Simulation of Steel Sheets Cold Rolling in Sticky Friction Conditions to Reduction of Scrap and Tools Wear

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Abstract

Rolling is a common method for production of metallic parts in various shapes and sizes. In this method, the raw material placed between two rigid rolls until take the shape and size. There are two rolling methods, hot rolling and cold rolling. To achieve higher mechanical properties, and better surface quality and dimensional accuracy, the hot rolled sheets undergo the cold rolling process. The friction between the metal and rolls affects the forming process, increase the required load for forming, reduce the surface quality and increase the wear of tools. The simulation of rolling process will be helpful to improve the forming procedure and quality of products. In this research, the Finite Element method is used to model, simulate and analysis the rolling process of St 37 steel sheets in sticky friction plane strain conditions. Because of stress strain behavior of material during the forming process and increase of frictional stress due to forming process, the analysis of forming load between the contact surface of rolls and sheet are shown by simulation. Finally, simulation of forging process as a friendly tool can reduce the scrap rate, tools wear and environmental effects of scraps.

Keywords: Cold Rolling, Sheet Rolling, Simulation, Friction, Rolling Force.

1. Introduction

Steel production have critical role in economy development of each country and is a criteria to measurement of economic development. Steel sheets with various thickness and dimensions have wide usage in automotive, aerospace, packing, communication and military industries [1]. Rolling technologies and facilities are basis for modern rolling products and parts. Increasing of production rate, higher production tonnages with better quality and lower cost and scrap are goals for researchers, engineers and production plants [2-3]. Its production level to some extent reflects a country's level of industrial development. Steel Sheet productions are the main products. Great demand for steel, the rapid development of the national economy increasingly required a very high dimensional accuracy of rolled products, whether it is the defense industry or in the general civilian industry, requires a large number of various specifications, various types of sheet, sheets, thin sheets and strip In automobile manufacturing, food packaging, machinery, light industry, instrumentation, communications and military industries in areas with various thickness or dimensions. How to improve the accuracy of the products a key issue, in each country with various scientific research institutions. More advanced equipment, modern cold rolling mill broadband and control system are basically the import of equipment, much of the theoretical issues and the use of advanced technology also need further research to digest [4-7].

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The first part of this research title “Simulation of Steel Sheets Cold Rolling in Normal Friction Condition” presented in ref [8]. Present part is related to sticky friction conditions which have better compliance with actual condition.
The first step in FEM modelling is certain accurate mechanical properties of the materials, thermo-physical properties and alloy-preparation methods [9]. In the absence of actual measurements of the roll-pack force during experiments, properties calculations were carried out based on previously developed analytical methods [10-11].
These parameters were used in the current study to apply the appropriate rolling boundary conditions of threat sheet at every pass and select the mechanical properties as an input to the FEM programmer.
As a validation step, predicted roll-forming forces and friction were compared to experimental measurements.
Simulations permit investigation of various aspects of the roll-pack shape such as friction, forming loads, rising temperature thickness variation during forming process [12-17]. Finally simulation results are presented and discussed.

2. Fundamental Concepts of Metal Rolling

To calculation and simulation of metal rolling process, it is necessary to do few assumptions [18-20]:
a. The curvature of contact between the rolls and the metal is a part of circle.
b. The coefficient of friction, μ, is constant in theory, but in reality μ various along the curvature of the contact.

c. The metal is considered to deform plastically during rolling.
d. The volume of metal is considered to be constant before and after rolling. In practical conditions, the volume might decrease a little bit due to close up of pores.
e. The velocity of the rolls is assumed to be constant.
f. The metal only extends in rolling direction and no extension in the width of the material.
g. The cross section normal to the rolling direction is not distorted.

