Application of Hot Rolling Lubrication on a Reversing Coil/Plate Mill

Roll lubrication was introduced to the 4-high Steckel mill at Nucor Steel Tuscaloosa Inc. in 2011. It was found that the benefits included a significant extension to roll service life and notable reduction of mill torque. This paper will describe the mechanism of lubrication in the roll system and present the improved rolling parameters of the Steckel mill.

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Nucor Steel Tuscaloosa Inc. is the first U.S. mill to employ Steckel mill technology for producing high-quality wide coiled plates and discrete plates. Since 1985, the Steckel mill has consistently demonstrated product versatility, quality and cost advantage over traditional plate mills.

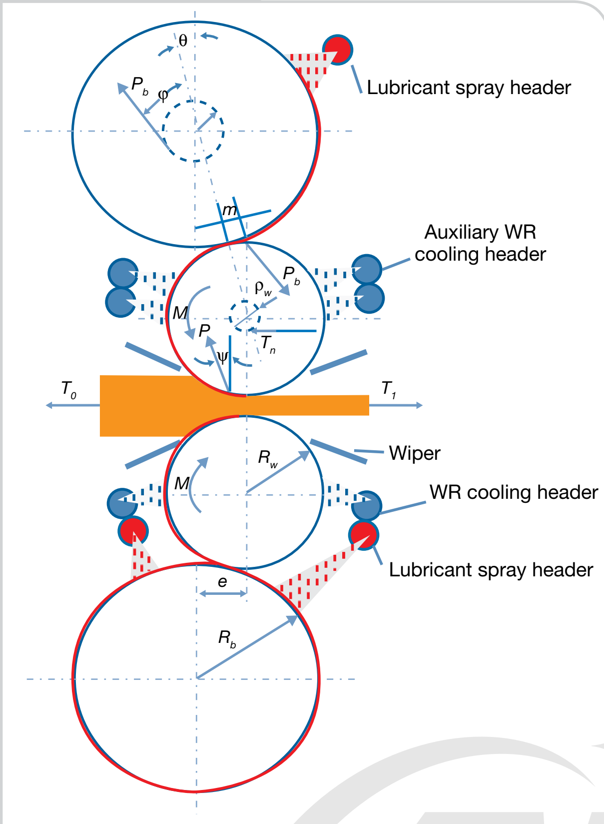
The single stand of a 4-high reversing Steckel mill carries out both roughing and finishing passes. With the increase of market demand on high-strength low-alloy (HSLA) steels, the mill needs to extend its roughing pass schedule to roll the steels due to the limit of torque. However, an extensive pass schedule does not meet the requirements of mechanical properties, since the strain rate is reduced. To resolve the contradiction of the pass reduction rate with the mill torque limit that was rated at 1.25 million ft-lbs, application of roll lubrication was discussed, since the technique showed the advantage in reducing the torque of tandem mills.

In addition, it was recognized that the roll wear in rolling HSLA steels is much faster than that in rolling carbon steels due to the increase of separating force. Application of roll lubrication could bring another benefit to the mill, i.e., reduction of roll wear. Most HSLA steels require thermomechanical control rolling to achieve the mechanical properties and high toughness under a low service temperature. Since the precipitation of microalloys occurs in rolling, the separating force increases sharply due to the raised flow stress of metal, which also creates difficulty for mill operators in controlling the shape of the strip.

In 2011, a portable lubricant mixer was used to spray the oil solution on the bottom backup roll. The initial trial result showed that the mill torque was reduced by about 8% on average over all passes. Furthermore, additional spray headers were installed permanently in 2012, as shown in Figure 1. The top backup roll allows one spray header to be installed due to the limited space, and the bottom allows for two headers to be installed. Six flat-fan spray nozzles were mounted on each header. The top and bottom spray distances from the roll surface are 12 inches and 18 inches, respectively.

In the application of roll lubrication technology to the reversing hot rolling mills, several concerns arise, i.e., bite and roll slippage and effectiveness. This paper studies the mechanism of roll lubrication of the reversing hot rolling mill theoretically and investigates the effect of the roll lubrication on mill separating force, torque, and backup roll profile and roll wear practically.

Figure 1



Configuration of lubricant headers.

Mechanism of Roll Lubrication in Hot Rolling

Since Tselikov[1] built a dry-slipping model in 1939 to predict the normal pressure in the roll bite by inducing external friction and tension, the importance of roll lubrication has been realized. The roll lubrication not only reduces mill separating force and torque, but also improves the surface quality of strip. One suspicion for hot rolling is that lubricants might burn off.

