ANALYSIS FRONT-END CURVATURE IN THE FINISHING STANDS OF A HOT STRIP MILL*

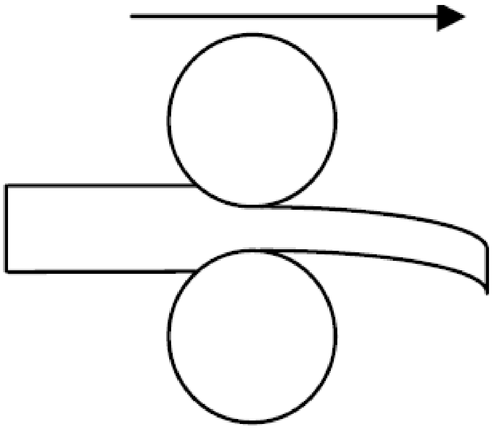
Leonardo Camilo dos Reis[1]
Claudio Silva de Paulo[2]
Edmilson Fernandes Dadomi[3]

Abstract
In the hot strip mill production, one of the factors that may affect the productivity is the occurrence of failure due to the geometry of the strip at the exit of the rolling mill, because the tip of the strip can turn-down or turn-up. This study had the objective of evaluating the behavior of the strip when leaving the working rolls, through numerical simulation, aiming to know the influences of the main variables that govern the formation of the turn-down. The methodology consisted in performing the computational simulation of the strip mill and to vary the operational and geometric parameters that could influence the process. The results showed that the rolling of hot strips of HSLA material with final thickness varying between of 3 to 6 mm and a reduction of 6.6% to 11.0% in the last stand of a hot strip mill, tends to bend towards the roll with larger diameter, higher friction coefficient , higher temperature and lower limit of material flow. It was observed that the variation in diameter is the main factor that contributes to the formation of the curvature of the front-end of strip. Based on these results, several measures were implemented in the industrial line, with a significant reduction in the occurrence of turn-down.
Keywords: Strip mill; Computer simulation; turn-down.

1 Mechanical Engineer, M.Sc., Specialist Researcher, Research Center, Usiminas; Ipatinga, MG, Brazil.
2 Hot Strip Manager, General Management Hot Rolling; Ipatinga, MG, Brazil.
3 Industrial Technical Assistan, General Management Hot Rolling; Ipatinga, MG, Brazil.

1 INTRODUCTION

During the production of hot strips mill the symmetry between the rolling parameters cannot be always guaranteed. Asymmetric conditions occurring during hot strip mill can cause a strip bend, where its tip may be directed downward, "turn-down", or upward, "turn-up", as shown in Figure 1.



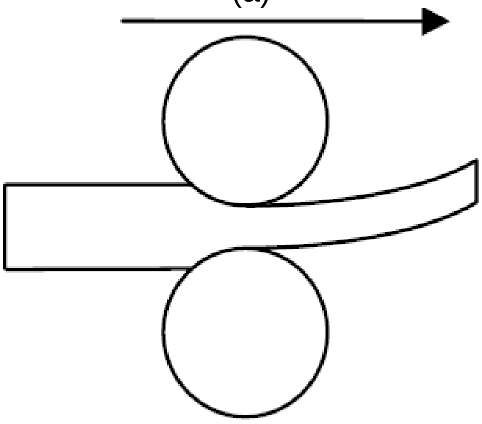


Figure 1. Curvature at the tip of the strip: (a) "turn-down"; (b) "turn-up".

These conditions may reduce the productivity and leads to deterioration in the dimensional accuracy of the rolling strip. In addition, considerable damage to the equipment can occur, especially when the curvature is severe. This mechanism of curvature of the rolling strip is not simple and has a high degree of difficulty to be evaluated [1,2]. The "turn-down" of strip is the main cause of damage to the roller table, caused by the continuous impact between the tip of the strip and the rollers of the table. In more severe cases, the tip fragments of the strip could separate from the end of it and be rolled together with the strip, resulting in poor product quality and increased yield loss. This study had the objective to evaluate the behavior of the strip when leaving the working roll of the last stand of the Hot Finishing Mill, through numerical simulation, to know the influences of some parameters in the formation of "turn-down". According to Harrer and Philipp [3], the parameters which can influence the front-end curvature of the strip are: speed of the working roll, different temperature along the thickness, rolling pass, reduction, difference between the diameters of the upper and lower roll and difference between the friction of the upper and lower roll with the strip.

