of this model. Therefore, this model indicates that the arc voltage (B), welding speed (C), and included angle (D) have the greatest impact, while the welding current (A) has slight effect on the residual stress.

The empirical quadratic predicted model built for the residual stress developed in submerged arc welding of low carbon steel (A516 Grade 60) is given as follows:

**Residual stress** = - 1349.19048 – 6.77798* Current + 229.20536*Voltage – 54.36310*Welding speed + 2.10417*Included angle + 8.24643*Current$^2$ - 3.68973*Voltage$^2$ + 0.72964*Welding speed$^2$

The checking for the model adequacy was executed by residual analysis, and the results are revealed in figures (3) and (4). Figure (3) presents the plot of the normal probability. The errors distribute normally as appear in this figure where the residuals exist on a straight line. The standardized residuals relative to the predicted values are showed in figure (4). The residuals do not appear any explicit uncommon style and are spread in each negative and positive direction. This reveals the adequate model. Figure (5) manifests the predicted values of residual stresses are near to actual ones measured in the tests, indicating that both the experimental and predicted results have a good agreement. Figure (6) reveals the perturbation of residual stresses in this model. It also shows that the welding speed (C) increased greatly the residual stresses over the whole selected input levels (35 – 45 cpm), this result is ascribed to the increase of welding speed that leads to the risk of arc instability and arc blow, which are minimizing the weld quality. While arc voltage (B) has an adverse effect, and the residual stresses value decreased largely at high level (34 Volt), this result is attributed to the increasing of arc voltage that causes flux consumption increase that leads to more alloying elements enter the weld metal. Where, the filler metal affected the stress values in the weld bead and the location of peak residual stress in the parent metal, and also compressive residual stress at the weld bead can be resulted from low transformation temperature weld metals. But, the current (A) and included angle (D) remained with the same effect on the residual stresses at both levels.The result is also confirmed by the 2D contour plot and 3D surface plot depicted in Figures (7 and 8), respectively as a function to current and voltage at medium value (center level) of welding speed (40 cpm) and included angle (60°).

**Table (6):** ANOVA for response surface reduced quadratic model for residual stress

| *Source* | *Sum of Squares* | *df* | *Mean Square* | *F Value* | *p-value Prob> F* |
|---|---|---|---|---|---|
| *Model* | 49408.24 | 7 | 7058.32 | 11.71 | <0.0001 significant |
| *A-Current* | 1962.04 | 1 | 1962.04 | 3.25 | 0.0849 |
| *B-Voltage* | 4620.37 | 1 | 4620.37 | 7.67 | 0.0112 |
| *C-Welding speed* | 9640.04 | 1 | 9640.04 | 15.99 | 0.0006 |
| *D-Included angle* | 3825.37 | 1 | 3825.37 | 6.35 | 0.0195 |
| *A²* | 11900.63 | 1 | 11900.63 | 19.74 | 0.0002 |
| *B²* | 6099.13 | 1 | 6099.13 | 10.12 | 0.0043 |
| *C²* | 9316.63 | 1 | 9316.63 | 15.46 | 0.0007 |
| *Residual* | 13261.13 | 22 | 602.78 | | |
| *Lack of Fit* | 12448.29 | 17 | 732.25 | 4.50 | 0.0520 Not significant |
| *Pure Error* | 812.83 | 5 | 162.57 | | |
| *Cor Total* | 62669.37 | 29 | | | |
| *Std. Dev.* | *24.55* | | *R-Squared* | | *0.7884* |
| *Mean* | *-46.23* | | *Adj R-Squared* | | *0.7211* |
| *C.V. %* | *53.10* | | *Pred R-Squared* | | *0.5171* |
| *PRESS* | *30265.59* | | *Adeq Precision* | | *15.762* |

