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OPTIMIZATION OF THE LASER GMA HYBRID WELDING PARAMETERS USING GENETIC ALGORITHM

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ABSTRACT

In order to obtain high-quality welding, it is required to maximize ultimate tensile strength and minimize bead width. Moreover, it is significant to limit the penetration to the desired length. These three-output data are affected by some input parameters such as the wire type, the shielding gas, the laser power, the laser focus, the travelling speed and the wire feed rate. Optimization of these input parameters is quite substantial to reach desired weld quality. Before optimization, it is required to develop suitable mathematical models for each output parameters. Thus, intermediate values outside the experimental data can be acquired. First objective of this study is to propose modified second-order polynomial to develop high-accurate mathematical models compared to first-order linear models. The modified model may be described as cancelling of some redundant interaction terms in second-order polynomial. If the number of experiments is restricted as in this study, it is impossible to use second-order polynomial model because number of unknowns should be lesser than number of experimental data in order to obtain well-posed numerical solution. The number of unknown constants in modified model is lesser than second-order polynomial and it is more accurate than first-order polynomial. Proposed models were designed in Matlab software using data from the previous studies. The second aim of this study is optimization of input parameters using a genetic algorithm to get desired penetration, minimum bead width and maximum ultimate tensile strength. According to optimum data, 29.9 % of improvement on ultimate tensile strength was observed in addition to 36.7 % lesser bead width compared to Taguchi optimization in previous study. Finally, this study is to present open source Matlab codes to the users. It is very adaptable for different experimental data and different physical models by making very small changes in the given codes.

Keywords: Mathematical Modeling, Genetic Algorithm, Open Source Matlab.

1. INTRODUCTION

Due to their light weight, aluminum alloys are widely used in many industries, especially in the automobile industry. Welding of aluminum alloys in a uniform shape with high speed and laser beam is very difficult, so the welding method should be chosen correctly. Researchers have not done much work using the laser beam source and the GMA source together. The hybrid welding method is preferred due to advantages such as high welding speed, accurate alignment and high penetration.

Kim et al. (2008) optimized the welding parameters by combining Taguchi's method [1, 2] with gray relational analysis [3]. Thus, they obtained the best output parameters by choosing the most suitable input parameters in the experiment set. On the other hand, optimum welding parameters may be between two any experiment as interval values. It is impossible to determine this interval values only using Taguchi technique. It is required to design mathematical modeling of welding operation by means of

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experimental data set. This study is to propose establishing the mathematical modeling of the experiment set and optimization of welding parameters using genetic algorithm.

2. PREVIOUS STUDY

Optimization of the laser and gas metal arc hybrid welding parameters was carried out by Kim and Lee according to Taguchi's recommendation [3]. The input and output data are indicated in Table 1 [3]. There are six welding parameters which are the wire type; the shielding gas, the laser power, the laser focus, the travelling speed and the wire federate in Table 1.

Table 1. Input parameters.

Group No.	Wire type	Shielding gas	Laser power	Laser focus	Travelling speed	Wire feedrate
1	ER 5356	None	2	0	120	5.2
2	ER 5356	None	2.5	-0.5	150	5.7
3	ER 5356	None	3	-1	180	6.5
4	ER 5356	Ar	2	0	150	5.7
5	ER 5356	Ar	2.5	-0.5	180	6.5
6	ER 5356	Ar	3	-1	120	5.2
7	ER 5356	He	2	-0.5	120	6.5
8	ER 5356	He	2.5	-1	150	5.2
9	ER 5356	He	3	0	180	5.7
10	ER 4043	None	2	-1	180	5.7
11	ER 4043	None	2.5	0	120	6.5
12	ER 4043	None	3	-0.5	150	5.2
13	ER 4043	Ar	2	-0.5	180	5.2
14	ER 4043	Ar	2.5	-1	120	5.7
15	ER 4043	Ar	3	0	150	6.5
16	ER 4043	He	2	-1	150	6.5
17	ER 4043	He	2.5	0	180	5.2
18	ER 4043	He	3	-0.5	120	5.7

In their study, eighteen experiments were performed using these six inputs. They obtained eighteen results for each three outputs namely the ultimate tensile strength, the bead width, and the penetration which are shown in Table 2 [3].

