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Modeling and Analysis of Mechanical Properties in Structural Steel-DOE Approach

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Abstract

The present work focuses on the modeling and analysis of mechanical properties of structural steel. The effect of major alloying elements namely carbon, manganese and silicon has been investigated on mechanical properties of structural steel. Design of experiments is used to develop linear models for the responses namely Yield strength, Ultimate tensile strength and Elongation. The experiments have been conducted as per the full factorial design where all process variables are set at two levels. The main effect plots showed that the alloying elements Manganese and Silicon have positive contribution on Ultimate tensile strength and Yield strength. However, Carbon and Manganese showed more contribution as compared to Silicon. All three alloying elements are found to have negative contribution towards the response- Elongation. The present work is found to be useful to control the mechanical properties of structural steel by varying the major alloying elements. Minitab software has been used for statistical analysis. The linear regression models have been tested for the statistical adequacy by utilizing ANOVA and statistical significance test. Further, the prediction capability of the developed models is tested with the help of test cases. It is found that all linear regression models are found to be statistically adequate with good prediction capability. The work is useful to foundrymen to choose alloying elements composition to get desirable mechanical properties.

Keywords: Structural steel, Alloying elements, Linear model

1. Introduction

The main alloying elements in structural steel are carbon, manganese and silicon. Steels for structural uses may be classified by chemical composition, tensile properties, and method of manufacture as carbon steels, high-strength low-alloy (HSLA) steels, heat-treated carbon steels, and heat treated constructional alloy steels. Structural steel is widely used in traditional and medium density housing due to its versatility, strength and competitive price.

Structural Steel is the material of choice for numerous structures such as steel bridges, high rise buildings, towers and other structures. This is due to the desirable properties such as good strength, uniformity, light weight, ease of use, formability, etc. possessed by the material.

Design of Experiments (DOE) is one of the powerful statistical tool that can be used to investigate the effect of parameters and develop accurate input-output relationship [1]. Many of the researchers have successfully applied DOE and Response surface methodology to model and analyze casting process.

It is to be noted that not much of the work is carried in analyzing the effect of alloying elements and modeling of structural steel production by using statistical regression analysis. However good amount of literature is available on successful application of DOE and RSM tools in metal casting. Zyska et. al.[2] used two level full-factorial design of experiment to study the effect of squeeze pressure, die temperature and percentage of modifier on percent elongation and tensile strength of squeeze cast components. Further linear and non-linear regression models were successfully applied to establish the input-output relationship in different casting processes, namely cement bonding molding,[3-4], green sand molding[5-6], resin-bonded sand mold[7], sodium-bonded molding system[8], die casting[9-11] and evaporative casting process[12]. A study conducted by Laz'ko et al.[13] showed that the strength of high strength weldable steel 03G4N2MAF increases significantly as its carbon content increases from 0.05 to 0.10–0.12% with retention of plasticity and resilience. A further increase in carbon content is not rational, since the resilience of the steel decreases sharply with an insignificant increase in yield point. Babichev and Velikanova [14] found that manganese added to steels containing 1% C affects their wearability. The wearability of quenched steels (1% C) and the hardness decrease with increasing amounts of manganese, while in annealed steels containing 0.90–1.20% C, manganese has no effect either on the hardness or the wearability. A study by Kharitonov et al.[15] showed that the plasticity and resilience of aged steel, N18K9M5T containing more than 0.2% of Si decrease as a result of the negative effect of this element on these properties of the steel in the aged state. [16]H. E. Townsend conducted experiments and it was observed that P, Si, Cr, C, Cu, Ni, Sn, and Mo are beneficial to improve corrosion resistance. Sulphur had shown a very large adverse effect whereas V, Mn, Al, Co, As, and W had a little, if any, effect on corrosion. Izelu et al.[17] conducted the study in which the contributions made by the alloying elements on the mechanical properties of the weld metal were analyzed using Regression analysis. Six alloying elements namely C, P, Ni, Cr, Nb and V have been identified to constitute the chemical composition of the weld that is expected to achieve the required impact strength. A study conducted by Rosado et al. [18] showed that significant progress has been achieved during last years in the development of HSS pipe steels for strain-based design applications. High strength steel grades have shown improvement in mechanical properties. Increase of strength in high strength steel is resulted with the increase of alloying elements namely Mo, Si and Ni.Ismar et al.[19] focused their study on importance of toughness parameter for novel structural materials such as high-strength steels.

