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Computer Simulation of Hot Rolling of Flat Products

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Abstract: Hot rolling process of flat products is a complex process involving plastic deformation of steel, multi-mode heat transfer, microstructure evolution and elastic deformation of rolls and strips. Computer simulation of this process is essential for design modifications of mill hardware and optimization of process parameters to achieve desired product quality with minimum processing cost and minimum energy consumption. This paper describes combined use of two commercially available softwares for computers simulation of hot rolling process after necessary customization. DEFORM, a general purpose Finite Element Method (FEM)software, has been customized for simulation of roll-bite deformation; HSMM, a general purpose software for simulation of overall hot rolling process, has been customized for simulation of entire rolling process of a hot strip mill. The roll force predicted by DEFORM software has been validated with experimental rolling mill data before making simulations. Computer simulations have been carried out in DEFORM to study the effect of coefficient of friction and pass reduction on roll force. A typical HSMM simulation reveals that there is scope of reducing alloy consumption in steel composition by improving laminar cooling system hot strip mills.

Keywords: DEFORM, HSMM, Simulation, Rolling, Finite Element Method, FEM

1. Introduction

Rolling of flat rolled products of steel involves large number physical processes. High temperature plastic deformation occurs at roll bite. Radiation heat transfer takes place at roller tables, convection heat transfer takes place during water spray at descaler, scale washers and run-out-tables and conduction heat transfer takes place when heat is transferred from rolled material to rolls and rollers. Heat is also generated at roll bite due to plasticity and friction work during rolling. The problem of rolling becomes more complex due to microstructure evolution during rolling which include static, dynamic and metadynamic recrystallization and grain growth. All the above processes are interdependent and therefore, it is required that the rolling problem must be studied in integrated manner. Though efforts have been made by many institutions throughout the world for develop models using different approaches, yet very few process models are commercially available for simulation of flat rolling mills.

In this paper, methodology of computer simulation of flat rolling process has been discussed. DEFORM is a Finite Element Method (FEM) based software to simulated elasto-plastic deformation process under hot and cold condition. FEM is the most accurate method for analysis plastic deformation. The software has been developed by Scientific Forming Technology Centre (SFTC), USA. The software has been customized for simulation of roll-bite deformation of flat rolled products.

The other software which is used for simulation of entire flat rolling line is Hot Strip Mill Model (HSMM). Though the name indicates that it is useful for hot strip rolling, yet it can also be used to simulate plate rolling and steckel mill rolling. The entire mill line can be simulated with this software from furnace to coiler with customization at each stage. Department of Energy (DoE), USA and American Iron & Steel Institute (AISI) had jointly sponsored a project for development of microstructure based off-line model to achieve energy efficient optimization of flat rolling process. University of British Columbia (UBC) was the principal investigator in this project. Eleven steel companies of USA participated in this project, where the model had been validated. The software named as HSMM has been developed from this project and is being marketed by Integ Process Group, USA.

2. Literature Review

The objective of the literature review is to summarize the work of different researchers in the field of FEM analysis of hot rolling process. During 1970s, researchers like Rowe [1] started predicting roll force in plane strain condition using principle of virtual work. Before that period, FEM analysis was used for elastic deformation problems and was not tried to solve bulk plastic deformation problems like hot rolling. A method called matrix method was developed at that time to solve plastic deformation problems assuming deformed material as rigid-plastic, neglecting elastic component of deformation. The principle of virtual work and matrix method became backbone of FEM analysis of plastic deformation problems. These principles were incorporated into a software named ALPID [2] developed by Battle Memorial Lab, USA initiated by United Air Force. This software was capable of predicting stress, strain, strain rate, particle velocity and temperature at any location within a deforming material. The ALPID software was later commercialized in the brand name of DEFORM.

