PREVENTION OF CONTACT FATIGUE DAMAGE OCCURRENCE IN REVERSING ROUGHING MILLS *

Sébastien FLAMENT [1]
Olivier LEMAIRE[2]
Gisèle WALMAG[3]
Mario SINNAEVE[47]

Abstract

Many hot rolling mills worldwide face nowadays bonding zone fatigue problems before reaching scrap diameter of the work rolls. This phenomenon is nowadays known to occur in reversing roughing mills both in stainless steel and in carbon steel rolling. The phenomenon can be explained through longer rolling campaigns, inadequate backup or work roll maintenance, harder steel grades or increased throughput by reduced amount of passes to achieve the same thickness.

In order to help users in optimizing the roll use, we developed a numerical tool to evaluate and optimize roll maintenance. This paper will review the influence of roll geometries on stresses generated at the roll surface but also at the bonding zone. We will also show how roll geometries can decrease contact fatigue damages by modifying crowning and chamfering procedures, shell thickness, material design or campaign length

Keywords: Roughing mill; Fatigue; Bonding zone; Design.

[1] *Chemical engineer, Senior project leader, CRMGroup, Liège, Belgium.*
[2] *Electromechanics (Aerospace) Engineer, Senior specialist, CRMGroup, Liège, Belgium.*
[3] *Metallurgical engineer, Senior expert, CRMGroup, Liège, Belgium.*
[4] *Master of Science, Industrial Engineering, R&D – Quality Control Manager, Marichal Ketin, Liège, Belgium.*

1 INTRODUCTION

The high chromium steel grade was developed in Europe in the early 80´s, in order to replace grades such as adamite steel, ICDP or forged steel grades exhibiting much lower performances. This grade was since then introduced in most of the existing roughing stands of hot strip mills (HSMs) as well as into the early finishing stands of compact strip mills.

The ever increasing requirements for roughing mills in terms of cost/performance ratio including higher throughput, improved product quality and higher safety have stimulated rollmakers to develop in the early 90´s a new roll grade for roughing stands which is known as semi-High Speed Steel (semi-HSS). Semi-HSS acquired rather rapidly a strong position especially in Western European HSMs. However, some applications like stainless and special steel rolling have shown interest of further development to overcome some insufficiencies of semi-HSS. A special High-Speed Steel (HSS) grade for roughing mill application was developed to meet this new challenge in the late nineties – see history of work roll development in Figure 1.

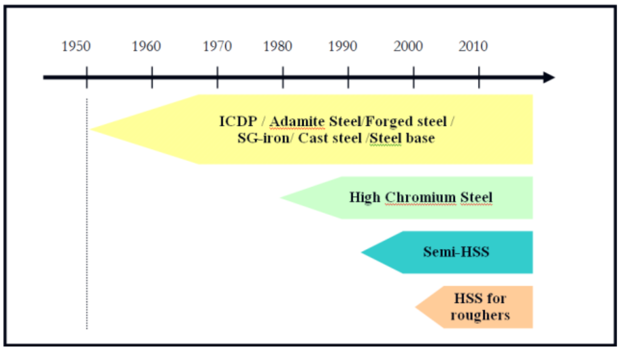


Figure 1: History of work roll grades development for roughing mill stands

After introducing the semi-HSS rolls, the potential of this grade was used to extend the campaign length of the roughing work rolls and to increase mill throughput in reversing roughing stands by moving from a standard 7 pass practice to a 5 pass rolling strategy. This process change was favored by the excellent biting behavior of semi-HSS grade. For semi-continuous mills, standard campaign length with high chromium steel rolls was ranging from 20 to 40 ktons in the late 80's, for full continuous mills the campaign length was around 80 to 100 ktons. Nowadays, semi-continuous mills are using semi-HSS rolls with campaign length ranging from 65 to 120 ktons, and up to 200 ktons in full continuous mills. One can easily understand that the total cycles per campaign are easily doubled or even tripled compared to the past.

The core material of the new generations of roughing mill rolls remains roughly unchanged and the properties of the shell-core interface also did not changed drastically by adopting the new shell chemistries. The higher mechanical loads of the rolls (increase campaign length and rolling strategy change from 7 to 5 passes) give nowadays raise to more and more fatigue phenomena. These fatigue problems are observed on roughing mill work rolls leading sometimes to premature failures initiated at the shell-core interface (bonding zone) of the roll. This type of failure mainly concern semi-continuous or ¾ mills and up to now was not observed in full continuous mills.

Table 1 illustrates the current situation of most of the European hot strip mills in terms of roll usage and campaign length. The table compiles data from mill rolling strips, both carbon and stainless steels but excluding plate and steckel mills. The table indicates the type of mill, the standard grade used in roughing stand, the standard campaign length and if the mill faces fatigue problems. In Europe, 8 out of 15 mills using a reversible roughing stand face fatigue issues. This figure increases every year and becomes a true problem both for users and roll makers. A standard practice is nowadays to increase the remaining shell thickness at scrap diameter of the roll by minimum 25mm and more (radius related) to prevent fatigue problems in the bonding zone in the concerned mills.