Design of experiments with Response surface methodology has been successfully used by the researchers to model and analyze manufacturing processes such as welding, machining etc. [22-22]. The literature shows conventional statistical tool such as Design of experiments, Taguchi and Response surface methodology have been used by many researchers to modify and analyze various manufacturing processes. It is important to mention that many researchers showed alloying elements and their quantity play important role in developing the required metallurgical structure and properties in metal casting. However not much of work is reported in literature on investigation of effect of alloying elements in manufacture of structural steel.

2. Methodology

In the present study an attempt has been made to establish the linear input-output relationships in production of structural steels. The methodology employed in the present work consists of following steps.

2.1. Identify the inputs and responses of the system

The following steps have been followed to identify the inputs and responses of the system:-

1. Identify the important process parameters (Input variable) and their feasible upper and lower limits. Decide on the number of replicates.
2. Develop the design matrix based on the number of variables and their levels chosen.
3. Conduct the experiments with the input variable combination as per design matrix and record corresponding response values.

Modeling of structural steel can be represented in Figure 1 as an input-output model. The alloying elements, namely carbon, manganese and silicon are treated as input parameters whereas yield strength, ultimate tensile strength and percentage elongation are considered as the process output.

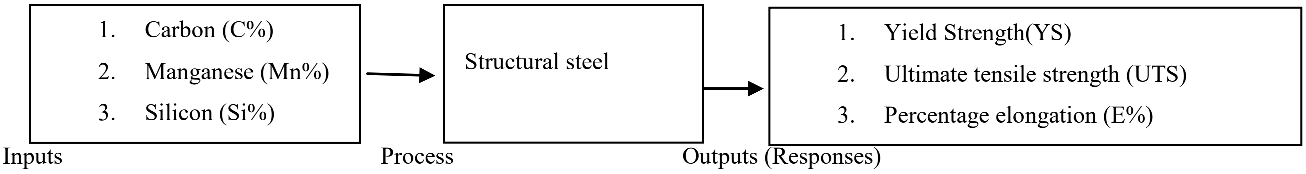


Fig. 1. Input Variables and Responses of the system

2.2. Selecting appropriate levels for process parameters

It is to be noted that the manufacture and preparation of test specimen has been carried out at Bhilai Steel Plant, Bhilai, India. The material used in the experimental work is structural steel (IS 2062 E250B).The major alloying elements, namely carbon, manganese, silicon with their low, medium and high level values are presented in Table 1.The operating range of each parameters (i.e. alloying element) is decided based on the literature and by consulting industry experts. However in the experimental analysis and testing, the alloying elements namely sulphur, phosphorus and aluminium are not considered as these are present in very small amount.

Table 1.
Process Parameters and their levels

Parameters	Notation	Levels		
		Low (-)	Medium(0)	High (+)
% Carbon	A	0.12	0.16	0.2
% Manganese	B	0.6	0.8	1
% Silicon	C	0.15	0.225	0.3

2.3. Experimental Design matrix

Full-factorial design of experiments with the parameters set at their respective two levels, can be used to develop linear relationships between the input-output parameters. The advantage of full-factorial design of experiments lies in the fact that the number of experiments required is less, though the analysis provides complete information on the main and interaction effects of input parameters on the response. The generalized 2-level full-factorial design of experiments for three factors (input variables) is shown in Appendix [A].

2.4. Experimental data collection

Structural steel specimen (Grade IS2062 E250B) is used for testing. There are two basic processes for the manufacture of structural steel. Hot-rolled shapes including wide-flange sections, angles and channels are produced in steel mills utilizing Electric Arc Furnaces (EAF). Hollow Steel Sections (HSS) are manufactured from rolls of sheet steel that may have originally been produced in either a Basic Oxygen Furnace (BOF) or an EAF. Plate steel may also have been produced through either a BOF or EAF process.

Tensile test has been carried for determining the Yield Strength, Ultimate Tensile Strength, % Elongation. The specimens of structural steel are tested in UTM (Refer figure 2) for obtaining the Yield Strength, Ultimate Tensile Strength and percentage elongation. The UTM machine is Lloyd make with the capacity of 60 Tons.

Fig. 2. Universal Testing Machine(UTM)

Fig. 3. Test Specimen of structural steel

“Figure 3” shows the pictures of the prepared specimen and fractured specimen of structural steel Grade-IS 2062 E250B, which is tested with the help of UTM. The test specimen were prepared as per the standards and experiments were conducted to measure YS, UTS and % elongation. The test is carried out as per ASTM E8/E8M-11.