During earlier phases, standalone FEM programs were being developed to calculate plastic deformation and thermal effects during rolling process separately. Later attempts were made to couple both the processes. Hartley et al. [3] used an elastic-plastic finite element program (EPFEP3) to simulate rolling process. The program was predicting rolling load and the nature of flow of material in roll bite very accurately. Hacquin et al. [4] described a coupled model of thermo-elasto-viscoplastic strip deformation and thermo-elastic roll deformation based on 3D FEM. They compared the model with earlier approaches and found that the coupled FEM model as highly robust. Lin and Shen [5] developed a two-dimensional FEM program to analyze large deformation coupled thermal-elastic-plastic finite element theory. The results of the numerical simulation were verified with the experimental data of A1-Salehi and Schey and were found reasonably accurate. Fukumura et al. [6] used a dynamic explicit method (DEM) for calculation of rolling force by considering the roll bite deformation as a elastic-plastic zone rather than rigid-plastic zone. This method provided an accurate rolling analysis in a reasonable computational time. Hwu & Lenard [7] made a finite element analysis at roll bite. They predicted the effect of roll deformation & the variation of coefficient of friction on roll force.

In the early 1990s general purpose FEM based softwares were commercially available. Researchers tried to customize the softwares for different processes as per requirement. Many researchers tried to analyze rolling process using these softwares. Chandrashekar et al [8] carried out a finite element analysis for tandem mill rolling operation through DEFORM software which had been validated by comparing with the experimental results of load and tension. Dyja and Korczak [9] used FEM program ELROLL having coupled thermal, plastic deformation and microstructure evolution processes during hot rolling. The results of simulation were compared with results from the actual rolling process and found to be accurate. A thermal coupling analysis was carried out by Shangwu et al. [10] using full three-dimensional rigid-plastic finite element method to simulate vertical-horizontal rolling process during width reduction in the roughing stands of a hot strip mill. They found that slab shape, spread and temperature as calculated were in good agreement with the experimental data.

Though FEM analysis of rolling process is highly accurate, yet it is to slow to calculate rolling parameters for on-line applications. Researchers tried to develop methods to use FEM output for on-line applications through some other methods like Artificial Neural Network (ANN). Lin [11] developed an incremental updated Lagrangian elasto-plastic FEM to predict the rolling force during the rolling process. Simulations were carried out with variation of different parameters like die radius, rolling ratio etc. The FEM output was used to train a neural network model for on-line use. Yang et al. [12] used a FEM software MARC to predict roll force and torque during rolling process and validated results with experimental data and integrated with neural network model for on-line control. Wang et al [13] developed simulated rolling force, temperature and microstructure using FEM and found that these parameters were in good agreement with the measured results. Gudur and Dixit [14] combined FEM and ANN to develop a very fast FEM code which can be applied for on-line application. Deng at al. [15] simulated biting zone of the strip rolling by using large deformation thermo-mechanical coupled rigid-plastic finite element methods. The conditions in simulation were consistent with those in practical rolling processes. The simulated result was compared with the real process data and the results were found to be reliable. Serajzadehand Mahmoodkhani [16] predicted velocity field using upper bound method and temperature distribution in the strip using FEM method. The main advantage of the model is that the model requires relatively lower computational effort in comparison with the required one in standard finite element codes. Zhang et al [17] formulated a rigid plastic fast finite element code (RPFFEC) and tested the result with practical rolling parameters. They found that solution speed and accuracy of RPFFEC can meet the requirements of online control in strip rolling process. Shahani et al [18] simulated rolling process of aluminum alloy using FEM software ANSYS. Temperature, the stress, strain and strain rate were evaluated and validated. The outputs of the FE simulation of the problem are used for training a neural network which was employed for prediction of the behavior of the slab during the hot rolling process.

