Optimization of cold rolling process parameters in order to increasing rolling speed limited by chatter vibrations

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Abstract  Chatter has been recognized as major restriction for the increase in productivity of cold rolling processes, limiting the rolling speed for thin steel strips. It is shown that chatter has close relation with rolling conditions. So the main aim of this paper is to attain the optimum set points of rolling to achieve maximum rolling speed, preventing chatter to occur. Two combination methods were used for optimization. First method is done in four steps: providing a simulation program for chatter analysis, preparing data from simulation program based on central composite design of experiment, developing a statistical model to relate system tendency to chatter and rolling parameters by response surface methodology, and finally optimizing the process by genetic algorithm. Second method has analogous stages. But central composite design of experiment is replaced by Taguchi method and response surface methodology is replaced by neural network method. Also a study on the influence of the rolling parameters on system stability has been carried out. By using these combination methods, new set points were determined and significant improvement achieved in rolling speed.

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Introduction

Chatter is one of the main problems in the cold rolling of strip in tandem mills. Reduction in productivity due to chatter vibration has important effect on the price of rolled strips. So chatter is not only an industrial problem, but also an economic concern in modern rolling mills. Third octave chattering is most important type of chatter that often occurs in cold rolling. The main feature of this chattering is that the strip thickness greatly fluctuates [1–3].

Yarita et al. [1] constructed a four-degrees-of-freedom stand model using a simple mass-spring-damper vibration system and provided methods to estimate the spring constants and damping coefficients of this system.
Tamiya et al. [2] proposed that the chattering phenomenon is self-excited vibration due to the phase delay between the strip tension and vertical vibration of the work roll. Yun et al. [3] developed a model that is more suitable for studying chatter. This model presents dynamic relationship between rolling parameters. Niziol and Swiatoniowski [4] studied the effect of vibrations in rolling on the profile defects of the final metal sheet. They presented some suggestions to avoid chatter based on their numerical analysis. Younes et al. [5] presented the application of parameters design to improve both the product quality and the equipment performance in a sheet rolling plant.

Farley [6] obtained the typical mode shapes of a rolling mill that can become excited during third and fifth octave chatter. They calculated a threshold rolling speed on all cold mills where gauge chatter vibration will become self-exciting.

Statistical analysis of the rolling parameters during the vibration of the five-cell cold rolling mill was conducted by Makarov et al. [7]. Brusa and Lemma [8] analyzed the dynamic effects in compact cluster mills for cold rolling numerically and experimentally. Their research activity was aimed to assess an approach suitable to model the cold rolling cluster mill. Xu et al. [9] formulated a single-stand chatter model for cold rolling by coupling the dynamic rolling process model, the roll stand structure model and the hydraulic servo system model. They linearized the model and represented it as a transfer matrix in a space state.

Jian-liang et al. [10] established the vibration model of the moving strip in rolling process. They built the model of distributed stress based on rolling theory and then conducted the vibration model of moving strip with distributed stress.

Many researchers focus on the effects of various rolling conditions on the occurrence of chatter. They studied several parameters such as rolling speed, friction, inter-stand tensions, reduction, inter-stand distance, and material properties. Tlust et al. [11] presented some suggestions to avoid chattering. They suggested to increase inter-stand distance, rolls mass, natural frequency, input thickness and to decrease rolling speed and reduction. Chefnou et al. [12] considered that there must be a zone of optimum values for the friction coefficient which must not be too low or too high. Meehan [13] used chatter criterion and simulation model and calculated the percentage changes in key rolling parameters required to produce a 10% increase in the critical third octave rolling speed. Kimura et al. [14] proposed a simplified analytical model to validate the existence of optimal friction conditions. In their verification, an indirect method that used a stability index was adopted.

Although many studies have been conducted to investigate the effects of rolling parameters on the rolling instability due to chatter, optimum values of these parameters are not completely understood and conclusions in the literature are somewhat conflicting. For example some researchers concluded that high friction leads to chatter [1], while others observed that low friction due to excessive lubricants results in rolling instability [12]. Yet some researchers indicated that both too high and too low friction coefficients increase the risk of vibration instability [15].

