

# FUME FORMATION RATE PREDICTIVE MODELS FOR GAS TUNGSTEN ARC WELDING OF MILD STEEL PLATES

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**Abstract.** The purpose of this study is to develop predictive models to predict the fume formation rate in a Tungsten Inert Gas welding process of mild steel plates. The fume samples were collected using fume extractors and filters, the experimental results was used as data to develop the models. The Response surface methodology was employed to develop the fume formation model in this study, the RSM is a very popular and robust technique applied in the field of engineering and applied sciences to predict desired responses. The second order quadratic model was selected as the model best fit, the decision was based on some statistical criteria such as Anova, Coefficient of determination, Cooks distance and contour plots. The model developed possess adequate signal, indicating the strength and capacity to predict the fume formation rate of TIG welding on mild steel specimen. The model developed showed that welding current is a very strong factor influencing the fume formation rate.

**Keywords:** fume formation, predictive model, mild steel, gas tungsten arc, welding

## Introduction

The Tungsten welding operation consists of intense heat input to melt the filler rod to create a fusion which might lead to the development of toxins. Fume development throughout arc welding operations happens to be an undesired phenomenon for the welding industry which poses a health risk on welding and metal fabrication workers as a result of the inhalation of these poisonous fumes. Inadequate management and control of numerous toxic materials produced throughout the welding activity is able to end up to both long-term and short health consequences (Verma and Singh, 2016). Studies on welders epidemiology disclosed that a huge number of welders encounter some kind of respiratory illness (such as bronchitis, airway irritation, lung function alterations, as well as a potential rise in the incidence of lung cancer) (Antonini, 2003). Fumes created through the shielded metal arc welding (SMAW) method can be a trigger for concern as a result of probable health concerns that is taking place on individuals inside the welding sector subsequently after long-term exposure. Welding fume particles could result in metal fume fever, as well as conceivably much more notably, manganese- or perhaps chromium associated poisoning following ingestion and inhalation inside the human body, it continues to be suggested that long term, minimal concentration doses of Mn are connected to neurological system disorders (Ashburner, 1989). Research studies have also proven that welders working with stainless steels which have had instances of lung cancer could be caused by potential hexavalent chromium influence, nonetheless, there continues to be no strong proof connecting the cancers to welding fume exposure (NIOSH, 1988).

Occupational exposure limits (OEL), that happen to be revised fairly frequently, figure out the volume of these elements and compounds which could be consumed with no getting bad for human cells. Although epidemiological responses to the various

elements contained in welding fume are essential, they're beyond the range on this research, that had been developed to characterize the fume particles released by steel joining operations (Pekkari, 2000) shielded metallic arc welding creates aerosol consisting of spatter and fume. Earlier scientific studies have revealed that SMAW fume includes an assortment of metals, oxides, and other compounds, which create through evaporation of components within the arc as well as fluxes overlaying the electrode (Voitkevich, 1995). Fume debris generally differ more than a broad range of sizes, therefore it becomes essential to take into account fume particles in every size range as opposed to bulk structure by itself. Interactions among composition and particle size have likewise been identified. Number and mass distributions of welding toxins were assessed with a variety of methods such as cascade impactors, scanning mobility particle sizers, and optical particle counters (Jenkins, 2003). Fume particles distributions have commonly demonstrated which fume particles are contained in an extensive range of sizes but are typically present in higher concentrations of small particle sizes as well as higher masses from the greater particle sizes. Fume development can be of great interest in order to recognize the different compositions and morphologies of bulk fume. The effect of aerosol physics on welding fume development have been discussed in detail (Zimmer et al., 2002). The aerodynamic diameter of a fume particle is the diameter of a unit density sphere with an equivalent particle mass as well as particle mobility while the particle in question (Kelly and McMurry, 1992).

