Modeling and Prediction of Heat Input in Arc Welding Process Using Response Surface Methodology Based on Simulation Software

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Abstract:

Estimation of heat input in arc welding process the estimation of heat input in the arc welding process is crucial for ensuring the quality and integrity of the welded joints. The heat input in the arc welding (AW) process plays a crucial role in determining the quality and efficiency of the weld. Heat input refers to the amount of thermal energy delivered to the workpiece during welding. It directly affects various aspects of the welding process, including the weld pool size, penetration depth, and overall metallurgical properties. In this study, three input process parameters, namely welding current (A), welding voltage (V), and welding speed (mm/min), respectively. Were utilized in order to predict the HI (KJ/mm) using response surface methodology (RSM). It was observed that the RSM prediction model gave a mean absolute percentage error MAPE 0.70% and Nash Sutcliffe efficiency NSE gave an 99%. Indicate that RSM model is accurate prediction model. Therefore, the RSM is recommended for prediction of the HI of arc welding process.

Keywords: Simulation Software, RSM, AW, and HI

الملخص

تقدير مدخلات الحرارة في عملية اللحام بالقوس يعد تقدير مدخلات الحرارة في عملية اللحام بالقوس أمرًا بالغ الأهمية لضمان جودة وسلامة الوصلات الملحومة. يلعب المدخلات الحرارية في عملية اللحام بالقوس الكهربائي (AW) دورًا حاسمًا في تحديد جودة وكفاءة اللحام. يشير الدخل الحراري إلى كمية الطاقة الحرارية التي يتم توصيلها إلى قطعة العمل أثناء اللحام. إنه يؤثر بشكل مباشر على جوانب مختلفة من عملية اللحام، بما في ذلك حجم حوض اللحام وعمق الاختراق والخصائص الميكانيكية. في هذه الدراسة، تم استخدام ثلاث معلمات لعملية الإدخال، وهي تيار اللحام (A)، جهد اللحام (V)، وسرعة اللحام (mm/min)،

على التوالي. تم استخدامها للتنبؤ بـ مدخلات الحرارة (KJ/mm) باستخدام منهجية الاستجابة السطحية (RSM). وقد لوحظ أن نموذج التنبؤ RSM أعطى متوسط نسبة خطأ مطلقة MAPE 0.70% و NSE أعطى 99%. تشير إلى أن نموذج RSM هو نموذج تنبؤ دقيق. ولذلك، يوصى بـ RSM للتنبؤ بمدخلات الحرارة لعملية اللحام بالقوس الكهربائي.

1. Introduction

Welding localized, or the connecting of two metallic components at their flaying surfaces, is what welding entails (Groover, 2010). The part surfaces that need to be connected and are in touch or close proximity are known as the faying surfaces. Although welding is typically used to join pieces made of the same metal, it can also be used to unite metals that are not the same. Some 50 different types of welding operations have been cataloged by the American Welding Society. They use various types or combinations of energy to provide the required power. We can divide the welding processes into two major groups: fusion welding and solid-state welding. Fusion welding procedures to melt the base metals. A filler metal is frequently added to the molten pool during fusion welding operations in order to speed up the process and provide the welded junction more mass and strength. An autogenous weld is a fusion-welding procedure where no filler metal is supplied. The most popular welding procedures fall within the fusion category. They can be divided into the following broad categories (American Welding Society names are indicated by initials in parenthesis) (Groover, 2010): **Arc Welding (AW)**: arc welding is the name given to a class of welding techniques in which the metals are heated using an electric arc. A few arcwelding procedures further apply pressure while working, and the majority use filler metal.

Resistance welding (RW): Resistance welding achieves coalescence using heat from electrical resistance to the flow of a current passing between the faying surfaces of two parts held together under pressure. **Oxyfuel gas welding (OFW):** These joining processes use an oxyfuel gas, such as a mixture of oxygen and acetylene, to produce a hot flame for melting the base metal and filler metal, if one is used. **Other fusion-welding processes.** Other welding processes that produce fusion of the metals joined include electron beam welding and laser beam welding.

