Finite Element Modeling of Strip Curvature During Hot Rolling

Anup A. Kuldiwar
M.E. (Mechanical-Production Engineer)
anup_kuldiwar@rediffmail.com
Tel: +91-09819826363

Abstract

Finite element techniques have been used to decouple some of the major causes of strip curvature in the finishing stages of a hot strip mill. A plane strain elastic-plastic finite element model (HYPERMESH$^{5.0}$) is used to predict the direction and severity of strip curvature caused by asymmetrical factors at each pass of the finishing mill. Predictions have been obtained using the elastic-plastic facilities of LS-DYNA Version 960. A full factorial experiment was then designed and performed, using finite element predictions, to identify which asymmetrical factors are most influential to strip curvature and to determine the interactions, between factors. The result show that some of the asymmetrical factors are significant to strip curvature, but their influence depends on the rolling pass. This study will allow the rolling operator to identify which asymmetrical factor may be causing strip curvature and, thus, provide a suitable course of action.

1. Introduction

During hot mill strip production the symmetry between rolling parameters cannot always be ensured. Asymmetrical conditions occurring during the rolling of hot strip can cause strip curvature i.e. turn up or turn down (Figure1.1) or it is also called as hooking. This can lead to reduced productivity and deterioration of the dimensional accuracy of the rolled stock. In addition, considerable damage to mill equipment may result, especially when the curvature is severe. The mechanism of rolled strip curvature is not a simple one. Turndown is the main cause of damage to the rolling table, caused by the continuous impact between the work piece and rolling table rollers. In the most serious of cases, fragments of the work piece break away from the head end and can be rolled back into the strip, leading to poor product quality and increased yield loss. Strip turn up needs to be avoided at all costs during rolling; a work piece with a head end curving towards the upper work roll can result in a cobble, where the work piece fails to enter the next roll gap and results in disastrous consequences on hot mill operations.

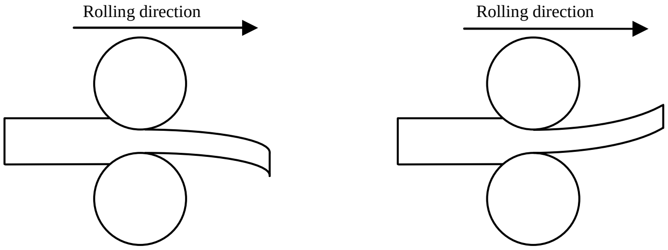

Fig. 1.1. Strip curvature: (a) turn down; (b) turn up

In the present investigation, the finite element method has been used to analyze the effect of asymmetrical factors and rolling parameters on the direction and severity of strip curvature. A plane strain finite element model has been constructed to simulate the rolling of low carbon steel strip at high temperatures (i.e. >1000 °C). This research work has been carried out in ISPAT Steel Industries Limited, India.

2. Literature Survey

Most of the recent work has been carried on strip curvature during hot rolling considering various asymmetrical parameters such as work roll speed mismatch, temperature differentials across the thickness of the work piece, pass height, reduction, differential roll diameters and frictional differences between upper and lower work rolls with different methods, the result showing sign and magnitude of the direction of the strip curvature. Shivpuri et al. [1] described sheet curling due to roll speed mismatch using an explicit time-integration elastic-plastic finite-element method. The results demonstrate that three regions exist in the sheet deformation: the front end region where large strain gradients and rotations are present, the middle steady state region where curvature develops due to plastic strain non-symmetry and the rear or entry region where sheet rotates causing the faster roller to have longer contact area and lower roll pressures.

The effect of two different sets of friction conditions at the upper and lower roll on the variation of the contact stresses at the roll/plate interfaces and the curvature of the plate has been examined by Richelsen [2] for a reduction of 20%, using the finite element method. The differences in contact stress variation result in curling of the plate. Jeswiet and Greene [3] carried out an experimental analysis of roll speed mismatch with increasing reduction on strip curvature. Results concluded that strip curvature changes direction with increased reduction. Lu et al. [4] discussed an elastic-plastic FE simulation studied the influence of different roll diameters, roll speed mismatch, reduction and initial height on curvature. Their results showed that strip curvature depends on the aspect ratio (or shape factor). In the investigation of rolling parameters on strip curvature by Knight [5], finite element techniques has been used to analyze the effect of asymmetrical factors and rolling parameters on the direction and severity of strip curvature. The rolling parameters include initial strip height, reduction, average roll speed, average work piece temperature and average coefficient of friction. Trials were conducted to investigate the effectiveness of roll speed mismatch as a means of controlling strip curvature.