In the late 1960s, the term "tribology" was discussed widely. The new discipline of tribology occurred all over the world. In the early 1970s, roll lubrication for hot rolling was revisited by several scientists.[2–4] The first experiment[3] was performed on a laboratory mill by using cast rolls and mineral oil. When the 10% concentration of mineral oil was sprayed into the roll bite, the frictional coefficient was reduced by 25%. Surprisingly, the lubricant did not burn off. Afterward, the roll lubrication in hot rolling was not paid sufficient attention since more overpowered mills were designed and installed.

Entering the 21st century, two significant subjects were brought up in the steel industry, i.e., consolidation and carbon footprints. Mills with low energy efficiency were gradually dismissed. Existing mills faced the challenge of expanding their capability and enhancing product quality. Hot strip mills began to apply the roll lubrication technology. Past studies reveal that roll lubrication can reduce the mill separating force/torque[5] and the tertiary scale thickness.[6]

For a 4-high hot rolling mill, roll lubrication occurs in two zones, i.e., the contact zone between the work roll and backup roll and the deforming zone in the roll bite. Since elastic deformation exists in the contact zone and plastic deformation in the deforming zone, the lubrication mechanism of the two zones shall be investigated.

Friction Between Work Roll and Backup Roll — To maintain the stability of the roll stack during the reversing pass, the work rolls were deviated horizontally toward the exit from the centerline of the backup rolls. The purpose of the deviation was to eliminate the clearance between the chocks and the mill window liners. Since the single stand of a reversing hot roll mill is used for roughing and finishing passes by driving the work rolls, the hardness of the work rolls is specified as 78–80 HSC, and the hardness of the backup rolls is specified as 64–68 HSC. The purpose of using the relatively soft backup rolls was to avoid the slippage of rolls and to improve the toughness and flexibility of the backup rolls.

Since the backup rolls are driven by the work rolls, normal pressure and tangential traction exist on the interface of the rolls. For two parallel cylinders under a frictionless condition, Hertz[7] already derived a solution of normal pressure. When the friction exists in the contact, normal pressure and tangential traction are described as follows:[8]

$$p_b(x) = \frac{2P_b}{\pi a}\sqrt{1-\left(\frac{x}{a}\right)^2}$$

(Eq. 1)

$$q_b(x) = \mu_b \frac{2P_b}{\pi a}\sqrt{1-\left(\frac{x}{a}\right)^2}$$

(Eq. 2)

where

$p_b(x)$ = normal pressure,

$q_b(x)$ = tangential traction,

P_b = specific separating force,

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μ_b = coefficient of dry friction and

a = contact half-width.

Normally, the backup rolls are dry. The tangential traction is subjected to Coulomb's dry friction law. The stress status of the contact zone is demonstrated in Figure 2.

When a backup roll is lubricated, the friction of the contact zone is no longer subject to Coulomb's dry friction law due to the emergence of lubricant film. In fact, the backup roll and work roll surfaces are inhomogeneous. The lubricant can deposit in small valleys and enter the contact zone. With the increase of the normal pressure, roll flattening also increases. Although the lubricant is compressive to a certain extent, its volume change is not comparable to the amount of flattening at the center of the contact zone. Therefore, the lubricant in the valleys is squeezed out, which forms a film on the interface of the rolls. The lubricant film takes over part of the normal pressure and reduces the normal pressure and tangential traction at the peaks. The mixed friction, i.e., a combination of dry and wet friction, occurs in the zone. At the entry and exit of the contact zone, the lubricant can be squeezed out of the contact zone due to small flattening deformation. The friction at the entry and exit is still treated as dry friction, as shown in Figure 3. The mixed friction of the contact can be simplified as follows:[9]

$$q_b(x) = \mu_b \frac{2P_b}{\pi a}\left[\sqrt{1-\left(\frac{x}{a}\right)^2} - \frac{c}{a}\sqrt{1-\left(\frac{x}{c}\right)^2}\right] \qquad c \geq x \geq -c$$

(Eq. 3)

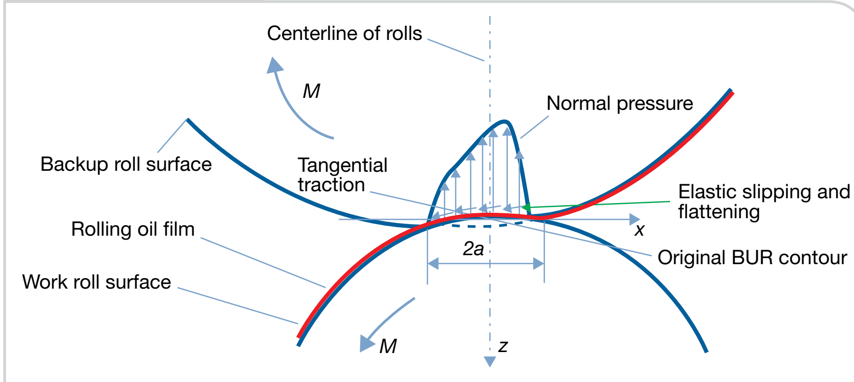
where c = half the width of the mixed friction.