Aerodynamic diameter could be very minimal for receptive integrated agglomerates, in comparison to spherical particles. Coarse fume debris tend to be produced by mechanical methods including ejection of spatter from the arc or perhaps molten weld pool. These formation factors must be considered when analyzing composition and particle size distributions (Kütz and Schmidt-Ott, 1990). Fume production rates (FGR) for flux cored arc welding (FCAW) operations is greater than which of SMAW welding procedure among the assorted welding systems which are used commercially. Fume production is a feature of various creation steps and competing mechanisms (Gray et al., 1982). The different components as well as substances inside the welding consumable and base material are vaporized as an outcome from the intensive temperature generated by the welding arc. A typical sequence of welding fume development can be as observe immediately after vaporization: 1) the aerosol debris will homogeneously nucleate through the supersaturated vapor; 2) then they are going to grow by condensation as well as coagulation; 3) perhaps produce a core-shell framework by condensation as a result of altering vapor stress of countless species, as well as due to fluid stage separation; 4) form an oxide shell within the metallic center because of the exposure on the aerosol particle to oxygen rich atmosphere; 5) completely respond with oxygen to create metal-oxides; as well as 6) coagulate to form aerosol particle agglomerates (Seinfeld and Pandis, 1998). In processes wherein flux is utilized, with FCAW and SMAW electrodes, subsequently the fume particle is going to be subjected to vapor produced out of the vaporized flux components causing condensation of extra components on preexisting debris. Condensation temperature variations involving substances such as SiO<sub>2</sub> and Fe<sub>3</sub>O<sub>4</sub> in aerosols were proven to play a role in areas of compositional variation within the single molecules, triggering a "core shell" morphology (Ehrman et al., 1998).

The various fume development systems are going to result in a huge size-range of dust during protected metal arc welding, which range from ultrafine (<0.1 μm) to fine (0.1-2.5 μm) to coarse (>2.5 μm) sizes. The fine as well as ultrafine sizing ranges have

actually been recommended to function as the primary problem with respect to potential health issues, since they're significantly more prone to generally be deposited in the lungs. Methods, for instance those discussed below, to characterize the character of welding fume as a feature of size distributions have to completely comprehend the health-related effect of welding fume. A fume collection system as well as technique was created and was employed to evaluate the three electrodes in this particular research along with a selection of other consumable/process combinations (Antonini et al., 1998). The procedure for fume formation testing along with analysis includes collection of measurement and fume of FGR using an AWS-type collection feature, merged with smaller sized filtration pore dimensions than those suggested by the F1.2:1999 standard. A crucial aspect of these experiments stands out as the fume collection with an electrical low pressure impactor (ELPI). The ELPI is efficient at sorting out dust by aerodynamic diameter and monitoring size distributions in real time (American Welding Society, 1999). Keskinen et al. (1992) reported that this could be achieved via numerous concepts including particle charging, inertial category, along with electrical detection of the dust using electrometers. Fume is drawn inside the ELPI through the use of a vacuum pump, as well as is passed by way of a particle charger prior to getting divided in the impactor. The impactor has several phase, which size particles as outlined by their aerodynamic diameter in the range of 0.03-10  $\mu$ m. A certain phase will trap particles if they're not able to produce the sharp turn expected, as a result of their inertia, to reach the new phase (Keskinen et al., 1992).

### ***Research methodology***

Research steps taken in order to achieve the desired objectives, are as follows; (1) selection of base metal and filler metal; (2) identify important weld parameters; (3) identification of range of process parameters; (4) development of experimental matrix; (5) conducting the experiment; and (6) measurement of fume formation rate.

## **Materials and Methods**

### ***Welding procedures***

Mild steel plates happened to be employed for this particular experiment with dimension measuring 60x40x10mm. The filler metal is equivalent to which of base metallic. A pilot analysis was performed prior to selecting the range of process parameters (current, type of gasoline, gas flow rate as well as groove angle). Power Hacksaw was employed to lower the moderate metal material. The grinding machine was utilized for setting up the groove on the double transverse side of the plates of Mild Steel and subsequently single 'V' groove angles (30 degree) ended up being cut in the plates with 2 mm root faces for a total of 60 degree predisposed position between two plates the TIG welding method was employed, with tungsten non consumable electrode experiencing diameter 3 mm was used in experiment. The argon gasoline is applied as a shielding gasoline. The water cooled torch were employed to avoid the overheating. The stress regulator continues to be applied to adapt the gasoline flow speed throughout operation. The filler metallic ER309L, having diameter 2 mm continues to be implemented for the welding. The immediate current Electrode optimistic (reverse polarity) is actually employed for the welding.

### ***Welding process parameters***

The welding process parameters consists of current, voltage, gas flow rate and welding speed, their range of values are shown in *Table 1*.

***Table 1. Process parameters.***

Parameters	Unit	Symbol	Coded value	
			Low (-1)	High (+1)
Current	Ampere	A	180	240
Gas flow rate	Lit/min	F	16	22
Voltage	Volts	V	18	24
Wire diameter	Mm	W	1.5	4

### ***Design of experiment***

An accurate experimental design is necessary for data collection, the design expert software is used to develop a matrix that helps to optimize the experimental process. The experimental data collected is shown in *Table 2*.

