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Steel Furnace Temperature Optimization for Wasted of Scale Reduction During Reheating Process by Experimental Design

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Abstract

In the hot rolling steel mill industry, substantial energy resources are consumed, and significant amounts of waste are produced. One notable waste product is scale formation, or iron oxide, on the surfaces of billets. Minimizing and properly treating this scale is crucial, as its disposal in landfills can lead to leachate contamination of groundwater and soil. The rate of scale growth increases with higher furnace temperatures. This study employs experimental design to investigate the impact of different furnace zone temperatures on scale formation. Scale thickness was measured and analysed using analysis of variance (ANOVA). The results indicated that the temperatures in the heating and soaking zones significantly affect the scale growth rate, while the preheating zone temperature does not, within a 95% confidence interval. Optimizing the temperatures reduced the scale thickness from 0.764 mm to 0.467 mm, with a 95% confidence interval. Overall, the waste from scale was reduced from 2.29% to 1.22%.

Keywords : Reheating furnace; Scale Formation; Experimental Design

Introduction

Scale formation is one of the significant wastes in the steel manufacturing process. It forms on steel surfaces through oxidation, with the growth rate increasing as surface temperature and oxygen content rise. When disposed of in landfills, scale can release toxins that contaminate groundwater and soil [1]. Therefore, minimizing and properly treating scale is crucial. Besides its environmental impact, scale causes substantial production yield losses, especially at the high temperatures used during the reheating process. Imperfections on the steel surface can occur, affecting production quality if scale enters the rolling mill process. To prevent this, scale must be removed using high-pressure descaling units before the rolling mill process. Numerous investigations have described the characteristics of scale and predicted its growth rate. This study focuses on optimizing process parameters to minimize scale formation in a factory setting.

Steel is oxidized during the billets are heated up to rolling temperature as 1300 Celsius degrees [2]. The scale is formed on the steel as high as furnace temperature. Ferrous (Fe) and O (excess oxygen) are the main compositional elements of scale. Scale is growth by three layers including outer layer of hematite (Fe_2O_3), an intermediate of magnetite (Fe_3O_4), and a thicken inner of wustite (FeO) [1]. In this study, the thickness of scale formation on steel billets (grade SS400) was examined during the reheating process. SS400 billets were the most selected for utilization, accounting for more than 60% of total production, minimizing variations caused by different steel grades in the process [2]. The experimental methodology employed a factorial design to evaluate the correlation between processing variables and the resulting scale formation. Three process variables, each tested at two levels, were analyzed to identify significant factors influencing the reheating process [3]. A Taguchi experimental design was used to determine the key variables affecting scale formation. To examine the impact of zone temperature on scale formation thickness (mm) during reheating, a 3^k full factorial design approach was implemented, where 3 represents the number of levels, and k denotes the number of input parameters [3]. This approach allowed for a comprehensive assessment of the influence of temperature variations across different zones on oxidation behavior.

The main objective, to determine the furnace temperatures optimization in each combustion zones that significantly effect to the growth rate of scale. The effects of zone temperatures on responses of interest in the reheating process are generated by general full factorial design method of experimental design approach, where the number of levels and the number of input variable factor are used [4]. Three of significant factors that affected to the scale formation are surface temperature of steel holding time in furnace and the percentage of oxygen in furnace atmosphere but furnace temperature is the most important factor which is strongly influences the oxidation of steel [5].

Methodology

In this experiment is applied at one of Thailand's walking beam reheating furnace where is designed by SMS Group (Germany) and combustion system is automated by Prometheus Level II 2013 series system [2]. There are 63 billets containing in furnace for 2 hours 37 minutes of heating time with heating pattern as Figure 1. The methodology is design of experiment for scale thickness minimization by furnace temperature analysis. The result was analyses by analysis of variance (ANOVA) and retest of experiment was implemented in order to compare the differential between before and after the improvement by 2 sample t test.

The oxidation rate of steel in the reheating furnace is influenced by three main factors: free oxygen level, furnace temperature, and steel duration time [5]. Among these, furnace temperature is the most critical factor affecting oxidation and is also the most controllable, as it can be directly adjusted via the furnace control panel. The growth rate of the scale increases as the temperature of the furnace increases and the temperature of the steel with scale is lower 10 Celsius degrees than without scale at the exit of the reheating furnace [6]. This study focuses on the effect of furnace temperature, while the oxygen level and steel duration time are treated as fixed parameters. The oxygen level, a key factor in scale formation, originates from two sources [7-9]: excess oxygen from the air-to-fuel combustion ratio, which is set at 1.10 for all experiments, and furnace pressure, which influences air infiltration. The furnace pressure is maintained at 10 Pascal, as per the manufacturer's default settings. Similarly, the billet charging temperature is fixed at room temperature, following a cold charging process. The steel duration time in the furnace is set at 2 hours and 30 minutes, with a continuous pacing of 2 minutes and 30 seconds, without considering heat conduction to the steel core. The experiments are conducted using a randomized approach, consisting of 16 trials, each producing 16 sample pieces across 16 production batches, all operated by the same personnel.

