Finite Element Simulation of Hot Rolling for an Aluminium 2024 Plate

Anikesh Tripathi[*], **Amit Medhavi**[**]

[*]Department of Mechanical Engineering, F. G. I. E. T., Raebareli-229001, India
[**]Department of Mechanical Engineering, Kamla Nehru Institute of Technology Sultanpur-228118, India

Abstract- Numerical simulation has become an important tool in the rolling industry. The use of two dimensional rolling model is quite common in Aluminum industries. In the present work A two dimensional elasto-plastic Finite Element model for hot rolling of an Aluminum plate has been developed. This model is used to study the behavior of the material under different values of coefficient of friction, roller diameter and initial thickness of the plate for attaining a specified final thickness of the rolled plate. The effect of coefficient of friction, initial thickness of plate and roller radius on maximum stress, equivalent plastic strain and reaction force has been studied. The current work has been carried out using the Finite Element software ABAQUS 6.10 (Explicit).

Index Terms- Rolling, simulation, FEM, Lean Manufacturing, von-mises stress, equivalent plastic strain.

I. INTRODUCTION

In metalworking, rolling is a metal forming process in which the metal stock is passed through a pair of rolls. Rolling is classified according to the temperature of the metal rolled. When the temperature of the metal during rolling process is above its re-crystallization temperature, then the process is termed as hot rolling. The Finite Element Method is a numerical analysis procedure used to obtain approximate solutions to boundary value problems, which are found in many fields of engineering. Finite Element Method (FEM) is widely being used to solve problems on complicated non-linear metal deformation processes. It is the inability to solve many complex structural mechanics, heat transfer analysis, and fluid mechanics problems, that the Finite Element Method became an indispensable tool in the field of engineering mechanics.

Hwang Y.M. et al. (1999) proposed a mathematical model using the dual-stream function method under cylindrical coordinates to investigate the position of neutral point and the plastic deformation region at the roll gap during plate rolling. Lin Zone-Ching et al. (2000) simulated 3D sandwich flat strip with a thermo-elastic plastic coupled model under the assumption of an elastic roller using Aluminium-Copper flat strip. Jiang Z.Y. et al. (2001) used different friction shear models, mesh division and number of elements in the deformation zone and analyzed the influence of friction variation on rolling pressure, forward slip & spread by a three dimensional model. Kwak W.J. et al. (2002) investigated the effect of diverse process variables on some non dimensional parameters by a series of finite element process simulations, characterizing the thermo mechanical behavior of the strip in strip rolling. Lee Y .et al. (2002) presented an integrated model for computing the thermo-mechanical parameters and metallurgical parameters to develop a "Thermo-Mechanical controlled process" technology in rod (or bar) rolling. Serajzadeh S. et al. (2002) proposed a mathematical model for predicting the temperature distribution & austenite micro structural changes during hot rolling. Esteban L. et al. (2007) studied the effect of different variables of the rolling operation on the lateral spread in the first pass of the finishing mill. Serajzadeh S. et al. (2008) predicted velocity & temperature distribution during hot rolling, employing a combined upper bound & finite element analysis. Zeng Jun et al. (2008) developed a general simulation model to study the dynamic process of roll plate bending using finite element method. Hambleton J.P. et al (2009) compared predictions of deformation and horizontal (drag) force resulting from three- and two-dimensional numerical simulation of a torque-free (towed) wheel operating on ductile material. Hojny Marcy et al. (2009) proposed a numerical FEM solver based on a coupled thermo mechanical model with changing density and mass conservation condition. Ould Ouali M. et al.(2009) used a micromechanical ductile fracture model, extended to take account thermal heating due to mechanical dissipation within the material to study a 3D-asymmetric rolling operation. Shahani A. R. et al. (2009) simulated the hot rolling process of AA5083 using thermo mechanical approach. Shahani A. R. et al. (2009) simulated the hot rolling process of AA5083 aluminium alloy using the finite element method. Wang M. et al. (2009) developed a 3D coupled thermo-mechanical FE model of the hot rolling process of a large ring of titanium alloy. Anjami Nassir et al. (2010) established a coupled thermo-mechanical and 3D rigid-plastic finite element model for hot rolling of large rings. Benasciutti D. et al. (2010) proposed a simplified numerical approach based on finite element to compute thermal stresses occurring in work roll of hot rolling mills. Chumachenko E. N. et al. (2010) discussed the finite-element modeling of rolling in passes based on the 2D method. Jiang Z.Y. et al. (2010) studied the effects of the flow stresses of the scale and steel, and the friction coefficients at the scale-steel and the roll scale interfaces on the final surface roughness. Kohboor B. et al. (2010) investigated the effect of rolling speed on strain aging phenomena in warm rolling of steel. Yue Chong-xiang et al. (2010) developed four 3-D finite element models to simulate the whole rod rolling process of GCr15 steel. Parvizi A. et al. (2011) presented an analytical solution for ring rolling process based on the slab method theory, in which the non uniformity of the normal and shear stresses across the section of deforming material throughout the plastic region was considered.