***Table 2. Experimental data.***

Run	Current	Voltage	Wire diameter	Gas flow rate	Fume formation rate
1	180.00	20.00	2.80	13.00	8.8
2	180.00	16.00	2.80	13.00	2.45
3	220.00	20.00	2.80	13.00	2.37
4	180.00	20.00	0.40	13.00	7.7
5	200.00	22.00	1.60	11.00	5.62
6	180.00	20.00	2.80	13.00	7.9
7	200.00	18.00	4.00	11.00	3.8
8	180.00	20.00	2.80	9.00	8.2
9	200.00	22.00	4.00	11.00	4.6
10	200.00	18.00	1.60	15.00	4
11	160.00	18.00	1.60	11.00	7
12	160.00	18.00	4.00	15.00	6
13	180.00	20.00	2.80	13.00	6.93
14	160.00	22.00	4.00	15.00	4.92
15	200.00	18.00	4.00	15.00	4.66
16	180.00	20.00	2.80	13.00	7.15
17	180.00	20.00	2.80	13.00	7.15
18	160.00	22.00	1.60	15.00	4.92
19	160.00	22.00	4.00	11.00	4.92
20	160.00	18.00	4.00	11.00	6.24
21	180.00	20.00	2.80	13.00	6.93
22	160.00	22.00	1.60	11.00	6.24
23	200.00	22.00	4.00	15.00	4.22
24	180.00	20.00	5.20	13.00	6.93
25	180.00	20.00	2.80	17.00	7.43
26	160.00	18.00	1.60	15.00	6.24
27	200.00	22.00	1.60	15.00	4.7
28	200.00	18.00	1.60	11.00	4.9
29	180.00	24.00	2.80	13.00	5
30	140.00	20.00	2.80	13.00	4.1

## Results and Discussion

The quadratic model was selected as the best model that can predict the fume formation rate accurately; the analysis of variance was employed to check for the models significance as shown in *Table 3*. *Table 3* shows that the model is very significant with the p value of 0.0001 a pvalue ,0.05 indicates that the model can be used to predict its target response.

**Table 3.** ANOVA for fume formation rate.

Source	Sum of Square	df	Mean square	F value	p-value Prob>F	Significant
Model	0.40	14	0.028	15.05	< 0.0001	
A-current	7.53	1	7.53	15.23	< 0.0001	
B-voltage	0.24	1	0.24	0.49	0.4965	
C-wire diameter	1.40	1	1.40	2.84	0.1128	
D-gas flow rate	1.13	1	1.13	2.28	0.1518	
AB	2.45	1	2.45	4.96	0.0417	
AC	9.025E-003	1	9.025E-003	0.018	0.8943	
AD	0.060	1	0.060	0.12	0.7323	Significant
BC	0.12	1	0.12	0.24	0.6307	
BD	0.16	1	0.16	0.32	0.5825	
CD	1.07	1	1.07	2.17	0.1616	
A^2	34.19	1	34.19	69.20	< 0.0001	
B^2	27.10	1	27.10	54.85	< 0.0001	
C^2	0.26	1	0.26	0.52	0.4834	
D^2	0.022	1	0.022	0.045	0.8345	
Residual	7.41	15	0.49	-	-	-
Lack of Fit	4.67	10	0.47	0.85	0.6139	Not significant
Pure Error	2.74	5	0.55	-	-	-
Cor Total	78.21	29	-	-	-	-

To check for the models strength and accuracy, the goodness of fit is determined for the fumr formation rate as shown in *Table 4*.

