Lubrication Strategies for Rolling Hard Steel Types

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In the cold rolling process, good lubrication can reduce roll forces, but for hard steel types there are limits to what can be achieved with a particular mill. In this paper, various options to improve lubrication are explored, related to lubricant design and application. A numerical roll bite model is used to investigate the effect of various lubricant properties on roll forces when rolling hard steel types. Experimental work is presented.

Hard steel types are becoming important materials in the automotive industry. At the same time, the manufacture of increasingly hard materials becomes more and more challenging. When cold rolling hard steel types, several limitations may be approached. Motor torques may reach their limit, or roll forces may become excessive and strip shape may be adversely affected. Several process-related parameters to reduce torque and roll forces are available in principle, but are not always practical or desirable. Good lubrication can reduce roll forces but, especially for harder steel types, there are limits to what can be achieved. Ultimately, the capacity of a particular mill will become insufficient due to increasing flow stresses of the material. Numerical modeling may be a useful tool in understanding the limitations of cold rolling hard steel and in finding ways to overcome these limitations by process parameters and lubricant design or application. In this paper, first the limitations involved in rolling hard steel types are illustrated. Then various options to improve lubrication are explored, related to lubricant design and application. The paper ends with some results of pilot mill trials in which two lubricant-related parameters are investigated that are expected to influence roll forces.

Modeling Cold Rolling — Three mathematical models for cold rolling were used in this paper. Two of these (the Friction Identification Rolling Model (FIRM) and Analytical Rolling Model (ARM)) are home-written rolling models. The third mathematical model, the Tribological Roll Bite Model (TRBM), was developed in a joint collaboration project between the University of Linz, voestalpine, Primetals Technologies and Quaker. Table 1 gives an overview of the input and output parameters in the three models. Note that, in contrast to the FIRM and ARM models, in the TRBM model none of the mill response parameters (roll force, forward slip, coefficient of friction (CoF)) are required as input parameters.

The FIRM and ARM models are based on an analytical expression for the friction hill in skewed plane-strain deformation. This expression follows from an integration of the force balance equation using the well-known slab method.[1] Strain hardening as the strip is progressively deformed is taken into account and elastic deformation of the work roll is taken into account as described by Hitchcock. The purpose of the FIRM model is to "identify" the CoF based on roll force and forward slip measured on the mill. The purpose of the ARM model is to explore rolling scenarios using

Table 1

Overview of Input and Output Parameters of the Three Used Models

	FIRM	ARM	TRBM
Material data (strip width, thickness, yield stress, strain hardening parameters)	Input	Input	Input
Process and mill data (reduction, front and back tensions, work roll radius)	Input	Input	Input
Strip and roll temperature and roughness	—	—	Input
Rolling speed	—	—	Input
Lubricant data (emulsion application details, including direct application, emulsion temperature, concentration, particle size, etc.; oil viscosity, viscosity-pressure/temperature/shear rate indices, etc.)	—	—	Input
Roll force	Input	Output	Output
Forward slip	Input	Output	Output
Coefficient of friction	Output	Input	Output

an analytical expression for the neutral angle[2] and an assumed CoF. The model calculates the roll force.

The TRBM is a much more advanced rolling model.[3] In this model, the emulsion application zone, the roll bite inlet zone and the deformation zone are modeled successively, taking into account measurable lubricant parameters, as indicated in Table 1. The model includes an option of pre-applied plate-out layers and a mechanism for the plating out of oil on the strip and roll by emulsion application. The roll bite inlet zone model incorporates oil wash-off from roll and strip, re-emulsification, and resulting oil concentration/starvation effects, after which the complete flow field is calculated in the wedge-shaped inlet zone. Simultaneously, the pressure field is calculated, with contributions from lubricant pressure and boundary contact pressure as the roll and strip asperities start to touch. The start of the deformation zone is defined as the location where the total pressure reaches the flow stress of the strip. Then, the contact area evolution in the deformation zone is calculated, and through that, the evolution of the areas of boundary lubrication, elastohydrodynamic lubrication and microplastohydrodynamic lubrication (MPHL, in-bite film formation by lubricant release from lubricant-filled roughness valleys by sliding velocity of work roll over strip[4]). A complex set of coupled non-linear equations is solved, resulting in, among others, a distributed — and averaged — CoF, roll force and forward slip.

The Challenges in Rolling Hard Steel Types — The issues involved in rolling hard steel types, and how this compares with rolling softer steel grades, will be illustrated by a hypothetical rolling scenario in a mill with four reduction stands. A soft and a hard steel grade will be compared. Their tensile stress, σ, as function of strain, ε, is given by the equations $\sigma = 680(\varepsilon + 0.04)^{0.26}$ MPa and $\sigma = 1{,}060(\varepsilon + 0.04)^{0.17}$ MPa, respectively, giving tensile yield stresses of 300 and 610 MPa, respectively. The comparison will be done using the TRBM model. See Tables 2a and 2b for some assumed strip and rolling data for the soft and hard steel, respectively, which serve as input parameters for the model. The plane-strain flow stress is indicated, which is related to the tensile stress (higher by a factor $2/\sqrt{3}$). The incoming gauge is assumed equal at 2 mm. The tables also reflect the fact that hard steels are usually rolled at significantly lower reductions and at lower speeds. The incoming strip temperatures are determined according to a calculated temperature rise due to deformation and an estimated cooling effect between stands. The incoming strip roughness is assumed to be 2 µm, and the roughness progression is calculated in the numerical model. Some other input parameters are: a roll diameter of 0.5 m and a strip width of 1 m. Roll roughness values are indicated in Table 2 and reflect the fact that the roughness is normally higher in stand 1. Selected lubricant parameters for these calculations are: emulsion concentration 2%, oil particle size 3 µm, oil viscosity 40 mPas (at 40°C), and CoF in the boundary regime 0.11. In the calculations it was also taken into account that the incoming (hot-rolled, pickled) strip is free of initial lubricant layers whereas the incoming strip in stands 2–4 (potentially) benefit from the lubricant "inherited" from the previous stand.

