MATHEMATICAL MODELLING FOR ROLLING FORCE AND TORQUE CONSIDERING CHATTER DURING COLD ROLLING PROCESS

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Abstract

The chattering in cold rolling mill is a major technical problem that affects iron and steel industries. This has attracted attentions of world's production engineers and persons from science and technology area. In order to improve the quality of production, the chattering problems in rolling mill must be resolved. So the study of the causes of chattering in the rolling mill, and putting forward the corresponding solutions is urgent researching task at present. Therefore, the present research had been planned to study the various process parameters and their optimization for rolling forces and torque during cold rolling process for solving the chattering problems in rolling mill.

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Introduction

The chattering phenomenon is more prone to occur with high rolling speed, greater pressure ratio and thinner plate. Chattering in rolling mill generally make light and dark lines on the surface of steel products, stripes, and change the thickness of the strip, making the strip thickness errors and reducing the quality of the products. This can leave chattering traces on the roller, the surface of rolled piece, accelerate the abrasion of the roll surface, shorten the life of the roller and increase the cost of production. Besides, it may cause accidents such as belt may break or equipment may damage, threatening the security of the staff and causing significant economic losses.

A number of researches on the chattering problems in rolling mill have been done and many scholars had done in-depth researches on different types of chattering problems in rolling mills from different angles which makes great contribution to promote the development of rolling mill chattering theory and progress of rolling process. With the development of science and technology, testing methods and instrumentation is continually being updated and changed. Due to this, the research of rolling mill chattering theory has entered into a new stage.

The chattering problem has received attention of experts and scholars, and at present, the solutions put up by scholars to solve the chattering problems in rolling mill are mainly for the vertical chattering. The suggested ways to reduce the vertical chattering of the mill are: reduce the rolling speed to reduce the chattering of rolling mill; appropriately distribute the pressure of each machine to reduce the chattering of rolling mill; reduce the inlet tension of rolled piece properly, or appropriately reduce the concentration of lubricant emulsion to restrain or delay the self-excited chattering, so that chattering in rolling mill can be reduced; appropriately decrease the gap between the side of the stage supporting rolle bearing and the lining plate of the frame window to reduce the chattering of rolling mill and using hydraulic lining plate to reduce the chattering of rolling mill. These are currently the popular research areas of reducing chattering.

