Development of Gap Correction and Recovery Functions for Thickness Control of Head End in Hot-Rolled Steel

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INTRODUCTION

In response to growing global attention on reducing carbon emissions, the automotive industry has faced increasingly stringent environmental regulations. One key strategy to meet these requirements is the lightweighting of steel components. However, the addition of advanced safety and comfort features in modern vehicles has led to a gradual increase in total vehicle weight. To address these competing demands, there is a growing need for manufacturing technologies capable of producing ultra-thin hot-rolled steel sheets that maintain high strength while reducing material usage [1].

Accurate production of hot-rolled products to meet customer-specified target thickness is a critical requirement for ensuring both productivity and quality. This challenge becomes even more pronounced when rolling high-strength steel to thicknesses below 2 mm, where the material's elevated flow stress and reduced thickness margin demand highly precise control strategies. While achieving uniform thickness along the entire strip length is important, the head end of the strip poses the greatest technical difficulty due to process uncertainties and control limitations [2].

The head end is particularly sensitive because it reflects the initial conditions of the rolling process in real time, and any deviations in thickness or temperature can critically affect overall product quality. Furthermore, deviations in head-end thickness frequently lead to early-stage quality deterioration and necessitate physical trimming of the coil, which reduces yield and efficiency. As such, head-end thickness control is not a localized issue, but a key determinant of overall dimensional stability and final product performance [3,4].

Two primary challenges hinder precise control of head-end thickness. First, the actual bar thickness after the roughing mill is not directly measured, but rather estimated based on slab dimensions and predefined reduction schedules. Any deviation between predicted and actual bar thickness can cause the final head-end thickness to miss the target. Second, the rapid temperature drops at the head end due to air cooling increases the material strength, further complicating precise thickness control.

Consequently, excessive thickness at the head end often necessitates additional trimming operations, resulting in increased material handling, higher environmental burden, and reduced yield, all of which contribute to economic loss.

To mitigate these issues, a Gap Correction algorithm based on roll gap offset control was introduced in this study. The function dynamically adjusts the roll gap at each finishing mill stand using a predetermined gain (Gap Correction Value), calculated to suppress excessive head-end thickness. However, as previously noted, uncertainties in bar thickness and thermal loss at the head end can lead to overcorrection, whereby the applied gap correction may result in thickness undershoot.

To compensate for this risk, a Recovery function was additionally implemented. This function is designed to regulate the effects of overcorrection by gradually adjusting the roll gap after the head end and before the automatic gauge control (AGC) becomes fully active. By progressively opening or closing the roll gap during this transitional zone, the Recovery function mitigates abrupt thickness deviations and ensures a stable handoff to subsequent control stages.

Through the combined application of the Gap Correction and Recovery functions, this study successfully improved head-end thickness control during hot rolling of high-strength steel sheets. The proposed control strategy effectively reduced head-end over-thickness and contributed to simultaneous improvements in product quality and operational efficiency.

Keywords: Hot rolling, Finishing Mill, Gap Correction, Thickness

EXPERIMENTAL PROCEDURE

Gap Correction

In this study, a series of hot rolling experiments were conducted on various steel grades to evaluate the effectiveness of the Gap Correction and Recovery functions. Fig. 1 presents the strip thickness profile of a representative low-carbon steel, to which the proposed control method was applied. As discussed in the Introduction, the thickness at the head end of the strip typically exceeds the target thickness due to initial control limitations, and the Gap Correction strategy was introduced to mitigate this issue.

