3D FINITE ELEMENT MODELING OF EDGE AND WIDTH DROP BEHAVIOR IN HOT ROLLING MILL

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Abstract: Hot rough rolling is a conventional forming process in modern steelmaking practice in which high deformations are applied to a steel slab at high temperatures. Due to the sequence of edge rolling followed by rough rolling, so-called edge and width drop phenomena are observed at the head and tail of the slab. These unwanted effects govern a yield loss and need to be minimized as much as possible. By means of a finite element study this research aims to discover the main influencing parameters on the observed edge and width drop behavior. An overview and comparison of the relative contributions of several edge rolling settings are presented. The net edger roll opening is the most important influencing parameter on edge and width drop behavior. The effect of width and thickness of the slab on the edge drop is less strongly pronounced; only the thickness influences the width drop behavior.
Keywords: edge drop; width drop; Finite Element Analysis, hot rolling, edger

1 INTRODUCTION

Steel is one of the most important structural materials used in each aspect of our everyday life, ranging from household appliances to large industrial equipment. The ArcelorMittal Group is the global leader in steel manufacturing, with branches all over the world. The production site of ArcelorMittal in the harbor of Ghent specializes in plate rolling with an annual production of 5 million tons of finished steel coils [1]. With such high capacities, every yield loss should be minimized as much as possible in order to maximize efficiency and remain profitable.

The process to transform iron ores into high-quality carbon steels involves a number of process steps. Without providing further detail, one of the most important steps in steel manufacturing at ArcelorMittal Belgium is hot rolling of large slabs coming from the continuous caster. During hot rough rolling, the first stage of hot rolling, the slab is rolled to a thickness ranging between 13% and 18% of its initial thickness in five or seven passes through a reversing mill stand. To allow for the high deformations occurring in hot rough rolling, initial temperatures of typically 1200°C, well above the recrystallization temperature of plain carbon steel, are used [2]. The reversing mill stand is composed of an edge (vertical) rolling mill and a rough (horizontal) rolling mill [3], as illustrated in Figure 1.

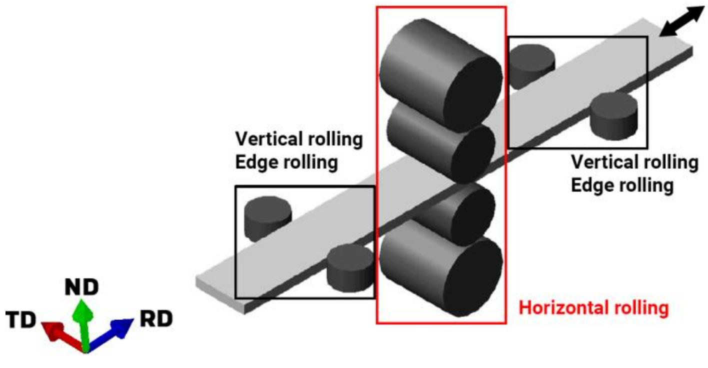


Figure 1. Schematic layout of hot rough rolling mill; RD = Rolling Direction; TD = Transverse Direction; ND = Normal-to-Rolling Direction (adapted from [3])

Edge rolling is applied to reduce the width of the slab, compensating for the width increase due to the Poisson effect in the subsequent horizontal rolling passes. This process is known as *strip width control* and determines the final width of the slab [4]. As shown by Ruan et al. [5], the edger tends to deform the slab only locally, giving rise to a so-called *dog bone shaped slab* (Figure 2). During horizontal rolling the dog bone is flattened, causing the heaped material at the edges to introduce uneven plastic deformation in both transverse and rolling direction. This is clearly visible at the slab end, where undesirable width and thickness changes give rise to so-called *edge* and *width drop* phenomena [4], illustrated in Figure 3. In practice the deformed slab end is cut off, governing a yield loss.

