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

$$\begin{aligned} YS = {} & 4038 - 2.4\,Thickness - 3.98\,FT - 6.45\,CT + 2323\,S + 583.4\,Ceq - 0.0695\,Thickness \times FT \\ & + 0.1033\,Thickness \times CT + 0.00667\,FT \times CT \end{aligned} \tag{5}$$

$$\begin{aligned} TS = {} & 370.4 + 0.8\,Thickness + 0.1938\,FT - 0.4161\,CT + 1050\,P + 491\,S + 89.6\,Al + 687.51\,Ceq \\ & - 0.0424\,Thickness \times FT + 0.05307\,Thickness \times CT \end{aligned} \tag{6}$$

$$\begin{aligned} EL = {} & -272 + 21.22\,Thickness + 0.339\,FT + 0.350\,CT + 188.1\,P + 213.5\,S - 56.27\,Ceq \\ & - 0.02144\,Thickness \times FT - 0.00653\,Thickness \times CT - 0.000351\,FT \times CT \end{aligned} \tag{7}$$

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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