3. Finite Element Modeling of Strip Curvature

Two two-dimensional plane strain elastic-plastic finite element models are used to predict strip curvature. Finite element model have been created in meshing software i.e. HYPER WORKS 5.0. Predictions have been obtained using the elastic-plastic facilities of LS-DYNA Version 960. Each model represents one pass of a typical finishing schedule; the reduction ratios for two passes are shown in Table 3.1.

The typical geometry of an undeformed finite element model is shown in Figure 3.1. This configuration represents the reduction of the steel in the first pass of the rougher before rolling. In each of the two models, the work piece is assumed straight, prior to entry into the roll gap.

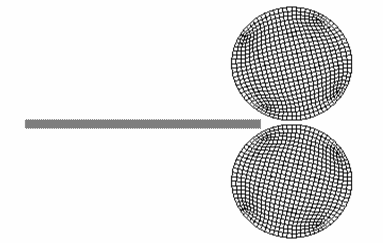

Fig. 3.1 Deformed finite element mesh

Four-node bilinear reduced integration elements are used to model the work piece, a total of eight elements are applied across the strip thickness, and the relative mesh density is determined by the ingoing strip thickness. The rolls are assumed to be rigid and therefore modeled are using rigid elements. Coulomb friction μ_f is assumed between the rigid rolls and work piece, and a value of $\mu_f = 0.4$ is applied on all simulations. An angular velocity ω is applied to the rolls. An equivalent velocity *v* is applied to the work piece, i.e. $v = \omega.r$, where r is the radius of the rolls. The initial velocity of the work piece is chosen to match the x component of the peripheral velocity of the rollers. This choice of initial velocity results in a net acceleration of zero in the x direction, which minimizes the initial impact between the work piece and the rolls. To reduce the computation time a mass scaling option has been used. The slab is made of steel whose physical and mechanical properties are: Young's modulus E = 200 x 10^3 Mpa, Poisson's ratio $\nu = 0.3$, Density $\rho = 7.871 \times 10^{-09}$ kg/mm^3.

Table 3.1 Typical reduction pattern of finishing schedule

Model Number	Pass Number	Strip Thickness (ingoing), mm	Strip Thickness (outgoing), mm	Reduction %
1	1	54	28	48
2	2	28	14	50

Three asymmetrical rolling factors were considered for these investigations. The values assigned to the asymmetric factors are shown in Table 3.2. A 20 % higher coefficient of friction is applied to the bottom roll to predict the effect of fraction differentials. Differences in the coefficient of friction may be caused by work roll oxide scale growth, work piece oxide scale growth, or work roll roughness. Pass height is the height above the pass line by which the bottom roll overlaps (Figure 3.2). The pass height value is calculated by Draft = $(h_i\text{-}h_f)/2 + 8$, i.e., 21mm for pass 1 and 15mm for pass 2 and this mimics the conditions found at the hot rolling mills of various finishing stand.

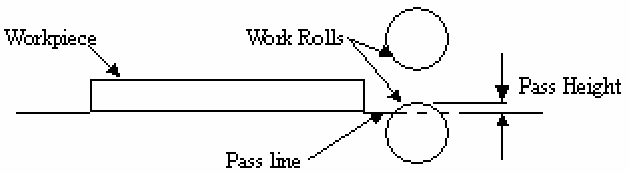

Fig. 3.2 Definition of pass height

To predict the effects of differential roll speed the upper work roll has been given a 5 % higher angular velocity. This represents the maximum limit that a rolling operator has on the control of roll speed mismatch. Variations in temperature are caused by a number of factors, including scale formation, differential cooling conditions, and furnace heating efficiency. The work piece is modeled at a temperature of 1073 and 1033°C for pass number 1 and 1033 and 933°C for pass 2, this temperature values are applied to all simulation models. During hot strip production, a parabolic temperature distribution exists across the thickness of the work piece; for the present study this effect is assumed negligible.

