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**INFLUENCE OF WIRE DROPLET DIAMETER ON THE PENETRATION DEPTH
OF TUNGSTEN INERT GAS MILD STEEL WELDS**

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ABSTRACT

The aim of this paper is to study the effect of the wire droplet diameter on the penetration depth of the weld bead. Experiments were conducted on mild steel plate of 10 mm thickness, by employing single pass welds of gas tungsten arc welding for 20 sets of weld samples. The ANOVA results revealed that the current, welding speed and wire diameter has effects on the depth of penetration in the welds, as the droplet diameter reduces the penetration depth also reduces. The data integrity was also tested using the cooks distance plot and the result showed that the data fell within the range of 0 and 1. An optimal solution of current 208.21 amp, welding speed of 3.02 mm/sec wire diameter of 2.55mm that will produce penetration depth of 10.30mm was achieved. This solution obtained will help control the settings of the welding process so as to achieve better weld quality output.

Keywords: penetration depth, wire droplet, mild steel, welds, tungsten, inert gas

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1. Introduction

The tungsten inert gas welding is a process that employs the use of a single electrode to form a welded joint. During this process the electrode is not consumed, however filler materials are used to balance the heat from the arc when dipped in the weld pool. The mechanical properties of welded joints such as hardness, tensile strength, are determined by the dimensions of weld bead profile. The bead geometry is influenced by welding process factors such as current, voltage, welding speed and electrode size as they control the heat distribution required to fuse the base metal and filler wire. A study on the influence of filler wire composition on the penetration depth of a weld, combination of chromium (Cr) molybdenum (Mo) titanium (Ti) and niobium (Nb) was considered. The percentage composition of Ti increases the wetting angle and penetration depth but discovered that Niobium has no effect on penetration (Villare et al. 2013). An evaluation on the effect of filler wire thickness on the mechanical properties of the welded joint was investigated. Variable welding parameters were reflected in different heat input and cooling rate values, which led to a change in the properties of the HAZ and thus the mechanical properties of the welded joints. The negative effect of the soft zone is more pronounced as the thickness of the material decreases (Mician et al. 2021). It is important to understand interrelationship between welding speed and depth of penetration. Single-pass welds of Mild Steel plates were fabricated using welding current and arc voltage as process factors. The depth of penetration was measured for each specimen after the welding process and the results were analyzed to study the effect of speed on depth of penetration. It was found that at constant arc voltage and welding current the depth of penetration will increase with increasing welding speed (Singh and Bhinder 2014). Mathematical models are important for the development of robotic welding equipment, the fractional factorial method has been used in this study to establish a relationship between welding speed, voltage, wire feed rate, welding speed, nozzle to plate distance on weld width (w), penetration (p), Reinforcement (R), %Dilution (D) in a gas metal arc welding process the models developed showed high adequacy and strength based on the F-test and T-test and coefficients (varma et al. 2001). The welding current was observed to be the dominant process factor influencing the weld penetration in a submerged arc welding experiment, A control system was developed to monitor and control weld penetration using a proportional integral derivative (PID) control algorithm. This algorithm is based on penetration feedback provided by the penetration model that correlates weld penetration depth to base metal current (Li et al. 2013). Evaluation of the influence of shielding gas type, voltage, wire feed rate, gas flow rate, electric current intensity and welding speed of TIG – MIG/MAG welding on Penetration, heat-affected zone (HAZ), bead width and bead height was done, the Taguchi experimental design was employed. The results showed that The bead height was significantly influenced by the wire feed and electric current intensity (Schneider et al. 2017). An experimental study on the weldability of 5052 aluminium alloy using tungsten inert gas welding technique, discovered that input factors such as arc voltage, welding current, welding speed, gas flow rate and heat input all have effect on the depth of penetration (Raveendra et al. 2014). Tungsten inert gas welding of HSLA steel was conducted with varying welding heat inputs, and the effects of welding heat input on the

microstructure, Vickers hardness, and impact toughness of heat-affected zone (HAZ) in prepared joints were scientifically investigated. The microstructure in HAZ with low welding heat input mainly consisted of martensite, and the microhardness of coarse grain HAZ was measured higher than that of fine grain zone. The results show that increasing the welding heat input could suppress the formation of martensite and reduce the micro hardness of HAZ (Dong et.al.2014).