As mentioned, the flow and pressure field in the inlet zone is calculated first. At the end of the inlet zone, i.e., the start of the deformation zone, the film thickness can be calculated and a first estimate of the lubrication, i.e., film formation, can be obtained. In Fig. 1a, the film parameter is plotted, which is simply defined as the oil film thickness divided by the combined roughness σ_c of roll and strip ($\sigma_c = (R_{a,r}^2 + R_{a,s}^2)^{0.5}$) with the Ra roughness of roll and strip, respectively. Note that in this part of the paper, data for the soft steel are indicated in blue, and data for the hard steel are indicated in orange. For both steel grades, the film parameter at the start of the deformation zone is relatively low in stand 1 due to

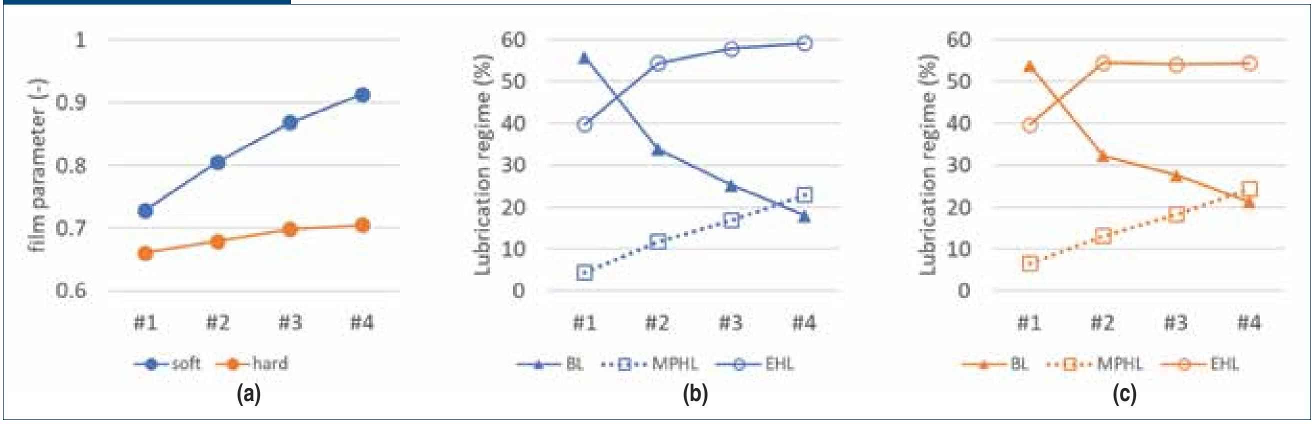
Table 2

		Stand 1		Stand 2		Stand 3		Stand 4	
(a) Input Parameters for the Soft Steel Grade									
Gauge (mm)	2		1.40		0.98		0.68		0.48
Reduction (%)		30		30		30		30	
Reduction cumulative (%)	0		30		51		65.7		76
Flow stress (MPa)	339		615		726		804		864
Tensions (MPa)	50		100		100		100		100
Speed (m/min)	288		411		588		840		1,200
Strip temperature (°C)	25		52		84		113		137
Strip roughness (µm)	2		1.15		0.87		0.74		0.67
Roll roughness (µm)		0.8		0.4		0.4		0.4	
(b) Input Parameters for the Hard Steel Grade									
		Stand 1		Stand 2		Stand 3		Stand 4	
Gauge (mm)	2		1.70		1.45		1.23		1.04
Reduction (%)		15		15		15		15	
Reduction cumulative (%)	0		15		27.7		38.6		47.8
Flow stress (MPa)	705		929		1,027		1,093		1,145
Tensions (MPa)	50		100		100		100		100
Speed (m/min)	130		154		181		212		250
Strip temperature (°C)	25		46		69		91		113
Strip roughness (µm)	2		1.31		1.08		0.97		0.88
Roll roughness (µm)		0.8		0.4		0.4		0.4	

the low film thickness (low speed) and the high roll roughness. For both steel grades, the film parameter increases from stand to stand due to increasing speeds, decreasing bite entry angle and decreasing combined roughness. It can be seen that for soft steel rolling, the film parameter increases quite sharply due to the strongly increasing speeds — and thus film thickness — from stand to stand. For hard steel rolling, the film parameter increases less sharply due to the lower speeds. Even though the film parameter gives an initial impression of the lubrication situation, it is unsuitable to accurately assess lubrication due to the further contact surface area evolution that takes place in the deformation zone. The relative areas of boundary, micro-plastohydrodynamic and elastohydrodynamic lubrication in each stand (averaged over the entire contact length) are plotted in Figs. 1b and 1c for soft and hard steel rolling, respectively. It can be seen that the contribution of boundary lubrication is relatively high for stand 1, which is mainly due to the higher roll roughness. For all stands, the contribution of boundary lubrication for hard and soft steel is similar: the lower film formation for hard steel (low speeds), which would normally lead to more boundary contact, is counteracted by the more difficult surface asperity deformation in the roll bite, resisting more boundary contact. It can also be seen that the relative contribution of MPHL increases from stand to stand, which is due to the increasing sliding speeds and decreasing roughness, both an important driving force for MPHL.[4] For hard steel, despite the lower sliding speeds and a slightly higher roughness, a considerable contribution of MPHL is found, which is due to the higher lubricant pressures in the contact zone, which is, through the lubricant viscosity, another important driving force for MPHL. Using the relative surface areas of boundary, MPHL, EHL and the local CoF for these areas, and accounting for how these values evolve over the contact length, a global average CoF can be calculated, which is plotted in Fig. 2a.