Furnace temperature analysis for scale thickness minimization by design of experiment

This study investigates the effects of temperature variations in three combustion zones (preheating, heating, and soaking) on scale formation thickness during the reheating process. The response variable of interest, scale formation thickness, is examined at two levels (maximum and minimum temperatures) for each combustion zone, based on normal operational adjustments in billet reheating furnaces.

A full factorial design was used to systematically plan and analyze all experimental combinations. The study follows a 2^k full factorial design approach, where each factor has two levels. In this case, the experimental design considers three factors (k=3), corresponding to the three combustion zones (preheating, heating, and soaking), with each factor varied at two levels (high and low), based on the minimum and maximum set points of the furnace recipe. To optimize scale minimization, the experiment follows a 2^3 full factorial design with two replicates. The results are analyzed using analysis of variance (ANOVA), including main effect plots and interaction plots to assess the influence of each factor on the response variable. Additionally, the relationship between input factors and scale thickness is modeled using a regression equation, as shown in Figure 2.

There are 16 runs number of experiments with three input variable factors with 2 levels following as minimum and maximum set point recipes of preheating temperature (X_1) with level of 990 and 1090 Celsius degrees, heating temperature (X_2) with level of 1210 and 1260 Celsius degrees and soaking temperature (X_3) with level of 1250 and 1290 Celsius degrees [2] as per Table 1. The level of each factor is referenced from the minimum and maximum setup criteria, as defined by the equipment limitations established by the main machine designer and manufacturer [2] as per Figure 3.