The main objective of this research is to show the capability of the optimization methods in increasing productivity while controlling the chatter to occur. Two separate methods were used to optimize a tandem rolling parameters. Each method was done in four stages: dynamic simulation of chatter in rolling, design of experiment, modeling the relation between rolling parameters and system tendency to chatter and finally optimization of the process. The first and last stages are similar in two methods. The method of design of experiment is central composite design [16] in the first method and Taguchi [17–19] in the second method. Response surface methodology [20] was used for modeling the relation between inputs and outputs in the first method but neural network [21] was used in the second method. The optimization problem was solved by genetic algorithm [22]. By these methods optimum value of each parameter is determined systematically.

**Methodology**

**Dynamic model of the rolling process**

The most important part in modeling rolling chatter is to construct a model for rolling process that represents the relations between various input rolling parameters and the required output parameters. Dynamic model of the rolling process that is used in this research is based on the relations that have been presented by Hu et al. [23]. This model relates the input and output parameters in a suitable form.

Input parameters include strip entry and exit tensile stresses (σ1 and σ2), strip thickness at entry (h1), roll horizontal movement (χr), roll gap spacing (hR), and roll peripheral velocity (vR).

Output parameters are rolling horizontal force per unit width (fX), rolling vertical force per unit width (fY), roll gap spacing (hR), and roll peripheral velocity (vR).

They are defined by following equations:

\[ f_X = \frac{\sigma_1}{2} (h_1 - h_2) - kh_2 \ln \frac{h_1}{h_2} - mh_2 \sqrt{\frac{R}{h_1}} \left[ 2 \tan^{-1} \left( \frac{x_2 - x_1}{\sqrt{R h_1}} \right) - \tan^{-1} \left( \frac{x_1 - x_2}{\sqrt{R h_1}} \right) \right] \]

\[ f_Y = (2k + \sigma_1) (x_2 - x_1) + 4k \sqrt{R h_1} \left[ \tan^{-1} \left( \frac{x_1 - x_2}{\sqrt{R h_1}} \right) - \tan^{-1} \left( \frac{x_2 - x_1}{\sqrt{R h_1}} \right) \right] + 2mk \sqrt{\frac{R}{h_1}} \left[ 2 \tan^{-1} \left( \frac{x_2 - x_1}{\sqrt{R h_1}} \right) - \tan^{-1} \left( \frac{x_1 - x_2}{\sqrt{R h_1}} \right) \right] + 2k (x_2 - x_1) \ln \left( \frac{h_1}{h_2} \right) \]

\[ M = mk R^2 \left[ 2 \tan^{-1} \left( \frac{-x_0 + x_2}{\sqrt{R^2 - (x_0 - x_1)^2}} \right) - \tan^{-1} \left( \frac{-x_0 + x_1}{\sqrt{R^2 - (x_1 - x_0)^2}} \right) \right] \]

\[ u_1 = \frac{1}{h_1} \left[ (x_1 + x_r) h_t + (x_1 + x_r) \frac{(x_0 - x_1)^2}{R} + (x_1 - x_0) h_t - h_1 x_r \right] \]
\[
\begin{align*}
\dot{u}_2 &= \frac{u_t h_1 + (x_2 - x_1) \dot{h}_c + \left( h_1 - h_c - \frac{(x_2 - x_1)^2}{R} \right) \dot{x}_c}{h_1 + \frac{(x_2 - x_1)^2}{R}} \\
\text{where } R &\text{ is the radius of the work roll, } k \text{ is the shear yield strength, } m \text{ is the friction factor. Position of the entry plane } (x_1), \text{ position of the exit plane } (x_2), \text{ thickness at exit } (h_2) \text{ and position of the neutral point } (x_n) \text{ are required in the above equations. These parameters can be calculated by the following equations } [23].
\end{align*}
\]

\[
x_1 = x_c + \sqrt{R(h_1 - h_c)}
\]