Friction Between the Work Roll and the Workpiece

— The friction coefficient of hot rolling depends on roll surface roughness, rolling temperature, rolling speed, slab chemistry and lubrication. The typical friction coefficient in the roll bite is about 0.3. Friction status of hot rolling is not classified as easily as cold rolling, due to scale, which acts like a solid lubricant. The formation of scale is determined mainly by the slab chemistry and temperature. In addition, the reheating thermal history and atmosphere (oxygen content and furnace pressure) of the slabs also play an important role in forming scale.

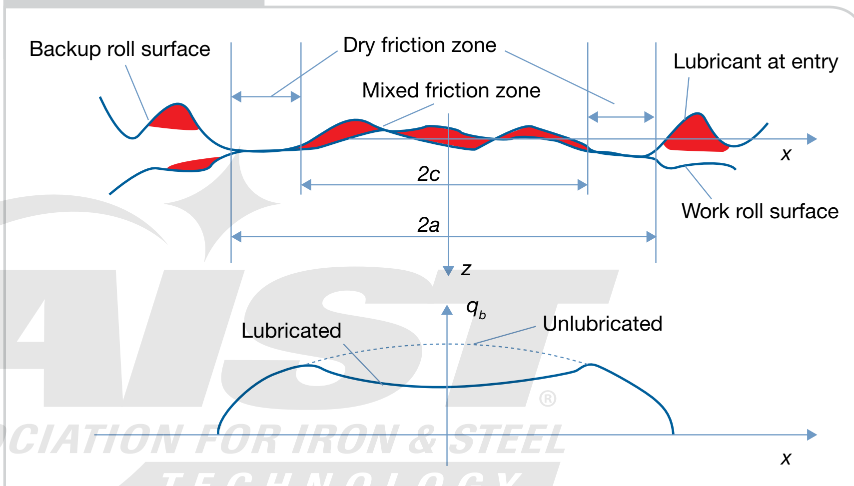
It is well known that slabs out of reheating furnaces contain ternary scale on the surface. From the surface to the substrate, the ternary scale is ordered in hematite (Fe_2O_3), magnetite (Fe_3O_4) and wüstite (FeO). The distribution of their thicknesses has been discussed in Reference 10. If the primary scale is not cleaned off by descaling, the friction coefficient in the roll bite can drop down to 0.15–0.20. The reason is that sliding easily occurs in the soft wüstite layer that possesses a relatively

Figure 2



Normal pressure and tangential traction of the contact zone.

Figure 3



Dry friction and mixed friction in the contact zone.

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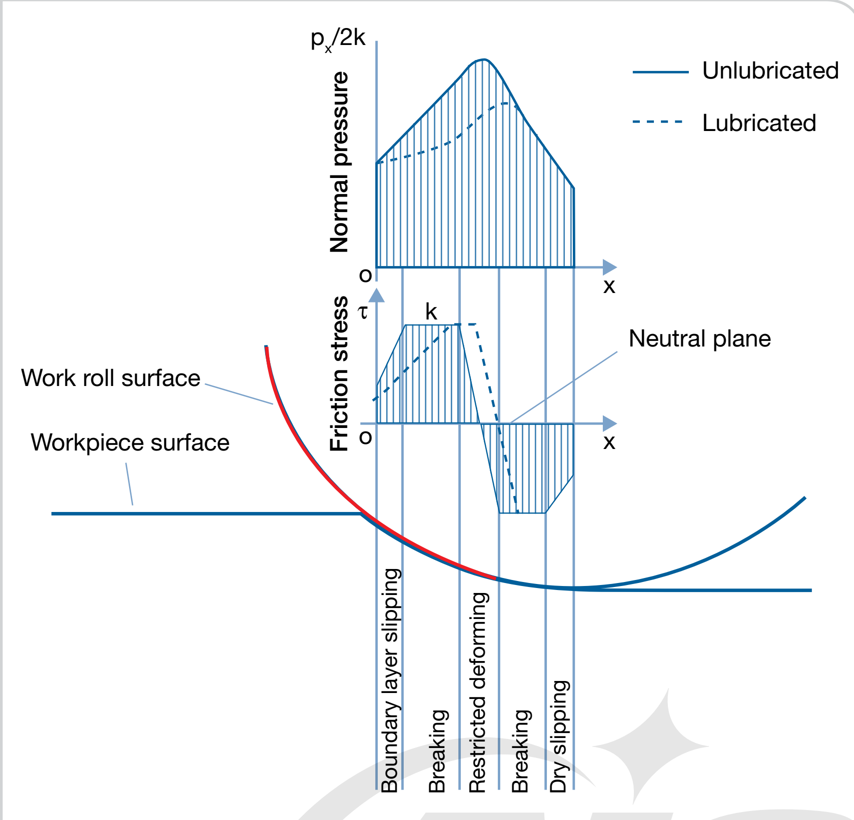
Figure 4



Friction stress and normal pressure in the roll bite.