3. Theoretical Aspects of Rolling Process

Consider a steel sheet with h0 enters the roll at entrance plane XX with a velocity V0. It passes through the roll gap and leaves the next plane YY with a reduced thickness hf and at a velocity Vf . Assume that there is no increase in width, the vertical compression of the metal is translated in to an elongation in rolling direction Fig. 1. [20].
Since there is no change in metal volume at a given point per unit time throughout the process, therefore Eq. (1) :

$$bV_0h_0=bV_f\,h_f \qquad \text{Eq. (1)}$$

Where b is the width of the sheet and V is the velocity at any thickness h intermediate between ho and hf. When ho > hf, we then have V0 < Vf. The velocity of the sheet must steadily increase from entrance to exit such that a vertical element in the sheet remain undistorted. Because there is no changes in width of sheet during rolling process, by assuming b0=bf,, and from Eq. (1) :

$$\frac{Vo}{Vf}=\frac{hf}{ho} \qquad \text{Eq. (2)}$$

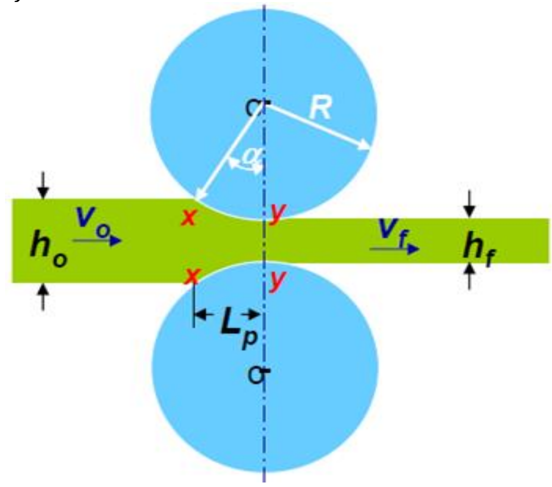

Fig. 1. Sheet metal rolling [20].

When $h_0 \geq h_f$, then we have $V_0 \leq V_f$ The velocity of sheet must steadily increase from entrance to exit such that a vertical element in sheet remain undistorted [22].

4. Forces and Geometrical Relationships in Rolling

A metal sheet with a thickness h0 enters the roll at the entrance plane xx with a velocity V0. It passes through the roll gap and leaves the exit plane yy with a reduced thickness hf and at velocity vf. . At only one point along the surface of contact between the roll and the sheet, two forces act on metal: 1- radial forces Pf and 2- tangential frictional force F. If the surface velocity of the roll Vr equal to the velocity of sheet, this point is called neutral point or no-slip point for example, point N [23-24]. Between the entrance plane xx, and the neutral point the sheet is moving slower than the roll surface, and the tangential frictional force, F act in the direction to draw the metal in to the roll which show in Fig. 2..
On the exit side yy, of the neutral point, the sheet move faster than the roll surface. The direction of the frictional force is then reversed and oppose the delivery of the sheet from the rolls [25].

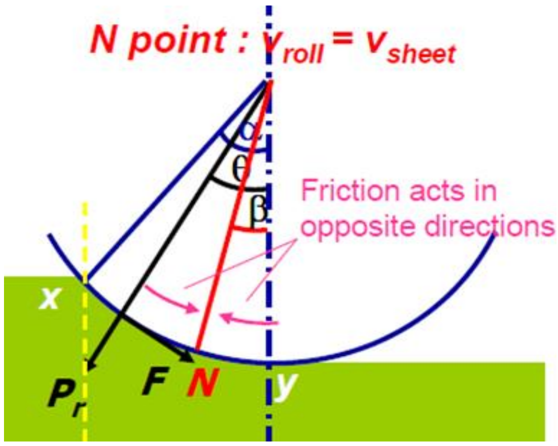

Fig. 2. Radial forces Pf and tangential frictional force F act in the direction to draw the metal in to the roll and neutral point [20].

In Fig. 3., Pr is the radial force, with a vertical component P (rolling load - the load with which the rolls press against the metal).