2. Research Methodology

20 sets of experiments was done ,the filler wire droplet diameter and the penetration depth was measured after each weld.The material used was mild steel because of its popularity and usability across the manufacturing sector.An optimal experimental design with the aid of design expert was developed. 100 sample of the weld specimen was produced. The welding equipment used was Tungsten Inert Gas equipment combined with argon shielding gas .

2.1. Identification of Input Parameters

1. Welding current

Amperage is used to increase or decrease the overall size of weld bead as well as the penetration depth of weld bead. It controls the depth of fusion, geometry and the electrode burn off rate. Change in welding current changes the transition current and mode of metal transfer get changed accordingly. So, Welding current is also one of the major factors dominating the metal transfer [4].

2. Arc Voltage

Arc voltage is the electrical potential difference between the tip of the electrode and the surface of the molten weld pool on the surface of job. It determines the shape of the fusion zone and weld reinforcement. Arc voltage is the voltage between electrode and the job during welding. Decrease in arc voltage cause narrow weld bead with deeper penetration.

3. Welding Speed

The speed of movement of the welding torch determines the welding speed. Broadly it may be defined as the rate of travel of the electrode along the seam or the rate of the travel of the work under the electrode along the seam. Welding Speed influences both penetration and weld pool width. High welding speeds increase penetration.The process factors and the range of value is shown in Table 1

Table1: Range of input process parameters

Parameters	Unit	Symbol	Coded value Low(-1)	Coded value High(+1)
Current	Amp	A	180	210
Welding speed	mm/min	S	2.1	3.5
Wire diameter	Mm	D	2.0	3.4

2.2. Method of Data Collection

In this study a scientific method of selecting and combining the process factors together called design of experiment is employed. The central composite design was selected because it is handling three input process factors, which gave a total of 20 sets of experiments. The input parameters and output parameters make up the experimental matrix, and the responses recorded from the weld samples were collected and used as the data. Table 2 shows the central composite design matrix.

Table 2: Experimental data

S/N	Current (Amp)	Welding speed rate (mm/min)	Wire diameter (mm)	Bead penetration (mm)	Droplet diameter (mm)
1	200.00	2.80	2.80	10.28	10.42
2	190.00	3.20	2.40	11.90	11.09
3	210.00	3.20	3.20	10.00	10.03
4	210.00	3.20	2.40	10.54	10.08
5	190.00	2.40	2.40	9.68	9.94
6	216.82	2.80	2.80	9.74	9.90
7	200.00	2.80	2.13	10.28	9.98
8	210.00	2.40	3.20	10.54	10.12
9	200.00	2.80	2.80	10.28	10.04
10	183.18	2.80	2.80	10.28	10,09
11	200.00	2.80	3.47	9.99	10.66
12	190.00	3.20	3.20	10.79	9.90
13	200.00	2.80	2.80	10.28	9.90
14	200.00	2.80	2.80	10.28	9.90
15	200.00	2.80	2.80	10.28	9.90
16	200.00	2.13	2.80	10.28	10.08
17	200.00	2.80	2.80	10.28	9.90
18	210.00	2.40	2.40	9.85	9.96
19	200.00	3.47	2.80	11.76	11.00
20	190.00	2.40	3.20	9.87	9.92

2.3. Experimental procedure

The samples were grinded, sand cleaned and etched to get a fine edge because sample has to be free from grease and dirt. 100 pieces of mild steel coupons was produced for this experiment using 100% argon gas as the shielding gas. 10 mm thickness of mild steel plate was used as the base material for the single-pass surface welding with a direct current of reverse polarity. In this process the tungsten non consumable electrode was used alongside gauge 2mm -3 mm diameter filler metal ER309L thereafter the responses were measured and recorded respectively.