It can be seen in Fig. 2a that the CoF, for both steel types, decreases from stand to stand, which, as mentioned, is caused by a combination of increasing speed (i.e., increasing film formation), decreasing bite entry angle and decreasing strip roughness in the inlet zone and, in the deformation zone, the contact area evolution and the relative contributions of the three lubrication regimes. It can also be seen that the CoF values for soft and hard steel are similar, which is in line with the similar relative areas of boundary lubrication, as seen in Figs. 1b and 1c. This relative similarity of the CoF for soft and hard steel is a coincidence

Figure 1

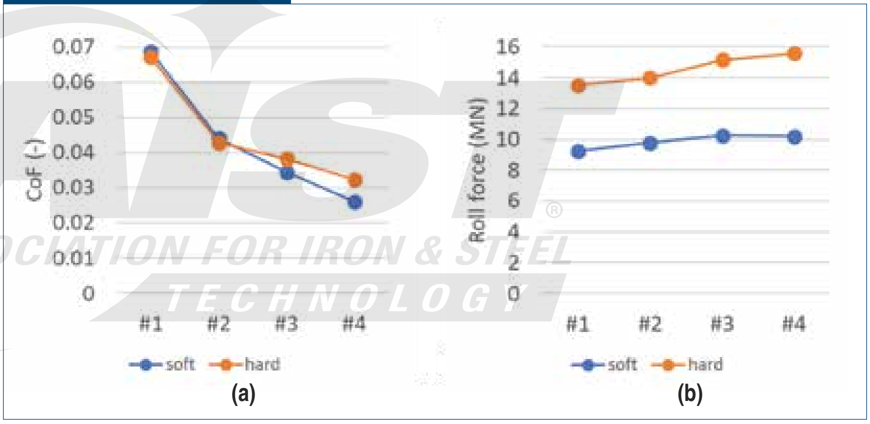


Film parameter at the end of the inlet zone, for stands 1–4, for soft and hard steel (a), and the distribution of the three lubrication regimes in the deformation zone for stands 1–4, for soft steel (b) and hard steel (c).

of the chosen process parameters. In Fig. 2b, it can be seen that, despite the similar CoF, the roll force is significantly higher for the hard steel, which is due to the much higher flow stress.

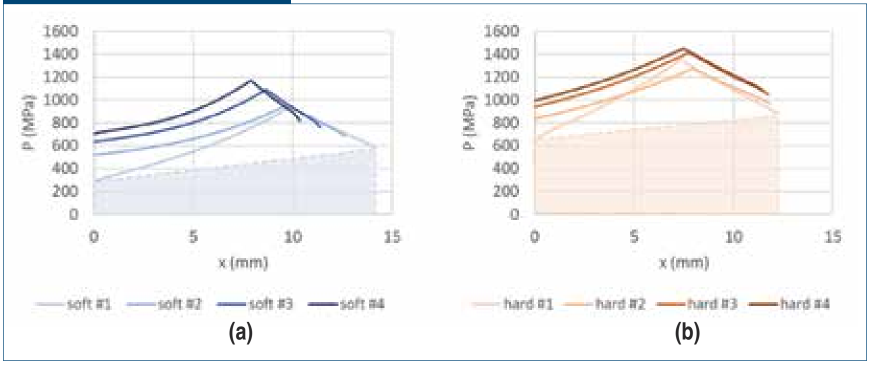
In Fig. 3, the pressure as a function of position in the roll bite (friction hill) is plotted. The shaded areas in the figures schematically show, for stand 1, the fraction of the pressure involved in deformation; the rest is due to friction. For hard steel, the fraction of the pressure involved in deformation is much larger due to the high flow stress, which is also true for stands 2–4. It can also be seen that the friction hills are "sharper" for the soft steel, especially for the later stands, which is due to the relatively low strip thickness. The contact length for soft steel compared to hard steel is relatively high in stand 1 due to the high reduction. The contact length for soft steel then decreases noticeably toward stand 4 due to the decreasing strip thickness. The contact length is relatively constant for the hard steel, which is due to the combined effect of the low reductions and, thus, lower variations in strip thickness and relatively large elastic work roll deformation, especially for the later stands.

Figure 2



Coefficient of friction (a) and roll force (b) for the four stands for soft and hard steel.

Figure 3



Pressure as function of position in the roll bite for the four stands, for soft steel (a) and hard steel (b).

Part of the roll force is required to provide the plastic deformation, part to overcome friction. In the model, it was calculated which fraction of the roll force is required to overcome the friction. This is shown in Fig. 4. It can be seen that — for the chosen rolling example, including an adequate lubrication quality — friction accounts for 30–35% of the roll force when rolling the soft steel type, and approximately 20% for the hard steel type. This shows that, for hard steel, it is comparatively difficult to reduce roll forces by improving lubrication — again, for the chosen rolling scenarios. At the same time, we must remember that, when improving lubrication, slip issues may occur (negative forward slip), which will limit the achievable reductions in roll force.