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lower melting point (2,511°F) than that of hematite and magnetite layers (2,851–2,896°F). Moreover, the wüstite layer of silicon-added steel possibly hides fayalite ($2FeO \cdot SiO_2$) with a melting point of 2,192°F.

In the roll bite, friction along the projected arc length can be divided into five segments, as shown in Figure 4. Since the lubricant is carried from the backup roll and the projected arc length of the roll bite is much greater than the contact width between the rolls, there is a boundary layer slipping zone at the entry. The friction coefficient of the boundary layer slipping is much less than that of dry slipping. The slipping segment at the entry is extended, which results in shifting the neutral plane to the exit. The shift of the neutral plane produces two advantages: reducing the friction hill of normal pressure and the distance of its resultant from the roll centerline. This is the key point for lubrication to reduce mill separating force and torque. At the exit of the roll bite, its friction can be treated as dry slipping since less lubricant remains on the work roll surface. The lubricant is most likely consumed prior to the neutral plane due to the backward slip of metal.

The friction status in the roll bite depends on the aspect ratio of the roll bite, which is defined as the projected arc length divided by the average gauge between the entry and exit. For example, the incoming slab is rolled from 5.25 inches thick to a finish gauge of 0.188 inch by using a 15-pass schedule. Since the aspect ratio of the roll bite is between 0.6 and 3.5 (less than 5.0), friction stress is much less than the shear strength of steel. Breaking zones could be neglected. The aspect ratio rises from the first roughing pass to the last finishing pass gradually. The normal pressure in the roll bite is derived as follows:[1]

Boundary layer slipping zone:

$$p_x = \frac{2k}{\delta_0}\left[\left(\varepsilon_0\delta_0 - 1\right)\left(\frac{h_0}{h_x}\right)^{\delta_0} + 1\right]$$

(Eq. 4)

Dry slipping zone:

$$p_x = \frac{2k}{\delta_1}\left[\left(\varepsilon_1\delta_1 - 1\right)\left(\frac{h_x}{h_1}\right)^{\delta_1} - 1\right]$$

(Eq. 5)

Restricted deforming zone:

$$p_x = p_c\left[\mu A\left(h_c - h_x - h_n \ln\frac{h_c}{h_x}\right) + 1\right] - 2k\ln\frac{h_c}{h_x}$$

(Eq. 6)

where

$$\varepsilon_0 = 1 - \frac{\sigma_0}{2k},$$

$$\varepsilon_1 = 1 - \frac{\sigma_1}{2k},$$

$$\delta_0 = \frac{\mu_0}{\tan\theta_0},$$

$$\delta_1 = \frac{\mu_1}{\tan\theta_1},$$

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$$\mu = \frac{1}{2}(\mu_0 + \mu_1),$$

$$A = [(h_c - h_n)\tan\theta_2]^{-1}$$

$2k$ = flow stress of the workpiece,

k = yield stress in shear,

σ_0, σ_1 = back and front tensile stress of the workpiece,

μ_0, μ_1 = friction coefficient at the entry and exit in the roll bite,

h_0, h_1 = thickness of the workpiece at the entry and exit in the roll bite,

h_n, h_c, h_x = thickness of the workpiece at the neutral plane, intersection between the boundary slipping zone and restricted deforming zone, and distance x from the entry,

θ_0, θ_1, θ_2 = angle with respect to the centerline of the workpiece and chords of the boundary layer slipping zone, dry slipping zone and restricted deforming zone and

p_c = normal pressure at the intersection between the boundary slipping zone and restricted deforming zone.

Generally, the aspect ratio of the roughing pass is less than 2.0. The lengths of the entry and exit slipping zones are very short. The boundary layer slipping zone and dry slipping zone could be also ignored. Equation 6 could be used to evaluate the normal pressure. When the aspect ratio of the roughing pass is greater than 2.0, the friction status of the finishing pass is composed of the boundary layer slipping zone, restricted deforming zone and dry slipping zone. The undetermined geometric parameters, h_c and θ_2, can be obtained by combination of Equation 6 with Equations 4 and 5.