With recent improvement in computational capability of computers, high level research is going on to use FEM codes directly in online models. Mei et al. [19] developed FEM program to calculate temperature distribution in strip during hot rolling process. In this FEM program, a new heat generation rate model has been developed considering influence of source current density, work frequency, air gap and distance to edge on induction heating. They have simulated various heating conditions during hot rolling using the program. Chen et al. [20] developed a Finite element method (FEM) program to predict temperature by FEM and embedded it in the online rolling control system program. The computational time and precision are satisfied in the strip rolling process. Mei et al. [21] developed FEM program using NR (Newton–Raphson) method and BFGS (Broyden–Fletcher–Goldfarb–Shanno) quasi-Newton method to improve computational efficiency of FEM for solving rolling process problems. They have found that the program could meet the requirements of online application of FEM in the strip rolling process.

The literature review reveals that roll force and strip temperature can be predicted by FEM method with high accuracy. The drawback of the method is that computational time for solving FEM is very high making difficulty for its on-line applications like calculation of roll force and temperature for online mill setup models (level-2 models). However, there are methods to take the output of FEM models and use it for online applications. Training of ANN models with FEM output is one such method.

This paper describes the methodology of applying output of a FEM software (DEFORM) to simulate the complete rolling mill conditions in a computer simulation software (HSMM) to find out optimum mill schedules which can be used for online applications. The advantages of this method over FEM-ANN based method is that the internal strip temperature and stress are calculated in the HSMM software using faster finite difference method codes whereas these variables are not calculated in ANN models. As internal strip temperature and stress play major role in deformation process, neglecting these factors often leads to inaccuracy of prediction leading to over-limiting of mill constraints like allowable roll force, torque and power.

3. Methodology of Simulation

3.1. Simulation of Roll Bite Deformation Using DEFORM

DEFORM, like other FEM softwares, works in three stages: Pre-processing, Solution and Post-processing. In the preprocessing stage, input data including slab geometry, boundary conditions, loading conditions are entered in its Graphical User Interface (GUI). In the simulations described in the present paper, parameters of simulations were selected on the basis of hot rolling condition of Hot Strip Mill, Bokaro Steel Plant, and India. Type of simulations is selected as plane strain, mode of simulation is selected as combination of Heat Transfer and Deformation, ambient temperature is entered as 20 0C, and number of simulation time steps is selected as 100 with each time step representing 0.002 sec. The deformed material is selected as plastic, neglecting elastic deformations. The rolls have been assumed to be rigid. Number of meshing elements is taken as 1000 with auto-meshing option. Besides above parameters, other parameters selected for simulations are listed in Table-1 and Table-2. Table-1 shows simulation parameters selected to study the effect of coefficient of friction on roll force. Reduction is kept constant at 35% whereas the coefficient of friction varies from 0.25 to 0.70 covering the entire range of practical values of coefficient of friction during hot rolling process. Total number of simulation is 10 for different values of coefficient of friction. Table-2 shows simulation parameters selected to study the effect of reduction on roll force. The coefficient of friction has been kept constant at 0.3 whereas reduction varies from 15% to 30%. Total number of simulation is 4. Steel Grade is selected as AISI-1015 which is a low carbon grade of steel with about 0.15% Carbon in steel composition. Material properties data like flow stress of material at different strain, strain rate and temperature of this grade of steel is available is DEFORM material library database. Thermal properties like thermal conductivity at different temperatures are also available in this database. The simulation results have been discussed in results and discussion section of the paper.

Table 1. *Parameters for simulations to study the effect of coefficient of friction on roll force.*

Parameter	Values
Roll diameter	700 mm
Initial length of slab	500 mm
Initial thickness of slab	35 mm
Reduction	35 %
Rolling Speed	9 m/s
Coefficient of friction(μ)	0.25,0.30,0.35,0.40,0.45,0.50,0.55,0.60,0.65,0.70
Roll material type	Rigid
Roll temperature	50°C
Slab initial temperature	1000°C
Slab material type	Steel-AISI:1015

Table 2. *Parameters for simulations to study the effect of reduction on roll force.*