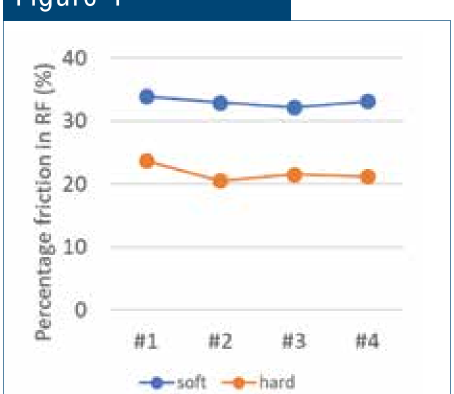
There are several process-related ways in which the roll force may be reduced when rolling hard steel types. This was investigated using the TRBM model. In Fig. 5, it is illustrated by how much the roll force, for the examples above, may be reduced when:

- Doubling the tensions (back tensions of stand 1 from 50 to 100 MPa, all other tensions from 100 to 200 MPa).
- Decreasing the roll diameter from 0.5 m to 0.4 m.
- Increasing the Young's modulus (E) of the work roll from 210 GPa to 500 GPa, reducing the elastic deformation of the work roll (500 GPa is a value typical for ceramics).
- Increasing the rolling speed by 20% (increasing the entrained lubricant film thickness).

It can be concluded that significant reductions in roll force can be achieved by tensions, roll diameter and modulus. The effect of increased tensions is highest for soft steel due to the relatively low yield stress. The effect of reducing the work roll diameter is comparable for soft and hard steel. The effect of increasing the elasticity modulus of the work roll is higher as the roll force and thus the elastic work roll deformation increases, i.e., for soft steel strongly increasing from stand to stand, but generally the highest for the hard steel. In contrast to these effects, the effect of rolling speed is small. Higher speeds do lead to higher entrained lubricant film thickness, reducing the CoF, but the effect on roll force is small. Indeed, the small reduction in roll force on speed increase is negligible compared to the 20% higher mill power required for the 20% speed increase. For the other process-related parameters, it must be stressed that their modification is not always desirable, practical or even possible. Increased tensions are likely already used to full benefit, given the capabilities of the mill, e.g., considering maximum reel torques. Let us therefore look at the ways in which the lubricant may influence friction, and thus roll force.

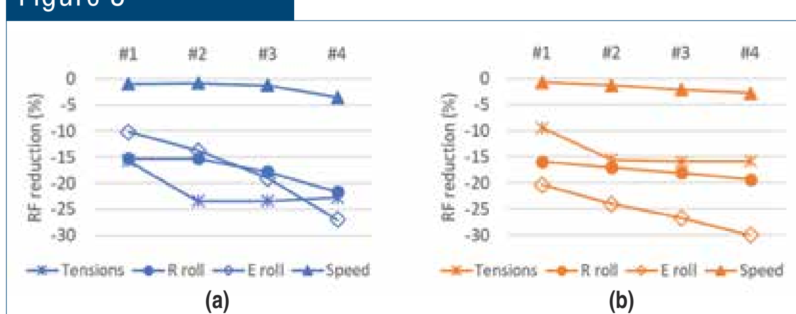
The Role of the Lubricant in Reducing Friction — In cold rolling, the lubricant plays an important role in reducing friction. The lubricant, applied in emulsion form in order to also cool the process, provides a thin oil film between the work roll and the strip, so that mixed lubrication conditions apply, required for satisfactory cold rolling. In mixed lubrication, areas of close contact coexist with areas of higher separation, characterized by boundary lubrication and elastohydrodynamic conditions, respectively. The friction in these areas can be minimized by the right choice of surface chemistry and bulk rheology under high pressure, respectively.[4] Additionally, in-bite film formation may occur by a micro-plastohydrodynamic lubrication mechanism, where the friction is governed by the high-pressure, high-shear-rate rheology of the

Figure 4



Percentage of the roll force (RF) involved in friction, for the chosen rolling scenarios, for soft and hard steel.

Figure 5



Percentage reduction in roll force by adjusting several mill parameters, such as back and front tensions, work roll radius (R roll), roll elasticity modulus (E roll) and rolling speed, for soft steel (a) and hard steel (b).

lubricant.[4] On the basis of these mechanisms, a wide range of lubricant properties is available to minimize friction, such as:

- Viscosity, plate-out, oil droplet size, influencing inlet zone film formation.
- Viscosity, influencing in-bite film formation.
- Molecule adsorption and reaction, influencing friction in the boundary regime.
- Viscosity, viscosity-pressure index, viscosity-temperature index and the Eyring stress (quantifying non-Newtonian, shear-thinning behavior), influencing friction in the EHL and MPHL regimes.

In addition to this, extra lubricant plate-out layers may be supplied in front of the roll bite by a direct application system, enhancing lubrication in critical conditions, for instance when rolling high-roughness, high-hardness material at low speed. All of these mechanisms may be described by a single 3D Stribeck curve, as was published earlier.[5]

Fig. 6 schematically shows this 3D Stribeck curve. Fig. 6a illustrates how the friction (z-axis) may be influenced by lubricant supply. Inlet film formation (x-axis) is influenced by lubricant viscosity, emulsion properties and process speed, and can be augmented by plate-out layers. In-bite film formation (MPHL) (y-axis) is influenced by lubricant viscosity and differential speed. Fig. 6b illustrates how the intrinsic friction levels in the 3D Stribeck curve, i.e., the indicated "anchor points" CoF_{BL}, CoF_{EHL} and CoF_{MPHL}, may be influenced by molecule adsorption/reaction, high-pressure rheology and high-pressure/high-shear-rate rheology, respectively.

Taking the example calculations discussed above as reference (Figs. 1–3), the effect of various lubricant parameters on friction in the cold rolling process, and thus the roll force, was investigated for soft and hard steel, using the TRBM model. The following parameters were selected:

- Supplying an extra 0.5-µm-thick plate-out layer on the strip.
- Increasing the emulsion concentration from 2% to 3%.
- Increasing the oil particle size from 3 µm to 6 µm.
- Increasing the oil viscosity from 40 mPas to 80 mPas.
- Decreasing the CoF in the boundary lubrication regime from 0.11 to 0.10.