2.5. Developing the Statistical Models, Statistical analysis and Testing of Models

The development and statistical analysis of the model is done by using Minitab software. The values of the responses measured are entered corresponding to different input variables in the design matrix generated by MINITAB software. The input-output data of ten test cases is shown in Appendix [B].

3. Results and Discussion

The chemical composition and alloying elements have the major impact in developing the required properties. However, the desired mechanical properties such as strength, hardness, ductility, etc. depends on the application required (i.e. load, type of load, environmental conditions, etc.)
The major alloying elements which can be varied in producing structural steel consist of Carbon (C), Manganese (Mn) and Silicon (Si). Carbon addition will increase strength and hardness, whereas reduce ductility, formability and weldability. Strength, Shock resistance, toughness, hardenability, weldability, hot formability will improve and not much change in ductility with the addition of manganese (Mn). It is to be noted that addition of silicon increases strength, decreases weldability, magnetic losses, oxide formation affinity and not much change in ductility. The different combination of these alloying elements (within the operating ranges) will result in structural steels with different set of mechanical properties. Hence, it is important to investigate the effect of these alloying elements on mechanical properties of structural steel.
The present research work aim at the study of the impact of these alloying elements and to develop input-output relations. In the present study, C, Mn and Si are considered as input and Yield strength, Ultimate tensile strength and percent elongation are treated as responses. Moreover, the accuracy of linear models for all responses have been tested by comparing model predicted response values with experiment(measured) values.

3.1 Response-Yield Strength

The linear regression model for the response-Yield strength has been developed by utilizing the experimental data collected as per the full factorial design. The linear regression equation is shown by equation (1).

$$YS = 313.71 + 20.958 * A + 20.958 * B + 7.542 * C - 2.292 * A * B - 1.042 * A * C + 0.625 * B * C - 0.125 * A * B * C \qquad (1)$$

A significance test is conducted to examine the effect of different process parameters and their interaction terms on the said response. Table 2 shows the results of the significance test. The different terms used in Table 2 are as follows. The term ‘Coef’ stands for the coefficients used in equation for representing the relationship between the said response parameter and the factors. The term ‘SE coeff’ indicates the standard error for the estimated coefficient, which measures the precision of the estimate. The smaller the standard error, the more precise will be the coefficient. The T values are calculated as the ratio of the corresponding value under coefficient and standard error. The T value of the independent variable can be used to test whether the predictor significantly predicts the response. The p value is the minimum value for a preset level of significance at which the hypothesis of equal means for a given factor can be rejected.

Table 2.
Significance Test Table for the response- Yield Strength

Term	Effect	Coef	SE Coef	T	P
Constant		313.71	0.9895	317	0
A	41.92	20.958	0.9895	21.18	0
B	41.92	20.958	0.9895	21.18	0
C	15.08	7.542	0.9895	7.62	0
AB	-4.583	-2.292	0.9895	-2.32	0.03
AC	-2.083	-1.042	0.9895	-1.05	0.31
BC	1.25	0.625	0.9895	0.63	0.54
ABC	-0.25	-0.125	0.9895	-0.13	0.9

S = 4.84768 PRESS = 846
R-Sq = 98.36% R-Sq (pred) = 96.32% R-Sq (adj) = 97.65%

Significance test is conducted (refer to Table 2) to examine the effect and contributions of various input variables and their interaction terms on the response-Yield strength.

ANOVA is performed to test the significance of the factors for this response (refer to Table 3).The different terms used in Table 4 are as follows. The term ‘DF’ indicates the degrees of freedom, which refers to the number of terms that will contribute to the error in prediction. The term ‘Seq SS’ represents the sum of squares for each term, which measures the variability in the data contributed by that term. The adjusted sum of squares (i.e. Adj SS) is the sum of squares obtained after removing insignificant terms from the model. The sum of squares is divided by the degrees of freedom to determine the mean square (MS). The adjusted mean square (i.e. Adj MS) is the mean square obtained after removing the insignificant terms from the response equation. The F value for regression is used to test the hypothesis, which is calculated as the ratio of adjusted mean square value to residual error.