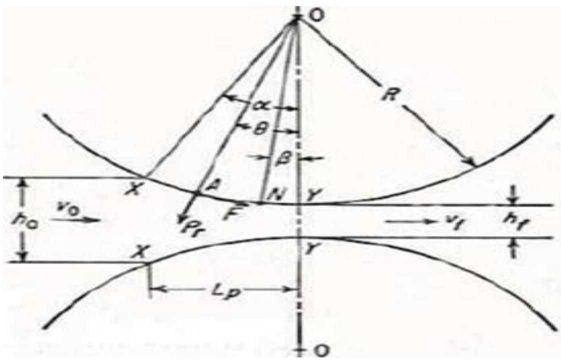

Fig. 3. Analysis of forces in contact area of rolls and sheet[20].

The specific roll pressure, p, is the rolling load divided by the contact area,

$$P = \frac{p}{bLp}$$

and we can find [12].

$$Lp = \left[R(ho-hf) - \frac{(ho-hf)^2}{4}\right]^{1/2} \approx [R(ho-hf)]^{1/2}$$

$$Lp \approx \sqrt{R\Delta h} \qquad \text{Eq. (3)}$$

5. Roll bit Condition

Fig. 4., shows the contact area conditions of rolls and sheet. For the workpiece to enter the throat of the roll, the component of the friction force must be equal to or greater than the horizontal component of the normal force [26].

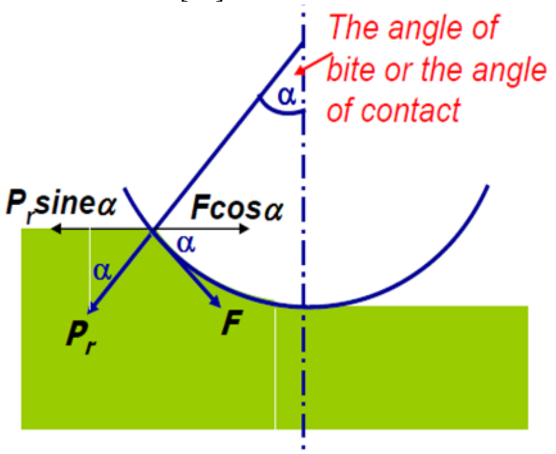

Fig. 4. Contact area conditions[26].

$$F\cos a \geq Pr\sin a$$

$$\frac{F}{Pr} \geq \frac{\sin a}{\cos a} \geq \tan a$$

$$F = \mu Pr\ , \quad \text{which} \quad \mu = \tan a \qquad \text{Eq. (4)}$$

If tan $\alpha > \mu$, the work piece cannot be drawn, and if μ=0, rolling cannot drawn.
Therefore free engagement will occur when $\mu >$ tan α. In this condition:
- Increase the effective values of μ, for example grooving the rolls parallel to the roll axis.
- Using big rolls to reduce tan α or if the roll diameter is fixed, reduce the h_0.

5.1. Simplified Analysis of Rolling Load

To modeling and simulation of rolling process, it is necessary to consider few parameters. The main variables in rolling are [27-28]:
- The elastic deformation of rolls and roll supports, roll diameter and contact areas situation of rolls and sheet metal..
- Deformation strain hardening of the metal as influenced by metallurgy, temperature and strain rate.
- The friction between the rolls and the work piece.
- The presence of the front tension and/or back tension in the plane of the sheet.
- The friction condition in contact area between rolls and sheet [27-29].

Concerning friction condition, there are 3 situations.
No friction
Normal friction condition
Sticky friction condition.
The Normal friction condition was studied by author and et al before [27]. But in practice, the sticky friction is in similarity with real condition in rolling of steel sheet. In the case of no friction situation, the rolling load (P) is given by the roll pressure (p) times the area of contact between the metal and the rolls (bLp) Eq. (4) [30].

$$P = pbL_p = \sigma'_0 b\sqrt{R\Delta h} \qquad \text{Eq. (5)}$$

5.2. Sticky Friction Condition

Where the roll pressure (p) is the yield stress in plane strain and when there is no change in the width (b) of the sheet. Continuing the analogy with compression in plane strain it would be find:

$$\bar{p} = \sigma'_0\left(\frac{a}{2\bar{h}} + 1\right) = \sigma'_0\left(\frac{Lp}{4\bar{h}} + 1\right) \qquad \text{Eq. (6)}$$