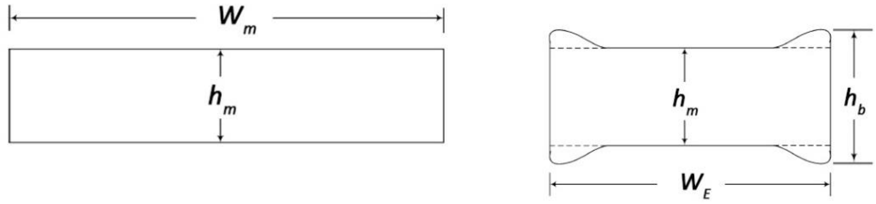


Figure 2. Dog-bone shaped slab resulting from edge rolling, left = initial slab cross-section, right = after edge rolling (adapted from [3])

Remark that edge and width drop phenomena are typically located only at the head and tail of the slab. Indeed, in the center of the plate the neighboring material prevents excessive inhomogeneous deformation in the rolling direction. However, since the end planes are unrestrained at one side, the deformation can freely occur in this direction.

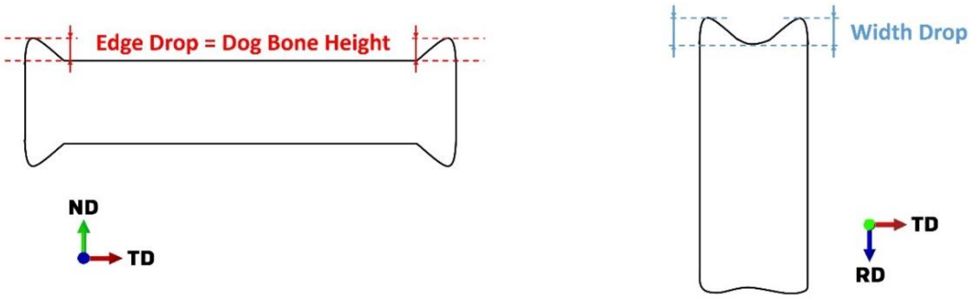


Figure 3. Definition of edge and width drop used throughout this paper

Edge and width drop behavior in the roughing mill has been the subject of several studies, e.g. by Lee et al. [6] or Xu et al. [7]. Also the dog bone shape formation has been studied in detail by e.g. Liu et al. [8]. Most of these studies applied the numerical finite element (FE) technique to model the rough rolling process. FE methods are preferred over analytical methods due to their higher possible accuracy and ability to include highly nonlinear material behavior [9]. However, FE models require high calculation times, making them inapplicable for on-line control schemes [3]. For on-line control, analytical models are the only feasible option. In such case, FE models can be used to simulate various rolling conditions off-line, generating results upon which an analytical model can be based.

A practical measure to reduce edge and width drop lengths, is adapting the edger rolls' geometry. Unlike the schematic representation of the edging mill in Figure 1, a real edger looks vastly different for material flow reasons. In the 1960s, a patent by Orr and Reinhardt [10] introduced the grooved edger roll, as illustrated in Figure 4. Modern edger roll designs are still based on this patented geometry.

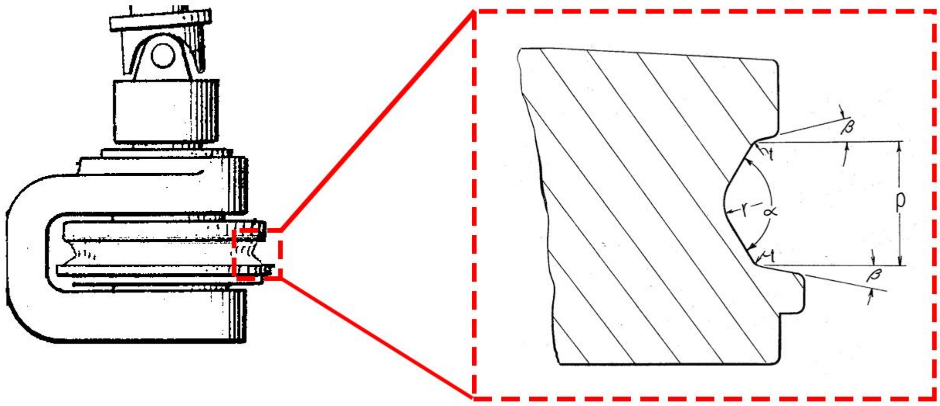


Figure 4. Grooved edger roll as patented by Orr and Reinhardt (adapted from [10])