In the chemical, nuclear power, and oil and gas industries, the welding process has long been regarded as a crucial step in the manufacturing process. Girth welding steel pipes is a widely used method in many sectors to create and connect pipeline networks. But it's well known that welding leaves behind a significant amount of residual stress. Remaining stresses have a detrimental effect on structural efficiency because they weaken fatigue strength, cause brittle fracture, or cause stress corrosion cracking (SCC), primarily in the longitudinal direction of the pipe. Therefore, to guarantee the integrity of welded structures, accurate residual stress behavior prediction and structural stress analysis are crucial. A technique used to forecast the amount and distribution of residual stresses in welding structures is numerical modeling (Moslemi, N. 2022). While selecting welding process parameters is frequently done so based on professional opinion or recommendations from welding manuals, it does not ensure the best or nearly best weld bead profile for that specific welding environment. A weld's mechanical qualities and decreased post-weld flaws are two elements that affect its quality; both are influenced by the chemical makeup and metallurgical traits of the weld metal. A weld's mechanical and metallurgical qualities are determined by the bead geometry, which is closely linked to the welding process. It is important to remember that post-weld flaws, such cracks, are created on the weld line when the weld product is bent or shock-tested. Poor mechanical qualities of the weldment are often caused by metallurgical anomalies associated with fusion welding techniques, such as solidification cracking, segregation, porosity present, and grain growth in the heat-affected area . An arc is created between the non-consumable tungsten electrode and the work piece during tungsten inert gas (TIG) welding. Usually argon, an inert gas protects the arc, electrode, and molten pool from contamination. Where the metal structure is dilated and there is a strong triaxial tensile stress, hydrogen is likely to be drawn to those regions. It is therefore drawn to these regions in front of stressed fractures or notches (Pondi, P. 2021). The principal applications of welding are (1) construction, such as buildings and bridges; (2) piping, pressure vessels, boilers, and storage tanks; (3) shipbuilding; (4) aircraft and aerospace; and (5) automotive and railroad [1]. Welding is performed in a variety of locations and in a variety of industries. Owing to its versatility as an assembly technique for commercial products, many welding operations are performed in factories. However, several of the traditional processes, such as arc welding and oxyfuel gas welding, use equipment that can be readily moved, so these operations are not limited to the factory. They can be performed at construction sites, in shipyards, at customers' plants, and in automotive repair shops. The majority of welding tasks require a lot of labor. For instance, a skilled professional known as a welder often performs arc welding, physically controlling the weld's route or placement to unite separate parts into a bigger unit. When performing manual arc welding in a factory, the welder frequently collaborates with a second employee known as a fitter. Prior to making the weld, the fitter is responsible for arranging each component for the welder. For this, positioners and welding fixtures are employed. A welding fixture is a tool used to clamp and hold the parts in place so they may be welded together. Since it is made specifically for the weldment's geometry, its economic viability must be demonstrated using the quantities of assemblies to be produced (Groover, 2010). A weld joint, which is a strong joining of two components, is the result of welding. The intersection of two surfaces or edges that have been bonded by welding is known as a weld joint. Two weld joint classes are covered in this section: There are two categories of joints: (1) forms of joints and (2) types of welds used to unite the parts of the joints. When putting two pieces together, there are five fundamental types of joints. The five joint types are applicable to other joining and fastening methods as well; they are not just restricted to welding. In this paper a model has been developed using response surface methodology (RSM) in order to predict heat input (HI).

2. Literature Review

A model was developed using expert systems such as Response Surface Methodology and Artificial Neural Network to optimize and anticipate weld heat input and heat impacted zone based on input parameters such as current, voltage, and welding speed. Based on data from twenty experimental runs in this study, one Response Surface Methodology analysis shows that a current of 130.00Amps, voltage of 20.94V, and speed of 0.48m/min will produce a heat input of 0.64277Kj/mm and a heat affected zone of 5.42078mm with a desirability of 0.962 (Yang, Y. 2009). Examined the impact of heat input on the mechanical characteristics and microstructure of weldments constructed from AISI 304 plates that were 6 mm thick and had double V-grooved edges prepared. For comparison, three different heat inputs have been employed, and the interpass temperature has been kept constant at roughly 150°C. It was discovered that the ultimate tensile strength increased with decreasing heat input (Yang, Y. 2008). Revealed the mechanical characteristics and structural characterization of stainless steel dissimilar multipass welds to INCONEL (AISI304/IN625 and AISI316L/IN625 joints). For the GTAW process of constant and pulsed mode power, a single V-groove joint was employed with filler rods made of ER2209, ERNiCr-3, and ERNiCrMo-3. Both optical and sophisticated (SEM/EDAX) microscopy techniques were used to characterize the joints. The fracture was consistently seen to occur at the parent metal of the stainless steel in both cases (Dhobale, A. L. 2015). It has been discovered that there is a tendency for tensile strength to grow as hardening cooling rate increases and a trend for tensile strength to increase as hardening heat input decreases. A faster rate of cooling will occur when the amount of heat input decreases. It was discovered that a faster cooling rate corresponded with a reduced heat input when taking into account the influence of HI on ultimate σ. The paper presents the specifics of the experimental, model development, testing, validation, impact of HI on σ, effect of laser process factors on heat input and ultimate σ, and performance comparison of RSM and ANN models. The results of Box–Behnken design of RSM and ANN models also indicate that the proposed models predict the responses adequately within the limits of input parameters being used. It is suggested that regression equations can be used to find optimum conditions for HI and σ of laser-hardened commercially pure titanium material (Uwoghiren, F. O. 2022).