As the ‘P’ values of C%, Mn%, Si%, C%*Mn% are found to be less than 0.05 (corresponding to 95% confidence level),these factors are considered to make significant contribution on the response – Yield strength. Moreover, the terms C%*Si%, Mn%*Si%, C%*Mn%*Si% are found to be non-significant as their P values are found to be more than 0.05.The coefficient of correlation for the response Yield strength is seen to be equal to 0.991 and thus it is statistically reliable.

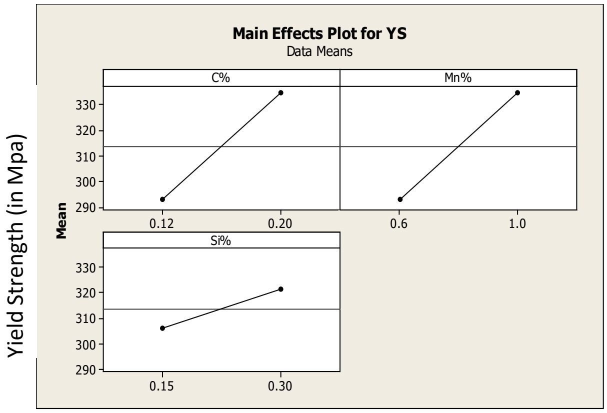
Table 3.
Results of ANOVA for the response – Yield Strength

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	22449.1	22449.1	7483	318.43	0
A	1	10542	10542	10542	448.6	0
B	1	10542	10542	10542	448.6	0
C	1	1365	1365	1365	58.09	0
2-Way Interactions	3	161.5	161.5	53.8	2.29	0.117
AB	1	126	126	126	5.36	0.034
AC	1	26	26	26	1.11	0.308
BC	1	9.4	9.4	9.4	0.4	0.537
3-Way Interactions	1	0.4	0.4	0.4	0.02	0.901
ABC	1	0.4	0.4	0.4	0.02	0.901
Residual Error	16	376	376	23.5		
Pure Error	16	376	376	23.5		
Total	23	22987				

Table 3 displays the results of ANOVA for the response- Yield strength. It is to be noted that all the 2-way interactions and 3-way interactions are found to be insignificant in the response equation. The uncoded units can be converted into coded units by using the following equation (2)

$$A = \left[X_1 - (H_i + L_o)/2\right] / \left[(H_i - L_o)/2\right] \quad (2)$$

Where H_i represents uncoded high level value, L_o represents uncoded low level value and X_1 represents uncoded (real) value for input variable.



Levels of different parameters

Fig. 4. Main Effects Plot for the response of Yield Strength (YS)

Figure 4 shows the main effect plot for the response “Yield Strength”. The horizontal axis denotes the levels of different parameters and the vertical axis shows the Yield Strength (in Mpa). It is to be noted that an increase in carbon, manganese and silicon will increase the Yield Strength. However, carbon and manganese will have more influence as compared to silicon.

3.2 Response - Ultimate Tensile Strength

The linear regression model for the response- Ultimate tensile strength has been developed by utilizing the data collected from experiments as per the full factorial design. The regression equation is shown by equation (3).

Significance test was conducted to examine the effect and contributions of various input variables and their interaction terms on the response-Ultimate tensile strength. As the ‘P’ values of C%, Mn%, Si%, C%*Mn% are found to be less than 0.05 (corresponding to 95% confidence level),these factors are considered to make significant contribution on the response – Ultimate tensile strength. Moreover, the terms C%*Mn%, C%*Si%, Mn%*Si% and C%*Mn%*Si% are found to be non-significant as their P values are found to be more than 0.05. The coefficient of correlation for the response Ultimate tensile strength is seen to be equal to 0.989

$$UTS = 479.958 + 22.375 * A + 20.958 * B + 10.042 * C + 0.375 * A * B - 1.208 * A * C - 0.958 * B * C + 0.792 * A * B * C \quad (3)$$

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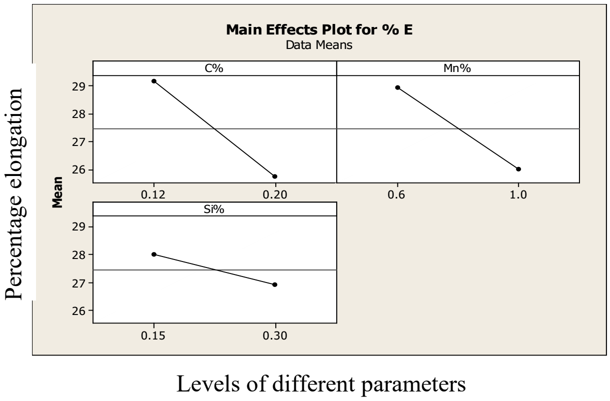

Fig. 6. Main Effects Plot for the response - % Elongation

Figure 6 shows the main effect plot for the response “Percentage Elongation”. The horizontal axis denotes the levels of different parameters and the vertical axis shows the Percentage elongation. It is to be noted that an increase in carbon, manganese and silicon will reduce the percentage elongation. However, carbon and manganese will have more influence as compared to silicon.