In the present research, a 3D finite element model of a rolling process has been developed in Abaqus/CAE [11] in order to simulate and predict the edge and width drop behavior. After validating the model with real process data from the hot rolling mill at ArcelorMittal Belgium, the relative effects of the influencing parameters on the deformed slab ends will be identified. This paper focuses on these relative effects in the edge rolling mill only.

2 MODEL OF EDGE ROLLING MILL

2.1 General Considerations

Hot rolling is a process in which large deformations at elevated temperatures are involved. In the contact zone between rolls and the slab, friction with the rolls causes the slab to be pulled through the roll gap [12,13]. The effects of contact and friction both depend on the dynamics of the system. Additionally, solving the dynamic equations of motion in a 3D finite element model will be computationally expensive. Therefore, a dynamic/explicit solution technique is chosen [13].

Conventional meshes become heavily distorted when large deformations take place. In adaptive meshes, however, the mesh is revised at a specified frequency and heavily distorted meshes are smoothened whereby the field variables will be remapped to the new mesh. As a result, with adaptive meshing the initial quality of the mesh will be maintained throughout the total analysis, even in applications involving high plastic deformation such as hot rough rolling. The advantages of adaptive meshing over conventional meshing led to the decision to apply adaptive meshing in the FE model of the hot rough rolling mill [14].

The slab cools down due to radiation, contact cooling with the rolls, and water jet cooling due to the presence of an oxide layer removing process step called *scale breaking* [15-17]. On the other hand, the slab heats up due to frictional dissipation and plastic deformation. Since the temperature of the slab affects its mechanical properties, a coupled thermo-mechanical simulation is required to accurately model hot rough rolling.

2.2 Geometry and Material Properties

2.2.1 Slab

After continuous casting, hence before edge rolling, the slab has a rectangular cross-section as in the left side of Figure 2. A typical initial thickness is 223mm and initial widths range between approximately 700mm and 2000mm [1]. For describing the material behavior of steel in this simulation, a modified version of the material property model of Eurocode 3 [18] for steel grade S355 was adopted. This material model suggests a stress-strain relationship in which temperature effects are taken into account. An overview of the mechanical properties (engineering stress values) is given in Table 1; values at intermediate temperatures can be determined by interpolation. Additionally, a Poisson's ratio of 0,3 was used in the linear elastic domain, a density of 7850 $\frac{\mathrm{kg}}{\mathrm{m}^3}$, a thermal conductivity of 27,3 $\frac{\mathrm{W}}{\mathrm{m \cdot K}}$, and a specific heat of 650 $\frac{\mathrm{J}}{\mathrm{kg \cdot K}}$.

Table 1. Mechanical properties (engineering stress values) of slab used in FE simulations

	Temperature = 1100 °C	**Temperature = 1200 °C**
Young's Modulus E	25,20 GPa	18,90 GPa
Proportional limit stress σ_p	23,67 MPa	17,75 MPa
Yield Stress σ_y	71,59 MPa	39,05 MPa
Stress at plastic strain = 0.1	72,68 MPa	39,64 MPa

2.2.2 Edger Roll

Referring to Figure 4, the geometry of the edger rolls in the FE model will include a grooved profile. However, the exact geometry of the edger roll profile cannot be disclosed for reasons of confidentiality. Rolls in the hot rolling mill are composed of very hard material, such as High Speed Steel or High-Carbon High-Chromium steel [19], which maintain their hardness at elevated temperatures. Ideally, the rolls can be modeled as rigid bodies compared to the thermally softened steel slabs.

2.3 Assumptions and Boundary Conditions

To speed up calculations, a quarter symmetric model is assumed. Also, not the full length (in the rolling direction) of the slabs is used in the simulation. At the center of the plate a steady state situation will be present, which will not influence the end effects. It has been verified that a slab with a length of 20% of the real length yields results concerning the edge and width drop behavior within a 1% error margin of simulations with the full length, as shown in Table 2.