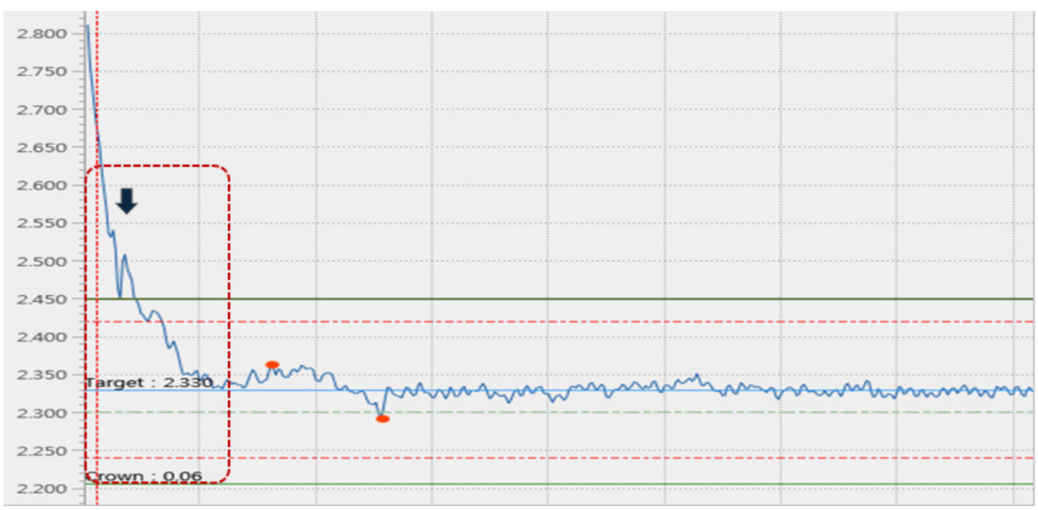

Fig. 1. Thickness profile at the head end of a low-carbon steel strip.

$$S_i^{setup} = S_i^{model} - \Delta S_i^{hdcor} \quad (1)$$

$$\Delta S_i^{hdcor} = \Delta S_{F\_cor}(gain) \times \frac{h_0 - h_i}{h_0 - h_F} \quad (2)$$

The model described in Equation (1), hereafter referred to as S_i^{model}, calculates the roll gap (in mm) for each stand based on the L2 model output. The corresponding S_i^{setup} denotes the final roll gap setting, incorporating the correction values applied to the S_i^{model} output. As shown in Equation (2), the term ΔS_i^{hdcor} represents the roll gap correction value for each stand, while ΔS_{F_cor} is the correction parameter used in the Gap Correction logic. In addition, hi indicates the calculated strip thickness at stand i, where i = 0 refers to the bar thickness and i = F corresponds to the exit thickness at Stand F7.

The rolling experiments were conducted not only on low-carbon steel but also on high-strength steels with tensile strengths exceeding 60K grade(kgf/mm2). In total, more than three steel grades were evaluated. To assess the effectiveness of the Gap Correction function, the correction parameter ΔS_{F_cor} was varied in the gap-closing direction, with test values set at various values. In addition, gap-opening trials were also performed under specific conditions to evaluate performance asymmetry. For this, ΔS_{F_cor} various values were applied specifically to Stand F7.

These tests enabled a comparative analysis of head-end thickness behavior and sensitivity under different correction settings. Furthermore, to prevent excessive roll gap adjustments resulting from aggressive gap correction and to ensure stable transition to automatic gauge control (AGC), a complementary Recovery function was also implemented. The operational principle of this function is illustrated in Fig. 2.

The Recovery function becomes active after the head-end region and before AGC control is fully engaged. It serves to compensate for potential thickness deviations—either undershoot or overshoot—caused by mismatch between the pre-applied Gap Correction setting and actual rolling conditions. Specifically, when rolling proceeds with the final roll gap that includes Gap Correction, the Recovery function gradually adjusts the roll gap (either opening or closing) in the transition region to maintain dimensional stability.

