Roll separating force in hot rolling under grooved rolls – A finite element analysis and experimental validation

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Finite element modeling and simulation of hot rolling under grooved roll has been carried out using commercial finite element based software ABAQUS® to compute roll separating force at rolling stand # 3 of Wire Rod Mill, TATA Steel Ltd. Online measurement of rolling load has been carried out using load cell for validation of simulation results. Other than experimental validation, simulated results are compared with published empirical relations. It has been found that at elevated temperature, rolling load decreases with increasing carbon content in plain carbon-manganese steel.

Keywords: Roll separating force, Finite element analysis, Hot rolling, Grooved roll

Wire Rod Mill (WRM) at TATA Steel-Jamshedpur (India) plant produces wire rod and ribbed bar of sizes Ø (5.5 to 12) mm from billet of cross-section 130×130 mm². There are 25 rolling stands, out of which, 7 are roughing stands, 6 are intermediate stands, 2 are pre-finishing stands and rest are finishing stands. During rolling as deformation takes place, work roll experiences a force, equal and opposite to the deformation resistance of work-piece material. The vertical component of this force is known as roll separating force (RSF), which tries to put the work rolls apart. Out of all rolling stands, rolling stand # 3 is more prone to roll barrel and bearing failure due to excessive rolling load. Therefore, qualitative estimation of RSF will help in considering corrective actions to avoid failure of this nature in future.

Research has been carried out in the areas of rod and bar rolling to compute RSF based on fundamental theory of flat rolling. Sims formula¹ for flat rolling is used in commercial roll pass design software, WICON®,² to compute RSF and rolling torque for rolling simulation. Lee and Kim³ developed a semi analytical method to predict RSF in rod and bar rolling based on weak plane strain formulation of actual 3-D rolling under grooved rolls. The basic assumption in these empirical relations is the approximation of incoming and outgoing work-piece cross-sections by equivalent rectangles under groove-less (flat) roll of effective diameter. Raghab and Samy⁴ suggested a simplified analytical model to estimate roll separating force in bar rolling based on descriptive geometric approach for evaluation of contact area between work roll and deforming work-piece. The roll separating force in their work is the product of contact area, mean unit pressure on the work roll and the flow stress within the roll gap. Abrina and Fazlirad⁵ proposed an analytical method based on generalized upper bound approach to predict rolling pressure, torque and cross-sectional shape of the outgoing work-piece in case of shape rolling. The parametric formulation in their work yields results in shape rolling much faster compared to numerical techniques such as finite element method (FEM) which requires lots of changes to be incorporated at pre-processing level for comparative analysis.

Besides, analytical work, researchers used experimental methods and computational techniques for detailed understanding of rod and bar rolling process. Said et al.⁶, in their experimental work, mentioned the importance of modeling and simulation based on FEM with an appropriate understanding of friction and heat transfer for more accurate prediction of RSF, compared to empirical relations. Kim and Im⁷ carried out a three-dimensional finite element study of shape rolling based on rigid thermo-viscoplastic approach and found the effect of friction is more significant compared to heat transfer on RSF.

The present work consists of modeling and simulation of hot rolling at rolling stand # 3 of WRM to compute RSF, using commercial finite element based software ABAQUS® and subsequent experimental
validation of the same. Besides, computation of RSF, other objective of this work is to establish a simplified finite element based model for simulation of rolling process under grooved rolls to estimate the effect of various process parameters on rolling outcome.

Modeling and Simulation

The hot rolling process is thermo-mechanically coupled, where, other than mechanical deformation under grooved rolls, there exists, heat generation due to plastic deformation as well as frictional work and heat loss due to convection and radiation. Besides, there is heat transfer from work-piece to work roll through contact conductance. Therefore, the temperature of the work-piece does not remain constant but varies during the process of deformation. Variation of work-piece temperature causes variation in material properties. In the present work, modeling has been simplified by approximating the rolling process under isothermal condition, where temperature of deforming work-piece is considered uniform and equal to the average rolling temperature at roughing stand # 3.