The first step of this study was to identify the main parameters that influence the curvature of the front end of strip. The parameters are: angular velocities, diameters and coefficient of friction between the rolls (lower and upper), reduction and reduction rate of the strip, initial thickness and hot properties of the strip material. Highlight the tendency of the strip in relation to its form factor. This factor is a function of the degree reduction, initial thickness and rolls radius.

According to Minton and Brambley [4] an analysis of the numerical and experimental studies was carried out over the last years. They verified that some conclusions of the experimental analysis were corroborated by the numerical studies, however, contradictions were also found. In study Minton and Brambley [4] indicate the tendency of the front-end curvature of strip, such as:

- The front-end curvature can be directed to the roll with greater or lesser rotation. The direction of curvature depends on the form factor and the reduction.
- The front-end curvature of the strip can be directed to the roll with a larger or smaller diameter. Again, the magnitude

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of the curvature depends on the shape factor and the reduction.

- The angular velocities of the upper and lower rolls when kept constant, however, with rolls of different diameters, can cause the front-end curvature of strip. This also depends on the form factor and the reduction. Thick strips curl towards the roll faster, that is, with larger diameter, and thin strips, in the opposite direction.
- The front-end curvature tends to be directed to the roll with the highest friction coefficient.
- Curvature also depends on specifically of the property of the material; smaller deformation modules induce to greater curvatures.

2 METHOLOGY

In this work, a computational simulation was performed to verify the influence of some parameters on the curvature formation at the strip tip. The models were developed usingLS-DYNA software to simulate the strip passing through the working rolls of six rolling stands of the Finishing Mill at Usiminas. In the simulation, some considerations were made to simplify the analysis and reduce the processing time:

- The model simulated the strip with reduced dimensions related to the real. This reduction was necessary to reduce the simulation time. The the strip dimensions considered in the model were 50 mm wide, 1 m long and the thickness ranging from 3.2 to 6.2 mm.
- In the model a constant strip temperature was considered, that is, it did not change during its contact with the rolls.
- Since the model simulated only the last stand of the finishing stands of a hot strip mill, the curvature tendencies of the roller strip were neglected in the previous stand roller.

The properties of the hot material were obtained using the equations developed by Misaka and Yoshimoto [5] (Equations 1 and 2) and the modified equation of Hensel and Spittel [6,7,8] (Equation 3), but the best result when compared to the rolling mill in the industrial area, was the model used by Misaka equation.

$$k_{m,M} = 9{,}81 \exp\left(f(C,T)\right).\left(\varepsilon^{0,21}\right).\left(\dot{\varepsilon}^{0,13}\right) \quad (1)$$

$$f(C,T) = 0{,}126 - 1{,}75C + 0{,}594C^2 + (2851 + 2968C - 1120C^2)/(T + 273) \quad (2)$$

Where:
$k_{m,M}$: Resistance to deformation in the original Misaka equation (MPa).
T: Pass temperature (°C).
C: Carbon content of steel (%).
ε: Strain (mm/mm).

$$\sigma_Y=2590e^{-0,0026T}\,(\varepsilon+0{,}002)^{0,3691}\,e^{-0,00263(\varphi+0,0(} \quad (3)$$

$\dot{\varepsilon}$: Strain rate (1/s).

Where:
σ_Y: Yield stress (MPa).
T: Pass Temperature (° C).
ε: Strain (mm / mm).
$\dot{\varepsilon}$: Strain rate (1/s).
$\varphi = \ln h_1 / h_2$: Reduction of the strip, where h1 and h2 are the input and output thicknesses of the strip in millimeters.

The coefficient of friction was calculated using the Geleji's equation [9,10] (Equation 4). In this equation the coefficient of friction is calculated as a function of the temperature and strip velocity.

$$\mu = 1{,}05 - 0{,}0005T - 0{,}056\nu \quad (4)$$

Where:
μ = Friction coefficient.
T = Sheet surface temperature (° C).
ν = Sheet surface temperature (° C).