\[
x_2 = x_c + \frac{Rh_1}{2[u_t h_1 - (x_1 - x_c)h_c + h_1 \dot{x}_c]}
\]

\[
h_2 = h_c + \frac{(x_2 - x_1)^2}{R}
\]

\[
x_u = x_c + \sqrt{Rh_c} \tan \left[ \frac{1}{2} \tan^{-1} \left( \frac{x_1 - x_c}{\sqrt{Rh_c}} \right) + \frac{1}{2} \tan^{-1} \left( \frac{x_2 - x_c}{\sqrt{Rh_c}} \right) \right] + \sqrt{\frac{h_c}{2mR}} \left( \ln \frac{h_2}{h_1} - \frac{\sigma_1 - \sigma_2}{2k} \right)
\]

This dynamic model of the rolling process does not facilitate an easy study of the interactions between the process and the structure because of its nonlinear nature. Similar to some researches [9,23], a linearized model is achieved by applying a first-order Taylor series approximation to the equations for the rolling process model, and eliminating the nominal value of each variable. So the process model can then be expressed in terms of the variations of system inputs and outputs. It is to facilitate to express the linearized rolling process model in the form of a transfer function matrix. Input parameters can be presented as a vector \( u_p \).

\[
u_p = \begin{bmatrix} d\sigma_{x,1} & d\sigma_{x,2} & dh_1 & dx_1 & dh_c & d\dot{x}_c \end{bmatrix}^T
\]

Output parameters also can be presented as a vector \( y_p \).

\[
y_p = \begin{bmatrix} df_x & df_y & dM & du_1 & du_2 \end{bmatrix}^T
\]

Dynamic model of the rolling process can be written in the transfer function matrix:

\[
y_p = G_i(s) u_p
\]

where \( G_i(s) \) is the transfer function of the rolling process in the above equation.

### Rolling structure model

In this research a simple unimodal structure model was used. It contains a simple spring-mass-damper combination to represent the dynamics of the mill stand structure. The relationship between the displacement of the work roll center \( y_c \), and the force variation \( df_y \) can be expressed by a second order differential equation:

\[
M \ddot{y}_c + C \dot{y}_c + Ky_c = wdM
\]

In the above equation, \( M \) is the roll mass, \( C \) is the damping coefficient, \( K \) is the spring constant and \( w \) is the strip width. It should be noted that the moment has direct influence on chatter phenomena in rolling. So the torsional motion should be considered in structure model. The relationship between the angular motions of the roll and the torque variation \( dM \) acting on can be written as follows:

\[
\dot{\theta} + B\dot{\theta} + k\theta = -wdM
\]

where \( I \) is the moment of inertia of the roll, \( B \) is the rotational damping constant, and \( k \) is the rotational spring constant of the roll. By combining the linear inertial structure model (vertical motion) with the rotational motion structure model, the input vector of the structure model is:

\[
u_t = \begin{bmatrix} df_x & df_y & dM \end{bmatrix}^T
\]

Output vector is:

\[
y_u = \begin{bmatrix} 0 & dh_c & \dot{d}_c \end{bmatrix}^T
\]

So the structure model can be represented as:

\[
y_u = G_i(s) \cdot u_t
\]

where \( G_i(s) \) is the transfer function of the structure model in the above equation.

### Dynamic chatter model

The chatter model for a single stand can be formulated by combining the rolling process model with structural model. To achieve a multi stand chatter model, interactions between stands should be considered. These interactions can be found by calculating front and back tension variations caused by the velocity differences between neighboring stands. Also strip gauge variations from the previous stand should be considered. Payoff reel and pick-up reel also added to model to apply the feedback of tension variations before the first stand and after the last stand.

According to low rotational frequency of payoff and pick-up reels it is assumed that they do not introduce any velocity variations in instance or exit of his model [14,24].

In this research a three-stand tandem mill is simulated and analyzed. Parameters for mill stand configuration and material properties were taken from Tlusty et al. [11]. Results of the simulation program are shown in the next figures. Fig. 1 shows the thickness variations of the last stand in an unstable case. The thickness disturbance of the strip enters first stand at \( t = 0 \) and results in vibration of stands.