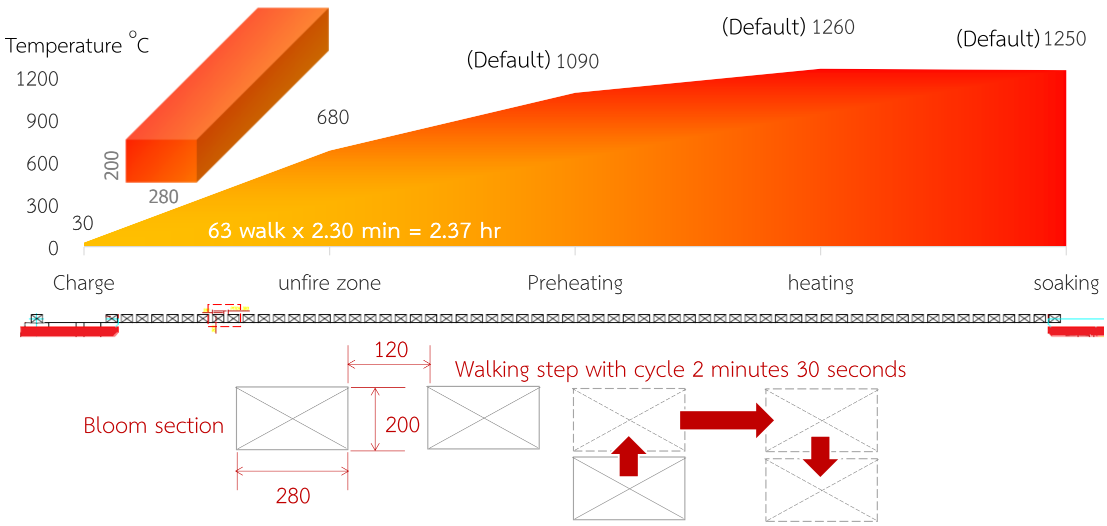


Figure 1 Default of furnace heating pattern and handling controlled

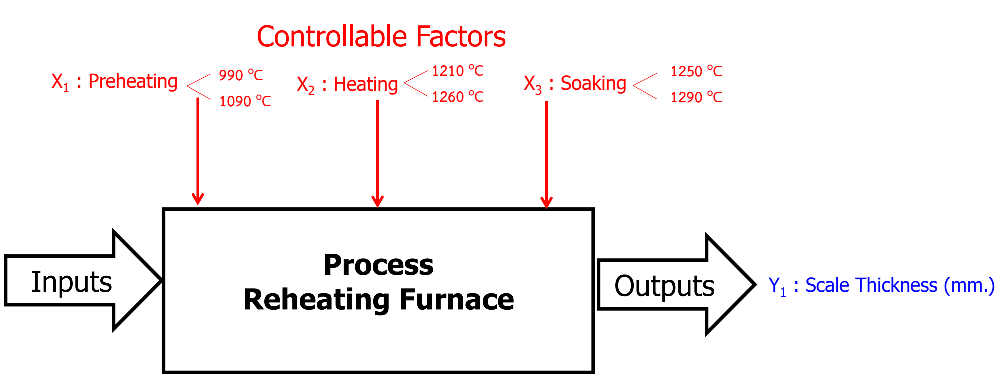


Figure 2 Input variable factor with experimental level

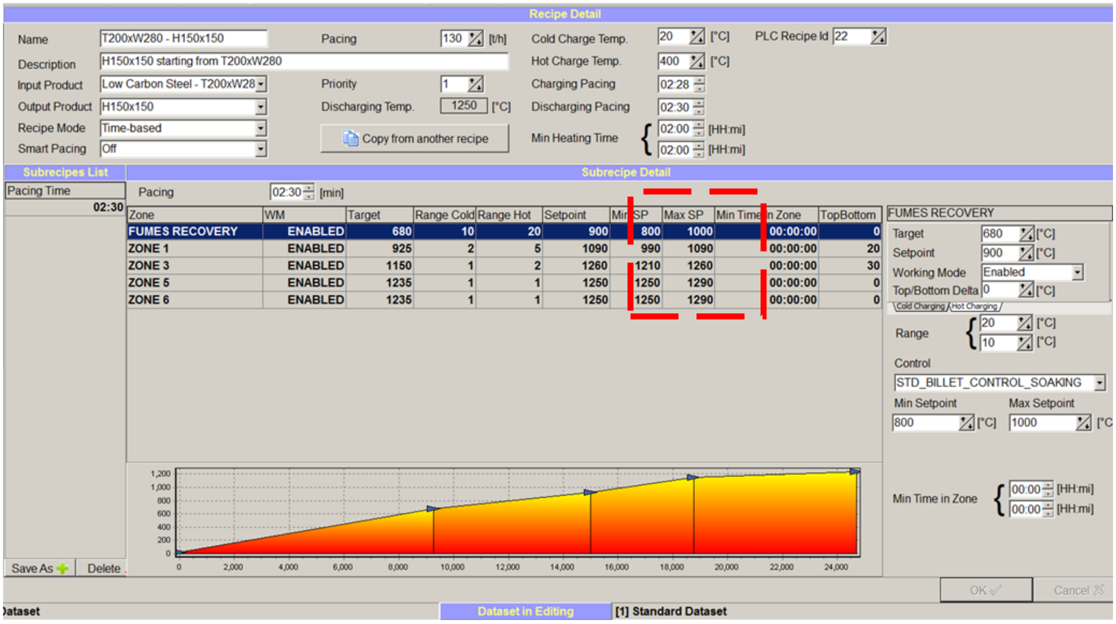


Figure 3 The temperature control criteria for each combustion zone in the setup recipe

Table 1 Input variable factors and level of factor

Input Variable Factors	*Level of factor : K*	
Controllable Factors	*Low (-1)*	*High (+1)*
X_1 : Preheating Temperature ^oC	990	1090
X_2 : Heating Temperature ^oC	1210	1260
X_3 : Soaking Temperature ^oC	1250	1290

The billets are charged into the furnace using a charging machine. During the process of reaching a steady state under different conditions, as per the experimental design, only 1 out of 63 billets in each of the 16 batches (a total of 16 billets) was rejected by the discharging machine. The response variable (Y1), which represents the scale thickness, is measured using a certified and calibrated micrometer (Mitutoyo IP65).

The scale thickness measurement follows the same standardized procedure used for measuring the thickness of test specimens in the laboratory. The laboratory is accredited under ISO 17025 by the Thai Industrial Standards Institute (TISI). Measurements are taken at three specific locations on the billets—head, middle, and tail—as illustrated in Figure 4. Each measurement point is measured twice, and the average value is used. The measuring instruments are calibrated according to internal standards and comply with the requirements of ISO 17025.

Results and Discussion

Results of temperature determining for scale minimization by experimental design

In this experiment, general full factorial analysis was implemented to evaluate, there are 16 totals run based on condition of 3 input factors and 2 levels of factor with 2 replicated of tests. The result of statistic power and samples size is 0.936743 with 0.05 significant level in 95% confidential level as shown in Figure 5.

The response of scale thickness (Y_1) are measured and averaged at three position of head middle and tail by instrument of micrometer following as run order of experiment tested with three input variable factors and two levels of preheating zone temperature (X_1), heating zone temperature (X_2) and soaking zone temperature (X_3). There are 16 results of 16 experiments from 2^3 general full factorial with 2 replicates. The average of scale thickness are varied from 0.396 mm. to 1.117 mm. The responses of data was recorded following as Table 2.

According to Figure 6, the residual plots for the response variable were analyzed to evaluate the adequacy of the statistical model. The residual analysis was conducted using a 4-in-1 residual plot, which includes the Normal Probability Plot, Versus Fits Plot, Histogram, and Versus Order Plot to assess model assumptions and reliability.

The Normal Probability Plot indicates that the residuals are approximately normally distributed, as most data points align well with the reference line, suggesting no significant deviation from normality. The Versus Fits Plot shows a random scatter of residuals without any discernible pattern, confirming that the residuals do not exhibit systematic trends related to the predicted values. The Histogram of residuals displays a roughly symmetric shape, further supporting the assumption of normality, although minor deviations are observed. Lastly, the Versus Order Plot demonstrates that the residuals are randomly distributed over time, indicating no autocorrelation or systematic bias. The Overall, the residual plots confirm that the assumptions of normality, independence, and homoscedasticity are reasonably met.

