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Mathematical Modeling of Acoustic Signals Generated During Gas Tungsten Arc Welding Process

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***Abstract*—Adoption of alternative advanced approaches for monitoring the ongoing welding can impart a transcendental process-control and can worthily substantiate the regulation of produced weld quality. Acoustic emission analysis, being a highly effective technology has paved way by facilitating the investigation of defects while operation is going on. Essential precise quantification has been carried out for inducing interrelationship of the response variables with the input parameters to predict further behavior of weld and rectification of these process parameters so that unintended defects during gas tungsten arc welding (GTAW) can be minimized. To verify the adequacy and agreeability of designed model, a corroborating evaluation has been performed.**

***Keywords*—acoustic emission; GTAW; regression; prediction; characterization.**

I. INTRODUCTION

Acoustic emission analysis is a non-conventional method of non destructive testing which is capable of detecting the generation of defect at the time of welding. Elasticity is an important property of solid materials which allows its compression under the effect of external forces and spring back phenomenon under the removal of these forces. A fracture generates if the elastic limit is exceeded either immediately or after certain plastic deformation. A rapid release of elastic energy occurs from the elastically strained material due to the containment or generation of defects such as non-metallic inclusion, weld joint defect, cracks, etc. This is called as an acoustic emission event. The propagation of elastic wave can be detected using sensitive and most appropriate sensors. The frequency of ultra-sound in an acoustic emission event generally ranges between 100 and 300 KHz and its reliable measurement can be done by short sensor distance in proper laboratory environment. For GTAW, acoustic variation can arise from geometrical or gas flow rate change, metallic transfer, etc. [1] Conjunction of mathematical models with designed experiments can be used for prediction of the magnitude of sound pressure recorded by means of proper arrangement. It can assure sufficient reliability. [2]

II. MATERIALS AND METHODS

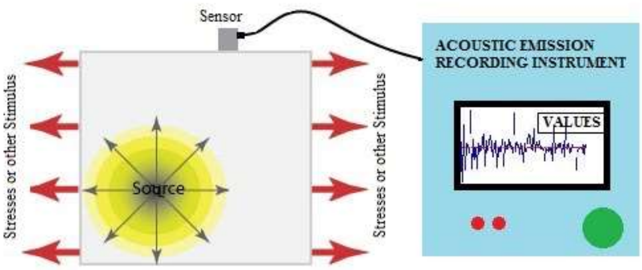


Figure 1. Acoustic signals recording

These signals can be recorded using a microphone and interpreted using various computer softwares for inspecting the weld quality and weld joint behaviour. This model can be helpful in recognition of intermediate sound pressure values. Features of arc sound signal can accurately exhibit the effect of modification of arc height, gas flow rate or current on the response variables during the GTAW welding process. [4] This system consists of a transducer for receiving acoustic signals generated during the welding process. The converter digitizes the acoustic signal. Hence, the system provides an intelligent method for real-time assessment of the output indicative of weld quality produced.

Once the acoustic waves have been recorded, die penetrant test can be performed on the welded area. Then, for detection of internal defects, Radiographic testing and/or Ultrasonic testing can be done. Such a correlation has been found successfully. [1] Acoustic emission produced by metal droplet transfer is due to rapid release of elastic energy when any discontinuity is encountered.

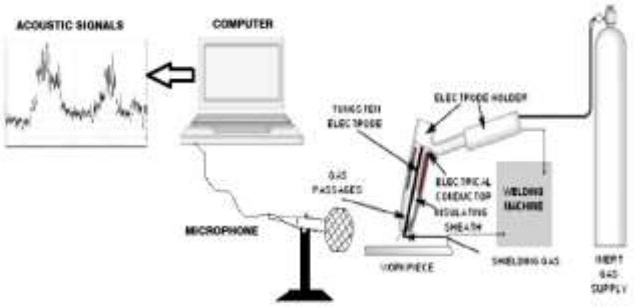


Figure 2. Experimental Set-up[1]

A microphone is firmly supported on a stand which is of unidirectional type. It is capable of recording the signals generated during the welding process. This microphone is connected to a computer on which Trial version of Multi Instrument software shows the fluctuation of acoustic waves on its display screen. The DCEN welding process takes place in synergic mode using Argon as inert gas.The experiments have been conducted by GTAW the work-piece of length 150mm. Figure 2 depicts sectional geometry of the work-piece.

