Three-dimensional simulation of a single pass hot rolling of carbon steel: Case of instabilities in steady state region

V Musonda[1, 2 a]*, and ET Akinlabi[1]

[1]Department of Mechanical Engineering Science, University of Johannesburg, Auckland Park Kingsway Campus, P.O. Box 524, Johannesburg, South Africa, 2006.

[2]Department of Mechanical Engineering, School of Engineering, The University of Zambia, Great East Road Campus, P.O. Box 32379, Lusaka , Zambia.

E-mail: [a]∗musondachandi@gmail.com

Abstract. The nature of instabilities in the steady-state region in the form of high amplitudes or peaks during hot rolling can be an indication of the problems in the roll mill stand. The aim of this study is to predict the variation in load, stress, strain, torque and power and the influence these parameters can have during the deformation of the workpiece in the roll gap. To achieve this aim, finite element modelling (FEM) was used in the simulation of a single pass hot rolling of AISI 1016 carbon steel. The results indicate that, large amplitudes in the stresses, strains and torque variations can result in vibrations in the mill stands compared to the steady state point values. This can also result in inhomogeneity in the microstructural properties of the rolled workpiece. Inaccuracies in the geometry of the rolled products too may arise. Elastic deformation occurred during the critical strain (ε_c)until the peak strain(ε_p) was reached after which steady state rolling (plastic deformation) commenced. Inhomogeneity in the rolled product also occurred during the reduction of the workpiece and this can lead to mill breakdowns. The results obtained are in agreement with the existing literature. Suggestions regarding improvement to the mills to optimise the process are also presented**.**

1. Introduction

The market in steel industry is currently setting up dimensional bench marks of the required tolerances for the thickness distribution along the workpiece or strip length and profile [1]. So for those in hot rolling, there is need to consider setting up some parameters correctly before starting the rolling process. It is important for example to control the roller speeds, roller diameter and select appropriate interface heat transfer coefficient (IHTC). The deformation stress in the workpiece is controlled by the temperature and IHTC is the parameter responsible for this control. This parameter is important in the prediction of FEM solution as it minimises the anticipated errors in the simulation. Information such as roll separating force (RSF), the appropriate torque and power to run the mills are critical for optimization purposes. Their time history and how they vary during the rolling process can provide insight into the causes of these deviations and hence useful for developing and optimizing pass schedules [1]. There has been extensive research work in the modelling and prediction of roll force and torque using various methods. Some of these methods are typically based on thermo-mechanical theory designed to establish how the rolling force, rolling torque, and how the power used relates to parameters such as the diameter of the work roll, the rolling speed, and the initial temperature of the workpiece. Other parameters of concern include, the thickness of the strip, reduction ratio and the number of passes [2, 3, 4]. In their study, Arif *et al*. [5], evaluated the distribution of pressure and the

and friction stress in the workpiece during hot rolling. The authors [5] extended their investigation to Von Mises stress inside the roll by considering different radii. Yang *et al* [6] also reported that, Duan and Sheppard [7] used FORGE 3 software to simulate and predict the contact pressure distribution and equivalent strain history. The authors [6] further noted that, Serajzadeh *et al* [8] examined different positions in the zone of deformation and predicted the distribution of strain in the rolled metal. The authors [8] considered various process parameters and their effects during hot rolling process. These included the initial strip temperature, rolling speed and the lubrication on the strain. Rigid-viscoplastic FEM was used in their analysis. Other co-workers [9, 10, 11, 12] assessed different stress distributions, which included shear stresses, distribution of pressure, thermal stresses, edge and horizontal stresses.