3. Methodology

3.1 Material selection

The material used in this study is 10 mm thick AISI 1008 mild steel plates for tungsten inert gas welding with a single V joint. Hundred (100) pieces of mild steel coupons measuring 60 x 40 x10 were used for the experiments. The experiment was performed 20 times, using 5 specimens for each run. The plate samples were 60 mm long with a wall thickness of 10mm. Table 1 and Table 2 give respectively the chemical compositions of the base metals and their mechanical properties. The welding process uses a shielding gas to protect the weld specimen from atmospheric interaction. For this study, 100% pure Argon gas was used. The weld samples were made from 10mm thickness of mild steel plate; the plate was cut to size with the power hacksaw. The edges grinded and surfaces polished with emery paper and the joints welded and thereafter, the response (preheat temperature) was measured and recorded (Pondi P. , 2021).

Table 1. Chemical composition of AISI 1008 (Pondi P. , 2021)

Steel	ASTM	Elements (wt.%)									
		Cr	Ni	Mn	Mo	Si	N	C	P	S	Fe
Mild steel	AISI 1008	-	-	0.22	0.007	0.03	-	0.094	0.02	0.006	Bal

Table 2. Mechanical properties of AISI 1008 (Pondi P. , 2021)

Base metal	Tensile strength (MPa)	Yield strength (MPa)	Percentage Elongation (%)
AISI 1008	395.93	295.95	48.13

3.2 Selection Welding Process Parameters

The key input process parameters considered in the study includes; welding current, welding voltage and welding speed while the response or measured variable is heat input (HI). The three input process parameters specified in Table 3 with their upper (+1) and lower (-1) levels as well as an appropriate design matrix had all been investigated (Pondi P. , 2021). The output variable is specified in Table 4.

Table 3. Input process parameters and their levels (Pondi P. , 2021)

No. S.	Factors	Notation	Unit	Level		
				-1	**0**	**+1**
1	welding Current	C	(A)	170	180	190
2	welding Voltage	V	(V)	21	23	25
3	welding Speed	S	(mm/min)	2	3.5	5

Table 4. The response selected for these experiments (Pondi P. , 2021)

No. S.	Response	Notation	Unit
1	Heat Input	HI	(KJ/mm)

3.3 Simulation and Prediction Models Approaches

In this study, the simulation approach by means of utilizing E-weld software will be implemented to represent the estimate the heat input in welding process. Moreover, the statistical approach namely RSM, and artificial intelligence technique will be utilized to develop two model.

3.3.1 E-Weld Simulation Prediction Approach

E-Weld Predictor is a tool that combines high-performance computing hardware and numerical weld modeling to predict heat input for arc welding processes. It gives consumers instant access to advanced modeling tools via the internet so they can examine a variety of welding scenarios. E-Weld Predictor and goes over a number of its uses. One use is to comprehend how heat input affects in welding process. (Yang Y. , 2009).

3.3.2 E-Weld Simulation Software

The E-Weld Predictor's software structure, theory, implementation, and validation are all covered in great depth. Additionally, it displays the simulation procedure used to apply this software to heat input prediction. In order to reduce trial and error experimentation, E-Weld Predictor is an automated, integrated environment for problem solving that is used for numerical studies of welding-induced impacts on structural materials. There are two interface types available for E-Weld Predictor: an internet interface and an Excel-based Microsoft Excel interface. The software can be installed locally on the user's PC and has an Excel-based interface that may be customized to the needs of the customer (Yang Y.-P. , 2008). Steps to estimation of heat input based on E-weld Software shown in figure 1.