2. Literature Review

Pei-Hua Hu, et al. (2004) studied various types of rolling chatter and considered that third- octave-mode chatter was the most critical because it generated large gauge variations in the rolled materials and may damage the rolling mill. Stability criteria for each mechanism were established in terms of relevant rolling process parameters, and their influences on overall system stability were demonstrated. Part 1 dealt with the general formulation of single- and multiple-stand chatter models.Muin Süleyman Oztop (2006) analyzed the development of incremental ring rolling process . Different approaches were developed: three-dimensional segment model, improved segment model and velocity coupling model. The results of these models were compared with experimentally verified full models. Numerical parameters such as mesh type, step size, convergence ratio were also examined. After verification of the model different applications of the process were developed and physical parameters affecting the process.Rudolf Pernis and J. Kasala (2006) main aim of the present research was the distribution of relative deformation in rolling zone; due to the fact that relative deformation along the length of contact arc I s changed. Limei Jing (2006) in this research, the researcher reviewed some previously published experimental and theoretical studies of hot rolling. A thorough understanding of the available roll design methods, and conditions of their application were extremely important in order to achieve the objective of producing high quality rolled products.K.P. Rao (2011) reported the softening behavior of a medium-carbon steel under hot working conditions in multi-stage compression. Continuous and interrupted compression tests were performed in the temperature range 800– 1100°C Alejandro Rivera (2012) developed a nonlinear finite element model of the hot and cold rolling processes for flat rolling stock with rectangular cross section. This model can be used to analyze the flat rolling of cold and hot steel rectangular strips under a series of different parameters, providing the rolling designer with a tool that he can use to understand the behavior of the steel as it flows through the different passes.Ali Heidari and Mohammad R. Forouzan (2012) stated that 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 was 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 was 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 had analogous stages. But central composite design of experiment was replaced by Taguchi method and response surface methodology was replaced by neural network method. Also a study on the influence of the rolling parameters on system stability had been carried out. By using these combination methods, new set points were determined and significant improvement achieved in rolling speed. The researcher concluded that rolling speed can be increased more than 29% using RSM (response surface methodology). Valentin Nikolayevich Danchenko (2012) this paper presented the fundamentals of plastic deformation of ferrous metals, non-ferrous metals and alloys. The deformation was conducted in heated state for decreasing the strain resistance and increasing the plasticity of the worked metal. S M Byon S I Kim and Y Lee (2013) this research basically concerned about, three- dimensional finite element analysis coupled with the proposed model. It had been performed to investigate the accuracy of the proposed constitutive model. A large-deformation constitutive model applicable to the calculation of roll force and torque in heavy-reduction rolling had been presented. Vivek Anil Vaidya (2013) Taguchi Method was a statistical approach to optimize the process parameters and improve the quality of products that are manufactured. This paper focuses on initial study of rolling parameters of cold rolling mill and its optimization of process parameters based on Taguchi Method of Design of Experiment. The purpose of a cold rolling mill is to successively reduce the thickness of the metal strip and/or impart the desired mechanical and micro structural properties. Optimization for cold rolling mills rolling parameters are continuously being improved due to today's stringent high throughput, quality and low scrap loss requirements for products to make process robust. Rolling parameter set up or rolling scheduling is an important aspect in the operation of cold rolling mills. The optimized rolling parameters lead to improved thickness, surface finish and shape performance of the products. V. Yadav et al. (2013) studied the material parameters for power law and coefficient of friction, were obtained using inverse analysis by measuring exit strip temperature and slip. The procedure made use of finite element model for deformation and an analytical method for the estimation of temperature. Liu Hai-sheng and Zhang Jie (2014) reviewed the researches on chattering in rolling mills and on this basis, analysed the causes and solutions of torsional chattering in main stream system of rolling mill and chattering in vertical system of rolling mill. But, because chattering in rolling mills is caused by multiple factors, when the mill begins to operate, it may have disturbances in many aspects, and these disturbances often influence each other. It is sometimes difficult to find out an effective solution to control. And the online monitoring system of chattering in developing engine can real-time monitor the running of the mill. Once there appears chattering, it will make real time alarm, so as to resolve the problems timely. Besides, it can make the statistics of the parameters of chattering rolling mill which has vital significance in research, forecast, prevention and of chattering in rolling mill. Befekadu Zewdie T.Mariam (2015) analyzed the performance of hot rolling mill rolls to improve the productivity of the rolling process using FEM was .This work was to analyze the deformation of billet size 120x120x3000mm, modeling and Simulation of hot rolling roughing mill first pass by finite element method. To do this three dimensional roll and billet was developed in CATIA version 5.This 3D model was imported to ANSYS work bench 16.0. FEM analysis was done after assigning, boundary conditions, displacement, rotational velocity, and load. Puneet Katyal (2015) reported the results concerning the simulation of the actual housing model on the software. Rolling was defined as a process in which metal is formed through a pair of revolving rolls with plain or grooved barrels. The metal changed its shape gradually during the period in which it was in contact with the two rolls. Mohammad Eghtesad et al. (2016) studied of Friction and Rollers Wear in Hot Strip Mill of Mobarakeh Steel Company. One of the main factors affecting the production of a uniform sheet profile in hot strip milling process was the amount of friction in strip rolls. The roll friction was considered as one of the complex phenomena in hot strip mill process. In this research, the researcher intend to obtain a mathematical model to calculate friction profile of rollers of Mobarakeh steel company hot strip mill unit. Kristina Nordén 2016 The main aim of this research was the evolution and reduction of cracks during shape rolling. To accomplish this, artificial longitudinal cracks were machined along the bars of high speed steel. The cracks were positioned at different sites and were evenly distributed along the periphery at the intervals of 45°. Asit Kumar Choudhary et al. (2017)

reviewed the state of research on the chatter problem and classified the existing methods developed to predict the chatter where the objective was to avoid chatter occurrence during the rolling process in order to obtain better surface finish of the product, higher productivity and tool life, that passively or actively, will modify the system behaviour. A great deal of research had been performed on the chatter problem. However, at this moment, it was difficult to explain why a certain mill produces coils with and without chatters while working under same conditions. However, chatter phenomenon can be controlled if certain mill parameters like rolling speed, reduction, work roll bender, roll surface finish and lubrication are controlled properly.