Mill	Type	Grade	Standard campaign length (kt)	Fatigue issues encountered
1	1/2	HSS	10-15	yes
2	1/2	Semi-HSS	50-55	no
3	1/2	HSS	80-90	yes
4	1/2	HSS	80	no
5	1/2	HSS/Semi-HSS	40-50	yes
6	1/2	Semi-HSS	45	yes
7	1/2	Semi HSS	100	no
8	1/2	semi HSS	80	yes
9	1/2	Cr Steel	25	no
10	1/2	Semi HSS	65	no
11	1/2	semi HSS	40	yes
12	1/2	HSS/semi-HSS	25	yes
13	1/2	Cr Steel	20-40	no
14	1/2	HSS	40	no
15	3/4	Semi HSS	80-120	Yes
16	FC	Semi-HSS	120	no
17	FC	HSS	150	no
18	FC	Semi HSS	150	no
19	FC	Cr Steel	50	no
20	FC	Cr Steel	no info	no
21	FC	Cr Steel	no info	no

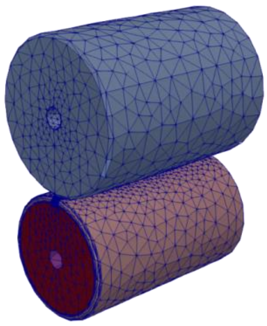
Table 1: Situation in European hot strip mills

2 DISCUSSIONS

Literature [1-6] has mentioned fatigue problems due to contact between the work and backup rolls (WR & BUR) for more than 15 years. It also indicates that a proper design of the backup rolls chamfers can reduce its severity by decreasing stresses in both work and backup rolls. Still nowadays fatigue in the roughing stands lead to premature failures or damages on both work and back-up rolls. In too many situations the fatigue problems could be limited by a good chamfering practice of the backup roll, crowning procedure, correct design of the shell thickness or limited campaign length. For this reason a special modeling tool has been developed with CRM.

2.1 Development of a numerical tool to predict stresses in work and backup rolls

A three-dimensional elasto-plastic FEM model (using Code ASTER & GMSH [7]) has been developed in order to evaluate stresses in the work roll shell and bonding zone as well as in the back-up roll. Figure 3 gives an overview of the model. We choose to model only the barrels in order to limit the amount of elements to be computed and thus the computation time. For the same reason, the mesh size was increased in areas far from the contact area between BUR and WR. Although not visible on the figure, the influence of the strip is considered in the model to take into account stresses generated by bending of the rolls.


a)

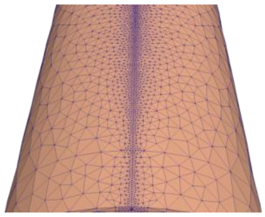

b)

Figure 3: a) Overview of the model: BUR (top roll) and WR (bottom roll); b) zoom on the refined mesh in the contact area of the WR

This tool is fully parametric to be adapted quickly to each mill configuration. The aim is to be flexible and adapt easily to the roll user situation taking into account material properties, roll design but also mill practices. In this way we are able to rapidly describe to the roll user the current roll mechanical loading and propose solutions for improving the roll use.

For both work and backup rolls, the following data are required:

- Diameter
- Barrel length
- Chamfer and edge relief geometries
- Crowning practice and geometry
- Wear profile
- Mechanical properties (for shell, bonding zone and core)
- Shell thickness

- Fatigue resistance (core material only)

The model requires some rolling parameters:

- Rolling force
- Average, minimum and maximum slab width
- Campaign length

They are of primary importance for the accuracy of the model. These concern geometries and rolling parameters. Material properties (mechanical and fatigue resistances, shell thickness) are issued from roll maker databases. Figure 4 a illustrates typical compressive properties of roll materials including work roll shell (WR), work roll core (core) and backup roll (BUR). Mechanical properties in the model are based on experimental measurements of the compressive yield stress of the materials and fitted with theoretical work hardening laws. The ultimate strength of the materials are not taken into account as we do not consider crack initiation and crack propagation laws in the model. The use of this model requires checking manually if the maximal stresses reached are in agreement with the ultimate strength of the materials.

The model takes also into account the fatigue resistance [9] of the weakest part of the work roll, namely the core (Figure 4 b). The bonding zone properties are known to be in between shell and core properties but have been assimilated to core material to stay safe in the interpretation of the results.