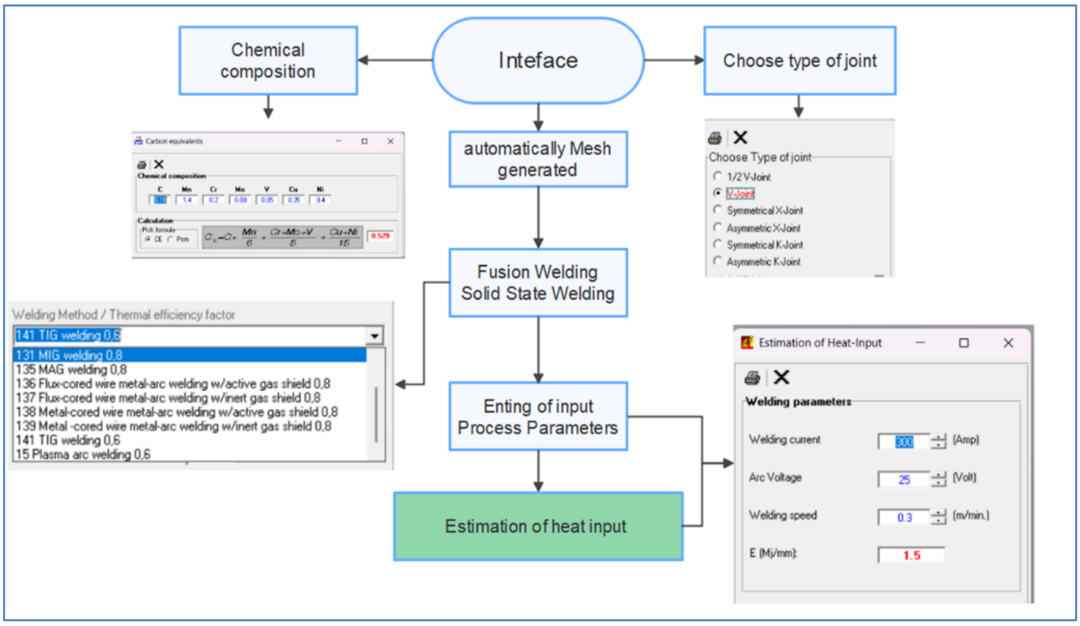

Fig 1. Steps to estimation of heat input based on E-weld Software

3.4 Design of Experiments (DOE)

When conducting studies with multiple factors and needing to look into the combined impact of the factors on a response variable, factorial designs are frequently employed. Main effects and interactions are usually meant when we talk about joint factor effects. The fact that each of the k elements of interest has just two levels is a highly significant specific case of the factorial design. These designs are sometimes referred to as 2k factorial designs since every copy of such a design has precisely 2k experimental trials or runs (MYERS, 2016).

3.4.1 Factorial Design

Many experiments involve the study of the effects of two or more factors. In general, factorial designs are most efficient for this type of experiment. By a factorial design, we mean that in each complete trial or replicate of the experiment all possible combinations of the levels of the factors are investigated. For example, if there are a levels of factor A and b levels of factor B, each replicate contains all ab treatment combinations. When factors are arranged in a factorial design, they are often said to be crossed. The effect of a factor is defined to be the change in response produced by a change in the level of the factor. This is frequently called a main effect because it refers to the primary factors of interest in the experiment (Montgomery, 2013).

Table 5 using the range and levels of the independent variables presented in Table 3.3, statistical design of experiment (DOE) using factorial design method was done. The total number of experimental runs that can be generated using the factorial design method.

Table 5. Experimental result using factorial design

Run	Current(A)	Voltage(V)	Speed(mm/min)
1	180	23	210
2	190	23	300
3	180	21	210
4	170	21	210
5	180	21	300
6	180	25	120
7	170	25	300
8	180	23	300
9	190	25	120
2	190	21	120
11	170	25	210
12	180	21	120
13	180	23	120
14	170	25	120
15	170	21	300
16	180	25	300
17	190	23	210
18	190	21	210
19	190	25	210
20	190	25	300
21	190	23	120
22	170	23	120
23	170	21	120
24	170	23	210
25	180	25	210
26	170	23	300
27	190	21	300