By increasing the strip speed, it is expected that the system goes to instability [2,3,14,23]. In order to compare the simulation results with critical speed that is reported by Hu et al. [23], which used same parameters for simulation, the critical speeds for chatter is achieved from simulation program. Calculated critical speed is 3.55 m/s that is exactly the same value for rolling speed limit, reported by Hu et al. [23]. Fig. 2 shows the thickness variations of the last stand in an unstable case.

### System equivalent damping

For optimization process a parameter, namely, System Equivalent Damping (SED) is defined that quantitatively determines the stand potential of chatterhancing. Suppose that the general response of the work roll center vibration can be written as:

\[
x(t) = X_0 e^{-\omega t} f(t)
\]

where \( f(t) \) is a function of time less than unity which defines the nature of the vibration of the work roll center. As the
exponential term acts as envelop for the vibration curve, by fitting an exponential through local maximum points of any sample vibrational data, the envelop can be estimated. Then a curve in the form of \( a e^{bt} \) is fitted to these points. By comparing \( a e^{bt} \) with \( X_0 e^{-b_{out}} \), SED can be defined by:

\[
b = -\zeta_0 \text{ SED}
\]

It is obvious that SED values less than zero mean positive damping or \( \zeta > 0 \), and show that the vibration is going to be damped. SED values greater than zero mean negative damping, which represents the chattering will occur. Defining the SED, damping of the rolling systems can be evaluated with a continuous parameter. In other words, the SED can quantitatively present the tendency of a rolling mill to chatter.

**Optimization steps**

In optimization process, objective function and constraints should be specified explicitly. Thus mathematical form of objective function and constraints should be obtained by a modeling technique. Two methods for modeling are used in this paper: Response Surface Methodology (RSM) and Artificial Neural Network (ANN). These models were used for construction a relation between SED and process parameters. Required data for mathematical modeling is produced based on Design of Experiment (DOE). This data can be produced by experiment, simulation,… In this research, required data is taken from simulation program. Using of design of experiment improves the quality of data, so number of required data for modeling is reduced. In the first method Central Composite Design (CCD) of experiment was used before statistical modeling. In the second method Taguchi method in design of experiment is utilized before neural network modeling. Finally optimization problem was solved by genetic algorithm.

**Results and discussions**

**First combined optimization method**

In the first method, required data were planned on the basis of response surface methodology (RSM) technique. RSM commonly is used to find improved or optimal process settings. So it needs an especial design of experiment. Usually Central Composite Design (CCD) is used before RSM. CCD contains an imbedded factorial or fractional factorial design with center points that is augmented with a group of star points that allow estimation of curvature. CCD is adequate for optimization because each factor has five levels. The mathematical model correlates process parameters and their interactions with SED.

Selected design factors are friction factor, reductions in each stand, back tension of first stand (equals with front tension of last stand [11]), inter-stand tensions and speed of the strip. The value of the rolling process parameters in any level...
are listed in Table 1. According to principles of CCD, for eight factors 90 experiments are needed. Then required data was produced by use of simulation program.

Response surface methodology was performed in accordance with the obtained data from design of experiments. Fig. 3 shows the normal plot of residuals. Residual is the difference between the observed values and predicted or fitted values. The residual is the part of the observation that is not explained by the fitted model. Residuals can be analyzed to determine the adequacy of the model. This graph shows the distribution of the residuals. Its vertical axis presents the probability percentage of normal distribution. The points in this