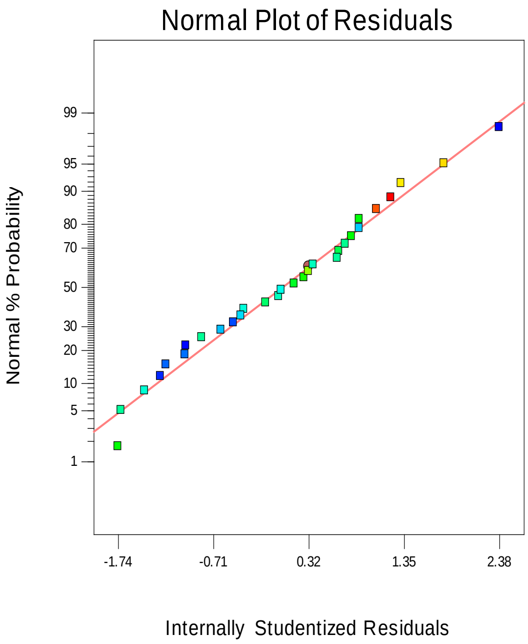


**Figure (3):** Normal probability plot for residual stress data

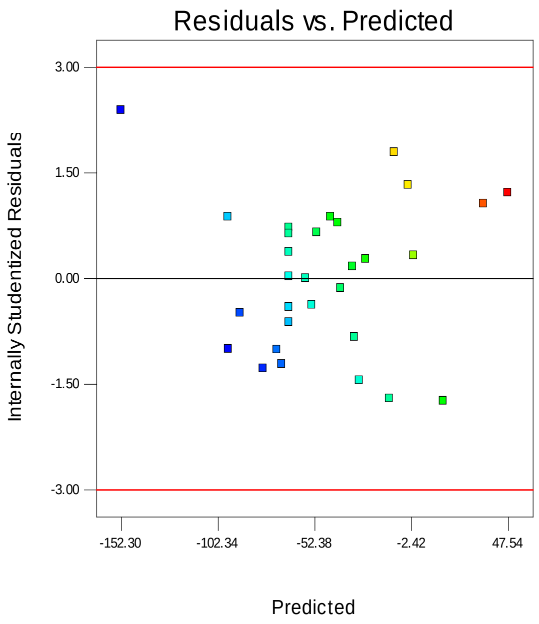


**Figure (4):** Residual versus predicted responses for residual stress data

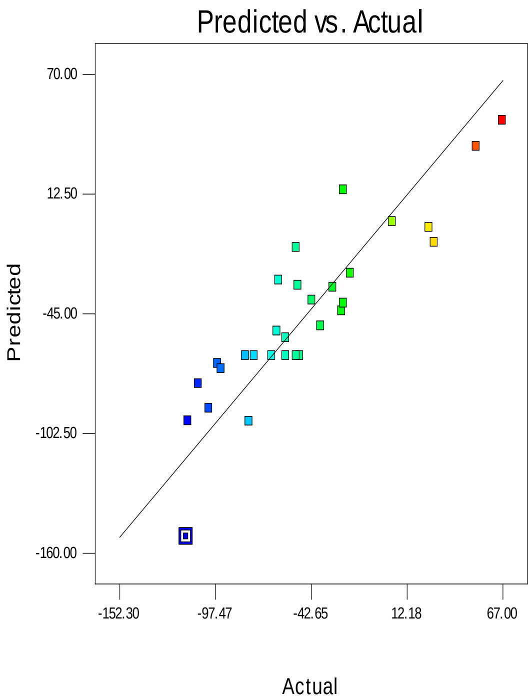


**Figure (5):** Predicted versus actual residual stress data for comparison

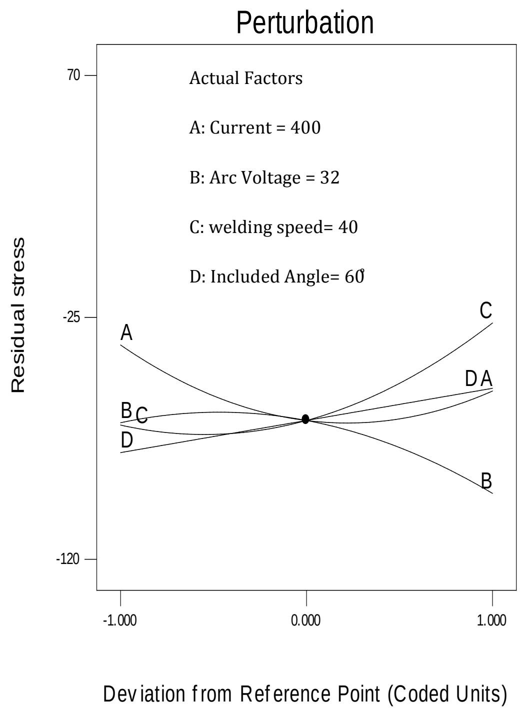


**Figure (6):** Perturbation of residual stress showing the effect of each input parameter over the selected level.

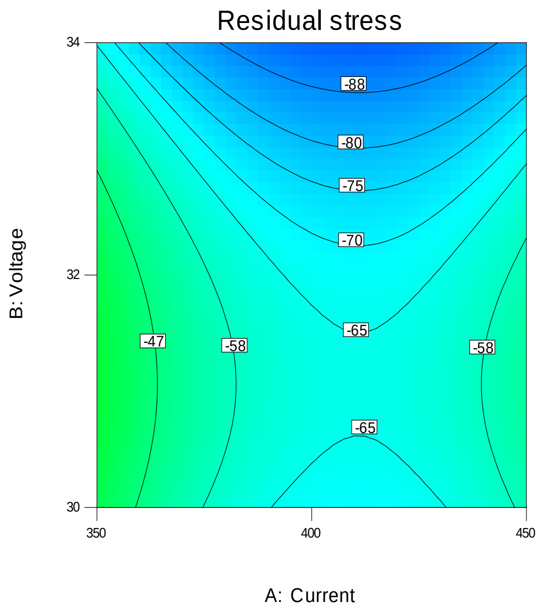


**Figure (7):** 2D plot of residual stressat as a function atcenter level of welding speed (40 cpm) and included angle (60°).

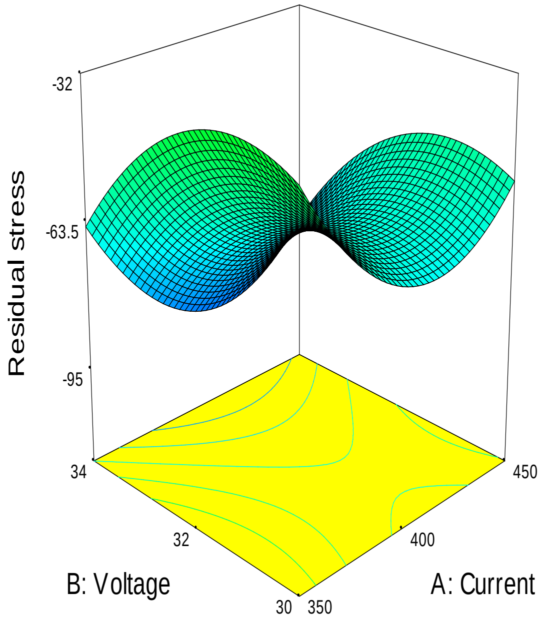


**Figure (8):** 3D plot plot of residual stressat as a functionat center level of welding speed (40 cpm) and included angle (60°).

## 3.2 Numerical Optimum of Residual Stress

The design of experiment software was used to perform the numerical optimization and to determine the optimum combinations of factors to accomplish the requirements as desired. Therefore, this software was used for optimization purpose developing on the results of prediction model of one response, residual stress, as a function of four input factors: welding current, arc voltage, welding speed and included angle. To establish a new predicted model, an objective function called desirability that permits for suitable combining the aims, was estimated. Desirability should be maximized by numerical optimization, and it ranges from 0 to 1 for the aim. Characteristics of the aim may be changed by adjusting the weight or importance of the desirability, and the goal of optimization is to determine the proper set of conditions to satisfy all the aims. Normally, the weights are utilized to developed the estimation of the aim's 3D importance during maximizing the desirability of this work, weights were not changed, since the residual stress(response) has the main importance. The major purpose of the optimization was to determine minimum response satisfying the variable features with a maximum desirability. The constrains of each factors for optimizing residual stress are listed in Table (7). According to this table, one possible run fulfilled these specified constrains to obtain the minimum value for residual stress (-88.4 MPa), as given in table (8). It can be seen that for this run, the maximum selected desirability is (0.781). Figures (9 and 10) depict the optimum value of the minimum residual stress in 2D contour plot and 3D surface plot.