Table 2. Comparison of simulations with full length and with reduced length

Simulated length of slab (%)	Relative dog bone height (%)	Relative width drop (%)	Calculation time (%)
100	100,0	100,0	100,0
30	100,0	100,0	14,1
20	100,2	100,8	6,9
15	93,6	99,2	3,0

The roll is constrained to be fixed, only a rotation with constant rotational velocity of 35 rpm around its axis is imposed. In reality, the initial opening of the edger rolls cannot be maintained due to the high reaction forces when a slab is rolled, broadening the gap and giving rise to a net edger roll opening which is slightly larger than the initial edger roll opening. Hence, in this model only the net edger roll opening is taken into account, i.e. the measured edger roll opening after initial contact with the slab.

The kinematic contact method is chosen as contact definition. To describe friction between the edger rolls and the slab, Coulomb friction with a constant coefficient of friction of magnitude 0,5 was assumed. The severity of this assumption will be assessed by varying the friction coefficient, as will be discussed in Section 3.4.

From a thermal point of view, a radiative boundary condition is applied at the surface planes of the slab. During contact, a thermal contact conductance coefficient of 200 $\frac{W}{m^2 \cdot K}$ is defined, to take contact cooling with the rolls into account. The water jet cooling is modeled as an external thermal load at the surface of the slab.

2.4 Validation

A convergence study was conducted to obtain the dimensions of the mesh as described in Table 3. The model shown in Figure 5 was validated by means of process data from the hot rough rolling mill at ArcelorMittal Belgium. Measured forces on the edger roll are compared to the reaction forces acting on the modeled edger roll. With the higher defined material model for S355 steel reasonable agreement with the measured values was obtained: within a 10% error margin, except for very small edger roll openings.

Table 3. Detail of mesh used in edge rolling mill FE model

Edger Roll	Slab
5 951 elements	96 480 elements
Linear tetrahedral	Linear hexahedral
Type C3D4T	Type C3D8RT
Element size = 92mm	Element size = 10mm to 100mm

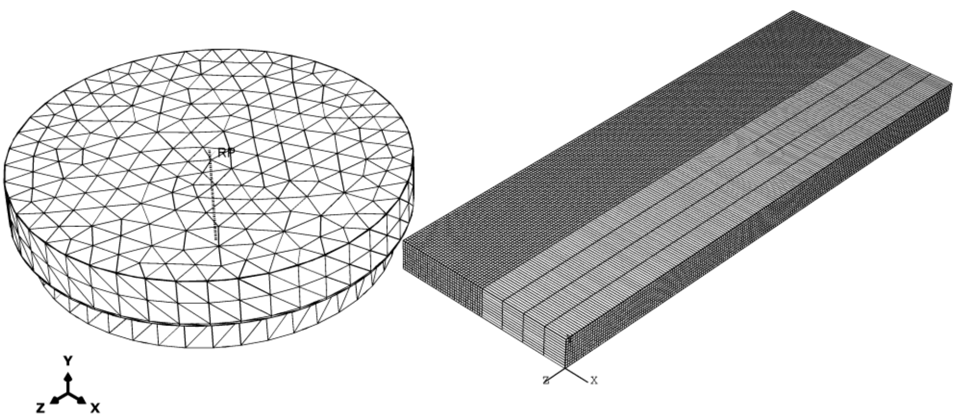


Figure 5. View of edge rolling mill FE model

To verify the simulated temperature profile, a numerical finite difference scheme for solving the temperature equations over the slab in open air and in contact conditions was implemented using Matlab. Using the Matlab script, the average cooling rate during contact with the edger roll and during transport in open air were determined. After this, a number of dummy runs of the FE model in which all cooling effects were simulated individually, allowed to validate the proposed thermal conductance of 200 $\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}$ and emissivity coefficient of 0,7 for the slab.