Table 3.2 Asymmetrical factors and their values

Variables	Unit	Value	Comments
Differential friction roll	%	20	Higher friction applied to bottom
Pass height	No	Yes	
Differential roll speed	%	5	Higher upper roll peripheral velocity

3.1 Finite Element Results and Discussion

An example of a deformed mesh (due to a 5% roll speed mismatch) after an analysis time of 3 sec is shown in Figure 3.3. Here the work piece has been pulled approximately halfway through the roll bite, and there is prominent visual evidence of strip turndown. Strip curvature is approximated over the first meter of strip (head end). The radius of curvature R is calculated according to the definition shown in Figure 3.4, and is achieved by approximating a radius of curvature to the deformed mesh. The strip curvature δ is then given by the value 1/R. Finite element predictions of strip curvature for pass 1 and 2 are shown in Figure 3.5. Positive strip curvature indicates bar turn up, whereas negative strip curvature shows bar turndown.

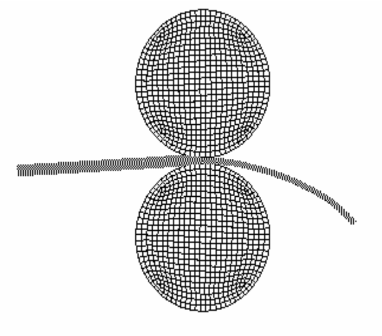

Fig. 3.3 Deformed finite element mesh

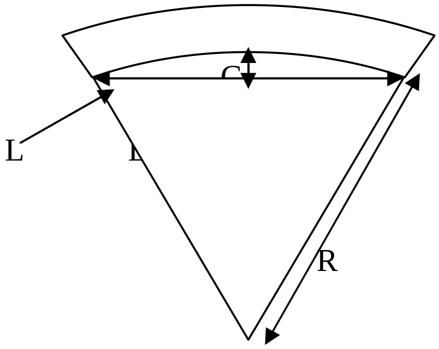

Fig. 3.4 Definition for radius of curvature; from geometry $R = (4\,c^2 + L^2) / 8\,c$

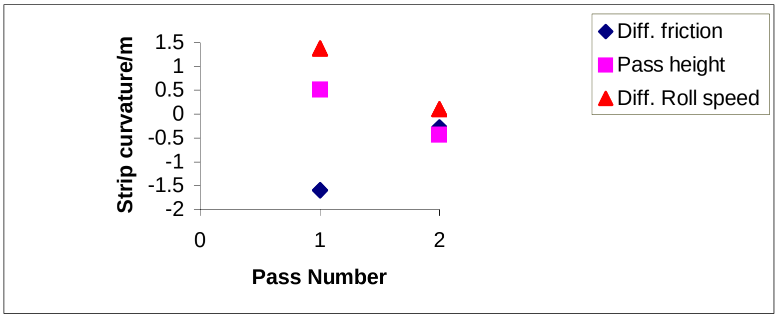

Fig. 3.5 Effect of asymmetrical parameters on curvature

It can clearly be seen from the results that differential friction induce bar turndown at each pass and differential roll speed induce bar turn up at each pass of the rougher. This suggests that the work piece turns towards the work roll with the higher value of friction, and the work piece turns towards the roll surface with the higher velocity. Pass height causes turn up on pass 1 and turndown on pass 2. The effect of pass height on strip curvature cannot be easily explained and requires further investigation. A possible cause may be the result of the work piece entering the roll gap at an inclined angle. This result in the work piece being in contact with the lower work roll before the upper, given the bottom work rolls a larger effective diameter. Differential roll speed causes turn up on passes 1 and 2, where the strip curves towards the roll with the higher velocity. An intuitive assumption would be that the rolled strip would always curve towards the roll with the higher peripheral velocity.

