Mathematical Modeling to Predict the Mechanical Properties of Hot Rolled Steel Sheets

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Abstract

The prediction of the mechanical properties of hot rolled steel sheet is one of the most challenging tasks for the steel manufacturer. Typically, the chemical composition of raw material for hot rolling process is not stable. Therefore steel manufacturer has to predict the mechanical properties including yield strength (YS), tensile strength (TS) and elongation (EL) based on input chemical composition. Currently, the method for prediction is the simple linear regression (SLR). The predictor in SLR is only the carbon equivalent which is inadequate to accurately predict the mechanical properties. Thus, this paper proposes the multiple linear regression (MLR) to determine more accurate regression equation. There are three important rolling process parameters considered in MLR including sheet thickness, finish temperature, and coiling temperature. It is found that MLR can yield better prediction value in terms of yield strength and elongation while SLR is still the appropriate method for the prediction of tensile strength. Based on the comparisons, both SLR and MLR can enhance the accuracy in predicting the mechanical properties of hot rolled steel sheet.

Keywords
Hot rolled steel sheet, Prediction of mechanical properties, Simple linear regression (SLR), Multiple linear regression (MLR)

1. Introduction

Hot rolled steel sheet for some business, for instant, the automotive industry are required the high quality and the specialized properties. The high quality of the hot rolled steel sheet can be reflexed by the mechanical properties. In hot rolling process (or hot strip mill), there are many parameters that can affect the mechanical properties. In present, the prediction of quality characteristics of the hot rolled steel sheets for automotive industry has been performed by utilizing the simple linear regression model. The input data including the material compositions and hot rolling process parameters are considered as the independent variables in prediction equation. Not only the input parameters but also the output data from hot rolling process were continuously collected from production line. These big data have been utilized in anticipating the mechanical properties of hot rolled steel sheet. In present, customer requirement for the mechanical properties is so variety depending on customers. Therefore, manufacturer give much attention in process control of hot rolling process so that they can accurate control the vital material properties. This paper intends to determine the accurate mathematical model that is more accurate in predicting the important quality characteristics of hot rolled sheet.

The use of big data from prediction of mechanical properties have been received much interest in the many manufacturing. There are many techniques that can be utilized to make the mathematical model in order to study the

relationship of input and output of process. The regression analysis is one of statistical techniques that can be used to construct the empirical model. The objective of this model is to find the proper relationship between input and output. However, the accuracy of the prediction is a big issue that has to be addressed. The accurate prediction model can effectively be used to control the quality of product. Typically, mechanical properties of materials can be improved by 5 mechanisms; solid solution strengthening, precipitation strengthening, phase transformation strengthening, grain boundary strengthening and work hardening. For the metallurgy model, there were many empirical model to predict the mechanical properties such as Hall-Petch relation (Llewellyn, 1998), Pickering model (Pickering, 1983) and Hodgson and Gibbs model (Hodgson and Gibbs, 1992). However, for hot rolled steel sheet, hot rolling process also contribute to the mechanical properties. Many researches were investigated about the effects of chemical composition on the mechanical properties. Carbon is the most effective alloy on the boost up strength of the steel, thus, the practical method to predict the mechanical properties of steel can be used by converted other alloying elements into carbon term. The conversion of other alloying elements to carbon was called carbon equivalent (*Ceq*) as shown in Equation (1) (Japanese International Standard, 2004).