2. Finite element model

The finite element model includes: the workpiece, the work roll and the pusher. Due to symmetry only a quarter of the workpiece was analysed. The mesh for the workpiece is brick type with 12528 elements. The work roll material is AISI-D3 with tetrahedral mesh, 7776 elements and 9432 nodes. All the three models are shown in Figure 1. The assumption of plane-strain deformation conditions in the direction transverse to the rolling direction was considered. The rolling speed was 4.8 m/s and forces of inertia during rolling were neglected. To save on computational time, the workpiece was 250 mm long and 32 mm diameter. The work rolls' outer diameter was 1000 mm. The position of the workpiece in Figure 1, shows the initial contact with the work roll at entry during the 30% reduction of the workpiece in the roughing mill stands. A detailed view of the contact at (1) is also shown alongside the model. Coulomb friction was used in the model and the friction coefficient taken as 0.7. Heat transfer coefficient (HTC) was $5KW/m^2K$. The strain rate range was $1.5s^{-1}$ to $100s^{-1}$ for strain values ranging from 0 to 0.7. The temperature range was 898℃ to 1198℃. The type of simulation used in DEFORM 3D, was Lagrangian incremental formulation. Other thermophysical properties were obtained from DEFORM database [13].
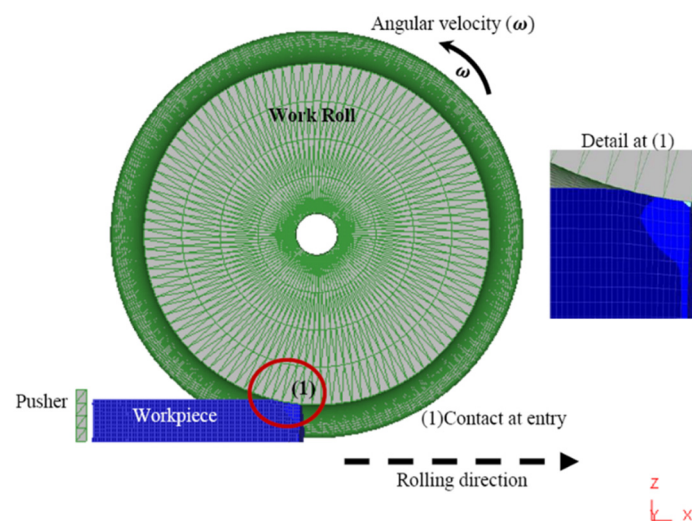

Figure 1: Quarter symmetry of workpiece-roll model at entry into the roll gap.

3. Results and discussion

3.1. Torque variation with time

The plot in Figure 2, shows that, as the rolling force increases gradually during workpiece entry into the roll gap, there is a point where the peaks change from high to low after which the rolling reaches the steady state. The contact length between the roll and the workpiece is small during the initial contact. Therefore, the friction force resisting the flow in the rolling gap varies between adhesion and slip hence the fluctuation in the peaks. Moreover, in hot rolling, friction forces are very high with rolls

that are not lubricated. The frequency of the peaks in steady state region is moderate in this plot. The highest torque value reached was 1.02e+08 N-mm.
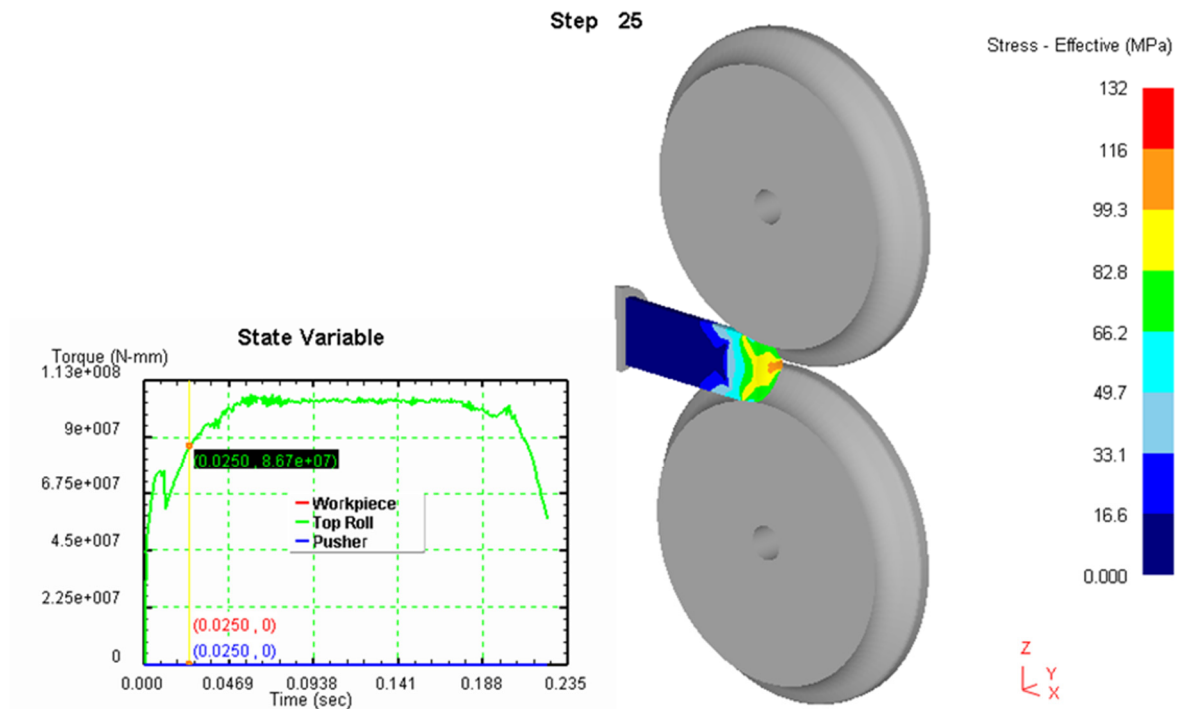