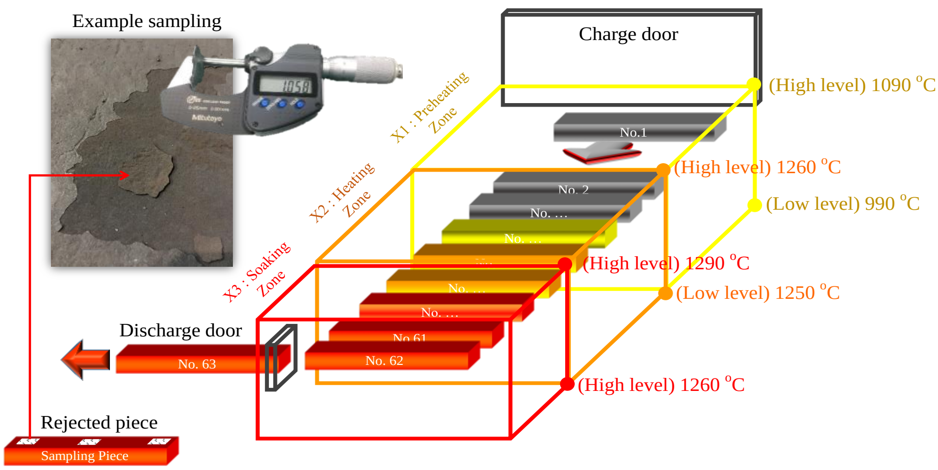


Figure 4 Scale thickness measured

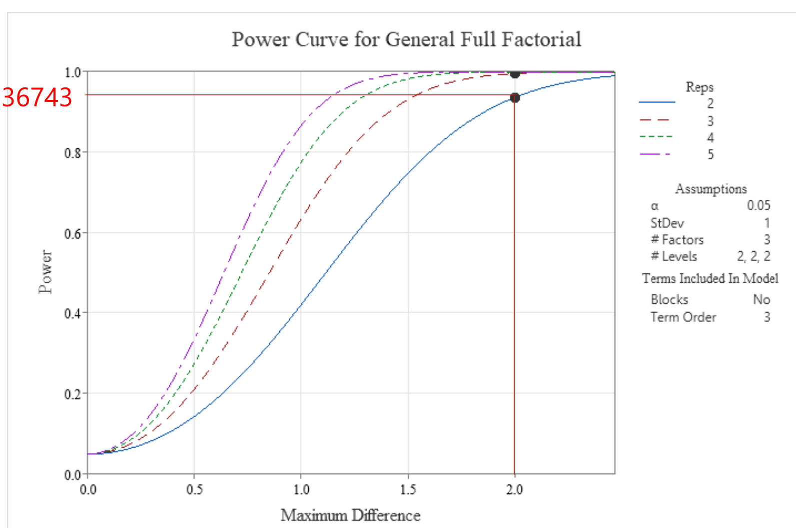


Figure 5 Power and errors of sample size for general full factorial in experimental design

Table 2 Result of response as standard run of experimental design

Standard run	Temperature Factor °C			Y_1 : Scale Thickness (mm.)			
	X_1	X_2	X_3	Head	Middle	Tail	Average
1	990	1210	1250	0.447	0.428	0.433	0.436
2	990	1210	1290	0.712	0.709	0.715	0.712
3	990	1260	1250	0.849	0.823	0.842	0.838
4	990	1260	1290	1.056	1.012	1.094	1.054
5	1090	1210	1250	0.431	0.411	0.421	0.421
6	1090	1210	1290	0.694	0.676	0.688	0.686
7	1090	1260	1250	0.839	0.746	0.809	0.798
8	1090	1260	1290	0.988	0.976	0.991	0.985
9	990	1210	1250	0.407	0.375	0.406	0.396
10	990	1210	1290	0.716	0.675	0.706	0.699
11	990	1260	1250	0.861	0.896	0.898	0.885
12	990	1260	1290	1.141	1.098	1.112	1.117
13	1090	1210	1250	0.425	0.398	0.416	0.413
14	1090	1210	1290	0.737	0.721	0.756	0.738
15	1090	1260	1250	0.915	0.856	0.911	0.894
16	1090	1260	1290	1.054	1.021	1.042	1.039