$$Ceq = C + \frac{Mn}{6} + \frac{Si}{24} \tag{1}$$

Gladman and Pickering (1961) developed the model to predict the mechanical properties by using chemical composition and microstructure of steels but the model focused on the 0.2% C. Moreover, the relationship between hot rolling parameters and the mechanical properties was investigated in many researchers, Kozasu (1972), Matsubara et al (1972), Tsukada et al (1982), Kokasu (1984), Bakkaloglu (2002) and Prasad and Sarma (2005). All of the studies could prove that the hot rolling parameter, such as rolling temperature can affect the mechanical properties. Sellars and Whiteman (1979) and Majta et al. (1996) developed the model that can predict the mechanical properties by using the evaluation of the microstructure during the hot rolling production. Other literatures that study about the mathematical modeling and the prediction of mechanical properties of hot rolled steel sheet can be found in Rudkins and Evans (1998), Xu et al. (2008), Zhang et al. (2009), and Agarwal et al. (2014). Since there are many variables affect the mechanical properties, the development of accurate mathematical model is so important for manufacturing. Moreover, the metallurgy models are very complex, so the users cannot easily implement them. The statistical models, which are more practical than the metallurgy models, can be developed by using the measured production data in the past. Therefore, this study aimed to develop the mathematical models to predict the hot rolled steel sheets by using multiple linear regression (MLR) compared with the simple linear regression (SLR) which is currently used in this case study.

2. Problem Definition

Hot rolling process is the process to produce the hot rolled steel sheets which are supplied to many downstream industries. Slab is the raw materials for the hot rolling process, the chemical composition of the slab is an input parameter that can affect the mechanical properties, Pickering (1983). Slab is heated up to 1,200-1,250°C and pass to next process which is the roughing mill process. At this step, the slab thickness is reduced to a certain thickness and so called bar. Next process step is finishing mill process which tries to reduce the bar thickness to final thickness sheet. The temperature of sheet after the last stand of the finishing mill is called finishing temperature (FT). After the finishing mill process, the hot rolled steel is cooled down to the coiling temperature (CT) and proceeded to the coiling process. Both finishing temperature and coiling temperature are the significant hot rolling parameters that can affect the mechanical properties, Kozasu (1972), Matsubara et al (1972), Tsukada et al (1982), Kokasu (1984), Bakkaloglu (2002) and Prasad and Sarma (2005). The final product is called hot rolled steel in coil.

For the conventional method, the production data were used to construct the simple linear regression (SLR) in finding the mathematical models for the relationship between the mechanical properties and carbon equivalent (Ceq). The current production data with sample size of 982 are collected to conduct the SLR. Figure 1-3 show the scatter plots and regression equations. Equation (2) – (4) are regression equation which are used to predict the yield strength (YS), tensile strength (TS), and elongation (EL). It is seen that coefficient of determination (R^2) for all regression models are lower than 31% which may result in inaccurate prediction of the required mechanical properties. Table 1 depicts the mean square error (MSE) of the SLR currently used in this manufacturer. The MSE is used to measure the error between the measured value and the predicting value. The larger MSE, the worse predicting accuracy. The hot rolling process parameters such as finish temperature ranging from 820 to 890 degree Celsius and cooling temperature ranging from 580 to 650 degree Celsius are set based on the engineering experience. Since the accuracy in predicting

the quality characteristics of the finish goods are so important, this paper try to determine a better approach to enhance the prediction accuracy.