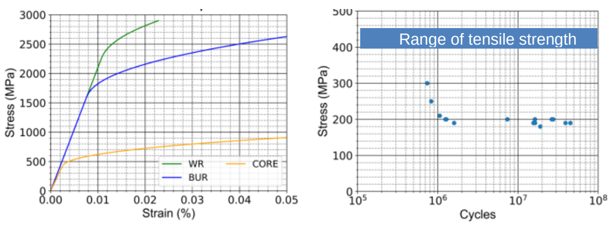


Figure 4: a) Mechanical properties (compression) of BUR and WR shell and core; b) Wöhler diagram of work roll core material [9]

2.2 Definitions

To avoid misunderstanding by readers, we have thought necessary to define some terms related to roll diameters and shell thicknesses. Indeed vocabulary can differ between users concerned by life duration of the roll, roll makers concerned with the residual shell at scrap diameter and modeler concerned by total shell thicknesses. Figure 5 a illustrates a cross section of a roll:

- D1 is the external diameter of the roll
- D2 is the scrap diameter i.e. the diameter of the roll above which the roll can be used in the mill with the same properties as delivered. Below this diameter, properties are no more guaranteed.
- D3 is the diameter of the core material.

Figure 5 b illustrates:

- 1: the total shell thickness. This can be related to the total shell thickness at delivery of the roll but also the total remaining shell thickness if the roll has already been used and ground.
- 2: the usable shell thickness which is the parameter interesting roll users.
- 3: the residual shell thickness at scrap diameter which correspond to the thickness of shell material below which the properties of the roll are no more guaranteed. The standard practice until the late 90's was a residual shell thickness of 15mm but tends to be increased to 30 mm and even more to prevent fatigue problems in the concerned mills.

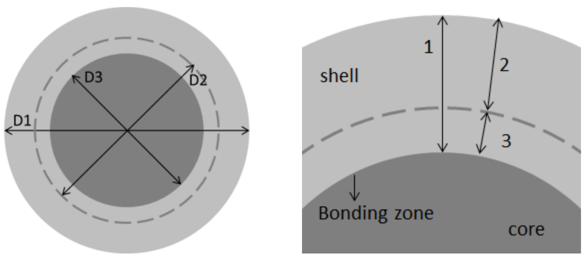


Figure 1: definition of a) diameters and b) shell thicknesses

3 INFLUENCES OF SHELL THICKNESS AND ROLL PROFILE ON STRESSES

Based on industrial data and configuration we have computed the influence of the shell thickness on stresses at the work roll surface and in the bonding zone for several cases. The configuration is mentioned in Table 2. This mill uses straight chamfers on the BUR (Figure 6 a). Work and backup rolls wear respectively reach 1750µm and 1000 µm in the center of the barrels (Figure 6 b).

Roll parameters	Work roll	Backup roll
Diameter nominal - scrap (mm)	1100 - 990	1600
Total shell thickness at delivery (mm)	70	NA
Usable shell thickness (mm)	55	NA
Barrel length (mm)	1800	1800
Chamfer / edge relief		Straight 175 x 6mm / 25mm 45°
Crown (mm/radius)	None	NA
Wear (µm/radius)	-1750	-1000
HRM parameters		
Strip width (mm)	1500	
Rolling force (ton)	Maximum 4000	

Table 2: configuration 1

a)

b)

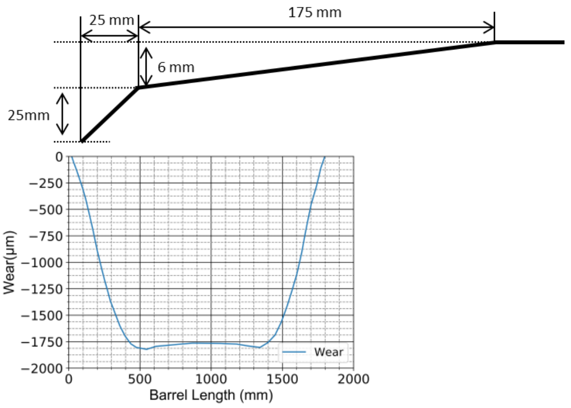


Figure 6: a) BUR straight chamfer and edge relief; b) work roll wear profile;

It has to be noted that this mill usually begins to observe work roll fatigue damages at the bonding zone when the total remaining shell thickness reaches 30mm, for an total shell thickness of 70mm (15mm earlier than the normal residual shell thickness which is 15mm). It means that the delivery of a work roll with a lower residual shell thickness than 30mm will not reach its scrap diameter. For this reason, we have evaluated the stresses distribution for three total shell thicknesses:

- 60 mm: simulating stresses in the shell after several campaigns (10mm ground out of the total shell thickness at delivery of the roll).
- 30 mm: simulating the total shell thickness from which the mill begins to observe fatigue damages at the bonding zone.
- 15 mm: simulating the former residual shell thickness at scrap diameter in this mill.

The influence of the roll profiles on stresses generated has been evaluated for three cases: as ground (no wear – flat barrel) rolls, worn BUR and ground WR, worn BUR and WR - Table 3).