3. Methodology

From study of various mathematical models a model was selected that has considered the chatter vibrations into account and has the following variables as input and output. The relation between these variables is taken in into account to develop a mathematical model Using FEM technique.Various input and output parameters are listed below which are shown in figure too in the symbolic form and here below their meaning along with their symbol is givem.

Input Parameters	**Output parameters**
• Strip entry and exit tensile stresses (σ_1 and σ_2) • Strip thickness at entry (h_1) • Roll horizontal movement (x_c) • Roll gap spacing (h_c) • Roll peripheral velocity (v_r)	• Rolling horizontal force (f_x) • rolling vertical force (f_y) • Rolling torque (M or tau)

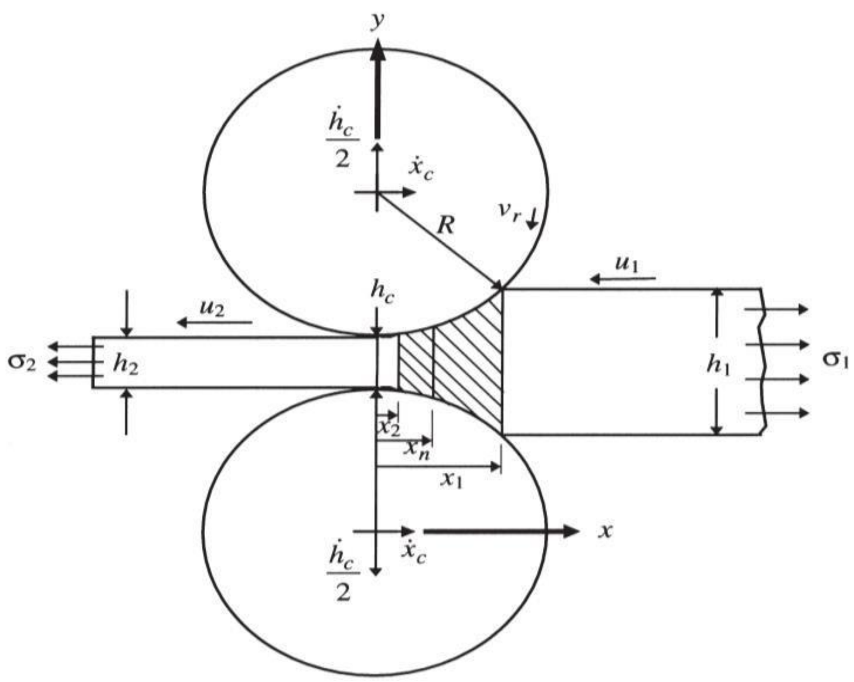


Figure 1. Rolling Process

$$f_x = \frac{\sigma_1}{2}(h_1 - h_2) - kh_2 \ln\frac{h_1}{h_2} - mkh_2\sqrt{\frac{R}{h}}\left[2\tan^{-1}\left(\frac{x_n - x_c}{\sqrt{Rh_c}}\right) - \tan^{-1}\left(\frac{x_1 - x_c}{\sqrt{Rh_c}}\right) - \tan^{-1}\left(\frac{x_2 - x_c}{\sqrt{Rh_c}}\right)\right]$$

$$f_y = (2k + \sigma_1)(x_1 - x_2) + 4k\sqrt{Rh_c}\,[\tan^{-1}(\frac{x_1 - x_c}{\sqrt{Rh_c}}) - \tan^{-1}(\frac{x_2 - x_c}{\sqrt{Rh_c}})] + 2\mathrm{mk}\sqrt{\frac{R}{h_c}}(x_2 - x_c)\,|2\tan^{-1}(\frac{x_n - x_c}{\sqrt{Rh_c}}) - \tan^{-1}(\frac{x_1 - x_c}{\sqrt{Rh_c}}) - \tan^{-1}(\frac{x_2 - x_c}{\sqrt{Rh_c}})| + mkR\,[ln\frac{h_1}{h_n} + ln\frac{h_2}{h_n}] + 2k(x_2 - x_c)ln\frac{h_1}{h_2}$$