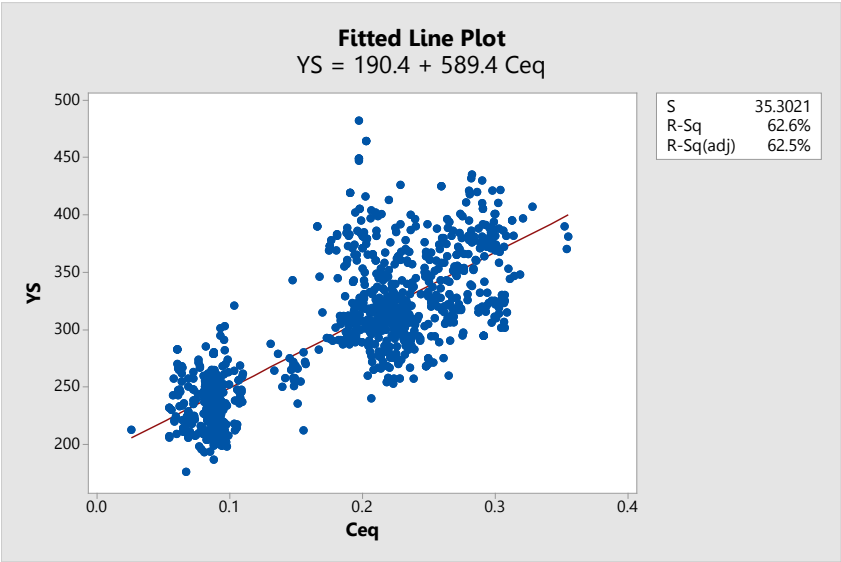

Figure 1. Scatter Plot between Yield Strength and Carbon Equivalent

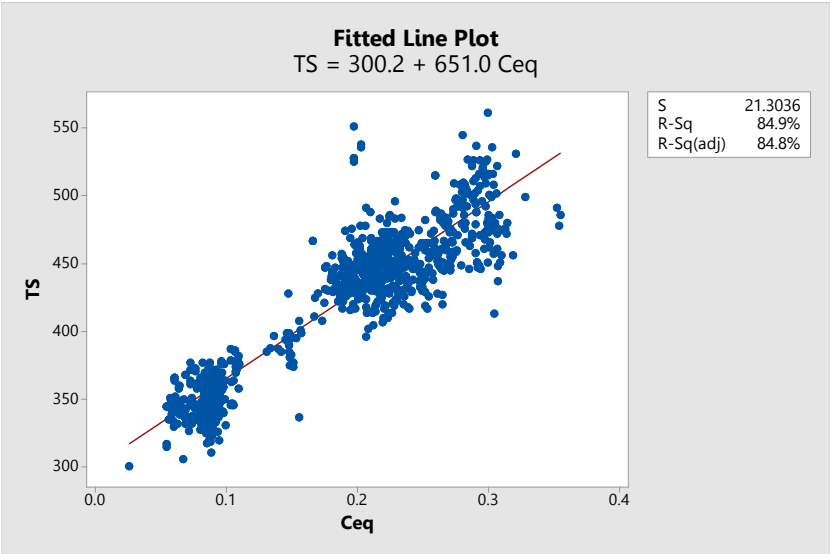

Figure 2. Scatter Plot between Tensile Strength and Carbon Equivalent

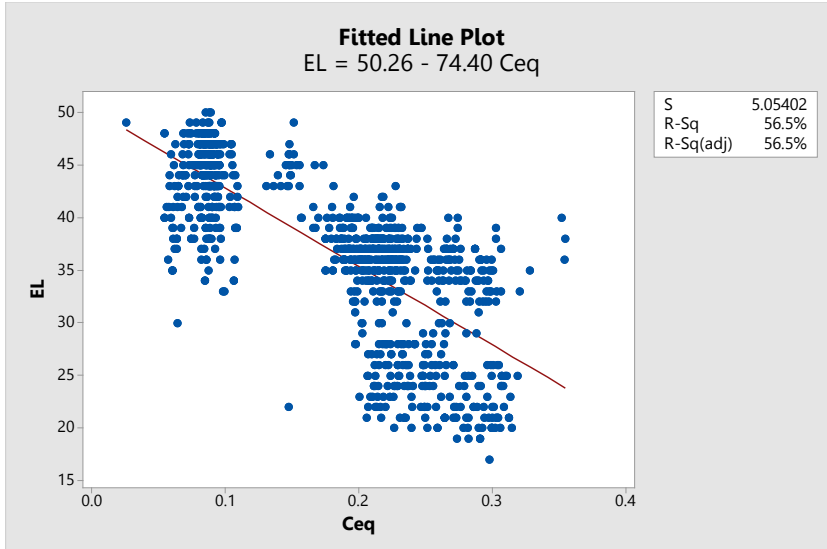

Figure 3. Scatter Plot between Elongation and Carbon Equivalent.