II. FORMULATION OF PROBLEM

A two – dimensional elasto-plastic Finite Element model for hot rolling of a plate of Aluminium-2024 has been developed to study the behavior of the material for different values of coefficient of friction, roller diameter and initial thickness of the plate for obtaining a particular final height of the rolled plate.

There are numerous mathematical models for flat rolling process. In each, the equations of motion, thermal balance, material properties and roll deformation are used to calculate stress, strain, strain rate, velocity and temperature fields, the roll pressure distribution, roll separating forces and roll torques. The accuracy of these models depends on the quality of the assumptions made. In the conventional models, most researchers made an assumption that for homogeneous compression of a strip, considered to be made of an isotropic and homogeneous material, is incompressible in plastic state [7]. Further, plane strain conditions are assumed to exist and either a constant friction factor or Coulomb friction conditions apply at the roll-strip interface. Assumptions and simplifications vary broadly when finite element methods are employed. The same applies to the material models, the main models being used are elastic plastic models and rigid plastic models.

A mathematical model of the flat rolling process includes [2]:

a) Equations of motion of the deformed metal,
b) Heat balance of the roll/strip system,
c) Equations of equilibrium of the work roll,
d) Description of the frictional forces between the work roll and the metal,
e) Description of the material properties.

As the strip enters the roll gap it is first deformed elastically. It speeds up; the relative velocity between the roll and the strip is such that friction draws the metal in. The criterion of plastic flow governs the manner in which the transformation from elastic to plastic material takes place. This conversion is what is known as the elastic-plastic interface. The strip proceeds through the roll gap and the plastic flow of material increases until the roll pressure is removed at exit. As the strip is unloaded and it returns, through the elastic state to the original, load free condition. It is observed that during rolling, the relative velocities of the roll and the strip change and as the strip is accelerating forward it reaches the roll surface velocity at the no-slip or neutral point. From then on, as further compression occurs, the strip speeds up and the direction of friction changes in such a way that it now retards motion. Exit velocity of the strip is often larger than that of the roll velocity and the difference between the two velocities is determined by the forward slip [1], [3].

In order to formulate the model several assumptions regarding material behavior must be made. The material is usually assumed to be, and to remain, isotropic and homogeneous; it is considered to be elastic-plastic even when gross plastic straining takes place, elastic deformations may be quite small in comparison to plastic strains. During forming the volume of the plastic region is taken as constant, and finally, a plane state of strain is assumed to exit.

III. PARAMETERS STUDIED

The important parameters which were studied in the different cases of rolling in the study are Roll separating force, Mean effective plastic strain & Maximum stress (Von Mises equivalent stress).

3.1. Mean effective plastic strain: The mean effective plastic strain is defined as the maximum average effective (equivalent) plastic strain during the rod/bar rolling process. Calculation of mean effective plastic strain is extremely important for predicting and controlling the mechanical properties of the plate after rolling because all mathematical models of microstructure evolution requires thermo-mechanical variables such as mean effective plastic strain, mean effective plastic strain rate and temperature at each rolling stands. Temperature evolution due the mechanical energy converted to heat during the deformation process is also dependent on mean effective plastic strain and mean effective plastic strain rate. Furthermore, mean effective plastic strain rate is in turn a function of mean effective strain and the process time.