| Factor                              | Sign | Level | 2.828 | -1.0 | 0.0 | 1.0 | 2.828 |
|-------------------------------------|------|-------|-------|------|-----|-----|-------|
| Friction factor of each stand       | f    |       | 0.050201 | 0.063 | 0.07 | 0.077 | 0.089799 |
| Reduction of stand 1 (%)            | r1   |       | 7.9792 | 15.75 | 20.0 | 24.25 | 32.0208 |
| Reduction of stand 2 (%)            | r2   |       | 7.9792 | 15.75 | 20.0 | 24.25 | 32.0208 |
| Reduction of stand 3 (%)            | r3   |       | 7.9792 | 15.75 | 20.0 | 24.25 | 32.0208 |
| Back tension of stand 1 (MPa)       | s1   |       | 49.9584 | 65.5  | 74.5 | 82.5  | 98.0416 |
| Inter-stand tension (stands 1 and 2) (MPa) | s12  |       | 140.059 | 162   | 174  | 186   | 207.941 |
| Inter-stand tension (stands 2 and 3) (MPa) | s23  |       | 140.059 | 162   | 174  | 186   | 207.941 |
| Rolling speed (m/s)                 | v    |       | 2.81005 | 3.45  | 3.8  | 4.15  | 4.78995 |

![Figure 3](image1.png) Normal plot of residuals.

![Figure 4](image2.png) Residuals versus fitted values.
plot should generally form a straight line if the residuals are normally distributed. If the points on the plot depart from a straight line, the normality assumption may be invalid.

*p*-Value is also a criterion to evaluate accuracy of the model. If the *p*-value is lower than the chosen a-level (0.05 in this case), the data do not follow a normal distribution. In this analysis *p*-value is 0.917 so the error normality assumption is valid.

A value of 0.995 was obtained for the $R^2$ statistic, which signifies that the model explains 99.5% of the variability of SED, whereas the adjusted $R^2$ statistic ($R^2_{\text{adj}}$) is 0.989.

The plot of residuals versus fitted values is illustrated in Fig. 4. This plot should show a random pattern of residuals on both sides of 0. If a point lies far from the majority of points, it may be an outlier. Also, there should not be any recognizable patterns in the residual plot. The random distribution of dots above and below the abscissa (fitted values) in Fig. 4 illustrates both the error independency and variance constancy [20].

Fig. 5 depicts the plot of factor effects on SED. This plot can be used to graphically assess the effects of factors on response and also to compare the relative strength of the effects across factors. This figure indicates that all reductions and speed have significant effect on SED. Furthermore, it is seen from Fig. 5 that friction coefficient is inversely proportional to SED. Tensions present little effect on SED.

As mentioned previous the objective function for optimization is rolling speed. Various constraints exist in this problem: bounds that present the minimum and maximum values of

| Table 2 Optimum values of parameters. |
|---------------------------------------|
| Factor | Optimum value | Allowable range |
|--------|---------------|-----------------|
| f      | 0.09          | 0.05–0.09       |
| r1     | 30.8          | 8–32            |
| r2     | 10.4          | 8–32            |
| r3     | 27.4          | 8–32            |
| s1 (MPa) | 50.1          | 50–98           |
| s12 (MPa) | 150.6         | 140–208         |
| s23 (MPa) | 149.5         | 140–208         |
| v (m/s) | 4.6           | –               |

Fig. 6 Thickness variations of the third stand in optimum conditions.
each variable, nonlinear constraint according to SED (response surface created by regression) and nonlinear equality constraint according to total reduction constancy. Total reduction is set to be constant at the same value in Tlusty et al. research [11].

The optimization problem according to above constraints was carried out by genetic algorithm and optimum values were achieved. Table 2 presents the optimum values of the parameters.

Using the outputs of optimization problem as the inputs of the simulation program, the stability of the system for such a high-speed can be checked. Fig. 6 shows the response of the optimal system to arbitrary excitation pulse.

The maximum possible rolling speed for default condition was 3.55 m/s, so that the rolling speed is increased by more than 29% for the optimum point.

Second combined optimization method

Second method is the combination of Taguchi method in design of experiment, artificial neural network and genetic algorithm. In the first step, L50 orthogonal array from Taguchi standard arrays was chosen [17,18]. This array is adequate for optimization because each factor has five levels. Selected design factors are friction factors of each stand, reductions of each stand, back tension of first stand, front tension of last stand, inter-stand tensions and speed of strip. The value of the rolling process parameters in any level are listed in Table 3.