3 RESULTS

Using the developed and validated FE model, the relative effects of edger roll opening, width and thickness of the slab, and the friction formulation on the edge and width drop length in hot edge rolling are examined. All relative effects in the following paragraphs are referred to the edge and width drop values found in the standard configuration as described in Table 4.

Table 4. Standard configuration as reference for single-parameter influence study

Slab Width	1400mm	Edger Roll Rotational Velocity	35 rpm
Slab Thickness	223mm	(Coulomb) Friction Coefficient	0,5
Net Edger Roll Opening	30mm	Initial Temperature	1200°C
Edge Drop	13,55mm	Width Drop	27,91mm

3.1 Effect of Edger Roll Opening

Simulations for 20mm to 90mm net edger roll opening were carried out. If more width reduction is given by the edger mill, both dog bone height and width drop increase proportionally, as illustrated in Figure 6. The edger roll opening is intimately linked with the volume of material at the edges being displaced, explaining the large influence on the edge and width drop behavior.

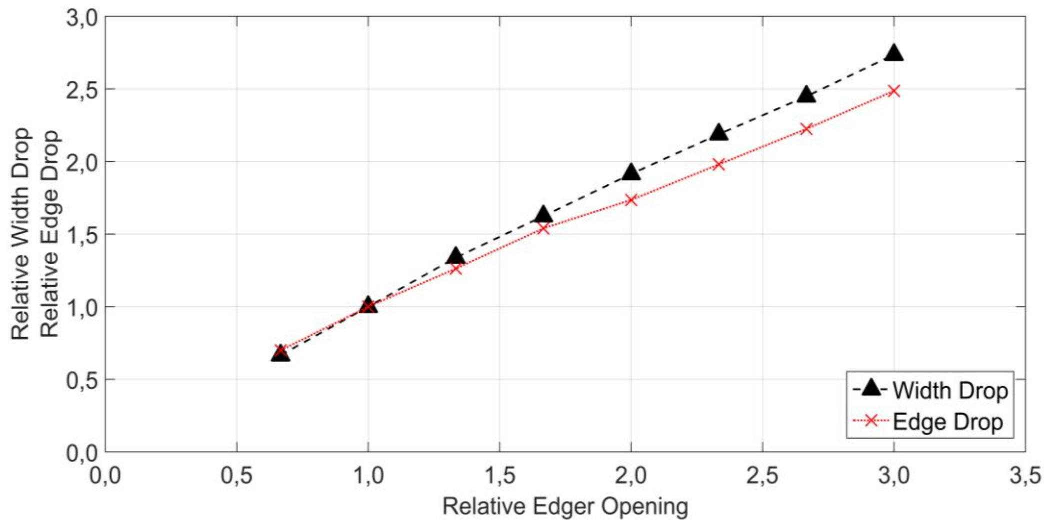


Figure 6. Relative effect of edger opening on edge and width drop

3.2 Effect of Width

Slabs with a width between 800mm and 1750mm have been simulated, the results of these simulations are plotted in Figure 7. Regarding the width drop behavior, no influence of the width of the slab is noticed. As for the edge drop behavior, width variations will affect the total edge drop up to some point; in this case the reference slab width. Increasing the width above 1400mm does not influence the edge drop anymore. The edge drop reduction at smaller widths is less strongly pronounced than for the same relative reductions in edger opening. The reduced edge drop at smaller widths can be attributed to the influence zone of the contact pressure in the slab. In smaller slabs the region of stress exceeding the yield stress extends across the entire slab width, whilst for larger slab widths these regions do not reach the center of the plate. This is schematically shown in Figure 8, where the von Mises stress contour in a 800mm wide slab is compared to that in a 1750mm wide slab (both at the same time instant and at the same scale). Once the stress magnitude drops below the yield strength of the material, no plastic deformation occurs anymore in that part of the slab, which is why further increasing the width has no noticeable effect on the edge drop anymore from some point on.