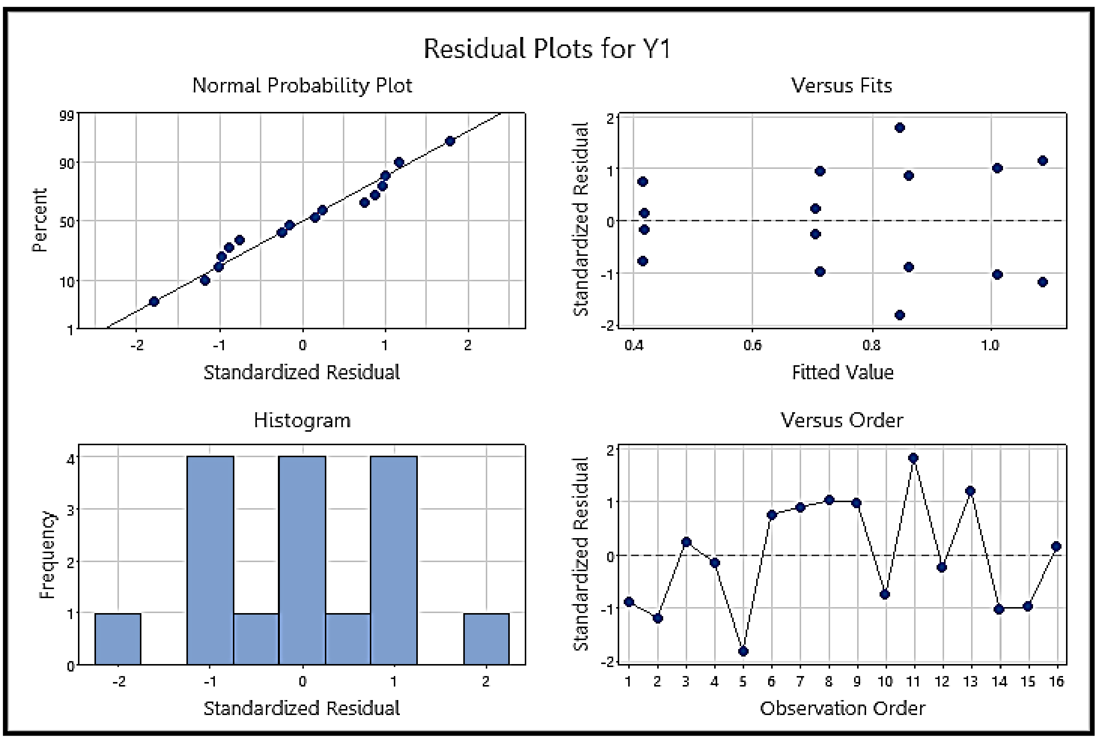


Figure 6 Residual plots on response

Table 3 Analysis of Variance for Average

Source	DF	SS	MS	F-Value	P-Value
Model	7	0.856673	0.122382	85.71	0.000
Linear	3	0.843191	0.281064	196.83	0.000
X_1	1	0.001661	0.001661	1.16	0.312
X_2	1	0.604118	0.604118	423.07	0.000
X_3	1	0.237413	0.237413	166.26	0.000
2-Way Interactions	3	0.012475	0.004158	2.91	0.101
X_1*X_2	1	0.002328	0.002328	1.63	0.237
X_1*X_3	1	0.000689	0.000689	0.48	0.507
X_2*X_3	1	0.009458	0.009458	6.62	0.033
3-Way Interactions	1	0.001008	0.001008	0.71	0.425
X_1*X_2*X_3	1	0.001008	0.001008	0.71	0.425
Error	8	0.011424	0.001428		
Total	15	0.868097			

According Table 3 demonstrate the results from the Analysis of Variance (ANOVA) indicate that the overall model is statistically significant, with an F-Value of 85.71 and a P-Value of 0.000, suggesting that at least one of the examined factors has a significant effect on the response. When analyzing the main effects, it was found that X_2 (P-Value = 0.000) and X_3 (P-Value = 0.000) significantly influence the response, whereas X_1 (P-Value = 0.312) does not exhibit a significant effect. This implies that variations in X_2 and X_3 contribute significantly to changes in the response, while X_1 does not play a critical role in determining the outcome.

In terms of interaction effects, the two-way interaction between $X_2$and X_3 (P-Value = 0.033) was found to be statistically significant, indicating that the combined influence of these two factors has a notable impact on the response. However, other interaction terms, including X_1X_2 (P-Value = 0.237), X_1X_3 (P-Value = 0.507), and the three-way interaction $X_1X_2X_3$ (P-Value = 0.425), did not show statistical significance, suggesting that their combined effects do not meaningfully alter the response.

Table 4 Coefficients for Average

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.75694	0.00945	80.12	0.000	
X_1					
990	0.01019	0.00945	1.08	0.312	1.00
X_2					
1210	-0.19431	0.00945	-20.57	0.000	1.00
X_3					
1250	-0.12181	0.00945	-12.89	0.000	1.00
X_1*X_2					
990 1210	-0.01206	0.00945	-1.28	0.237	1.00
X_1*X_3					
990 1250	-0.00656	0.00945	-0.69	0.507	1.00
X_2*X_3					
1210 1250	-0.02431	0.00945	-2.57	0.033	1.00
X_1*X_2*X_3					
990 1210 1250	0.00794	0.00945	0.84	0.425	1.00

Further analysis of the coefficients as per Table 4 provides additional insights into the magnitude and direction of the effects. X_2 has a coefficient of -0.19431, and X_3 has a coefficient of -0.12181, both with P-Values of 0.000, confirming that increases in X_2 and X_3 result in a decrease in the response variable. In contrast, X_1 has a coefficient of 0.01019 with a P-Value of 0.312, reaffirming that its effect is not statistically significant. The interaction between X_2 and X_3 has a coefficient of -0.02431 with a P-Value of 0.033, indicating that the joint effect of these two factors leads to a further reduction in the response. The other interaction terms exhibit higher P-Values, confirming that they do not contribute significantly to the variation in the response variable.