4. Designed Factorial Experiments

A single un-replicated 2^3 experimental factorial design has been carried out, using the finite element models to predict the effect of asymmetric factors on strip curvature. Each factor is present at two levels and the factorial design is constructed according to the Yates' algorithm. The experiment and the predicted strip curvature obtained from pass 1 and pass 2 of 2^3 single replicated experiments are shown in Table 4.2. Here, each test condition is given a coded value, where -1 indicates a factor set at the low level and +1 indicates a factor set at the high level. Hence, two 2^3 single replicated designs each involving 8 tests for each pass of the rougher were conducted. Thus, a total of 16 finite element model simulations were carried out. A single replicated design was used, as there are obviously no experimental errors associated with the finite element model.

Table 4.2 Coded test combination and predicted strip curvature for pass 1

Factor			Predicted Strip Curvature (m^{-1})
A	**B**	**C**	
-1	-1	-1	0.163
+1	-1	-1	1.594
-1	+1	-1	0.5128
+1	+1	-1	1.522
-1	-1	+1	0.9416
+1	-1	+1	1.373
-1	+1	+1	0.4323
+1	+1	+1	0.80

Table 4.3 Coded test combination and predicted strip curvature for pass 2

Factor			Predicted Strip Curvature (m^{-1})
A	**B**	**C**	
-1	-1	-1	0.0797
+1	-1	-1	0.277
-1	+1	-1	0.431
+1	+1	-1	0.01975
-1	-1	+1	0.1037
+1	-1	+1	0.1806
-1	+1	+1	0.0852
+1	+1	+1	0.1091

4.1 Factorial Experimental Results

Table 4.2 and 4.3 shows the results of the predicted strip curvature for the various test combinations for passes 1 and 2. Table 4.4 and 4.5 gives the estimated effect of each factor and interaction for the each pass.

Table 4.4 Effects and estimates for pass1

Treatment Combination	Effect	Estimate
a	A	0.4049
b	B	-0.1005
ab	AB	-0.0607
c	C	-0.0306
ac	AC	-0.2051
bc	BC	-0.1700
abc	ABC	0.0447

An estimate of the 7 factorial effects was completed for each pass. The normal probability plot of the first pass and the second pass are shown in Figures 4.1 and 4.2. Effects that lie along the line are negligible, whereas the large effects, those which have the greatest effect on the process, lie far from the line. The results at each pass are described below.
Pass 1 (Fig. 4.1)

The influential factors that emerge from the first pass are the main effects of differential friction (A) and other factors are lying approximately along a straight line. There are no important interaction effects that occur in pass 1. Therefore, the asymmetrical factors of differential friction (A) is most significant to strip curvature in pass 1.

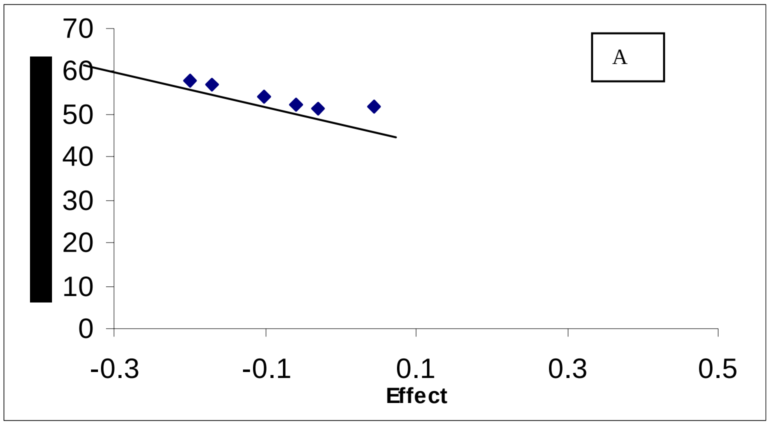

Fig. 4.1 Probability plot of estimated effects for pass 1

Pass 2 (Fig. 4.2)

The important effects that lie away from the straight line were those of friction-roll speed differential (AC) interaction effect and first order of friction - pass height-roll speed mismatch interaction effects are identified in second pass. The friction – roll speed differential interaction indicates that the differential friction counteracts the influence of the roll speed mismatch, resulting in very low values of friction - roll speed mismatch shows negative strip curvature causing bar turndown and all high values of AC interactions indicates positive strip curvature that means bar turn up. The first order interaction effects show that ABC affects the strip curvature simultaneously. In pass 2 there are two significant factors that affect the strip curvature.