$$YS = 190.4 + 589.4\,Ceq \tag{2}$$

$$TS = 300.2 + 651.0\,Ceq \tag{3}$$

$$EL = 50.26 - 74.4\,Ceq \tag{4}$$

Table 1. Mean square error (MSE) of the prediction by SLR using the current production data

Mechanical Properties	MSE
YS	568.21
TS	326.60
EL	25.49

3. Determination of Prediction Equations by MLR

To achieve the accurate control of mechanical properties, the multiple linear regression is then employed to determine the regression equations or prediction equations. The material composition including carbon equivalent (*Ceq*), Phosphorus (P), Sulfur (S), and Aluminium (Al) are the independent variables for the MLR. Phosphorus and Sulfur can be considered as the impurity in steel. Phosphorus can increase strength of hot rolled steel sheet but it can decrease the ductility of hot rolled steel. Sulphur can increase slightly strength of hot rolled steel sheet, however it has an effect in decreasing the ductility of hot rolled steel sheets. Aluminium is an element that is added to steel in order to control the cleanliness of the steel and it can increase the toughness of steel. In addition, the hot rolling process parameters which are finish temperature (FT), coiling temperature (CT) and the sheet thickness are also the independent variables for the MLR used to create the mathematic models to predict the mechanical properties. Furthermore, the interaction effects between process parameters are considered in the MLR analysis as well. Minitab 17 is utilized to obtain the coefficient of the regression equation. The same data sets used in the simple linear regression are used to conduct the regression analysis and to determine the coefficients of regression equations.

The stepwise technique (alpha to enter and remove = 0.15) is used to select the significant predictors into the regression model. For coded coefficient, all data are converted to a Z-value which is called standardization. The coded coefficients of all terms in the regression model for each mechanical property are shown in the Figure 4 to 6. If P-value of any terms are less than significant level ($\alpha = 0.05$), those terms can be considered as the vital terms to the MLR model. It is seen that *Ceq* is significant in all MLR models (P-value < 0.05), while Al is insignificant in all MLR models. Other main effects, for instance, FT and CT are also the important factor to the response variables.

Interaction effects such as (Thickness)x(FT) and (Thickness)x(CT) have significant effect to YS, TS, and EL. All main effects which are corresponding to the interaction effect are kept into the MLR model as well. The uncoded coefficients in MLR models are also shown in Equation (5) to (7). Typically, the uncoded regression model is more practically used to predict the mechanical property since the actual value of factors can be substituted into the regression model directly.

Regression Analysis: YS versus Thickness, FT, CT, P, S, Al, Ceq

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
33.2374	67.07%	66.80%	66.47%

Coded Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	294.35	1.16	254.51	0.000	
Thickness	1.18	1.35	0.87	0.382	1.61
FT	-2.80	1.19	-2.36	0.018	1.25
CT	-10.02	1.35	-7.44	0.000	1.61
S	5.01	1.15	4.37	0.000	1.17
Ceq	45.17	1.30	34.68	0.000	1.51
Thickness*FT	-2.25	1.11	-2.02	0.043	1.22
Thickness*CT	7.67	1.25	6.15	0.000	1.12
FT*CT	3.177	0.900	3.53	0.000	1.50

Figure 4. Coded coefficients from MLR analysis for YS

Regression Analysis: TS versus Thickness, FT, CT, P, S, Al, Ceq

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
17.5086	89.85%	89.76%	89.58%

Coded Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	417.382	0.590	707.33	0.000	
Thickness	-7.886	0.718	-10.98	0.000	1.65
FT	0.431	0.616	0.70	0.485	1.21
CT	-6.967	0.657	-10.60	0.000	1.38
P	3.523	0.582	6.05	0.000	1.08
S	1.059	0.609	1.74	0.083	1.19
Al	0.865	0.570	1.52	0.129	1.04
Ceq	53.227	0.688	77.33	0.000	1.52
Thickness*FT	-1.377	0.563	-2.45	0.015	1.13
Thickness*CT	3.941	0.660	5.97	0.000	1.14