In view of Equations 4–6, it is obvious that the friction coefficient has a significant influence on the normal pressure. The application of roll lubrication reduces not only the torque produced by the normal pressure in the roll bite, but also the torque generated by the friction between the backup roll and work roll. In summary, the lubricant is more effective in the mill with the aspect ratio of the roll bite within 0.5–5.0, since the breaking zones do not exist.

Chemistry and Tribology of Roll Lubricant — The hot rolling environment is very different from that found in cold rolling, where roll lubrication is a necessity. Due to the more extreme environment in hot rolling, specifically the elevated temperatures, roll lubricant chemistry must be altered. The lubricant must contain compounds that can survive in this extreme environment for the duration of time they are needed. Additionally, to avoid slippage and bite refusal, any remaining organic components must be destroyed in the rolling process.

These fluids are standardly classified as class 1, class 2 or class 3 roll bite lubricants. Lubricants in class 1 are petroleum oil-based formulations that may contain synthetic esters, vegetable oils or animal-derived triglycerides. Class 2 lubricants contain the same petroleum oil base as those in class 1, but differ due to anti-wear and extreme pressure additives. Class 2 lubricants may also contain dispersant agents. The newest class of roll bite lubricants, class 3, are petroleum-based formulations with controlled burn-off synthetic materials, extreme pressure and anti-wear additives, surface-reactive agents, and carefully selected dispersant agents.

The surface-reactive agents mentioned in this section are unique to hot rolling lubricants and allow the lubricant to react with metal surfaces before entering the heat and pressure found in the roll bite. These specific chemistries form a very thin, sacrificial layer on the rolls. Because this reaction occurs at ambient temperatures outside the roll bite and does not require additional pressure, class 3 roll bite lubricants are excellent for application to backup rolls.

As discussed, the purpose of roll bite lubrication is to reduce the coefficient of friction in the roll bite. With class 3 hot rolling lubricants, this is accomplished through plate-out and a uniform film thickness. The film thickness provides a combination of elastohydrodynamic and boundary lubrication regimes. Due to the reactive chemistry of this specific lubricant class, the greatest benefits are realized through boundary lubrication.

On-Line Experiment

For a 4-high reversing hot rolling mill with work roll driving by employing lubricant, a few concerns need to be clarified, i.e., slippage between the backup roll and work roll and the critical bite angle of roughing passes.

Excessive lubrication may cause backup roll slippage during acceleration and deceleration and difficulty for table rolls to feed slabs into the roll bite. Since the acceleration of the mill is restricted to 0.2

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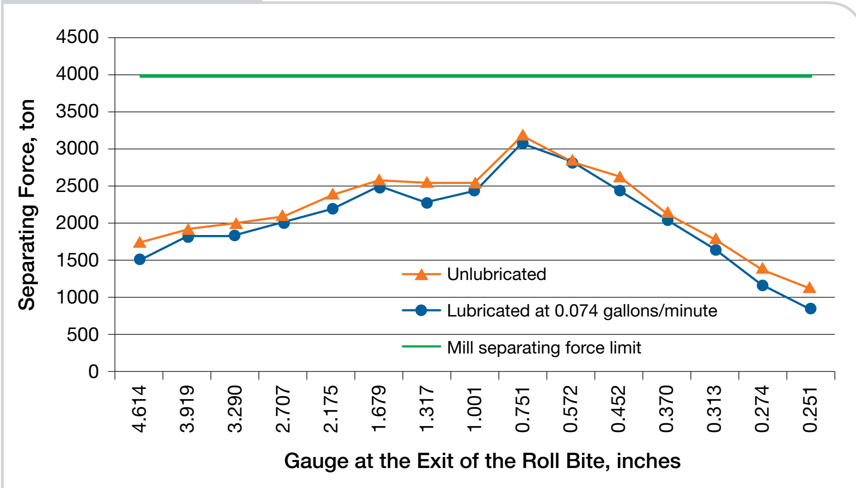
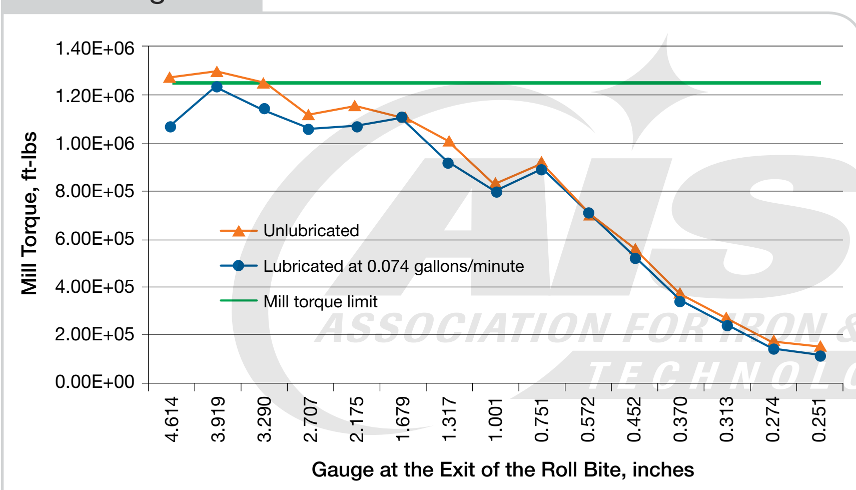
Figure 5