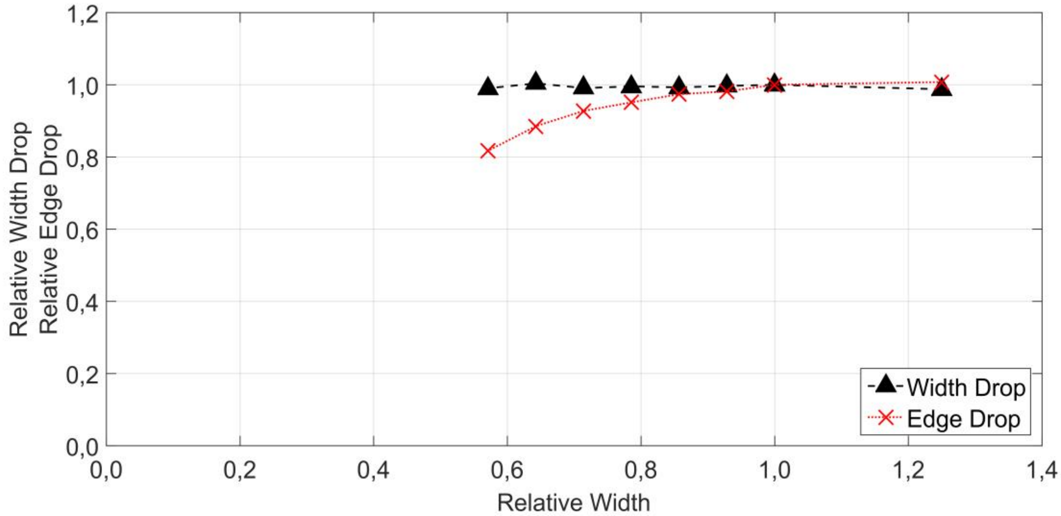
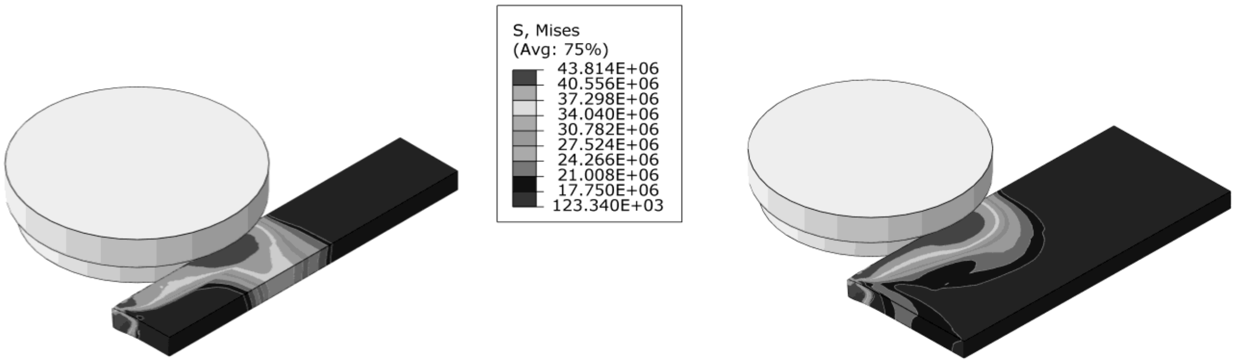


Figure 7. Relative effect of width on edge and width drop



a. 800mm wide slab

b. 1750mm wide slab

Figure 8. von Mises stress contour plot in (a) 800mm wide slab and (b) 1750mm wide slab

3.3 Effect of Thickness

Varying thicknesses are encountered when a multi-pass rolling scheme is modeled. A simulation with a thickness of 223mm models the first rolling pass, smaller thicknesses model the following steps. Figure 9 visually represents the simulated results for various thicknesses between 60mm and 223mm. Reduced thicknesses result in smaller edge and width drop values, although the effect is less strongly pronounced than with reduced edger openings. The edge drop varies proportionally with the thickness variation; the width drop reducing effect diminishes at smaller thicknesses, hence in later steps of the rolling steps.