		BUR	WR	Total remaining shell thickness (mm)	Acronym
	#1	No wear	No wear	60	BNWN60
	#2	Worn	No wear	60	BWWN60
	#3	Worn	No wear	30	BWWN30
	#4	Worn	No wear	15	BWWN15
	#5	Worn	Worn	60	BWWW60
	#6	Worn	Worn	30	BWWW30
	#7	Worn	Worn	15	BWWW15

Table 3: cases studies – explanation of the acronyms: for case #4: Bur Worn, Work roll No wear, shell thickness 60 mm results in the acronym BWWN60

The results are illustrated as the evolution of Von Mises stresses along the barrel width. We have considered the case of ground BUR and WR with a work roll shell thickness of 60 mm as the reference case.

The Von Mises stresses for this case have been set at 100%. All other cases are related to the reference case. Figure 7 illustrates the stress evolution at the work roll surface for the seven cases. We can conclude that for this configuration:

- The maximum stresses are located at 175 to 200 mm from the edges, corresponding to the end of the chamfer of the BUR.
- When the BUR is worn, contact between WR and BUR is limited to a 400mm wide area on each side of the work roll. The contact area being smaller the stresses are higher compared to the reference case (ground rolls) reaching 220% vs 150 for the reference case in this zone.
- The shell thickness has a limited impact on surface stresses
- When the shell thickness reaches 15mm (thickness at scrap diameter) a stress increase in the center of the work rolls is observed. This is due to higher bending of the work roll, less stiff than a roll with thicker shell, compensating BUR wear. Both rolls make thus contact in the center of the barrel.

Figure 8 illustrates the stresses evolution along the barrel length at the work roll bonding zone. One observe that:

- When the BUR is worn, a stress increase of 400% occurs at the WR edges compared to the reference case
- WR wear has a more limited impact on stresses compared to BUR wear (400 to 500%)
- The shell thickness decrease from 60 to 30 and 15mm respectively increase the stresses in the bonding zone from 500 to 850 and 1200% in the worn situation.

As no fatigue damage is observed at customer site by US control of the bonding zone as long as the total remaining shell thickness remains above 30mm, we can conclude that the maximal Von Mises stresses at the bonding zone must remain below 850%.

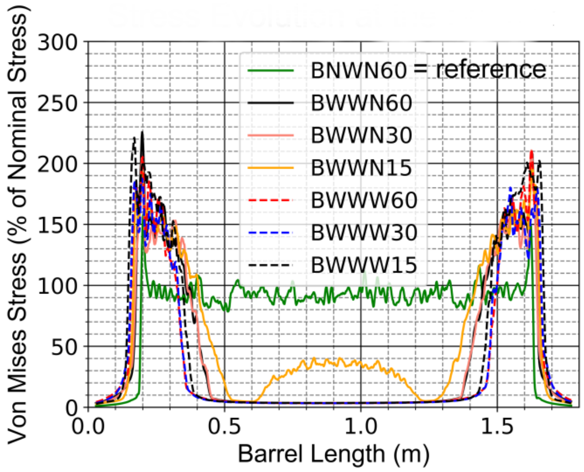


Figure 7: Stress Evolution at the WR surface

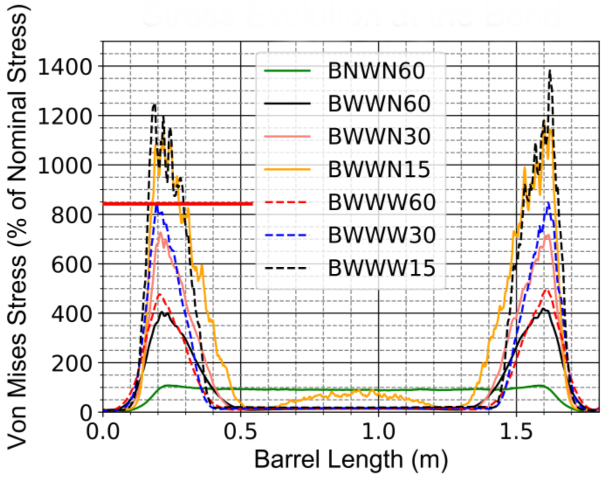


Figure 8: Stress Evolution at the WR bonding zone. Red line indicates the Von Mises stresses at which fatigue is observed on the roll

3.1 Modification of backup roll chamfer and edge relief

Based on this configuration, we have modified the chamfer and edge relief from a straight configuration to a double radius (see illustrations in Figure 9 a and b). Three cases were simulated:

- Ground BUR and WR with a total shell thickness of 60mm
- Worn BUR and ground WR, shell thickness = 30mm
- Worn BUR and ground WR, shell thickness = 15mm

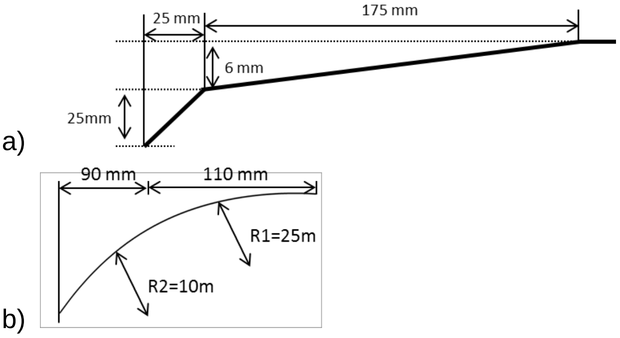


Figure 9: a) initial straight chamfer and edge relief; b) double radius chamfer and edge relief

Surfaces stresses are not highly influenced by the change of chamfer design. However, in the bonding zone, the modification of chamfering procedure has an influence for a thickness of 30mm. Stresses at the bonding zone are limited to 600% compared to 750% when using a straight chamfer.