The 3-D part modeling of work roll and work-piece are carried out in ABAQUS/CAE® based on dimensional details, mentioned in Fig. 1. For simplicity of computation, the work roll has been modeled as analytical rigid body and work-piece as deformable one. Simulation has been carried out with two different grades of steel as work-piece material. These are carbon-manganese steel and their chemical compositions are mentioned in Table 1. The elastic properties of the rolled material are derived considering Eqs (1) and (2) based on Ancas and Gorbanescu.8

\[
E = 1.0 + \frac{T}{E_{20}} \ln \left( \frac{T}{1100} \right) \quad \text{for} \quad 20°C < T \leq 600°C
\]

\[
= \frac{690 - 0.69T}{T - 53.5} \quad \text{for} \quad 600°C < T \leq 1000°C \quad \ldots (1)
\]

\[
\nu = 3.78 \times 10^{-5}T + 0.283 \quad \text{for} \quad 0 \leq T \leq 450°C
\]

\[
\nu = 9.2 \times 10^{-5}T + 0.259 \quad \text{for} \quad T > 450°C \quad \ldots (2)
\]

Where, \( T \) is temperature of rolled material (°C), \( E \) is Young's modulus at temperature \( T \), \( E_{20} = \) Young's modulus at 20°C and \( \nu \) is Poisson’s ratio at temperature \( T \).

The flow characteristic or plastic behavior of the rolled material is considered based on Shida’s constitutive model9 which is widely applicable in the following range of carbon content, true strain, strain rate and temperature: (i) carbon contents: < 1.2%, (ii) true strain: < 70%, (iii) strain rate: 0.1-100 S\(^{-1}\) and (iv) temperature: 700 - 1200°C.

According to this model, flow stress \( (\sigma_f) \) of steel is a function of percentage weight of equivalent carbon content \( (C_{eq}) \), material temperature \( (T) \), true strain \( (\varepsilon) \), and strain rate \( (\dot{\varepsilon}) \). It is expressed as a product of deformation resistance function \( [\sigma_d(C_{eq}T)] \), strain hardening function \( [f(\varepsilon)] \) and strain rate hardening function \( [\dot{f}(\dot{\varepsilon})] \) and is described in Eqs (3)-(7). The percentage weight of equivalent carbon content in steel is derived considering Eq. (8) from Lenard et al.10

\[
\sigma_f = \sigma_d(C_{eq}T_n)f(\varepsilon)f(\dot{\varepsilon}) \text{ kg/mm}^2 \quad \ldots (3)
\]

Where,

\[
\sigma_d = 0.28 \exp \left( \frac{5.0}{T_n} - \frac{0.01}{C_{eq} + 0.05} \right) \quad \text{for} \quad T_n \geq T_P
\]

\[
= 0.28 g(C_{eq}T_n) \exp \left( \frac{C_{eq} + 0.32}{0.19(C_{eq} + 0.41)} - \frac{0.01}{C_{eq} + 0.05} \right)
\]

for \( T_n < T_P \) \ldots (4)

\[
g(C_{eq}T_n) = 30(C_{eq} + 0.9) \left( T_n - 0.95 \frac{C_{eq} + 0.49}{C_{eq} + 0.42} \right)^2 + \frac{C_{eq} + 0.06}{C_{eq} + 0.09}
\]

\ldots (5)

Table 1 – Chemical composition (in % weight)

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
<th>Si</th>
<th>Ni</th>
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<tbody>
<tr>
<td>Grade-1</td>
<td>0.07</td>
<td>1.43</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.84</td>
<td>0.02</td>
</tr>
<tr>
<td>Grade-2</td>
<td>0.58</td>
<td>0.68</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.16</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Fig. 1 – Geometry details of work roll and work-piece at stand # 3 (in mm)
\[ f(\varepsilon) = 1.3 \left( \frac{\varepsilon}{0.2} \right)^n - 0.3 \left( \frac{\varepsilon}{0.2} \right) \]  \quad \ldots (6)

\[ f(\dot{\varepsilon}) = \left( \frac{\dot{\varepsilon}}{10} \right)^n \]  \quad \ldots (7)

Further,

\[ T_n = \frac{T + 273}{1000} \]

\[ T_p = 0.95 \frac{C_{eq} + 0.41}{C_{eq} + 0.32} \]

\[ n = 0.41 - 0.07C_{eq} \]

\[ m = (-0.019C_{eq} + 0.126)T_n + (0.075C_{eq} - 0.05) \] for \( T_n \geq T_p \)

\[ m = (0.081C_{eq} - 0.154)T_n + (-0.019C_{eq} + 0.207) + \frac{0.027}{C_{eq} + 0.32} \] for \( T_n < T_p \)