The computational simulation was divided into two steps. In the first one were validated the models that would be used to evaluate the changes in the parameters that influence the formation of front-end curvature of the strip. The validation of the analysis was carried out by measurement of the rolling force during strip mill process in the industrial line and compared to the force calculated by the simulation. Table 1 shows the list of materials processed in the hot rolling mill line used in the validation of the model.

Table 1. Material and parameters used to validate the models.

Validation	Material	Initial Thickness (mm)	Reduction (mm)	Rolling force (tf)	Strength/Width (tf/mm)
1	HSLA	7.2	1.02	1139.8	1.036
2	HSLA	6.4	1.16	1231.4	1.201
3	HSLA	5.4	1.20	1481.5	1.457
4	HSLA	3.7	0.53	1239.2	0.995

In the second step, the influence of some parameters in the front-end curvature formation of the strip was verified. The parameters evaluated were: upper and lower working rolls diameters, friction coefficient, material properties, temperature difference between the upper and lower surfaces of the strip and offset of one of the working rolls by 5 mm. This offset would be the recoil of the upper roll relative to the material inlet at the mill. For each of the parameters mentioned above, four different initial thicknesses of the strip and its reduction were verified (see Table 2).

Table 2. Cases evaluated to verify the influences of the rolling parameters.

	Parameters	Temperature on strip surfaces (ºC)		Yield stress on half strip (MPa)		Roll diameters (mm)		Friction coefficient	
		upper	lower	upper	lower	upper	lower	upper	lower
1	Diameter	900	900	147.6	147.6	707.0	707.6	0.306	0.306
2		900	900	147.6	147.6	708.0	708.6	0.306	0.306
3		900	900	147.6	147.6	706.0	706.6	0.306	0.306
4		900	900	147.6	147.6	710.0	710.6	0.306	0.306
5	Friction coefficient	900	900	147.6	147.6	707.0	707.0	0.306	0.356
6		900	900	147.6	147.6	708.0	708.0	0.306	0.356
7		900	900	147.6	147.6	706.0	706.0	0.306	0.356
8		900	900	147.6	147.6	710.0	710.0	0.306	0.356
9	Material	900	900	147.6	151.5	707.0	707.0	0.306	0.306
10		900	900	147.6	151.5	708.0	708.0	0.306	0.306
11		900	900	147.6	151.5	706.0	706.0	0.306	0.306
12		900	900	147.6	151.5	710.0	710.0	0.306	0.306
13	Temperature	900	890	147.6	151.5	707.0	707.0	0.306	0.311
14		900	890	147.6	151.5	708.0	708.0	0.306	0.311
15		900	890	147.6	151.5	706.0	706.0	0.306	0.311
16		900	890	147.6	151.5	710.0	710.0	0.306	0.311
17	Offset 5 mm	900	900	147.6	147.6	707.0	707.0	0.306	0.306
18		900	900	147.6	147.6	708.0	708.0	0.306	0.306
19		900	900	147.6	147.6	706.0	706.0	0.306	0.306
20		900	900	147.6	147.6	710.0	710.0	0.306	0.306

All models at Table 2 were considered having the same speed and geometry of the strip. Figure 2 presents a typical model used for validation and study of the parameters.

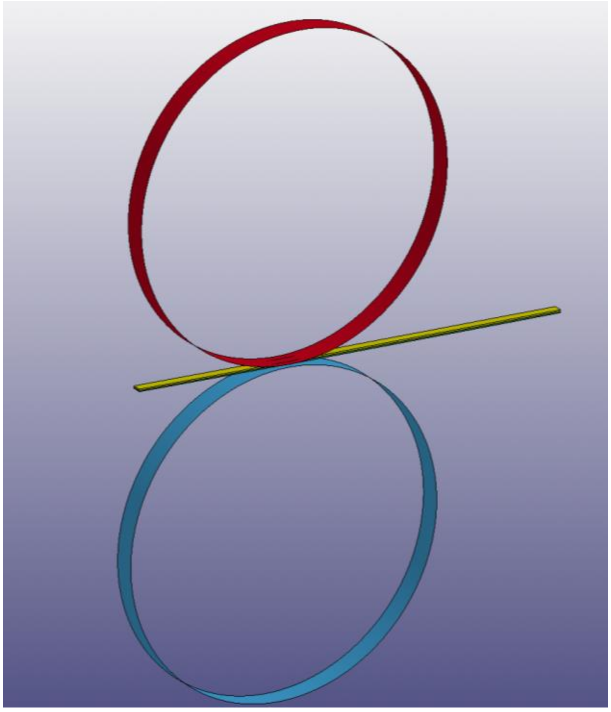

Figure 2. Typical model developed for validation and evaluation of rolling parameters.