Kim and Lee (2008) obtained the ninth experiment set in Table 1 as optimum welding inputs using grey relation analysis. But optimum values which are better than 9th group may be out of the Taguchi experiment set. Therefore, it is required to design mathematical model of the physical system to predict interval data. This study is to propose obtaining the mathematical model of the previous study and application of the genetic algorithm into designed mathematical model in order to achieve optimum welding parameters.

3. MATHEMATICAL MODELS

There are a number of techniques in literature [4, 5, 6] to obtain mathematical models of any experimental data, but two of them stand out due to their simplicity. The first simple method is linear mathematical model. It is shown in equation 1.

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6 \qquad (1)$$

In equation 1*; y is response variable (ultimate tensile strength or the bead width or the penetration)*, x values are independent variables (wire type, the shielding gas, the laser power, the laser focus, the travelling speed and the wire federate) and b values are coefficient (unknown values) of each independent variables. The linear models are first-order polynomial, so it is very difficult to validate mathematical model with experimental values especially for complex input data. One another technique is second-order polynomial model which is more accurate than linear model. Mathematical expression of second-order polynomial is indicated in equation 2.

Table 2. Output parameters.

Group No.	Ultimate tensile strength (Mpa)	Bead width (mm)	Penetration (mm)
1	155.325	1.95	1
2	73.175	2.549	1
3	118.5	2.355	1
4	137.65	2.046	0.824
5	89.95	1.677	1
6	187.96	2.67	0.229
7	158.31	2.65	1
8	133.12	2.082	1
9	234.645	2.101	1
10	129.49	2.229	1
11	152.38	3.447	1
12	141.28	2.785	1
13	73.515	2.804	1
14	142.525	2.695	1
15	140.03	4.451	1
16	131.08	3.633	1
17	74.42	1.429	0.582
18	189.775	3.2	1

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6 + b_7 x_1^2 + b_8 x_2^2 + b_9 x_3^2 + b_{10} x_4^2 + b_{11} x_5^2 + b_{12} x_6^2 + b_{13} x_1 x_2 + b_{14} x_1 x_3 + b_{15} x_1 x_4 + b_{16} x_1 x_5 + b_{17} x_1 x_6 + b_{18} x_2 x_3 + b_{19} x_2 x_4 + b_{20} x_2 x_5 + b_{21} x_2 x_6 + b_{22} x_3 x_4 + b_{23} x_3 x_5 + b_{24} x_3 x_6 + b_{25} x_4 x_5 + b_{26} x_4 x_6 + b_{27} x_5 x_6 \quad (2)$$

In order to get well-posed numerical solution of mathematical models, number of equation have to equal to the number of unknown values or number of equation have to be greater than number of unknown values. Otherwise, it is impossible to obtain well-posed numerical solution. Furthermore, it is recommended that number of equation should be greater than number of unknown values in order not to observe ill-posed numerical solution.

In this study, three different mathematical models (for ultimate tensile strength, bead width and penetration) were developed using eighteen experimental data which includes six type input data and three type output data. According to second-order polynomial model, it is required to find twenty eight unknowns (one free term, six linear terms, six quadratic terms and fifteen interaction terms). However, eighteen equations (eighteen experimental data) are available. In that case, it is impossible to determine unknown values, since number of unknown values (twenty eight) is greater than number of equations (eighteen).