Besides, material specification, it is important to specify appropriate boundary conditions and contact interactions between work roll and work-piece for complete modeling of the process. The assembled condition of the work rolls and work-piece with necessary boundary conditions is shown in Fig. 2. All degrees of freedom are restricted for work rolls, except rotation about x-axis. The work-piece is moving towards work roll with an initial velocity, similar to the exit velocity of previous stand in the mill. Contact between the work roll and the work-piece is established based on general contact algorithm available in ABAQUS®. The friction coefficient (\( \mu \)) required for contact interaction is derived considering Eq. (9) for cast iron rolls, based on Ekelund's empirical relation\(^1\). Process data related to angular velocity of the work roll (\( \omega \)), initial speed of the entry work-piece (\( V_{in} \)) and rolling temperature (\( T \)), require for simulation are mentioned in Table 2. These data are considered from mill during rolling of grades mentioned in Table 1.

\[ \mu = 1.05 - 0.0005T \]  \quad \ldots (9)

Where \( T \) is temperature of rolled material (°C).

The work-piece is meshed using 3-D continuum 8 node brick element (C3D8R). Simulation has been carried out using ABAQUS®-explicit solver. Computation time has been reduced using mass scaling algorithm with a scaling factor of 250, without compromising the solution accuracy. As shown in Fig. 2, the front end of the work-piece has a revolving cut face. This is to avoid excessive element distortion during computation due to high angle of bite (\( \beta = 40^\circ \)) at rolling stand # 3.

### Experimental Measurement

In absence of any lab scale experimental set-up, an online measurement facility has been introduced in stand # 3 for measuring rolling load. This involves incorporation of load cell at a location in stand housing, where the effect of RSF can be sensed properly. The appropriate location for this is to place the load cell in between bearing chock and screw down of top roll as shown schematically in Fig. 3. During rolling, RSF gradually increases as biting progresses and reaches to a maximum value when complete biting takes place. The RSF on work roll is simultaneously experienced by both side bearings mounted on the roll barrel in a proportion to the location of active pass with respect to the center distance between bearings. In case of bottom roll the RSF is transferred to the foundation directly, via bearing chock. The top roll is placed on bottom roll through four locating pins with metal cushion in between. The RSF on top roll is transferred to the foundation via bearing chock and screw down mechanism. Therefore, the load cell which is placed...
in between screw down and bearing chock at work side of rolling stand # 3 will experience an amount of compressive force, equal to the bearing load at that location and is displayed as load cell output. The magnitude of RSF is then calculated from load cell output based on lever rule as mentioned in Fig. 3.

The size of the load cell depends upon its capacity. Higher is the capacity, higher will be the size of it. Therefore, it is necessary to specify the load cell capacity as well as its dimensions, accurately for easy installation. While, the capacity of the load cell is specified based on computed value of RSF with additional factor of safety, the dimension of it, is specified based on the space available between bearing chock and screw down. The actual set up for online measurement of RSF at stand # 3 of WRM as well as the load cell being used in this experiment is shown in Fig. 4.

**Empirical Relations**

Other than experimental validation, simulated results for RSF are compared with analytical predictions based on empirical formulae by Shims\(^1\) and Lee and Kim\(^3\) respectively. Sims formula to calculate RSF in hot rolling under plane strain condition is shown in Eq. (10). In this equation \(k\), is the shear yield strength of deforming work-piece material, \(L_\text{e} \), \(W_{\text{mean}}\), \(Q_p\) are respectively, effective projected contact length between work roll and work-piece, mean width of work-piece in roll bite zone and a multiplier which itself is a function of neutral angle, roll effective diameter and heights of work-piece before and after rolling. In using Sims formula for present analysis, the shape of incoming and outgoing work-pieces are approximated by equivalent rectangles\(^{12}\) based on width of the rolled material and work roll as groove less roll of effective diameter as shown in Fig. 5. Further, in

![Fig. 3 – Schematic diagram of load cell arrangement at stand # 3 of WRM](image)

![Fig. 4 – Online measurement of RSF at rolling stand # 3 of WRM](image)

![Fig. 5 – Equivalent rectangle-representation of incoming and outgoing work-piece](image)
approximating equivalent rectangle for outgoing work-piece the width of it, is predicted based on maximum spread formula by Shinokura and Takai. The empirical relation for RSF prediction in rod rolling based on Lee is shown in Eq. (11). Lee has developed this formula based on weak plane strain assumption of rod rolling under grooved roll. In this formula, $\varepsilon_s$ is strain in lateral direction, $k_m$ is average flow stress of work-piece material, $H_m$ being the mean height of work-piece in roll bite zone, $A_p$ is projected area of contact between work roll and work-piece and $\mu$ is friction coefficient.