2.1 Three-Dimensional Modeling

The 3D CAD models generated for the analysis were developed in Ansys 16.1 software. In order to facilitate the simulation process and to reduce the study time, a strip with a 50 mm width and 1000 mm length was simulated without affecting the quality of the results.

2.2 Material Properties

The materials used in the rolls were considered rigid and the properties of the hot rolled strip were extracted from the equations 1 and 2 in [5]. To determine the strain x strain deformations of the rolled strip used in the validation of the model, the following material conditions were considered:

• Hot rolling temperature (T) = 890 °C and 900 °C.
• Carbon steel content (% C) = 0.09.
• Deformation rate = 24.5 1/s.

Figure 3 shows the graph of the strain x strain curve calculated through the Misaka and **Yoshimoto's** equation [5] for the condition described aforementioned.

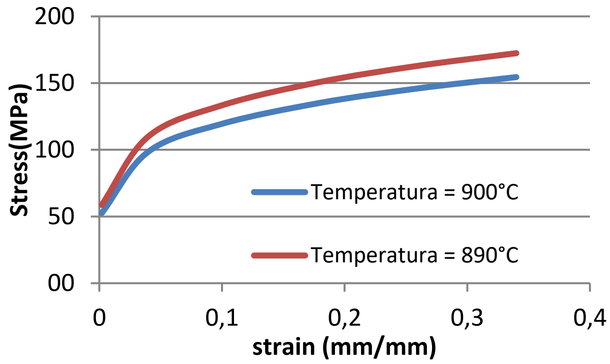

Figure 3. Tension x deformation curve.

2.3 Finite Element Mesh

The finite element mesh is the subdivision of the models to be analyzed with complex geometry in several small elements that have the simple and known geometry. This makes the calculation process easier. So, the finite element mesh for the two models studied is presented in figure 4.

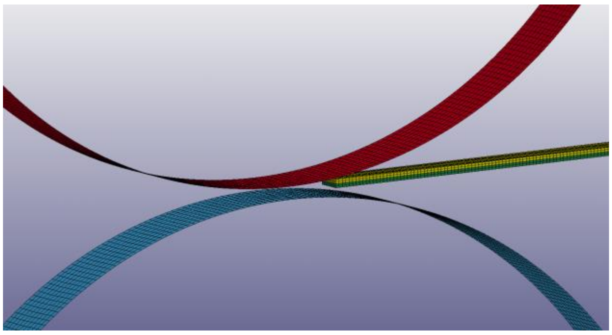

Figure 4. Typical finite element mesh used in the models.

2.4 Boundary Conditions

In the analyzed models a 3.6 rad/s angular velocity was applied in the upper and lower rolls and also was considered the strip rolled at initial velocity of 5,250 mm/s. Figure 5 shows the boundary conditions applied.

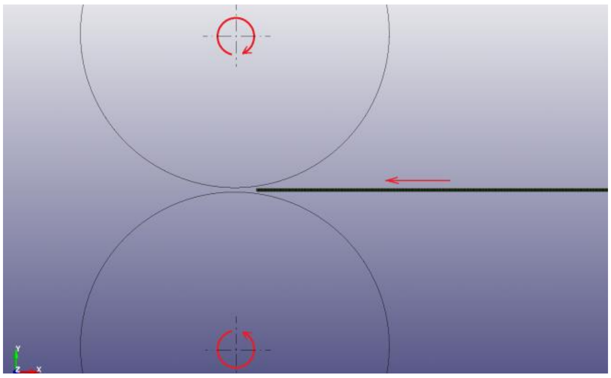

Figure 5. Boundary conditions applied to models

3 RESULTS

1.1 Validation

In order to validate models four different hot strip mills were evaluated and, for each situation, the rolling load was extracted. In these validations the simulation calculated the rolling force of 50 mm wide, 1 m long strip and its thickness as defined in Table 1. Figures 6 to 9 present the results of the rolling force calculated by the computational simulation of the materials and indicated in Table 1.