According to L50 orthogonal array, 50 experiments are needed. This data was produced by use of simulation program. Then artificial neural network was used for construction a relation between SED and process parameters. This model is produced by function approximation. One of the problems that occur during neural network training is called overfitting. One method for improving generalization is called regularization. This involves modifying the performance function. Using new performance function causes the network to have smaller weights and biases, and forces the network response to be smoother and less likely to overfit. So modified performance function based on regularization is used in training. In this study, the structure of the neural network is 11-14-8-1. A mean network error of 2.3% and 3.4% for network training and testing data was achieved respectively. Finally ANN model is optimized by genetic algorithm. Optimization problem is like the first combined method. Similar to first method, the objective function for optimization is rolling speed. Definition of constraints is similar to first method, but mathematical function of SED is taken from neural network model. Table 4 presents the optimum values of the parameters from second method.

Using the outputs of optimization problem as the inputs of the simulation program, optimization results are validated again. So the rolling speed is increased more than 26% for the optimum point in the second method.

Conclusion

Optimization of the rolling process parameters according to chatter phenomena was performed successfully. Selected design factors were friction factor, reductions, tensions and strip speed. Two combination methods were used for optimization. In the first method central composite design of experiment and response surface methodology were used. Results show that rolling speed is increased more than 29% using the first method. Taguchi method in design of experiment and neural network techniques were used in the second method. In this case more than 26% growth was achieved in critical rolling speed. SED was the key to optimization problem of the rolling process, where it enables one to mathematically define the chatter occurrence. Also a study on the influence of the most relevant factors over SED has been carried out. It was shown that increasing in all reductions and rolling speed, increases the risk of occurring chatter severely. According to optimum values of the parameters, friction coefficient should be maximized to avoid system instability. It was illustrated that tensions have

| Table 3 | Process parameters and their levels. |
|---------|------------------------------------|
| Factor  | Sign | Level |
| Friction factor of stand 1 | f1   | 0.05 0.06 0.07 0.08 0.09 |
| Friction factor of stand 2 | f2   | 0.05 0.06 0.07 0.08 0.09 |
| Friction factor of stand 3 | f3   | 0.05 0.06 0.07 0.08 0.09 |
| Reduction of stand 1 | r1   | 8 14 20 26 32 |
| Reduction of stand 2 | r2   | 8 14 20 26 32 |
| Reduction of stand 3 | r3   | 8 14 20 26 32 |
| Back tension of stand 1 (MPa) | s1   | 50 62 74 86 98 |
| Inter-stand tension (stands 1 and 2) (MPa) | s12  | 140 157 174 191 208 |
| Inter-stand tension (stands 2 and 3) (MPa) | s23  | 140 157 174 191 208 |
| Front tension of stand 3 (MPa) | s3   | 50 62 74 86 98 |
| Rolling speed (m/s) | v    | 2.8 3.3 3.8 4.3 4.8 |

| Table 4 | Optimum values of parameters. |
|---------|--------------------------------|
| Factor  | Optimum value | Allowable range |
| f1      | 0.09           | 0.05-0.09       |
| f2      | 0.089          | 0.05-0.09       |
| f3      | 0.09           | 0.05-0.09       |
| r1 (%)  | 24.4           | 8-32            |
| r2 (%)  | 13.2           | 8-32            |
| r3 (%)  | 31.4           | 8-32            |
| s1 (MPa)| 95.7           | 50-98           |
| s12 (MPa)| 194.5 | 140-208         |
| s23 (MPa)| 143.5 | 140-208         |
| s3 (MPa)| 51.1           | 50-98           |
| v (m/s) | 4.5            | –               |
a little effect on chatter phenomena. The proposed optimization methods were used to optimize the operational parameters of existing rolling stands. These methods can also be used to optimum design of new rolling stands by considering new parameters such as inter-stand distances, roll masses, system stiffness, and damping.