Figure 2.   Rolling torque variation with time during entry into roll gap.

3.2. Power variation with time

Calculation of energy requirements is the most important component for a hot rolling mill. The mill which is underpowered will stall and lead to loss of productivity [1]. So the motor to drive the mill must be sufficient. The plot in figure 3, shows the power variation with time. The frequency of the peaks is similar to that of the torque (figure 2). The maximum power, attained on average during steady state was 5.85 N/mm/sec after which there was no contact between the rollers and the workpiece as demonstrated by the drop in the graph from step 200 in Figure 3.

3.3. Strain rate effective with time

The entry of the workpiece into the roll gap was initially hard as expected- because of the frictional resistance arising from further reduction in the material. This is also the oscillation stage where the dislocation density in the deformed workpiece rises. However, once in the roll gap, the rolling is steady state as shown in Figure 4(a). The steady state region in Figure 4(a) is a stage where there is equilibrium between the dislocations created and annihilated. This region in Figure 4(a), however, shows that plastic deformation is not homogenous. The region is characterized by high amplitudes, which is not consistent with the expected steady state point values. This is an indication of instability in the rolling process. During the entry point, a critical strain (ε_c) in the elastic region develops almost linearly before reaching the peak strain (ε_p). Figure 4(a), however, shows early signs of peaks before reaching the peak strain. From the frequency of the peaks shown, Figure 4(a) also shows that strain rate is not uniform and this can affect the microstructure evolution and other mechanical properties such as yield strength, yield stress and hardness to a certain extent. Figure 4(b) is the strain rate distribution in the workpiece showing the maximum value of 37.8 mm/mm/sec.
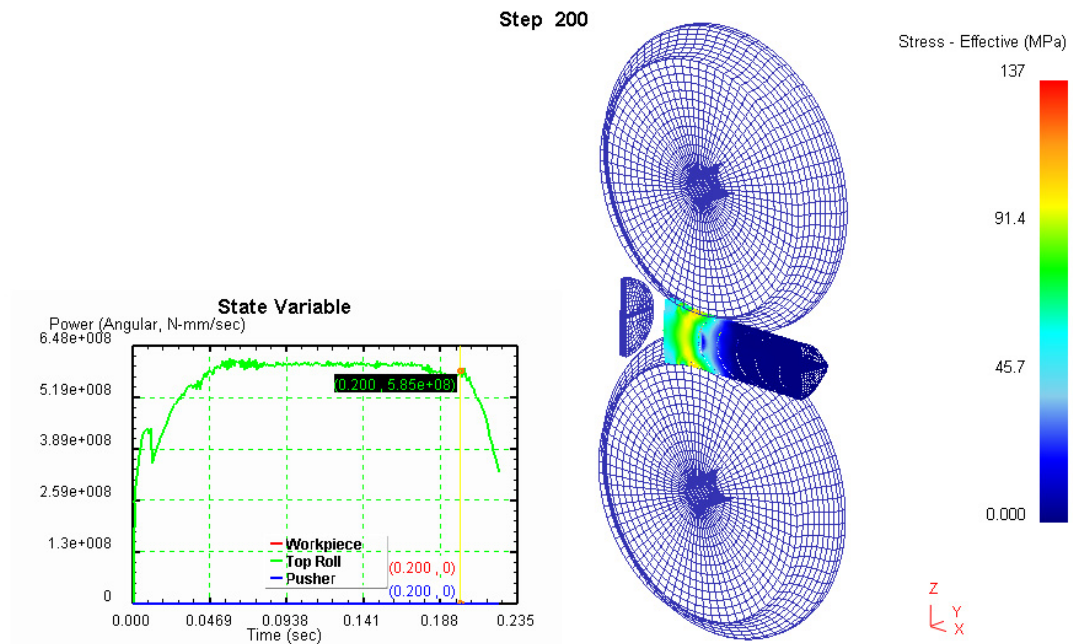
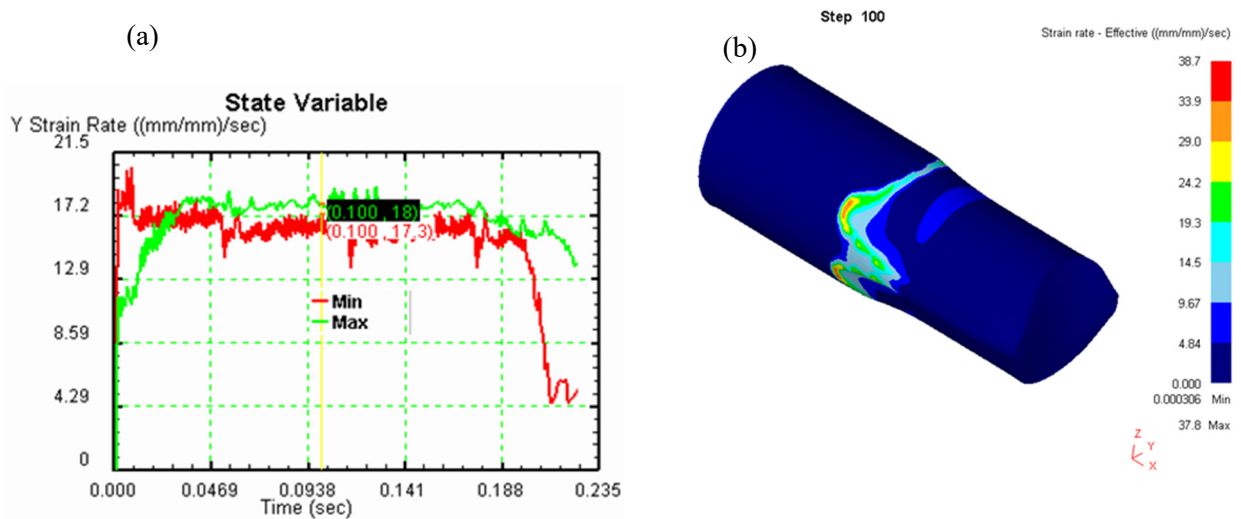Figure 3. Power variation with time.