3.4.2 Regression Models

Creating an approximation model for the actual response surface is necessary for the practical implementation of response surface methodology (RSM). Usually, an unexplained physical process drives the actual reaction surface underlying. The approximation model is an empirical model that is based on observed data from the system or process. A group of statistical methods called multiple regression are effective for developing the kinds of empirical models needed for RSM. Let's take an example where we want to create an empirical model that relates the cutting tool's effective life to the tool angle and cutting speed. A response surface model of the first order that could explain this relationship (MYERS, 2016)

3.5 Response surface methodology approach

In this study a model has been developed using Response Surface Methodology (RSM) via Minitab software order to predict heat input. The design of experiment (DOE) method is a statistical method for studying a process with a limited number of tests. Response surface methodology (RSM) is a common and powerful regression-based modeling approach that uses a mathematical model to determine the relationship between multiple complicated factors and process responses It also has significant uses in the development, formulation, and design of new items as well as in the improvement of designs for already-existing ones (ALFazani, 2022). The manufacturing industry is where RSM is most commonly utilized, especially when multiple input factors have the ability to affect measurements of performance or process or characteristics of a product. The response refers to these characteristics of quality or performance indicators. While sensory reactions, ranks, and attribute responses are not uncommon, they are usually measured on a continuous scale. The majority of RSM practical uses will require multiple responses. When used in a test or experiment, the input variables—also referred to as independent variables—are within the engineer's or scientist's control (MYERS, 2016).

4. Results and Discussion

4.1 Discussion based on RSM

The effects of the three input process parameters welding Current, input 1 (C (A)), input 2 (welding Voltage (V), and input 3 (welding Speed (mm/min)) and their effects on the response Heat Input HI (KJ/mm) is analyzed and studied using the experimental values. An experiment is a sequence of tests, referred to as runs, in which modifications are made to the input process parameters in order to determine the causes of variations in the output response. The experimental results are given in Table 6.

Table 6. Actual and predicted RSM output for MRR

Run	Current(A)	Voltage(V)	Speed(mm/min)	Actual Heat Input value HI (KJ/mm)
1	180	23	210	1.18
2	190	23	300	0.87
3	180	21	210	1.08
4	170	21	210	1.02
5	180	21	300	0.76
6	180	25	120	2.25
7	170	25	300	0.85
8	180	23	300	0.83
9	190	25	120	2.38
2	190	21	120	2
11	170	25	210	1.21
12	180	21	120	1.89
13	180	23	120	2.07
14	170	25	120	2.13
15	170	21	300	0.71
16	180	25	300	0.9
17	190	23	210	1.25
18	190	21	210	1.14
19	190	25	210	1.36
20	190	25	300	0.95
21	190	23	120	2.19
22	170	23	120	1.96
23	170	21	120	1.78
24	170	23	210	1.12
25	180	25	210	1.29
26	170	23	300	0.78
27	190	21	300	0.8

The goal is to predict a response (output variable) that is impacted by a number of independent variables (input process parameters) through accurate experiment design in Table 7.

Table 7. Actual and predicted RSM output for MRR

Run	Current(A)	Voltage(V)	Speed(mm/min)	Actual Heat Input value HI (KJ/mm)	Predicted Heat Input value HI (KJ/mm)
1	180	23	210	1.18	1.18
2	190	23	300	0.87	0.87
3	180	21	210	1.08	1.06
4	170	21	210	1.02	0.99
5	180	21	300	0.76	0.76
6	180	25	120	2.25	2.25
7	170	25	300	0.85	0.84
8	180	23	300	0.83	0.83
9	190	25	120	2.38	2.36
2	190	21	120	2	2.00
11	170	25	210	1.21	1.22
12	180	21	120	1.89	1.90
13	180	23	120	2.07	2.07
14	170	25	120	2.13	2.13
15	170	21	300	0.71	0.73
16	180	25	300	0.9	0.89
17	190	23	210	1.25	1.26
18	190	21	210	1.14	1.14
19	190	25	210	1.36	1.38
20	190	25	300	0.95	0.94
21	190	23	120	2.19	2.18
22	170	23	120	1.96	1.96
23	170	21	120	1.78	1.79
24	170	23	210	1.12	1.11
25	180	25	210	1.29	1.30
26	170	23	300	0.78	0.79
27	190	21	300	0.8	0.80

Based on the value of the mean absolute percentage error (MAPE) as given by eqn -1, a comparison between the actual values and the anticipated values of HI is used to validate the RSM model. It was determined what (MAPE) was 0.70%. Additionally, figure 2 HI predicted values to their actual values in the RSM model. Indicate accurately represent actual HI values the RSM model.