Figure 5. Coded coefficients from MLR analysis for TS

Regression Analysis: EL versus Thickness, FT, CT, P, S, Al, Ceq

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4.22623	69.85%	69.57%	68.96%

Coded Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	37.063	0.147	251.89	0.000	
Thickness	-2.803	0.172	-16.30	0.000	1.62
FT	0.607	0.151	4.02	0.000	1.25
CT	0.705	0.172	4.11	0.000	1.62
P	0.631	0.141	4.49	0.000	1.09
S	0.461	0.147	3.13	0.002	1.19
Ceq	-4.356	0.166	-26.29	0.000	1.51
Thickness*FT	-0.696	0.142	-4.89	0.000	1.23
Thickness*CT	-0.485	0.159	-3.04	0.002	1.13
FT*CT	-0.167	0.114	-1.46	0.144	1.50

Figure 6. Coded coefficients from MLR analysis for EL

$$YS = 4038 - 2.4\,Thickness - 3.98\,FT - 6.45\,CT + 2323\,S + 583.4\,Ceq - 0.0695\,Thickness \times FT + 0.1033\,Thickness \times CT + 0.00667\,FT \times CT \quad (5)$$

$$TS = 370.4 + 0.8\,Thickness + 0.1938\,FT - 0.4161\,CT + 1050\,P + 491\,S + 89.6\,Al + 687.51\,Ceq - 0.0424\,Thickness \times FT + 0.05307\,Thickness \times CT \quad (6)$$

$$EL = -272 + 21.22\,Thickness + 0.339\,FT + 0.350\,CT + 188.1\,P + 213.5\,S - 56.27\,Ceq - 0.02144\,Thickness \times FT - 0.00653\,Thickness \times CT - 0.000351\,FT \times CT \quad (7)$$

4. Comparisons on the Prediction Performances

The comparisons between the SLR model and MLR model are done by 20 samples of steel sheet. The material composition of samples are measured and the hot rolling process parameters are specified as in Table 2. The prediction of three mechanical properties is compared to the actual values measured from laboratory. All data of measured mechanical properties and the prediction values from two modeling methods are shown in Table 3. The Mean square error of prediction methods (SLR and MLR) for three mechanical properties are in Table 4. It is found that MLR is more accurate in predicting both yield strength and elongation while SLR is suitable for predicting the tensile strength. Addition of hot rolling process parameters, thickness and material composition to the multiple linear regression models can obviously improve the prediction error. For the prediction of YS and EL, mean square error (MSE) of prediction are reduced by more than 25%. That means the hot rolling process parameters, thickness and material composition including Phosphorus (P), Sulfur (S) are significant to both mechanical properties.

Table 2. Hot rolling process parameters and material composition of 20 samples used to validate the models

Sample No.	Thickness	FT	CT	P	S	Al	*Ceq*
1	2.9	860	589	0.0142	0.0031	0.0347	0.2599
2	2.6	880	613	0.0174	0.0037	0.0430	0.2529
3	2	863	608	0.0122	0.0035	0.0405	0.2484
4	3.2	860	596	0.0180	0.0041	0.0446	0.2792
5	4.5	850	624	0.0134	0.0042	0.0390	0.2777
6	2.6	872	605	0.0135	0.0035	0.0331	0.2491
7	4	846	592	0.0135	0.0053	0.0415	0.2848
8	2	865	624	0.0157	0.0030	0.0282	0.0792
9	2.3	885	612	0.0147	0.0029	0.0320	0.2521
10	1.6	843	621	0.0145	0.0031	0.0382	0.2574
11	2.5	846	656	0.0170	0.0033	0.0399	0.2910
12	4	864	614	0.0080	0.0040	0.0340	0.1871
13	3.6	872	593	0.0135	0.0034	0.0465	0.2907
14	4	888	645	0.0150	0.0039	0.0514	0.2161
15	4	880	623	0.0171	0.0052	0.0531	0.2137
16	2	862	631	0.0131	0.0039	0.0342	0.0787
17	2.6	857	591	0.0200	0.0045	0.0382	0.2468
18	2.9	860	597	0.0121	0.0046	0.0372	0.2404
19	4	839	570	0.0173	0.0041	0.0376	0.2849
20	3.2	853	597	0.0160	0.0030	0.0486	0.2814