2.4. Testing the integrity of the data used

2.4.1 Cooks distance

Cooks distance is used in regression analysis to find a set of predictor values or responses. It was introduced by an American Dennis R. Cook (1957). The cooks distance plot is an important diagnostics that is used to check for erroneous data. The data used are all supposed to fall within the upper and lower level of the plot any data falling out of place is observed to be an outlier, the values fall between 0 and 1.

2.4.2 Analysis of variance

The coefficient of determination R^2 was used to validate the developed model Equation 1 shows the expression for the diagnostic tool. The model target is predicted using the R^2 .

$$R^2 = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (1)$$

The experimental observation is represented with y_i . \hat{y} is the fitted observation.

\bar{y} is the average observation

$R^2 \leq 1$ (R^2 is less than or equal to one in most cases)

ii) The adjusted coefficient determination is determined and used to validate the developed model It is expressed in Equation 2.

$$AdjR^2 = \frac{\sum (y_i - \hat{y}_i) / n - k}{\sum (y_i - \bar{y}) / n - 1} \quad (2)$$

When n is the input process parameters, K is the no of responses and the observation for the experiment is represented with y_i and \bar{y} is fitted observation with \bar{y} as the average observation. R^2 value is always below 1.

3 Results and Discussion

In this study, an attempt is made to develop a second order mathematical model with selected input variables, namely; current (I), welding speed and wire diameter coupled with two

response variables namely; penetration depth, droplet diameter using response surface methodology (RSM).

The target of the optimization model was to:

- i. Maximize bead penetration
- ii. minimize droplet diameter

To check for existence of any outlier the cooks distance plot is required to detect any erroneous data, the cooks distance plot for Droplet diameter is presented in Figure 1

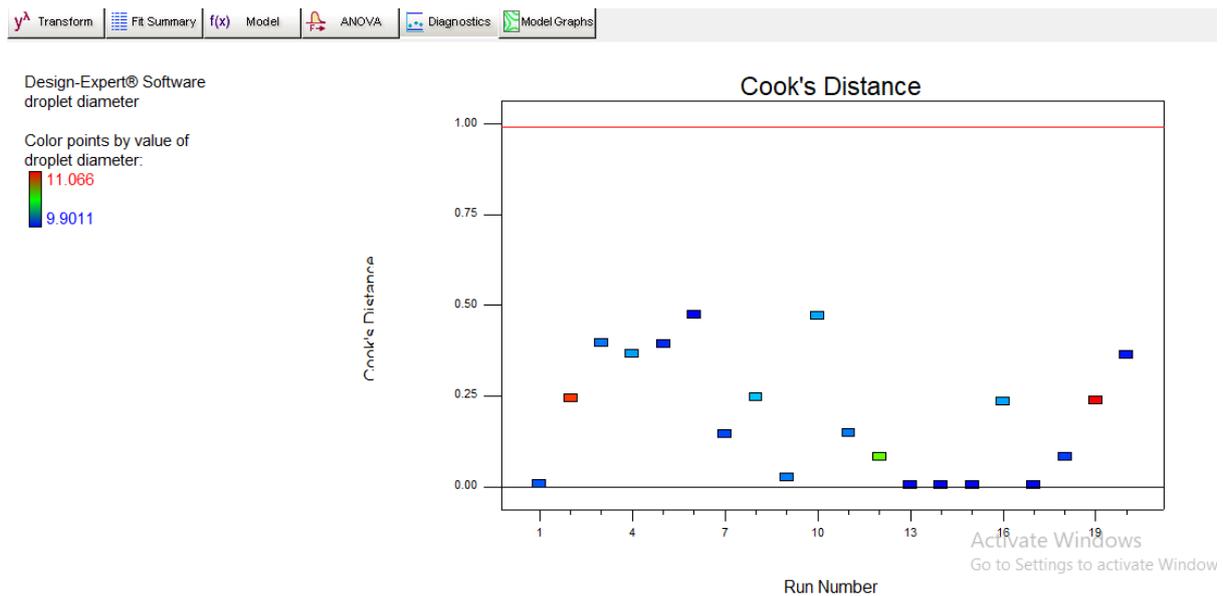


Figure 1: Generated cook's distance for Droplet diameter

In Figure 1 the droplet diameter data all fall between value 0 and 1 ,indicating that there is no outlier observed in the data used. The cooks distance plot was also produce for the penetration depth response to detect for any outlier, the cooks distance plot for the penetration depth is shown in Figure 2