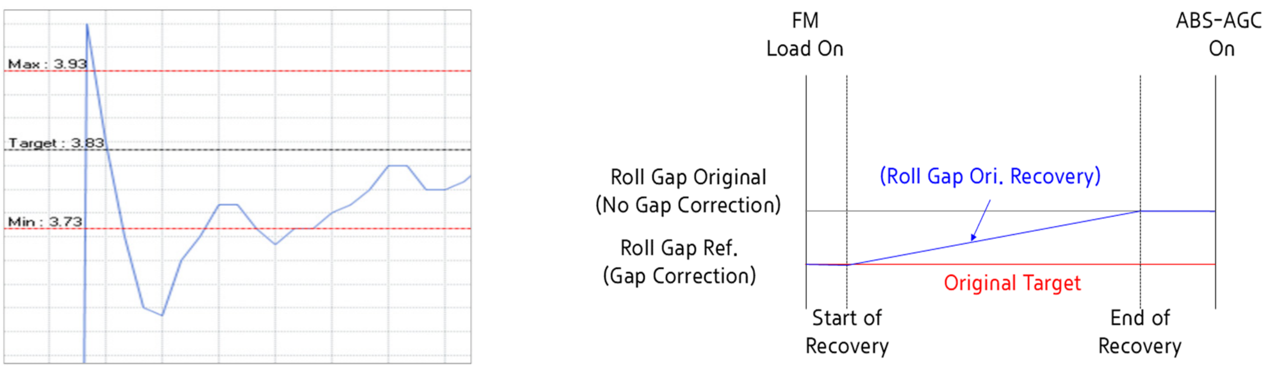

Fig. 2. (a) Head-end thickness undershoot profile and (b) schematic image of the Recovery control function.

RESULTS & DISCUSSION

Improvement of Thickness Accuracy via Gap Correction at Strip Head End

The Gap Correction function can be defined as a roll gap offset control technique designed to compensate for thickness deviations—either overshoot or undershoot—occurring at the head end of the strip. In this control framework, the roll gap for each stand is initially computed by the Level 2 (L2) model. A correction value is then applied to this computed value to produce the final roll gap setting (S_i^{setup}), which is subsequently transmitted to the Level 1 (L1) automation system for actual implementation.

Fig. 3(a) presents a representative head-end thickness profile for a low-carbon steel strip. As illustrated, the head-end region exhibits a clear overshoot beyond the upper thickness tolerance limit (indicated by the red dashed line), with the measured thickness exceeding the target value by approximately 400 µm. This phenomenon is attributed to the excessive cooling of the head-end portion just prior to entry into the finishing mill (FM), which leads to a substantial increase in material strength. Under such conditions, the roll force calculated by the model is insufficient to achieve the desired reduction, resulting in an over-thickness defect at the strip head. This represents a commonly encountered issue in hot strip mills worldwide and remains a persistent quality challenge across the industry.

Excessive head-end thickness often necessitates trimming during the correction stage, which increases production costs and reduces material yield. To address this issue, a controlled offset was intentionally introduced by narrowing the roll gap (Gap Close) in the head-end region. The resulting thickness profile is shown in Fig. 3(b). In contrast to Fig. 3(a), the modified roll gap condition effectively reduced the head-end overshoot to approximately 70 µm, well within the specified tolerance range (red circle). This corresponds to an approximate six-fold improvement in thickness accuracy, confirming the efficacy of the Gap Correction strategy in mitigating head-end thickness errors.