Firstly, this study is to propose canceling of free term and decreasing of number of interaction terms from fifteen to five. Second objective of this study is choosing of five most significant interaction terms out of possible fifteen interaction terms. In order to obtain most substantial five interaction terms, trial and error method was carried out using ‘’while loop’’ in Matlab (please see Appendix A in order to reach open source numerical codes). Owing to this method, three different mathematical models (for ultimate tensile strength, bead width and penetration) were developed that are very compatible with experimental data. The mathematical models for ultimate tensile strength, bead width and penetration are shown in equation 3, 4 and 5 respectively.

$$y_{uts} = b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6 + b_7x_1^2 + b_8x_2^2 + b_9x_3^2 + b_{10}x_4^2 + b_{11}x_5^2 + b_{12}x_6^2 + b_{13}x_1x_2 + b_{14}x_5x_2 + b_{15}x_4x_2 + b_{16}x_3x_1 + b_{17}x_5x_3 \quad (3)$$

$$y_{bw} = b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6 + b_7x_1^2 + b_8x_2^2 + b_9x_3^2 + b_{10}x_4^2 + b_{11}x_5^2 + b_{12}x_6^2 + b_{13}x_5x_4 + b_{14}x_1x_3 + b_{15}x_6x_3 + b_{16}x_4x_6 + b_{17}x_6x_1 \quad (4)$$

$$y_p = b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6 + b_7x_1^2 + b_8x_2^2 + b_9x_3^2 + b_{10}x_4^2 + b_{11}x_5^2 + b_{12}x_6^2 + b_{13}x_3x_2 + b_{14}x_1x_3 + b_{15}x_3x_4 + b_{16}x_4x_6 + b_{17}x_4x_5 \quad (5)$$

In equations *3*, *4* and *5*; y_{uts}, y_{bw} and y_p are response of ultimate tensile strength, bead width and penetration respectively. x_1, x_2, x_3, x_4, x_5 and x_6 represent wire type, the shielding gas, the laser power, the laser focus, the travelling speed and the wire federate respectively. *b* values and their *p*-values for each three mathematical models are shown in Table 3.

Generally, results with 0.05 p-values are considered statistically significant [7]. The ranges of the p-values of estimated ‘’*b*’’ values for each developed mathematical models are very close to the 0.05. In addition to suitable p-values ranges, R-squared values are greater than 98 percent for each three mathematical models. Therefore, validation of mathematical models with experimental data was completed. Ordinary and adjusted R-squared values are indicated in Table 4. Figures related to validation are added to Appendix C.

Table 3. Estimated coefficients (*b* values) and p-values.

	Ultimate Tensile Strength		Bead Width		Penetration	
	Estimate	p-values	Estimate	p-values	Estimate	p-values
b1	-1519.225	0.009	52.162	0.027	-57.693	0.001
b2	-176.405	0.006	-0.643	0.085	5.410	0.001
b3	-1185.138	0.000	-18.949	0.009	12.044	0.001
b4	44.996	0.036	-10.814	0.021	9.689	0.001
b5	-10.200	0.002	0.185	0.012	-0.177	0.001
b6	1145.620	0.001	-9.066	0.025	14.029	0.001
b7	455.691	0.012	-17.359	0.032	19.276	0.001
b8	17.764	0.005	0.273	0.080	-0.825	0.001
b9	245.488	0.001	2.445	0.007	-1.597	0.001
b10	61.409	0.006	-1.921	0.016	0.117	0.065
b11	0.034	0.002	-0.001	0.014	0.000	0.001
b12	-96.054	0.001	0.492	0.046	-1.320	0.001
b13	-34.684	0.001	0.030	0.043	-1.383	0.001
b14	1.286	0.004	-1.051	0.036	-0.241	0.014
b15	-25.276	0.020	1.436	0.012	3.377	0.001
b16	67.007	0.008	0.752	0.029	-1.095	0.001
b17	-0.657	0.027	0.561	0.074	-0.075	0.001

Table 4. R-squared values.