**Table (7):** Constraints of the optimization of residul stress

| *Name* | *Goal* | *Lower Limit* | *Upper Limit* | *Lower Weight* | *Upper Weight* | *Importance* |
|---|---|---|---|---|---|---|
| *A:welding current* | *is in range* | *350* | *450* | *1* | *1* | *3* |
| *B:arc voltage* | *is in range* | *30* | *34* | *1* | *1* | *3* |
| *C:welding speed* | *is in range* | *35* | *45* | *1* | *1* | *3* |
| *D:included angle* | *is in range* | *54* | *66* | *1* | *1* | *3* |
| *Residul stress* | *minimize* | *-114* | *67* | *1* | *1* | *3* |

**Table (8):** Optimum solution for minimum residual stress

| *Welding current (Amp.)* | *Arc voltage (vol.)* | *Welding speed (cpm)* | *Included angle (degree)* | *Residusl Stress (Mpa.)* | *Desirability* |
|---|---|---|---|---|---|
| *450* | *34* | *38* | *60* | *-88.4* | *0.781 Selected* |

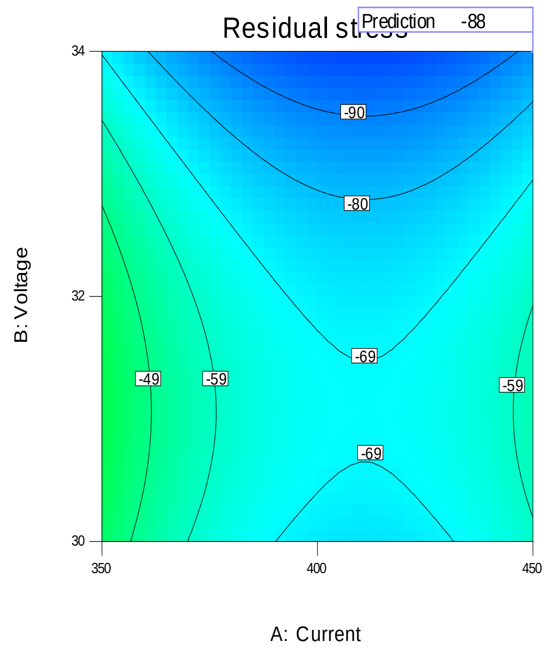


**Figure (9):** The minimum residual stress at the optimum welding parameters (welding current of 450 amp. arc voltage of 34 volt, welding speed of 38 cpm, and included angle of 60°).

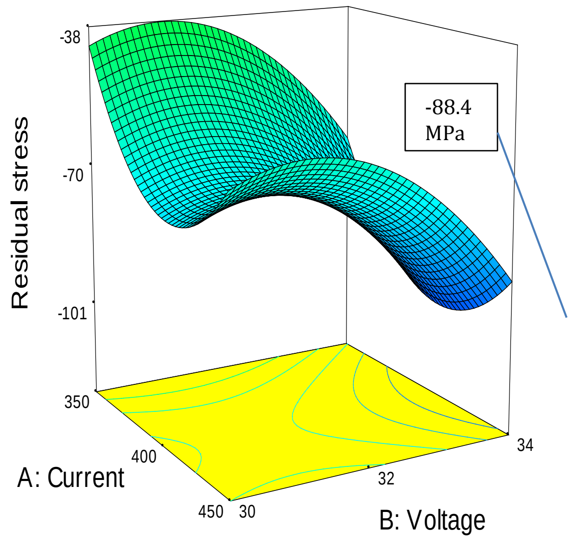


**Figure (10):** The minimum residual stress at the optimum welding parameters (welding current of 450 amp., arc voltage of 34 volt, welding speed of 38 cpm, and included angle of 60°)