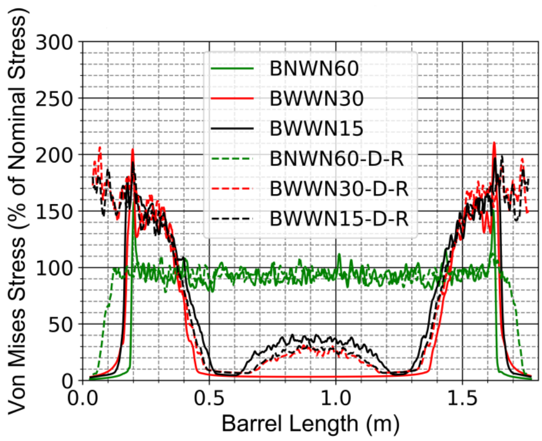


Figure 10: Stress Evolution at the WR surface (no index: straight chamfer, index D-R: double radius)

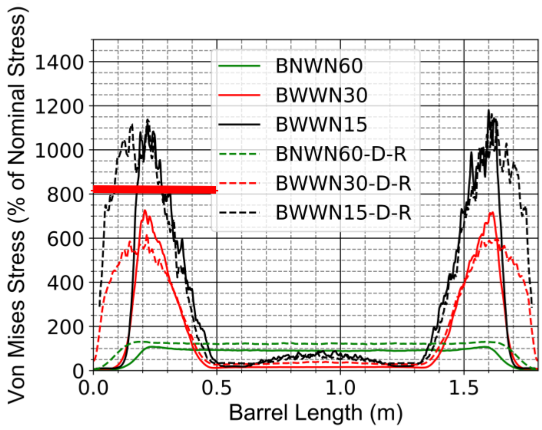


Figure 11: Stress Evolution at the WR bonding zone (no index: straight chamfer, index D-R: double radius). Red line indicate the Von Mises stresses at which fatigue is observed on the roll

3.2 Conclusions

The model clearly explains where and why fatigue damage can occur in this mill as well as the influence of the BUR chamfering procedure. The full study includes also the evaluation of the maximal admissible wear of work and backup rolls to be able to reach the scrap diameter with a residual shell thickness of 15mm. The complete study enables roll makers and user to find an optimal situation.

4 EVALUATION OF A WORK ROLL SPALLING

In a second mill, a semi-HSS work roll suffered of a spalling (Figure 12 a) located at 650mm from the edge. The WR diameter when the spalling occurred was 1155 mm being 30 mm from scrap diameter. The roll was delivered with a residual shell thickness at scrap diameter of 15 mm. All parameters are mentioned in Table 4. When spalling occurred, the total remaining shell thickness was 30 mm. In order to understand the origin of the spalling several analyses were performed:

- Cross section analyses of roll material in the spalling zone
- Estimation of the amount of contacts between work roll and slab
- Numerical modeling of the stresses distribution for several roll diameters

4.1 Cross section analyses

The analysis of a sample taken out of the spalling zone was carried out by scanning electron microscopy (SEM) to evaluate the causes of the breakage. This standard practice enables to evaluate if the reason of the spalling is linked to the production of the roll (presence of defects, slag or porosities) or to mill practice (overloading of the roll). The examination indicates a secondary crack in the core material, parallel to the roll surface. Surrounding the secondary crack, many smaller cracks parallel to the initial roll surface are also observed (Figure 12 b). These cracks are known to be fatigue cracks due to the contact between work roll and backup roll. No defects linked to casting problem could be observed.

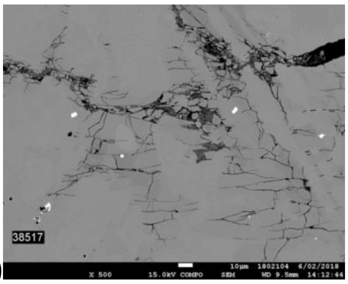
a)  b) 

Figure 12: a) picture of the spalling; b) illustration of contact fatigue cracks in sample issued from spalled work roll

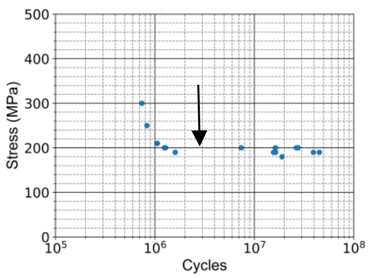
4.2 Fatigue resistance

Analysis of the data collected from the mill indicated a total rolled tonnage of 1.3 Mton for this roll, mainly in 7 passes, sometimes 5 passes. An estimation of the total amount of revolutions in contact with the strip has been performed. Some assumption needed to be done as the average tonnage of a slab, its average length and its thicknesses at the entry and exit of the roughing mill. Based on the figures indicated in Figure 13 a, we estimate that the roll is 103 times in contact with each slab. Based on the fact that the roll has rolled 1.3 Mton, we estimate it to 65000 slabs and finally a total of 6.7 million revolutions in contact with a slab.