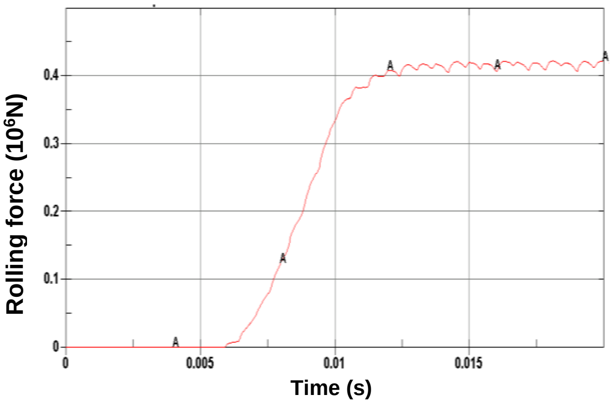

Figure 6. Validation 1 - Rolling force.

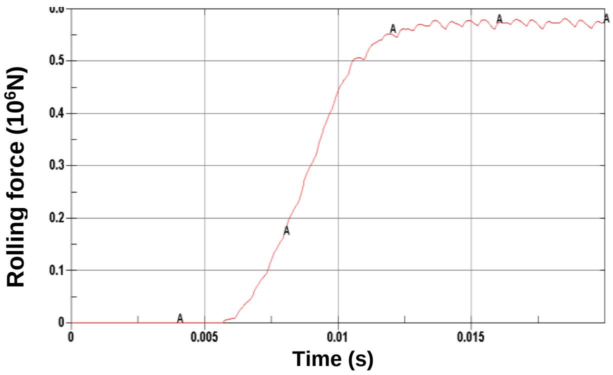

Figure 7. Validation 2 - Rolling force.

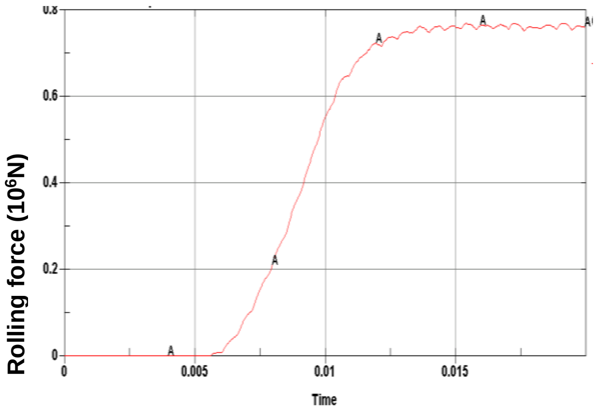

Figure 8. Validati[illegible]olling force.

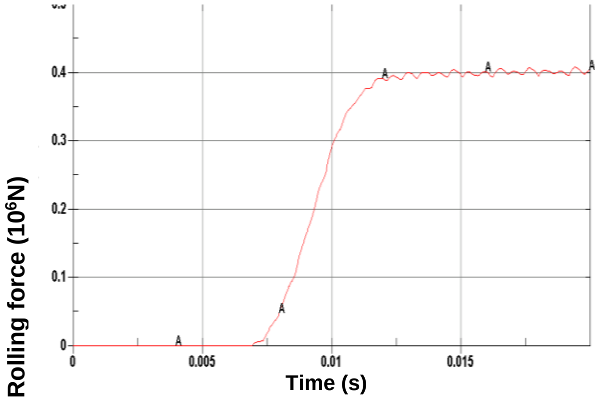

Figure 9. Validation 4 - Rolling force.

The measured and simulated rolling force results were divided by the width of the rolled strip. Table 3 presents and compares the results of the model with the real process.

Table 3. Comparison of the rolling force as a function of the width of the rolled strip in the industrial area and the simulated process.