3.2. VON MISES EQUIVALENT STRESS: In a body that is subjected to a system of loads in three directions, a complex three dimensional system of stresses is developed. That is, at any point within the body there are stresses acting in three different directions and the direction and magnitude of the stresses changes from point to point. The Von Mises criterion combines these three stresses into an equivalent one, which is then compared with the yield stress of the material. This equivalent stress (σ') can be defined as:

For a 3-D case:

$$\boldsymbol{\sigma' = (\sigma_1 + \sigma_2 + \sigma_3 - \sigma_1\sigma_2 - \sigma_1\sigma 3 - \sigma_2\sigma_3)^{1/2}} \quad (3.1)$$

For a 2-D case, $\sigma_3 = 0$:

$$\boldsymbol{\sigma' = (\sigma_1 + \sigma_2 - \sigma_1\sigma_2)^{1/2}} \quad (3.2)$$

3.3. ROLL separating force: The roll separating force or simply the roll force is defined as the force with which the rollers pull each other apart. It is also equal to the force with which the rolls press against the metal. Calculation of roll force is important because calculation of torque and power in a rolling mill is based on calculation of roll force, which are then used in the design of spindle, motor power specification and bearing design. [3]

IV. CASE FORMULATION

Thus, the problem has been formulated to study the effect of variation of coefficient of friction, initial height of the plate and the roller radius on rolling parameters namely the von Mises Equivalent Stress, Equivalent Plastic Strain and Reaction Force. Thus, the finite element simulation of hot rolling of an aluminum plate will be done at coefficient of friction 0.1, 0.2, 0.3, 0.4 & 0.5, initial height of the plate 100 mm and roller diameter 100 mm & 200 mm, with different percent of reduction, thereby giving as many as 30 cases of different combinations of coefficient of friction, initial height of plate and roller radius. The effect of each case on the rolling parameters will be studied.[3], [7], [12]