Models	Ultimate Tensile Strength	Bead Width	Penetration
R-squared Ordinary	0.9998	0.9986	0.9976
R-squared Adjusted	0.9982	0.9876	0.996

4. OPTIMIZATION OF WELDING PARAMETERS

The genetic algorithms have been developed inspired by principles of genetics [8]. It is quite useful and effective optimization technique for not only linear or non-linear but also continuous or discontinuous objective functions. Genetic algorithm proceeds iteratively with constant population size. Each population consists of a great number of individuals. Individuals in first iteration (initial generation) are randomly generated. A score is given to each individual considering the response of the objective function for that individual. The individuals that will be in the next generation are determined according to these scores. Individuals with better scores are more likely to be in the next generation. Generally, there are three genetic operators (elite, crossover and mutation) to generate new individuals. Individuals with the best scores in the current population are identically used in the next population. These individuals are defined as elite. The revised of two new individuals (offspring) by combining the parts of two individuals (parents) in the current population is called as crossover. On the other hand, mutation can be described as randomly modification of parts of single parent.

In this study, default mode (population size: 200, elite count: 10, crossover count: 152 and mutation count: 38) of genetic algorithm in Matlab was used to optimize welding parameters. Optimum input data and responses of the objective functions for ultimate tensile strength, the bead width, and the penetration are given in Table 5.

Table 5. Optimum values.

Welding Parameters	Output Data	Taguchi Optimization in Previous Study	Improved Optimization using Genetic Algorithm
Wire type		ER5356	ER5356
Shielding gas		He	He
Laser power, kW		3	3
Laser focus, mm		0	-1
Travelling speed, mm s^{-1}		180	179.9998
Wire feedrate, m min^{-1}		5.7	5.7655
	UTS, MPa	234.64	304.7817
	Bead width, mm	2.1	1.3289
	Penetration, mm	1	1.0096

According to optimum data, 29.9 % of improvement on ultimate tensile strength was observed in addition to 36.7 % lesser bead width compared to Taguchi optimization in previous study.

4. CONCLUSION

In numerical simulations, there are two usual alternatives to diminish numerical errors. The first way is to decrease time step intervals. Using small time step intervals leads to very large total simulation time. Second way to reduce the numerical errors is to use higher order finite difference approximation instead of the using first order accurate schemes in order to calculate first and second derivatives. Central difference method can be used to approximate first and second derivatives and it has second order accuracy. Nevertheless, central difference approximation of first derivative does not involve current time step values. Discarding of current time step values causes significant numerical errors because approximation of first derivative primarily depends on current time step values. On the other hand, numerical approximation of the first derivative using Quick method depends not only next and previous time step data but also current and two previous time step data and it is third order accurate. This study proposes novel Hybrid method which is combination of Quick and central difference technique to approximate first and second derivative respectively. The proposed Hybrid method has highest order of convergence compared to other techniques.