Validation	Thickness (mm)	Width (mm)	Measures values Force/Width (tf/mm)	Simulation Force/Width (tf/mm)	Error (%)
1	6.18	1100	1.036	0.857	17.3
2	5.20	1025	1.201	1.179	1.8
3	4.20	1017	1.457	1.556	-6.8
4	3.20	1245	0.995	0.815	18.2

Table 3 shows a maximum error of 18.2% between the simulation and the real process. This error is acceptable because of during the process there is no information about the temperature value of the material before being rolled, and because this temperature is only measured, approximately, 1 s after its rolling mill. Thus, this model is recommended to evaluate the influences of the rolling parameters of the front-end curvature of the strip.

3.2 Parameters Evaluation

Figures 10 to 14 show the curvature of the strip at the exit of the six stand of hot strip mill as a function of the parameters: cylinder diameter, friction coefficient, material properties, temperature and offset of the working cylinder by 5 mm.

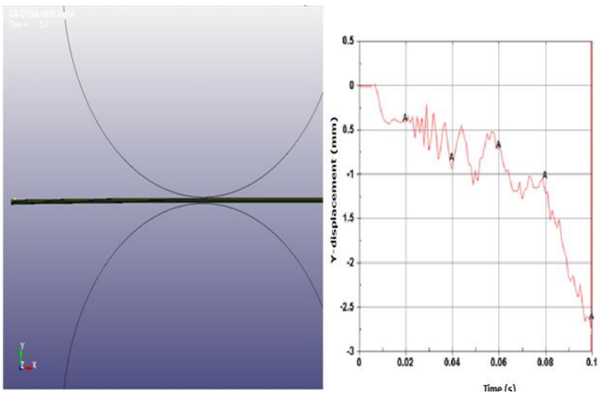

Figure 10. Strip curvature - Case 1 - Parameter: Diameter.

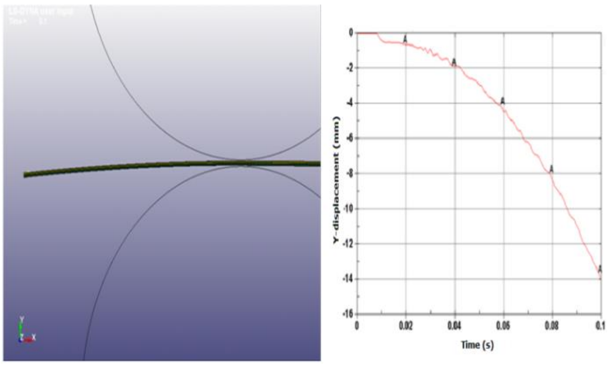

Figure 11. Curvature of the strip - Case 5 - Parameter: Friction.

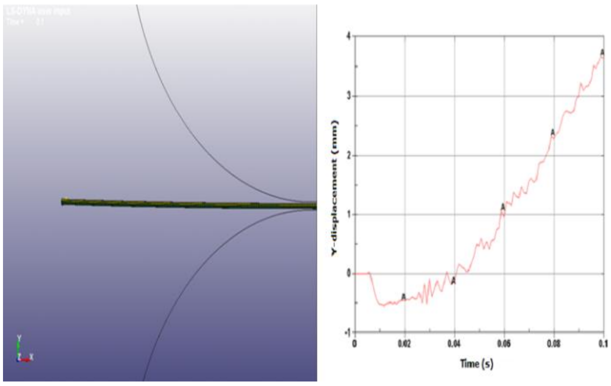

Figure 12. Curvature of the strip - Case 9 - Parameter: Material.

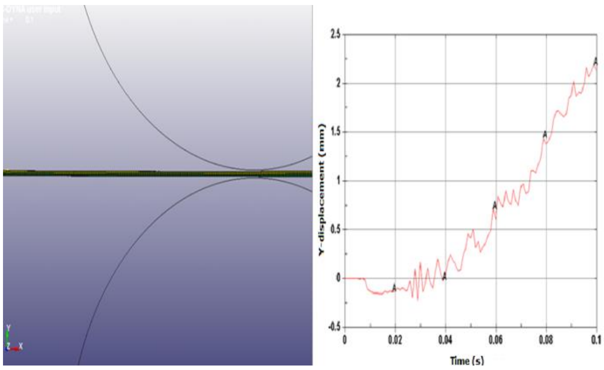

Figure 13. Curvature of the strip - Case 13 - Parameter: Temperature.