In Fig. 7 and Table 3, it is shown which effects these lubricant-related parameters have on the roll force in stands 1–4, for soft and hard steel. It can be seen that the effect of these lubricant-related parameters are generally much smaller than the effect of some of the mill-related parameters shown in Fig. 5. Nevertheless, some interesting effects can be identified.

For stand 1, extra plate-out layers, emulsion concentration, oil particle size and viscosity are all relatively effective in reducing the roll force, for soft as well as for hard steel rolling. This is due to the fact that the reference calculations were based on a hot-rolled, pickled incoming strip that was free of lubricant, which causes an improvement of these lubricant properties to have a relatively large effect.

For stand 2, extra plate-out layers, emulsion concentration, oil particle size and viscosity are relatively ineffective. For the first three properties, this is due

Figure 6

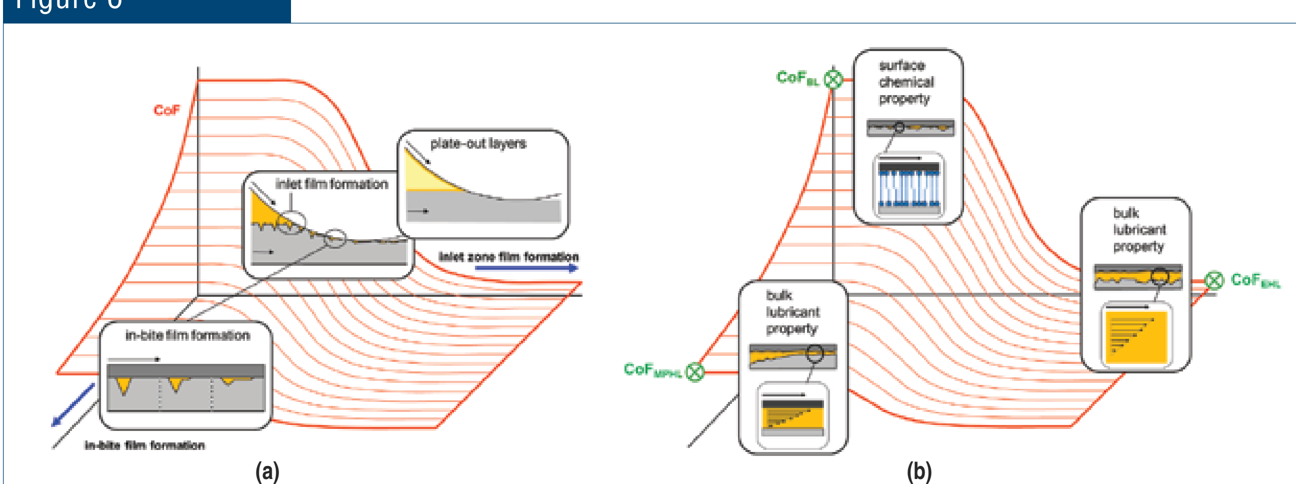
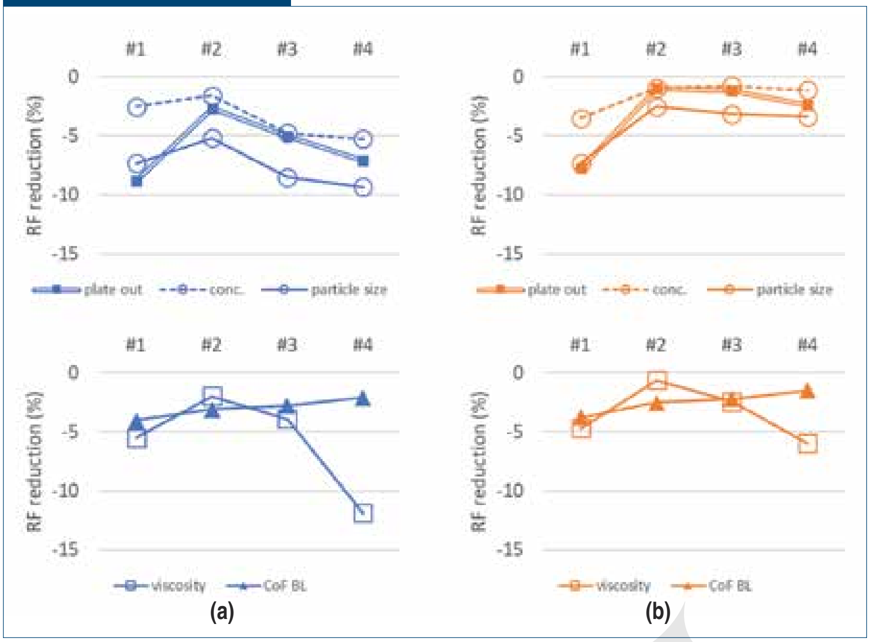


Illustration of the 3D Stribeck curve.

Figure 7



Percentage reduction in roll force by adjusting several lubricant parameters for soft steel (a) and hard steel (b). For reasons of clarity, the data are split up into two graphs for each steel type.

to the fact that the speeds are relatively low and comparatively little oil starvation has taken place, i.e., the oil concentration at the start of the deformation zone is relatively high. Due to this, extra oil supply has a limited effect. For a viscosity increase, one would normally expect an improvement due to a higher hydrodynamic effect, but it was found that this effect is counteracted by an additional mechanism.

For stands 3 and 4, additional plate-out layers, emulsion concentration, oil particle size and viscosity become more effective again. This is due to the higher degree of starvation found in these stands, due to which an extra oil supply becomes increasingly effective. It can be seen that increased oil viscosity is particularly effective in reducing the roll forces in stands 3 and 4, even introducing a danger of mill slippage in these stands. This is particularly true for the soft steel. For soft steel in rolling stand 4, it was calculated that by increasing the viscosity from 40 to 80 cSt, the forward slip decreases from 2.3 to 0.6%. For hard steel rolling, the forward slip only decreases from 2.0 to 1.6%.