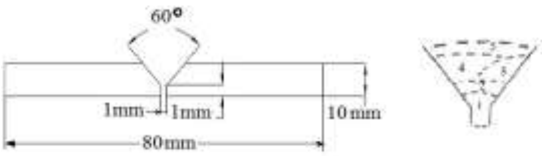


Figure 3. Geometry of work-piece

The chemical composition of work-piece and its mechanical properties with their designation code are mentioned in table I and II respectively as follows.

TABLE I. CHEMICAL COMPOSITION OF WORK-PIECE

Jindal Designation/code	%C	%Mn	%P	%S	%V	%Cr	%Ni	%Mo	%Fe	N (ppm)
J-304 L	0.03	1.19	0.05	0.03	0.28	17.93	8.56	0.27	Rest	1000

TABLE II. MECHANICAL PROPERTIES OF WORK-PIECE

Jindal Designation/code	Tensile Strength (MPA)min.	%Yield Strength(MPA)min	% Elongation(min.)	Hardness (HRB) max.
J-304L	485	170	40	95

The chemical composition of filler wire and its mechanical properties with their designation code having diameter Ø1.6mm are mentioned in table III and IV respectively as follows.

TABLE III. CHEMICAL COMPOSITION OF FILLER WIRE

Electrode code	%C	%Mn	%Si	%Cr	%Ni	%Mo	%Fe
ER-316L	0.02	1.50	0.40	19.00	12.00	2.0	Rest

TABLE IV. MECHANICAL PROPERTIES OF FILLER WIRE

Electrode code	Process	Tensile Strength (N/mm^2)	Impact J (RT)	Recommended flux	Melting Point (°C)	Hardness (HRB)	Welding Conditions
ER-316L	TIG & Gas	590	60	Stainless Steel	1440ºC	180	DC+, AC

A unidirectional microphone has been used for experimentation. The reason behind using a unidirectional microphone is that the effect of sounds generated from the external environment is minimized and only those signals are measured which are of same nature and falling in the proximity of the sensor as per the specified range.

TABLE V. MICROPHONE SPECIFICATIONS

Manufacturer	Directivity	Frequency Response (Hz)	Output Impedance	Sensitivity (dB)	Dimensions (mm)	Mass (g)	Cord Length (m)
SONY Ltd, Japan	Unidirectional	60-12000	600 in 1kHz Ω	-53.0	Ø51 x 204	140g	3

On a Gas Tungsten Arc Welding machine, various modes for welding are available. Experimentation has been carried out for test bead and visual examination has been performed. It can be observed from figure 3 that the weld test bead produced in synergic mode as compared to other modes and it can be concluded that best quality along with clear acoustic emission can be achieved. A back-plate is welded on the opposite side of the groove to prevent the distortions and bending of the joint.

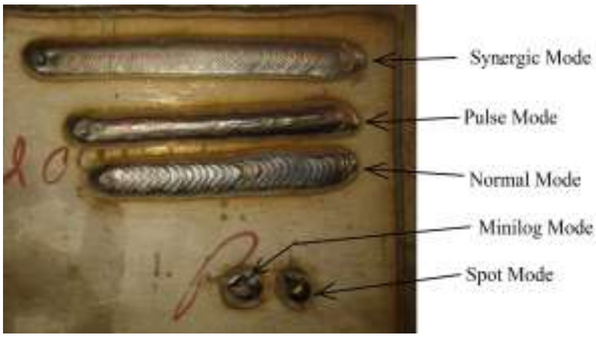


Figure 4. Various available modes of welding

III. DESIGN OF EXPERIMENTS

The experiments have been designed and performed using appropriate statistical software by selection of mixed level of L8 Taguchi design. The experiments have 4 levels and consideration of 2 factors. The levels are mainly four different currents and factors are two gas flow rates in following combination as shown in table VI. Figure 5 shows welded work-pieces with their respective numbers.

TABLE VI. DESIGN OF EXPERIMENTS

Work-piece No.	Current (A)	Gas Flow Rate (l/min)
1	150	15
2	170	10
3	150	10
4	180	10
5	180	15
6	170	15
7	160	10
8	160	15

Figure 5. Experimental Work-pieces

IV. REGRESSION

In various processes, responses are affected by combination of input parameters. Their combined effect cannot be easily detected by the traditional trial and error method. The method implies following limitations.

- Difficulty in prediction of accurate input parameters and significance level prediction
- Method is time consuming & costly as it requires large amount of experimentation.