As illustrated by the Wöhler diagram of the core material (Figure 13 b) we can estimate that the maximal allowable stress to avoid fatigue damages of the bonding zone, at this stage of the roll life is 180 MPa.

a)

Rolled quantity (10^6 ton)	1.3
Slab average weight (ton)	20
Slab average length entre RM (m)	15
Slab thickness entry RM (mm)	240
Slab thickness exit RM (mm)	30
# passes	7
Roll average diameter (mm)	1200
Other assumptions: same reduction at each pass	



b)

Figure 13: a) Figures and assumption to estimate the amount of contacts with the strip; b) Wöhler diagram of the core material at calculated number of cycles

4.3 Stress distribution modeling

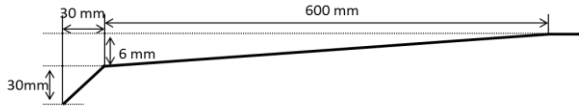
The 3D model has been used to evaluate stresses in the work roll based on the configuration mentioned in Table 4.

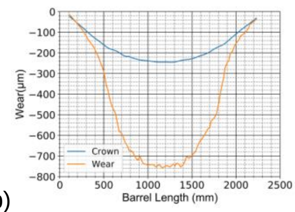
Roll parameters	Work roll	Backup roll
Diameter nominal - scrap (mm)	1250 - 1125	1600
Total shell thickness at delivery (mm)	77.5	
Usable shell thickness (mm)	62.5	
Diameter when spalling occurred (mm)	1155 (Total remaining shell thickness: 30 mm)	1525
Barrel length (mm)	2030	2030
Chamfer / edge relief		Straight 600 x 6mm / 30mm 45°
Crown (mm/radius)	-0.2	
Wear (mm/radius)	-0.75	-0.17
HRM parameters		
Strip width (mm)	1500	
Rolling force (ton)	~ 4000	

Table 4: configuration 2

The backup roll has a 600mm long straight chamfer (Figure 14 a). To help in strip guidance, a negative crown of 200 µm is applied to the work roll. Wear profiles of both rolls are illustrated in Figure 14 b and c. The same approach as for configuration 1 has been adopted. The seven cases of Table 3 were simulated. Three total remaining shell thicknesses were selected:

- 60 mm: shell thickness of the roll after several campaigns (17.5mm ground out of the delivered total shell thickness)
- 30mm: total remaining shell thickness when spalling occurred
- 15mm: residual shell thickness at scrap diameter

a)


b)


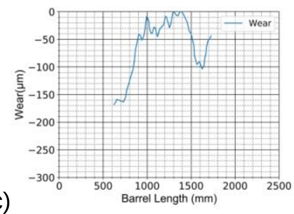
c)


Figure 14: top: chamfer design of the BUR, bottom left: crown and wear profile of the WR; bottom right: wear profile of the BUR

The results are expressed as in configuration 1 as Von Mises stresses increase related to the reference case. The reference cases being the case considering ground BUR and WR with a work roll shell thickness of 60mm. Stresses of this case have been set at 100%. The results indicate that the maximum stresses are located at 650mm from the edge of the roll, which corresponds to the spalling location occurrence.

Figure 15 illustrates stresses at the WR surface. Contrary to the first presented case, the wear profiles on BUR and WR do not hinder contact in the centre of the rolls. In this configuration, surface stresses are similar in every tested condition.