The effect of lubricant on separating force.

Figure 6



The effect of lubricant on mill torque.

g maximum and the lubricant is applied under a stable rolling state, only the bite angle needs to be examined. The stable bite condition is described as follows:

$$\mu_0 > \tan\left(\frac{\alpha}{2}\right)$$

(Eq. 7)

where α = bite angle.

For 5.25-inch slabs, the bite angle under 20% reduction is 15.16°. From Equation 7, the friction coefficient in the roll bite must be greater than 0.133. Compared to the normal friction coefficient in hot rolling, 0.3, there is great potential for the mill to reduce the friction coefficient.

To validate the effect of roll lubrication on the mill separating force and torque, a spray header was installed on the bottom backup roll. Six 0.25-inch VeeJet nozzles were mounted on the header. The lubricant was injected into a water pipe via a portable pump and digital flow control valve. The flow control valve was set to 0, 0.037, 0.055 and 0.074 gallon/minute (gpm) while the mill rolled HSLA grade 50 slabs into 0.25-inch by 96-inch coils.

Under the flowrate of lubricant at 0.037 gpm, a few passes showed the reduction of the mill separating force and torque. When the flowrate was increased to 0.055 gpm, more passes displayed the reduction. When the lubricant flowrate was set to 0.074 gpm, the actual mill separating force and torque demonstrated a significant reduction from roughing passes to finishing passes, as shown in Figures 5 and 6.

In Figure 5, it can be seen that the highest separating force occurred in the first finishing pass that intended to build a high strip crown for improving stability of thread by using 25% reduction. The finishing passes are defined as the passes with gauge less than 1 inch thick. In the finishing passes, the strip went on Steckel drums that establish the front and back tensions. The early roughing and late finishing passes showed a significant reduction of separating force. Although the separating force is under the mill limit, reducing the separating force in the last three finishing passes provides the flexibility for the rolling operators to control the shape of the strip.

From Figure 6, it can be seen that there was higher torque in the first three roughing passes without using lubricant. Roughing pass 2 exceeded the mill torque limit slightly, which caused the mill to slow down. The loss in speed may generate the fire cracks of work rolls and enlarge the temperature variation

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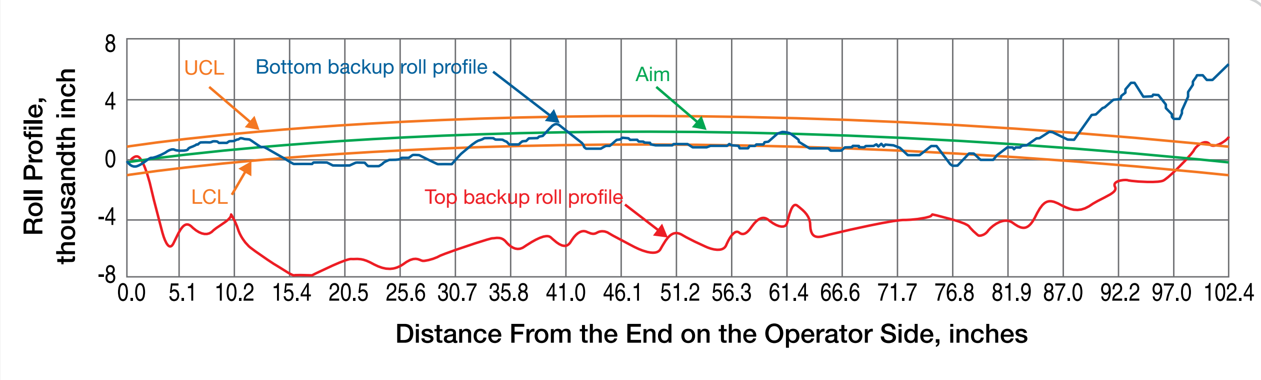
Figure 7



Profiles of the unlubricated backup rolls after 5.27 million linear feet.

within the bar. After adding lubricant, the actual mill torque is under its limit. The mill rolled the strip smoothly and coiled the strip successfully.