Table 4.5 Effects and estimates for pass 2

Treatment Combination	Effect	Estimate
a	A	-0.01415
b	B	0.000505
ab	AB	-0.08269
c	C	-0.04111
ac	AC	0.039345
bc	BC	-0.02301
abc	ABC	0.069443

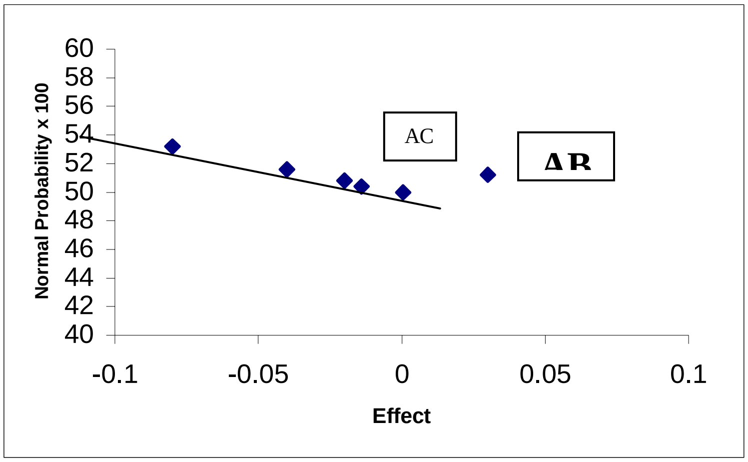

Fig. 4.2 Probability plot of estimated effects for pass 2

5. Conclusion

Asymmetrical factors believed to influence strip curvature have been investigated using finite element techniques. A finite element model was developed and used to predict the expected strip curvature. A summary of the asymmetrical investigation is given below:

1) When a differential interface friction was applied between upper and lower rolls, the strip consistently turned towards the higher friction value; again, the magnitude of strip curvature decreases with aspect ratio.
2) Pass height was shown to cause bar turn up on pass 1 and bar turndown on pass 2.
3) The most interesting effect was that of roll speed mismatch. Here the bar turn up on pass 1 where an aspect ratio < 3.5 is found, but bar turn up of little strip curvature was caused on pass 2 ($I_d/H_m > 3.5$).

The second half of this investigation involved the development of a factorial design to determine which of the asymmetrical factors had the greatest effect and at which pass. A summary of the results is given below.

1) Pass height had an insignificant effect on the strip curvature.
2) The most dominant factor, differential friction, had a main location effect on all passes.
3) Only one interaction effect occurred. This was on pass 2, being the friction-roll speed differential interaction.
4) There is also one significant factor of first order interaction effect had affect the strip curvature on pass 2.

These results can now be used to provide a reference for the hot mill operator when problems with strip curvature arise. For example, heavy strip curvature turning down on the first pass would be expected to be caused by either an electrical fault affecting roll speed or a temperature differential which would be related to the reheat furnace or de-scaling operations and changing the diameter of work rolls continuously due to large wear because of hard material of slab.

Scope for the Future Work

In order to get further insight into this process, following things can be done.

- More exact analysis to predict the value can be done using the higher value of mass scaling options.
- Additional rolling parameters of asymmetrical values like work roll diameter, temperature difference across the thickness of the work piece can be studied for further investigation for affecting the strip curvature.
- Prediction of strip curvature can be done for each pass of rolling stand.

Acknowledgements

I am very thankful to ISPAT INDUSTRIES LTD. who had sponsored to carry out this investigation in their esteemed organization and I am also grateful to Mr. Mukesh Surana, Sr. Design Engineer, M S Ramaiah School of Advance Studies, Bangalore, for his instruction and advice in design and analysis software works in HYPERMESH and LS-DYNA throughout the project.

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