Table 3. Mechanical properties of measured values and the predicted values from SLR models and MLR models

Sample No.	Measured values			Predicted values from SLR			Predicted values from MLR		
	YS	TS	EL	YS	TS	EL	YS	TS	EL
1	360.00	476.00	36.00	343.59	469.41	30.92	343.37	477.30	32.58
2	329.00	456.00	38.00	339.46	464.84	31.44	328.73	473.21	36.11
3	344.00	460.00	34.00	336.80	461.91	31.78	328.84	466.44	34.80
4	342.00	474.00	37.00	354.95	481.95	29.49	353.81	492.86	32.29
5	313.00	444.00	41.00	354.07	480.98	29.60	346.63	476.27	30.36
6	322.00	449.00	37.00	337.23	462.38	31.73	329.63	467.08	34.79
7	344.00	455.00	37.00	358.23	485.57	29.07	364.98	489.49	29.78
8	220.00	340.00	46.00	237.08	351.75	44.37	221.17	347.69	45.55
9	336.00	456.00	35.00	339.00	464.33	31.50	326.52	470.43	36.32
10	339.00	460.00	34.00	342.10	467.75	31.11	325.13	469.22	33.88
11	328.00	480.00	37.00	361.89	489.61	28.61	328.59	483.71	33.15
12	349.00	436.00	43.00	300.67	421.99	36.34	293.19	411.21	35.21
13	351.00	468.00	38.00	361.73	489.43	28.63	356.34	495.41	30.77
14	278.00	430.00	41.00	317.76	440.87	34.18	302.18	434.27	36.12
15	297.00	452.00	40.00	316.36	439.32	34.36	307.28	439.92	36.40
16	208.00	341.00	46.00	236.76	351.41	44.41	219.34	343.08	45.29
17	344.00	459.00	37.00	335.85	460.85	31.90	339.12	475.88	34.86
18	321.00	445.00	39.00	332.09	456.70	32.37	332.11	460.54	33.83
19	350.00	480.00	35.00	358.34	485.69	29.06	374.30	496.99	29.28
20	334.00	467.00	37.00	356.25	483.39	29.32	353.73	491.44	31.16

Table 4. Mean square error (MSE) of SLR and MLR models

	Mean square error (MSE)	
Mechanical Properties	SLR	MLR
YS	508.34	382.42
TS	225.68	328.28
EL	41.06	23.68

5. Conclusions

This paper aims to improve the control of hot rolling process. In order to achieve proper process control, the regression equation is needed to be appropriately modeled so that the quality characteristics in terms of yield strength, tensile strength, and elongation will be accurately predicted and controlled. The current prediction method of this steel manufacturer relies on only the carbon equivalent as Equation (1) and the simple liner regression is mainly used for predicting the mechanical properties. To improve the prediction of these mechanical properties, the multiple linear regression (MLR) model is employed to deal with the accuracy of prediction. The addition of factors which are hot rolling process parameters, thickness, and material composition successfully yields more appropriate prediction models for YS and EL. However, the SLR model is still the preferable method for prediction of the tensile strength. It can be concluded that the big data and the mathematical modeling techniques can significantly improve the prediction of the mechanical properties of hot rolled steel sheet in coil.

In addition, these prediction equations can be utilized for process control so as to get the desired product characteristics. The recommended process parameters can be determined by solving these equations with optimization approach as well. The future research that should be done is the development on the accurate prediction equation by other modeling techniques.

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