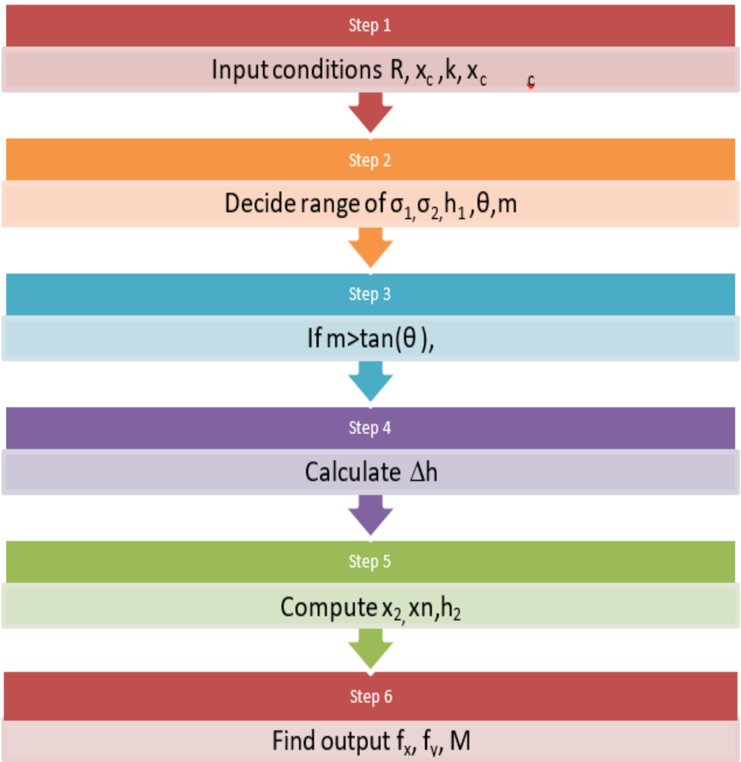
$$\mathrm{M} = \mathrm{mkR}^2\,[2\tan^{-1}(\frac{x_n - x_c}{\sqrt{R^2 - (x_n - x_c)^2}}) - \tan^{-1}(\frac{x_1 - x_c}{\sqrt{R^2 - (x_1 - x_c)^2}}) - [\tan^{-1}(\frac{x_2 - x_c}{\sqrt{R^2 - (x_2 - x_c)^2}})]$$

3.1 Input Parameters

- $u_1 = \frac{1}{h_1}[(v_r + \dot{x}_c)\,h_c + (v_r + \dot{x}_c)\frac{(x_n - x_w)^2}{R} + (x_1 - x_n)\dot{h}_c - h_1\,\dot{x}_c]$
- $u_2 = \frac{u_1 h_1 + (x_2 - x_1)\dot{h}_c + (h_1 - h_c - \frac{(x_2 - x_c)^2}{R})\dot{x}_c}{h_c + \frac{(x_2 - x_c)^2}{R}}$
- $x_1 = x_c + \sqrt{R(h_1 - h_c)}$
- $x_2 = x_c + \frac{Rh_c\dot{h}_c}{2[u_1 h_1 - (x_1 - x_c)\dot{h}_c + h_1\dot{x}_c]}$
- $\Delta h = m^2 R$
- $h_2 = h_1 - \Delta h$
- $x_n = x_c + \sqrt{Rh_c}\tan[\frac{1}{2}\tan^{-1}(\frac{x_1 - x_c}{\sqrt{Rh_c}}) + \frac{1}{2}\tan^{-1}(\frac{x_2 - x_c}{\sqrt{Rh_c}})| + \frac{\sqrt{h_c}}{2\mathrm{m}\sqrt{R}}(ln\frac{h_2}{h_1} - \frac{\sigma_2 - \sigma_1}{2k})$

where R is the radius of the work roll, k is the shear yield strength, m is the friction factor. Position of the entry plane (x_1), position of the exit plane (x_2), thickness at exit (h_2) and position of the neutral point (x_n) are required in the above equations.