Unlike the parameters discussed above, decreasing the boundary friction does not influence the processes in the inlet zone, but only affects the friction of the true contact areas as they evolve in the deformation zone. Consequently, the effect on roll force is in line with the fraction of boundary contact as shown in Figs. 1b and 1c, i.e., a decreasing effect as the fraction of boundary contact decreases from stand 1 to stand 4, which is similar for soft and hard steel.

The effects on roll force shown above, such as the beneficial effect of emulsion concentration, particle size (emulsion stability) and viscosity, are of course largely known in the steel industry. However, when trying to reduce roll forces, lubricant and application have to be considered carefully; a beneficial effect on stand 1 may lead to slip in the last stand. This issue becomes especially critical when mixing materials of varying hardness on the same mill.

It must be stressed that many more lubricant parameters than mentioned in this paper play a role in satisfactory cold rolling (many of these are indeed accounted for in the TRBM model). The viscosity-pressure and viscosity-temperature indices, the Eyring stress (quantifying high-shear viscosity), surface protection by extreme-pressure/anti-wear additives and choice of type and amount of emulsifiers all have a critical influence on roll force and forward slip, but also on, e.g., mill cleanliness, strip cleanliness and strip quality. Especially when the rolling conditions become very difficult, such as when rolling hard steel types, the right choice of these lubricant parameters becomes very important.

Table 3

Percentage Roll Force Decrease for Stands 1 – 2 – 3 – 4, by Several Lubrication-Related Parameters, for Soft and Hard Steel. See also Fig. 7. The values in the table are rounded off to the nearest integer.

	Plate-out layers (0.5 µm on strip)	Concentration (2 → 3 %)	Oil particle size (3 → 6 µm)	Viscosity (40 → 80 mPas)	Boundary friction (0.11 → 0.10)
Soft steel	8 – 3 – 5 – 7	3 – 2 – 5 – 5	7 – 5 – 8 – 9	5 – 2 – 4 – 12	4 – 3 – 3 – 2
Hard steel	8 – 1 – 1 – 2	3 – 1 – 1 – 1	7 – 2 – 3 – 3	5 – 1 – 2 – 6	4 – 3 – 2 – 2

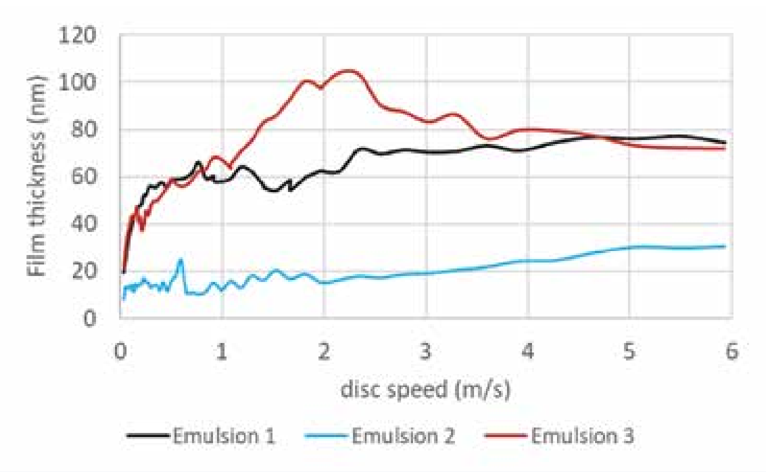
Experimental

To investigate lubrication in hard steel rolling, several pilot mill trials were carried out. These trials were done on the Quaker Pilot Mill, for which some specifications can be seen in an earlier paper.[6] A hard steel type was rolled, with yield stress 610 MPa and tensile stress σ as function of strain ε given by the equation $\sigma = 1{,}060(\varepsilon + 0.04)^{0.17}$ MPa. Strip width was 0.15 m and incoming thickness 2.5 mm. Three emulsions were tested, all in duplicate. Emulsion 1 serves as a reference emulsion, emulsion 2 is a high-stability variation of emulsion 1, and emulsion 3 is a high-viscosity variation of emulsion 1.

During the trials, several emulsion properties were monitored; Table 4 shows the oil concentration and oil droplet size as well as the lubricant viscosity and the CoF in the boundary lubrication regime (CoF_{BL}) for the emulsions. Fig. 8 shows the film formation that is obtained from the emulsions, measured with an ultrathin-film interferometer (PSC Instruments, London). As expected, the film formation of emulsion 2 is clearly worse than for emulsion 1, and it is better for emulsion 3, although not at all speeds. The measurements largely confirm expected behavior, with small oil particle size giving less film formation due to strong oil starvation, and higher viscosity giving better film formation due to stronger hydrodynamic effects.

The mill trials were carried out according to the pass schedule shown in Table 5. Passes 1 and 2 were carried out with a low reduction. These passes were included to remove the rust-protective oil, using a low-percentage cleaner emulsion of the same product of the subsequent trial, located in a separate cleaner emulsion system. Passes 3–7 involved reductions between approximately 11 and 15%, and were carried

Figure 8



Film formation of the three emulsions, measured at 55°C.