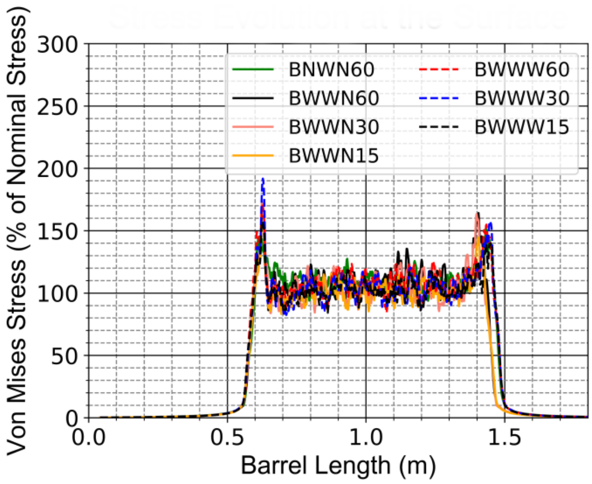


Figure 15: Stress Evolution at WR surface

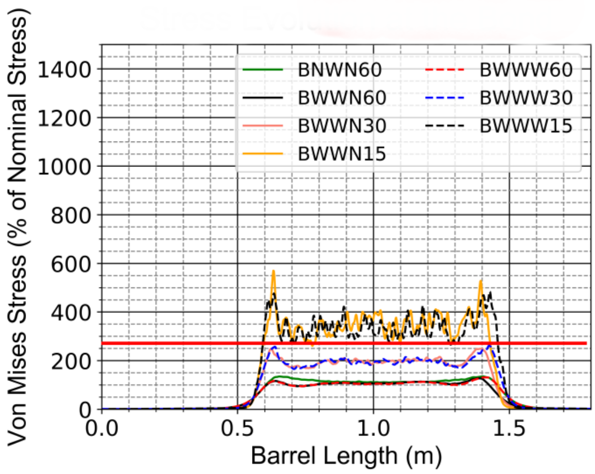


Figure 16: Stress Evolution at WR bonding zone. Red line indicate the Von Mises stresses at which the roll broke

Figure 16 illustrates the stresses at the WR bonding zone for the different cases. Similarly to the first configuration, decreasing shell thickness increases the stresses at the bonding zone. However, the relative increase is more limited compared to the first configuration. Nevertheless, spalling occurred for a Von Mises stress of 250% (curve BWWW30 in Figure 16). This figure also indicates that reaching the scrap diameter (residual shell thickness of 15 mm) with the actual configuration is impossible. Indeed, Von Mises stresses for a residual shell thickness of 15mm reach 580% in the bonding zone corresponding to more than 2 times the Von Mises stresses which led to spalling.

4.4 Modification of the chamfering procedure

An evaluation of the chamfering procedure has been established to evaluate its importance on stresses intensity and distribution at the bonding zone, all other parameters being kept identical. Figure 17 illustrates the three chamfers having been evaluated: the standard chamfer design, a shortened chamfer length and a double radius chamfer. The evaluation was done for a remaining shell thickness of 30mm which corresponds to the shell thickness when spalling occurred. As we have modified the BUR chamfer length, we decided to evaluate the chamfer design of ground BUR and worn work rolls to be able to compare the situations and avoid inconsistencies due to incomplete BUR wear profile data.

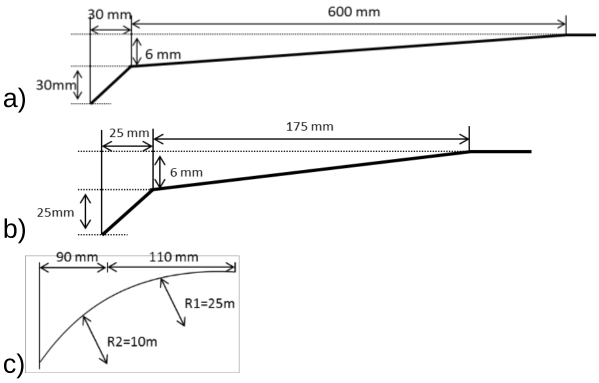


Figure 17: a) original chamfer of this mill; 200mm-straight chamfer; double radius chamfer

Figure 18 illustrates the influence of the chamfer design on surface stresses of the work roll. Modifying the chamfer design induces a decrease of the maximal surfaces stresses on the work roll from 150 to 100% when using a double radius chamfer. If the chamfer is kept straight but shorter, the maximal stresses on the work roll surface are increased compared to the original chamfer design. This can easily be understood as the slope of the chamfer is higher for the shortest one.

Concerning the bonding zone, the maximum stresses are decreased if the chamfer length is shortened or machining a double radius. If a double chamfer was applied on the BUR, the maximal stresses would be lowered from 250 to 150% (Figure 19).

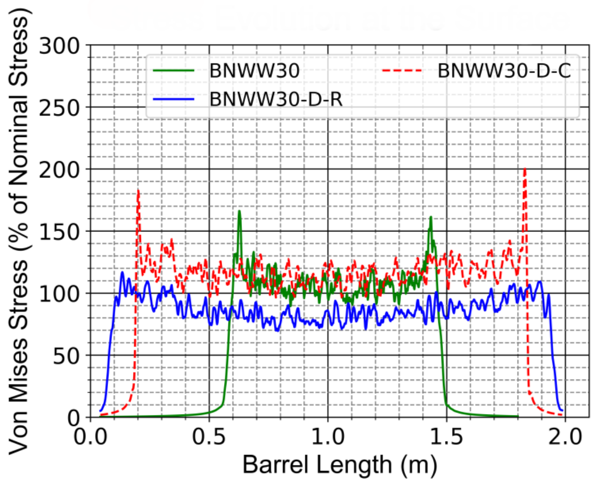


Figure 18: Stress Evolution at WR surface (BNWW30: original 600mm chamfer; D-C: 200mm straight chamfer; D-R: double radius chamfer)