3.2Development of mathematical model for force and torque.



Various Process Parameters

Sr. No	Parameters	Levels		
1	σ_1	50	75	100
2	σ_2	40	60	80
3	h_1	2	3.5	5
4	θ	3	3.5	4
5	m	0.05	0.07	0.09

where

- σ_1 - Strip entry tensile stress (in MPa)
- σ_2 - Strip exit tensile stress (in MPa)
- h_1 - Strip thickness at entry (in mm)
- θ - angle of bite (in degree)
- m – friction coefficient

3.3 Design of Experiments

After mathematical modelling of rolling process parameters as discussed in this chapter, a programme has been developed by using MATLAB. Further, for the validation of the developed programme, various set of experiments have been run and results have been verified. Therefore for the experimentation the set of experiments have been designed by using central composite design (CCD) technique of Response Surface Methodology (RSM).

Total 50 Experiments have been design according to CCD, then each experiments have been run on the MATLAB programme which is programmed by using various model. The design Matrix as shown in table as shown below.

3.4 Results and Discussions

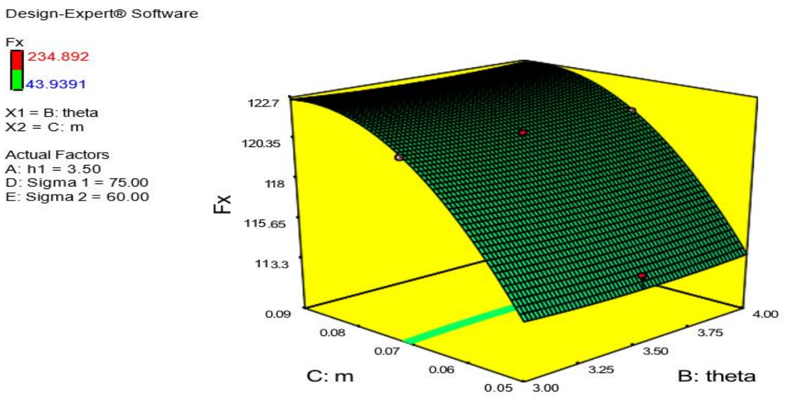
Results obtained from Mathematical model

Run	**A:h1**	**B:theta**	**C:m**	**D:Sigma 1**	**E:Sigma 2**	**Fx**	**Fy**	**Tau**
	Mm	(degree)		(MPa)	(Mpa)	(N)	(N)	Nmm
1	5	4	0.05	50	80	103.4955504	28189.47395	160105.6538
2	3.5	3.5	0.07	75	60	120.6592613	36943.18489	137049.6447
3	5	4	0.09	100	40	234.8917024	46807.17533	66482.81119