To deal with challenges in a manufacturing industry for a specified process based on input parameters and their respective effect on output, various statistical techniques and analyses have been developed. One of such is Regression analysis. It is one of the methods to predict the effects of input parameters on output for complex systems and processes. Regression allows examination of the relationships between a number of predictor variables and a response variables which further enables values on one variable to be predicted from the values recorded one or more other variables. Regression analysis is used for explaining or mathematically modeling the relationship between a single variable Y, called the response, output or dependent variable, and one or more predictor, input, independent or explanatory variables in the form, $Y = f(X_1, X_2, X_3 \dots X_n)$

Where n = numbers of input parameters. When n=1 is called simple regression but when n>1, it is called multiple regression or sometimes multivariate regression. The reason for selection of best mathematical model is that, such model gives minimum error in prediction of Y. This is carried out by determining the best value of coefficient of determination (R^2) for all the models. R^2 measures the proportion of variation in data point which is explained by regression model. For example if $R^2 = 0.95$, the 95% of the variation in the dependent or response variable is explained by the regression model. If a value of $R^2 = 1.0$ indicates that the curve pass through every data point. A value $R^2 = 0.0$ indicates the regression model does not describe data any better than horizontal line passing through the average of the data point. The table VII shows Standard Error, Residual Sum, Residual average, RSS, R^2, R_a^2 values for all models for A_{max}, A_{min} and A_{rms} respectively. These values can be easily determined using trial version of Data-fit software developed by Oakdale Engineering, USA. Mathematical modeling is based on multiple nonlinear regression analysis for modeling acoustic signals with appropriate parameters. It can be represented by: A = f (I, G).

Where, A is the value of acoustic pressure, I is input current, G is the gas flow rate and a, b, c… k are the coefficients for respective series. The different regression models are as follows:

- Linear
$$A = a + bI + cG \tag{1}$$
- Second order polynomial
$$A = a + bI + cI^2 + dI^3 + eG + fG^2 \tag{2}$$
- Higher degree polynomial
$$A = a + bI + cI^2 + dI^3 + eI^4 + fI^5 + gG \tag{3}$$
- Simple Logarithmic
$$A = a + b\log_e I + c(\log_e I)^2 + d(\log_e I)^3 + e\log_e G + f(\log_e G)^2 + g(\log_e G)^3 \tag{4}$$
- Exponential
$$A = aI^bG^c \tag{5}$$
- Mixed
$$A = a + \frac{b}{I} + \frac{c}{I^2} + \frac{d}{I^3} + \frac{e}{I^4} + \frac{f}{I^5} + g\log_e G \tag{6}$$
- Improved Logarithmic
$$A = a + \frac{bI\log_e I}{(\log_e G)^3} + \frac{c}{G(\log_e I)^{10}} + d(\log_e I)^2 + \frac{eIG^2}{(\log_e I)^{10}} + \frac{f\log_e I}{G(\log_e G)^3} + \frac{gI}{\log_e I} \tag{7}$$

TABLE VII. ACCURACY OF ALL MATHEMATICAL MODELS

Name	Std Error	Residual Sum	Residual Avg.	RSS	R^2	Ra^2
Linear	132.57	1.24E-07	1.55E-08	87875.52	0.2905	0.0067
Second degree polynomial	120.55	90.27	11.28375	29065.64	0.7653	0.1786
Higher degree polynomial	174.79	0.00075938	9.49E-05	30551.49	0.7533	0
Simple Logarithmic	174.9	-5.73	-0.71625	30590.12	0.7530	0
Exponential	19.626	20.3230195	2.540377434	1925.874	0.0923	0
Mixed	291.83	-1.8382387	-0.229779835	85166.91	0.3124	0
Improved Logarithmic	34.888	1.16E-08	1.45E-09	1217.206	0.9901	0.9312

These different types of models can be inputted in the software and accordingly the regression analysis can be performed.