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APPENDIX A

```
clc
clearvars
close all
tic

%% Input Data
in=xlsread('w');

lb=[1 2 2 -1 120 5.2];
ub=[1 2 3 0 180 6.5];
Intcon=[1,2];
%% Model Function
fun=@(b,x,k)(b(1)*x(:,1)+b(2)*x(:,2)+b(3)*x(:,3)+b(4)*x(:,4)+...
    b(5)*x(:,5)+b(6)*x(:,6)+b(7)*x(:,1).^2+b(8)*x(:,2).^2+...
    b(9)*x(:,3).^2+b(10)*x(:,4).^2+b(11)*x(:,5).^2+...
    b(12)*x(:,6).^2+b(13)*x(:,k(1)).*x(:,k(2))+...
    b(14)*x(:,k(3)).*x(:,k(4))+b(15)*x(:,k(5)).*x(:,k(6))+...
    b(16)*x(:,k(7)).*x(:,k(8))+b(17)*x(:,k(9)).*x(:,k(10)));
%% Ultimate Tensile Strength, MPa
l_uts=0;
u_uts=400;
while l_uts<50 || u_uts>320
pv1=1;
R2o=0;
R2a=0;
while pv1>0.1 || R2o<0.95 || R2a<0.95
%Mathematical Modelling
%k=randi([1,6],1,10);
%k=[1 3 2 4 2 1 2 5 3 3];
k=[1 2 5 2 4 2 3 1 5 3];
mf=@(b,x)(fun(b,x,k));
mdl1=fitnlm(in(:,1:6),in(:,7),mf,rand(1,17));
b=mdl1.Coefficients.Estimate;
pv1=max(mdl1.Coefficients.pValue);
R2o=mdl1.Rsquared.Ordinary;
R2a=mdl1.Rsquared.Adjusted;
R2=min(R2o,R2a);
hold off
figure(1)
plot(in(:,10),in(:,7),'bo-','markerfacecolor','b')
hold on
plot(in(:,10),mdl1.Fitted,'k-','linewidth',2)
xlabel('Numbers of Experiment','fontsize',16)
ylabel('Ultimate Tensile Strength, MPa','fontsize',16)
legend({sprintf('Experiments'),sprintf('UTS Model Function')},...
    'Location','Best','fontsize',12)
title({sprintf('R^2=%.4f',R2)},'fontsize',16)
%Optimization
f = @(x)(mf(b,x));
f1=f;
[lxuts,fval]=ga(f,6,[],[],[],[],lb,ub,[],Intcon);
l_uts=fval;
[uxuts,fval]=ga(@(x)(-f(x)),6,[],[],[],[],lb,ub,[],Intcon);
u_uts=-fval;
```

```
%% Bead Width, mm
l_bw=-1;
u_bw=10;
while l_bw<0 || u_bw>9.5
pv2=1;
R2o=0;
R2a=0;
while pv2>0.1 || R2o<0.95 || R2a<0.95
%Mathematical Modelling
%k=randi([1,6],1,10);
%k=[5 6 1 3 4 6 2 6 4 3];
k=[5 4 1 3 6 3 4 6 6 1];
mf=@(b,x)(fun(b,x,k));
mdl2=fitnlm(in(:,1:6),in(:,8),mf,rand(1,17));
b=mdl2.Coefficients.Estimate;