**Table 4.** Goodness of fit statistics for fume formation rate.

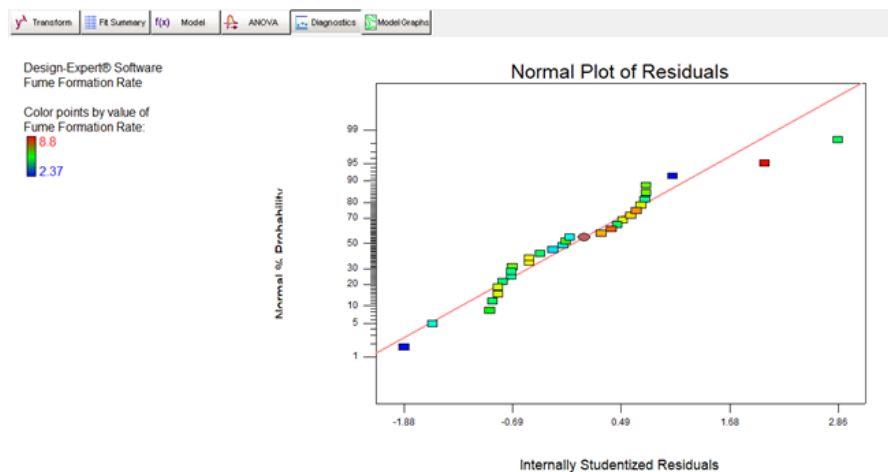
Category	Frequency
Std. Dev.	0.70
Mean	5.73
C.V. (%)	12.26
PRESS	30.85
R-square	0.9352
Adj. R-square	0.9168
Pred. R-square	0.8056
Adeq. Precision	12.340

The response surface model has produced fume formation rate prediction with statistical results to justify the accuracy of the predictions as shown in *Table 5*. *Table 5* shows that the predictive model lacks errors having cooks distance between 0 and 1, as cooks distance 0.1 indicates that there are outliers in the data being analysed.

**Table 5. Diagnostics case statistics for fume formation rate.**

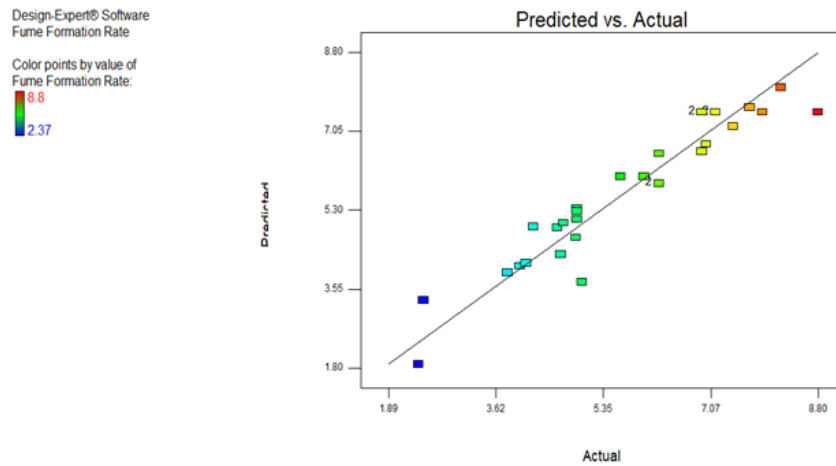
Standard order	Actual value	Predicted value	Residual	Leverage	Studentized		Fitted value DFFITS	Cook's distance	Run order
					Residual A	Residual B			
1	7.00	6.77	0.23	0.583	0.514	0.501	0.593	0.025	11
2	4.90	4.69	0.21	0.583	0.454	0.441	0.522	0.019	28
3	6.24	6.55	-0.31	0.583	-0.692	-0.680	-0.804	0.045	22
4	5.62	6.05	-0.43	0.583	-0.940	-0.936	-1.108	0.083	5
5	6.24	5.89	0.35	0.583	0.770	0.759	0.898	0.055	20
6	3.80	3.91	-0.11	0.583	-0.250	-0.242	-0.286	0.006	7
7	4.92	5.33	-0.41	0.583	-0.911	-0.905	-1.071	0.077	19
8	4.60	4.92	-0.32	0.583	-0.707	-0.695	-0.822	0.047	9
9	6.24	5.89	0.35	0.583	0.770	0.759	0.898	0.055	26
10	4.00	4.06	-0.063	0.583	-0.140	-0.135	-0.160	0.002	10
11	4.92	5.28	-0.36	0.583	-0.801	-0.791	-0.936	0.060	18
12	4.70	5.02	-0.32	0.583	-0.707	-0.695	-0.822	0.047	27
13	6.00	6.05	-0.050	0.583	-0.110	-0.107	-0.126	0.001	12
14	4.66	4.32	0.34	0.583	0.755	0.744	0.880	0.053	15
15	4.92	5.10	-0.18	0.583	-0.391	-0.380	-0.449	0.014	14
16	4.22	4.93	-0.71	0.583	-1.565	-1.653	-1.955	0.229	23
17	4.10	4.13	-0.031	0.583	-0.068	-0.066	-0.078	0.000	30
18	2.37	1.89	0.48	0.583	1.056	1.060	1.255	0.104	3
19	2.45	3.30	-0.85	0.583	-1.875	-2.071	-1.45	0.328	2
20	5.00	3.70	1.30	0.583	2.863	1.11	1.86	0.765	29
21	7.70	7.57	0.13	0.583	0.277	0.269	0.318	0.007	4
22	6.93	6.61	0.32	0.583	0.711	0.699	0.827	0.047	24
23	8.20	8.02	0.18	0.583	0.388	0.376	0.445	0.014	8
24	7.43	7.16	0.27	0.583	0.601	0.587	0.695	0.034	25
25	7.90	7.48	0.42	0.167	0.660	0.647	0.289	0.006	6
26	6.93	7.48	-0.55	0.167	-0.852	-0.844	-0.377	0.010	13
27	7.15	7.48	-0.33	0.167	-0.509	-0.496	-0.222	0.003	16
28	7.15	7.48	-0.33	0.167	-0.509	-0.496	-0.222	0.003	17
29	6.93	7.48	-0.55	0.167	-0.852	-0.844	-0.377	0.010	21
30	8.80	7.48	1.32	0.167	2.062	2.354	1.053	0.057	1