\[
RSF = 2k_L\varepsilon_s Q W_{mean} \quad \ldots (10)
\]

\[
RSF = (1 - \varepsilon_s)k_m \exp\left(\frac{L_e \mu}{H_m}\right)A_p \quad \ldots (11)
\]

**Results and Discussion**

Mesh sensitivity analysis has been carried out with mesh size varying from ~ (750-75000) elements to identify the appropriate number of elements required for simulation to carry out. The variation of computed value of RSF and corresponding computation time with respect to number of elements is shown in Fig. 6. Clearly, the variation of RSF is not significant even with a coarser mesh of 762 elements. Contrary to that, the computation time by an Intel® i7 processor with 1.73 GHz speed, significantly increases from few minutes to several hours for the above range of mesh density. Further, it is also required to have an appropriate mesh refinement in order to map the geometry of the work-piece with reasonable accuracy. Considering all these aspects, simulation has been carried out with a mesh size of 11,700 elements.

A typical state of deformed work-piece with Mises stress contour and computed value of RSF are shown respectively in Fig.7 (a) and (b). Comparison of RSF values, obtained from simulation, analytical formulae and experimental measurement is given in Table 3. Clearly, analytical formulae predicts RSF value close to measured one but on underside, whereas simulation over predicts by an amount ~ 20%. Therefore, considering simulated results for design of roll barrel.

![Fig. 6 – RSF and computation time vs mesh density](image1)

![Fig. 7 (a) – Stress contour of deforming work-piece (Grade-1) and (b) simulated results for RSF](image2)

<table>
<thead>
<tr>
<th>Material</th>
<th>Simulation</th>
<th>Sim$^a$</th>
<th>Lee &amp; Kim$^b$</th>
<th>Experimental</th>
<th>Simulation</th>
<th>Sim$^a$</th>
<th>Lee &amp; Kim$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade-1</td>
<td>904.1</td>
<td>735.2</td>
<td>708.8</td>
<td>746.4</td>
<td>21.1</td>
<td>-1.5</td>
<td>-5.0</td>
</tr>
<tr>
<td>Grade-2</td>
<td>822.0</td>
<td>641.5</td>
<td>616.2</td>
<td>688</td>
<td>19.5</td>
<td>-6.8</td>
<td>-10.4</td>
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</table>
and associated accessories are more conservative from operation point of view. Further, the value of RSF in case of Grade-2, having higher carbon content is less compared to Grade-1 by an amount of \(\sim (60-90) \text{ kN} \), even though the difference in rolling temperature between them is only 9\(^\circ\)C. This is due to decrease in flow strength of Grade-2 material as compared to Grade-1 at corresponding rolling temperature (ref. to Fig. 8). This decrease in flow strength of plain carbon steel with increasing carbon content is explained by Wray\(^{14}\) which says, if deformation occurs in the temperature range of 850 -1300\(^\circ\)C, the work hardening decreases with increasing carbon content due to enhanced dynamic recovery. The decrease in work hardening, decreases flow strength of plain carbon steel. Further, simulated results for exit velocity and spread of the work-piece are compared with actual mill data and are shown in Table 4 with good agreement.

### Conclusions

The following conclusions can be drawn from this study:

(i) A simplified finite element model has been developed in ABAQUS\(^9\) to compute RSF in hot rolling under grooved rolls.  

(ii) Simulation over predicts RSF as compared to empirical relations, more conservative for design of roll barrel and other accessories.  

(iii) At elevated temperature of \(\sim 975\)\(^\circ\)C, the value of RSF decreases with increasing carbon content in plain carbon-manganese steel due to corresponding reduction in flow strength.  

(iv) The present simulation technique is a useful in optimizing various process parameters in hot rolling which is useful for enhancement of product quality and equipment health.

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<table>
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<th>Material</th>
<th>Exit velocity (m/s)</th>
<th>Spread (mm)</th>
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<td></td>
<td>Simulation</td>
<td>Mill data</td>
</tr>
<tr>
<td>Grade-1</td>
<td>0.347</td>
<td>0.329</td>
</tr>
<tr>
<td>Grade-2</td>
<td>0.351</td>
<td>0.333</td>
</tr>
</tbody>
</table>

Fig. 8 – Flow curve derived from Shida’s model\(^9\)
References
2 Handemark M, Improved roll pass design for long products with WICON Rolling Library, (Millennium Steel India), 2010.