Figure 4. (a) Instability of peaks in steady state region due to variation in strain rate in the workpiece, (b) strain rate variation in the workpiece.
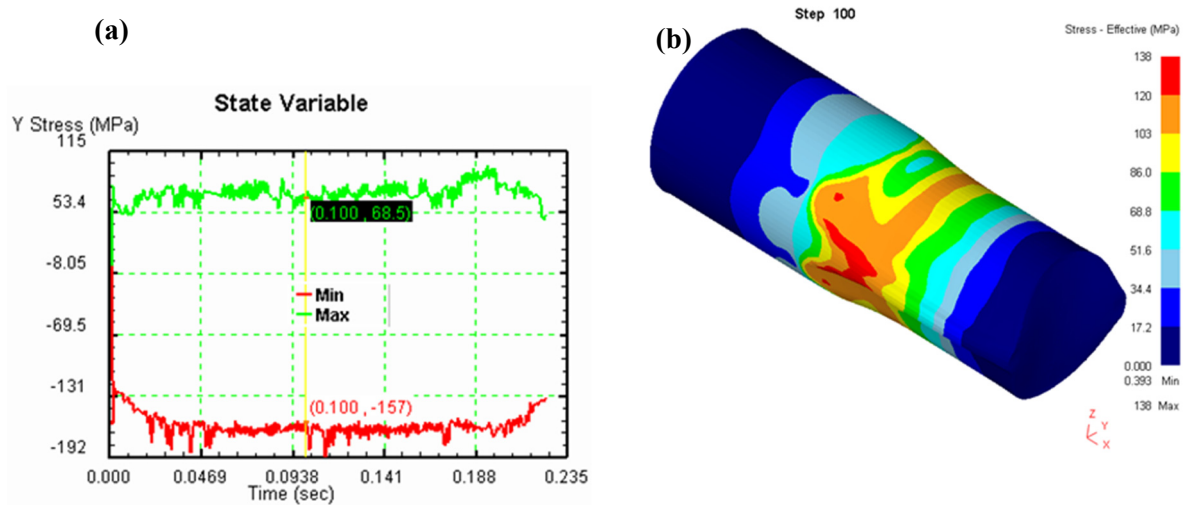
Figure 5. Instability of peaks: (a) Variation of stress in steady-state region in the workpiece (b) Stress effective during contact with roller and workpiece.