As mentioned previously, the surface scale and temperature, as well as roughness of the workpiece, also have a significant impact on the mill separating force and torque. This may explain why the reduction margin of the mill separating force and torque varies pass by pass.

Validation of Lubricant Performance

The on-line experiment demonstrates that the roll lubrication can deliver the result as analyzed theoretically. To investigate the effect of lubricant on the wear of the backup rolls, the lubricant flowrate was set to 0.015 gpm as the minimum level, and the nozzles were set to 1.0 gpm under a pressure of 40 psi. The lubricant concentration after mixing water is 0.063%.

By means of the Pro-Mic profile meter, two backup roll cycles were tracked under the similar product mix. The profiles of the unlubricated backup rolls are shown in Figure 7, and the profiles of the lubricated backup rolls in Figure 8. The backup rolls started at 0.002 inch of crown. In the case of no lubrication, Figure 7 shows that the crowns of the top and bottom backup rolls after 5.27 million linear feet were worn 0.010 and 0.004 inch, respectively. In order to reveal the advantage of roll lubrication, Figure 8 shows that the crowns of the top and bottom backup rolls after 9.99 million linear feet were worn 0.008 and 0.002 inch, respectively. The profile wear of the lubricated backup rolls is much less than that of the unlubricated, although the linear footage is almost doubled. In addition, the lubricated profiles tend to favor the symmetric distribution, which is beneficial to shape control of the strip.

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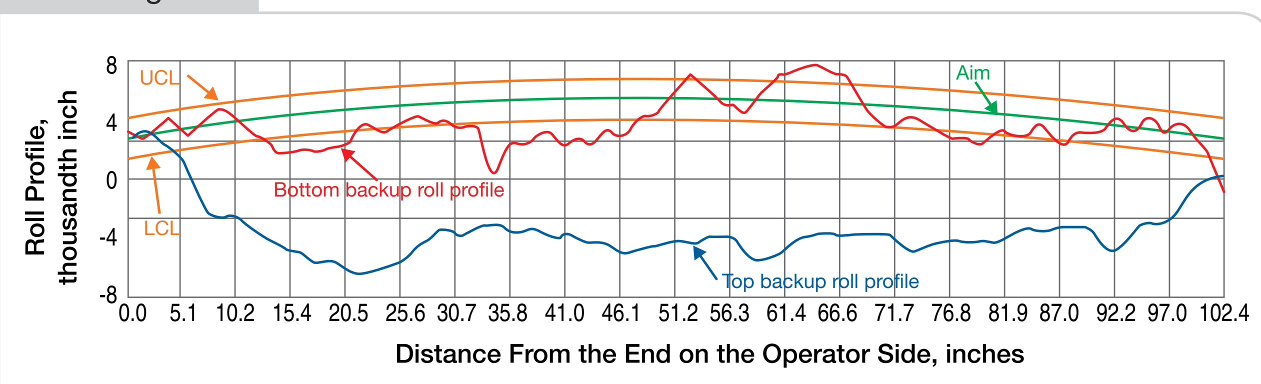
Figure 8



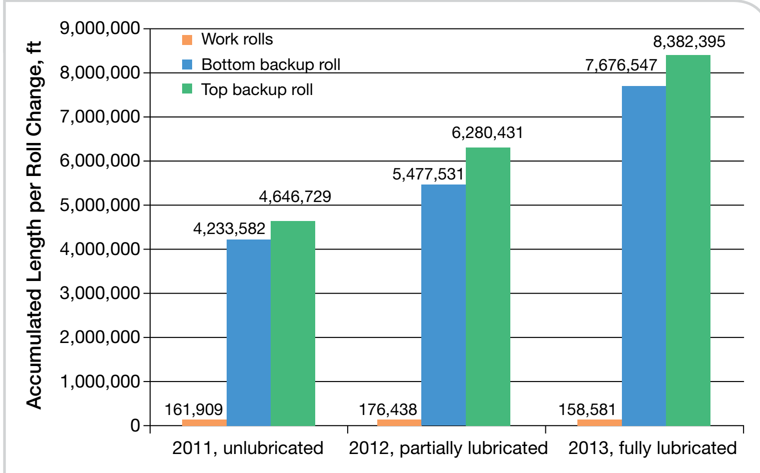
Profiles of the lubricated backup rolls after 9.99 million linear feet.