Based on these findings, it can be concluded that X_2 and X_3 are the primary factors influencing the response, both individually and in combination with each other, while X_1 does not play a significant role in determining the outcome. This highlights the importance of considering X_2 and X_3 when optimizing the response variable, as well as acknowledging the interaction effect between them. Future studies may further investigate the underlying mechanisms driving these relationships and explore potential modifications to improve predictive accuracy.

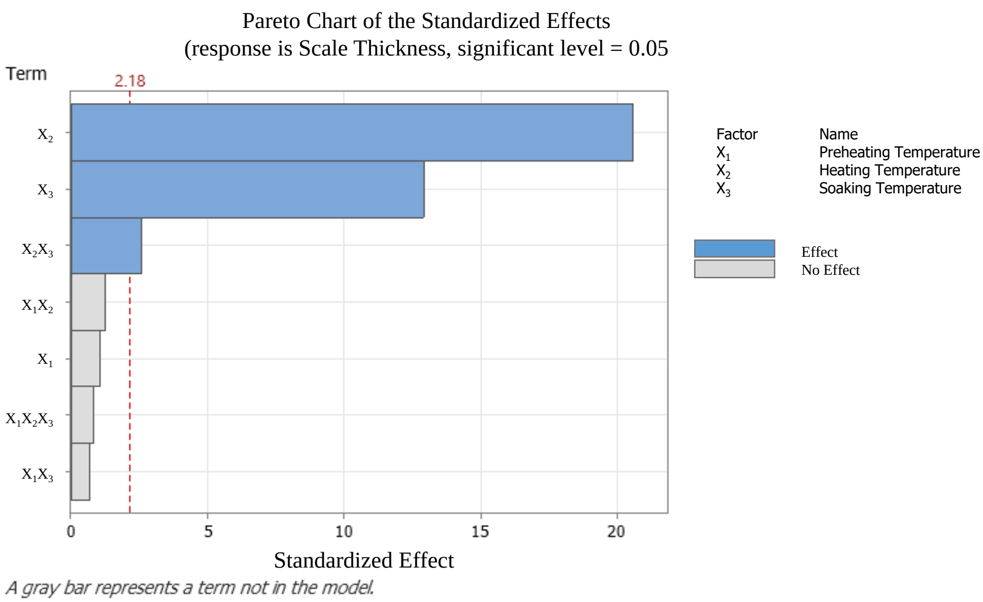
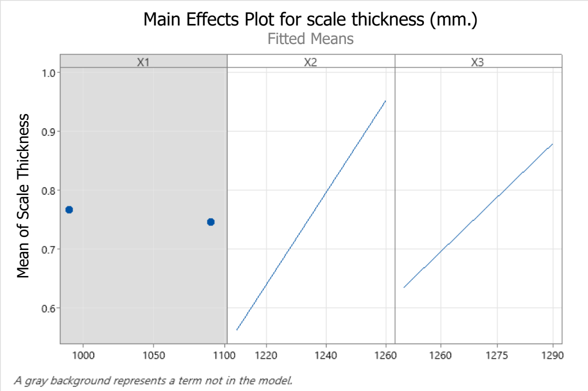


Figure 7 The statistically significant factors affecting the response by Pareto chart

Figure 7 shows the results analysis of standardized effect by pereto chart. There are only 2 out of 3 main input variable factor of heating zone temperature (X_2) and soaking zone temperature (X_3) are affected to the differentiate of scale thickness in the reheating furnace whereby the heating zone temperature (X_2) has the significantly greatest effect and soaking zone temperature (X_3) has the lower than heating zone temperature (X_2) effect meanwhile, both of main effect factors are also interaction between factor of heating and soaking temperature but the preheating zone temperature of X_1 has on effect to the changed of scale thickness.

The result of general full factorial analysis were analyzed to evaluate the correlation of input variable factors with the mean values of the scale thickness by analysis of variance (ANOVA). The details of effect are analyzed by main and interaction effect plot. The results of factorial analysis are demonstrated in Figure 8 for main effect and for interaction between factor effects.