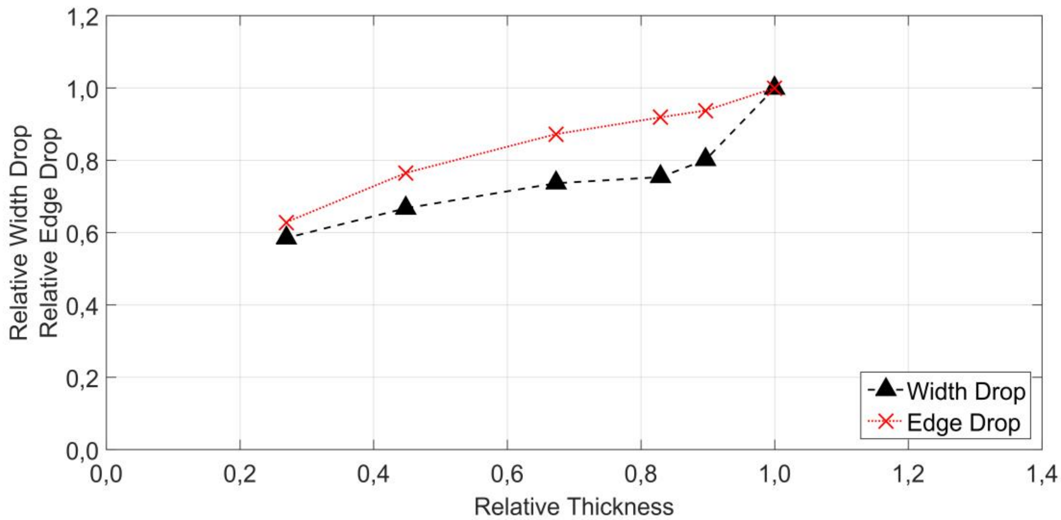


Figure 9. Relative effect of thickness on edge and width drop

3.4 Effect of Friction

In the standard configuration, Coulomb friction is considered. The friction between the rolls and the slab is the driving force behind rough rolling, meaning that too low friction coefficients will cause the slab to be rebound instead of being pulled through the roll gap. Therefore, no friction coefficients smaller than 0,5 were taken into consideration. Table 5 summarizes the results of simulations with higher friction coefficients. As is clear from this table, friction seems to be having no significant influence on the simulated edge and width drop behavior. A similar observation was also reported by Xiong et al. [20].

Table 5. Relative influence of friction on edge and width drop behavior

Friction coefficient (-)	0,5	0,8	0,95
Relative dog bone height	1,000	0,998	0,974
Relative width drop	1,000	0,997	0,972

3.5 Summarizing Remarks

Edge and width drop behavior in the edge rolling mill tend to be primarily influenced by the net edger opening and the thickness of the slab. In smaller slabs also the width contributes to the edge drop behavior in the same proportion as the thickness. Hence, if edge and width drop are to be reduced, the width reduction in the first passes (largest thickness) needs to be minimized as much as possible. Smaller slabs tend to be most beneficial in the context of edge and width drop behavior.

4 CONCLUSIONS

This research focused on the formation mechanisms of undesirable edge and width drop behavior in a hot roughing mill. By means of a FE model in Abaqus/CAE the relative contribution to the edge and width drop behavior of the net edger opening, the width and thickness of the slab, and the friction between slab and roll are identified. The net edger opening is the most important influencing parameter, whereas friction seems to only have a negligible effect. Both width and thickness of the slab contribute more or less equally to the edge drop behavior, albeit less strongly pronounced than the effect of the edger opening; only the thickness influences the width drop behavior, but its width drop reducing effect diminishes at smaller thicknesses.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] “Staalfabriek." [Online]. Available: http://gent.arcelormittal.com/werkomgeving/staalfabriek/ [Accessed April 12, 2017].

[2] S. Vervynckt, Control of the Non-Recrystallization Temperature in High Strength Low Alloy (HSLA) Steels. PhD thesis, Ghent University, 2010.