To check for the experimental data integrity a normal probability plot of residual for fume formation rate is presented in *Figure 1*.

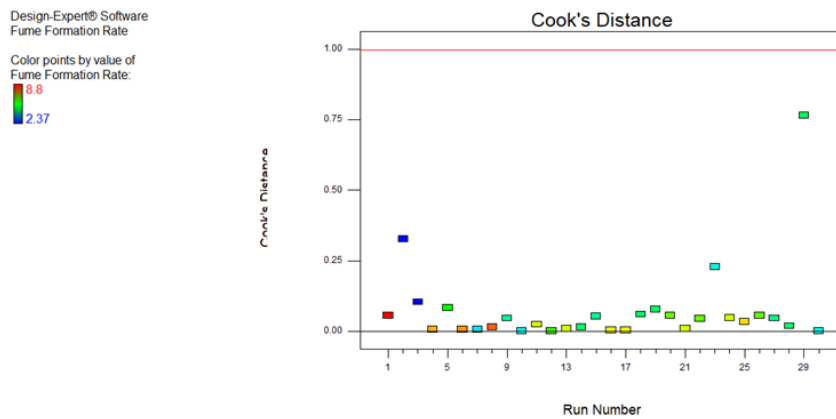


**Figure 1. Normal probability plot of studentized residuals for fume formation rate.**

*Figure 1* indicates the probability plot towards the fume formation rate data, the information tend to be expected to cluster over the direction 45 degree line. In order to identify a value or perhaps cluster of values which aren't conveniently noticed by the model, the expected values is plated alongside the specific values, for fume formation rate that is certainly displayed in the *Figure 2*. A cooks distance plot is generated to check for outliers existing in data set as found in *Figure 3*.