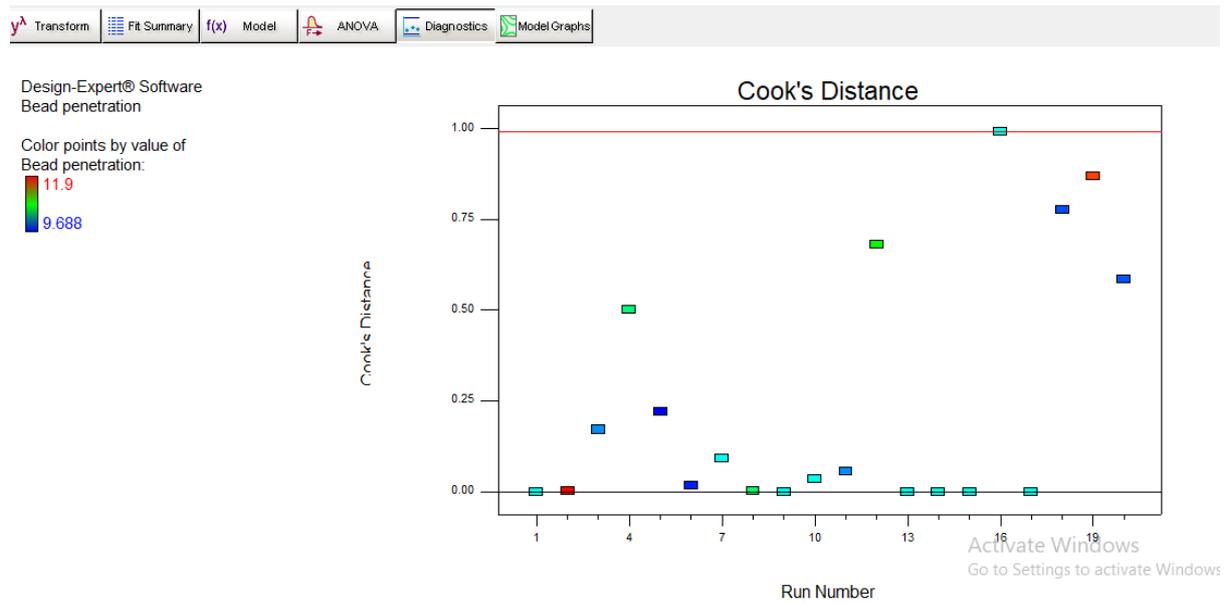


Figure 2: Generated cook's distance for penetration depth

Figure 2 shows the cooks distance plot for the penetration depth, the data all fall within the values between 0 and 1 indicating that no error was observed during data collection for penetration depth.

The strength of the model developed needs to be determined and the goodness of fit statistics reveals the strength by measuring the coefficient of determination R^2 . The goodness of fit table for penetration depth is presented in Table 3.

Table 3: Goodness of fit statistics for penetration depth

Std. Dev.	0.019	R-Squared	0.9994
Mean	10.36	Adj R-Squared	0.9989
C.V. %	0.19	Pred R-Squared	0.9954
PRESS	0.029	Adeq Precision	163.913

In the Table above, the result showed that the model has 99.9% capacity to predict the penetration depth when any of the input process factors is varied. The goodness of fit statistics for the filler wire droplet diameter measures the strength and adequacy of the quadratic model as shown in Table 4.