[3] D. Yun, D. Lee, J. Kim, and S. Hwang, “A New Model for the Prediction of the Dog-bone Shape in Steel Mills," ISIJ INTERNATIONAL, vol. 52, no. 6, pp. 1109-1117, 2012

[4] Industrial Automation Services (IAS), “International rolling technology course - strip width control," 1997.

[5] J. H. Ruan, L. W. Zhang, S. D. Gu, W. B. He, and S. H. Chen, “3D FE modelling of plate shape during heavy plate rolling," Ironmaking & Steelmaking, vol. 41, no. 3, pp. 199-205, 2014.

[6] D. H. Lee, K. B. Lee, J. S. Lee, S. J. Yun, T. J. Shin, and S. M. Hwang, “A New Model for the Prediction of Width Spread in Roughing Mills," JOURNAL OF MANUFACTURING SCIENCE AND ENGINEERING-TRANSACTIONS OF THE ASME, vol. 136, OCT 2014.

[7] L. Xu, W. Hong-yu, D. Jing-guo, X. Jiu-jing, and Z. Dian-hua, “Analysis and prediction of fishtail during V-H hot rolling process," JOURNAL OF CENTRAL SOUTH UNIVERSITY, vol. 22, pp. 1184-1190, APR 2015.

[8] Y. Liu, D. Zhao, D. Zhang, G. Ma, and F. Yin, “Study on dog-bone shape of edge rolling using cosine model," in PROCEEDINGS OF THE 2015 INTERNATIONAL CONFERENCE ON INTELLIGENT SYSTEMS RESEARCH AND MECHATRONICS ENGINEERING (Liu, J and Wang, Y and Xu, H, ed.), vol. 121 of Advances in Intelligent Systems Research, pp. 1587-1590, 2015. International Conference on Intelligent Systems Research and Mechatronics Engineering (ISRME), Zhengzhou, PEOPLES R CHINA, APR 11-13, 2015.

[9] K. L. Halm, “On the modeling of rolling: a special look at edge cracking," mathesis, University of Illinois, Urbana-Champaign, 2012.

[10] H. S. Orr and A. D. Reinhardt, “Method of rolling slabs in planetary mill," U.S. Patent 3,422,656, Jan. 21, 1969.

[11] Dassault Systèmes, “Abaqus/CAE 6.14 User’s Guide“, Dassault Systèmes – Simulia, 2014.

[12] Industrial Automation Services (IAS), “International rolling technology course - rolling theory," 1997.

[13] Dassault Systèmes, “Abaqus Example Problems Manual - 1.3.6 Rolling of thick plates”, Apr. 2010.

[14] Dassault Systèmes, “Abaqus Analysis User's Manual - 12.2.1 ALE adaptive meshing: overview”, Feb. 2010.

[15] B. Merci, “Conductie," in Warmte- en Verbrandingstechniek, ch. 2, pp. II/1 - II/37, Unpublished, 2014.

[16] B. Merci, “Straling," in Warmte- en Verbrandingstechniek, ch. 4, pp. IV/1 - IV/34, Unpublished, 2014.

[17] H. Okada, T. Fukagawa, H. Ishihara, A. Okamoto, M. Azuma, and Y. Matsuda, “PREVENTION OF RED SCALE FORMATION DURING HOT-ROLLING OF STEELS," ISIJ INTERNATIONAL, vol. 35, no. 7, pp. 886-891, 1995.

[18] “Eurocode 3: Design of steel structures - part 1-2: General rules - structural fire design," EN 1993-1-2 , Apr. 2005.

[19] R. D. Mercado-Solis, J. Talamantes-Silva, J. H. Beynon, and M. A. L. Hernandez-Rodriguez, “Modelling surface thermal damage to hot mill rolls," WEAR, vol. 263, pp. 1560-1567, SEP 10 2007.

[20] S. Xiong, Z. Jiang, H. Xie, and X. Liu, “Numerical simulation of slab edging process by the Reproducing Kernel Particle Method considering friction effect," INTERNATIONAL JOURNAL OF SURFACE SCIENCE AND ENGINEERING, vol. 3, no. 5-6, pp. 482-489, 2009.