From Eq. (5) and Eq. (6):

$$P = \bar{p}bL_p \qquad \text{Eq. (7)}$$

These equations used for modelling and simulation

6. Materials and Methods

The experiments were performed at the Private Steel Company. They were carried out in a single-stand 4high plate mill. The width is 1000 mm and the maximum work roll diameter is 1045 mm and the maximum backup roll diameter is 1400 mm.
The sheet with lengths of about 13 m was rolled to finishing dimensions of 2800x10 mm. In the last pass the gauge adjustment was changed when 3 quarters of the sheets had been rolled so that the last quarter was not reduced in thickness at all. Therefore it is possible to measure thickness before the last pass. It is 12.70 mm.
The total rolling force was measured to be 21500 kN in the experiment. The CROWN software package for calculations of sheet profile and flatness in 4high rolling mills was used [31]. The calculated rolling forces per unit length (i.e. per unit length transverse to the rolling direction) in the mid-section of the sheets are 420 Mpa in the experiment.

Table. 1. and Table. 2. givens the chemical composition and mechanical properties of St37 carbon steel which used in experiment.

Table. 1. Chemical Composition of St37 Steel [31].

Alloying Elements	%C max	%Si max	%Mn max	%S max	%P max
wt, %	0.17	0.35	0.40	0.035	0.035

Table. 2. Mechanical Properties of St37 Steel [31].

YS (Mpa)	UTS (Mpa)	Haddness (BHN)	Impact Energy (J)	El%	RA%	Young Mo (Mpa)
235	340-510	120	27	22	40	210

To accurate modeling and simulation, the plane strain condition considered for rolling process. To analysis the rolling process it is necessary to consider the physical phenomena which can affect the forming process. The steps for modelling of process consist of followings:

- Definition of geometrical model for rolling part
-Identify the steel type and its mechanical properties.
- Identify the analytical method and simulation out pouts.
- Boarder condition and loading procedure
- Definition of fixtures and contact area between the sheet and rolls.
- Meshing process of parts and rolls.
- Adjusting the parameters and analysing the equations
- Assessment and Discussion of results of results

Table. 1. denoted the chemical composition of steel sheet used in research and Table. 2. shows its mechanical properties [32-33].

Finite element program FLUENT is used for meshing of the cross-section of the work rolls and the sheet. Fig. 5. Illustrate meshing system for process.

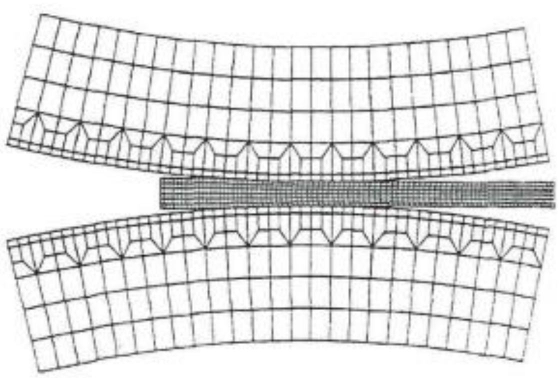

Fig. 5. The finite element meshing for roll and sheet.

Due to symmetry only the upper half of the sheet and the upper roll is analyzed. Plane strain conditions are assumed in the direction transverse to the rolling direction. Thus the simulations are representative of the mid-section along the rolling direction. No inertia forces are accounted for. The outer diameter of the work rolls is 1014 mm and the gap between the work rolls is 10 mm before rolling. The distances between the inner and outer radii of the work rolls in the finite element models should be identified. The right part of the sheet is curved so that it fits exactly to the rolls at the start of the simulations. In the simulations the sheet is pulled into the rolling section during the first step.