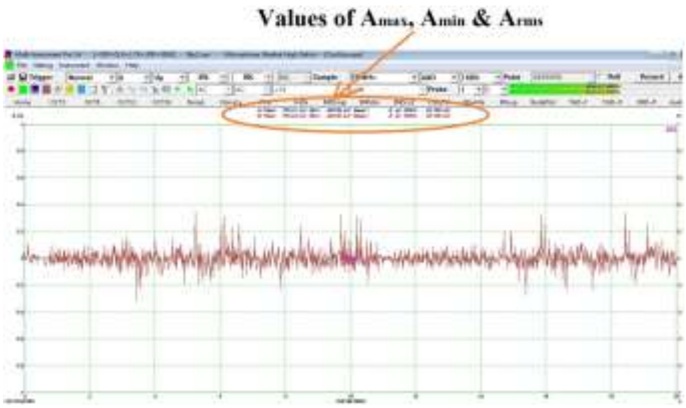


Figure 6. Values of Amax, Amin and Arms for calculation

Considering the values of Amax, Amin and Arms for each pass, mean of the readings have been considered for calculation so that errors can be reduced. Amax, Amin and Arms are the maximum, minimum and root mean square values of sound pressure values.

A. Regression for Amax

TABLE VIII. VALUES OF AMAX FOR EACH PASS

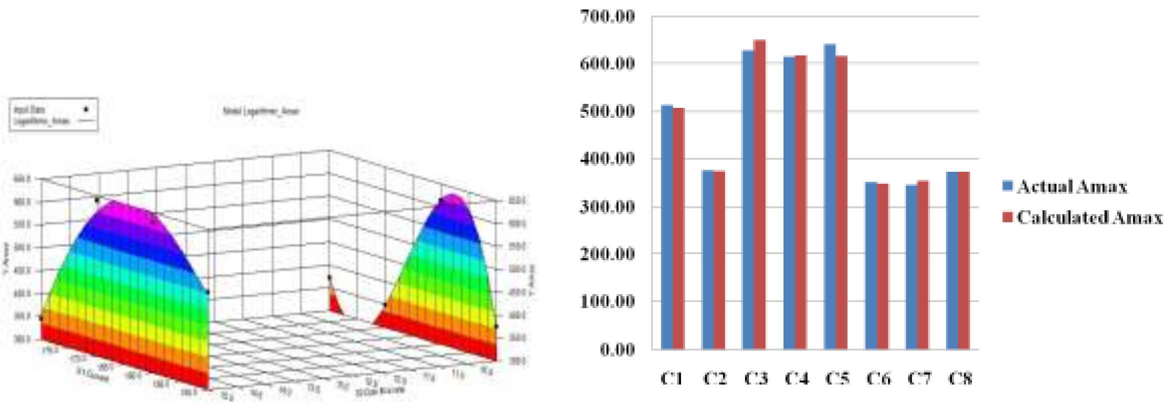
Values of Amax for each pass (in mV)					
Amax1	***Amax2***	***Amax3***	***Amax4***	***Amax5***	***Average Amax***
742.07	668.58	157.84	229.25	765.05	512.56
508.82	377.47	377.32	318.97	293.79	375.27
815.28	649.17	509.55	433.83	728.70	627.31
661.77	579.44	608.92	696.87	519.07	613.21
789.52	815.25	649.20	509.58	433.90	639.49
141.08	714.72	319.46	246.67	326.02	349.59
337.04	325.53	507.77	216.67	335.75	344.55
290.89	282.26	536.10	253.21	498.99	372.29

The regression model generated for values of Amax is:

$$\mathrm{Amax} = 1090310.46 - 116825\,\frac{I\,\log_e I}{(\log_e G)^3} + 3.59\,\frac{1}{G(\log_e I)^{10}} + 1461988.17\,(\log_e I)^2 + 281161015.20\,\frac{I}{G^2(\log_e I)^{10}} - 4068514\,\frac{\log_e I}{G\,(\log_e G)^3} - 324939.54\,\frac{I}{\log_e I} \tag{8}$$

TABLE IX. REGRESSION ANALYSIS FOR AMAX

Condition	Current (A)	Gas Flow Rate (l/min)	Arms	Calculated Arms	Residual	% Error	Absolute Residual	Min. Residual	Max. Residual
1	150	15	512.56	506.00	6.55	1.28	6.55	-22.01	24.36
2	150	10	375.27	373.70	1.57	0.42	1.57		
3	160	15	627.31	649.31	-22.01	-3.51	22.01		
4	160	10	613.21	616.55	-3.34	-0.54	3.34		
5	170	15	639.49	615.13	24.36	3.81	24.36		
6	170	10	349.59	347.62	1.97	0.56	1.97		
7	180	15	344.55	353.45	-8.90	-2.58	8.90		
8	180	10	372.29	372.49	-0.20	-0.05	0.20		



(a) (b)

Figure 7. (a) Plot of values of Amax (b) Comparison for values of Amax

As all the values obtained are greater than zero, the plot is in upright manner. Also, negligible difference between generated and calculated values of Amax is found. Thus, the model depicts its accuracy.