Table 4

Selected Lubricant/Emulsion Properties

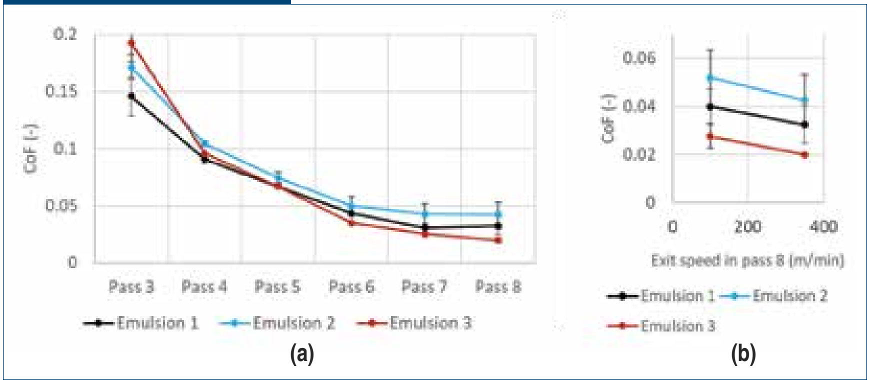
	Concentration (%)	Oil droplet size (μm)	Viscosity (at 40°C, cSt)	CoF_{BL} (-)
Emulsion 1	2.56	10.1	59.3	0.104
Emulsion 2	2.55	2.1	58.4	0.104
Emulsion 3	2.50	12.5	116.2	0.110

Table 5

Pass Schedule for the Pilot Mill Trial and the Roll Force Results for Emulsions 1, 2 and 3

	Incoming gauge (mm)	Target reduction (%)	Back tension (MPa)	Front tension (MPa)	Exit speed (m/min)	Roll force (average of duplicates) (kN)		
						1	2	3
Pass 1	2.50	4.9	50	60	20	—	—	—
Pass 2	2.38	3.4	50	60	20	—	—	—
Pass 3	2.30	11.3	50	100	100	715	744	775
Pass 4	2.04	13.4	50	118	150	773	792	778
Pass 5	1.76	12.7	55	140	200	739	743	741
Pass 6	1.54	14.9	55	145	250	763	786	762
Pass 7	1.31	15.1	55	145	300	747	774	743
Pass 8-a	1.11	14.2	65	145	100	703	770	748
Pass 8-b	1.11	15.0	65	145	350	698	786	722

Figure 9



Coefficient of friction in the mill trials for the three emulsions, from pass to pass (for pass 8 it is the value for 350 m/minute) (a), and in pass 8, for the two chosen speeds (b).

out at constant speeds of 100, 150, 200, 250 and 300 m/minute, respectively. Finally, pass 8 was carried out at two speeds, 100 and 350 m/minute.

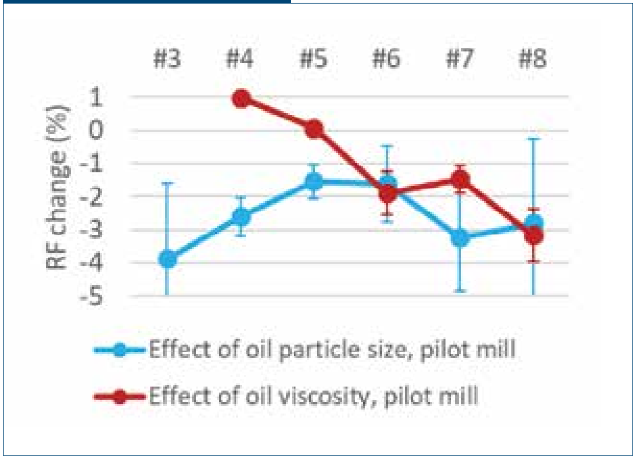
The roll forces mentioned in Table 5 give a rough estimate of the level of lubrication in these trials. However, from pass to pass, these roll forces are also influenced by the chosen reductions and tensions. Moreover, for each trial there were small additional differences in incoming gauge and reductions, especially for the trials with emulsion 3. In order to account for these variations, the actual values for the incoming gauge, reduction, tensions and roll force were used, for each pass in each trial, to calculate a CoF. This was done using the FIRM model. A plot of the "identified" CoF in these three duplicate trials is shown in Fig. 9. The data point for pass 8 in Fig. 9a corresponds to the speed of 350 m/minute. Note that the absolute values may contain systematic deviations, but trends and differences are reliable.

In Fig. 9a, it can be seen that for all emulsions, the CoF shows a steady decrease from pass to pass. This is due to the increasing speed and decreasing bite entry angle (both leading to increased film formation) and decreasing roughness. Fig. 9b shows that the CoF decreases with speed for pass 8 for all emulsions. Friction values for pass 3 are high. This was also found in an earlier paper[6] and the reason for this is not clear. In Fig. 9, it can be seen that for all passes, the CoF for emulsion 2 is higher than for emulsion 1, which confirms the expected effect of decreasing the oil particle size, which reduces the film formation and thus worsens the lubrication. The CoF for emulsion 3 in the later passes is clearly lower than for emulsion 1, which confirms the expected effect of increasing the viscosity, namely better film formation and thus improved lubrication. The expected effect of increasing viscosity is, however, not found in the earlier passes. The friction for emulsion 3 in pass 3 seems abnormally high, and was confirmed by an extra trial. As yet there is no explanation for this.

Discussion

Earlier in this paper, the effect of several parameters on roll force was calculated using the TRBM model. Mill parameters were explored such as back and front tensions, roll diameter, roll elasticity modulus and rolling speed (Fig. 5), and lubricant parameters were explored such as plate-out layers, oil concentration, oil particle size, oil viscosity and boundary CoF (Fig. 7). Now the focus will turn to the effect that the oil particle size and oil viscosity had in the pilot mill trials. For this, the measured roll forces as mentioned in Table 5 will not be used, as these were affected by small variations of thickness and gauge. The calculated CoF in Fig. 9 is much less affected by these variations. Therefore, for every pass, the roll forces were "reconstructed" from the CoF values in Fig. 9 and the target values of incoming gauge and reduction as shown in Table 5, using the ARM model. In Fig. 10 the percentage the roll force decreases when the particle size or the viscosity increases is plotted. In line with the plots of the theoretical effects of particle size and viscosity on roll force shown in Fig. 7, the better-lubricating emulsion is compared with the worse emulsion, i.e., in Fig. 10 the effect on roll force is plotted of emulsion 1 versus

Figure 10



Plot of the effect of an increased oil particle size and viscosity on the roll force, from pass to pass, as seen on the pilot mill.