$$\text{MAPE}=\frac{1}{n}\sum_{i=1}^{n}\left|\frac{A-P}{A}\right| ☒ 100\% \qquad (1)$$

where:

A: The actual value for HI

P: The predicted value for HI n: Number of Experiments

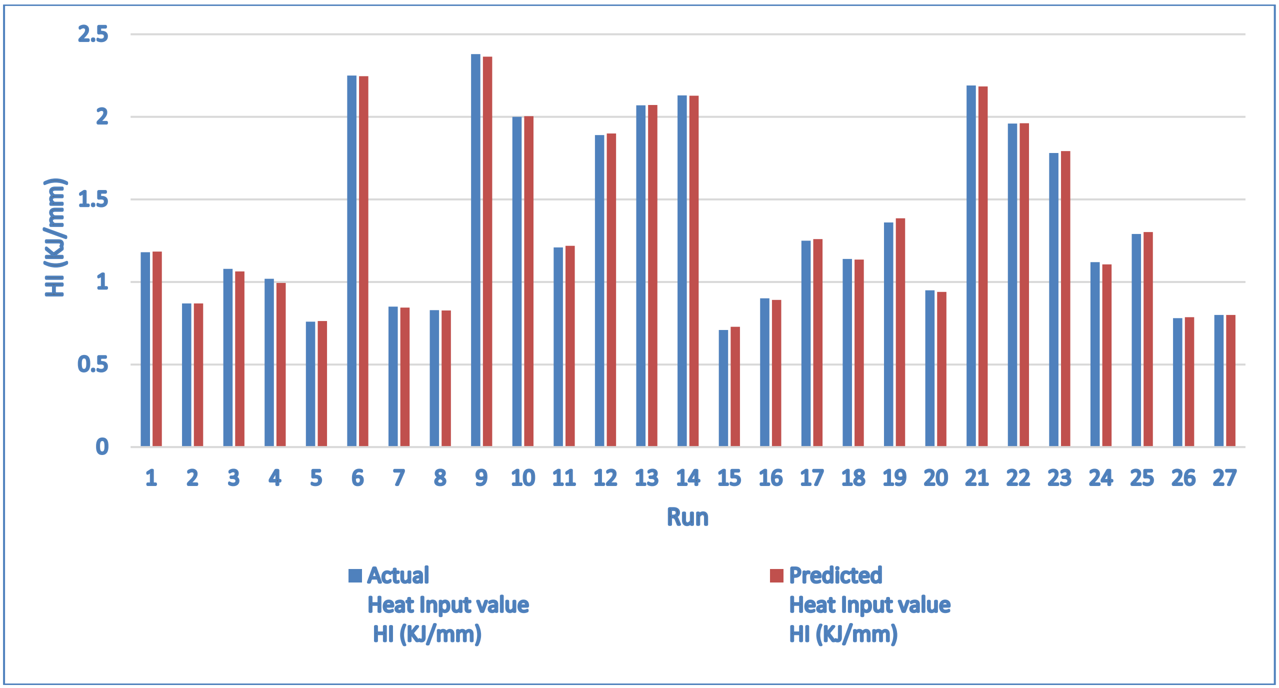

Fig. 2 Comparison between actual and predicted of MRR by RSM

Based on the value of the Nash-Sutcliffe Efficiency (NSE) as given by eqn -2, a comparison between the actual values and the anticipated values of HI is used to validate the RSM model. It was determined what (NSE) was 99%. Indicate accurately represent actual HI values the RSM model. The Nash-Sutcliffe Efficiency (NSE) was also calculated to evaluate the efficiency of the model by eqn 2 (ALFazani, 2022).

$$\text{NSE} = \frac{\sum(A-P)^2}{\sum(A-\overline{A})^2} \qquad (2)$$

Where:

A: Actual value for HI.

$\overline{A}$: Average actual value for HI

P: Predict a value for HI

5. Conclusions

In this study, three input process parameters, namely welding current (A), welding voltage (V), and welding speed (mm/min), respectively. Were utilized in order to predict the HI (KJ/mm) using RSM. It was observed that the RSM prediction model gave an MAPE 0.70% and NSE gave an 99%. Indicate that RSM model is accurate prediction model. Therefore, the RSM is recommended for prediction of the HI of arc welding process.

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