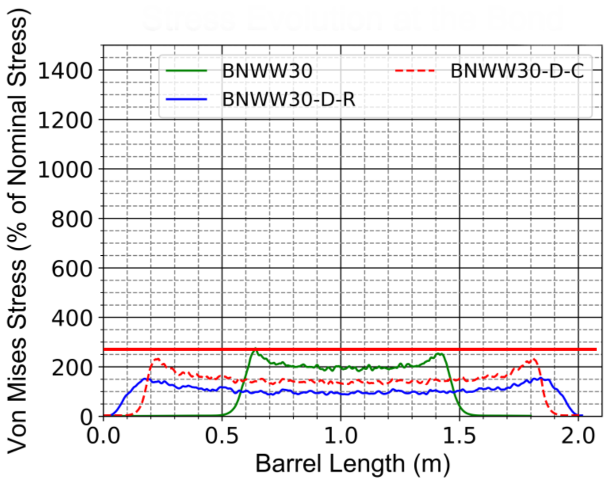


Figure 19: Stress Evolution at WR bonding zone(no index: original 600mm chamfer; index D-C: 200mm straight chamfer; index D-R: double radius chamfer). Red line indicate the Von Mises stresses at which the roll broke

4.5 Conclusion

The study of this spalling case has pointed out the origin of the breakage. It results from the cumulated stresses along the roll life exceeding the fatigue resistance of the bonding zone (core material). The 3D model enables also to propose an optimised chamfer design to the mill to decrease mechanical loads in the bonding zone, avoiding spalling occurrence.

5 OUTLOOK

The numerical tool developed to estimate stresses in the shell material of a work roll has already proven its usefulness for several cases both for mill operators and roll makers.

A potential outlook would be to develop a simplified tool to avoid the repeated use of the time consuming FEM modeling. It would be based on abacus calculated by the FEM model for various roll geometries and forces. The aim is to use the abacus while in the rollshop to rapidly give guidelines to the user.

It must be pointed out that the accuracy of the required data to feed the FEM model directly influences the simulation results. In the frame of industry 4.0 many activities are launched like data acquisition and direct communication with server, tracking of rolls in the hot strip mill. Some mills are already evaluating roll tracking with chips (RFID or NFC) to be able to track them in the mill or workshop and rapidly get all information about rolling conditions, grinding, quality, etc.

Currently with the FEM model, when all data are available, a first evaluation requires one week to be able to propose optimization guidelines.

6 CONCLUSIONS

For the past decades, increased competitiveness in European mills leads to longer campaigns. Rolling campaigns have increased by a factor 2 or even 3 the number of contact of a roll with the slab but the core material did not drastically changed. Besides, the higher stresses generated during rolling due to harder materials and modified rolling schemes have been loading rolls more and more. The roll makers have to adapt. In roughing mills, the only actuator available for roll makers is to increase the total shell thickness, keeping the same usable shell thickness. This practice has however a non-negligible impact on residual stresses in the roll but also a negative impact on core material. Indeed the thicker the shell thickness the more prone the core material to pick up alloying element which decrease its mechanical strength and fatigue resistance

Furthermore, mechanical properties of work roll shell materials have improved to sustain these harsher conditions but the core material almost never changed, the bonding zone properties neither.

To find optimal working situation for both roll maker and user, a 3D model has been developed. It enables to localize the maximal stresses in work and backup rolls as well as the stress evolution through the shell thickness and bonding zone of the work roll. Its use allows us to analyze the current situation and propose solutions to decrease mechanical load of the rolls. The use of this tool enabled to show the influence of chamfer and edge relief geometries on stresses distribution and levels, especially at the bonding zone of the work roll. A proper design can avoid roll fatigue damages leading to spalling in some cases.

Acknowledgments
The authors gratefully acknowledge the Walloon Region for their financial contribution in the research works.

REFERENCES

1 X. Wang & al. “Design and application of an optimum backup roll contour configured with CVC work roll in hot strip mill”, ISIJ International, Vol 52, 2012, pp 1637-1643

2 X. Wang & al., “VCR backup roll and negative work roll contour design for solving roll spalling and transfer bar profile problems in hot strip mill”, Iron and steelmaking Vol 37, 2010, pp 633-639
3 Y. Liu & al., “Mechanical study for reducing shell/core bond separation of duplex cast work rolls for hot strip mill”, AISTech 2010 proceedings Volume 2, 2010
4 F. Decultieux & al., “Backup roll chamfer design, profile and maintenance", MS&T 2004 conference proceedings, 2004
5 M. Fraser Frolish, “Design criteria for rolling contact fatigue resistance in backup rolls”, University of Sheffield thesis report, 2002
6 K.H. Ziehenberger & al. “Recent developments in HSM rougher rolls – risks and chances” MS&T 2005 conference proceedings, 2005
7 C. Geuzaine and J.-F. Remacle. “Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities.” International Journal for Numerical Methods in Engineering 79(11), pp. 1309-1331, 2009
8 S. Flament, “CIFOR final report”, CRM internal research, 2011
9 MK internal document, 2016