4	5	3	0.05	50	80	103.4955504	28344.25833	160105.6538
5	5	3	0.09	50	40	109.8917024	48489.74032	44807.77163
6	5	4	0.09	50	80	109.7203691	48247.19411	26909.74888
7	5	3	0.09	100	40	234.8917024	47089.73135	66482.81119
8	3.5	3.5	0.07	75	60	120.6592613	36943.18489	137049.6447
9	2	3	0.05	50	80	43.93909657	26674.59406	111314.4504
10	2	4	0.09	100	40	106.1487369	37265.768	38621.92429
11	3.5	3.5	0.07	75	60	120.6592613	36943.18489	137049.6447
12	2	4	0.09	100	80	106.12007	37225.73856	38822.45026
13	3.5	3	0.07	75	60	120.6592613	37052.79133	137049.6447
14	2	4	0.09	50	80	56.04840303	38525.70028	39081.55217
15	5	4	0.09	100	80	234.7203691	46847.18593	49201.12251
16	2	3	0.05	100	40	94.0224299	25834.57327	130507.2885
17	3.5	3.5	0.07	75	40	120.726928	36923.17941	143166.2703
18	5	3	0.09	100	80	234.7203691	47129.74195	49201.12251
19	5	4	0.09	50	40	109.8917024	48207.1843	44807.77163
20	5	3	0.09	50	80	109.7203691	48529.75013	26909.74888
21	5	4	0.05	100	40	228.7788837	27349.45179	229317.6638
22	3.5	3.5	0.07	75	60	120.6592613	36943.18489	137049.6447
23	5	3	0.05	100	80	228.4955504	27544.24364	197036.9777
24	2	3	0.09	100	80	106.12007	37244.18654	38822.45026
25	2	3	0.09	50	80	56.04840303	38544.14826	39081.55217
26	2	4	0.09	50	40	56.07706993	38565.72863	38873.51118
27	2	4	0.05	100	40	94.0224299	25726.25751	130507.2885
28	2	3	0.09	50	40	56.07706993	38584.1766	38873.51118
29	2	4	0.05	100	80	93.93909657	25766.26938	121790.8553
30	3.5	3.5	0.07	75	60	120.6592613	36943.18489	137049.6447
31	5	3.5	0.07	75	60	173.5492387	37092.271	1012684.14
32	5	3	0.05	100	40	228.7788837	27504.23617	229317.6638
33	3.5	3.5	0.07	75	60	120.6592613	36943.18489	137049.6447
34	3.5	3.5	0.05	75	60	114.0760494	27991.49409	-264178.915
35	3.5	3.5	0.07	75	60	120.6592613	36943.18489	137049.6447
36	2	3	0.05	100	80	93.93909657	25874.58515	121790.8553
37	5	3	0.05	50	40	103.7788837	28304.24593	189385.6161
38	2	3	0.09	100	40	106.1487369	37284.21598	38621.92429
39	2	3	0.05	50	40	44.0224299	26634.5835	119661.0825
40	3.5	3.5	0.07	75	60	120.6592613	36943.18489	137049.6447
41	5	4	0.05	100	80	228.4955504	27389.45925	197036.9777
42	3.5	3.5	0.07	100	60	164.4092613	36393.18014	144698.342
43	2	3.5	0.07	75	60	74.604037	32937.59388	936393.6744
44	3.5	3.5	0.07	75	80	120.5915947	36963.19019	130947.4272
45	5	4	0.05	50	40	103.7788837	28149.46155	189385.6161
46	3.5	3.5	0.09	75	60	121.3909651	48422.71956	3956298.146
47	3.5	4	0.07	75	60	120.6592613	36859.7846	137049.6447
48	2	4	0.05	50	80	43.93909657	26566.27829	111314.4504
49	3.5	3.5	0.07	50	60	76.90926133	37493.18925	129423.4639
50	2	4	0.05	50	40	44.0224299	26526.26773	119661.0825

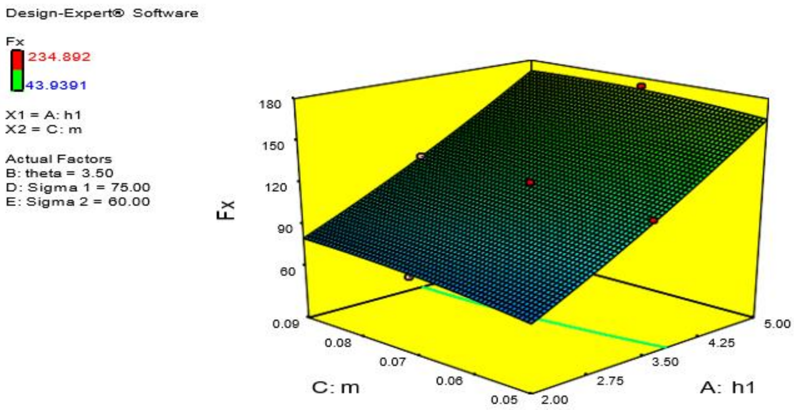
The Effects Of Process Parameters

To investigate the effects of the process parameters on cold rolling process interaction effects of two parameters are checked over the other two. The plots are constructed using the RSM technique.