B. Regression for Amin

TABLE X. VALUES OF AMIN FOR EACH PASS

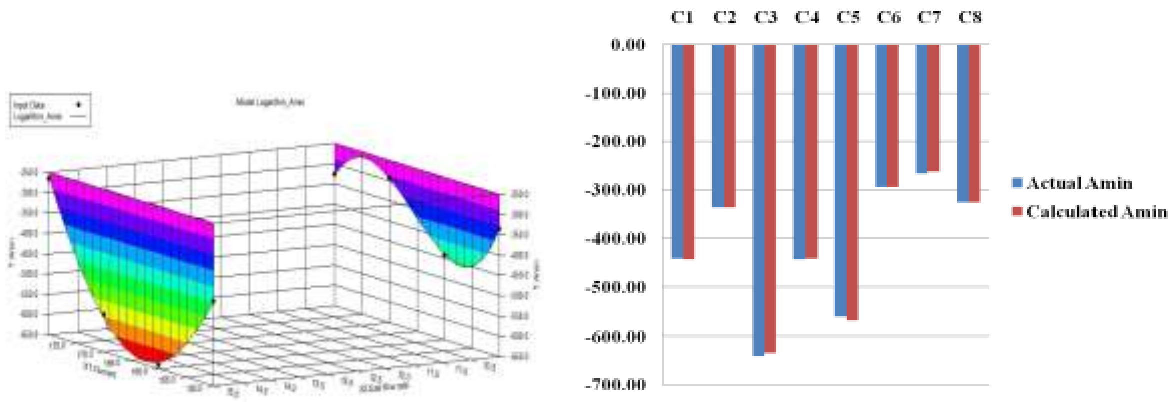
Values of Amin for each pass					
Amin1	***Amin2***	***Amin3***	***Amin4***	***Amin5***	***Average Amin***
-494.42	-668.27	-230.07	-318.63	-495.51	-441.38
-337.04	-355.45	-483.12	-288.88	-213.32	-335.56
-819.28	-514.80	-398.93	-483.76	-988.89	-641.13
-506.81	-430.02	-442.11	-410.83	-421.69	-442.29
-577.91	-819.27	-514.80	-398.93	-483.76	-558.93
-158.33	-557.74	-251.98	-251.71	-249.60	-293.87
-284.21	-275.27	-251.61	-197.51	-320.47	-265.81
-381.44	-255.58	-450.13	-263.40	-280.15	-326.14

The regression model for Amin is as follows.

$$\mathrm{Amin} = -472430.97 + 59536.25\frac{I\log_e I}{(\log_e G)^3} - 1.85\frac{1}{G(\log_e I)^{10}} - 741756.42(\log_e I)^2 + 136199430\frac{I}{G^2(\log_e I)^{10}} + 2034176.88\frac{\log_e I}{G(\log_e G)^3} - 168392.68\frac{I}{\log_e I} \qquad (9)$$

TABLE XI. REGRESSION ANALYSIS FOR AMIN

Condition	**Current (A)**	**Gas Flow Rate (l/min)**	**Arms**	**Calculated Arms**	**Residual**	**% Error**	**Absolute Residual**	**Min. Residual**	**Max. Residual**
C1	150	15	-441.38	-443.57	2.19	-0.50	2.19	-7.35	8.14
C2	150	10	-335.56	-336.09	0.52	-0.16	0.52		
C3	160	15	-641.13	-633.78	-7.35	1.15	7.35		
C4	160	10	-442.29	-441.18	-1.12	0.25	1.12		
C5	170	15	-558.93	-567.07	8.14	-1.46	8.14		
C6	170	10	-293.87	-294.53	0.66	-0.22	0.66		
C7	180	15	-265.81	-262.84	-2.97	1.12	2.97		
C8	180	10	-326.14	-326.07	-0.07	0.02	0.07		



(a) (b)

Figure 8. (a) Plot of values of Amin (b) Comparison for values of Amin

As all the values obtained are less than zero, the plot is in inverted manner. Also, negligible difference between calculated and generated values of Amin is found, which indicates accuracy of the designed model.