pv2=max(mdl2.Coefficients.pValue);
R2o=mdl2.Rsquared.Ordinary;
R2a=mdl2.Rsquared.Adjusted;
R2=min(R2o,R2a);
end
hold off
figure(2)
plot(in(:,10),in(:,8),'bo-','markerfacecolor','b')
hold on
plot(in(:,10),mdl2.Fitted,'k-','linewidth',2)
xlabel('Numbers of Experiment','fontsize',16)
ylabel('Bead Width, mm','fontsize',16)
legend({sprintf('Experiments'),sprintf('BW Model Function')},...
    'Location','Best','fontsize',12)
title({sprintf('R^2=%.4f',R2)},'fontsize',16)
%Optimization
f = @(x)(mf(b,x));
f2=f;
[lxbw,fval]=ga(f,6,[],[],[],[],lb,ub,[],Intcon);
l_bw=fval;
[uxbw,fval]=ga(@(x)(-f(x)),6,[],[],[],[],lb,ub,[],Intcon);
u_bw=-fval;

%% Penetration, mm
l_p=-3;
u_p=5;
while l_p<-2 || u_p>4.5
pv3=1;
R2o=0;
R2a=0;
while pv3>0.1 || R2o<0.95 || R2a<0.95
%Mathematical Modelling
%k=randi([1,6],1,10);
k=[3 2 1 3 3 4 4 6 4 5];
mf=@(b,x)(fun(b,x,k));
mdl3=fitnlm(in(:,1:6),in(:,9),mf,rand(1,17));
b=mdl3.Coefficients.Estimate;
pv3=max(mdl3.Coefficients.pValue);
R2o=mdl3.Rsquared.Ordinary;
R2a=mdl3.Rsquared.Adjusted;
```

```
R2=min(R2o,R2a);
end
hold off
figure(3)
plot(in(:,10),in(:,9),'bo-','markerfacecolor','b')
hold on
plot(in(:,10),mdl3.Fitted,'k-','linewidth',2)
xlabel('Numbers of Experiment','fontsize',16)
ylabel('Penetration, mm','fontsize',16)
legend({sprintf('Experiments'),sprintf('P Model Function')},...
    'Location','Best','fontsize',12)
title({sprintf('R^2=%.4f',R2)},'fontsize',16)
%Optimization
f = @(x)(mf(b,x));
f3=f;
[lxp,fval]=ga(f,6,[],[],[],[],lb,ub,[],Intcon);
l_p=fval;
[uxp,fval]=ga(@(x)(-f(x)),6,[],[],[],[],lb,ub,[],Intcon);
u_p=-fval;

%% Welding Parameters Optimization
f = @(x)(0.34*(f1(x)-l_uts)/(u_uts-l_uts)+...
    0.33*(u_bw-f2(x))/(u_bw-l_bw)+...
    0.33*(1-abs(f3(x)-dv)./max((u_p-dv),(dv-l_p))));

[opx,fval]=ga(@(x)(-f(x)),6,[],[],[],[],lb,ub,[],Intcon);
grade=-fval;
f1(opx)
f2(opx)
f3(opx)
disp(opx)
toc
```