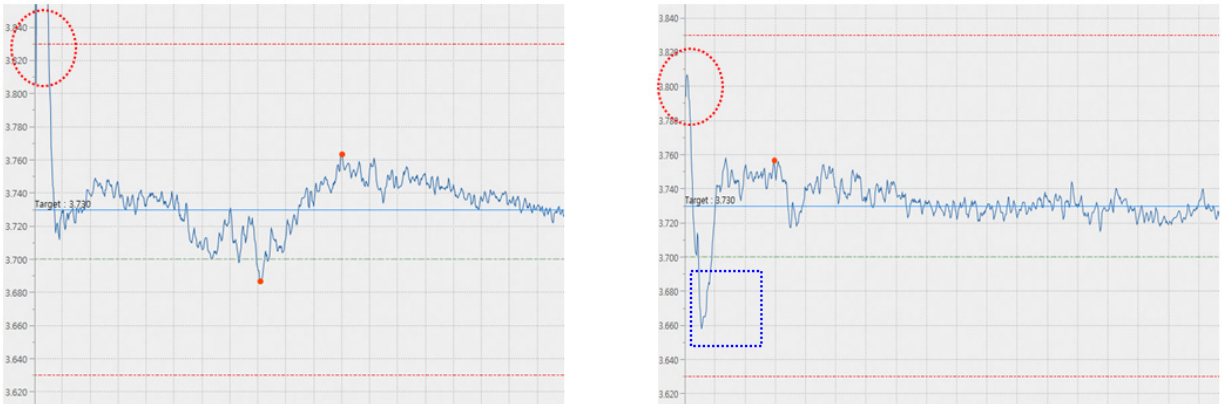

Fig. 3. (a) Thickness profile before applying Gap Correction and (b) thickness profile after applying Gap Correction.

Recovery Function for Stabilizing Head-End Thickness

However, as shown in the region marked with a blue dashed box in Fig. 3(b), localized areas exhibited excessive reduction, indicating that the roll gap was closed more than necessary. Although the thickness remained within the minimum tolerance limit and did not result in an undershoot defect, the degree of over-reduction approached the lower threshold. In extreme cases, such behavior could lead to thickness undershoot, thereby increasing the trimming length and negatively affecting material yield. This highlights the necessity of addressing potential over-control phenomena associated with the Gap Correction strategy.

Fig. 4 displays the thickness profile obtained after the Recovery function was implemented in conjunction with the Gap Correction control. As shown, the head-end thickness was effectively maintained within the maximum tolerance range, while no undershoot beyond the minimum tolerance limit was observed. These results indicate that the Recovery function successfully compensated for the excessive correction following Gap Correction, stabilizing the head-end thickness.

Furthermore, the control performance was validated through analysis of the electrical signal history, as presented in Fig. 5. The Gap Correction parameter was set to -0.2, confirming that the gap-close adjustment was properly applied. The Gap Feedback signal initially indicated movement in the closing direction, followed by a gradual shift toward the opening direction, which coincided with a progressive increase in the AGC Gap Correction Reference signal. This coordinated signal behavior confirms that the Recovery function was activated at the appropriate time, and that thickness control was maintained consistently within the specified tolerance range throughout the transition.

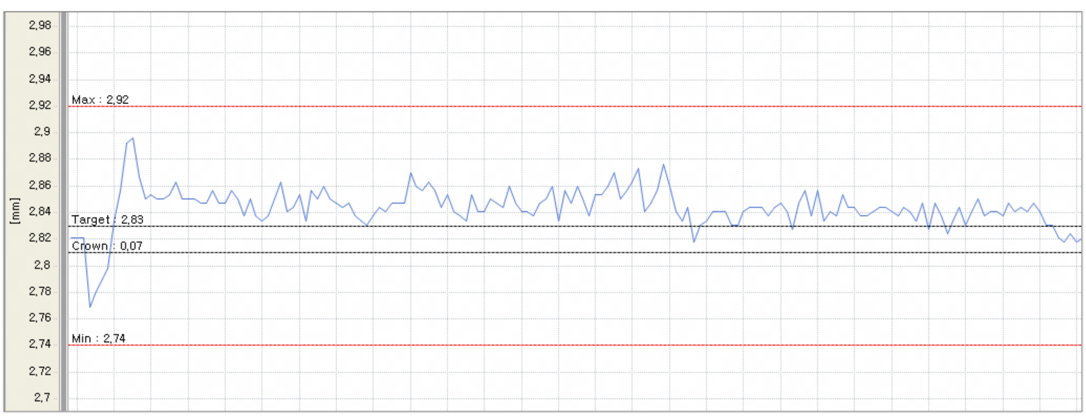

Fig. 4. Thickness profile after applying Gap Correction with Recovery function.