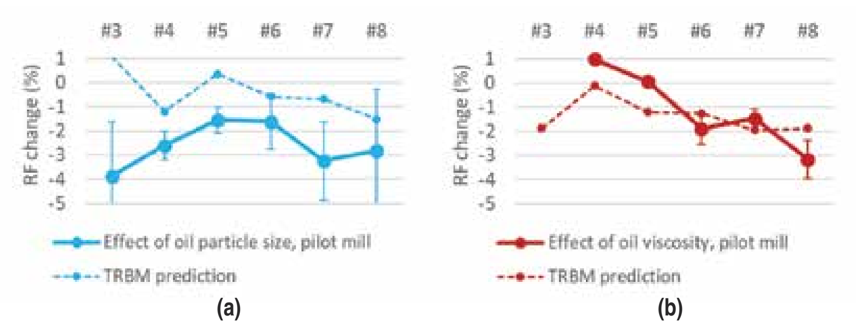
emulsion 2, and of emulsion 3 versus emulsion 1. It can be seen that when increasing the oil particle size from 2 µm to 10 µm, the roll force decreases by 2 to 4%. This effect appears to be similar for all passes, considering the significant error bars for passes 3, 7 and 8. When increasing the viscosity from 60 to 120 cSt, the roll force decreases by 0 to 3%. The effect of viscosity appears to increase especially toward the later passes.

The effect of oil particle size and viscosity found in the pilot mill trials is in line with the expected behavior based on the film formation measurements in Fig. 8. The significantly higher film formation for emulsion 1 compared to emulsion 2 is reflected in a modest roll force decrease. The comparison must be viewed only qualitatively, as the conditions in the interferometer and pilot mill differ significantly. The same is true for the effect of viscosity; in the interferometer, an increase in film thickness is found — for an intermediate speed range — which is also reflected in a modest roll force decrease on the pilot mill. The speeds applied in the interferometer cannot simply be compared to the rolling speeds, mainly due to the greatly different inlet geometry, such as entry angle and the fact that a ball-on-disc geometry is used in the interferometer.

The effect of oil particle size and viscosity on roll force can also be compared, albeit qualitatively, with the effects predicted for the hypothetical 4-stand tandem mill for hard steel rolling in the first part of this report (Fig. 7b). Ignoring the effects on stand 1, with dry hot-rolled pickled incoming strip, a few-percent roll force decrease is predicted with oil particle size and viscosity, and for viscosity a clearly larger effect for the later stands. The comparison is of course only qualitative, as the rolling conditions in the pilot mill differ considerably from the hypothetical 4-stand tandem mill.

This is the reason that the TRBM model was also used to calculate the effect of oil particle size and viscosity on roll force, specifically aimed at the present pilot mill trials. The target values of incoming strip thickness and reductions as mentioned in Table 5 were used as input parameters, together with the back and front tensions of Table 5, and using lubricant parameters such as emulsion concentration, particle size, viscosity and CoF_{BL}, as shown in Table 4. This was done for all three emulsions. The predicted effect on roll force, for increasing oil particle size and increasing viscosity is plotted in Fig. 11 (dotted lines) with also inserted the curves showing the effects on the mill (the data in Fig. 10). It can be seen that the predicted effect of oil particle size (at most 1 to 2%) slightly underestimates the actually found effect. The effect of viscosity, on the other hand, but excluding pass 3, is well-predicted.

Figure 11



Plot of the effect of an increased oil particle size (a) and viscosity (b) on the roll force, from pass to pass, as seen on the pilot mill (lines with large dots). The dotted line is the effect calculated with the tribological roll bite model.

Conclusions

In this paper, an advanced mathematical model was used to calculate the roll forces in a hypothetical 4-stand rolling mill, comparing rolling scenarios for soft and hard steel rolling. The entrained oil film thickness varies from stand to stand and is lower for hard steel rolling. The relative areas of boundary lubrication, micro-plastohydrodynamic and elastohydrodynamic lubrication in the contact zone varied from stand to stand and were not too dissimilar for soft and hard steel. Consequently, the CoF values for soft and hard steel, which decreased from stand to stand, were similar for soft and hard steel, but this is a result of the chosen process conditions. It was also shown that the percentage of the roll force involved in overcoming friction was lower for hard steel, showing that for hard steel, under the chosen rolling conditions, there is less scope for roll force reduction by reducing friction. The model predicts significant roll force reductions for three mill-related parameters, a small effect of mill speed and modest roll force reductions for five lubricant-related parameters. The effect of two lubricant-related parameters on roll force in hard steel rolling was investigated on Quaker's pilot mill. It was found that small but significant reductions of roll force could be achieved by an increased oil particle size in the emulsion and a higher viscosity of the base oil. These effects were qualitatively confirmed by laboratory film formation measurements and were also in line with the model calculations of the effect of these parameters on roll force in the hypothetical

4-stand rolling mill. Finally, the advanced mathematical model was used to calculate the actual pilot mill trials and the predicted effect of oil particle size and viscosity proved to correspond well with the pilot mill results. An extensive program of pilot mill trials is planned to further explore the effect of lubricant and emulsion properties on the rolling of hard steel types.

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