Table 4: Goodness of fit statistics for droplet diameter

Std. Dev.	0.091	R-Squared	0.9637
Mean	10.13	Adj R-Squared	0.9311
C.V. %	0.90	Pred R-Squared	0.7690
PRESS	0.52	Adeq Precision	18.607

The result in Table 4 shows that the model has 96 % capacity to predict the penetration depth when any of the input factors are varied. To check for the significance of the input parameters on the response, the analysis of variance (ANOVA) is done for the penetration depth as presented in Table 5

Table 5: ANOVA table for the penetration depth

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	
Model	6.22	9	0.69	1877.97	< 0.0001	significant
A-current	0.36	1	0.36	973.61	< 0.0001	
B-welding speed	2.42	1	2.42	6584.40	<0.0001	
C-wire diameter	0.12	1	0.12	316.85	<0.0001	
AB	1.12	1	1.12	3033.78	<0.0001	
AC	0.14	1	0.14	388.08	<0.0001	
BC	0.80	1	0.80	2183.50	<0.0001	
A ²	0.13	1	0.13	347.86	<0.0001	
B ²	0.98	1	0.98	2672.47	<0.0001	
C ²	0.038	1	0.038	104.61	<0.0001	
Residual	3.667E-003	10	3.677E-004			
Lack of Fit	3.667E-003	5	0.057	0.42	0.8170	not significant
Pure Error	0.000	5	0.000			
Cor Total	6.22	19				

The result in Table 5 shows that the welding current, welding speed and wire diameter all have significant effect on the penetration depth of the welded joint. To check for the significance of the input parameters on the droplet diameter response, the analysis of variance (ANOVA) is presented in Table 6.

Table 6: ANOVA table for the droplet diameter

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob. > F	
Model	2.19	9	0.24	29.52	< 0.0001	Significant
A-current	0.18	1	0.18	22.23	0.0008	
B-welding speed	0.84	1	0.84	102.36	<0.0001	
C-wire diameter	3.410E-003	1	3.410E-003	0.41	0.534	
AB	0.36	1	0.36	44.12	<0.0001	
AC	0.035	1	0.035	4.24	0.0666	
BC	0.043	1	0.043	5.16	0.0464	
A ²	4.433E-003	1	4.433E-003	0.54	0.4799	
B ²	0.72	1	0.72	87.11	<0.0001	
C ²	7.873E-003	1	7.873E-003	0.96	0.3512	
Residual	0.082	10	8.233E-003			
Lack of Fit	0.065	5	0.013	3.73	0.0875	not significant
Pure Error	0.017	5	3.482E-003			
Cor Total	2.27	19				

The final numerical optimal solution was obtained showing optimal results for current, welding speed and wire diameter that will produce maximum penetration and minimum droplet diameter is shown in Table 7.

Table 7: Numerical optimal solutions

Number	Current	welding speed	Wire diameter	Droplet diameter	penetration depth	Desirability
1	208.21	3.02	2.55	9.98058	10.3068	0.824
2	159.32	17.76	2.00	11.33	10.9416	0.824
3	159.34	17.72	2.00	11.30	10.9475	0.824
4	159.59	17.72	2.00	11.39	10.912	0.824
5	160.00	17.77	2.00	11.39	10.9243	0.824

4.0 Conclusion

In this study, the influence of current, welding speed and filler wire diameter on the penetration depth has been investigated, the response surface methodology mathematical model was employed to establish this relationship.

The results obtained showed that the welding speed and wire diameter has significant effect on the droplet diameter and the welding current has a significant effect on the welding penetration which is in agreement with the work of kaewsakul et.al (2015), the statistical tests conducted on the model possessed satisfactory results, with high coefficient of determination R^2 . The data integrity was also tested using the cooks distance plot and the result showed that the data all fell within the range of 0 and 1. An optimal solution of current 208.21 amp, welding speed of 3.02 mm/sec wire diameter of 2.55mm that will produce penetration depth of 10.30mm was achieved. This solution obtained will help control the settings of the welding process so as to achieve better weld quality output.

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