C. Regression for Arms

TABLE XII. VALUES OF ARMS FOR EACH PASS

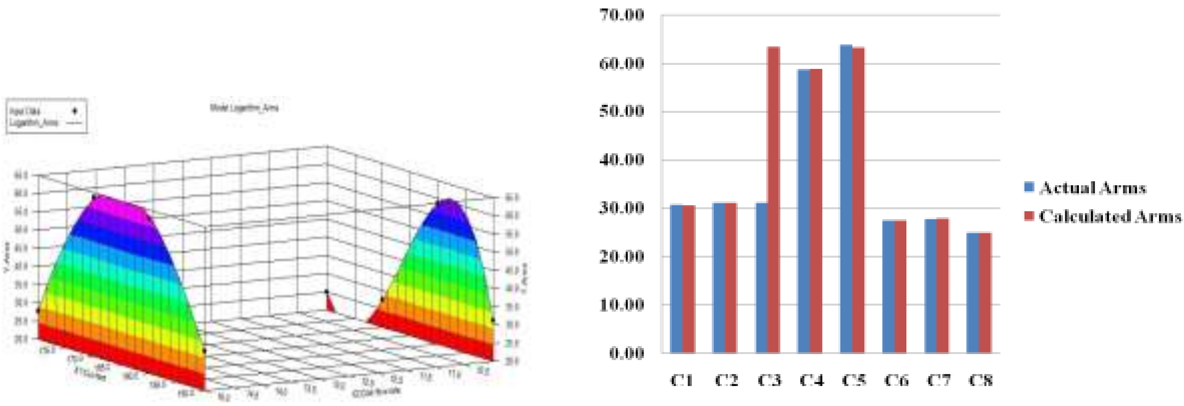
Values of Arms for each pass					
Arms1	***Arms2***	***Arms3***	***Arms4***	***Arms5***	***Average Amax***
37.13	24.95	22.80	28.24	40.47	30.72
40.80	35.24	21.12	34.42	24.02	31.12
89.35	55.82	54.40	49.21	64.87	62.73
65.29	63.11	55.08	58.27	51.64	58.68
69.70	89.35	55.81	54.40	49.11	63.67
20.20	31.69	26.49	29.91	28.80	27.42
27.95	28.18	28.32	22.24	31.84	27.71
27.12	24.71	25.31	22.32	25.07	24.91

The regression model for Arms is as follows.

$$\mathrm{Arms} = 110779.83 - 12537.97\frac{I\log_e I}{(\log_e G)^3} - 0.39\frac{1}{G\,(\log_e I)^{10}} - 156857.95(\log_e I)^2 + 29769101.17\frac{I}{G^2(\log_e I)^{10}} - 434556.72\frac{\log_e I}{G\,(\log_e G)^3} - 35065.57\frac{I}{\log_e I} \quad (10)$$

TABLE XIII. REGRESSION ANALYSIS FOR ARMS

Condition	Current (A)	Gas Flow Rate (l/min)	Arms	Calculated Arms	Residual	% Error	Absolute Residual	Min. Residual	Max. Residual
C1	150	15	30.72	30.57	0.14	0.47	0.14	- 0.49	0.54
C2	150	10	31.12	31.09	0.03	0.11	0.03		
C3	160	15	31.12	63.22	-0.49	-0.78	0.49		
C4	160	10	58.68	58.75	-0.07	-0.13	0.07		
C5	170	15	63.67	63.14	0.54	0.85	0.54		
C6	170	10	27.42	27.37	0.04	0.16	0.04		
C7	180	15	27.71	27.90	-0.20	-0.71	0.20		
C8	180	10	24.91	24.91	0.00	-0.02	0.00		



(a) (b)

Figure 9. (a) Plot of values of Arms (b) Comparison for values of Arms

As all the values obtained are less than zero, the plot is in inverted manner. Also, almost all the calculated values match the generated values of Arms is found. Hence, the model indicates precision.

V. CONCLUSION

The mathematical models designed can predict intermediate sound pressure values which can be helpful in weld quality prediction and thereby result in improved weld. Characterization of the process can be developed by increasing numerical and experimental evaluations for GTAW process at different working environment so that accurate standardized system of online weld monitoring can be developed with diminished level of error. The combined effect of welding and locating induced defects can be considered for controlling the quality of weld. Also, once the cause of generation of defects is known, modifications can be made in the process parameters to achieve minimization of defects. Comparisons between numerical predictions and experimentally obtained values can be portrayed by graphical representations and surface plot.

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