3.4 Testing of the Linear Model

The linear model is tested by developing regression equations for the responses obtained from ten test cases. The test cases are presented in Table 4.

From “Table 4” it can be observed that maximum percentage deviation for Yield strength(YS) is -2.54%,for Ultimate tensile strength it is 3.26% and for the response of percentage elongation it is equal to -6.25%.Thus the linear model is accepted.

Once the model have been tested for their statistical adequacy, it is required to test the practical utility i.e. the response prediction capability of the developed regression models. The test cases considered are the experimental data collection in which responses have been measured for different combination of process parameters (i.e. alloying elements) selected at random within their respective operating range. The percentage deviation values for the response-Yield strength is found to lie in the range of -2.54 to +2.53. “Figure 7” shows the percentage deviation of model predicted values. It has been observed that the deviation is found to lie on both above and below zero line with many points close to zero line. From the above discussion it can be concluded that the linear regression model developed for the response-Yield strength is capable to make prediction with good accuracy.

Table 4.
Test results of the responses-Yield strength, Ultimate tensile strength and percentage elongation

	Uncoded Values			YS(in Mpa)			UTS(in Mpa)			%E		
S.N.	C%	Mn %	Si%	Experiment Value(a)	Equation Value(b)	% Deviation (a-b)/a	Experiment Value(a)	Equation Value(b)	% Deviation (a-b)/a	Experiment Value(a)	Equation Value(b)	% Deviation (a-b)/a
1	0.14	0.77	0.3	305	305.75	-0.25	477	473.61	0.71	27	28.29	-4.78
2	0.16	0.8	0.2	310	314.21	-1.36	470	480.63	-2.26	27	27.42	-1.56
3	0.15	0.72	0.3	302	303.38	-0.46	470	471.06	-0.23	28	28.26	-0.91
4	0.18	0.88	0.3	330	338.39	-2.54	492	507.59	-3.17	25	25.52	-2.08
5	0.19	0.7	0.2	325	316.78	2.53	498	481.77	3.26	26	27.31	-5.05
6	0.17	0.82	0.2	327	321.48	1.69	502	488.3	2.73	26	26.85	-3.27
7	0.16	0.73	0.3	312	310.77	0.39	474	478.85	-1.02	27	27.6	-2.22
8	0.18	0.84	0.2	328	325.77	0.68	501	492.27	1.74	25	26.56	-6.25
9	0.16	0.85	0.3	322	321.52	0.15	488	488.47	-0.1	26	26.93	-3.58
10	0.15	0.91	0.2	318	318.68	-0.21	481	483.9	-0.6	27	27.12	-0.46

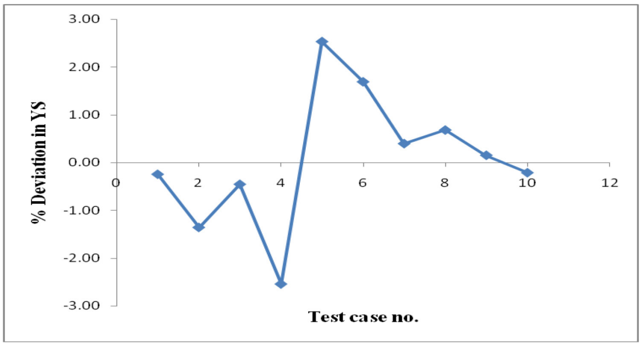

Fig. 7. Comparison of model predicted values of Yield strength with experimental results

The percentage deviation values for the response-Ultimate tensile strength lies between -3.17 to +3.26. “Figure 8” shows the percentage deviation of model predicted values.The deviation points lies on both above and below the zero line with many points close to zero line.So,it can be concluded that the linear regression model for the response-Ultimate tensile strength is capable to make prediction with good accuracy.