APPENDIX B

It is important note that, it is required to generate w.xlsx Excel file using following table. The name of the Excel file have to be ‘’w’’ without quotes. Secondly, generated w.xlsx Excel file and Matlab file (in Appendix A) have to be at the same path. Thirdly, if you don’t want to use Appendix A and B in order to run Matlab file, you can use Appendix C.

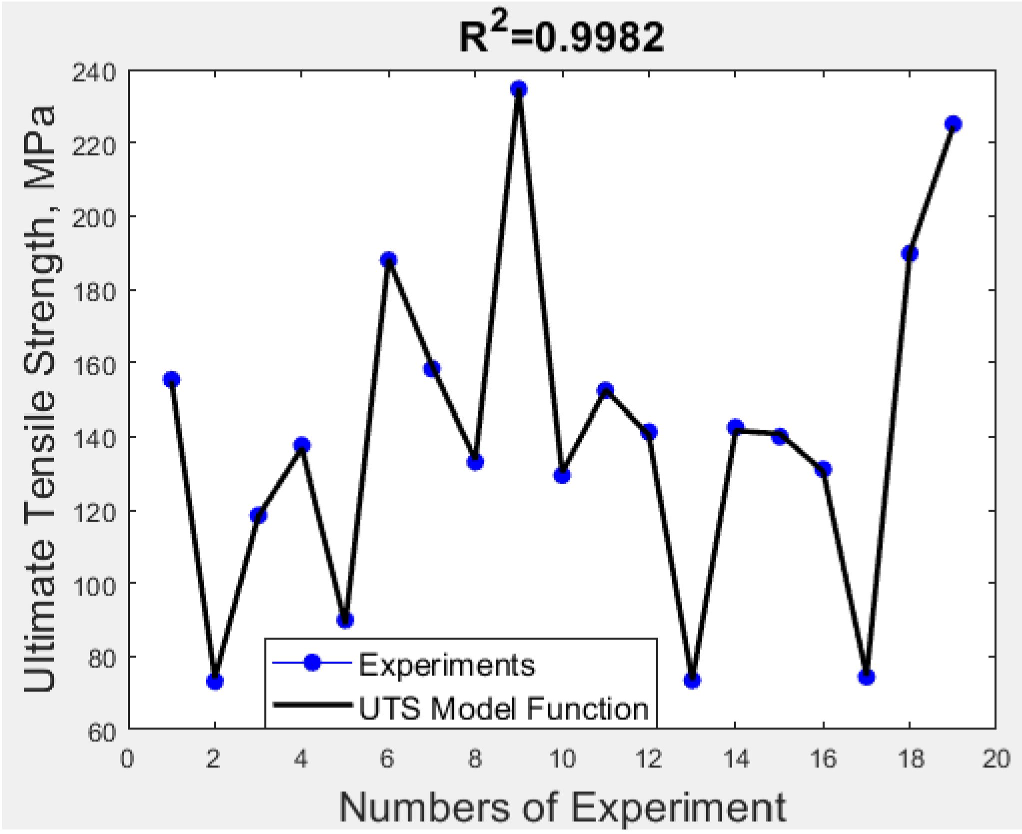
1	0	2	0	120	5.2	155.325	1.95	1	1
1	0	2.5	-0.5	150	5.7	73.175	2.549	1	2
1	0	3	-1	180	6.5	118.5	2.355	1	3
1	1	2	0	150	5.7	137.65	2.046	0.824	4
1	1	2.5	-0.5	180	6.5	89.95	1.677	1	5
1	1	3	-1	120	5.2	187.96	2.67	0.229	6
1	2	2	-0.5	120	6.5	158.31	2.65	1	7
1	2	2.5	-1	150	5.2	133.12	2.082	1	8
1	2	3	0	180	5.7	234.645	2.101	1	9
2	0	2	-1	180	5.7	129.49	2.229	1	10
2	0	2.5	0	120	6.5	152.38	3.447	1	11
2	0	3	-0.5	150	5.2	141.28	2.785	1	12
2	1	2	-0.5	180	5.2	73.515	2.804	1	13
2	1	2.5	-1	120	5.7	142.525	2.695	1	14
2	1	3	0	150	6.5	140.03	4.451	1	15
2	2	2	-1	150	6.5	131.08	3.633	1	16
2	2	2.5	0	180	5.2	74.42	1.429	0.582	17
2	2	3	-0.5	120	5.7	189.775	3.2	1	18
1	3	3	0	120	5.7	225.13	2.75	1	19