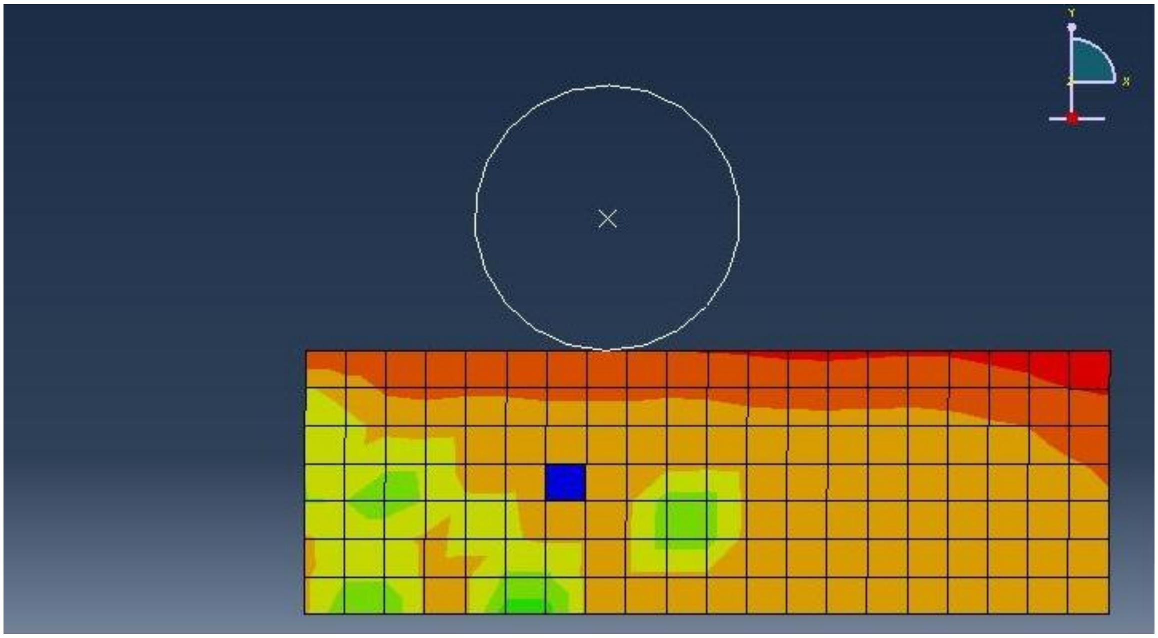

Fig. 4.1 Finite Element Simulation of Rolling of an Aluminium Plate

4.1. MESHING: The meshing of the model of the aluminum plate was done with C3D8R elements with hourglass control of ABAQUS 6.10 FE tool, which due to its shape, is also known as 4 node brick element. As this analysis was expected to have very large deformations, the adaptive meshing capability available in ABAQUS/Explicit was used with a frequency of 10 and 3 mesh sweeps per increment. The adaptive mesh control manager of ABAQUS reduces the amount of mesh distortion and maintains a high quality mesh throughout the analysis.[1]

4.2 MATERIAL: Alloy 2024 was introduced by Alcoa in 1931 as an alclad sheet. It was the first Al-Cu-Mg alloy to have a yield strength approaching 50,000-Kg/cm^2 and generally replaced 2017-T4 (Duralumin) as the predominant 2XXX series aircraft alloy. With its relatively good fatigue resistance, especially in thick plate forms, alloy 2024 continues to be specified for many aerospace structural applications. It is considered as the "aircraft" alloy because of its strength. Good machinability but only fair corrosion resistance. Not recommended for brazing or soldering. Alloy 2024 is available in bar and alclad sheet and plate product forms in the annealed state and several tempers. [9],[10]

V. RESULT AND DISCUSSION

5.1. VON-MISES STRESS: The effect of variation in Initial Height of the Aluminum plate on von Mises Equivalent Stress at different roller radius and different values of coefficients of friction is shown in the figure:-