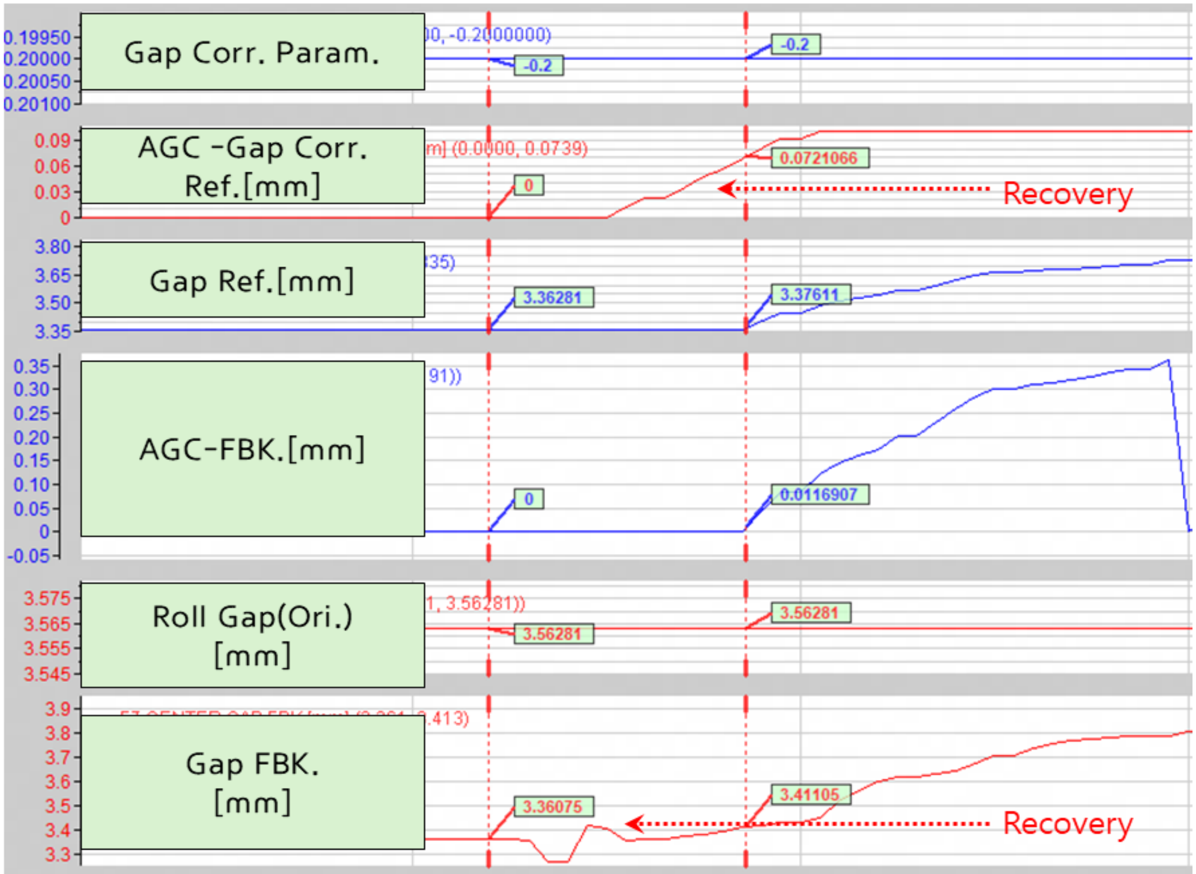

Fig. 5. Electrical signal data (IBA) during application of the Recovery function.

Application of Gap Open Control for Roll and Strip Surface Protection

In addition to its primary role in head-end thickness control, the Gap Correction function is also recognized as a versatile control strategy with potential benefits for improving work roll integrity and strip surface quality. Fig. 6 illustrates the surface condition of a work roll used for rolling patterned steel sheets. As highlighted in the yellow circled region, partial damage is observed on the patterned marks engraved on the roll surface.

Such localized damage is attributed to the non-uniform distribution of roll force across the width of the patterned roll, which differs from that of conventional flat work rolls. Due to stress concentration in specific areas, the embossed patterns are more susceptible to mechanical failure under standard rolling loads.