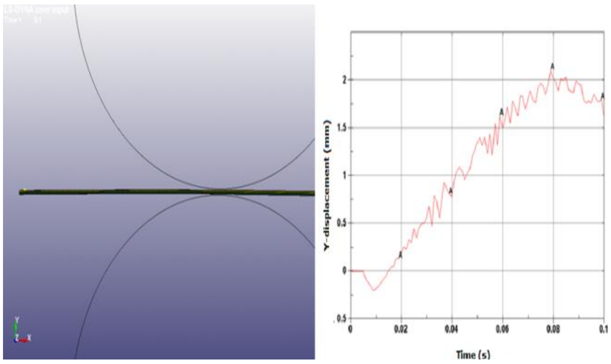

Figure 14. Curvature of the strip - Case 17 - Parameter: Offset in 5 mm.

Table 4 shows the bending values and the curvature radius of the strip after 0.1 s of rolling for all simulated cases. This table also shows the radius of the front-end curvature of the strip.

Table 4. Bending values and radius of curvature of the strip according to the parameters evaluated.

Cases	Parameters	Final Thickness (mm)	Reduction (%)	Shape Factor	Tip Offset (mm)	End Curvature – Radio (mm)
1	Diameter	6.2	6.6	4.09	-3.311	40.27
2		5.2	8.7	5.11	-3.442	39.43
3		4.2	10.9	6.31	-3.788	35.41
4		3.2	6.6	5.72	-7.634	15.31
5	Friction coefficient	6.2	6.6	4.09	-17.863	6.51
6		5.2	8.7	5.10	-13.888	8.48
7		4,2	10,9	6,31	-12,768	9,28
8		3,2	6,6	5,72	-14,089	8,17
9	Material	6,2	6,6	4,09	4,526	22,41
10		5,2	8,7	5,10	3,141	30,31
11		4.2	10.9	6.31	2.475	36.67
12		3.2	6.6	5.72	4.091	25.91
13	Temperature	6.2	6.6	4.09	0.745	89.92
14		5.2	8.7	5.10	1.854	46.34
15		4.2	10.9	6.31	1.243	61.14
16		3.2	6.6	5.72	2.302	43.97
17	Offset	6.2	6.6	4.09	0.921	78.86
18		5.2	8.7	5.10	1.279	60.65
19		4.2	10.9	6.31	5.239	19.32
20		3.2	6.6	5.72	2.030	49.18

According to the results presented in table 4 was verified that a curvature occurred in the strip directed to the roll with larger diameter, higher coefficient of friction, lower value of the yield stress, higher surface temperature and in the direction of roll offset. Since the variation of the parameters was not simulated, a linear verification of the parameters that most contributed to the curvature of the strip was performed, dividing the arrow of the strip by the percentage of the altered value in each parameter. Table 5 presents the results obtained from linearization.

Table 5. Linearization of the bending as a function of the percentage change of each parameter

Parameters	Variation (%)	Mean bending (mm)	Bending / Variation (mm/%)
Diameter	0.1	-4.1	-40.5
Friction coefficient	14.0	-14.2	-1.0
Material	2.6	4.0	1.6
Offset 5 mm	0.4	2.9	8.1

The results obtained in Table 5 determined that among all evaluated parameters, the change in roll diameter is the factor that most contributed for the formation of the front-end curvature of the strip. It should be noted that in the simulations the same angular velocities were considered for the two rolls.

4 CONCLUSIONS

The results analysis demonstrated that the hot rolling mill in six finishing stands of HSLA quality materials, final thickness ranging from 3 to 6 mm and a reduction of 6.6% to 11.0% tended to curve towards the roll with the largest diameter, higher coefficient of friction, higher temperature and lower yield stress of the material. The offset of the upper roll by 5 mm in the direction of the inlet of the strip causes a curvature of the upward end.

The variation in diameter is the main factor that contributes with the formation of the front-end curvature of the strip, followed by the roll offset. The friction coefficient and material require high variations to affect to the curvature of the strip tip. As for the offset, before any changes, a fine evaluation must be performance in the structure of the six finishing stands in order to verify its resistance.

Based on these results, several measures were implemented in the industrial line, with a significant reduction in the occurrence of "low-end".

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