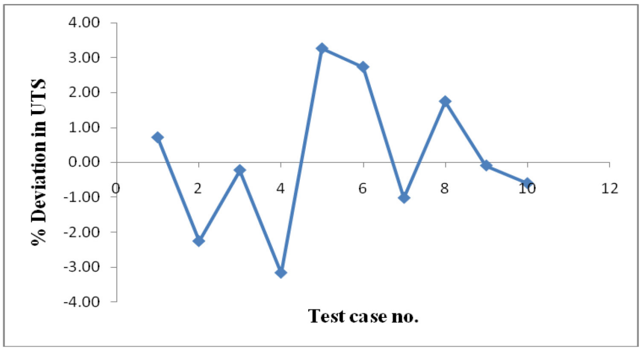

Fig. 8. Comparison of model predicted values of Ultimate tensile strength with experimental results

The percentage deviation values for the response-Percentage elongation lies between -0.46 to -6.25. "Figure 9" shows the percentage deviation of model predicted values.It has been observed that all the deviation is found to lie below the zero line with many points close to zero line.Hence it can be concluded that the linear regression model developed for the response-Percentage elongation is capable to make prediction with good accuracy.

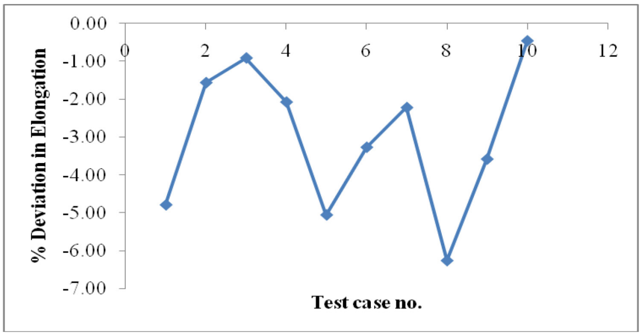

Fig. 9. Comparison of model predicted values of percentage elongation with experimental results

4. Conclusion

In the present work , the effect of three alloying elements namely Carbon , Manganese and Silicon on the mechanical properties of structural steel is studied. Further, linear regression models have been developed for the responses Ultimate tensile strength , Yield Strength and percentage elongation. The analysis shows that alloying elements Carbon ,Manganese and Silicon have positive influence on mechanical properties like Ultimate tensile strength and Yield Strength. Whereas, all alloying elements have negative contribution on the response like Percentage elongation. The influence of alloying elements, Carbon and Manganese is more compared to Silicon on all the responses. The experimental data collected as per full factorial design is used to develop linear regression models (input/output relations). MINITAB software is used for this purpose. The linear models are tested for the statistical adequacy with the help of ANOVA test and coefficient of correlation values. It is observed that the linear regression models developed for all three responses are found to be statistical adequate. Further, the performances of three models have been tested for their prediction capability with the help of 10 test cases. The average absolute percentage deviation values are found to be equal to 1.03,1.58,3.02 for the responses Yield strength, Ultimate tensile strength and percentage elongation respectively. From the present work it can be concluded that the statistical tool Design of experiments can be used to effectively model and analyze the mechanical properties (quality) of structural steel.

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Appendix [A] Design matrix of 2-level full-factorial design

Sl. NO.	Level of the factors							Response value
	Main factors			Interaction factors				
	X_1	X_2	X_3	$X_1 X_2$	$X_1 X_3$	$X_2 X_3$	$X_1 X_2$	
1	-	-	-	+	+	+	-	Y_1
2	+	-	-	-	-	+	+	Y_2
3	-	+	-	-	+	-	+	Y_3
4	+	+	-	+	-	-	-	Y_4
5	-	-	+	+	-	-	+	Y_5
6	+	-	+	-	+	-	-	Y_6
7	-	+	+	-	-	+	-	Y_7
8	+	+	+	+	+	+	+	Y_8

Appendix B. Input –Output data of the test cases (Uncoded input variables)

Test no.	C%	Mn%	Si%	YS (in MPa)	UTS (in MPa)	%E
1	0.14	0.77	0.28	305	477	27
2	0.16	0.8	0.23	310	470	27
3	0.15	0.72	0.26	302	470	28
4	0.18	0.88	0.26	330	492	25
5	0.19	0.7	0.19	325	498	26
6	0.17	0.82	0.23	327	502	26
7	0.16	0.73	0.27	312	474	27
8	0.18	0.84	0.2	328	501	25
9	0.16	0.85	0.25	322	488	26
10	0.15	0.91	0.21	318	481	27