To address this issue, a Gap Open control condition was selectively applied to the affected stand using the Gap Correction function. As a result, no further damage was observed on the patterned regions, indicating that localized reduction of roll force effectively mitigated the mechanical stress and improved roll durability. This control strategy is schematically illustrated in Fig. 7.

Moreover, similar surface damage mechanisms may also occur in standard pickled and oiled (PO) hot-rolled steels, where descaling (black scale) detachment or micro-defects on the work roll surface can induce surface scale-related defects on the strip. In such cases, Gap Open control can be strategically applied to specific stands prone to repeated roll surface degradation, thereby preventing roll damage and its associated strip defects.

Experimental observations under selected conditions have already demonstrated the beneficial effects of Gap Correction in reducing roll-related surface defects. Further trials and optimization of process parameters are expected to quantify and validate its effectiveness more systematically for both work roll protection and strip surface quality enhancement. These findings suggest that the Gap Correction function is a promising and expandable control technique, capable of improving not only dimensional accuracy but also the surface integrity of both rolls and products in hot rolling operations.

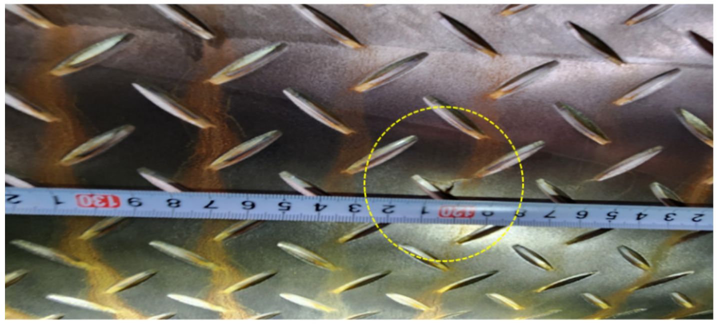

Fig. 6. Pattern defects observed on the surface of a work roll surface.

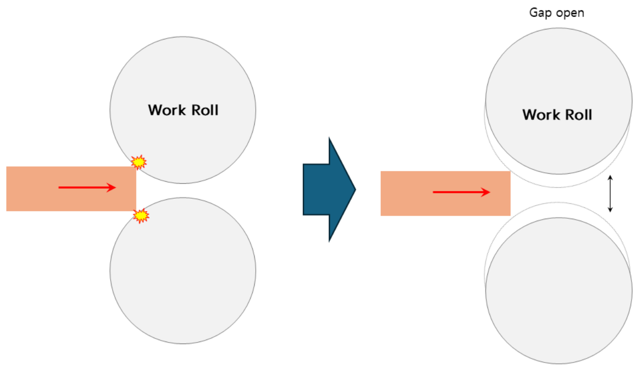

Fig. 7. Schematic image of Gap Correction with Gap Open control.

CONCLUSIONS

This study focused on addressing the most critical and challenging task in hot strip rolling: the precise control of head-end thickness deviations.

To achieve this, the Gap Correction and Recovery functions were implemented as control strategies targeting dimensional stability in the head region.

The Gap Correction function effectively suppressed excessive thickness at the head end through model-based roll gap offset adjustments, while the Recovery function mitigated the risk of thickness undershoot caused by overcorrection. Together, they enabled stable and accurate thickness control within the target tolerance range at the head end of the strip.

The effectiveness and operational timing of these functions were validated through electrical signal (IBA) feedback analysis, confirming their robustness and applicability to real-time industrial operations.

Additionally, exploratory tests using Gap Open control suggested potential applicability in scenarios such as localized stress mitigation on patterned work rolls or prevention of scale-related surface defects in PO steels. While these results are preliminary, they indicate the potential for broader use of the control logic in surface-related defect management.

In conclusion, the Gap Correction function has been demonstrated as a core control mechanism for head-end thickness precision, offering high reliability and scalability. With further tuning under various rolling conditions, this approach is expected to significantly enhance both product quality and yield in hot rolling operations.

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