3.4. Variation of stress in Y- direction

The plot in figure 5(a), shows the variation of stress as the workpiece deforms in the *Y*-direction (spread). The stress is fluctuating between 52 MPa and 58 MPa. The frequency of peaks during spread in this case seems to be higher compared to those experienced during elongation(*X*-direction not in the report). During rolling the metal elongates in longitudinal direction due to compression by work rolls and spreads in the transverse direction and the resistance is less in longitudinal direction. The issue, however, is on the instability of the peaks which can be a source of geometrical inaccuracy of the product.
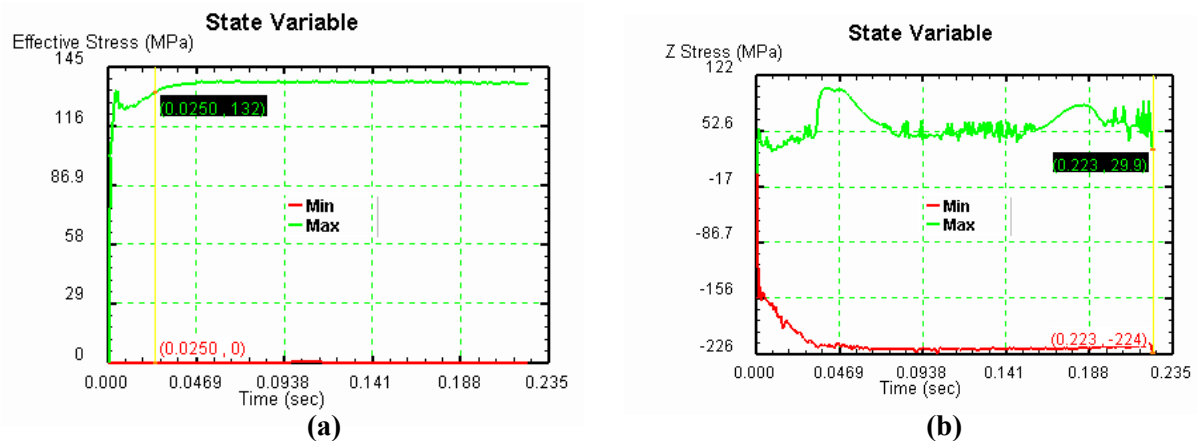

Figure 6. (a) Effective stress (b) Variation in vertical direction during the reduction of the workpiece.

3.5. Effective stress variation and Z-stress with time

It is hard for the workpiece to enter the roll gap initially. However, once the workpiece enters the roll gap, the rolling is assumed to be in steady- state as shown in figure 6(a). During the entry point, a critical strain (ε_c) (in Figure 6(a)) developed somewhere around 132 MPa, after which a peak strain (ε_p) was reached. Steady state point values were noted as shown in Figure 6(a) and represented by smooth and steady- state rolling. Figure 6(b) shows the stress variation at entry point in Z-direction (Z-stress).This is typical of deformation in vertical direction (reduction in the workpiece). The peaks

are not stable and this can be the source of inhomogeneity in the workpiece which is also due to unstable strain rate. This can also result in geometrical inaccuracies of the profile which industry is against apparently. The plot in Figure 6(a), shows the elastic deformation represented by almost straight line during the critical strain. The maximum stress reached was 137 MPa after steady- state.

4. Conclusion
This study has revealed optimal conditions during unsteady conditions in the rolling of AISI 1016 steel. Understanding the mill installation and roll geometry for each roll pass is inevitable. The features of the installation should include appropriate diameters and lengths of the rollers, distance between roll stands, starting from the last stand to the shear and the tolerances that can be maintained. Correct adjustment of the reduction per pass can maximize the use of the installation. Overloading the roll stands should be avoided. Over and above, mill constraints should be understood.

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