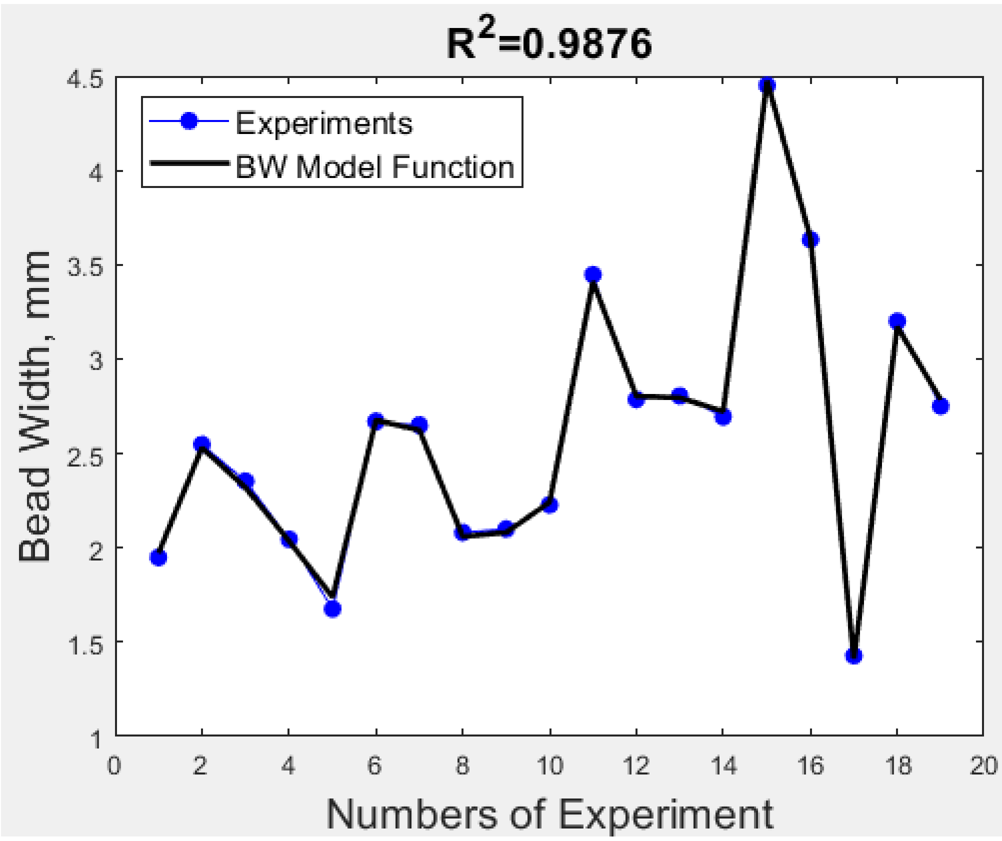
APPENDIX C

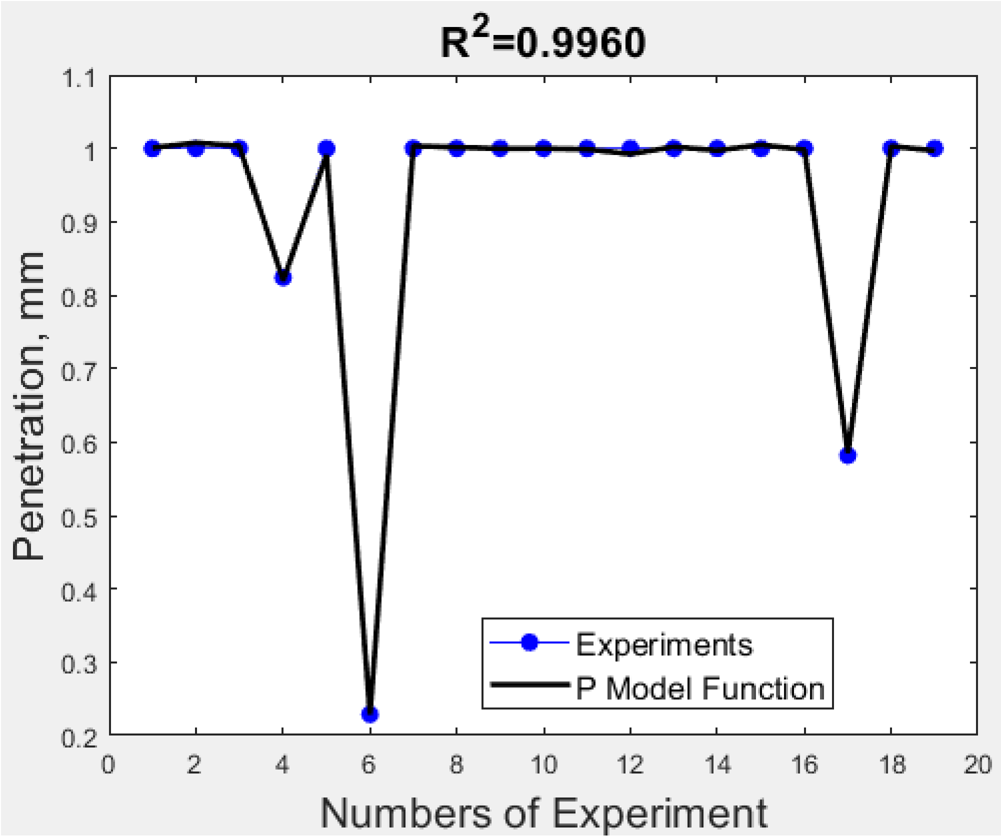
In order to reach Matlab file and Excel file (w.xlsx), please use following Google Drive link:

https://drive.google.com/drive/folders/1RAT4XhAbAFcCKi38yA_qYkFaj9Qa4u1f?usp=sharing

APPENDIX D


R2=0.9982
Ultimate Tensile Strength, MPa
240
220
200
180
160
140
120
100
80
60
Experiments
UTS Model Function
0
2
4
6
8
10
12
14
16
18
20
Numbers of Experiment


R2=0.9876
Bead Width, mm
4.5
4
3.5
3
2.5
2
1.5
1
Experiments
BW Model Function
0
2
4
6
8
10
12
14
16
18
20
Numbers of Experiment


R2=0.9960
Penetration, mm
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
2
4
6
8
10
12
14
16
18
20
Numbers of Experiment
Experiments
P Model Function