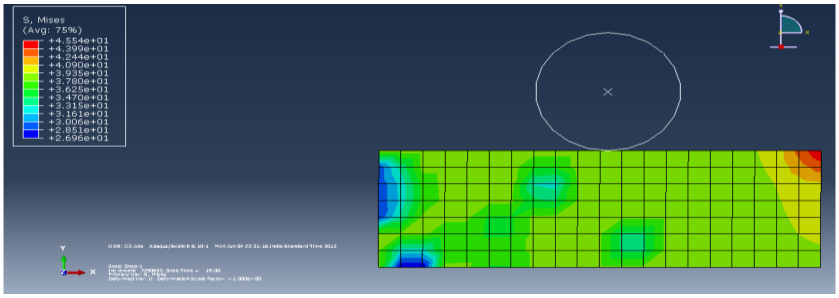

Fig 5.1Effect At Roller Diameter 50 mm & reduction is 5%

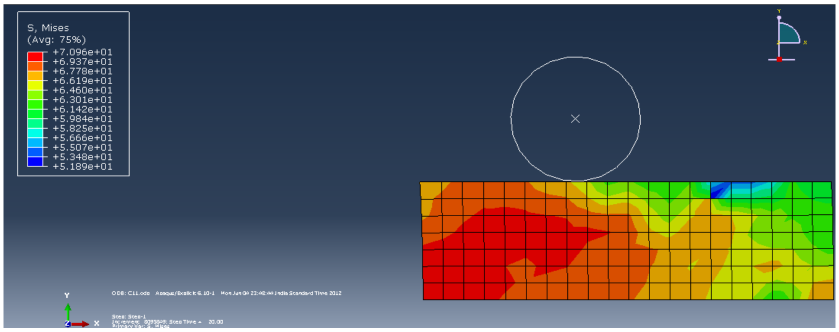

Fig 5.2: Effect At Roller Diameter 100 mm & reduction is 10%

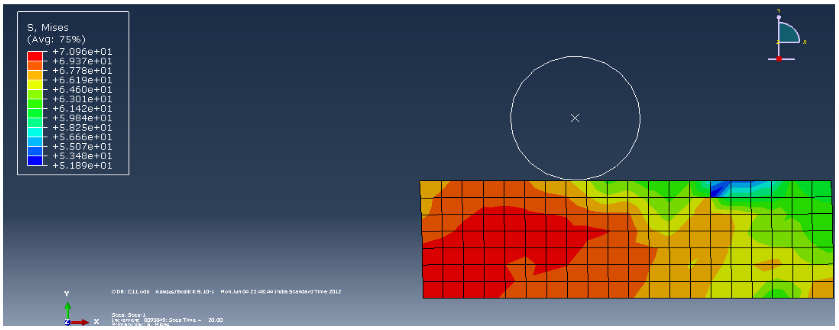

Fig 5.3: Effect At Roller Diameter 50 mm & reduction is 15%

Similarly doing the cases and result received which are as follows:

ROLLER RADIUS	INITIAL HEIGHT	FRICTION	VON MISES STRESS(N/ mm^2)	EQ. PLASTIC STRAIN	REACTION FORCE (N)	% REDUC -TION
50	100	0.1	49.82	0.04570	2631	5
50	100	0.2	45.51	0.03474	2312	5
50	100	0.3	47.57	0.03992	2335	5
50	100	0.4	44.24	0.03143	2001	5
50	100	0.5	48.97	0.04359	2385	5
100	100	0.1	70.32	0.3998	2970	10
100	100	0.2	70.43	0.1174	2788	10
100	100	0.3	54.94	0.06539	3073	10
100	100	0.4	54.72	0.05719	3140	10
100	100	0.5	59.51	0.07056	2273	10
50	100	0.1	70.96	0.7957	2919	15
50	100	0.2	70.97	0.3120	2058	15
50	100	0.3	70.68	0.1587	2368	15
50	100	0.4	70.81	0.1211	2836	15
50	100	0.5	70.76	0.09962	2993	15

Thus, we see that the effect of increase in coefficient of friction has a small effect on the von Mises Equivalent Stress at a particular initial height of the Aluminum plate. When the coefficient of friction is increased from 0.1 to 0.2 and to 0.5, the von Mises Stress increases linearly at a particular initial height of the plate, but the increase is much smaller as compared to that when the initial height of the Aluminium plate is increased. Thus, the effect of increase in initial height of the plate is more pronounced than increase in coefficient of friction. In the case of Equivalent Plastic Strain as well, the increase in coefficient of friction from 0.1 to 0.2 and to 0.5 results in a small linear increase in the magnitude of Equivalent Plastic Strain at a particular initial height of the plate. However, the increase is much smaller as compared to the increase in Equivalent Plastic Strain with increase in the initial height of the plate. Therefore, the effect of increase in initial height of the Aluminium plate is more pronounced than the effect of increase in coefficient of friction. In the case of Reaction Force as well, the effect of increase in coefficient of friction is smaller as compared to the effect of increase in initial height of the Aluminium plate. Also, the increase in Reaction Force with increase in coefficient of friction is more pronounced at higher reduction. However the increase in Reaction Force with increase in initial height of the plate is not as much as it is in the case of von Mises Equivalent Stress and Equivalent Plastic Strain.

VI. DISCUSSION

In this study, we have analyzed the effect of variation in coefficient of friction, initial height of the plate and roller radius on the rolling parameters viz. Maximum Stress (von Mises Equivalent Stress), Equivalent Plastic Strain & Reaction Force using finite element simulation. Commercially available FE software ABAQUS 6.10 has been used in this study. The Aluminium plates of different initial thicknesses were meshed by using C3D4R elements (4 node brick elements). The material chosen for the simulation was Aluminium 2024.