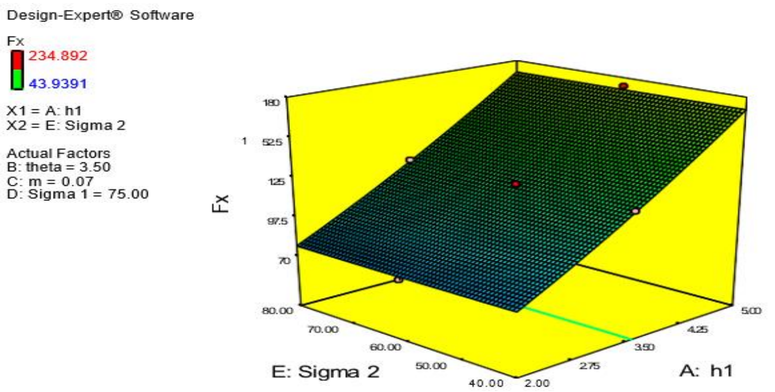
Variation of of f_x with m and θ

- The effects of friction coefficient and angle of bite are shown in the figure 4.1. The figure shows that the horizontal force per unit width increases with the increase in the friction coefficient and angle of bite has less influence on the horizontal force per unit width. This graph obtained from mathematical model shows the good agreement of the predicted results with experimental results.



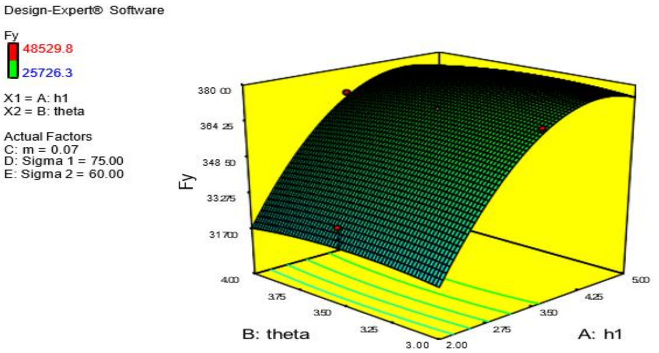
Variation of f_x with m and h_1

- The effects of friction coefficient and strip thickness at entry are shown in the figure 4.2. The figure shows that horizontal force per unit width increases with the increase in strip thickness at entry and friction coefficient. This graph obtained from mathematical model shows the good agreement of the predicted results with experimental results.



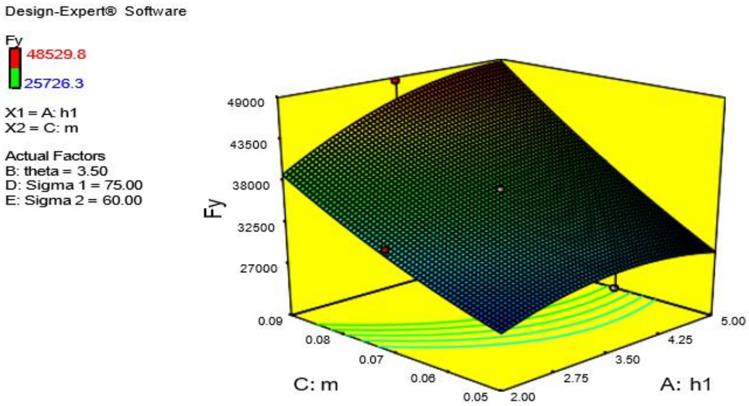
Variation of f_x with σ_2 and h_1

- The effects of friction coefficient and strip thickness at entry are shown in the figure 4.3. The figure shows that horizontal force per unit width increases with the increase in strip thickness at entry and strip exit stresses have minor effect over it. This graph obtained from mathematical model shows the good agreement of the predicted results with experimental results.



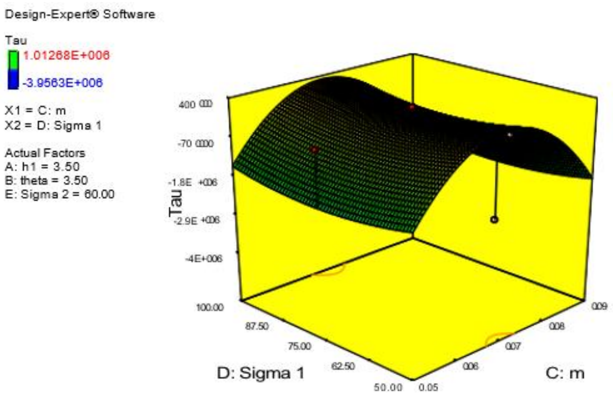
Variation of $f_y$with θ and h_1

- The effects of angle of bite and strip thickness at entry are shown in the figure 4.4. The figure shows that vertical force per unit width increases with the increase in strip thickness at entry and angle pf bite have minor effect over it. This graph obtained from mathematical model shows the good agreement of the predicted results with experimental results.