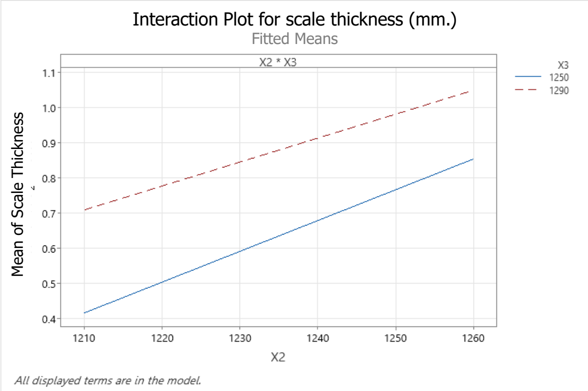


Figure 8 Main effect plot and interaction plot of each input variable factors for scale thickness

Figure 8 shows the factors affecting the change of scale thickness during reheating process. The variable input factors of preheating zone temperature (X_1) has no effect to the response and would not in term of model. In meanwhile heating zone temperature (X_2) and soaking zone temperature (X_3) are significantly affected to growth of scale thickness. The largest inclination of (X_2) heating zone temperature has the highest effect, the runner up inclination is (X_3) soaking zone temperature. The result only main effect and interaction effect of input variable factors, the lowest of scale thickness are result from low level of X_2 at 1210 Celsius degrees and while low level of X_3 at 1250 Celsius degrees.

The results of scale thickness value is optimized by response optimizer in Figure 9. The optimal of scale thickness minimization are analysed and predicted through regression. The optimization are demonstrated that value of input variable factors that affected the lowest of scale thickness at 0.4165 mm. There are set temperature of heating zone (X_2) at low level of 1210 Celsius degrees, also of soaking zone (X_3) at low level of 1250 Celsius degrees with result desirability 0.9716. The growth of scale thickness is predicted by regression equation (1)

$$Y_1 = -92.8 + 0.0695\ X2 + 0.0661\ X_3 - 0.000049\ X_2{*}X_3 \quad (1)$$

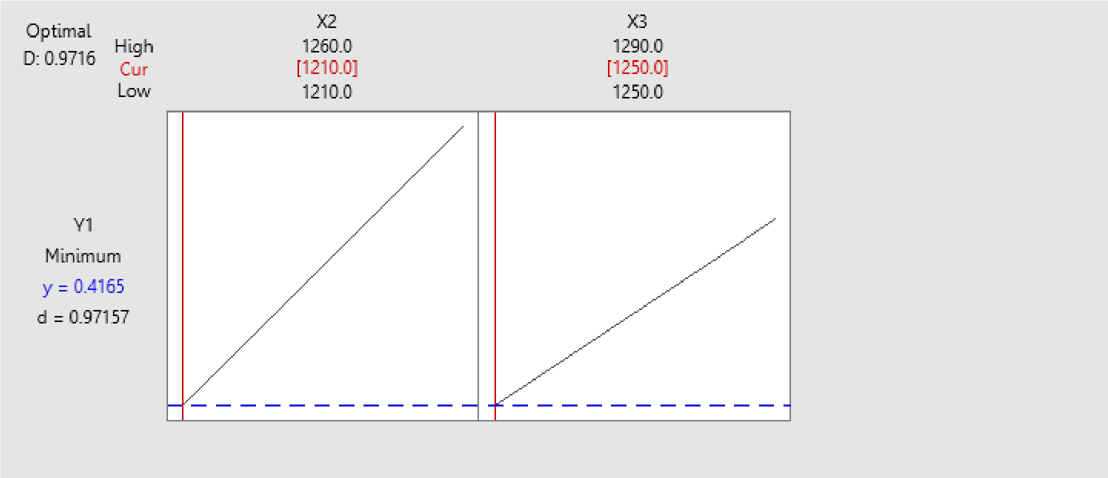


Figure 9 Response of scale thickness optimization

Process implemented and compared the differential between exist set point and optimize set point the improvement by 2 sample t test

The process implementation is retested by comparison between before and after experimental design. The beginning test is set all of parameter as a default factory data and after is set all of parameter as an optimizing data from experimental design. The result between before and after is compared by hypothesis 2 sample t-test with 0.05 significant level. The result of hypothesis test is significant difference by P-Value of 0.000.

Regarding As a results of scale thickness value is optimized in Figure 8. The process implementation are set following as optimizer of (X_2) heating temperature at low level of 1210 Celsius degrees, also of soaking zone (X_3) at low level of 1250 Celsius degrees. Fiure11 shows the bow plot of scale thickness reduction rate is compared between before and after improvement. Result indicates that the growth of scale thickness is significantly reduced. The average growth of experiment are reduced from 0.7644 mm. to 0.4670 mm. as Figure 10. Due to temperature optimization, the decrease in scale thickness contributed to a reduction in total annual factory waste loss from scale oxide, lowering it from 2.29% to 1.22%, as reference reported in the 2023 case study factory report.

According discussed to empirical equation of E. M. Kotliarevsky [5], the actual result of scale thickness is lower than empirical equation of E. M. Kotliarevsky [5] and kinetic parameter [6] at 2.525 mm. and 1.025 respectively. After using set point of optimization, the existing set point is reduced from 0.764 mm. to 0.467 mm. as Figure 11.