Parameter	Values
Roll diameter	700 mm
Initial length of slab	500 mm
Initial thickness of slab	35 mm
Reduction	15%,20%,25%,30%
Speed	9 m/s
Coefficient of friction(μ)	0.3
Roll material type	Rigid
Roll temperature	50°C
Slab initial temperature	1000°C
Slab material type	Steel-AISI:1015

3.2. Simulation of Overall Flat Rolling Mill Using HSMM

For simulating the hot rolling process in HSMM, the first thing required is customization of the software for a particular mill using the customization procedure described in HSMM manual [22]. Different elements of a mill like Reheating Furnace, Reversing Roughing Stands, Continuous Roughing Stands, Edgers, Descalers, Interstand cooling headers, Pyrometers, Flying Shears, Secondary Shears and Run-Out-Tables with different types of headers can be customized. In the present study, a particular case of Hot Strip Mill, Bokaro Steel Plant, India has been customized in HSMM.

The HSMM software has two modes of calculations. In the Single Node mode, it calculates parameters like roll force, torque, power, strip temperature and mechanical properties considering uniformity along strip thickness based on one-dimensional rolling theory. In the Multiple Node mode, internal stress, speed and temperature are calculated at different nodes along the strip thickness using Finite Difference Method (FDM) algorithm. Mill parameters like roll force, torque, power, strip temperature and mechanical properties are predicted from this FDM output. Single Node mode is for rapid calculation and verification of plant data whereas the Multiple Node mode is for detailed analysis and study. In the present work, the DEFORM outputs were compared with HSMM Multiple Mode outputs and mill schedules have been found out.

The flow stress of deformed material plays a major role in predicting roll force. In DEFORM software, there is a built-in database in which the measured values of flow stress for different grades of steel are available. In HSMM software, there is also a built-in database in which coefficients of flows stress equations of different grades of steel are available. It has also a facility to modify coefficients of standard flow stress equations using parameter estimation technique by minimizing error between measured and predicted roll force.

The objective of this simulation is to study the effect of change in cooling rate at run out table at different temperature on final properties of hot rolled coils. It is known that when the speed of the strip at roller table increases, the coiling temperature increases leading to decrease in cooling rate. At the same time, the time of cooling decreases resulting in increase of the cooling rate. It was very difficult to predict the range of speed for various steel grades and sizes where the cooling rate is maximum. Again at slow speed, the mill productivity is affected. Therefore, this simulation study has been conducted to find out windows of operating speed, where the desired mechanical properties can be obtained with maximum possible speed at run-out-table.

4. Results and Discussions

Before making simulations, the roll force predicted by DEFORM software was validated with experimental data obtained from rolling of steel samples at experimental rolling mill located at R&D Centre for Iron & Steel, Ranchi, India. The experimental roll force data was logged in a data acquisition system developed for the purpose.

Experiments were conducted with 5 steel samples at experimental rolling mill with varying reduction at different passes. Figure- 2 shows measured roll force and corresponding model predicted roll force for total 27 passes of experiment conducted on these 5 samples. The r-square value calculated for the correlation is found to be 0.91. This shows that there is very close agreement between predicted and measured values of roll force.