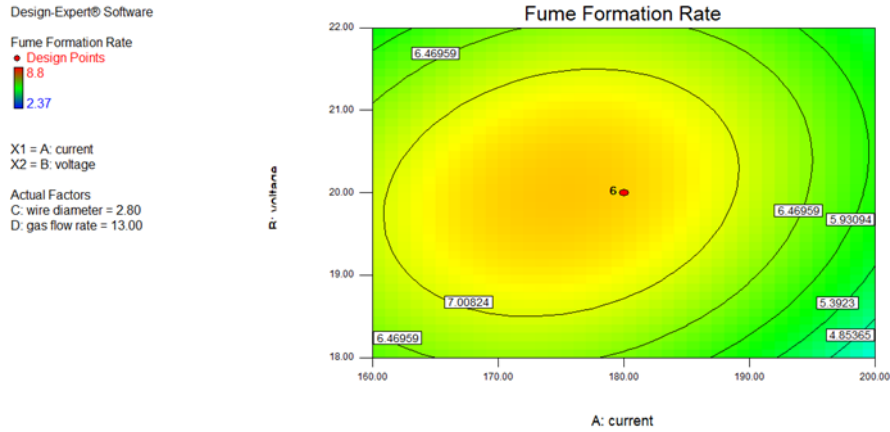


**Figure 2.** Plot of predicted vs actual for fume formation rate.

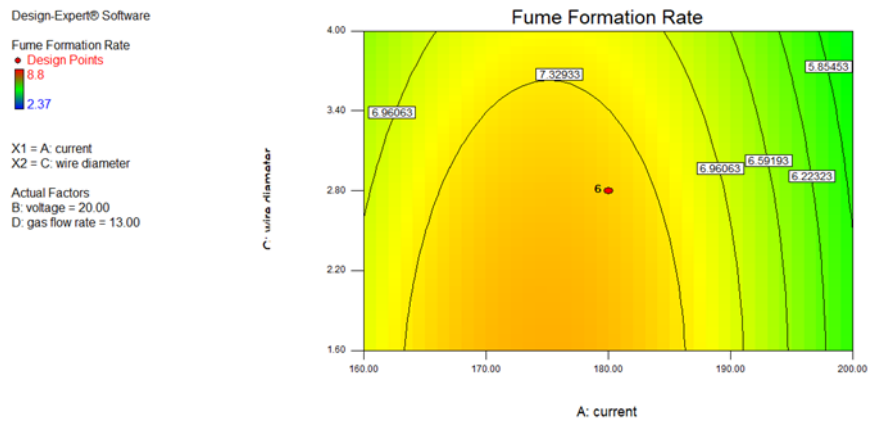


**Figure 3.** Generated cook's distance for fume formation rate.

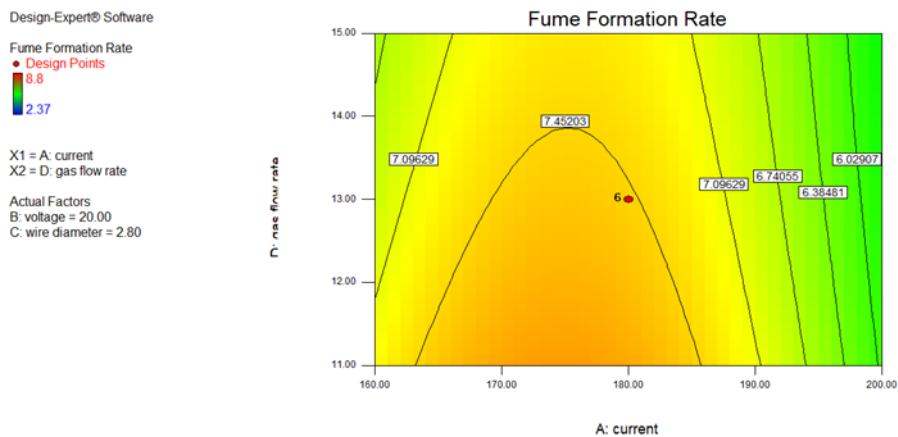
*Figure 3* enables us determine the existence associated with a possible outlier in the experimental data, the cook's distance plot was created when it comes to the fume formation rate results. The cook's distance is a measure of what amount of the regression would improve if the outlier is omitted through the assessment. A spot with an extremely high distance value relative to additional details could be an outlier as well as must be examined. The contour plots indicating fume formation rate reaction variable resistant to the optimized value of existing along with voltage can be provided in *Figure 4*. The contour plots demonstrating fume formation rate reaction variable contrary to the optimized value of existing as well as gasoline flow rate is provided in *Figure 5*. The contour plots indicating fume formation rate response variable resistant to the enhanced value voltage and gas flow rate is given in *Figure 6*.



**Figure 4.** Fume formation rate response variable against the optimized value of current and voltage.



**Figure 5.** Fume formation rate response variable against the optimized value of current and gas flow rate.



**Figure 6.** Fume formation rate response variable against the optimized value voltage and gas flow rate.

In this study predictive models have been developed using the response surface methodology. The target is to use the quadratic models to predict the fume formation rate in GTAW of mild steel. The models developed are statistically significant with p

values  $<0.005$ , coefficient of determination values  $> 90\%$ , noise to signal ratio  $> 4$ . The contour plot prediction is in reasonable agreement with the numerical predictions in the diagnostic statistics. The model developed shows adequate strength to predict the fume formation rate.

## Conclusion

This research study has successfully developed a model that can adequately and accurately predict the fume formation rate in a typical tungsten inert gas welding process considering current gas flow rate, wire diameter and voltage using mild steel plates. The results obtained shows reasonable agreement with that of the experimental results., the models developed is robust and has satisfied critical statistical diagnostics.

## Acknowledgement

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## Conflict of interest

There is no conflict of interest with any partners or organisations in this research study.

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