## 4. Confirmation tests

To check the validity of this model, proofing tests were carried out at the optimum predicted values of the welding input parameters obtained in this model to measure the residual stresses. The experimental results of these measurements are given together with the predicted results in table (9) for comparison purposes. This table indicates that both the experimental and predicted results have a good agreement with a maximum error of 1.8%.

**Table (9):** Comparison between the experimental and predicted residual stress

<table>
<tr><th colspan="2">TheOptimum Welding Parameters</th><th colspan="3">Residual Stress (MPa.)</th></tr>
<tr><td>Welding current</td><td>450 Amps.</td><td rowspan="3">Predict</td><td rowspan="3">Exp.</td><td rowspan="3">Max. Error %</td></tr>
<tr><td>Arc voltage</td><td>34 Vol.</td></tr>
<tr><td>Welding speed</td><td>38 cpm</td></tr>
<tr><td>Included angle</td><td>60°</td><td>-88.4</td><td>-90</td><td>1.8</td></tr>
</table>

## Conclusions

**1-** Arc voltage and welding speed have a significant effect on the residual stress. The welding speed greatly increased the residual stresses over the whole selected input levels (35 – 45 cpm). Whereas, arc voltage has an adverse effect, and the residual stresses value decreased largely at high level (34 Vol.).

**2-** According to DOE with RMS, the optimum solution for minimum residual stress was found at 450 Amp welding current, 34 volt mm arc voltage, 38 cpm welding speed, and 60 included angle. Where, the optimum value of residual stress was (-88.4 MPa).

**3-** According the experimental results obtained, the SAW process of low carbon steel (516 Gr. 60) has resulted more compressive stress (-90 MPa) than the base metal (-8 MPa).

**4-** It was found a good agreement between the experimental and predicted results of residual stress with a maximum error of 1.8%.

**5-** It was proved that DOE with RSM can be a good tool to predict the residual stress for all given input parameters values used in the SAW process.

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# دراسة تأثير عوامل اللحام على الاجهادات المتبقية المتولدة بعملية لحام القوس المغمور


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**الخلاصة**

تؤثر الأجهادات المتبقية المتولدة من عملية اللحام على كل من الكلل والتآكل والكسر الميكانيكي. لذلك فمن المهم دراسة تأثير عوامل اللحام على تولد الاجهادات المتبقية. في هذه الدراسة تم تم دراسة حالة الاجهادات المتبقية المتولدة من اللحام بطريقة القوس المغمور لصلب واطيء الكاربون نوع (A516 Gr 60), حيث تم استخدام اربعة عوامل لحام هي التيار والفولطية وسرعة اللحام وزاوية اخدود اللحام, ان ابعاد القطع المعدنية المعدة للحام هي (300x150x10 mm). تم بعد ذلك قياس الاجهادات المتبقية المتولدة بطريقة حيود الاشعة السينية (XRD) ثم عمل موديل رياضي وحساب القيمة المثلى بوصفها دالة لعوامل اللحام المستخدمة بواسطة تقنية تصميم التجارب (DOE) مع منهجية الاستجابة السطحية (RSM). حيث اظهرت النتائج ان التأثير الاكبر على تولد الاجهادات المتبقية كان لفولطية القوس وسرعة اللحام, كذلك وجد ان الظروف المثلى التي تعطي اقل اجهادات متبقية هي (450 Amperes, 34 Volt, 38 cpm and $60^0$ Included Angle) حيث تكون القيمة المثلى للاجهادات المتبقية عند هذه الظروف هي (-88.4). واخيراً كان هنالك توافق كبير بين النتائج المتوقعة والعملية للاجهادات المتبقية مع نسبة خطاء قليلة جداً لا تتجاوز 1.8%.