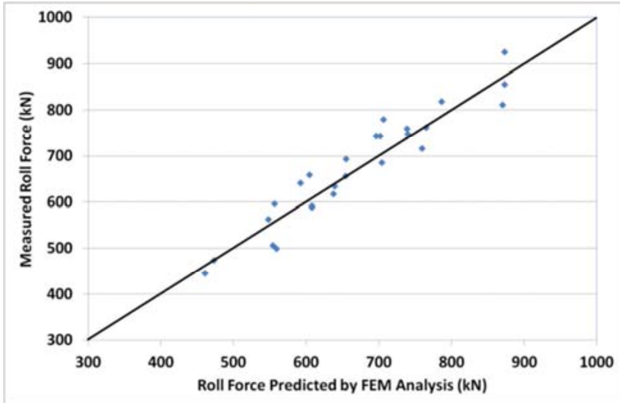

Figure 1. *Validation results of roll force predicted by DEFORM software.*

FEM predicted stress distribution at roll bite at different coefficient of friction and reduction are shown in Figure 2 and Figure-3. These figures show the stress distribution (in MPa) at a very low coefficient of friction 0.25 and a very high coefficient of friction at 0.7 respectively at a fixed pass reduction value of 30%. It can be seen from these two figures that increase in maximum stress at roll bite is very less. Maximum stress is 224 MPa when coefficient of friction is very low at 0.25 and 229 MPa when coefficient of friction is very high at 0.7. It can also be seen from the figures that exit end of the strip case is concave-shaped when coefficient of friction is 0.25 whereas it is convex-shaped when coefficient of friction is 0.7. The elements in the roll-strip contact area move slightly faster than the elements in the central area of deformation zone when the friction between roll and strip is less making the exit end of the strip convex-shaped. On the other hand, elements in the roll-strip contact area move slightly slower than the elements in the central area of deformation zone when the friction between roll and strip is more making the exit end of the strip concave-shaped. So, one can suggest whether friction is more or less just looking at the shape of exit-end of the rolled material. It is also found from the simulation that the area of distribution of maximum stress is much higher in case of 20% reduction in comparison to 10% reduction case. So, in the roll bite, a high stress of deformation can be generated at lower reduction, but its area is less.

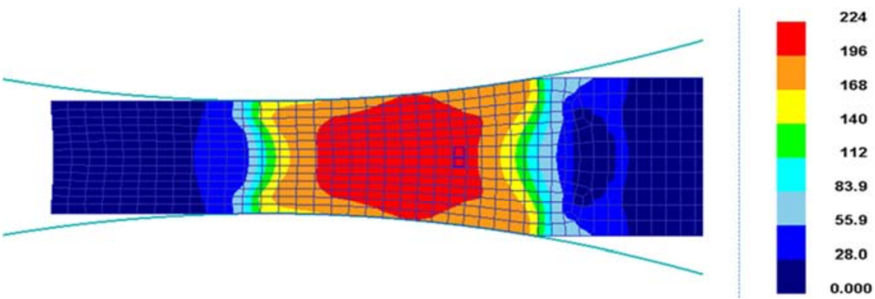

Figure 2. *Stress distribution with coefficient of friction = 0.25 and reduction = 30%.*

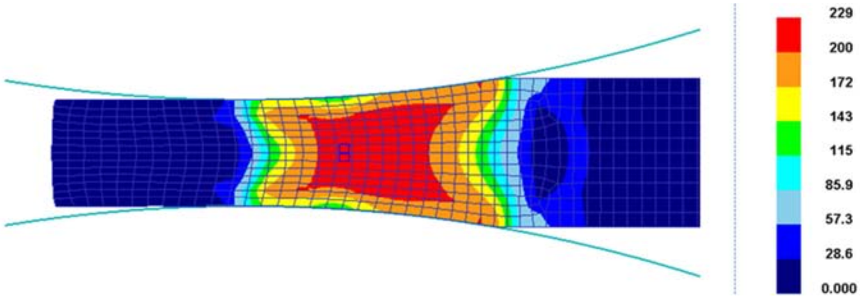

Figure 3. Stress distribution with coefficient of friction = 0.7 and reduction = 30%.

Figure 4 shows roll force per unit width of rolled material in a pass for different coefficient of friction. Roll force is about 27 kN/mm of width at coefficient of friction of 0.25. It is about 29kN/mm and 30.5 kN/mm at coefficient of friction of 0.5 and 0.7 respectively. It has been found that the rate of rise in roll force decreases with increase in coefficient of friction. But the roll force variation is decreased. Figure-5 shows that roll force increases with increase in reduction. It is about 13 KN/mm of width at reduction of 10%, 21.5 KN/mm at reduction of 20% and 27.5 KN/mm at reduction of 30%. The rate of increase in roll force reduces with increase in reduction.