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References

[1] Yarita I, Furukawa K, Seino Y, Takimoto T, Nakazato Y, Nakagawa K. Analysis of chattering in cold rolling for ultra thin gauge steel strip. T Iron Steel I Jpn 1978;18(1):1–10.
[2] Tamiya T, Furui K, Iida H. Analysis of chattering phenomenon in cold rolling. In: Proceedings of the mineral waste utilization symposium; 1980 September 29–October 4; Tokyo, Japan. Tokyo: Iron and Steel Inst of Jpn; 1980.
[3] Yun IS, Wilson WRD, Ehmann KF. Chatter in the strip rolling process. J Manuf Sci E – T ASME, 1998;120(2):337–48.
[4] Niziol J, Swiatoniowski A. Numerical analysis of the vertical vibrations of rolling mills and their negative effect on the sheet quality. J Mater Process Tech 2005;162–163(spec. iss.):546–50.
[5] Younes MA, Shahtout M, Damir MN. A parameters design approach to improve product quality and equipment performance in hot rolling. J Mater Process Tech 2006;171(1):83–92.
[6] Farley T. Rolling mill vibration and its impact on productivity and product quality. Light Met Age 2006;64(6):12–4.
[7] Makarov YD, Beloglazov EG, Nedorezov IV, Mezrina TA. Cold-rolling parameters prior to vibration in a continuous mill. Steel Transl 2008;38(12):1040–3.
[8] Brusa E, Lemma L. Numerical and experimental analysis of the dynamic effects in compact cluster mills for cold rolling. J Mater Process Tech 2009;209(5):2436–45.
[9] Xu Y, Chao-nan T, Guang-feng Y, Jian-ji M. Coupling dynamic model of chatter for cold rolling. J Iron Steel Res Int 2010;17(12):30–4.
[10] Jian-liang S, Yan P, Hong-min L. Non-linear vibration and stability of moving strip with time-dependent tension in rolling process. J Iron Steel Res Int 2010;17(6):11–5.
[11] Tlusty J, Crichtley S, Paton D. Chatter in cold rolling. Ann CIRP 1983;31(1):195–9.
[12] Chefneux L, Fischbach JP, Gouzou J. Study and control of chatter in cold rolling. Iron Steel Eng 1984:17–26.
[13] Meehan PA. Vibration instability in rolling mills: modeling and experimental results. J Vib Acoust 2002;124(2):221–8.
[14] Kimura Y, Sodani Y, Nishiura N, Ikeuchi N, Mihara Y. Analysis of chatter in tandem cold rolling mills. ISIJ Int 2003;43(1):77–84.
[15] Kong T, Yang DC. Modelling of tandem rolling mills including tensional stress propagation. Proc Inst Mech Eng Part E J Process Mech Eng 1993;207(E2):143–50.
[16] Lorenzen TJ, Anderson VL. Design of experiments: a no-name approach. New York: Marcel Dekker, 1993.
[17] Phadke MS. Quality engineering using robust design. Englewood Cliffs NJ: Prentice-Hall International Editions; 1989.
[18] Ross PJ. Taguchi techniques for quality engineering. New York: McGraw-Hill Book Company; 1996.
[19] Bendell A, Disney J, Pridmore WA. Taguchi methods: applications in world industry. UK: IFS Publications; 1989.
[20] Montgomery DC. Design and analysis of experiments. 6th ed. New York: John Willy & Sons Inc.; 2004.
[21] Freeman JA, Shapura DM. Neural networks-algorithms, applications and programming techniques. New York: Addison Wesley; 1991.
[22] Gen M, Cheng R. Genetic algorithms and engineering design. New York: Wiley; 1997.
[23] Hu PH, Zhao H, Ehmann KF. Third-octave-mode chatter in rolling. Part 1: chatter model. Proc Inst Mech Eng Part B J Eng Manuf 2006;220(8):1267–77.
[24] Zhao H, Ehmann KF. Regenerative chatter in high-speed tandem rolling mills. In: Proceedings of the international manufacturing science and engineering; 2006 October 8–11, Ypsilanti, MI, United States. United States: American Society of Mechanical Engineers; 2006.