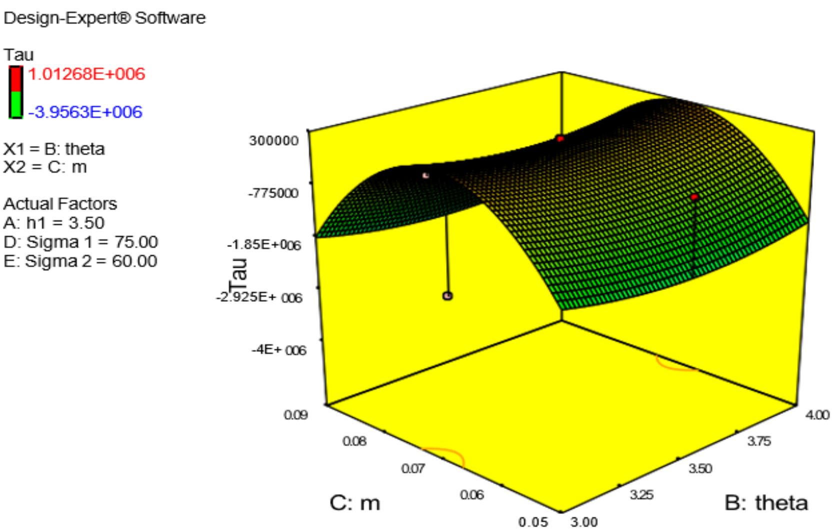
Variation of f_y with m and h_1

- The effects of friction coefficient and strip thickness at entry are shown in the figure 4.5. The figure shows that vertical force per unit width increases with the increase in strip thickness at entry and friction coefficient. This graph obtained from mathematical model shows the good agreement of the predicted results with experimental results.



Variation of M with σ_1 and m

- The effects of friction coefficient and strip entry tensile stress at entry are shown in the figure 4.6. The figure shows that torque acting per unit width increases with the friction coefficient for some particular value after that it decreases with increase in friction coefficient. In crease in Strip entry tensile stress leads to increase in torque . This graph obtained from mathematical model shows the good agreement of the predicted results with experimental results.



Variation of M with m and θ

- The effects of friction coefficient and angle of bite are shown in the figure 4.7. The figure shows that torque acting per unit width increases with the friction coefficient for some particular value after that it decreases with increase in friction coefficient. Increase in angle of bite leads to increase in torque .This graph obtained from mathematical model shows the good agreement of the predicted results with experimental results.

Optimisation of Response Parameters

This study of effect of the process parameters during cold rolling process finds these as optimisation results .For these values of various input parameters the best results can be obtained. The optimized results for the selected rolling parameters are shown in table 2 with desirability 1.

Optimized Results	
h_1	2.31 mm
θ	3.47°
m	0.08
σ_1	79.8 MPa
σ_2	74.82 MPa

Conclusions

In this study a mathematical model has been developed by considering the chatter vibration during rolling process and the model is programmed by using MATLAB. Further the rolling process parameters are being optimized using the response Surface methodology.

. From the study the following specific conclusions have been drawn.

- It has been observed that rolling vertical force is much higher than the rolling horizontal force.
- The study shows that forces are increases with increase in friction coefficient and strip thickness.
- Study reported that rolling torque is almost independent of strip entry tensile stress.
- The process parameters are optimized for the maximum desirability for effective stress and strain for the designed condition. The results are as:
- h1 =2.31mm, θ =3.37, m=0.08, σ1 =79.8MPa, σ2=74.82MPa,
- Study shows the good agreement of the results with industrial data of VIZAG STEEL.

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