- **Effect of Initial Height:** It was found that the effect of increase in coefficient of friction has a small effect on the Von Mises Equivalent Stress at a particular initial height of the Aluminium plate. When the coefficient of friction is increased from 0.1 to 0.2 and to 0.5, the Von Mises Stress increases linearly at a particular initial height of the plate, but not as much when the initial height of the Aluminium plate is increased. Thus, the effect of increase in initial height of the plate is more pronounced than increase in coefficient of friction. In the case of Equivalent Plastic Strain as well, the increase in coefficient of friction from 0.1 to 0.2 and 0.5 results in a small linear increase in the magnitude of Equivalent Plastic Strain at a particular initial height of the plate although the increase was much smaller as compared to the increase in Equivalent Plastic Strain with increase in the initial height of the plate. Therefore, the effect of increase in initial height of the Aluminium plate is more pronounced than the effect of increase in coefficient of friction. In the case of Reaction Force, the effect of increase in coefficient of friction is smaller as compared to the effect of increase in initial height of the Aluminium plate. Also, the increase in Reaction Force with increase in coefficient of friction is more pronounced at higher reduction. However the increase in Reaction Force with increase in initial height of the plate is not as much as it is in the case of von Mises Equivalent Stress and Equivalent Plastic Strain.

Effect of Roller Radius: The effect of increase in coefficient of friction is smaller than the effect of increase in Roller Radius on the von Mises Equivalent Stress. However, the increase in von Mises Stress with increase in Roller Radius is not as much as it is with increase in Initial Height of the plate. Thus, the effect of increase in Initial Height of the plate on von Mises Stress is more pronounced than increase in Roller Radius. The effect of increase in coefficient of friction on Equivalent Plastic Strain is much smaller than the effect of increase in Roller Radius. However, the increase in Equivalent Plastic Strain with increase in Roller Radius is not as much pronounced as it is with increase in Initial Height of the plate. Thus, the effect of increase in Initial Height of the plate on Equivalent Plastic Strain is more pronounced than increase in Roller Radius. In the case of Reaction Force as well, the effect of increase in coefficient of friction is smaller as compared to the effect of increase in Roller Radius. However, the increase in Reaction Force with increase in Roller Radius is not as much as it is with increase in Initial Height of the plate. Therefore, the Initial Height of the plate has a greater effect on the Reaction Force as compared to the Roller Radius.

VII. FUTURE WORKS

- The effect of friction, initial height of plate & roller radius can also be studied in cold rolling.
- This problem can also be analyzed from the viewpoint of Artificial Neural Network (ANN).
- Such a study can also be done on strips, sheets and bars of various shapes.

REFERENCES

[1] ABAQUS 6.10 User Manual.
[2] Chumachenko E. N “ Mathematical modeling and energy conservation for rolling in passes” Metallurgist, 54 (2010), 7–8.
[3] Esteban L., Elizalde M.R., Ocana I.“Mechanical characterization and finite element modeling of lateral spread in rolling of low carbon steel” Journal of Materials Processing Technology, 183(2007), 390-398.
[4] Farhat-Nia F., Salimi M., Movahhedy M.R. “Elasto - plastic finite element simulation of asymmetrical plate rolling using an ALE approach” Journal of Materials Processing Technology, 177 (2006), 525–529.
[5] Hambleton J.P., Drescher A. “On modeling a rolling wheel in the presence of plastic deformation as a three or two- dimensional process” International Journal of Mechanical Sciences, 51 (2009), 846–855.
[6] Hojny Marcin, Glowacki Miroslaw “The Physical and Computer modeling of plastic deformation of low carbon steel in semisolid state” Journal of Engineering Materials and Technology, 131 (2009),
[7] Hwang Y.M., Hsu H.H. “An investigation into the plastic deformation behavior at the roll gap during plate rolling” Journal of Materials Processing Technology, 88 (1999), 97-104.
[8] Jiang Z.Y., Tieu A.K. “A simulation of three dimensional metal rolling processes byrigid plastic finite element method” Journal of Materials Processing Technology, 112 (2001), 144-151.
[9] Jiang Z.Y., Tang J., Tieu A.K., Wei D.“Analysis of tribological feature of the oxide scale in hot strip rolling” Tribology International, 43 (2010), 1339-1345.
[10] E.Paul DeGarmo, J T. Black, Ronald A. Kohser, “MATERIALS AND PROCESS IN MANUFACTURING”09(2003)

AUTHORS

First Author – Anikesh Tripathi, Department of Mechanical Engineering, F. G. I. E. T., Raebareli-229001, India
Second Author – Amit Medhavi, Department of Mechanical Engineering, Kamla Nehru Institute of Technology Sultanpur-228118, India, Email:amitmedhavi@gmail.com