Thus the deformations and the stresses in the right part of the sheet are not representative for simulation of rolling. It is found that there is a steady-state condition relative to the rolling section prevailing. The friction along the slide line between the roll and the sheet is assumed to be 0.25 which represent sticky friction condition. The Young's modulus for the sheet material is assumed to be 210 Mpa at room temperature. Poisson's ratio is set to 0.35. The yield condition according to von Mises and the associated flow rule are used. Isotropic hardening is assumed. Linear hardening is assumed in model.

The yield stress is taken as 370 MPa and the hardening modulus as 510 MPa in that model. The effective stress-effective plastic strain relations for the variable hardening model are given from linear interpolation between the values in Table. 2.. The data for plastic yielding in both models are based on a strain rate Suzuki. The simulations show that the strain rate is approximately constant.

7. Results and Discussion

7.1. Contact Forces

The calculated contact force is about 460 KN for finite element meshes when the linear hardening material model is used. The time history for the vertical contact force for the mesh in Fig. 5. can be seen in Fig. 6. It is a decrease in the contact force when a larger part of the roll is included into the model.

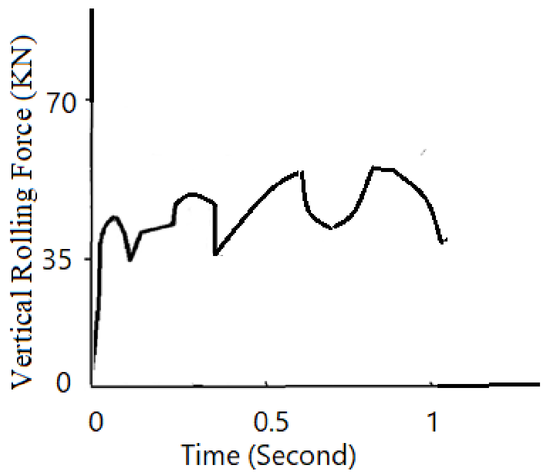

Fig. 6. Calculated rolling force for the mesh in Fig. 5.

7.2. Longitudinal Stress

The longitudinal stress state after rolling and thicknesses changes during rolling process by using the finite element meshes in Fig. 5. are illustrate in Fig. 7. These results obtained using the linear hardening model. The increase in thickness for the latter cases is due to the flattening of the work roll. A steady-state condition relative to the rolling section can be observed in this figure. This observation has been confirmed by other results not presented here, where part of the sheet is shown magnified. The stress is 460 MPa at the surface and 420 MPa in the middle of the sheet. The pressure distribution for the sheet is shown in Fig. 8. The pressure dip at special distance of the left end of the contact line between the sheet and the work roll is the same as for ball bearings and interesting parallels can be found in other research [20]. It is caused by the deformation of the work rolls. The contact line will not be a circle segment. The stress distribution, shown in Fig. 8., corresponds to the friction force per unit area. Fig. 6.,Fig. 7. and Fig. 8. are obtained from simulations using the model in Fig. 5. combined with a linear hardening material model. The maximum effective plastic strain is 0.35. This value is found at the surface of the sheet. The maximum hydrostatic pressure during rolling is 460 MPa.

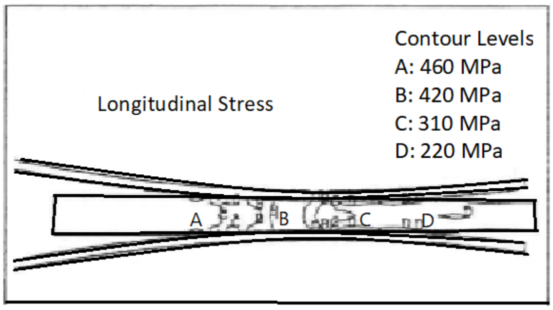

Fig. 7. Pressure distribution along the contact line versus distance.

along contact line during the cold rolling of St37 Carbon Steel.