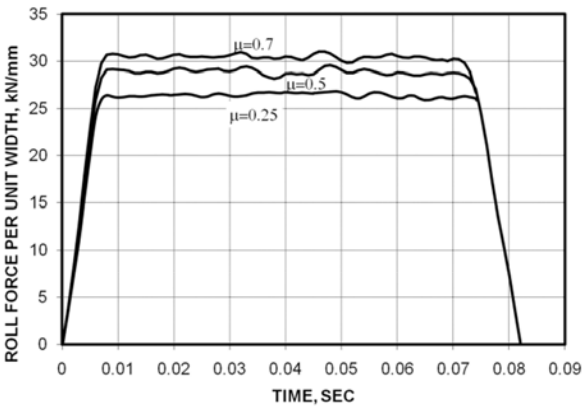

Figure 4. Roll Force in a pass different coefficient of friction at 30% reduction.

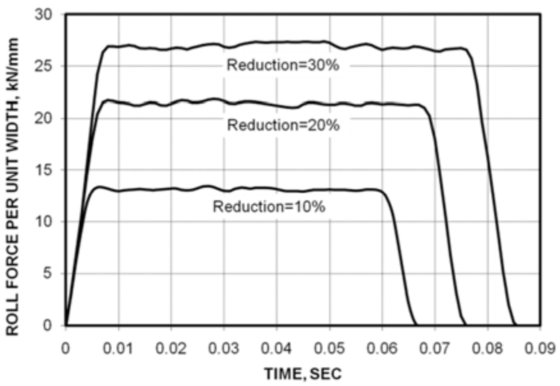

Figure 5. Roll Force in a pass for different reductions at coefficient of friction of 0.3.

Figure-6 shows average value of roll force at different coefficient of friction. Though roll force increases with increase in coefficient of friction, the absolute value of increase is very less. Increase in force is about 24% when coefficient of friction increases from 0.25 to 0.70. Figure-7 shows increase in roll force at different reductions. Increase in roll force is about 100% when reduction increases from 10% to 30%.

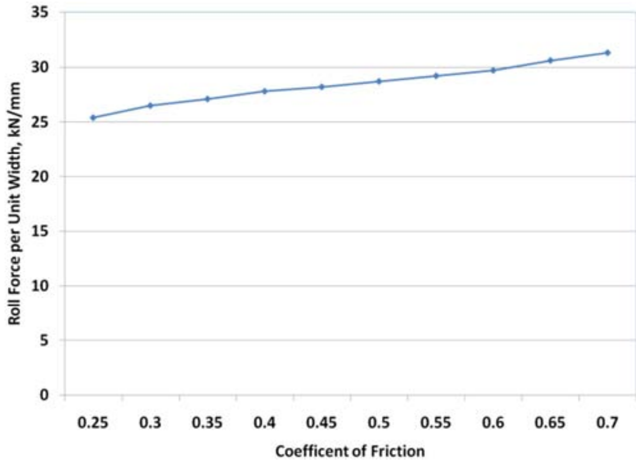

Figure 6. Average pass roll force at different coefficient of friction with 30% reduction.

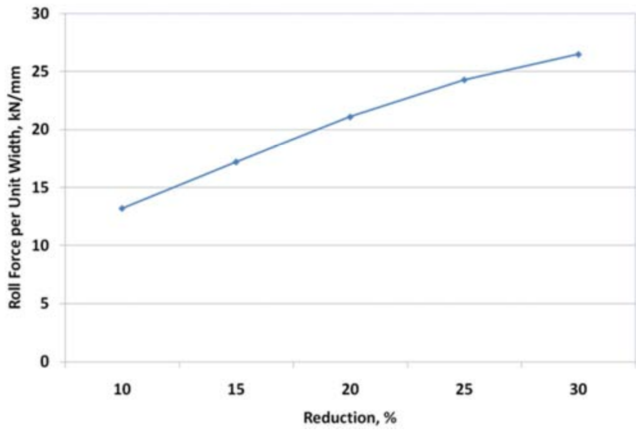

Figure 7. Average pass roll force at different reduction with coefficient of friction = 0.3.