In this paper is only experimental designed for temperature optimized to minimized growth of scale formation in walking beam reheating furnace but the significant effect of oxygen excess and heating time are not evaluated. Three significant factor of temperature, oxygen level and heating time including to evaluate of side effect and engineering economic [10].

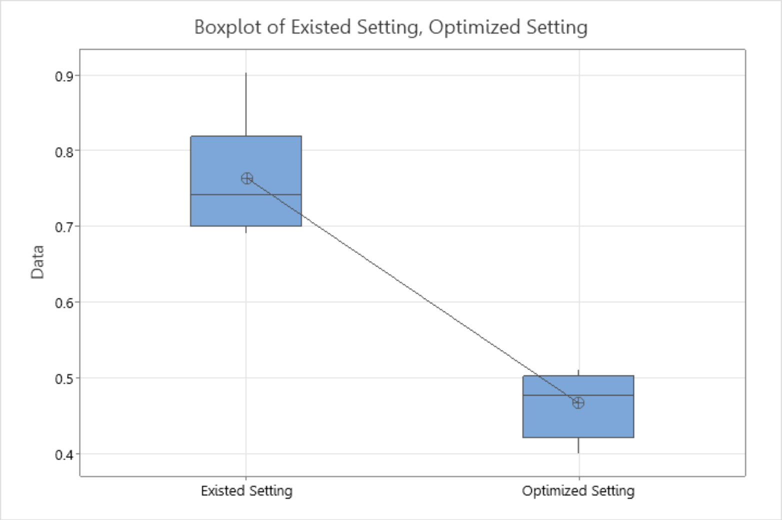


Figure 10 Boxplot of exist setting and optimized setting

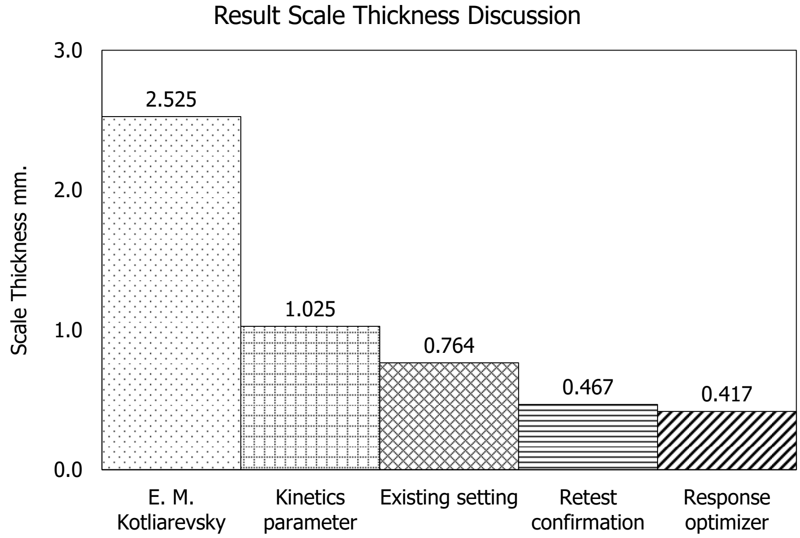


Figure 11 Result discussion and comparison

Conclusions

The reheating furnace is always highly oxidizing and the billet are heated up and rate of scaling will increase as the surface temperature. The one of several wasted in steel manufacturing is scale formation. The effect of highly temperature of furnace are cause of iron oxide or scale formation. In this research is involved the method of temperature determining to maintain a low scale formation that the thickness of scale are collected and measured by instrument of micrometre and the method of design of experiment are defined by 16 experimental of 2^3 general full factorial design of 2 levels with 3 input variable factors multiply by 2 replicates with statistic power of 0.9367 and analyses by analysis of variance (ANOVA) and the minimum of scale thickness are analysed. There are only 2 main input variable factors of heating zone (X_2) and soaking zone (X_3) effect to response. The result demonstrated that the optimization value that made the lowest of scale thickness at 0.4165 mm. at 95% confidential interval (0.3754, 0.4576) where was set temperature of heating zone (X_2) at low level of 1210 Celsius degrees and while temperature of soaking zone (X_3) was set at low level 1250 Celsius degrees but results of heating zone (X_2) and soaking zone (X_3) are related by interaction between factors. There is a reason of result indicates that the difference of scale thickness between exist and optimum set point is significantly differed. The scale thickness of experiment are reduced from 0.7644 to 0.4670 with standard deviation of 0.0748 and 0.0411 respectively. For future research, addressing the limitations of this study is essential. It is crucial to comprehensively consider other key factors, including (1) oxygen levels, (2) steel residence time duration, (3) air pollution factors such as nitrogen oxides and carbon monoxide, and (4) thermal efficiency. Additionally, both the engineering and economic implications of scale minimization should be evaluated. Incorporating these factors into future studies will provide a more comprehensive understanding of the overall benefits of scale oxide formation in industrial processes.

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