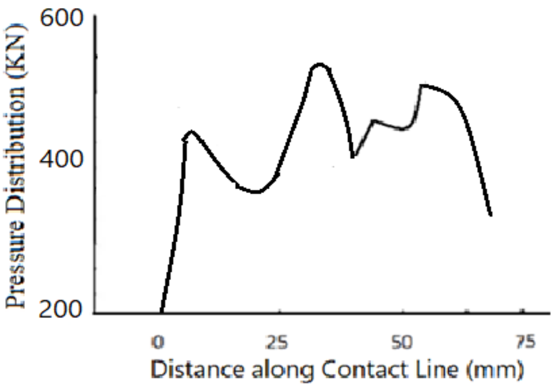

Fig. 8. Pressure distribution along the contact line versus distance.

along contact line during the cold rolling of St37 Carbon Steel.

7.3. Friction coefficient

Fig. 9. shows the sensitivity of roll force to coefficient of friction and reduction. Increasing the reduction, and friction coefficient, increase the required rolling force.

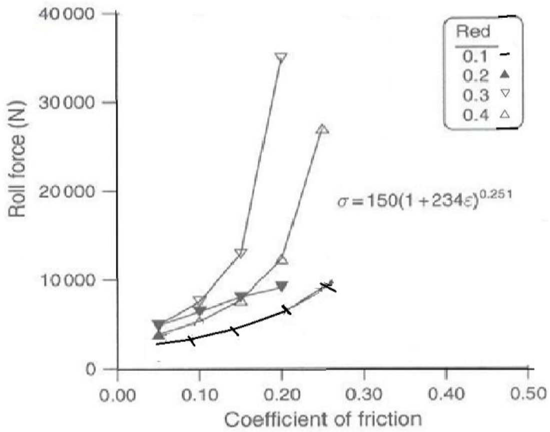

Fig. 9. Variation of roll force with friction coefficient for various reduction in rolling

This research shows a methodology to estimate the coefficient of friction from the asymmetric roll process. A code based on slab method formulation has been developed for estimating the curvature of the rolled sheet under asymmetric rolling conditions. Sticky friction condition required higher rolling force which can affect the rolling surface quality and reduction of rolling performance [34-36].

The strain-hardening behavior of the material and the roll flattening effect are incorporated along with friction model. It has been found that strain hardening and roll flattening have significant effect on the overall rolling process. When the asymmetry due to speed mismatch is considered it has been found that the sheet curls towards the slower rotating roll, the magnitude of the curvature being dependent on the value of friction. The inverse problem of finding out the coefficient of friction given the radius of curvature is solved using the special method. Simulation results indicate a good potential of the method.

8. Conclusion

1. A new model for rolling mechanics of thin sheet in cold rolling has been developed successfully. A sheet plastic deformation-based model of the rolling force was employed in the calculation and Simulation. Based on the theory of sticky friction condition, the special rolling deformation was simulated using a modified influence function method.

2. Modelling and simulation are powerful tools to prediction of sheet behavior and its mechanical properties during rolling process.
3. The calculated results show that the specific forces such as the rolling force, intermediate force and the shape and profile of the strip for this special rolling process are significantly different from the forces in the traditional cold rolling process, and those form a new theory of metal plasticity in metal rolling.
4. With an increase of reduction, the rolling force, intermediate force and edge contact force increase significantly, however the sheet shape becomes poor.
5. When the friction coefficient increases, the edge contact force between the two work rolls increases.
6. The friction has a significant effect on the rolling force, edge contact force and the length of edge contact. It affects the sheet shape and profile significantly, which is helpful in improving the sheet shape and profile by modifying transverse friction. The calculated rolling force increases when the strip width increases and the rolling speed decreases, and it is in good agreement with the measured value.
7. According to the results the SALF program permits simulating the cold flat rolling process. However, domestic steel industries now have a national tool to simulate their processes using FEM.
8. The effect of the reduction, the rolling speed and various friction conditions Simulated. The coefficient of friction was found to drop when the rolling speed was increased in all instances. The coefficient dropped or increased with increasing reduction, depending on the material’s resistance to deformation.
9. Modeling and simulation are powerful tools to prediction of sheet behavior and its mechanical properties during rolling process.

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