In Figures 7 and 8, it is noted that the top backup rolls were worn much more than the bottom backup rolls. Two factors may contribute to this phenomenon: inertia force of the backup rolls and the amount of fluid between rolls. Since automatic gauge control (AGC) capsules sit on the chocks of the top backup rolls, the frequent adjustment of its servo system will generate additional normal pressure between the rolls due to its fast response. On the other hand, it is hard to keep water or lubricant between the top work roll and top backup roll.

There are many uncertainties that affect consumption of roll stock. Besides roll quality, roll service life is significantly impacted by roll lubrication, product mix, pass schedule and product quality requirements. The annual average linear footages of roll changes are shown in Figure 9. In Figure 9, it can be seen that both top and bottom backup rolls had their service lives extended considerably. The linear footage of the bottom backup roll is less than that of the top backup roll. The reason is that the bottom backup roll is easily bruised by the fallen primary scale and slab kerfs. To maintain the constant contact barrel length and to avoid propagation of the localized microcracks, the bottom backup roll is changed more than the top backup roll. The work roll service life is influenced mainly by product mix and gauge profile. There is a small variation in linear footage of work roll change over a three-year period.

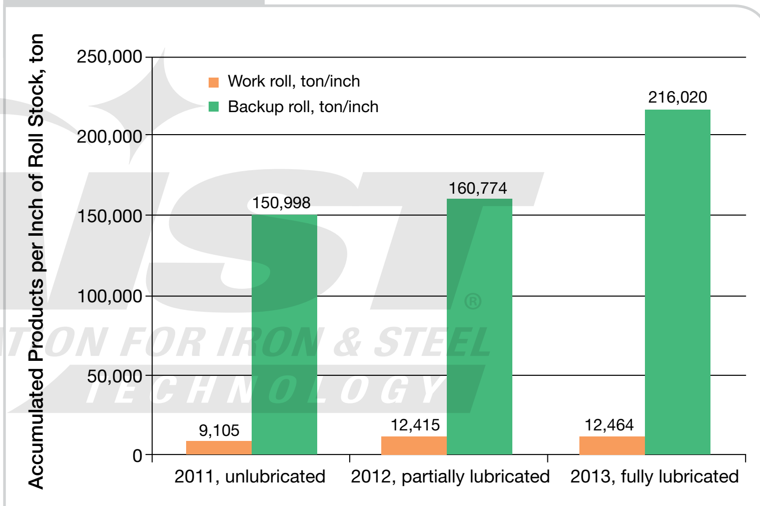
In steel mills, the tonnage produced per inch of roll stock is commonly used for analysis of roll cost and control of roll inventory. The tonnage of 1-inch roll stock is shown in Figure 10. In Figure 10, it can be observed that the tonnage of the backup roll stock rose sharply after roll lubrication was applied. With higher tonnage, fewer roll changes are required, which results in the reduction of roll change time, especially for the backup rolls.

Figure 9



Average linear feet of roll changes.

Figure 10



Coils/plates produced per inch of roll stock.

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Summary

This study described the mechanism of lubrication in the roll system and investigated the effect of lubricant on the rolling parameters of the 4-high reversing hot rolling mill, i.e., mill separating force and torque. Based on a lengthy trial, the collection of mill data proves that lubricant is still applicable to reversing hot rolling mills. The mechanism and benefits of the backup roll lubrication in the reversing hot rolling mill are summarized as follows:

- Lubricating the backup rolls forms a mixed friction zone that reduces the normal pressure and friction traction between the backup rolls and work rolls. The wear of the backup rolls decreases significantly. When the lubricant is set to 0.015 gpm, the service lives of the backup rolls are doubled. The result not only reduces roll cost, but also increases utilization of the mill due to fewer roll changes needed.
- The lubricant can be carried to the roll bite. The lubrication at the entry establishes a boundary layer slipping zone instead of dry friction, which pushes the neutral plane toward the exit of the roll bite. The increase of the slipping zones relatively reduces the length of the breaking zone. This feature prompts the mill separating force and torques to decrease. By lubricating a single backup roll, the trial result demonstrates that the average force and torque over all passes reduced by 8% when the lubricant was set to 0.074 gpm.
- The lubricant is more effective for the mill or pass with the aspect ratio of the roll bite within 0.5–5.0, since the breaking zones do not exist. Although the friction at the roll bite and between the rolls decreases, their friction coefficients are far away from the roll bite friction and roll slippage criteria. The bite and roll slippage are no longer concerned.

In addition, the direct lubrication to the roll bite and the influence of lubricant on plate surface quality will be researched in a further study.

Acknowledgments

The authors would like to recognize the dedication of Kip Robertson and Donny Venable to the lubrication project. Also, the authors want to thank all of the mill technicians at Nucor Steel Tuscaloosa Inc. for their collaboration.

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