On the other hand, HSMM simulation predicts the coiling temperature, cooling rate and mechanical properties in terms of YS, UTS and % elongation. One of the typical simulation results has been shown in Figure-8. This figure shows that when ROT speed increases, YS decreases initially, then increases and then further decreases after a particular speed range. There exists a speed range where the desired mechanical properties can be achieved with higher mill productivity. The figure shows that recommended speed for the particular grade and size of HR coil is 8 m/s.

Further HSMM simulations reveals that same mechanical properties can be achieved by reducing 0.05% of Manganese level in steel composition and restoring the first laminar cooling bank of the mill, which is not in operation for some time. If the cooling bank is operated, coiling temperature can be decreased by 15°C by redistributing same quantity of total water flow in the laminar cooling. It has also been found that same mechanical properties can be achieved by reducing 0.1% of Manganese level in steel composition and by increasing water flow of laminar cooling from existing level of 6000 m^3/hr to the designed level of 8840 m^3/hr. Coiling temperature can be decrease by 25°C in this case thereby reducing the alloy consumption.

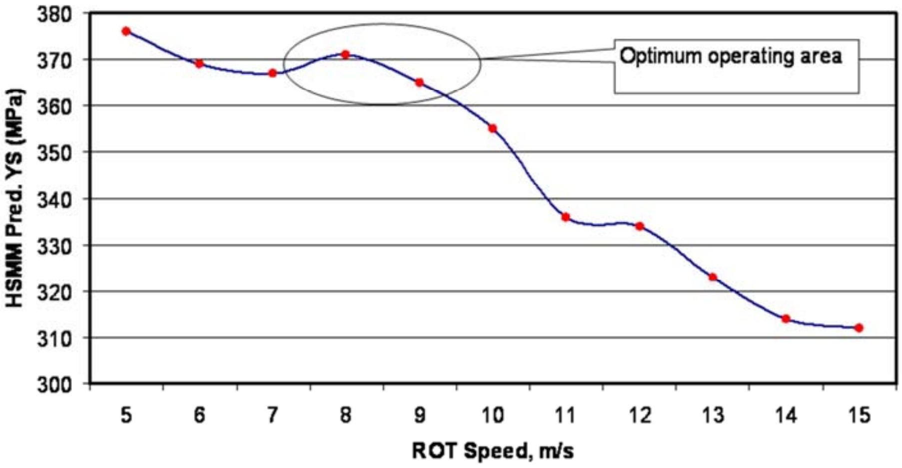

Figure 8. *Effect of rolling speed on Yield Stress obtained from HSMM simulation.*

5. Conclusion

Following conclusions can be concluded from above results and discussions:

- This paper demonstrates methodology of roll bite deformation analysis of hot rolling process using FEM based software DEFORM. It also demonstrates overall rolling mill simulation using customized HSMM software.
- The roll force predicted by DEFORM software has been validated with experimental rolling mill data before making simulations. There is a good agreement between the predicted and measured roll force with r-square value of 0.91.
- From the typical DEFORM simulation it has been found that increase in roll force with increase in coefficient of friction is not very high during hot rolling of steel. It is about 24% when coefficient of friction increases from 0.25 to 0.70. Roll force nearly doubles when pass reduction increases from 10% to 30%.
- It has been found from a typical HSMM simulation that there is a scope of reducing alloy consumption in steel composition of the hot rolled products as it is possible to obtain the desired mechanical properties by improving the laminar cooling system hot strip mills either by addition of additional banks or by increasing quantity of water flow.

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